From the Earth to the Moon: Economic Viability of Commercial Spaceports & Science and Technology Planning for MIT Lunar Exploration

by

Rebecca Leigh Browder

B.S., Mechanical Engineering, University of Oklahoma (2015)

Submitted to the Institute for Data, Systems and Society
and Department of Aeronautics and Astronautics
in partial fulfillment of the requirements for the degrees of
Master of Science in Technology and Policy
and
Master of Science in Aeronautics and Astronautics
at the
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
June 2021

Author . . . .
Institute for Data, Systems and Society
and Department of Aeronautics and Astronautics
May 17, 2021

Certified by . . . .
Dava J. Newman
Apollo Program Professor of Aeronautics and Astronautics
Thesis Supervisor

Accepted by . . . .
Noelle E. Selin
Director, Technology and Policy Program
Associate Professor, Institute for Data, Systems, and Society and
Department of Earth, Atmospheric and Planetary Sciences

Accepted by . . . .
Zoltan Spakovszky
Professor, Aeronautics and Astronautics
Chair, Graduate Program Committee

From the Earth to the Moon: Economic Viability of Commercial Spaceports & Science and Technology Planning for MIT Lunar Exploration

by

Rebecca Leigh Browder

Submitted to the Institute for Data, Systems and Society
and Department of Aeronautics and Astronautics
on May 17, 2021, in partial fulfillment of the
requirements for the degrees of
Master of Science in Technology and Policy
and
Master of Science in Aeronautics and Astronautics

Abstract

Despite an overcapacity of launch sites in comparison to demand, there are 11 existing commercial spaceports in the United States and at least another six under consideration. While a spaceport can bring economic growth and STEM development to a region, it requires significant and sustained investments of public funding in an uncertain and volatile market. This thesis conducts a two-case study of the Mid-Atlantic Regional Spaceport (MARS) in Virginia and Spaceport America (SA) in New Mexico, incorporating four analysis methods: financial, business case, economic impact, and profitability. A cross-case analysis studies both cases and reveals lessons learned and recommendations for other commercial spaceports. This research employs a multidisciplinary approach, incorporating policy, economic and business analysis to help policymakers, regulators and the general public understand the operations and impact of commercial spaceports that will enhance stakeholders' decision-making about proposed spaceports. Ultimately, an improved understanding of commercial spaceports will allow this network of infrastructure to support continued innovation and growth in the commercial space sector.

As the commercial space sector continues to expand through efforts like the first civilian trip to the International Space Station, commercial spaceports will become critical infrastructure to future commercial missions to the Moon. With the renewed global interest in exploring the lunar surface, there is a shift from the Apollo program in that NASA aims to establish a significant number of commercial partnerships.

As countries and companies around the world aim to return to the Moon, including the U.S. through NASA's Artemis Program, MIT has an opportunity to leverage its knowledge and resources to be part of the next phase of Moon missions. MIT has significant experience in lunar science and exploration, from the early days of the Apollo Program to more recent missions like GRAIL (2011) and collaborations with Israel's Beresheet mission (2019). MIT is well poised to leverage both its lunar experience and its science and technology expertise to assist in returning humans to the Moon. This thesis presents an analysis of MIT's unique areas of expertise and its alignment with prominent science and technology goals in order to develop a strategic plan to bring together the entire MIT community to achieve them. Through the use of MIT's Lunar Open Architecture and extensive data collection, the author has developed a science traceability matrix and a technology multi-domain matrix that are the first step toward charting the future of MIT lunar exploration. This strategic planning exercise revealed many areas of mutual interest among research groups at MIT as well as a broad interest in creating a cohesive, organized strategy for MIT's next steps on the lunar surface. This work will help the MIT community optimize its efforts toward lunar exploration, maximize investments into lunar research, and develop a cohesive plan for MIT's role in future lunar exploration. This work also serves as a case study for how a large, complex organization can develop a strategic plan for deep space exploration that leverages its resources while meeting high-level, external science goals. By following the plan laid out in this paper, MIT can add to its expertise in lunar exploration, gather new scientific knowledge, and be part of the team that lands the first woman and the next man on the Moon.

Thesis Supervisor: Dava J. Newman
Title: Apollo Program Professor of Aeronautics and Astronautics

Acknowledgments

While academic theses and dissertations appear to be the work of a single individual, any successful one is the product of guidance, feedback, and the kind ears of numerous advisers, colleagues, friends, and family members. This thesis would not have possible without the support network that I cherish so dearly.

First, significant thanks go to my research adviser, Dr. Dava Newman. You have taught me so much about space exploration and leadership, especially the importance of prioritizing principles over rules. Thank you for investing in me, for connecting me with amazing research partners and industry experts, and for showing me the importance of building community. The most important piece of advice I give to prospective students is to pick an adviser they like, because the student-adviser relationship can make or break the grad school experience. I am so fortunate to have worked with you for the past three years and truly believe that you are one of the best advisers at MIT. A substantial part of my very positive experience at MIT comes from working with you.

One of the best things Dava has done for me was connecting me with Mehak Sarang and Ariel Ekblaw in MIT's Space Exploration Initiative. I have had way too much fun working in this incredible four-woman working group and am so grateful that I was able to write my AeroAstro thesis in collaboration with Mehak and Ariel after working together informally for more than a year. Mehak: thanks for being my partner in Moon crime and for balancing my practicality with ambitious dreams. Ariel: thanks for believing in me and helping me see a whole new world of career opportunities. Thanks also to Elissa for UROPing with me and uncovering fascinating lessons about MIT's history in lunar exploration.

Special thanks go to my informal "thesis committee," the people who have generously offered their time to help shape my thesis. Dave Thompson and Matt Weinzierl invested serious time my work, helping to frame my analysis and writing. Thanks also to Alex MacDonald, Mike French, Jane Kinney and Larry Susskind for helping me learn about spaceports and case study methodology.

I am grateful to the groups that funded my work for the past three years: the MIT Portugal Program, the MIT Technology and Policy Program's Research to Policy Engagement Initiative, and the MIT Media Lab's Space Exploration Initiative. I have learned so much from working with each group and will miss these interdisciplinary work environments.

Next, thank you to TPP and AeroAstro for bringing me into your communities. To Barb, Frank, Ed and Noelle: thanks for keeping TPP intact through a few tumultuous years, including a complete transition to Zoom university. I love this program and the people in it, and I can't wait to see where it goes in the coming years. I miss seeing you all in person but I hope we can celebrate appropriately at in-person graduation next year. To Beth, Liz and Joyce, thanks for keeping things together, especially after the pandemic hit. To GA3 and GWAE, thanks for always reminding me to have fun.

To my labmates in HSL, thanks for being the best lab around. Eric: thanks for teaching me that work should be fun and also how to create and seize opportunities. Brandon: thanks for showing me the importance of developing fulfilling hobbies and for always providing good feedback on communication. Rachel, Allison, Marc, and Alvin: thanks for being my first friends in the lab and for always being down to do something fun.

To the MELLTT team: we pulled off a crazy thing during an unprecedented global pandemic. You all inspire me. I can't wait until our tower launches to the Moon!

Thanks especially to Anna, the other half of the TPSS matriarchy and the person who brought out my fun side. The pandemic separated us so much earlier than expected—MIT is not the same without you. I miss you dearly and fully expect a crazy celebration with you when you come back for our joint graduations.

Thanks to my Oxford Street roommates, Hannah, Nolan and Tomas, for listening to me whenever I wanted to talk about spaceports. You've always done this, but your patience rose to heroic levels during quarantine when I didn't have other people around to share my newfound information with. And thanks to Jess, Will, Erin and Adrianna, who kept me sane during my last year of grad school and thesis writing season, both of which took place under the shroud of the global pandemic.

My MIT experience would not have been half as enjoyable without an amazing TPP cohort to share it with. Thanks to Sohum, Nic, Dylan, Sophia, Pedro, and Wade for our lounge chats, late-night philosophical discussions, and random adventures.

To Emily, Patrick, Susan and Jackie: the most difficult part of coming to MIT was leaving Houston behind. I miss you all so much. Thank you for listening during the several weeks in which I debated my grad school choice and for supporting me throughout my time here.

To my other far-flung friends, particularly Savannah and Kaitlin, thank you for your support and providing perspective to my complaints about grad school. Thanks also to the MechEs, Bri, Sarah, Brent, Alex, Aaron and Scott, for encouraging me since day one and being the most generous group of humans I know.

For my siblings, Laura, Jim and Jennifer: thanks for helping me grow up and cultivating my interest in school. Laura: you inspire me. I'm so excited that we'll be in the same city again and can't wait for our many trips to bookstores. Jim: thanks for always reminding me that some rules should be broken and for setting an impossibly high standard with your spouse. Jennifer: thanks for being my first cheerleader.

Finally, thank you to my parents for their constant support ever since I took my first step on a different path, namely turning down the only full-time engineering job offer I had to take a minimum-wage policy internship in DC. You both have such passion for your work, which inspired me to seek out my own passion and to now be pursuing it with everything I have. Your unwavering commitment to family and doing the right thing is truly incredible and serves as my guidepost during difficult times.

"It's a lesson that I've learned over and over again but it bears repeating. No one achieves anything alone." - Leslie Knope

Having never been especially interested in science fiction, it was only after creating the title for my thesis that I realized Jules Verne had written a book with the same

name. I bought and read it to make sure I did my due diligence for research, and there are two pieces that are particularly relevant to this thesis. The first is relevant to spaceports, and the second to planning a mission to the Moon:

"It will now be easy to understand why the rivalry between Texas and Florida was so great, and why the Texans were so irritated when their claims were dismissed by the Gun Club's choice. In their farsighted wisdom they had realized what a region could gain from Barbicane's project, and the benefits that would flow from such a mighty cannon shot. Texas had lost a great business center, railroads, and a considerable growth in population. All these advantages had gone to that wretched Florida peninsula, lying like a breakwater between the Atlantic and the Gulf of Mexico. Barbicane was therefore no more popular in Texas than General Santa Anna."

"Since it was important that such a serious discussion should not be disturbed by the cries of the stomach, the four members of the Gun Club sat down around a table covered with sandwiches and large teapots."

- Jules Verne, From the Earth to the Moon, 1865

Contents

THIS PAGE INTENTIONALLY LEFT BLANK

List of Figures

THIS PAGE INTENTIONALLY LEFT BLANK

List of Tables

Chapter 1

Introduction to Commercial Spaceports

1.1 Motivation

Over the past 10 years, there has been a flurry of activity in the space industry as private investment in space companies has increased dramatically [Bryce Space and Technology LLC, 2020], the U.S. federal government has shifted its relationship from "oversight" to "insight," and visiting space has become more accessible [1]. In the context of this activity, people both inside and outside of the industry must plan for a future that can accommodate potential expansion while preparing for the chance that the projected growth doesn't happen. This tension exists throughout the industry and is especially evident in the topic of commercial spaceports. Despite a current overcapacity of space launch sites in comparison to demand, many communities around the world are considering their own space launch site in the hopes of a future surge in demand that could bring economic growth to their region. However, spaceports cost on the order of $200 million to build and usually required a sustained investment of public money. While the regulatory issues of spaceports are complex, this thesis focuses on the economic viability of commercial spaceports and aims to begin closing

[1] Some of the work in this chapter was published in a conference paper [Browder and Newman, 2019].

the knowledge gap on the topic in order to help policymakers and communities decide if a proposed spaceport is a good investment.

In the current state, there is “a significant overcapacity of launch services" for commercial launches with "little growth expected" in demand [International Space University, 2008]. This statement from the International Space University is reinforced by looking at U.S. data for 2019 (Figure 1-1) [Federal Aviation Administration, 2020b, Reimold, 2018, Bryce Space and Technology, 2019, Messier, 2019a], which shows there were only 2 launches per launch site in the U.S. that year. In contrast to this overcapacity, there are numerous new spaceports being considered throughout the U.S. [Robert, 2017, Kubota, 2019, Hughes, 2018, Wilkinson, 2019] and around the world [Reimold, 2018, Gulliver, 2016, Pappalardo, 2019, Ompusunggu, 2017] (the exact number of proposed spaceports is difficult to track as some plans fizzle out and other proposals emerge). Figure 1-2 shows a map of 21 proposed spaceports that were up for consideration as of July 2019. This trend of proposing spaceports may be partially explained by industry projections. Three reputable investment banks (Goldman Sachs, Morgan Stanley, and Bank of America Merrill Lynch) separately predicted that the space industry will grow to around $1 trillion (about triple its current size) by the 2040s [Foust, 2018]. These projections captured the attention of the industry and policymakers, and may explain why so many spaceports are being proposed in spite of overcapacity: policymakers and communities want to secure first mover advantage by being ready for future space launch demand if it materializes. Industry, governments and the public therefore have to make choices about spaceports in the context of both overcapacity and predicted growth, which is complicated by questions of economic viability, regulations and policy. While the regulatory issues of commercial spaceports are complex, economic viability is a more pressing concern, according to conversations with industry experts. Therefore, this research project focuses on the issue of economic viability of commercial spaceports.

The question of economic viability of commercial spaceports is not new. In fact, the question arose as early as 1996, when the state of Alaska aimed "to develop an economically feasible spaceport," as reported in a research paper written in 1997 by

Major John W. Raymond, who is now the first person to lead the United States Space Force [Raymond, 1997].

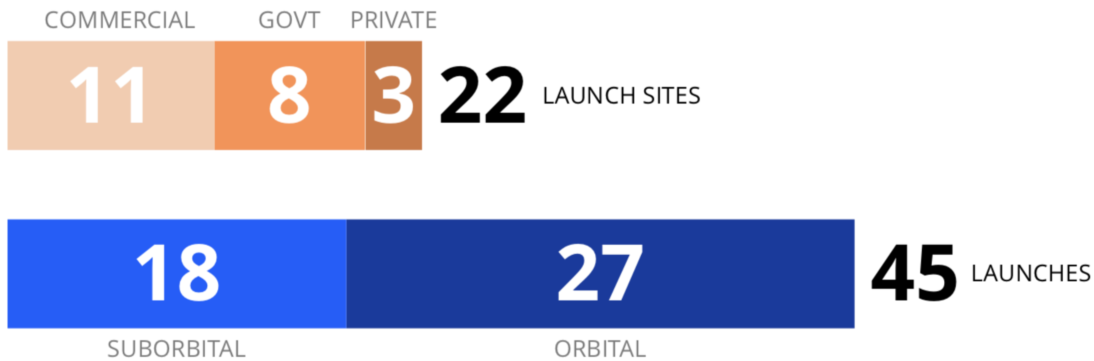


Figure 1-1: Number of launch sites compared to number of launches in the United States for 2019.

Within the topic of economic viability, there are two major issues: 1) a gap in knowledge about existing spaceports and 2) an individual actor problem. Each issue is described briefly below, and this thesis focuses on issue #1.

While some work on commercial spaceports has been published, there has not been a publicly-available effort to perform a broad economic study about the state of the spaceport market. There is no consolidated, publicly available data about the costs and benefits of a spaceport, particularly in terms of finances. This concerns public policy because spaceports require a significant investment of taxpayer dollars. Although there are cases of private companies building their own launch sites (e.g., Blue Origin in Van Horn, TX and SpaceX in Boca Chica, TX), these large infrastructure projects are typically undertaken by governments and cost a substantial amount. According to spaceport consultant Brian Gulliver, a new spaceport costs more than $230 million in FY 2021 dollars [Gulliver et al., 2012]. Investments into Spaceport America and the Mid-Atlantic Regional Spaceport (MARS) verify this number: the state of New Mexico spent $220 million building Spaceport America [Burrington, 2018, Moss Adams LLP, 2020b], and the Virginia Commercial Space Flight Authority (VCSFA, a state agency) spent approximately $170 million on launch pad infrastructure, based on a review of their annual financial reports [Commonwealth of Virginia Auditor of Public Accounts, 1998, Commonwealth of Virginia Auditor

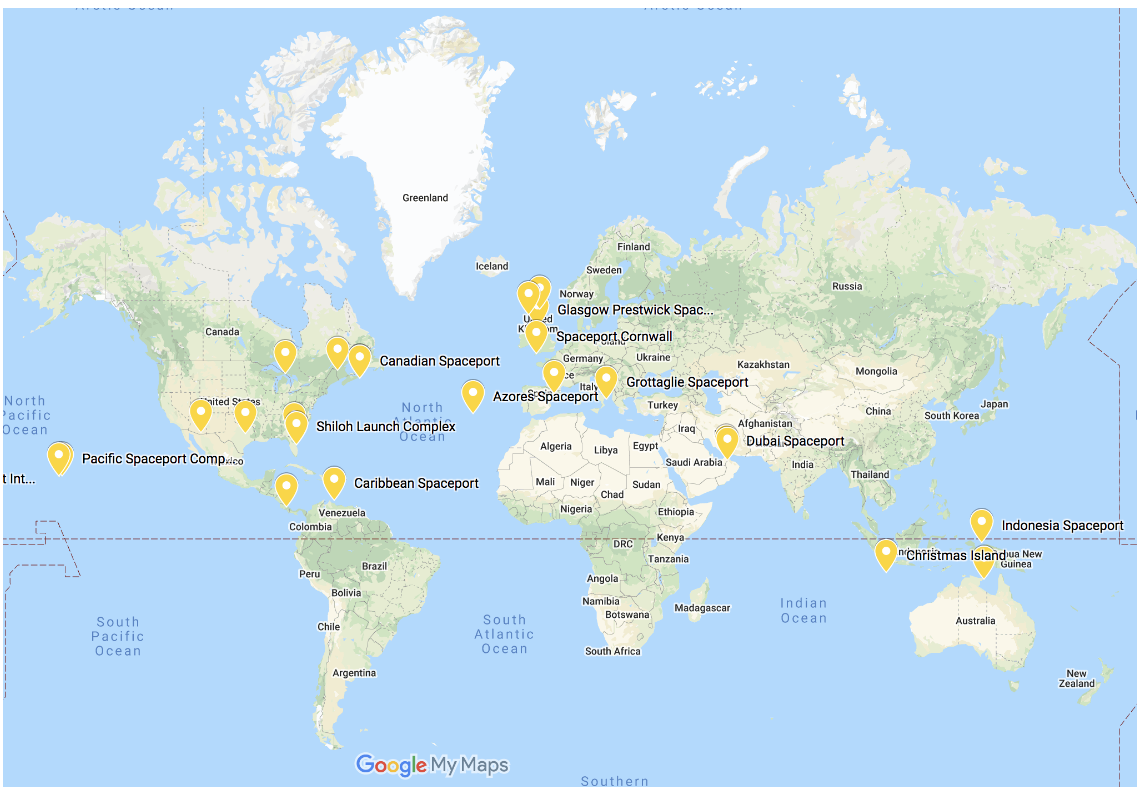


Figure 1-2: Proposed spaceports around the world. Map constructed by the author, last updated in July 2019.

of Public Accounts, 1999, Commonwealth of Virginia Auditor of Public Accounts, 2000, Commonwealth of Virginia Auditor of Public Accounts, 2001, Commonwealth of Virginia Auditor of Public Accounts, 2002, Commonwealth of Virginia Auditor of Public Accounts, 2003, Commonwealth of Virginia Auditor of Public Accounts, 2004, Commonwealth of Virginia Auditor of Public Accounts, 2005, Commonwealth of Virginia Auditor of Public Accounts, 2006, Commonwealth of Virginia Auditor of Public Accounts, 2007, Commonwealth of Virginia Auditor of Public Accounts, 2008, Commonwealth of Virginia Auditor of Public Accounts, 2009, Commonwealth of Virginia Auditor of Public Accounts, 2010, Commonwealth of Virginia Auditor of Public Accounts, 2011, Dixon Hughes Goodman LLP, 2012, Dixon Hughes Goodman LLP, 2013, Dixon Hughes Goodman LLP, 2014, Dixon Hughes Goodman LLP, 2015, Dixon Hughes Goodman LLP, 2016, Dixon Hughes Goodman LLP, 2017, Dixon Hughes Goodman LLP, 2018].

In addition, new commercial spaceports are frequently considered at a local or regional level, rather than at a national or industry level, creating an individual actor problem. With this structure, each individual is incentivized by the promise of economic growth to pursue their own spaceport, and they don't coordinate as a larger group. This means that decisions aren't being made based on the launch demand in a country or in the world, resulting in many competing spaceport proposals. If all the proposed projects become operational spaceports, it could create a glut in the space launch market at the detriment to all actors.

As the commercial space industry continues to grow, policymakers and investors want to know how to determine if and when commercial spaceports are a good investment. This question is not easy to answer: while financial statements can be analyzed, a spaceport is an investment in infrastructure, which is often supplemented by governments. In these cases, objectives are different from those of a private business: rather than focusing on pure return on investment, a state and its residents may invest in order to achieve economic gains or improvements in STEM education and development. A financial analysis alone does not answer the question of whether or not a commercial spaceport is a worthwhile investment for a state, but it is a useful first step.

This thesis focuses on the issue of the knowledge gap and aims to begin closing it, which will be integral to planning for the future of the space launch market.

In order to fill the knowledge gap about economic viability, a two-case study of commercial spaceports was conducted, focusing on the Mid-Atlantic Regional Spaceport in Virginia and Spaceport America in New Mexico. Each case incorporates a financial analysis, a historical review of the business case, information about economic impact, and a profit model. Chapter 2 covers the two cases and Chapter 3 summarizes lessons learned and recommendations from performing a cross-case analysis.

This work can support decision-making of policymakers, industry, regulators and the public. In particular, this information can help people to decide when individual commercial spaceports are a good investment, how to coordinate across the entire US market of spaceports, and how to develop policies that support continued innovation and growth in the commercial space sector while protecting taxpayer dollars.

1.2 Problem Formulation

1.2.1 Research Questions

In order to address the question of economic viability of commercial spaceports, a few research questions were developed. These questions center on understanding what commercial spaceports are, why they exist, how they work, and whether they are beneficial to the governments that invest in them.

- How do commercial spaceports operate?
  - Finances, economic impact
- Why do people build spaceports?
  - Motivations, context, decisions of policymakers
- How do spaceports affect the local community?

  - Support/lack thereof; economic impact/lack thereof; taxes

1.2.2 Rationale

The decision to focus on economic viability stemmed from conversations with three industry experts:

- Alex MacDonald, Chief Economist, NASA
- Mike French, Vice President of Space Systems, Aerospace Industries Association
- Scott Pace, Executive Secretary, US National Space Council

MacDonald, French and Pace all said that the main question concerning commercial spaceports was whether there would be enough demand to support them. All three agreed that regulatory issues are challenging, but are a smaller hurdle.

From all the potential research methodologies that could have been leveraged to study economic viability of commercial spaceports, a two-case study emerged as the beset option for a few reasons:

- Case studies focus on "how" and "why" questions, which are the focus of this work
- Case studies do not require control of behavioral events, which is not possible in the case of commercial spaceports
- Case studies are useful for studying a phenomenon and its context, which is important because the context surrounding commercial spaceports helps to explain why they exist
- Case studies are useful for developing analytical generalizations rather than statistical generalizations, which is useful since statistical generalizations would be difficult for such a small sample size

In order to scope the research for this Master's thesis, the candidate cases were limited to commercial spaceports in the United States. This decision was made for a few reasons:

- Including cases under different regulatory regimes would add complexity, making cross-case analysis difficult
  - The US has a unique regulatory regime and is leading the world in spaceport regulation development
  - Other countries, including Portugal, are looking to US spaceport policy for their own policy design; mixing US and international cases would make this difficult to account for
- Data and site access will be easier for US sites than for international sites

1.3 Research Methodology

1.3.1 Overview of Case Study Methodology

One of the most pressing questions about commercial spaceports is, "are they economically viable?" In order to answer that question, more information is needed to understand how existing commercial spaceports operate. After an initial exploration phase to discover that economic viability is a major open question on this topic, this work focused on descriptive research to build up information about how commercial spaceports operate, why people build them, and how they affect the local community.

To answer these questions, a research method was selected. Table 1.1 outlines three questions to guide selection of the appropriate research method: 1) the form of research question, 2) the control of behavioral events, and 3) contemporary vs historical events. The question of economic viability of commercial spaceports incorporates "how and why" questions ("how do commercial spaceports operate?" and "why do people want them?"), as well as "who, what, where, how many, how much" questions ("who pursues them?" "how many are there?" "how much money do they make?"). In terms of behavioral events, a study of commercial spaceports can have no control. As for contemporary vs. historical, commercial spaceports are a contemporary trend. Answering these three questions narrows down suitable research methods to

Table 1.1: Relevant situations for different research methods [Yin, 2014]

Method	(1) Form of Research Question	(2) Requires Control of Behavioral Events?	(3) Focuses on Contemporary Events?
Experiment	how, why?	yes	yes
Survey	who, what, where, how many, how much?	no	yes
Archival Analysis	who, what, where, how many, how much?	no	yes/no
History	how, why?	no	no
Case Study	how, why?	no	yes

survey, archival analysis and case study. This thesis encompasses a two-case study that incorporates archival analysis.

Robert Yin outlines a twofold definition of a case study [Yin, 2014]:

- "A case study is an empirical inquiry that
  - investigates a contemporary phenomenon (the "case") in depth and within its real-world context, especially when
  - the boundaries between phenomenon and context may not be clearly evident
- A case study inquiry
  - copes with the technically distinctive situation in which there will be many more variables of interest than data points, and as one result
  - relies on multiple sources of evidence, with data needing to converge in a triangulating fashion, and as another result
  - benefits from the prior development of theoretical propositions to guide data collection and analysis"

In addition, Yin asserts that case studies are good at explaining how and why a phenomenon works, and that they're useful for analytical generalization rather than statistical generalizations. Cases should not be a sample, but rather "can shed empirical light about some theoretical concepts or principles." Given this information, a case study emerges as a suitable way for studying the phenomenon of commercial spaceports, in which there are few to study and each one is relatively unique, making the topic ripe for generalizing theories and unsuitable for generalizing statistics.

For this commercial spaceport study, two cases will be studied in-depth. Although a single case study was considered, it was rejected because single case studies are only useful in five rationales:

- Critical: a critical test of existing theory; theory has clear circumstances in which it should be true, and the single case can be used to determine whether or not the theory is correct
- Extreme/unusual: where the case deviates from the norm, but "the findings may reveal insights about normal processes" (i.e., clinical studies)
- Common: can reveal information about conditions of everyday
- Revelatory: when the researcher has an opportunity to study something that hasn't been accessible before (i.e., drug-dealing marketplace in Spanish Harlem)
- Longitudinal: studying the same case at multiple points in time

The focus of this work is to develop generalizable theories about how commercial spaceports operate, so it would be more useful to pursue a multiple-case study, which will eliminate unique circumstances that could arise in a single case and instead focus on conditions and results that are generalizable to more spaceports. Pursuing a multiple-case study requires more resources, but also results in more compelling analysis. In order to achieve more compelling results while also scoping the amount of work to a Master's thesis, two cases will be studied in-depth.

For each case, the research design will pursue holistic cases rather than embedded cases, meaning that it will focus on one unit of analysis rather than multiple units of analysis. A graphical comparison of single- vs multiple-case designs and holistic vs embedded cases is shown in Figure 1-3. An embedded case would include multiple levels of analysis: for example, the case could be the spaceport operator (e.g., the New Mexico Spaceport Authority) and subunits could include individuals within the organization. This study will focus on just one unit (the spaceport operator) and will not study subunits, thereby making it a holistic case.

Finally, the two cases will be selected following Yin's "replication logic." There are two types of replication: 1) literal replication, in which individual cases are selected to predict similar results or 2) theoretical replication, in which individual cases are selected to predict different results but for predictable reasons. This study aims to follow a theoretical replication in order to study how different spaceport characteristics affect outcomes. The specific cases will be selected in Section 1.3.3.

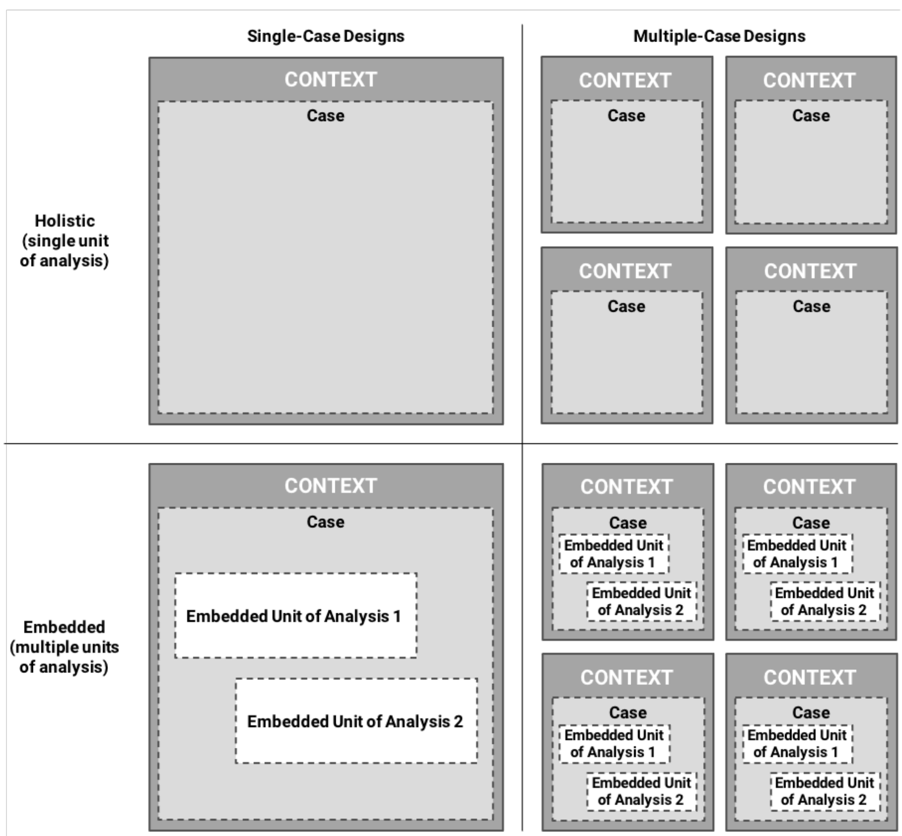


Figure 1-3: Basic Types of Designs for Case Studies (adapted from [Yin, 2014])

1.3.2 Methodology for Commercial Spaceport Case Study

A case study research design has five components, listed below. These components define the structure of the case study and will lead into detailed analytical methods for studying the economic viability of specific commercial spaceports.

1. Questions
2. Propositions
3. Unit(s) of analysis
4. Logic linking the data to the propositions
5. Criteria for interpreting the findings

The questions of this case study were detailed in Section 1.2 and are repeated below for reference.

- How do commercial spaceports operate?
- Why do people build spaceports?
- How do spaceports affect the local community?

Propositions are similar to hypotheses: they offer initial explanations to the research questions. The propositions that address operations, motivations and impact of commercial spaceports are:

- In order stay operational, a commercial spaceport needs either state financial support or customer demand; ideally, they'd have both.
  - Suspect that in most cases, state support will be required (Mojave could be an exception, but even they get some, although minor, state support)
  - Can show this through models about how many launches it would take to break even, and that it's an unrealistic number
  - Can compare to airport operational model

- States/people/policymakers build spaceports for prestige and economic growth
    - Think prestige is a bigger motivator since the economic growth has not been proven
- Spaceports have a significant impact on the local community because of traffic, noise, taxes, economic impact, STEM education and workforce impact
    - Traffic: supply chain movement and/or tourists
    - Noise: launches
    - Taxes: even Mojave, which has less state support than others, imposes a tax

The research questions guide the unit of analysis: a single commercial spaceport. Drawing a clear boundary around the unit of analysis will keep the work focused and clear. This includes both the physical infrastructure as well as the organizational infrastructure of the state agency running the spaceport. The unit of analysis is generally bound by when each spaceport began operating (defined as when it received its FAA license), up through the latest financial data available when this work began (FY2018 for MARS and FY2019 for Spaceport America). However, in order to incorporate historical context, some information about a spaceport prior to it becoming operational is included in each case.

The logic linking data to propositions relies on business and policy analysis. The data to be incorporated include annual financial reports, economic impact reports, news articles, and interviews. Four key methods of analysis, listed below, will link these data to the propositions. Each method is briefly described below, with detailed explanation in Chapter 2.

- A business financial analysis
- An analysis of how the business plan evolved over time
- A review of the economic impact

- A spaceport profit model

The business financial analysis incorporates standard business methodology to study the finances of commercial spaceports, which will reveal sources of money as well as if and how a spaceport breaks even. This links to the proposition that spaceports rely on state funding and customer demand to stay in business.

The analysis of the business plan over time reveals how commercial spaceports actually operate and how that differs from what people initially expected, which sheds light on how a spaceport stays financially operational and why policymakers pursue them as tools of economic growth.

The review of economic impact reveals the ways in which spaceports impact local economies and show how much impact they have.

The spaceport profit model incorporates details about capital costs of the infrastructure as well as marginal costs and revenues of launches, which will reveal the feasibility of relying on launch revenue alone to sustain a commercial spaceport.

Contribution

This two-case study can inform the development of a U.S. spaceport strategy, help other countries understand and make their own decisions about commercial spaceports, and improve U.S. regional policy-making for spaceports. While prior research into spaceports have explained their history and context [Pappalardo, 2019] and the complicated process of how to actually build one [International Space University, 2008], little public work has been done to understand whether there is a viable business plan for commercial spaceports. While the logistical and operational considerations are important, a viable business plan should precede operational considerations. This thesis aims to fill that gap by improving understanding of how commercial spaceports actually operate, focusing on whether they are economically viable.

A U.S. national spaceport strategy is not just a nice idea: it is an initiative that is currently under way. The concept of a national-level strategy for spaceports is not new: in fact, it was suggested as early as 1997 by John Raymond, the first and current head of the United States Space Force, in his graduate research paper at the

Air Command and Staff College [Raymond, 1997]. As Chief of Space Operations, General Raymond recently commissioned a study (published in August 2020) by the Aerospace Corporation to analyze the creation of a national spaceport strategy [Raymond and Browder, 2021, Commercial Space Transportation Advisory Committee (COMSTAC), 2021, Aerospace Corporation, 2020]. In particular, the Space Force wants to allow commercial launch providers to use federal launch sites when they're available, in order to support the growth of the commercial space sector. However, the federal ranges were designed for a different purpose and need to be updated to support commercial launches. General Raymond is pursuing the development of a national spaceport strategy that will bring together all the stakeholders to create a plan that balances the needs of the different communities involved.

Other countries are also looking into building commercial spaceports, as seen in the proliferation of proposed spaceports around the world shown in Figure 1-2. Many countries are looking to the United States as an example, since the U.S. is the current world leader in commercial space sector, particularly in commercial spaceports. This study on economic viability of commercial spaceports can inform their decision-making, particularly in lessons learned and recommendations (see Chapter 3).

Finally, this work can improve U.S. regional decision-making. With the growth in the commercial space sector, new proposed spaceports regularly pop up. Since this is a niche topic with little publicly available, rigorous research, many policymakers lack sufficient knowledge to make well-informed decisions about commercial spaceports. This work can fill a knowledge gap, providing information about lessons learned and recommendations from two states (Virginia and New Mexico) that have been working on commercial spaceports for about 20 years.

During the course of this project, the author has spoken to the Chief of Space Operations for the United States Space Force, a staffer for the United States National Space Council, and a staffer for the United States House of Representatives because all three organizations are figuring out their approach to commercial spaceports. This work can directly and immediately impact policy at both the national and regional levels.

1.3.3 Commercial Spaceport Mini Case Study Summary

In order to select the two cases for in-depth study, a mini case study was conducted. This involved a brief analysis of each commercial spaceport in the United States, culminating in a summary table for all 11 US commercial spaceports. The summary table is included here, with the full study in Appendix A.

In the United States, there are 11 commercial spaceports (as shown in Figure 1-4) [FAA/AST, 2020], using the term "commercial spaceport" to mean a non-federal launch site that is licensed by the Federal Aviation Administration (FAA). The mini case study focused on answering several questions for each commercial spaceport:

- What was proposed?
- Who proposed it and why?
- Who opposed it and why?
- What impacts/risks were raised and by whom?
- What regulators were involved and why/how?
- Who are the other key stakeholders?

Table 1.2 (augmented from two FAA tables [FAA Office of Commercial Space Transportation, 2018]) provides an overview of the 11 commercial spaceports in the United States, incorporating key information for selecting the final two case studies. From column 2 alone, six spaceports are eliminated from the running because they have not yet supported a space launch (although they may have supported other launch activities, such as a captive carry test). The remaining five cases are:

- Mojave Air and Space Port
- Spaceport America
- Cape Canaveral Spaceport
- Pacific Spaceport Complex Alaska

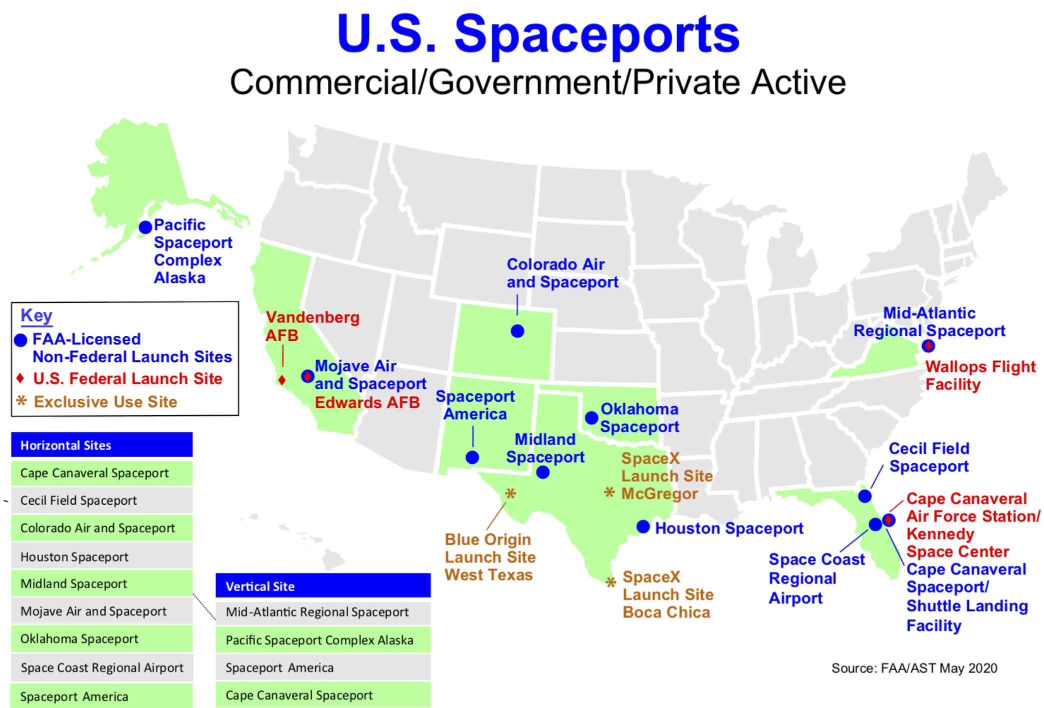


Figure 1-4: Map of all spaceports in the United States [FAA/AST, 2020]

- Mid-Atlantic Regional Spaceport

From these five cases, the author had unique access to information about the Mid-Atlantic Regional Spaceport (MARS), so it became the pilot case for the in-depth case studies. The access came from a class taught by MIT Hunsaker Visiting Professor Dave Thompson, retired founder and CEO of Orbital ATK, which is the anchor tenant at MARS.

From conversations with industry experts, it became clear that the Mojave Air and Space Port is a unique case that people should not attempt to recreate. Mojave is world-renowned as an experimental aerospace vehicle development facility; it has significant activity, but it is already filling the need for experimental facilities and should not be copied. Since this work aims to do a two-case study in order to facilitate broader generalizations, a unique case should not be included. Based on this information, Mojave was removed as a candidate.

Of the remaining three cases, the mini case study research resulted in Spaceport America emerging as the second case for in-depth study. Although Cape Canaveral

Table 1.2: Overview of all active U.S. commercial spaceports, last updated in July 2020.

Spaceport	Supported Space Launch?	Operator	State	Construction Type	Type of Launch Supported	License First Issued
Cecil Field Spaceport	No	Jacksonville Airport Authority	FL	Augmented airport	Takeoff/landing methods • Horizontal Spaceflight types • Suborbital • Orbital	2010
Midland International Air and Space Port	No	Midland International Airport	TX	Augmented airport	Takeoff/landing methods • Horizontal Spaceflight types • Suborbital	2014
Mojave Air and Space Port	Yes	East Kern Airport District	CA	Augmented airport	Takeoff/landing methods • Horizontal • Vertical Spaceflight types • Suborbital	2004
Spaceport America	Yes	New Mexico Spaceport Authority	NM	Greenfield	Takeoff/landing methods • Horizontal • Vertical Spaceflight types • Suborbital	2008
Cape Canaveral Spaceport*	Yes	Space Florida	FL	Federal transitioned to commercial	Takeoff/landing methods • Horizontal • Vertical Spaceflight types • Suborbital • Orbital	1999
Pacific Spaceport Complex Alaska	Yes	Alaska Aerospace Development Corporation	AK	Greenfield?	Takeoff/landing methods • Vertical Spaceflight types • Suborbital • Orbital	1998
Colorado Air and Space Port	No	Adams County	CO	Augmented airport	Takeoff/landing methods • Horizontal Spaceflight types • Suborbital	2018
Mid-Atlantic Regional Spaceport	Yes	Virginia Commercial Space Flight Authority	VA	Federal transitioned to commercial	Takeoff/landing methods • Vertical Spaceflight types • Suborbital • Orbital	1997
Oklahoma Spaceport	No	Oklahoma Space Industry Development Authority	OK	Augmented airport	Takeoff/landing methods • Horizontal Spaceflight types • Suborbital	2006
Houston Spaceport	No	Houston Airport System	TX	Augmented airport	Takeoff/landing methods • Horizontal Spaceflight types • Suborbital	2015
Space Coast Regional Air and Space Port	No	Titusville-Cocoa Airport Authority	FL	Augmented airport	Takeoff/landing methods • Horizontal Spaceflight types • Suborbital • Orbital	2020

** Throughout this mini case study, the Cape Canaveral Spaceport encompasses two FAA launch site operator licenses: the Cape Canaveral Spaceport/Shuttle Landing Facility and the Cape Canaveral Air Force Station.*

Spaceport is perhaps the most famous launch site in the world, it is unique in its prominence and in its operation, which is shared by Space Florida (a space-focused economic development agency for the state of Florida), NASA, and the US Air Force. While Pacific Spaceport Complex Alaska provided an interesting case, Spaceport America was ultimately selected because it is a greenfield construction, similar to the proposed Azores spaceport, and because it is one of the most highly publicized commercial spaceports in the world. This research is being funded by the MIT Portugal Program, so studying a spaceport that most closely represents the Azores spaceport was of interest. In addition, it provides a comparison point for the Mid-Atlantic Regional Spaceport (MARS) in terms of construction type, because MARS is a federal site that transitioned to commercial operator. Spaceport America is also one of the most prominent commercial spaceports in the United States, and industry experts agreed it would be difficult to have a comprehensive spaceport case study without including it. Using MARS and Spaceport America as the two cases follows the theoretical replication logic discussed in Section 1.3.1. Here, the theoretical replication means that the author anticipates different results from each case because of the different in construction type (federal transitioned to commercial vs. greenfield, respectively).

In summary, this thesis conducts a holistic two-case study of the Mid-Atlantic Regional Spaceport and Spaceport America.

1.4 Literature Review

In order to begin answering the question of the economic viability of commercial spaceports, a literature review was performed. While there is not much literature on the topic of commercial spaceports, there is enough information published and in the news to develop a broad understanding of commercial spaceports.

This section defines key terms, describes the different types of spaceports (in which commercial is just one), and provides of an overview of U.S. spaceport history. This information will serve as the foundation for developing an appropriate financial analysis methodology for commercial spaceports. A summary of key references is provided in Table 1.3.

Table 1.3: Overview of Key Literature for Commercial Spaceports

Spaceports	Commercialization	Case Study Research
[Pappalardo, 2019]	[Stone, 2012]	[Yin, 2014]
[International Space University, 2008]	[Augustine Commission et al., 2009]	
[Roberts, 2019b]	[Logsdon and Nye, 2018]	
[Finger et al., 2008]		
[Gulliver, 2016]		
[Gulliver et al., 2012]		

1.4.1 Relevant Concepts and Terminology

The major terms in this thesis include "spaceport," "commercial spaceport," and "commercial viability." There are different definitions used for the term spaceport, but only one is selected for this research and the terms "commercial spaceport" and "commercial viability" are defined around it.

When using the word "spaceport," this research does not mean ports in space (i.e., the proposed Lunar Gateway), but rather refers to terrestrial ports to space, which are more commonly referred to as launch sites. People use the term "spaceport" in a variety of ways. These varying definitions stem from different perspectives, priorities and values. Some of the different definitions for "spaceport" include ones from the International Space University, the National Aeronautics and Space Administration (NASA), the Federal Aviation Authority (FAA), and the Center for Strategic and International Studies (CSIS), as well as one that mirrors airport terminology.

This thesis uses the definition from an International Space University report: "An area of land or water that is used or intended to be used for the launch and recovery of space access vehicles, and includes its buildings and facilities, if any" [International

Space University, 2008]. The benefit of this definition is its broadness, which provides flexibility to capture future changes in spaceports that can't be anticipated while avoiding the elimination of any existing space launch sites from consideration.

From discussions with Poker Flat Research Range and NASA representatives, NASA seems to use the term spaceport exclusively for space launch sites that are operated by state agencies and have commercial space launch companies as customers. For example, NASA does not consider their Wallops Flight Facility to be a spaceport because they run it, making it a federal space launch site.

The FAA has a somewhat controversial definition: a spaceport is any launch site that holds an FAA launch site operator license [Reimold and Sloan, 2017]. This definition is controversial because many of the FAA-licensed "spaceports" have not hosted a space launch, and some have no near-term plans to do so.

A fourth definition of the term "spaceport" comes from the Center for Strategic and International Studies, a D.C. think tank. Their spaceport report focuses on ground-based launch sites that have achieved orbital spaceflight; this definition does not include sea- or air-based platforms, or any launch site that hosts other types of spaceflight without orbital launches [Roberts, 2019b].

Another way to define a "spaceport" would be to mirror the naming convention in the aviation industry, in which commercial airports are referred to differently than private airports and military air bases. In order to refrain from eliminating launch sites from this analysis, this work uses ISU's broad definition, which diverges from the naming convention in the aviation industry.

This research focuses specifically on commercial spaceports, which are just one type of spaceport (see Section 1.4.2: Types of Spaceports for more information). In this thesis, the term "commercial spaceport" uses the definition that the FAA uses for "spaceport" described above, meaning that a commercial spaceport in the United States is one that has an FAA launch site operator license. Any commercial spaceport that has not received a license from the FAA will be referred to as a proposed commercial spaceport. The word "commercial" does not mean the spaceport is run by a commercial company, but rather that it targets commercial customers. In fact, commercial spaceports are typically run by a state agency and supported by state money. While they are not run by commercial companies, commercial spaceports aim to operate more like businesses than traditional federal launch sites do, which is why standard business analysis methods can be used to analyze them.

The term "commercial viability" can also mean different things to different people. This thesis will use the same ISU report for a definition for commercial viability: "the ability of the spaceport to facilitate the space mission goals of all potential customers while operating under reasonable present and future market conditions" [International Space University, 2008]. This definition leaves room to determine what "reasonable conditions" are and how a spaceport can operate within them.

1.4.2 Spaceport Literature Review

As mentioned previously, this work will not focus on regulatory and legal issues, although those are also important to consider for commercial spaceport. The regulatory and legal issues have been discussed with varying depth by other authors [International Space University, 2008, Smith and Zervos, 2010].

U.S. Spaceport History

Historically, U.S. spaceports were the exclusive purview of the federal government, but this started to change in the 1980s. Finger, Keller and Gulliver [Finger et al., 2008] outline the transformation of U.S. spaceports over time in five phases:

- **Pre-Spaceport Phase (1950s):** ballistic missile programs based at military ranges
- **Federal Spaceport Phase (1960s):** federal orbital spaceflight programs at joint military/NASA sites programs led some sites to partially convert to commercial, enabled by federal grants
- **Federal-State Mixed Spaceport Phase (1980s):** addition of commercial orbital spaceflight

- **CONUS vs. OCONOUS Phase (1990s):** (continental US vs outside continental US) commercial providers were not satisfied with the sites developed during previous phase, so began to explore OCONUS options like sea-based launch platform
- **Mixed and Customized Spaceport Phase (2000s):** additional growth of commercial space companies plus a mix of funding from different sources has started phase of more responsive and customized spaceports

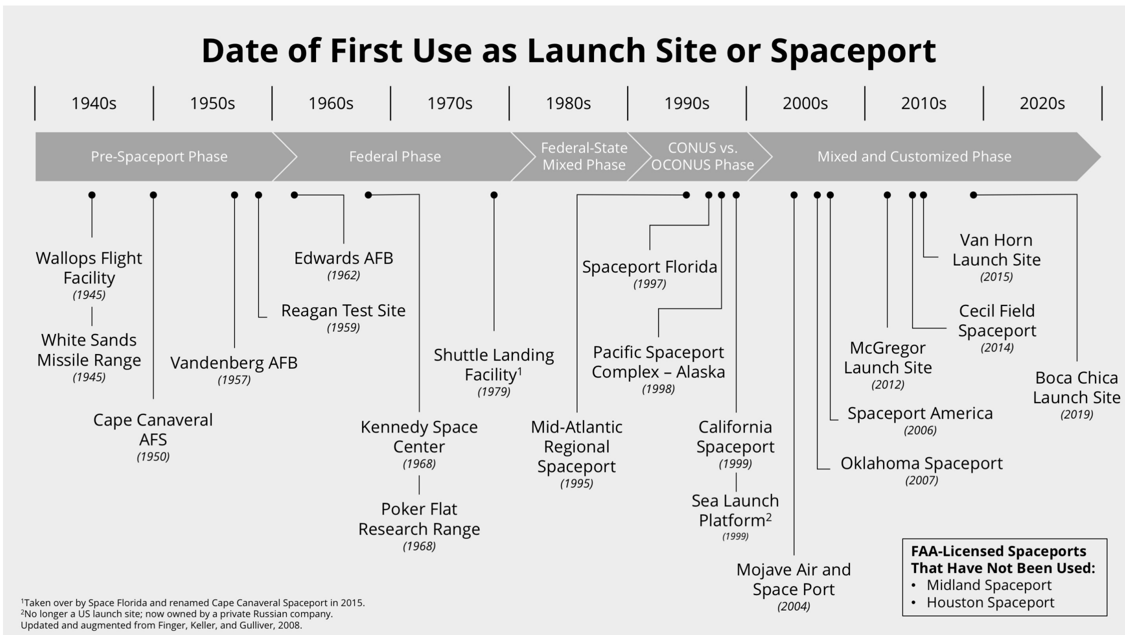


Figure 1-5: Timeline of 21 U.S. spaceports and their date of first use as a spaceport, last updated in October 2019.

Operators of spaceports expanded from just federal agencies to include state agencies because federal launch sites couldn't meet all of the requirements of emerging entrepreneurial launch providers, which had different needs than traditional launch vehicle providers. While all launch providers have some similar requirements like proximity to the equator (for orbital launch), entrepreneurial companies focus more on "technical, business and schedule factors" as opposed to the focus that traditional providers put on "technical, military and political factors."

Finger, Keller and Gulliver's paper presents a table of spaceport development over time, which includes 11 spaceports. Their table was used as the baseline for creating an updated U.S. spaceport timeline, with additional data compiled by the author to cover 21 U.S. spaceports, as shown in Figure 1-5 [Finger et al., 2008, NASA Administrator, 2013, Wade, 2008, Ryba, 2012, Public Affairs Office, , Oklahoma Space Industry Development Authority, 2019, Dickerson, 2015, Hawes, 2016, Plait, 2012, Martin, 2019, Reagan, 2019, Foust, 2016]. For this timeline, the "date of first use as a spaceport" is defined as the first time the site was used for any launch operations, even if the launch was not successful. For example, while the Mid-Atlantic Regional Spaceport did not host a successful space launch until 2006 [Associated Press, 2006], it hosted its first launch attempt in 1995. Although the 1995 launch failed [Wade, 2008], this date is marked as the first use of the spaceport because this marks the point at which the spaceport began operating as a launch site. This timeline does not include former spaceports that are no longer operational.

Types of Spaceports

There are many ways to categorize spaceports, including by management type, by construction type, and by types of launch supported, to name a few. Each of these categorizations affects the infrastructure and operation of a spaceport. Below is a summary of these spaceport categorizations.

- Management type
  - Federal
  - Commercial
  - Private
- Construction type
  - Greenfield
  - Augmented airport
  - Federal transitioned to commercial
- Types of launch supported

  - Takeoff/landing methods
    * Vertical
    * Horizontal
  - Spaceflight types
    * Balloon
    * Sounding rocket
    * Suborbital
    * Orbital

In terms of management type, this thesis focuses on commercial spaceports (as defined in Section 1.4.1), but there are also federal and private spaceports. A federal spaceport is operated by the federal government, specifically either NASA or the military. Two examples of federal spaceports are Kennedy Space Center and Vandenberg Air Force Base. In addition, there are private spaceports that are each owned by a single company. One benefit of privately operating a spaceport is that the company doesn't have to get a site operator license [Reimold and Sloan, 2017]. SpaceX's McGregor, TX and Boca Chica, TX sites, as well as Blue Origin's Van Horn, TX site are all private spaceports.

Another method of spaceport categorization is construction type. A spaceport can be a greenfield project, an augmented airport, or a federal site that transitioned to commercial. A "greenfield" project means that the spaceport was built from the ground up, like Spaceport America. An augmented airport—an increasingly popular method of commercial spaceport construction recommended by consultants for its cost savings [Gulliver et al., 2012]—refers to a spaceport that develops by augmenting an existing airport to support spaceflight, like Mojave Air and Space Port [Pappalardo, 2019]. The final construction type, federal transitioned to commercial, refers to a commercial spaceport that took over federally-owned launch facilities, as is the case with the Cape Canaveral Spaceport run by Space Florida. While building a greenfield spaceport "provides significant operational and design flexibility," it is expensive, costing more than $200 million. Augmenting an airport to support spaceflight (usually horizontal takeoff and landing) costs less since some of the necessary infrastructure comes from the existing airport [Gulliver et al., 2012].

In addition, a spaceport can be categorized by the types of launch it supports, including both takeoff/landing methods and types of spaceflight. Takeoff and landing methods include horizontal and vertical, and types of spaceflight include balloon, sounding rocket, suborbital and orbital flight. Since the infrastructure and support required for each type of launch varies, spaceports typically don't host all types of space launch.

As commercial spaceports become more common, regulatory authorities like the FAA are taking notice and want to address the topic of spaceport categorization. In 2017, the FAA stood up a Spaceport Categorization Aviation Rulemaking Committee (ARC) tasked with helping the FAA "identify potential spaceport integration issues and provide early regulatory clarity to municipalities and enterprises developing their business plans" [Federal Aviation Administration, 2017]. A final report from the Spaceport Categorization ARC was released in March 2019 [FAA Spaceport Categorization ARC, 2019]. Although the ARC was created to provide guidance to the FAA on a spaceport categorization scheme, the group decided that was unnecessary and only one way to approach the problem of an increasing number of spaceports. Instead, the ARC proposed that prospective spaceports be required to disclose certain data that is relevant to stakeholders and the public, much like airports do. The report lists the specific data that should be included, i.e. GPS coordinates of the site, what types of launch and landing it can accommodate, etc. Most of the report focuses on defining commonly used terms in the aviation and commercial space communities, which may reflect that part of the purpose of the ARC was to bring these two communities together on a topic that has caused tension.

As of 2019, there were 22 active launch sites in the United States, including 11 commercial spaceports, 8 federal spaceports, and 3 private spaceports. More information about the 11 commercial spaceports is available in Section 1.3.3. The number of proposed spaceports fluctuates as some initiatives stop work on them and new initiatives pop up, but a brief list is provided in Table 1.4 below. A FAA map of

Table 1.4: Summary of U.S. spaceports, last updated in October 2019.

Commercial	Federal	Private	Proposed	Inactive
• Cecil Field Spaceport, Jacksonville, FL • Midland International Air and Space Port, Midland, TX • Mojave Air and Space Port, Mojave, CA • Spaceport America, Truth or Consequences, NM • Spaceport Florida* • Pacific Spaceport Complex Alaska, AL • Colorado Air and Space Port, CO • Mid-Atlantic Regional Spaceport, VA • Oklahoma Spaceport, Burns Flat, OK • Houston Spaceport, Houston, TX	• Poker Flat Research Range • Vandenberg Air Force Base • Edwards Air Force Base • White Sands Missile Range • Cape Canaveral Air Force Station • Kennedy Space Center • Wallops Flight Facility • Reagan Test Site	• Blue Origin, Van Horn, TX • SpaceX, McGregor, TX • SpaceX, Boca Chica, TX	• Waco, TX • Hawai'i • Camden County, GA • Michigan • Tucson, AZ • Maine • Shiloh Launch Complex (north of Kennedy Space Center), FL	• California Spaceport

**Spaceport Florida is considered a single site because it encompasses the commercial parts of Cape Canaveral Air Force Station and is operated by Space Florida, but it has two spaceport licenses: 1) Cape Canaveral Spaceport/Shuttle Landing Facility and 2) Cape Canaveral Air Force Station, FL*

commercial, federal and private spaceports is shown in Figure 1-4.

Key Characteristics of Spaceports

While the literature on spaceports is limited, a few key people have studied how these spaceports operate [International Space University, 2008, Pappalardo, 2019, Finger et al., 2008, Gulliver et al., 2012, Gulliver, 2016, Browder and Newman, 2019]. In addition, spaceports are a common topic of conversation in the news as communities deal with proposed launch sites and the impacts from existing ones [Wilkinson, 2019, Kubota, 2019, Scoles, 2018, Hughes, 2018, Burrington, 2018, Macvean and Hernandez, 2019, Boyle, 2019, Foust, 2019h, Hilburg, 2020, Pound, 2016, BBC, 2019, Whittle, 2018, Landers, 2018, Collier, 2013, Decamp and Gibbons, 2005]. Key takeaways from reviewing this information include [Browder and Newman, 2019]:

- There is an overcapacity of rocket launch sites in comparison to launch demand
- The term "commercial spaceports" is a bit of a misnomer because the most prominent sites receive subsidies from state and local governments
- There can be economic benefits to building a commercial spaceport, but these should be realistically weighed in comparison to costs

A working group at the International Space University (ISU) wrote a report that aimed to help spaceport operators and developers evaluate qualitatively how commercially viable a proposed spaceport is, using "business, technical and regulatory criteria" [International Space University, 2008]. The report is a comprehensive and detailed review of key aspects of commercial spaceport operations, including:

- Infrastructure
- Facilities
- Commercial aspects
- Policy and law
- Safety and security
- Medical and training
- Geography, community and environment

While these are all important aspects of commercial spaceports, the report focuses more on logistical and operational considerations rather than on development and assessment of a viable business plan. More work should be done earlier in the planning process to determine whether or not a new commercial spaceport is a good investment before decision-makers begin to evaluate topics like facilities, safety and training. Spaceport projects often begin with a technical feasibility study, when instead they should begin with a business plan that includes alternative projects; first of all, the technical aspects of designing a spaceport are irrelevant without evidence of demand; second, there may be lower-risk and cheaper options for investing into the space industry.

Space journalist Joe Pappalardo visited more than a dozen spaceports around the world (including a nuclear missile silo) and wrote a great book that provides useful context to spaceports' history, their role in competitive business relationships, how they've supported ambitious space endeavors, and the competition for customers within the spaceport market itself [Pappalardo, 2019].

Brian Gulliver and George Finger are spaceport consultants who have published several conference papers on spaceports [Finger et al., 2007a, Finger et al., 2007b, Finger et al., 2008, Finger and Gulliver, 2009, Finger and Gulliver, 2010, Gulliver et al., 2009, Gulliver and Finger, 2010, Gulliver et al., 2012, Gulliver et al., 2014, Gulliver and Finger, 2014, Gulliver, 2016, Gulliver et al., 2017, Lemon et al., 2017]. Gulliver and Finger have worked for aerospace consulting firms RS&H and Kimley-Horn. They have consulted on several spaceport projects and written about how an airport can become a spaceport [Gulliver and Finger, 2010, Gulliver et al., 2012], what characteristics are needed for to ensure responsiveness of a launch site [Finger and Gulliver, 2009], and other topics. One of their key papers advises on the characteristics needed at a spaceport to support commercial launch providers [Finger et al., 2007b]:

- Competitive Cost Structure: The Spaceport's cost structure must allow the Entrepreneurial operator to evaluate the business case without a large fee and operate in an ongoing a manner to make a profit. The pricing structure needs to be less costly than any other Spaceport option for that particular non-traditional user.

- Responsive Scheduling: The Spaceport must commit and provide operational infrastructure on a schedule which is responsive to the business plan needs of the Entrepreneurial user. The schedule must allow the user to launch on desired dates/times without a concern for postponement or cancellation due to other overriding launches.

- Technical:

  - Siting: The Spaceport would likely be located in a large, mostly uninhabited area within the US at a relatively high elevation which would be licensed and regulated through the FAA rather than controlled by a Federal launch range (e.g. central US desert). Aviation flight corridors should not interfere with the Spaceport's airspace because they can impact the flexibility of the launch schedule. Even remote sites can be limited due to aircraft over-flight restrictions.
  - Site Layout: Operational areas would include runway(s) for horizontal take

offs and horizontal landings; large, relatively smooth landing zones (up to a mile in diameter) for parachute landings; hardened concrete pads for vertical powered landings; small concrete pads for rail guided launches, and larger vertical launch pads with exhaust ducts and vehicle specific adapters. Sites may want to provide the flexibility to support testing vehicles of a variety of types and scales.

  – Streamlined and Independent Range Operations: Operations will be managed in such a way as to support launches on demand by the non-traditional operators.

  – Support Infrastructure: Support infrastructure will include not only the technical support (propellants, gasses, power, communications, transport, etc.) but also business support (related training facilities, entertainment facilities, themed hotels and restaurants.)

While these readings don't focus on the importance of a viable business plan, they provide important information about context, history, and characteristics necessary for success.

1.4.3 Commercial Space Literature Review

U.S. Commercial Space Policy History

While the use of commercial partnerships to provide resupply services to the International Space Station is relatively new, the US commercial space policy that supports it has been in development for decades. US space policy comes in many forms, including presidential space policy directives, Congressional legislation, and regulations to name a few. Some of the most prominent pieces of legislation on the topic include:

- The Commercial Space Launch Act of 1984
- The Commercial Space Act of 1998
- The Commercial Space Transportation Competitiveness Act of 2000

- NASA Authorization Act of 2010
- The Commercial Space Launch Competitiveness Act of 2015
- NASA Authorization Act of 2017

The first US legislation supporting the commercial space sector was enacted during President Ronald Reagan's administration: the Commercial Space Launch Act of 1984 (commonly known as the CSLA). The CSLA aimed to facilitate the commercialization of space and the commercial development of space technology [Stone, 2012].

During the Clinton administration, the Commercial Space Act of 1998 was signed. This legislation encouraged the commercialization of the International Space Station (none of which had been launched yet), commercial space launch, and what would later become known as commercial spaceports. It was also the first space legislation that encouraged the government to look into commercial space alternatives to programs operated by the government, laying the groundwork for the later COTS program [Stone, 2012].

While Clinton was still in office, another major piece of commercial space legislation was passed: the Commercial Space Transportation Competitiveness Act of 2000. This bill established the Office of Commercial Space Transportation (which now sits in the Federal Aviation Administration) and encouraged "the development of the commercial space transportation industry" [Stone, 2012], further leading toward the commercial cargo and crew programs.

Following the 2009 Augustine Commission (more information below) conducted at the beginning of President Obama's administration, Congress took up and passed the 2010 NASA Authorization Act, which included budget and policies for fiscal years 2011-2013. The major policy provisions included funding for the programs now known as the Space Launch System and Orion, funding for a final flight of the Space Shuttle (STS-135), and support for continued development of commercial cargo and crew programs [Bergin, 2010, Klamper, 2010].

During Obama's presidency, another major piece of commercial space legislation was passed: the Commercial Space Launch Competitiveness Act of 2015. Signed into law under President Obama, this act included several provisions, such as removing liability from space launch companies for harm to any commercial space flight participants, indemnification of third-party damages for commercial launches above the insured level, and granting rights to resource extraction on extraterrestrial bodies [Foust, 2015].

Obama's administration saw a second NASA Authorization Act but not until 2017, several years after the previous one. This bill passed NASA's fiscal year 2017 budget and included several major policies. The bill continued the 2010 Authorization Act's support of the Space Launch System and Orion programs, but also authorized "development of a detailed plan for NASA's human exploration programs, with the long-term goal of sending humans to Mars" and gave "NASA the ability to establish long-term medical monitoring of former astronauts" [Foust, 2017].

These major pieces of legislation make up just one part of US space policy, but they have been critical in leading up to NASA's commercial partnerships for cargo and crew missions to the International Space Station.

NASA engages in public-private partnerships for a variety of reasons, but the recent, more commercial partnerships have grown out of developments in US space policy, increased private interest in space exploration, and increase commercial capabilities. The public questions why the United State hasn't been outside of low Earth orbit in 50 years, but this analysis shows how stagnant public support and thus stagnant funding for NASA led to this outcome. In contrast to steady levels of public investment into space exploration, private investment in the space sector has grown significantly in the last 20 years. After decades of failed attempts at commercializing the space sector, now may finally be the time for significant commercial space exploration alongside continued government space exploration.

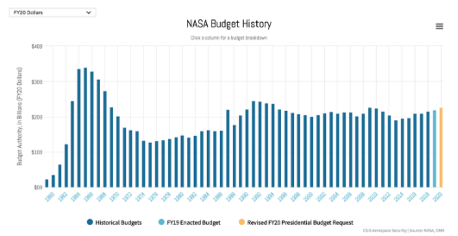
U.S. space policy tends to shift with each new presidential administration, and the administration of President Barack Obama was no different on this count. In May 2009, a few months after President Obama took office, the White House Office of Science and Technology Policy (OSTP) announced an independent review of NASA's human spaceflight strategy, which became known as the Augustine Commission [Wall, 2017]. The final report came out several months later and resulted in the cancellation of the agency's Constellation program because the committee deemed it impossible for the program to succeed under the budget and timeline constraints. The Augustine Commission called for the agency to increase investment into commercial partnerships in order to "create the possibility of lower operating costs" and potentially accelerate the development of new U.S. spacecraft to access LEO, since America's only spacecraft (the Space Shuttle) would retire in 2011 [Augustine Commission et al., 2009]. The report also advised NASA to let commercial partners take over activities they were interested in, such as cargo and crew transportation to the International Space Station, so that NASA could focus on a clear technology development strategy that had been lacking for decades and which they blamed for causing the "gap" in American access to LEO. The Augustine Commission concluded that achieving NASA's human exploration goals would require increasing NASA's budget.

In 2014, the National Research Council of the National Academies conducted another independent assessment of U.S. human spaceflight (as mandated by Congress via the 2010 NASA Authorization Act) with a goal of "identifying a sustainable rationale" for human exploration [Logsdon and Nye, 2018]. This committee conducted the study and came to two main conclusions:

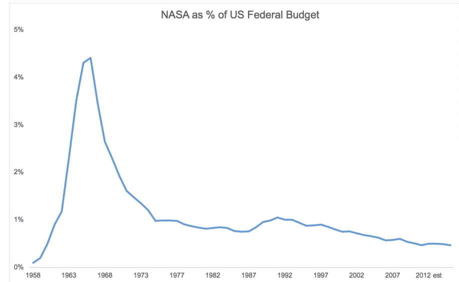
1. The United States needs a consistent vision for US space policy

2. Setting a policy goal is not sufficient to achieve exploration goals, because you need to address "programmatic, technical, and budgetary realities." This conclusion specifically called out a lack of public interest in increasing NASA's exploration budget to a level that could result in sustained human spaceflight.

Despite the concerns from both the Augustine Commission and the National Research Council's assessment of US human spaceflight strategy, NASA did not suddenly receive more money from Congress. Figures 1-6a and 1-6 provide two views of NASA's budget since the 1960s. Figure 1-6a shows NASA's budget over time, in FY20 dollars [The Guardian, 2010]. Figure 1-6 shows the NASA budget as a percentage of



(a) Total NASA spending over time. Data from the Center for Strategic and International Studies [Roberts, 2019a].



(b) NASA funding as a percentage of the US federal budget. Data from the Office of Management and Budget via The Guardian [The Guardian, 2010]

Figure 1-6: NASA budget over time, in total and as a percentage of the US federal budget

total federal spending, which highlights the prioritization the nation gives to NASA's budget.

The point about a lack of public interest in increasing NASA's budget is reinforced in a Harvard Business School case study [Weinzierl and Acocella, 2016]. Public support is key to increasing federal budgets, especially in the case of NASA, whose budget is often questioned by those who are skeptical about the benefits of space exploration.

While the reports from the Augustine Commission and the 2014 National Research Council about US human spaceflight seem grim, they stand in stark contrast to work performed in the commercial space sector by Bryce Space and Technology. Bryce, a consulting firm that specializes in the space industry, conducts an annual "start-up space" study that looks at private space investment. In comparison to the steady NASA budget, private investment in space has grown dramatically over the last 20 years, as shown in Figure 1-7 [Bryce Space and Technology LLC, 2020]. This chart shows that the number of private space investors has increased from a couple dozen to a few hundred in the last 20 years, reflected in a six-fold investment magnitude increase to $6B in 2019. These private investments are going into companies working to develop new space technologies, including companies like SpaceX that are integral to NASA's commercial strategy.

One data point for comparing the utility of a more commercial partnership to

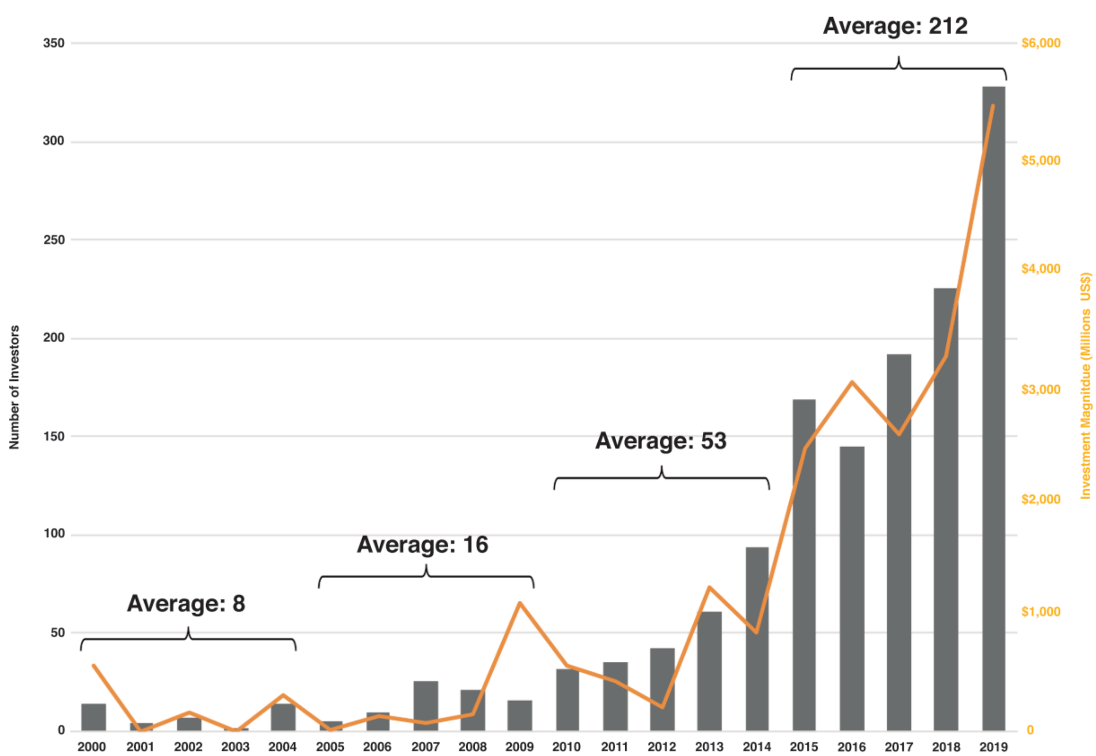


Figure 1-7: The average number of space investors per year has grown from 8 to 212, looking at five year periods [Bryce Space and Technology LLC, 2020].

a more traditional industry partnership (similar to the ones used in the Mercury, Gemini and Apollo programs) would be NASA's recent crewed spaceship development efforts: the Commercial Crew program and the Orion program. As described above, Commercial Crew is a flagship commercial partnership with Boeing and SpaceX to develop crewed vehicles capable of transporting astronauts to the International Space Station. In April 2021, SpaceX ferried its third crew to the ISS on board their Crew Dragon vehicle [Brown, 2021]. Boeing is scheduled to launch a second orbital flight test of its Starliner vehicle later this year [Foust, 2021b]. Casey Dreier of the Planetary Society analyzed the costs of thee Commercial Crew Program in comparison to other spacecraft programs; summaries of his analysis are shown in Tables 1.5, 1.6 and 1.7. In total, NASA has spent $7.6B on the Commercial Crew program, as shown in Table 1.7. While the per-seat price is comparable to what NASA pays for a seat on a Russian Soyuz flight, it's less than the price of a seat on any other American spacecraft (Table 1.6). Through the Commercial Crew program, NASA has decreased the cost of developing a crewed vehicle by an order of magnitude (Table 1.5). Overall, the Commercial Cargo and Crew programs cost NASA about 1/3 of what it has spent on the comparable Orion program, and less than almost every other NASA human space program (Table 1.7). At the very least, NASA has secured one operational crewed vehicle and saved a significant amount of money. If all goes well with Boeing's second orbital flight test this summer, NASA will add a second operational crewed vehicle to its roster.

In contrast to this new type of commercial partnership is a more traditional partnership NASA has with Lockheed Martin to develop the Orion crew vehicle. The Orion program has spent $23.7B on development and will cost $291M per seat in comparison to Crew Dragon's $60-$67M and Starliner's $91-$99M (Table 1.7). While this cost comparison appears to show Commercial Crew as the more successful of the two programs, it's difficult to directly compare them because Orion has been subject to significant changes in US space policy that undoubtedly affected its budget and schedule. In addition, the Orion vehicle is intended for human exploration beyond low Earth orbit, whereas Commercial Crew is limited to LEO transportation.

Table 1.5: Comparison of total spacecraft development costs for several crewed NASA spacecraft. Inflation adjusted using NASA's New Start Index [Dreier, 2020]

	Spacecraft Development Costs (NASA portion, inflation adj)
Mercury	$2.7 billion
Gemini	$7.6 billion
Apollo CSM	$30.9 billion
Shuttle Orbiter	$27.4 billion
Crew Dragon	**$1.7 billion**
Starliner	**$2.8 billion**
Orion	$23.7 billion

Table 1.6: Comparison of per-seat cost across several crewed spacecraft [Dreier, 2020].

	Per-Seat Cost (millions, inflation adj)
Mercury	$142 million
Gemini	$117 million
Apollo (to LEO)	$390 million
Shuttle Orbiter	$170 million
Soyuz	$90 million
Crew Dragon	**$60 - $67 million**
Starliner	**$91 - $99 million**
Orion	$291 million

Table 1.7: Comparison of total program costs for all of NASA's crewed programs. [Dreier, 2020]

	Total Program Development Costs (NASA portion, inflation adj)
Mercury	$2.7 billion
Gemini	$11.9 billion
Apollo	$175 billion
Shuttle	$50.1 billion
Commercial Cargo & Crew	**$7.6 billion**
Orion	$23.7 billion

This brief overview of public and private space investment, as well as a comparison of the budgets for the Commercial Crew and Orion vehicles, highlights differences in how NASA and commercial companies operate. The overview of U.S. commercial space policy shows how policy has been essential to the development of a robust commercial space sector that has saved NASA a significant amount of money.

Chapter 2

Commercial Spaceport Case Studies

This two-case study takes a deep dive into the Mid-Atlantic Regional Spaceport (MARS) in Virginia and Spaceport America in New Mexico. MARS was used as the pilot case, meaning that methodology was developed to analyze MARS first, and then applied to Spaceport America as a second case.

Each case study will incorporate:

- Business financial analysis
- How the business plan changed over time
- Economic impact analysis
- Profit model

Table 2.1: Overview of the Mid-Atlantic Regional Spaceport.

Spaceport	Operator	State	Construction Type	Type of Launch Supported	License First Issued
Mid-Atlantic Regional Spaceport	Virginia Commercial Space Flight Authority	VA	Federal transitioned to commercial	Takeoff/landing methods • Vertical Spaceflight types • Suborbital • Orbital	1997

2.1 Pilot Case: Mid-Atlantic Regional Spaceport

The Mid-Atlantic Regional Spaceport (MARS)[1] (overview of the spaceport shown in Table 2.1), which supports vertical takeoff and landing for suborbital and orbital launches [Space Florida, 2018, Federal Aviation Administration, 2012], is run by the Virginia Commercial Space Flight Authority (VCSFA), a state agency in Virginia (Maryland has also been involved [Bernstein et al., 2004]). The spaceport was established in 1997 and leveraged a Reimbursable Space Act Agreement between VCSFA and NASA that "allowed VCSFA to access NASA services and construct necessary infrastructure on government property," making it a launch site that transitioned from federal to commercial [Bernstein et al., 2004]. It has two main launch pads: Pad 0A (a medium-class launch facility) and Pad 0B (a small class launch facility). MARS also has an airfield for testing unmanned aerial systems (UAS) and a payload processing facility (PPF) [Dixon Hughes Goodman LLP, 2018]. From the time it became a FAA-licensed spaceport in 1997 through the end of FY 2018, MARS hosted 16 launches, as shown in Figure 2-1. Note that this figure lists launches by the fiscal year (FY) rather than the calendar year (CY).

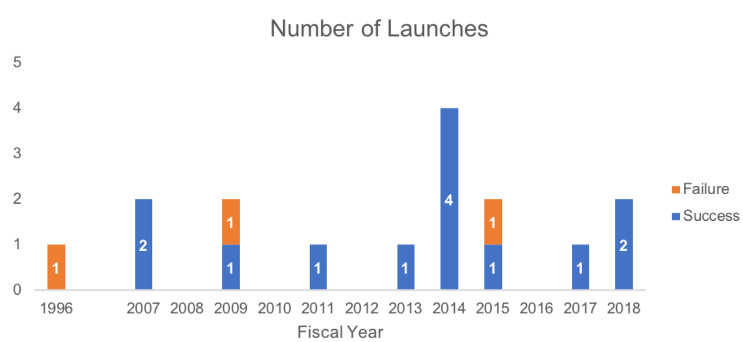


Figure 2-1: History of space launches hosted at the Mid-Atlantic Regional Spaceport, operated by the Virginia Commercial Space Flight Authority. All three failures were rocket explosions [Graham and Bergin, 2014, Tennant, 2008]

.

MARS continues a long relationship between Virginia and the space industry. In 1945, the National Advisory Committee for Aeronautics (NACA) and the Navy

[1]Information contained in this case study was previously reported by the author at two conferences [Browder and Newman, 2019, Browder and Newman, 2020].

started working at a beach on Wallops Island for rocket testing. The testing eventually expanded to supersonic vehicle research, and NASA bought the site to establish a permanent research center, which is now the Goddard Spaceflight Center [Pappalardo, 2019]. Over time, the amount of work at Wallops (which became part of Goddard) declined, and in 1995, NASA considered closing the facility [Handberg, 2002]. Maryland Senator Barbara Mikulski, a prominent Congressional advocate for space exploration, protested the decision to close Wallops and eventually helped keep the center open [Wright, 2004]. As part of a broader trend in U.S. space policy (spurred by the Commercial Space Launch Act of 1984) NASA started to allow commercial use of its excess launch site capacity, so Goddard began working to commercialize parts of its launch facility at Wallops, resulting in Virginia's establishment of the Virginia Commercial Spaceflight Authority (VCSFA) and the licensing of a commercial spaceport at Wallops [Gulliver, 2016, Bernstein et al., 2004, Raymond, 1997]. NASA Goddard center director Joseph Rothenberg helped Virginia gain the FAA license to establish the Mid-Atlantic Regional Spaceport (MARS) [Wright, 2004]. The strong support from Mikulski, as well as other political leaders including Mark Warner (VA), Chuck Robb (VA), and Paul Sarbanes (MD), has been integral to both NASA Wallops and MARS [Wright, 2004].

Although state legislators and the spaceport originally planned for the spaceport to become self-sufficient, that business model has not come to fruition; instead, MARS continues to receive state funding for operations and acts as a middleman between launch operators and NASA, shouldering the work required to maintain collaboration between a federal agency and a private company [Dixon Hughes Goodman LLP, 2018]. For a while, MARS' only tenant was Northrup Grumman (formerly Orbital ATK, formerly Orbital Sciences), who has launched a majority of their International Space Station cargo resupply missions from MARS. Over time, the spaceport has worked to diversify revenue sources, bringing in Rocket Lab as a second tenant and expanding to support unmanned aerial systems (UAS) testing [Pappalardo, 2019, Dixon Hughes Goodman LLP, 2015]. VCSFA partners with the Virginia Economic Development Partnership, Old Dominion University, NASA, Virginian's Center for Innovative

Technology, and private industry. It is overseen by a board appointed by the state governor [Handberg, 2002]. NASA was directly involved with MARS following Orbital Sciences' rocket accident in 2014, for which the repairs cost $15M and were split equally by Orbital ATK (the merger of Orbital Sciences and Alliant Techsystems, Inc.), NASA and VCSFA [Pappalardo, 2019, Dixon Hughes Goodman LLP, 2016]. Questions arose about this cost sharing, since the NASA Inspector General originally believed that NASA would not be responsible for damages to infrastructure at MARS [Pappalardo, 2019]. MARS has become one of the more active commercial spaceports in the United States and maintains significant financial support from the state [Dixon Hughes Goodman LLP, 2018].

Archival analysis of annual financial statements and key documents will reveal information about VCSFA and MARS' operations, business plan, and economic impact. This information will be used to create a baseline profit model for the spaceport.

2.1.1 Financial Analysis

As the commercial space industry continues to grow, policymakers, industry, investors and the public will need to determine if and when a commercial spaceport is a good investment. Currently, there is a gap of data and evidence that makes these decisions difficult. This section outlines a business financial analysis of a commercial spaceport, which will help in understanding the economic viability of commercial spaceports.

While standard business methods are useful for financial analysis, a commercial spaceport is not a standard business: in fact, it is not a commercial business at all. Commercial spaceports in the United States are run by state agencies, a fact that must be accounted for in a financial analysis because the goals of businesses and agencies are different and therefore should affect the financial metrics used. While a commercial business would focus on a true return on investment (ROI), a state agency may define ROI differently: for example, a state agency may prioritize regional economic development and be willing to accept a revenue loss for a strong economic impact. Ultimately, a commercial spaceport is an infrastructure investment, and infrastructure development is often supported by government funding because of the impact on economic development. Commercial spaceports are a hybrid between government and commercial because they target commercial customers, so they must be commercially viable. A financial analysis that considers a spaceport as a business investment can support policymakers in determining the commercial viability of a proposed spaceport, but the analysis must account for this government perspective. This leads to an augmented business analysis for commercial spaceports: the first five metrics defined below are standard business metrics, whereas the sixth is included to show how government financial investment affects spaceport financial performance.

For a commercial spaceport, six financial performance metrics to study are [Thompson and Browder, 2019]:

- Revenue per launch
- Amount of capital investment
- Amount of subsidies
- Cash flow analysis
- Net operating income/loss
- Net total income/loss

This thesis analyzes the Mid-Atlantic Regional Spaceport (MARS) by reviewing audited annual financial statements of the spaceport operator, the Virginia Commercial Space Flight Authority (VCSFA), for all years that annual statements are available: 1998 to 2018.

VCSFA is a state agency, so their financial statements are made available to the public via the Auditor of Public Accounts for the Commonwealth of Virginia [Commonwealth of Virginia Auditor of Public Accounts, 2020]. The state auditor's website only has reports for the years 2000-2018, but the Virginia Commercial Space Flight Authority supplied copies of the reports for 1998 and 1999 upon request. As noted in Figure 1-5, the Mid-Atlantic Regional Spaceport was first used as a spaceport in 1995; however, the VCSFA said that the spaceport did not receive state-appropriated funding during 1995-1997, so the state auditor did not create financial reports for those years.

The following six subsections will describe the methodology used to analyze the 6 spaceport performance metrics for VCSFA. The final subsection will discuss the implications of these performance metrics.

Revenue per Launch

One key metric for assessing a spaceport is revenue per launch, which at MARS includes two pieces of data: 1) the launch fee and 2) the launch support revenue.

In FY 2018, MARS supported two launches of the medium-class orbital rocket, Antares. According to analysis of VCSFA's annual financial reports and conversations with key industry leaders, for each launch, VCSFA charged Northrop Grumman a flat launch fee of $1.5 million, which represents about 2% of the total vehicle price [Thompson and Browder, 2019]. The VCSFA also provided commodities (e.g., fuel and utilities) to Northrup Grumman for each launch, at a price of approximately $500K. This brings VCSFA's average revenue per launch to $2 million.

Amount of Capital Investment

Another important metric for a commercial spaceport is the capital investment required to build the infrastructure.

VCSFA's portion of the investment to build the spaceport cost about $130 million [Dixon Hughes Goodman LLP, 2018]. There was additional funding of the spaceport by NASA and what is now Northrup Grumman Innovation Systems (formerly Orbital ATK and Orbital Sciences) that was paid separately from VCSFA's investment that increased the total amount spent on spaceport construction to $168 million [Dixon Hughes Goodman LLP, 2016].

Amount of Subsidies

To offset this capital investment and other costs, VCSFA received support from a variety of sources, including the state of Virginia, the federal government, and private contracts. While the federal government and private contracts make up a portion of VCSFA's revenue (shown in Figure 2-3), the support from the state government makes up the majority of subsidies. This financial investment is representative of the level of political support from the state, which is vital to a spaceport's success [Thompson and Browder, 2019].

To illustrate how state support of the spaceport has changed over time, Figure 2-2 shows the subsidies VCSFA received from state appropriations, state grants and state bond revenue over the past 20 years [Dixon Hughes Goodman LLP, 2018]. The state appropriation for VCSFA was steady at a magnitude of a few hundred thousand USD from 1998 to 2010, but then steadily increased every year to $36 million in 2018.

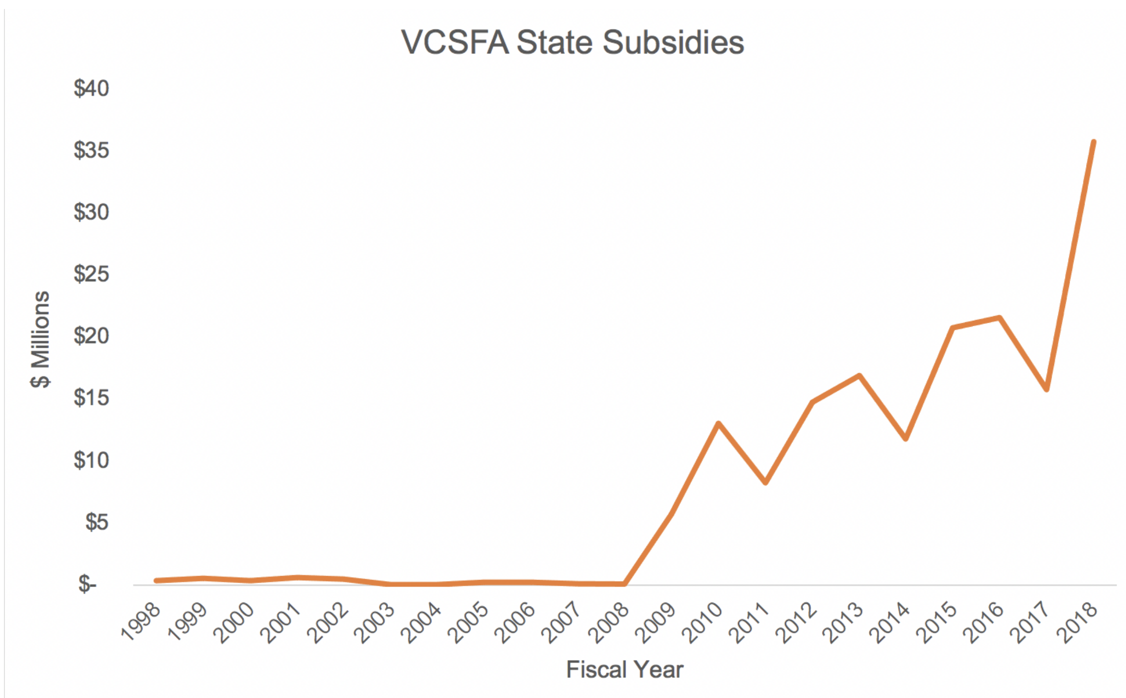


Figure 2-2: Subsidies provided to the Virginia Commercial Space Flight Authority by the state of Virginia over time.

Cash Flow Analysis

A cash flow analysis is a standard tool for analyzing the financial health of a company. It shows how a company receives and distributes payment, as well as the amount of cash on hand. Company annual financial statements typically include a cash flow

Table 2.2: Line items included in each category for spaceport cash flow analysis.

Category	Included Line Items
Commercial Launch Revenue	• Cash received from customers
State Government Support	• Cash received from state appropriation(s)
Federal Government Support	• Cash payments for nonoperating contracts • Cash received from federal contracts
Private Support	• Cash received from private contracts
Operating Expenses	• Cash paid to employees • Cash paid to suppliers
Capital Investments	• Investment in construction-in-progress • Investment in capital assets
Other Expenses	• Cash paid to employees on nonoperating contracts
Net Cash Flow	• Net increase/change in cash

statement. For analyzing a spaceport, this work will look at both a year-over-year (YOY) analysis plus a 5-year cumulative analysis. The year-over-year analysis will reveal trends, while a 5-year cumulative analysis will show longer-term performance rather than limiting to a single year in which the spaceport could have performed unusually well or unusually poorly.

For the cash flow analysis, the line items from VCSFA's statements of cash flows were grouped into eight categories, as listed in Table 2.2.

These eight categories were used to create a year-over-year analysis in Figure 2-3. The direction of cash flow in this figure remains the same for most years in most categories. However, there are two exceptions. First, the federal government support alternates between cash flow in and cash flow out in different years. Second, in FY 2014, private support and other expenses were zero.

All of the data for FY 2014-2018 are summarized in Figure 2-4, which shows cash flow in from commercial launch revenue, state government support, and private support. The summary shows cash flow out from operating expenses, capital investments, other expenses and federal government support. The total net cash flow of

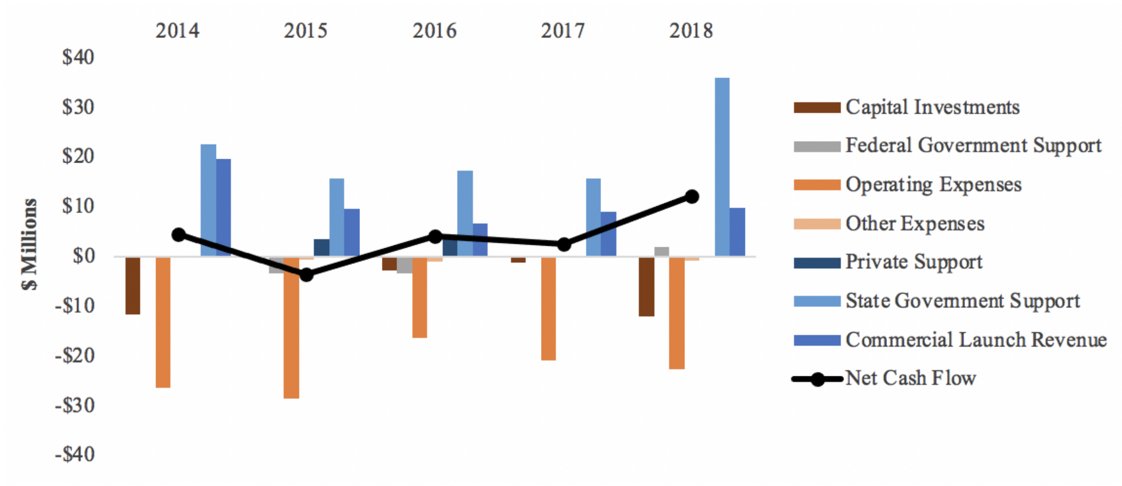


Figure 2-3: Year-over-year cash flow analysis of VCSFA for FY 2014-2018.

the spaceport over these five years was $19.6M, meaning the spaceport took in more money than it spent.

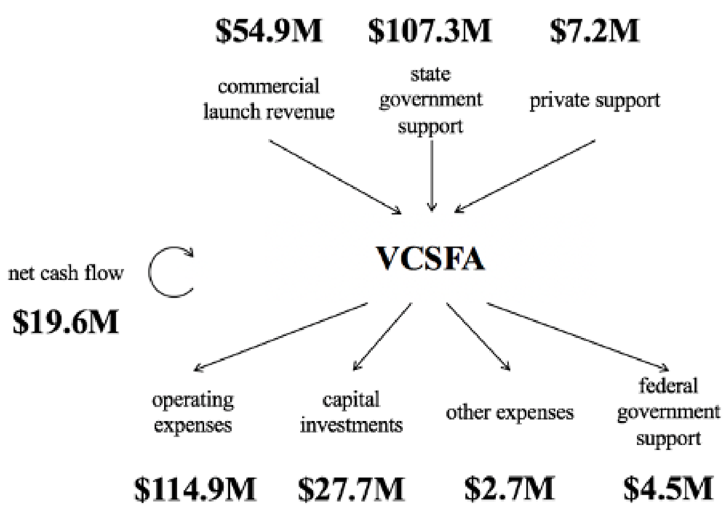


Figure 2-4: Summary of cash flow for the Virginia Commercial Space Flight Authority for FY 2014-2018.

Net Operating Income/Loss

The net operating income/loss and net total income/loss are compared in Figure 2-5. This chart shows that the operating income was near zero from 1998 to about 2009, then steadily declined until the largest net operating loss of $18.2M in FY 2017.

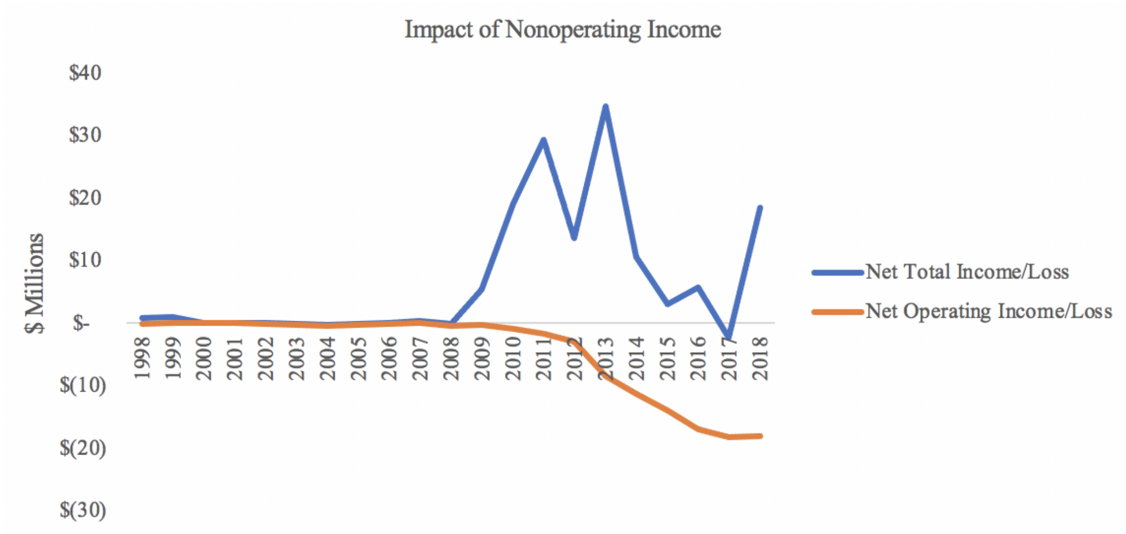


Figure 2-5: Impact of nonoperating income on MARS finances. Net total income/loss is the sum of operating income/loss and nonoperating income/loss.

Net Total Income/Loss

While the net operating income/loss is a useful metric, it is designed to be used analysis of a traditional business and not as suited to analysis of a state agency that operates a spaceport. While a business must prove that it will eventually make a profit, a spaceport can be viewed as an infrastructure investment. Therefore, a state may decide that some sustained investment into the spaceport is worth the economic impact on the region, even if without that investment the spaceport would consistently have a net operating loss. Thus, including nonoperating income/loss an additional metric accounts for the fact that a spaceport is a public infrastructure investment that can have beneficial returns beyond money. Some returns besides money include economic impact, STEM education, national security, and prestige.

In comparison the nonoperating income/loss comes from the Statement of Revenue, Expenses and Changes in Net Position for each annual financial statement. This line remains in a steady state for a similar time period as Figure 2-2, with a discernable change in 2009. The chart shows an increasing trend in net income from 2009 to 2013, then a net decreasing trend from 2013 to a net loss in 2017, and finally another strong net income in 2018. Past 2008, the trends in this chart reflect the increasing state investment in the spaceport.

Discussion

To add more context to the discussion, we can compare finances against the numbers of launches hosted at MARS from FY 1996 to FY 2018, shown in Figure 2-1. This information is important for financial analysis of commercial spaceports because an underlying question of spaceports is whether they can profit off launches. It appears from comparing finances in Figure 2-5 and launches in Figure 2-1 that a major change in the spaceport's finances occurred around the same time it started supporting space launches. The first launch was supported at MARS in 2006. Up until 2008, the finances of the spaceport remained relatively steady, and changed significantly in the following 10 years. While the finances became more active in the years since the spaceport began supporting launches, it does not seem that the spaceport has been profiting from launches. As explained above, the spaceport profits about $2M from each launch it hosts. However, the net operating income/loss has been consistently negative since 2008. The net total income/loss has been positive largely because of sustained state investment. This reflects the idea that state support of a commercial spaceport is critical to its success.

If a spaceport were considered a traditional business, Figure 2-5 would be concerning because it shows sustained operating loss; but because the spaceport is a type of infrastructure investment, consideration of net operating income/loss alone is insufficient. Including the net total income/loss begins to shed light on the amount of state investment needed to sustain a commercial spaceport, which will help policymakers decide whether a spaceport is a good investment for their community.

In addition to studying the net total income/loss, policymakers should also consider the amount of capital investment and the amount of subsidies needed to support a commercial spaceport. These two metrics detail the state of Virginia's financial commitment to Mid-Atlantic Regional Spaceport, and provide guidance for what other policymakers should expect for these numbers. The $168M spent on capital investment to build the spaceport, as well as the additional financial commitment reflected in Figure 2-5, reveal that Virginia has continually invested a significant amount of money into the spaceport.

The year-over-year cash flow analysis reveals trends in sources of income and recipients of payment over time, showing that federal and private support of the spaceport is much lower than state support of the spaceport. It also shows that operating expenses have been higher than launch revenue. Overall, the five-year cash flow summary shows a significant positive cash flow, meaning the spaceport is well-positioned for unexpected events or future capital investments. It also reveals that over five years, the spaceport paid more to the federal government than it received.

More work needs to be done in order to determine why the change in net position remains low in some years of significant state appropriation and to understand why the state appropriation increased substantially from 2010 to 2018. This analysis serves as an important first step in developing a methodology for spaceport financial analysis.

This financial analysis is useful for two purposes: 1) for beginning to close the knowledge gap about economic feasibility of commercial spaceports and 2) to create a methodology for analyzing existing commercial spaceports. This methodology would not be applicable to proposed spaceports, because they do not have annual statements to study. Future work could develop a methodology for analyzing proposed commercial spaceports.

While a financial analysis does not substitute for human judgment of investments, it's an important tool that policymakers can use to augment their understanding of a spaceport. The main goal of a decision-maker considering investment into a commercial spaceport is to determine commercial viability, which this thesis has defined as "the ability of the spaceport to facilitate the space mission goals of all potential customers while operating under reasonable present and future market conditions" [International Space University, 2008]. This financial analysis will help to determine the commercial viability of existing commercial spaceports, ultimately safeguarding taxpayer money by ensuring that policymakers only invest in spaceports that are commercially viable.

Based on this financial analysis, the verdict is still out on the commercial viability of the Mid-Atlantic Regional Spaceport operated by the Virginia Commercial Space Flight Authority. While the current level of state investment is high, the spaceport is in the midst of an expansion to add a new launch site and a satellite processing facility, so this level of investment may be temporary. This expansion requires substantial capital investment and it will take time to achieve a return in investment. In addition, determing the return on investment (ROI) for a spaceport is difficult because the focus is largely on economic impact, which is difficult to quantify. There is a recent report on the economic impact of the "Wallops Aerospace Cluster," which includes the commercial spaceport [56], but this thesis does not attempt to account for economic impact. It is too soon to tell whether VCSFA has a feasible and sustainable business model.

One thing can be said for sure: the term "commercial spaceport" is a bit of a misnomer. While a spaceport operated by a state agency may behave more like a business than one operated by a federal agency, there is still a significant investment of taxpayer dollars required to keep this spaceport in good financial standing. The net operating losses reported by VCSFA may not justify feasibility for a business, but the spaceport could have corollary benefits typical of public infrastructure investments (such as a strong economic impact) that would justify sustained state investment.

The financial analysis developed in this thesis can be applied to other existing commercial spaceports to determine commercial viability. The six key metrics for financial analysis are revenue per launch, the amount of capital investment, the amounts of operating subsidies, the cash flow summary, the net operating income/loss, and the change in net position. These metrics can be used by policymakers and investors to improve their understanding of spaceports and to help in determining when a commercial spaceport is a good investment for a community. However, an analysis for a proposed commercial spaceport would require different metrics, since there would be no annual statements to calculate some of these metrics.

While growth in the commercial space sector is promising, it remains to be seen whether there will be a significant increase in launch demand that would make commercial spaceports a feasible business model, let alone justify the construction of additional spaceports when there is already an overcapacity of launch sites.

2.1.2 The Business Case: 2004 to 2019

Established by the Virginia state legislature in 1995, the Virginia Commercial Space Flight Authority (VCSFA) has now been operating for 25 years [Virginia Commercial Space Flight Authority, 2012]. In that time, the organization and its business plan have changed multiple times as it responded to external factors. Reviewing key documentation from this time period reveals details about the changes to the business plan and VCSFA's operations of the commercial spaceport at Wallops Island [Bernstein et al., 2004, KPMG Corporate Finance LLC, 2011, Virginia Commercial Space Flight Authority, 2012, Virginia Commercial Space Flight Authority, 2016, Filer, 2019]. At a high level, VCSFA has shifted from low activity and investment, to higher activity and periodic investment, to sustained activity and investment. While the spaceport has long aimed to become self-sustaining, the emphasis on this appears to be declining as VCSFA pursues increased economic development that is supported by significant government investment.

For the first decade of its existence, activity at the Mid-Atlantic Regional Spaceport (MARS) was low. However, activity picked up when Orbital Sciences (Orbital) began using the facility for testing and development, hosting its first two launches at the spaceport in FY 2007 [Commonwealth of Virginia Auditor of Public Accounts, 2007]. In 2008, NASA awarded Orbital one of two contracts to resupply the International Space Station (through the Commercial Resupply, or CRS, program), and Orbital announced that the testing and launches would take place at MARS [Commonwealth of Virginia Auditor of Public Accounts, 2008, Filer, 2019]. The program ultimately resulted in a phase 2 award of additional launches for the company, bringing the total number of Orbital CRS launches to at least 16, the majority of which will be launched from MARS [NASA Glenn Research Center, 2020]. Orbital's commercial resupply launches had a significant impact on the activity at and investment in MARS, evidenced by increased state funding and political support [Virginia Commercial Space Flight Authority, 2012, Virginia Commercial Space Flight Authority, 2016]. In 2012, spurred by a state budget review and subsequent analysis of VCSFA, the organization underwent a major shift. Since 2012, VCSFA has worked to become a multi-user spaceport with diversified revenue streams [Virginia Commercial Space Flight Authority, 2012, Virginia Commercial Space Flight Authority, 2016]. However, it appears that government funding of the spaceport may be necessary to achieve the desired economic impact.

Below is a timeline summarizing significant events in the spaceport's history:

- 1995: VCSFA created by Virginia General Assembly, the state legislature [Virginia Commercial Space Flight Authority, 2012]

- 1999: public-private partnership established between VCSFA and DynSpace, who became the commercial operator of the spaceport [Bernstein et al., 2004]

- 2003: Establishment of a memorandum of agreement (MOA) between Virginia and Maryland "that expanded the management of the spaceport" to both states [Virginia Commercial Space Flight Authority, 2012]

- 2004: Virginia/Maryland MARS implementation plan released [Bernstein et al., 2004]

- 2007: Orbital Sciences hosts two launches at MARS [Commonwealth of Virginia Auditor of Public Accounts, 2007]

- 2008: NASA awards one of two Commercial Resupply Services contracts to Orbital Sciences, and Orbital Sciences announces MARS as the location for testing and launches [Commonwealth of Virginia Auditor of Public Accounts, 2008, Filer, 2019]

- 2011: Virginia biennial budget led to review of VCSFA and request for report on "governance, organization and competitive landscape for VCSFA," authored by KPMG [Virginia Commercial Space Flight Authority, 2012]

- 2012: consideration of the KPMG report recommendations was used to create new state legislation (HB 813 and SB 284) "to reconstitute the Authority, reform its Board of Directors, amend its powers and duties, and provide the Authority with the requisite funding to become a truly independent authority of the Commonwealth"; state appropriation required VCSFA to submit strategic plans every four years; the first VCSFA strategic plan was released [Virginia Commercial Space Flight Authority, 2012]

- 2014: Orbital Sciences Orb-3 (the third flight in the Orbital CRS contract) exploded on the launch pad, resulting in $15M in damages [Pappalardo, 2019, Virginia Commercial Space Flight Authority, 2016]

- 2016: second VCSFA strategic plan released; NASA awarded phase 2 CRS contract to Orbital; MARS began construction on an unmanned aerial systems (UAS) airfield [Virginia Commercial Space Flight Authority, 2016]

- 2018: Rocket Lab announces MARS as location for second launch pad [Pappalardo, 2019]

- 2019: Old Dominion University (ODU) conducted an economic impact study of the Wallops aerospace cluster, including VCSFA [Filer, 2019]

VCSFA was established in 1995 "to provide low cost, responsive, safe and reliable space access as well as stimulate economic development and education" in the region [Bernstein et al., 2004]. The original strategic objectives were [Virginia Commercial Space Flight Authority, 2012]:

- "Develop and enhance infrastructure that facilitates timely, efficient, safe, and low-cost access to space;

- Provide education and research in aerospace technologies and processes;

- Preserve, as a national asset, the expertise and capability for launch operations resident at the NASA Wallops Flight Facility; and

- Stimulate aerospace-related economic activity in the region."

A few years later, VCSFA partnered with private company DynSpace to streamline operations. The public-private partnership left legal authority with VCSFA and made DynSpace a private sector investor and the operator of the spaceport. In addition to managing operations, DynSpace also invested $1.5 million in the spaceport between 1999 and 2004 [Bernstein et al., 2004].

In 2003, a MOA was signed by then-Governors of Virginia and Maryland, Mark Warner and Bob Ehrlich, establishing a working group between the two states that would create an implementation plan for joint governance of the commercial spaceport, which was then known as the Virginia Space Flight Center. The implementation plan (which led to the spaceport being renamed the Mid-Atlantic Regional Spaceport) was released in 2004, and recommended that Maryland provide financial support to the spaceport of $150,000 per year for five years, assuming that by the end of that period, the spaceport would be able to generate enough revenue to cover operating costs [Bernstein et al., 2004].

In 2008, NASA awarded a CRS contract to Orbital. As an incentive, Virginia provided $16 million so that Orbital would conduct CRS work in the state, and the Governor agreed to seek additional funding for the work [Commonwealth of Virginia Auditor of Public Accounts, 2008].

When the Virginia state legislature began the biennial budget review process in 2011, they studied VCSFA and requested a report on its "governance, organization and competitive landscape," which was then conducted by consulting firm KPMG [Virginia Commercial Space Flight Authority, 2012]. KPMG's report stated the VCSFA needed to make a decision about a strategic direction for the spaceport, and recommended they establish a pricing structure that would allow the spaceport to generate enough revenue to cover at least annual operating costs, if not also future infrastructure development. The firm laid out three options for strategic directions: a conservative approach of "status quo," a riskier approach of making significant investments in pursuit of a big payoff, and an "Opportunistic Midcourse" that would balance new investments with caution [KPMG Corporate Finance LLC, 2011]. Importantly, KPMG called out that "projections for the Authority to be self-sustaining by 2010 do not reflect its current or near-term state."

KPMG's recommendations were considered in the 2012 creation of new state legislation (HB 813 and SB 284) "to reconstitute the Authority, reform its Board of Directors, amend its powers and duties, and provide the Authority with the requisite funding to become a truly independent authority of the Commonwealth" [Virginia Commercial Space Flight Authority, 2012]. That year's state appropriations required VCSFA to write a strategic plan every four years, with the first being released in December 2012 [Virginia Commercial Space Flight Authority, 2012]. The VCSFA 2012 strategic plan selected KPMG's "Opportunistic Midcourse" strategic direction, which would allow the spaceport to support its anchor tenant (Orbital) while pursuing new customers, but only making investments when customers seemed viable. They cited the need to balance the inherent volatility of the space industry against the significant investment needed to support new customers as a reason for selecting this midcourse option. At this time, VCSFA still had becoming self-sustaining (generating enough revenue to cover operating costs) as a strategic objective.

Over the course of the next four years, as VCSFA pursued its 2012 strategic goals, rebounded from an accident when Orbital's 3rd CRS mission exploded on the launch pad, and got more embedded in the industry, it appears that a shift in the business plan occurred, evidenced by the 2017 strategic plan. VCSFA had not been able to become self-sustaining. Of the objectives laid out in 2012, this was the only one unfulfilled. It was revised "to ensure that Virginia Space is a sustainable entity for the future" [Virginia Commercial Space Flight Authority, 2016]. The shift here is subtle but noticeable. The 2012 plan cited a changing space industry, which was evolving from one "led by government objectives, to one which can be supported by the private sector (emphasis from the author). The 2017 plan slightly changed the wording to: "one that is supplemented by the private sector" (emphasis from the author). The difficulty in becoming self-sustaining is also shown by their 2017 strategic objectives, which include bringing on 1-2 new launch customers and diversifying revenue streams. This continued infusion of government funding into a commercial project reflects a broader trend in the commercial space industry [Davidian, 2016].

On the path to self-sustaining operations, VCSFA's goals of diversification have been relatively successful so far. In 2018, New Zealand rocket company Rocket Lab announced that MARS would become its second launch site (their first in the US), with their first US launch slated for 2020 [Pappalardo, 2019, Filer, 2019]. In 2016, VCSFA broke ground on an unmanned aerial systems (UAS) airfield to support drone testing and development as an alternate revenue stream [Dixon Hughes Goodman LLP, 2016, Virginia Commercial Space Flight Authority, 2016, Filer, 2019]. As of 2019, Rocket Lab projected conducting up to 12 launches per year at MARS, which would be a significant increase in the number of launches hosted at the spaceport annually. It's too soon to tell how this diversification will impact VCSFA's long-term goal to become self-sustaining.

Looking over key VCSFA documents from the last 25 years show how the goal of becoming self-sustaining has not been met. However, this outcome is not so different from the rest of the commercial space industry. Questions about self-sustaining commercial activities exist throughout the industry—including Commercial Crew, the International Space Station, and the Artemis Program [National Aeronautics and Space Administration, 2019, International Space Station (ISS) Cooperative Agreement Independent Review Team, 2020, National Aeronautics and Space Administration, 2020b, Foust, 2019e]. So rather than wondering *when* a space project will become self-sustaining, perhaps the better question is to ask *if* it ever will.

2.1.3 Economic Impact

VCSFA has not yet been able to become self-sustaining, but it had other long-term objectives. When it was founded in 1995, VCSFA's goals (see Section 2.1.2) included economic development. If a spaceport is considered a type of public infrastructure investment, a focus on economic impact makes sense—impact on the economy, while difficult to quantify, is often used to justify government investments. This section focuses on one economic impact analysis conducted for the spaceport, which was ultimately limited in utility and flawed because of a conflict of interest. To get a

Table 2.3: Summary of Wallops Island aerospace cluster economic impact estimate from ODU 2019 report.

Impact Category	Jobs	Dollars
Direct	1,940	$820 M
Indirect	1.649	$284 M
Induced	2,503	$265 M
Total	6,092	$1,370 M

better understanding of economic impact, another study would need to be conducted by a third party that focuses on jobs rather than estimating economic impact in dollars, which is notoriously subjective.

There have been a handful of studies conducted on economic impact related to VCSFA, including a few reports written for NASA and one written for VCSFA:

- Competitive Analysis of Virginia's Space Industry, published in 2011, written by the Performance Management Group at Virginia Commonwealth University [The Performance Management Group in the L. Douglas Wilder School of Government and Public Affairs at Virginia Commonwealth University, 2011]

- The Economic Impact of NASA Virginia Operations for Fiscal Year 2015, published in 2015, written by Chmura Economics and Analytics [Filer, 2019]

- The Economic Impact of NASA Langley Research Center (LaRC) and Wallops Flight Facility (WFF) During Fiscal Year 2016, published in 2016, written by Kapur Energy Environment Economics LLC for NASA [Filer, 2019]

- The Economic Impact of NASA Langley Research Center (LaRC) and Wallops Flight Facility (WFF) During Fiscal Year 2017, published in 2017, written by Kapur Energy Environment Economics LLC for NASA [Filer, 2019]

- The Economic Impact of the Wallops Aerospace Cluster, published in 2019, written by Larry Philer at Old Dominion University for VCSFA [Filer, 2019]

These five studies are the major ones conducted that encompass the work of VCSFA, but other studies have been conducted as well. The reports listed here vary in their scope. The Virginia Commonwealth University (VCU) report focuses on the space industry in the entire state of Virginia. The Chmura and Kapur Energy Environment Economics (KEEE) LLC reports focus on NASA's Langley Research Center and the Wallops Flight Facility, where MARS operates. The Old Dominion University (ODU) report focuses on the impact of activities at Wallops Island on Virginia and part of Maryland.

This thesis focuses on the ODU report, since the VCU report focuses on the entire state of Virginia and the other three reports focus primarily on NASA's economic impact. One major drawback of the ODU report is that there's an inherent conflict of interest since ODU is closely tied to MARS. Accorrding to a 2011 analysis conducted by consulting firm KPMG, VCSFA's "reliance on ODU Research Foundation detracts from organizational identity and business continuity." According to the report, ODU was responsible for a variety of administrative tasks at the spaceport, including "finance, human resources, administration, marketing, management and strategy" [KPMG Corporate Finance LLC, 2011]. However, since this is the best economic analysis of the spaceport available, a review is still included.

Two notes about the ODU are important for understanding the assessment economic impact: 1) the report encompasses all activities occurring at Wallops Island, not just VCSFA's activities, and 2) the report includes three counties in Maryland as part of the impacted region, in addition to all counties in Virginia. The report defines an "aerospace cluster" to include all of the activity on Wallops, some of which are outside of the aerospace industry. As defined, the cluster encompasses work from the following organizations: NASA's Wallops Flight Facility (WFF), Virginia's Mid-Atlantic Regional Spaceport (MARS), Northrup Grumman Innovation Systems (formerly Orbital ATK), US Navy, US Coast Guard, NOAA, Virginia Commercial Space Flight Authority (VCSFA), and Rocket Lab. As mentioned earlier in this thesis, non-aerospace activities at the UAS airfield have become part of VCSFA's revenues, which explains why Filer included them in the ODU report. The revenue from non-aerospace activities include "sectors like sensors, coastal engineering, physics, information technology and national security" [Filer, 2019]. In addition to including non-aerospace activities in the economic impact report, the ODU report defines the impacted area to include the entire state of Virginia as well as three counties in Maryland that are close to Wallops Island because "commuting data suggests a substantial number of employees at Wallops live in the three southern counties of Maryland."

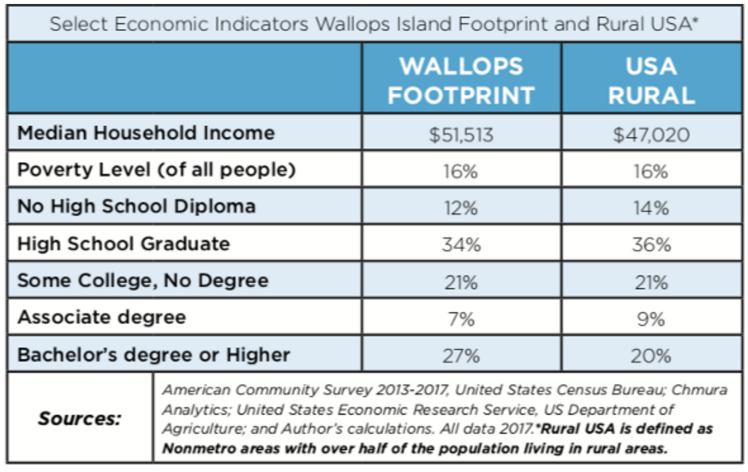
Economic impact is notoriously difficult to quantify. It's hard to track how money invested into a business cascades through a region and across numerous individuals. Economic impact is often broken into three categories in an attempt to capture all the effects [Filer, 2019, Moss Adams LLP, 2020a, Moss Adams LLP, 2020b]:

- Direct: "employment, compensation, and associated purchases that are directly tied to the firms and employees within the cluster…they become the primary input to the analysis"
- Indirect: "spinoff activity into the economic region of interest that was generated by" the activities in the Wallops aerospace cluster
- Induced: "the activity associated with the income increases emanating from the initial demand shock"

While it is difficult to estimate economic impact, and there isn't a second report to directly compare against the ODU report (since its scope is different from the other economic impact studies), this work at least provides some guidance as to how activities on Wallops Island (including VCSFA/MARS) impact the local economy. Table 2.3 shows a summary of ODU's estimated economic impact of the Wallops Island aerospace cluster. These numbers appear to reference a total number of jobs and an annual dollar impact. Economists say that economic impact dollar estimates are very subjective [Wassmer et al., 2016], so jobs are a better number to look at. It's good to have an estimate, but this study is limited because it doesn't compare to the number of jobs created by the Wallops Island aerospace cluster prior to the creation of the commercial spaceport.

The ODU report also compares economic statistics of the Wallops region to the average U.S. rural region to provide another way to assess economic impact, as shown

Table 2.4: ODU economic impact report's comparison of the Wallops Island impacted region to the average U.S. rural area



Select Economic Indicators Wallops Island Footprint and Rural USA*		
	WALLOPS FOOTPRINT	USA RURAL
Median Household Income	$51,513	$47,020
Poverty Level (of all people)	16%	16%
No High School Diploma	12%	14%
High School Graduate	34%	36%
Some College, No Degree	21%	21%
Associate degree	7%	9%
Bachelor's degree or Higher	27%	20%
Sources:	*American Community Survey 2013-2017, United States Census Bureau; Chmura Analytics; United States Economic Research Service, US Department of Agriculture; and Author's calculations. All data 2017.* ****Rural USA is defined as Nonmetro areas with over half of the population living in rural areas.***	

in Table 2.4. While the author asserts that this data "clearly illustrate that the presence of Wallops Flight Facility and the various organizations that call the area home has a positive influence on many important measures of economic well-being," the metrics differ by relatively small amounts that may not be statistically significant, particularly since the metrics were developed by different groups and likely used different methodologies.

Verifying that this analysis is correct would be difficult, particularly considering the subjectivity inherent in economic impact analyses. Conducting additional analyses using the same methodology in the future would help track changes, which would be useful for analyzing VCSFA's economic impact. However, any future economic impact analyses should focus more on the number of jobs, which is easier to verify, and less on the impact in dollars, which is harder to estimate accurately. Since VCSFA has also stated a goal of having a positive impact on STEM education and national security (see Section 2.1.2), clear metrics for measuring that impact should also be incorporated.

2.1.4 Profit Model

One method for studying the feasibility of a business plan is to construct a profit model, which provides an estimate for the cost and revenue of operations and an estimate for what it would take to breakeven on an initial investment. In order to construct a profit model for the Mid-Atlantic Regional Spaceport (MARS), a few key metrics are needed:

- Cost of building the spaceport
- Baseline cost to operate the spaceport
- Marginal cost per launch
- Baseline revenue for operating the spaceport
- Marginal revenue per launch

Incorporating these five metrics into a model will reveal how many launches would be needed for MARS to break even on its investment of constructing the spaceport, and thus achieve VCSFA's goal of becoming self-sustaining.

For the purposes of creating a MARS profit model focused on launch, this section uses a different number for the cost of building the spaceport than the one reported in Section I, $130M. The $130M price tag encompasses the total infrastructure investment by VCSFA as of FY 2018, which includes MARS' new UAS airfield. This profit models aims to focus on breaking even for just space launches, so it will use a FY 2015 metric for infrastructure investment, since 2015 was the year that modifications to MARS' launch infrastructure was completed and was the final year of operations before the UAS airfield was constructed. This price tag, $122M, includes construction on Launch Pads 0A (a medium class launch facility) and 0B (a small class launch facility) [Dixon Hughes Goodman LLP, 2018]

The cost of operating MARS is based on a linear fit of data (shown in Figure 2-6) from FY 2013 to FY 2018 data. Data from prior years was not included because of a significant change to VCSFA's operational model and state funding that occurred

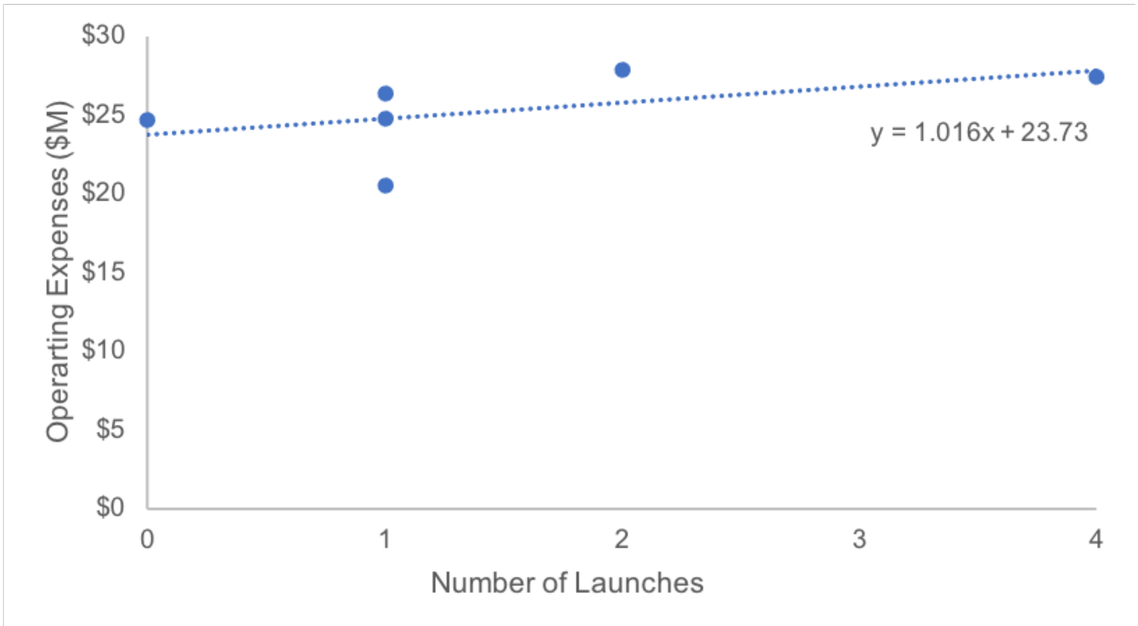


Figure 2-6: Linear fit to estimate operating costs for the Mid-Atlantic Regional Spaceport

at the beginning of FY 2013 as a result of the 2012 legislation discussed in Section III [Dixon Hughes Goodman LLP, 2013]. This figure compares the total operating expenses of the spaceport against the number of launches conducted in a single year in order to estimate the baseline cost of running the spaceport and an average marginal cost per launch. A baseline cost of running the spaceport is needed because even in a year with no launches, some money would still be needed for operations. This model estimates a baseline cost of operations (staffing, maintenance, etc.) to be $23.7M and a marginal cost for supporting each launch to be $1.0M.

Revenue data was estimated following the same logic. The revenue from operating MARS is based on a linear fit of data (shown in Figure 2-7) from FY 2013 through FY 2018 and estimates a baseline revenue for operating the spaceport and marginal revenue for each launch. This model is limited because the data point for 0 launches comes from FY 2016, in which MARS 1) supported a wet dress rehearsal and hot fire stage test of new Antares vehicle and 2) finished repairs to pad caused by Orbital Sciences Orb-3 accident, both of which could skew the data. This model estimates a baseline revenue for running the spaceport to be $7.9M and the marginal revenue per launch to be $1.9M. While a baseline revenue of $7.9M might seem counter-intuitive, the spaceport did conduct the aforementioned revenue-generating activity in FY 2016, and based on the current scope of its work, VCSFA will likely continue to have revenue-generating activity outside of just launch. The marginal revenue of $1.9M/launch meets expectations for this figure, based on knowledge that MARS charges $1.5M as a flat launch fee and about $0.5M for commodities per launch (for a medium class orbital rocket launch), as mentioned in Section 2.1.1.

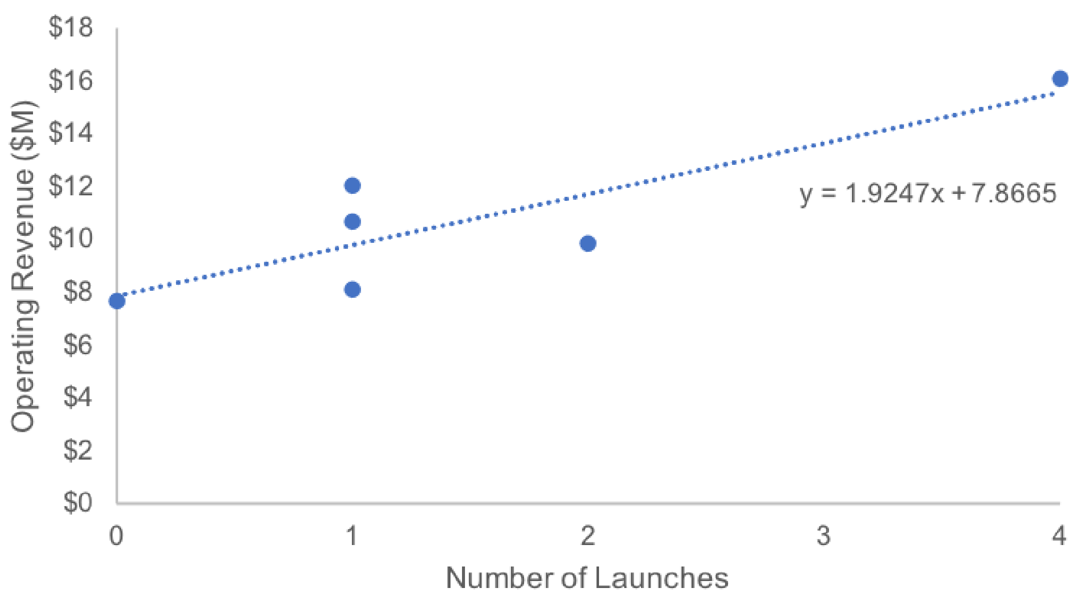


Figure 2-7: Linear fit to estimate operating revenue for the Mid-Atlantic Regional Spaceport

Combining the cost and revenue metrics for a single year creates a baseline profit model for MARS, represented by the equation below and illustrated by Figure 2-89. "x" refers to the number of launches in a year and "y" refers to the profit in $M.

$$y = .9087x - 15.8635$$

This model estimates that in order to break even on the operating costs in a single year (which was defined in multiple key documents as the point of "self-sustaining"), VCSFA would have to host 18 launches (the breakeven point is at 17.5 launches,

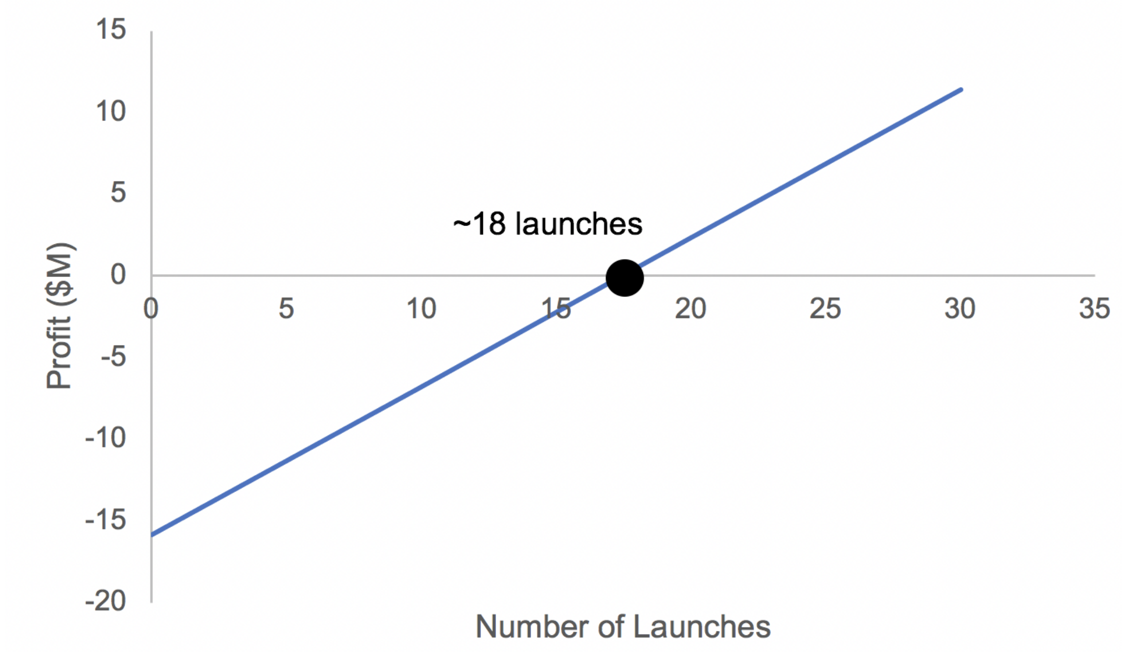


Figure 2-8: Baseline profit model for the Mid-Atlantic Regional Spaceport. Note: this does not incorporate infrastructure investments.

and half-launches aren't possible as far as the author knows). However, this baseline profit model does not incorporate infrastructure costs, either the money already invested or funding that will likely be necessary in the future for accommodating more customers and keeping infrastructure updated. In order to increase profitability and begin covering infrastructure costs in addition to operating costs, VCSFA would have to host more than 18 launches per year. The exact number of launches needed for breakeven would depend on how much capital investment they want to pay off and over what period of time. An additional limitation of this profit model is that it only encompasses Northrup Grumman's launch vehicles. It is possible that VCSFA's marginal cost and revenue would be different for a different launch vehicle, such that a complete profit model for its two current customers (Northrup Grumman and Rocket Lab) would be more complicated.

2.1.5 Discussion

Based on analysis conducted in this thesis, VCSFA has not reached its goal to become self-sustaining. A preliminary profit model for the spaceport shows that VCSFA would have to host 18 launches per year to break even on operating costs. In order to achieve a profit level that would leave money for paying off existing infrastructure investments or funding new infrastructure developments, the spaceport would need to host more than 18 launches per year. As of FY 2018, the most launches that VCSFA has hosted in a single year was four (see Figure 2-1), which leaves the spaceport well below the launch cadence needed to break even.

Despite continuing to rely on government support, VCSFA appears to have made a positive impact on the local economy, although the exact impact is difficult to quantify. VCSFA achieved most of the goals laid out in its 2012 strategic plan and is progressing toward its goals in the 2017 strategic plan. Rocket Lab became a second tenant and is scheduled to host its first launch from Virginia later this year. The UAS airfield is bringing in an alternate revenue stream and helping the spaceport to expand its network of users and supporters.

2.1.6 Conclusion

So, are spaceports economically viable? This question is complicated. Economic viability may be in the eyes of the beholder. It appears that at least in this case, MARS is not self-sustaining and thus requires continued government investment. However, MARS also has a positive economic impact on the surrounding region. The question then becomes: what level of government support is justifiable?

Answering this question will be different for each spaceport. But in order to come to a conclusion, reasonable projections about the future (including number of launches per year, revenue per launch, infrastructure costs, and economic impact) will be critical. Ultimately, it will be up to policymakers to decide.

This work begins to fill in a data gap about how commercial spaceports operate, which will help policymakers decide whether or not to pursue spaceport investment.

Table 2.5: Overview of Spaceport America.

Spaceport	Operator	State	Construction Type	Type of Launch Supported	License First Issued
Spaceport America	New Mexico Spaceport Authority	NM	Greenfield	Takeoff/landing methods • Horizontal • Vertical Spaceflight types • Suborbital	2008

Future work on this project will incorporate stakeholder interviews and expand the methodology to additional cases in order to begin building a more complete picture of US commercial spaceports and their economic viability.

2.2 Case 2: Spaceport America

Spaceport America (SA)[2] (overview of the spaceport shown in Table 2.5), which supports vertical and horizontal takeoff for suborbital launch vehicles, is run by the New Mexico Spaceport Authority (NMSA), a state agency in New Mexico. The spaceport was licensed as a commercial spaceport by the FAA in 2008. It is the world's first "purpose-built" commercial spaceport, meaning that it was built purely to serve as a space launch site for commercial launch companies. As such, it has become one of the most famous, if not the most famous, commercial spaceports in the United States. SA receives funding from state appropriations as well as a tax levied on two adjacent counties. They also earn revenue from tenants (rent and launch support), tourists and special events (e.g., commercial shoots and an annual student rocketry competition). While the concept for a New Mexico spaceport dates back to as early as 1990 [Messier, 2019b], the version of the spaceport that was eventually constructed was championed by New Mexico Governor Bill Richardson as a way to bring much-needed economic development to one of the poorest states in the country. Virgin Galactic signed on early as the anchor tenant after being wooed by Governor Richardson—a move that was integral to securing support from the state legislature. Two counties surrounding the spaceport voted to create a new tax that

[2]Some information in this case study was previously reported by the author in a Harvard Business School case study [Weinzierl et al., 2021].

would fund the spaceport's construction, although a third country voted against a new tax. SA is an interesting case of public infrastructure development because it shows how government, the private sector, and the public can come together to support a project.

The spaceport's profitability suffered because it was relying on fees from Virgin Galactic customer flights to become profitable, and despite originally targeting 2009 for its first spaceflight [BBC, 2008], Virgin Galactic has still not hosted a customer flight. Although the spaceport had always had multiple customers, it was focused on supporting Virgin Galactic. After Virgin Galactic had a fatal accident that killed one of its pilots in 2014, the spaceport shifted its business strategy to be less dependent on Virgin Galactic by increasing revenue diversification.

Throughout the spaceport's history, it has been home to multiple customers, although the total number has not changed significantly (see Figure 2-9). Virgin Galactic has always been the anchor tenant, but several other companies have used Spaceport America for a variety of activities, including systems tests, test flights, research and development, and balloon launches. Other customers include UP Aerospace, Lockheed Martin, Microgravity Enterprises Inc. (MEI), Payload Specialties, Armadillo Aerospace (which went bankrupt in 2013 and then reformed as Exos Aerospace, which still uses the spaceport), SpaceX, Pipeline2Space, Boeing, SpinLaunch, and ABL Space Systems. The number of launches supported by the spaceport is unclear, because they are reported inconsistently and without a clear explanation of what is counted as a launch. However, from a partial reconstruction of available launch data (see Table 2.6), it appears that there has been a somewhat consistent level of test and suborbital launches throughout the spaceport's history, and a large number of student rocket competition launches beginning in FY 2017, when the annual Spaceport America Cup rocketry competition was held for the first time [New Mexico Spaceport Authority and Meyners + Company, 2008, New Mexico Spaceport Authority and Meyners + Company, 2009, New Mexico Spaceport Authority and Meyners + Company, 2010, New Mexico Spaceport Authority and Clifton Gunderson LLP, 2011, New Mexico Spaceport Authority and CliftonLarsonAllen LLP, 2012, New

Table 2.6: Partial tally of launch history at Spaceport America.

FY	Spaceport America Cup	UP Aerospace	Armadillo	Exos	Other Suborbital	Total Suborbital	Year Total	Cum. Total	Note
2007	*SA Cup first held in 2017*	2	0	Armadillo reformed into Exos					One UP launch failed
2008		1	0						
2009		2	0						One UP launch failed, one partially successful
2010		3	0						
2011		1	4						
2012		1	0					15	
2013		1	3						
2014		1	Went out of business c. Aug. 2013	0				21	
2015		1		0					
2016		1		0				26	
2017	60	0		0	14	14	74	100	
2018	93	0		0	3	3	96	196	
2019	103	2		3					
Total	256	16	7						

Mexico Spaceport Authority and CliftonLarsonAllen LLP, 2013, New Mexico Spaceport Authority and CliftonLarsonAllen LLP, 2014, New Mexico Spaceport Authority and CliftonLarsonAllen LLP, 2015, New Mexico Spaceport Authority and Axiom Certified Public Accountants and Business Advisors LLC, 2016, New Mexico Spaceport Authority and Axiom Certified Public Accountants and Business Advisors LLC, 2017, New Mexico Spaceport Authority and Axiom Certified Public Accountants and Business Advisors LLC, 2018, New Mexico Spaceport Authority and Patillo, Brown and Hill, 2019].

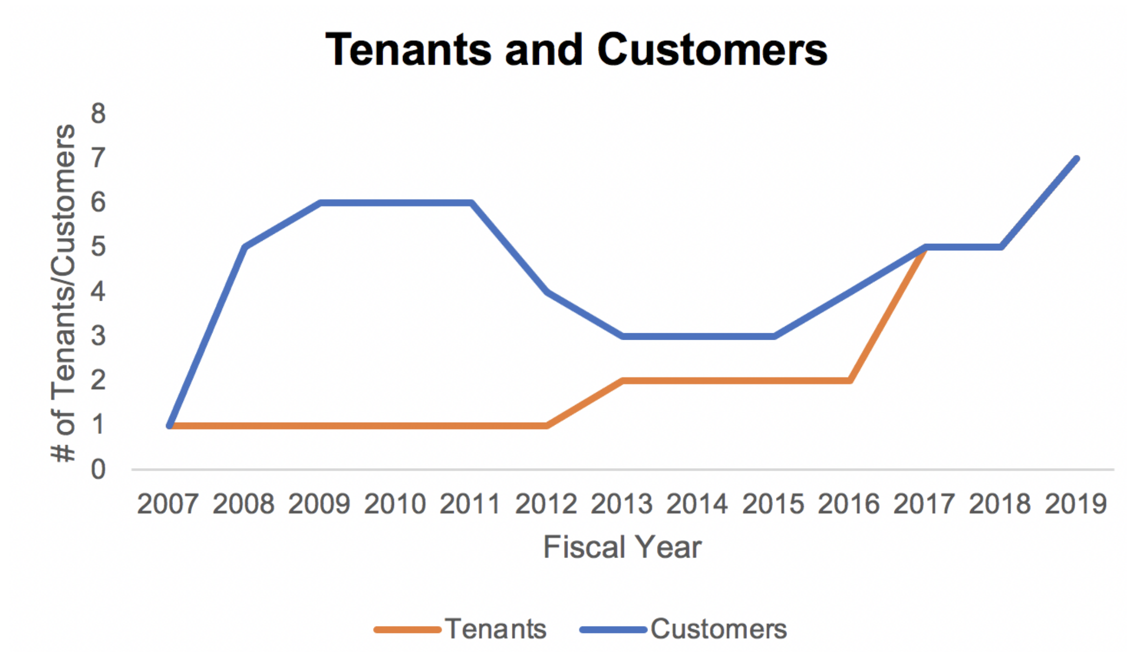


Figure 2-9: Number of tenants and customers throughout Spaceport America's history.

2.2.1 Financial Analysis

The pilot case on the Mid-Atlantic Regional Spaceport in Section 2.1 established a methodology to conduct financial analysis of a commercial spaceport. Where feasible, that methodology was applied to Spaceport America's finances. However, because Spaceport America does not report launch/flight revenue, a different approach was used for that metric.

A summary of the spaceport's financial sources and their uses comes from a report then-Executive Director Christine Anderson gave to the state's Legislative Finance Committee in 2013 [Anderson, 2013]:

- Construction/pre-operational budget
  - General Fund/Severance Tax Capital Funds
  - Gross Receipts Tax Capital Funds (Doña Ana & Sierra counties)
- Operational budget (day to day operations)
  - Appropriated operational funds
  - NMSA revenue
  - GRT excess pledged bond revenue

The spaceport's annual budget consists of both its construction budget and its operational budget—a key distinction when considering the state's investment in the spaceport. Originally, the state invested in the construction of Spaceport America, under the impression that it would eventually become financially independent, meaning it would generate enough revenue to cover its operating expenses. Thus, state appropriations and the gross receipts tax (GRT) would be used to cover construction costs, and state appropriations would supplement the spaceport's operational budget until it generated enough revenue to be independent from the state.

The state appropriation money comes from two sources: the state's general fund and severance tax bond proceeds. Severance taxes are levied when non-renewable resources are extracted from a state but intended to be consumed outside of the state

[Kagan and Uradu, 2020]. This tax has a long history in New Mexico, and is just another type of revenue the state receives [Clarke, 2013]. It has long been used to fund construction projects at Spaceport America, according to Christine Anderson [Anderson, 2013] (a former executive director of the spaceport) and Scott McLaughlin [Sloan, 2020] (current executive director of the spaceport), and confirmed by reviewing the spaceport's annual financial reports.

However, because of delays with Virgin Galactic, the spaceport's anchor tenants, expected revenues were lower than anticipated. This led the spaceport to seek and win approval from the state in FY 2011 to use excess revenue from the GRT toward operational expenses [Villagran, 2014]. Even though New Mexico's Finance Authority approved the use of excess funds toward operations, the GRT voted on by Doña Ana and Sierra counties was only supposed to be used to pay off construction bonds, and the tax would continue until the bonds were paid off—meaning that using the money for operational costs instead of paying off the bond debt could extend the length of the tax and thus cost the counties more money. This decision incited controversy within the state legislature, and State Senator Lee Cotter considered it mismanagement of public funds [Rubel, 2016]. A financial analysis conducted by the state estimated that the GRT would produce an excess of $600,000 over the amount needed to pay off construction bonds.

Another controversy has developed recently, as flight revenue from Virgin Galactic remains stalled: rather than decreasing the amount of state appropriations used to pay operating expenses, former executive director Dan Hicks pursued more money from the state in 2019: he requested the state increase its appropriations for operations from $1 million to $3.6 million, and said he planned for "the state's portion of the spaceport's budget to grow to 40%" [Gould, 2019]. Hicks was placed on administrative in 2020 following allegations of abusing authority, mismanagement of funds, and sex discrimination [Staten, 2020], and fired later that year after an investigation confirmed that Hicks had violated criminal and administrative statutes [Gould, 2020, Foust, 2020a, The State of New Mexico State Auditor and The McHard Firm, 2020].

Revenue Per Launch/Flight

Spaceport America does not report how much it charges customers for rent and launch/flight support, a position that is protected by a 2018 New Mexico law [New Mexico Spaceport Authority and Axiom Certified Public Accountants and Business Advisors LLC, 2018]. The Commercial Aerospace Protection Act [New Mexico State Legislature, 2018] allows the spaceport to keep the identity of customers a secret if they request it, and allows the spaceport to protect data about customer revenue, which it considers proprietary [McKay, 2018]. Virgin Galactic began one spaceflight, in December 2020, but it was terminated before reaching the Karman Line.

While the spaceport does not officially report its launch/flight revenue, for the purposes of financial analysis, this study use two previous estimates of Virgin Galactic user fees, which was supposed to range between $25,000 and $100,000 per flight [Alba Soular, 2013, Ortegon, 2014].

Amount of Capital Investment

The capital investment for the original construction of Spaceport America has been reported at about $220 million, with the state legislature appropriating 2/3 of the cost and the remaining 1/3 of funding coming from the gross receipts tax (GRT) voluntarily taken up by Doña Ana and Sierra Counties [Weinzierl et al., 2021, Moss Adams LLP, 2020b, Burrington, 2018]. This number is confirmed by reviewing the New Mexico Spaceport Authority's annual financial reports: for FY 2019, they reported about $170 million in capital assets and outstanding bond debt of about $50 million, which totals to $220 million [New Mexico Spaceport Authority and Patillo, Brown and Hill, 2019]. The state sold bonds as a financial vehicle to front the 1/3 of spaceport construction cost that would be covered by Sierra and Doña Ana counties. The bonds are being paid down by the GRT: essentially, the state gave a loan to the counties via the bonds, and the counties are slowly paying it back through the GRT. Therefore, combining NMSA's total capital assets with the remaining debt owed on the bonds should equal the total cost of spaceport construction.

Amount of Subsidies

As shown in Figure 2-10, the vast majority (99.5%) of subsidies that Spaceport America received during FY 2008-FY 2019 are from the state of New Mexico, with just 0.5% coming from a federal grant or unspecified grant source [New Mexico Spaceport Authority and Meyners + Company, 2008, New Mexico Spaceport Authority and Meyners + Company, 2009, New Mexico Spaceport Authority and Meyners + Company, 2010, New Mexico Spaceport Authority and Clifton Gunderson LLP, 2011, New Mexico Spaceport Authority and CliftonLarsonAllen LLP, 2012, New Mexico Spaceport Authority and CliftonLarsonAllen LLP, 2013, New Mexico Spaceport Authority and CliftonLarsonAllen LLP, 2014, New Mexico Spaceport Authority and CliftonLarsonAllen LLP, 2015, New Mexico Spaceport Authority and Axiom Certified Public Accountants and Business Advisors LLC, 2016, New Mexico Spaceport Authority and Axiom Certified Public Accountants and Business Advisors LLC, 2017, New Mexico Spaceport Authority and Axiom Certified Public Accountants and Business Advisors LLC, 2018, New Mexico Spaceport Authority and Patillo, Brown and Hill, 2019]. Looking at subsidies over time in Figure 2-11 reinforces the small amounts the spaceport received from grants. FY 2011 was a year of significant state investment, largely coming from $46 million appropriated via the state's severance tax.

To add in political context, New Mexico Governor Bill Richardson, who was a major proponent of the spaceport, left office on January 1, 2011 and was replaced by Susana Martinez, who was less fond of the spaceport project. Martinez remained in office until January 1, 2019, when she reached New Mexico's two-term limit for governors.

Cash Flow Analysis

The New Mexico Spaceport Authority does not include a statement of cash flows in its annual financial reports, so a cash flow analysis could not be conducted for Spaceport America.

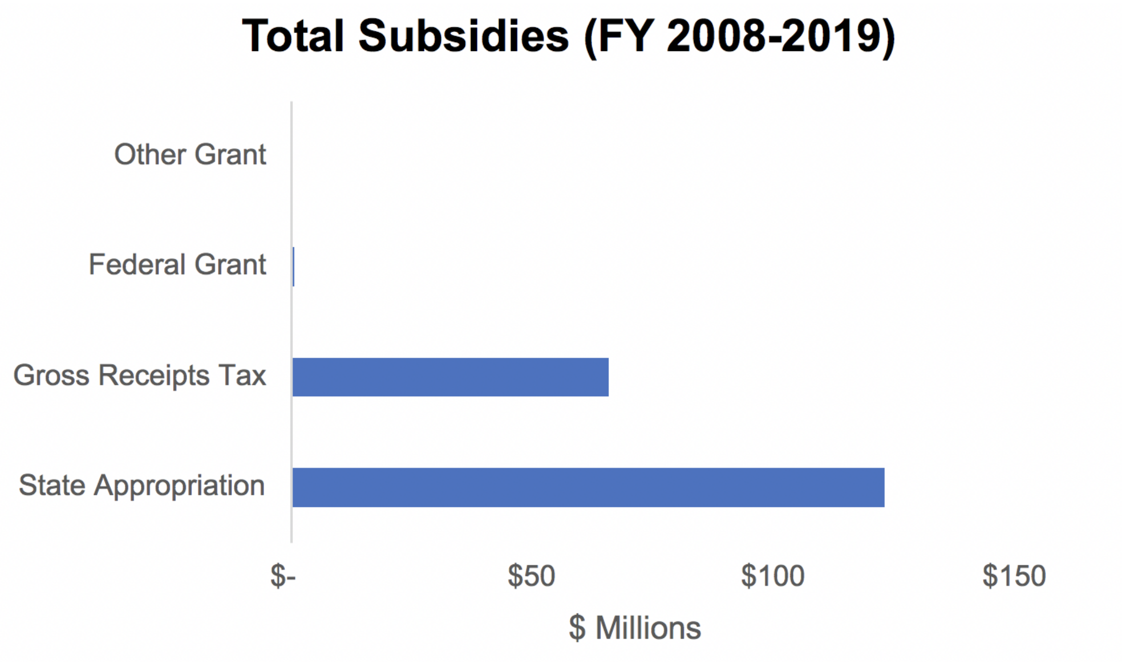


Figure 2-10: Total subsidies of Spaceport America over its history.

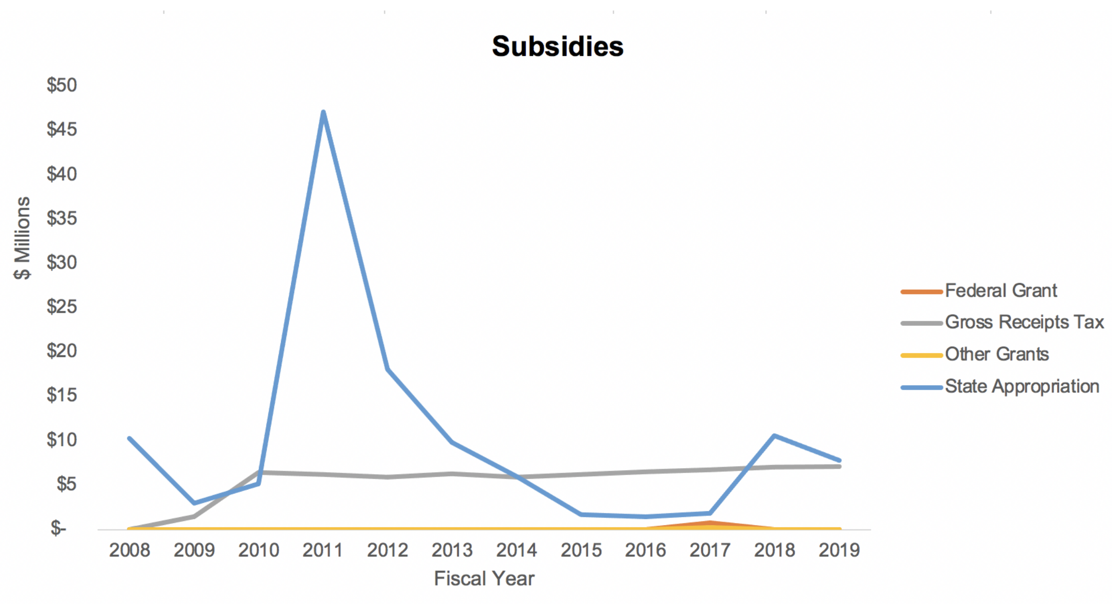


Figure 2-11: Annual subsidy amounts of Spaceport America.

Income (Loss)

Income (loss) in a category refers to the sum of revenues and expenditures. For example, operating income (loss) is the sum of operating revenues and expenditures, where the final number is reported without parentheses when it's income ($\$ > 0$) and with parentheses when it's negative ($\$ < 0$).

Figure 2-12 shows the operating income (loss), nonoperating income (loss) and total income (loss) (the sum of operating and nonoperating income (loss)) for Spaceport America from thee first year the spaceport reported operating revenues (FY 2012) until FY 2019. The FY 2020 report has been received by the state but not posted to the state auditor's website [New Mexico Office of the State Auditor,], so it was not included in analysis. This figure shows that operating income (loss) has never been positive in the spaceport's history, but that nonoperating income (loss) has steadily grown, to be in the black for FY 2017-FY 2019. The shift from negative to positive nonoperating income (loss) led to the total income (loss) exceeding 0 in FY 2018 and FY 2019.

For this analysis, line items in the spaceport's annual income statement were counted as either operating or nonoperating, and either revenue or expense. Each line item was categorized as follows:

- Operating revenue line items
    - Rental revenue
    - Tours and launch revenue
- Nonoperating revenue line items
    - Everything under "Other Financing Sources (Uses)" instead of "Revenues"
    - Gross receipts tax
    - Interest on loans
    - Interest on deposits

- Excess pledged revenue (only in FY 2012; per Note 14, this appears to be excess tax revenue, thus it should be nonoperating revenue)
- Federal grant
- Other grant

- Operating expenditures
  - Current – Personal services and benefits
  - Current – Contractual services
- Nonoperating expenditures
  - Current – Other
  - Capital outlay
  - Debt service – principal
  - Debt service – interest and other charges

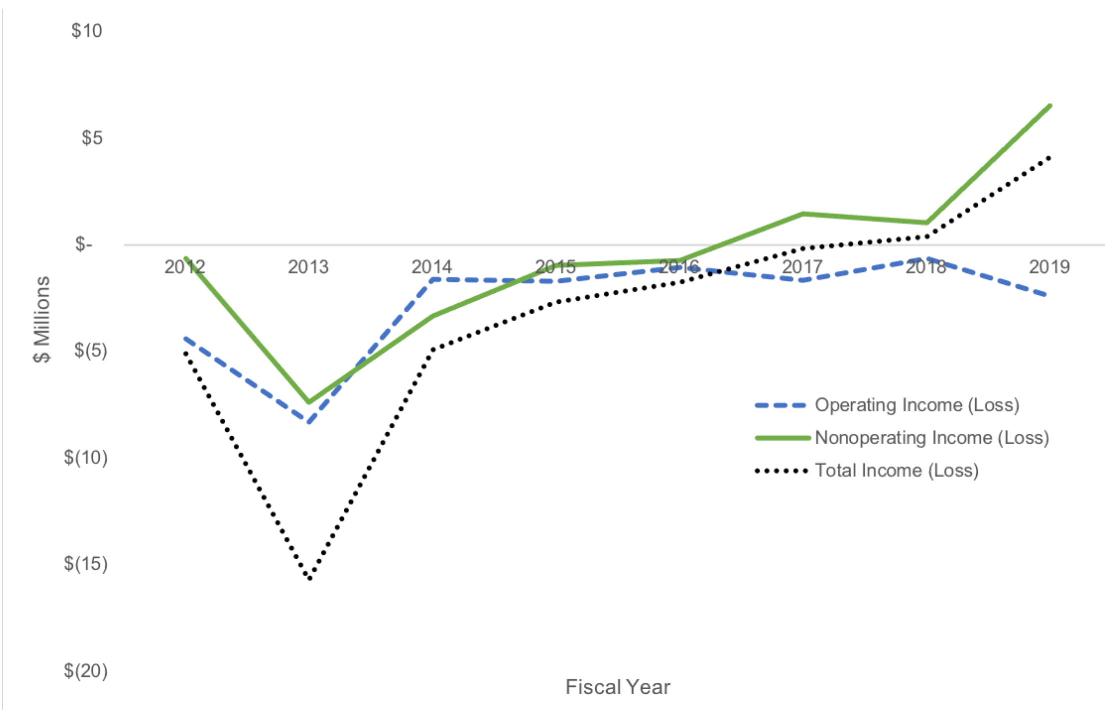


Figure 2-12: Spaceport America's operating, nonoperating and total income (loss).

Discussion

While exact data about the number of test flights and suborbital launches hosted at Spaceport America is difficult to come by, one thing is clear: their anchor tenant, Virgin Galactic, has yet to have a successful suborbital spaceflight. Outside of Virgin Galactic, the spaceport does have other tenants, although the number of launch activities conducted at Spaceport America has not changed significantly (see Figure 2.6), so launch activity doesn't explain the improvement in the spaceport's finances shown in Figure 2-12. However, the spaceport's finances do appear to be improving, so other aspects of the case study may explain why.

2.2.2 The Business Case: 2005 to 2020

Established by the New Mexico Spaceport Development Act in 2005 [New Mexico Spaceport Authority and Patillo, Brown and Hill, 2019], the New Mexico Spaceport Authority (NMSA) is a state agency that operates Spaceport America in Truth or Consequences, New Mexico. From 2005 to 2020, there were three key milestones in the progression of Spaceport America's business:

- 2005: Southwest Regional Spaceport Business Plan is published by the Arrowhead Center at New Mexico State University, written for the New Mexico Economic Development Department

- 2015: the Spaceport America Business Plan 2016-2020 is published

- 2019: Executive Director Dan Hicks testifies to the New Mexico legislature that the spaceport no longer intends to become self-sustaining, but will instead pursue increased appropriations from the state

Studying these documents, as well as the new business strategy introduced by Executive Director Dan Hicks in 2019, reveals how the spaceport's business plan changed over time. The initial 2005 business plan was very optimistic, estimating significant returns from suborbital launches, orbital launches, and tourism to the spaceport. By

2015, some of that optimism had faded after years of delays with the spaceport's anchor tenant, Virgin Galactic, so the spaceport began working to diversify its revenue stream so that it wouldn't rely so much on VG. But since its inception, the plan for the spaceport had been for it to wean off of annual appropriations from the state and instead become "self-supporting", meaning that it would cover its operational costs through customer revenue. In 2019, Dan Hicks acknowledged that he did not expect that to happen, and instead requested that the state increase its annual appropriation to the spaceport. Studying these milestones reveals how the spaceport shifted away from a strong reliance on VG for revenue and a goal to become "self-supporting to more diversified revenue streams and a plan to continue using state appropriations [New Mexico Spaceport Authority and CliftonLarsonAllen LLP, 2012, New Mexico Spaceport Authority and CliftonLarsonAllen LLP, 2013, New Mexico Spaceport Authority and CliftonLarsonAllen LLP, 2014, New Mexico Spaceport Authority and CliftonLarsonAllen LLP, 2015, New Mexico Spaceport Authority and Axiom Certified Public Accountants and Business Advisors LLC, 2016, New Mexico Spaceport Authority and Axiom Certified Public Accountants and Business Advisors LLC, 2017, New Mexico Spaceport Authority and Axiom Certified Public Accountants and Business Advisors LLC, 2018, New Mexico Spaceport Authority and Patillo, Brown and Hill, 2019].

Below is a timeline of significant events in Spaceport America's history, including events that led to its creation. This timeline is based on one developed by journalist Doug Messier [Messier, 2019b], but tailored to this research by removing some dates and adding some others. Information that comes from Messier is tagged with an asterisk.

- **March 1990:** The initial concept for the Southwest Regional Spaceport is proposed. Technical and marketing studies follow that focus on using the state's vast deserts to launch sounding rockets and to recover capsules from space.*

- **1992:** Southwest Space Task Force is formed. From about 25 sites considered, the task force eventually focuses on a 27-square mile tract of state-owned land near Las Cruces and Truth or Consequences that will become Spaceport

America.*

- **1994:** The New Mexico Office for Space Commercialization (NMOSC) is created. NASA initiates the Reusable Launch Vehicle (RLV) program, which includes the development of the X-33 single-stage-to-orbit (SSTO) experimental vehicle.*

- **June 1994 – July 1995:** Five DC-X flights are conducted in New Mexico with funding from NASA and the Advanced Research Projects Agency (ARPA).*

- **July 2, 1996:** NASA awards a contract to Lockheed Martin to build the X-33 experimental vehicle. The company plans to build a full-scale follow-on vehicle it calls VentureStar.*

- **July 7, 1996:** On its fourth flight, DC-XA is severely damaged in a fire after one of its landing struts fails to extend. The vehicle is too severely damaged to be rebuilt. NASA declines to build another vehicle in order to focus on the X-33 program.*

- **1998-2001:** New Mexico pursues but loses bid to host flight tests of NASA's X-33 SSTO experimental vehicle from WSMR. Southwest Regional Spaceport also bids on right to fly Lockheed's VentureStar. The SSTO would fly commercial and military missions from the spaceport.*

- **March 1, 2001:** NASA cancels the X-33 program due to technical challenges and rising costs. Lockheed Martin abandons VentureStar.*

- **January 1, 2003:** Bill Richardson becomes governor of New Mexico and begins looking for ways to bring economic development to one of the poorest states in the country.

- **2003:** Rick Homans becomes secretary of Economic Development as a member of Gov. Richardson's administration. He gains the governor's support for reviving the spaceport.*

- **May 11, 2004:** XPRIZE Foundation announces that New Mexico has won the competition to host the X-Prize Cup, a two-day air and space exposition. The annual event is designed as a follow-on to the ongoing Ansari X Prize, which is a $10 million competition for the first privately-funded, crewed suborbital vehicle capable of flying above 100 km (62.1 miles) twice within two weeks.*

- **Sept. 27, 2004:** Richard Branson announces the launch of Virgin Galactic Airways with plans to fly tourists on suborbital flights in the 2007-08 period. The company will license SpaceShipOne technology developed for the Ansari X Prize by Burt Rutan and Microsoft co-founder Paul Allen.*

- **Oct. 4, 2004:** Scaled Composites pilot Brian Binnie flies SpaceShipOne above 100 km to claim the $10 million Ansari X Prize.*

- **2005:** Negotiations are conducted to lure Virgin Galactic to the Southwest Regional Spaceport. The New Mexico Spaceport Authority is created to oversee development of the facility.*

- **Dec. 14, 2005:** Richardson and Branson announce that Virgin Galactic will locate its world headquarters from the spaceport.*

- **December 30, 2005:** A Futron Corporation study commissioned by New Mexico's government is released. The study projects that in the first five years the spaceport will generate $1 billion in spending with a payroll of $300 million, with employment reaching 2,300 by the fifth year of operation.*

- **March 1, 2006:** Southwest Regional Spaceport is formally renamed Spaceport America.*

- **2006:** New Mexico Legislature approves spaceport funding.*

- **September 25, 2006:** UP Aerospace conducts the first suborbital sounding rocket launch from Spaceport America. The SpaceLoft XL booster fails eight seconds into flight.*

- **October 20–21, 2006:** First X-Prize Cup held in Las Cruces.* It could not be held at Spaceport America because the facility had not been constructed yet.

- **April 3, 2007:** Residents of Dona Ana County approve a quarter-cent tax increase to help fund spaceport construction.*

- **April 28, 2007:** UP Aerospace conducts the first successful SpaceLoft XL launch at the spaceport.*

- **Oct. 26-28, 2007:** Second and final X-Prize Cup held in Alamogordo.*

- **April 22, 2008:** Residents of Sierra County approve a quarter-cent tax increase to help fund spaceport construction.*

- **Oct. 24-25, 2008:** X Prize Foundation managed Northrop Grumman Lunar Lander Challenge held in Las Cruces.*

- **Nov. 4, 2008:** Residents of Otero County reject a local tax increase to help fund spaceport construction.* Since only 2 of the 3 counties needed to approve the tax for the spaceport legislation to go through, and Doña Ana and Sierra counties had already approved the tax, the spaceport project proceeds [Weinzierl et al., 2021].

- **December 2008:** Spaceport America receives launch license from the Federal Aviation Administration.*

- **Dec. 31, 2008:** New Mexico announces that Virgin Galactic has signed a 20-year lease to serve as anchor tenant at Spaceport America.*

- **June 18, 2009:** Officials hold groundbreaking ceremony for Spaceport America.*

- **2010:** the spaceport's Executive Director, Steve Landeene, resigns after being suspended for conflict of interest allegations. Rick Homans, the state's Secretary of Economic Development, takes over.

- **October 22, 2010:** Virgin Galactic and New Mexico officials dedicate the runway at the partially completed Spaceport America. The runway is officially named the Governor Bill Richardson Spaceway. Branson predicts that commercial space tourism flights will begin in nine to 18 months (July 2011-April 2012).*

- **Jan. 1, 2011:** Susana Martinez replaces Bill Richardson as the Governor of New Mexico. Martinez is less supportive of the spaceport than Richardson was. She hires Christine Anderson, who led the audit of the spaceport for Martinez's transition team, to replace Rick Homans as the spaceport's executive director [Weinzierl et al., 2021].

- **Oct. 18, 2011:** Virgin Galactic and New Mexico officials dedicate the Virgin Galactic Gateway to Space at Spaceport America. Branson predicts SpaceShipTwo flight tests occurring in 2012 and commercial flights from Spaceport America in early 2013.*

- **November 2012:** Virgin Galactic threatens to abandon Spaceport America unless the state extends informed consent liability protections to spacecraft manufacturers and suppliers. The legislation would provide protections to Virgin Galactic's sister firm, The Spaceship Company, which builds SpaceShipTwo vehicles.*

- **Jan. 15, 2013:** Virgin Galactic begins monthly lease payments of about $85,000 at Spaceport America. The amount will later increase substantially in the years ahead.*

- **April 2, 2013:** New Mexico Gov. Susana Martinez signs law providing liability protections for Virgin Galactic's manufacturers and suppliers.*

- **April 29, 2013:** SpaceShipTwo VSS Enterprise makes first powered flight test from Mojave Air and Space Port in California. Following the 16-second engine burn, Branson announces an increase in ticket prices from $200,000 to$250,000 and predicts he will fly by Christmas.*

- **Oct. 31, 2014:** SpaceShipTwo VSS Enterprise breaks up in flight due to premature deployment of vehicle's feather during powered ascent. Scaled Composites co-pilot Mike Alsbury is killed in the breakup; pilot Pete Siebold parachutes to safety with serious but survivable injuries. Branson predicts a second SpaceShipTwo under construction in Mojave will be completed and ready for testing in five to six months. The vehicle, which will be named Unity, does not conduct a glide test until two years later.*

- **2015:** Spaceport America releases a new business plan, which focuses on revenue diversification as a strategy to insulate itself from Virgin Galactic after the fatal 2014 accident [Spaceport America, 2015]

- **2016:** Christine Anderson resigns from the executive director position and is replaced by aerospace industry veteran Dan Hicks.

- **Fall 2016:** Spaceport CFO Zach de Gregorio presents his economic analysis of the spaceport [de Gregorio, 2016, Haussamen, 2017].

- **Dec. 3, 2016:** VSS Unity performs first glide flight in Mojave.*

- **2019:** Virgin Galactic moves its operations to Spaceport America [REF?]

- **November 2019:** Executive Director Dan Hicks announces a new business strategy to increase, rather than decrease, the state's annual investment into the spaceport

- **January 2020:** MossAdams, a firm hired by the state, releases its economic impact analysis of the spaceport. It reports that the spaceport broke even (defined as when the economic and fiscal impacts equaled the amount of capital investment) in FY 2013, despite the fact that Virgin Galactic had not yet used the spaceport for a flight and few other activities were taking place. Unlike the analysis conducted by Futron in 2005, this report includes multiple potential future scenarios. However, the most pessimistic scenario still assumes that Virgin Galactic will be flying customers and that the pace of other launch activities will increase. The most optimistic scenario relies on the spaceport conducting orbital launches, which have never been allowed at an inland spaceport in the United States.

- **November 2020:** Dan Hicks is fired after allegations of abusing authority and mismanaging authority led to a state investigation, which revealed that Hicks "violated criminal and administrative statutes" [Gould, 2020, The State of New Mexico State Auditor and The McHard Firm, 2020, D'Ammassa, 2020b, D'Ammassa, 2020a, Gerstein, 2020]

- **December 12, 2020:** Virgin Galactic ends a test flight early because of an engine anomaly. The flight was supposed to be the first time Virgin Galactic flew into space from Spaceport America, and would have made New Mexico the third U.S. state to host a human spaceflight [Foust, 2020b]. It was also meant to be thee final test flight before Richard Branson would fly, which would mark the beginning of customer flights and thus the beginning of flight fees paid to the spaceport [Grush, 2020].

From as early as 1990, the state of New Mexico was pursuing the space industry as a tool for economic development efforts. Early work was in pursuit of government-led projects like using the state as recovery site for NASA capsules returning from space and supporting NASA's reusable launch vehicle (RLV) program. In 1994, the state created the New Mexico Office for Space Commercialization (NMOSC) within the Economic Development Department in order to pursue commercial space opportunities. NMOSC would later become the New Mexico Spaceport Authority [Weinzierl et al., 2021]. By 2001, technical difficulties and delays led NASA to shift away from the RLV program, dashing New Mexico's hopes of bringing in economic development through NASA.

However, just a few years later, a new group of private companies began working on commercial spaceflight. Much of the work centered around the X Prize Foundation's Ansari X Prize, which promised $10 million to the private company that could launch a reusable crewed vehicle into space twice within two weeks. At the same time as the

Ansari X Prize competition was underway, Bill Richardson became Governor of New Mexico and brought on Rick Homans as his Secretary for Economic Development. Homans convinced Richardson that attracting the commercial space industry to the state would be a good strategy for economic development for one of the poorest states in the country. Separately, Richard Branson had been looking for a space vehicle to start a space tourism company. He saw Scaled Composites' SpaceShipOne competing in the Ansari X Prize and purchased the rights to the technology for his new company, which later became Virgin Galactic. Richardson and Homans pursued Branson and Virgin Galactic (VG), and successfully got them to come on as the anchor tenant for the New Mexico spaceport. All of these activities happened in a relatively short period of time, and suddenly the spaceport project was focusing on commercial space tourism rather than supporting NASA's spaceflight efforts [Weinzierl et al., 2021, Messier, 2019b]. But bringing VG on as the anchor tenant was just one of the hurdles to jump though: in order for the New Mexico legislature to approve appropriating 2/3 of the estimated $220 million needed for construction, Richardson would also have to get at least two of the three counties surrounding the proposed site of the spaceport to agree to a new tax that would fund the final 1/3 of the spaceport's construction costs. Finally, Richardson would have to get a FAA license to conduct launches as a commercial spaceport and get approval to excavate near protected Native American sites.

With VG secured as an anchor tenant, next up was the tax vote within the three counties surrounding the spaceport: Doña Ana, Sierra and Otero. Doña Ana and Sierra voted to approve the tax, and Otero voted against it. With two of the counties on board by April 2008, Richardson secured the 1/3 construction funding from the counties and the 2/3 construction funding from the state legislature. By December, the spaceport received its spaceport license from the Federal Aviation Administration (FAA) [Federal Aviation Administration, 2008], fulfilling all the goals needed to establish the spaceport.

While Richardson and Homans were working to achieve these goals, they and the state legislature were working to better understand the potential impact of the spaceport. They hired New Mexico State University (NMSU) to create a business plan [Arrowhead Center at New Mexico State University, 2005]. While this report identified important information like multiple potential revenue streams and operational considerations for opening the spaceport, it focused more on how to open the spaceport instead of whether or not the spaceport should be built at all. Of the 45 pages in the report, 15 pages were spent on tactical considerations such as marketing and legal, whereas just 5 pages were spent on a situational analysis. There were three key gaps in this business plan.

The first and most important gap was the lack of a plan for how the spaceport would make money. The report estimated the amount of revenue needed to cover projected construction and operations cost, but did not identify revenue sources. The report itself identified this gap: "the critical question to be addressed is where the breakeven revenues will come from and whether they will be sufficient to meet these breakeven requirements [Arrowhead Center at New Mexico State University, 2005]." This was a severe flaw for a business plan that was used as justification for building the spaceport, but other organizations have followed a similar logic when considering spaceports. The International Space University published a report meant to help spaceport "developers and operators in the evaluation of the commercial viability of spaceport," [International Space University, 2008] but then focused more on logistics and operational considerations like law and safety than they did on ensuring a solid business plan was in place. While the logistical and operational considerations are important, a viable business plan should precede operational considerations.

Second, the NMSU report did not address the major technical distinctions between zero-g airplane flights, suborbital launches, and orbital launches. The differences are substantial: as altitude increases, the safety risk and business risk increase significantly. For example, the amount of energy required for an orbital launch is about 50 times the amount needed for a suborbital launch [The Planetary Society et al., 2020]. Acknowledging and understanding these technical differences is critical to developing a viable business plan.

Finally, the NMSU report fell into a common trap: it identified potential positive futures, but didn't address potential negative futures, such as how to respond if the suborbital tourism market this plan relied on never materialized. Once again, the authors recognized this flaw but did not address it: "Further, if the sub-orbital tourism markets do not develop as predicted, the industry may not experience the desired degree of growth [Arrowhead Center at New Mexico State University, 2005]."

Despite these gaps, the key takeaway of the NMSU business plan was that investing in the spaceport would be a good choice for New Mexico. So with a seemingly positive business plan, an anchor tenant in Virgin Galactic, and construction funding from the county tax and state appropriations, Spaceport America moved into the construction phase.

For the first few years of the spaceport's existence, they were waiting on Virgin Galactic to begin customer flights to ramp up the spaceport's revenues. As VG experienced delay after delay, including a fatal flight in 2014, the spaceport was not seeing those critical user fees from VG. Secondary tenants like UP Aerospace were conducting research and development activities consistently, including test and operational suborbital launches, but those activities didn't bring in significant revenues.

The 2014 accident shed light on the drawbacks of the tightly coupled partnership between SA and Virgin Galactic. In response, SA's executive team, led by executive director Christine Anderson, began thinking about how to rebrand itself as a separate entity from Virgin, including how to bring in other revenue streams. Given the fatal accident and the declining economy, asking for more public funding wasn't an option. In 2015, the team unveiled a new business plan [Spaceport America, 2015, The Associated Press, 2015] and a new tourist experience [Boyle, 2015b]. The business plan emphasized revenue diversification, aiming to increase the portion of non-aerospace revenue to 30% by 2020. The non-aerospace sectors it targeted included tourism (hence the new tourist experience), special events, sponsorship, merchandise, and virtual education. Although SA only had 3,000 visitors in 2015, they hoped to increase that number to 60,000 by 2017, when they expected suborbital tourism flights to begin.

Finances were still a main source of concern as revenues remained low. Given the strong economy at the time, the GRT coming from Doña Ana and Sierra counties was exceeding the amount it was expected to generate, so the spaceport requested and gained state approval to use the excess GRT funds toward covering operational costs. Although they had the support of multiple state agencies, some members of the legislature took issue with using the GRT toward operational costs, since the voters had agreed to the tax for the explicit purpose of covering only construction costs, and because the spaceport was supposed to become "self-supporting" [Weinzierl et al., 2021].

In 2016, executive director Christine Anderson stepped down and was replaced by aerospace industry veteran Dan Hicks.

Over the next few years, some activity as the spaceport picked up. By FY2018, Spaceport America held tenant leases with five companies (Virgin Galactic, Boeing, UP Aerospace, EXOS Aerospace, and Pipeline2Space), had signed multiple individual launch operations contracts, and had hosted 196 rocket launches (including 153 from Spaceport America Cup, the student rocketry competition) [New Mexico Spaceport Authority and Axiom Certified Public Accountants and Business Advisors LLC, 2018, Haussamen, 2017, Boyle, 2015b]. While SA had the same number of customers in 2018 as it had in 2008, there had been significant turnover. Of the five customers at SA in 2008, only two remained at the spaceport by 2018. SA replaced the three customers that left with three new ones, but given the high-risk nature of starting a space company, it was unclear whether the spaceport would be able to maintain a consistent customer base.

Spaceport CFO De Gregorio reported that direct spending into New Mexico from space companies reached $4.6 million in FY2017; $1.3 million of which stemmed from Virgin Galactic alone. The spaceport was expected to be fully self-funded – that is, Spaceport America would not request a General Fund appropriation for its operational budget – by FY2019. This projection was due in part to expected increases in customer activities, but largely due to Virgin Galactic's aggressive flight schedule and operations plans. Moreover, Spaceport America's ability to be self-funded relied heavily on its anchor tenant's annual rent, slated to increase from $1 million to $3 million in FY2018 [de Gregorio, 2016, Patricio Ruiloba Rep Tomás Salazar et al., 2016]. Virgin Galactic was tantalizingly close to flying customers. Their second spaceship, VSS Unity, had conducted more than a dozen flight tests [Boyle, 2018]. Five more Virgin Galactic employees earned their commercial astronaut wings, including four pilots and the first test passenger, Chief Astronaut Instructor Beth Moses [Wattles, 2018, Drake, 2019]. With that flight, Moses became the first woman to fly into space aboard a commercial vehicle. But all those flights took place at Mojave Air and Space Port.

Three years into his tenure running SA, Hicks oversaw a major shift in the spaceport's business plan. With increasing oil prices, New Mexico's revenue had gone up, and Hicks saw an opportunity. At a meeting with legislators in 2019, he requested the state increase its appropriations to cover spaceport operations, from $1 million to $3.6 million. The legislators were caught off guard by the request, since the spaceport's business plan had always included the goal of becoming self-sufficient, meaning it would fund its own operations from customer revenues rather than from state appropriation [Gould, 2019].

Hicks told legislators that the goal to become self-sufficient was no longer part of the spaceport's business plan. In fact, he wanted the state's portion of the spaceport's budget to grow to 40% [Gould, 2019].

Hicks had taken on a challenging role, running a controversial public infrastructure project tied to the high-risk commercial space sector. By 2020, it had gotten to him. In July, a whistleblower complaint from spaceport CFO De Gregorio led to Hicks being placed on administrative leave [D'Ammassa, 2020b, D'Ammassa, 2020a]. De Gregorio accused Hicks of abusing authority and mismanaging funds. Later that month, another allegation was levied against Hicks: human rights violations and sex discrimination [Staten, 2020]. The state hired the McHard Firm, a forensic accounting company, to conduct a formal investigation [Gould, 2020], which was completed in November and resulted in Hicks being fired [Foust, 2020a]. Scott McLaughlin, who had been in charge of spaceport business development, became the interim director [Gerstein, 2020].

McHard's 362-page report included details on Hicks' poor management of people, use of improper contracting processes, mismanagement of public funds, and several other allegations. The report ultimately concluded that "Hicks violated criminal and administrative statues, as well as the State of New Mexico Governmental Compliance Act, and Governor Lujan Grisham's Code of Conduct, during his tenure as Director of the Spaceport." McHard recommended that the case be referred to law enforcement for a criminal investigation [The State of New Mexico State Auditor and The McHard Firm, 2020].

Shortly after taking over as executive director, McLaughlin acknowledge that the spaceport's business model was built around Virgin Galactic. While he would continue the spaceport's focus on VG, he aimed to bring in more customers while working to rebuild the organization's reputation after the Hicks firing controversy. McLaughlin also stated that the spaceport was taking in about $10 million per year from customers and about $4 million per year from the state [Wyland, 2021].

2.2.3 Economic Impact

Economic impact is notoriously difficult to quantify accurately. Economists and public policy analysts have asserted that economic impact analyses "tend to overestimate both the likelihood and magnitude of public benefits" . In a paper on the use of economic impact studies to justify government investment in professional sports facilities, Wassmer, Ong and Propheter explain the limitations of this type of analysis:

The use of economic impact studies to justify subsidies for sports venues and major sporting events is frequent. As scholars have argued for some time, these studies suffer from numerous flaws that are too often present and, hence, yield inaccurate and usually overly optimistic economic impact estimates. Because there are no methodological or reporting standards to follow, elected officials desiring the professional sports activity are able to shop for a private consultant that will produce an analysis that yields a bloated level of positive local impacts. As a result, the public often overinvests its scarce public resources in these professional sports activities relative to the benefits generated by the professional sports activity to the jurisdiction.

This assertion has proven accurate over two decades of Spaceport America's operations. Four key documents show how economic impact analyses of the spaceport changed over time, with each document containing serious flaws:

- 2005: an economic impact study conducted by aerospace consulting firm Futron is published [Futron Corporation, 2005]

- 2015: the Spaceport America Business Plan 2016-2020 is published with a short economic impact summary [Spaceport America, 2015]

- 2016: Spaceport America CFO Zach De Gregorio reports his own economic impact analysis to the state [de Gregorio, 2016, Patricio Ruiloba Rep Tomás Salazar et al., 2016]

- 2020: an economic impact analysis conducted by accounting firm Moss Adams is published [Moss Adams LLP, 2020b, Moss Adams LLP, 2020a]

As a follow-up to the 2005 NMSU business plan, the state of New Mexico sponsored an economic impact analysis, conducted by aerospace consulting firm Futron in 2005, that estimated 14,310 customers for Virgin Galactic over 11 years. In addition to the customer projections, Futron also estimated that the 2015 economic impact of the spaceport would be $460 million [Futron Corporation, 2005], appearing to confirm the analysis conducted by NMSU that the spaceport would be a good investment. Based on these two reports, the state pursued development of Spaceport America.

However, with hindsight, the Futron analysis had three key limitations. As with the NMSU business plan, it addressed only positive potential futures. Futron was upfront about this, repeatedly saying its analysis was "a best-case scenario for such launch activity at the spaceport and not a definitive forecast." But this strategy didn't make much sense for a state deciding whether or not a proposed project would be a good investment; a more appropriate analysis would've addressed a wider range of possible futures.

In addition, the report wasn't strictly independent from other influences. In fact, the analysis "us[ed] Governor Richardson's vision as its baseline, along with key assumptions provided by the New Mexico state government." Again, this strategy didn't match the goal of gathering an objective perspective on the proposed spaceport project.

Finally, Futron relied on multiple assumptions (both of its own creation and from the state) that in hindsight were clearly flawed. The state assumed that it would capture one of the future NASA COTS providers as a customer, who would relocate to New Mexico and conduct ISS resupply launches there. Capturing such a lucrative customer was a lofty goal in and of itself, but considering that the United States had never hosted an orbital launch from an inland spaceport, this assumption was particularly optimistic. In addition, Futron conducted a survey of 450 high net worth individuals about their willingness to pay for space tourism, and then they extrapolated the results to estimate the global demand for suborbital space tourism [Futron Corporation, 2002]. While sample sizes for surveys must necessarily be smaller than the population size, extrapolating from 450 people to the global population of high net worth individuals introduces room for significant error. Finally, Futron assumed that if the suborbital space tourism market developed, that New Mexico would begin with 75% market capture since it would have Virgin Galactic, "the dominant company in the industry," as its anchor tenant. This is another optimistic assumption that biases the analysis toward a positive outcome. In reality, there were other companies competing to develop suborbital vehicles that could have significantly affected Spaceport America's market share.

Looking at the NMSU business plan and the Futron economic analysis together reveals two things about New Mexico's decision-makers: first, a lack of consideration for less desirable outcomes, and second, poor assumptions and understanding about the space industry. There was a kind of circular logic involved in this process, wherein legislators wanted to know whether or not a spaceport would be a good investment, but then solicited studies that were inherently biased to tell them it was a good investment. But despite holes in these analyses, New Mexico decision-makers chose to pursue the spaceport and bring in tenants.

Veteran space journalist Doug Messier summed up the situation well: "The promises made in December 2005 were unrealistic. But, they worked. The New Mexico Legislature voted to fund construction of a spaceport the state had been wanting to build for 15 years [Messier, 2019c]."

One decade and many delays later, criticism of the spaceport's sluggishness to produce economic benefit to taxpayers was common. Projections for demand and economic impact at SA varied widely, and the spaceport had not lived up to its own promises.

Futron's 2005 economic impact analysis, which had been used to justify the state's investment in the spaceport, estimated that in 2015, the economic impact of the spaceport would be $460 million [Futron Corporation, 2005]. But the 2015 Spaceport America Business Plan estimated that year's economic impact at just $10 million [Spaceport America, 2015].

Immediately following Hicks' arrival as CEO, Zach De Gregorio, Spaceport America's CFO, reported his own analysis of the spaceport's economic development impact to the New Mexico Finance Authority Oversight Committee [de Gregorio, 2016, Patricio Ruiloba Rep Tomás Salazar et al., 2016]. De Gregorio estimated that every dollar invested from the NM General Fund in FY2016 had seen a 20-fold return and new business at the spaceport grew 135 percent, with $2.3 million generated in customer revenue and 50 new full-time jobs created in that year.

Some critics, including members of the Oversight Committee, remained skeptical of the spaceport's economic impact, noting the high uncertainty in De Gregorio's revenue projections and a concern that the analysis incorrectly counted all public money invested in the spaceport as economic development for the region. "The spaceport economic impact study suffers from a classic mistake," added Chris Erickson, an economics professor at New Mexico State University, "which is to only count the benefits and not count the costs." Others were frustrated that the analysis included the investment of tax money in STEM education, but did not demonstrate how to measure that money's impact on student retention. "I want to know outcome," insisted Kevin Boberg, New Mexico State University's Vice President for economic development [Haussamen, 2017].

Still other skeptics attacked De Gregorio's methods of gathering data, noting that his analysis was based on anecdotal discussions with government officials and business owners. "Economists don't build spaceships, and spaceports shouldn't do economic impact analyses," Erickson said [Haussamen, 2017]. Hicks pushed back, acknowledging the need for a professional economic impact study but arguing that such studies could cost tens of thousands of dollars; given the tight financial situation Spaceport America already faced, the NMSA could not afford professional consultation.

With remaining concerns about economic impact that were brought up by the spaceport's 2015 business plan and spaceport CFO Zach de Gregorio's 2016 analysis, the state decided to hire outside professionals to clear up the situation.

New Mexico and NMSA released a request for proposals for an economic impact study, which was won by accounting firm Moss Adams [State of New Mexico and New Mexico Spaceport Authority, 2019]. In January 2020, the new economic impact analysis was released [Moss Adams LLP, 2020b, Moss Adams LLP, 2020a]. The main highlights of the Moss Adams report included assertions that the spaceport had been generating a positive return on investment (ROI) by FY2013 and that, by FY2019, the spaceport had been responsible for generating a total of 516 jobs and $118 million in direct economic impact. Moss Adams also reported that from FY2008 to FY2018, the spaceport's revenue had totaled $240 million—but 94% of that so-called "revenue" came from state appropriations and local taxes, with just 6% coming from tenants. In comparison, the spaceport's total expenditure for that period was $270 million.

Shortly after the Moss Adams report came out, New Mexico-based economic think tank The Rio Grande Foundation wrote a guest column in a local newspaper criticizing the report. They pointed out that claiming to have net positive impacts in FY2013, before Virgin Galactic had launched any flights there, didn't make much sense. In fact, SA's "audited financial statements do not list any revenue other than taxes and transfers from the state government before 2015, making the 2013 break-even date presented to the media especially egregious [Seymour, 2020]." But even critics were hoping for success at SA: "At this point, we at the Rio Grande Foundation are not calling for the state of New Mexico to sell this facility as we have in the past. In fact, like most New Mexicans we also hope for a successful manned flight out of Spaceport America in the near future. But, to call the facility a financial success before the primary purpose for which it was constructed rings false on its face. And, to use this as a talking point to request even greater access to taxpayer funding in the near future is to base important economic policy decisions on faulty information [Seymour, 2020]."

While there have been four economic impact analyses conducted on Spaceport America, this analysis shows that the actual economic impact remains unclear. Policymakers in New Mexico have attempted to understand the return on the state's investment in terms of economic impact, but accurately quantifying the impact is difficult. Studying the number of jobs created at the spaceport is an easier metric to study since its less subjective, but it doesn't capture the broader impact that policymakers strive to understand.

2.2.4 Profit Model

The profit model for the Mid-Atlantic Regional Spaceport developed in 2.1.1 was built on five financial metrics:

- Cost of building the spaceport
- Baseline cost to operate the spaceport
- Marginal cost per launch
- Baseline revenue for operating the spaceport
- Marginal revenue per launch

Unfortunately, Spaceport America does not publish the fees they charge customers for launch/flight support, so a different strategy is needed for developing a profit model. In addition, SA has only supported one test flight with Virgin Galactic, which was in December 2020, which is in FY 2021, which ends on June 30, 2021. Therefore, the financial report encompassing this activity is not available.

The profit model for Spaceport America has a different focus: it projects profit in three different scenarios, focused on profit from Virgin Galactic alone, since the spaceport's business model was developed around VG [Wyland, 2021]. This is a first pass at a profit model for SA that could be improved by incorporating revenue from other launch customers, tourism, and special events. The profit model incorporates the following assumptions:

- Spaceport America will earn $25k-$100k per VG flight [Weinzierl et al., 2021]
- Spaceport America will earn $1 million per year from VG's rent until they begin flying customers, then rent will increase to $3 million per year
- Spaceport America's profit margin on VG flight will be 50%. This is based on the profit margin uncovered during analysis of the MARS case 2.1.1

As a sanity check on the projected fee SA will earn for each VG flight, we can compare to data from the MARS case. We know that at MARS, the launch fee paid by Northrop Grumman to the spaceport is approximately 2% price of their launch vehicle. For SA, we can calculate the estimated price of an entire SpaceShipTwo flight and compare to the estimated flight fee. VG was selling seats for $200K-$250K [Alba Soular, 2013]. With six seats, that means a full SpaceShipTwo flight would bring in $1.2M-$1.5M in revenue to VG. The launch fee as a portion of their flight revenue would thus be 1.7% ($25k / $1.5M) to 10% ($100k / $1M). Those numbers are close to the MARS 2%, so the metrics seem reasonable.

The pieces of the profit model's structure are:

- SA's actual reported profit is used for FY 2012-2019
- FY 2020 profit is estimated to be the same as FY 2019
- Customer flights are projected to begin in FY 2021

The profit model does not include the capital investment that went toward building the spaceport, since SA is focused on becoming self-supporting for operations but not for capital expenses.

The review of SA's economic impact analysis 2.1.3 showed that in many cases, projections don't account for multiple future scenarios, particularly the most pessimistic scenario. This profit model incorporates that lesson learned and thus contains three potential futures:

- Scenario 1 – Moderate Future: By 2025, VG ramps up to 26 flights/year, the record for industry-leading launch provider SpaceX [Harwood, 2020]
- Scenario 2 – Optimistic Future: By 2025, VG achieves its goal of launching 3,000 people in its first five years of customer operations
- Scenario 3 – Pessimistic Future: VG never launches a customer flight

Scenario 3 is included not to be negative, but to be realistic: VG is attempting to create a suborbital tourism business, which has never been done before. While they are very close to launching customers, decision-makers in New Mexico took a huge gamble on VG—arguably a bigger gamble than they understood. Policymakers should be realistic about the high-risk nature of the space industry when investing public money.

This profit model shows that in Scenario 1 – Moderate Future, SA remains just below breakeven for the first five years of VG customer operations. In Scenario 2 – Optimistic Future, SA makes a significant profit, increasing rapidly to match the pace of VG flights. In Scenario 3 – Pessimistic Future, SA sustains a loss of $4 million per year. This model clearly illustrates the wide range of profit for SA's future as well as the extent to which SA still depends on VG's success.

Using the same logic, a breakeven analysis was conducted to estimate the number of VG flights needed for SA to break even on its operating expenses. Four breakeven points were calculated, for the four combinations of VG rent and flight fee laid out in the matrix below:

Figures 2-14 and 2-15 show the range in VG flight cadence needed for SA to break even depending on the financial metrics: 91-348 flights per year if VG's annual rent is $1 million, and 27-108 flights per year if VG's annual rent is $3 million. This shows

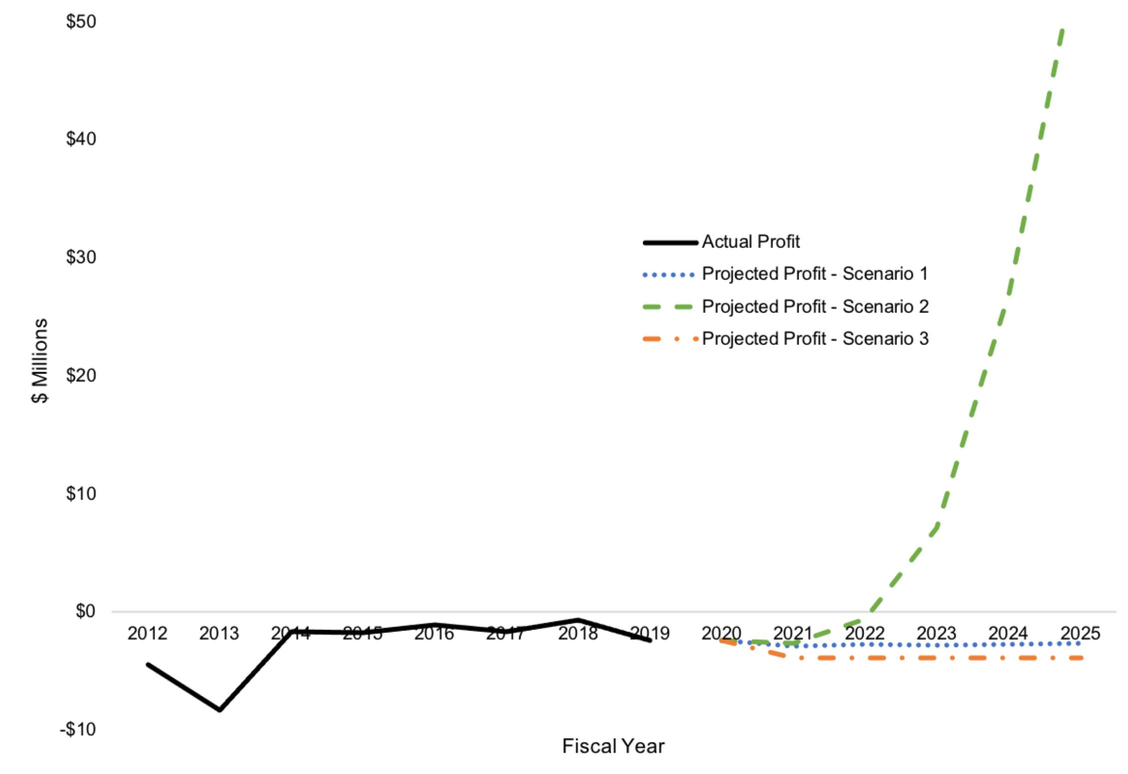


Figure 2-13: Profit model for Spaceport America with three potential future scenarios.

Table 2.7: Four financial breakeven scenarios for Spaceport America.

	$1M rent	$3M rent
$25k flight fee	331 flights/year	91 flights/year
$100k flight fee	83 flights/year	23 flights/year

that VG's annual rent has a significant impact on the breakeven point, reducing it by 64-240 flights per year with the higher rent.

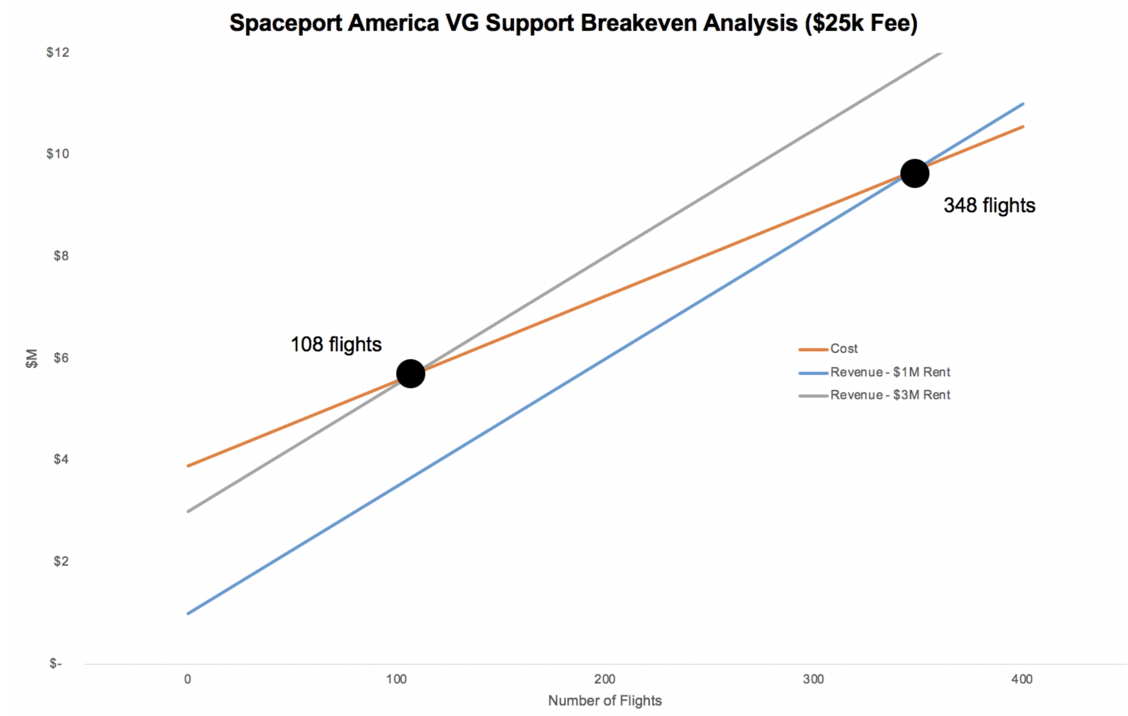


Figure 2-14: Breakeven points for Spaceport America, when earning $25,000 per Virgin Galactic flight.

2.2.5 Discussion

Based on this case study, Spaceport America has not achieved its original goal to become "self-supporting" (meaning that it would cover its operational expenses with customer revenue). In hindsight, this was an ambitious goal to set, since it depended so heavily on the success of Virgin Galactic, who is trying to develop a new business model in the high-risk space industry.

A full financial analysis was not possible because SA does not include a cash flow statement in their annual financial statements. However, the financial analysis did show that the spaceport continues to rely on state appropriations and the gross receipts tax on two of the counties surrounding the spaceport.

A preliminary profit model, focused on just Virgin Galactic, estimated a wide

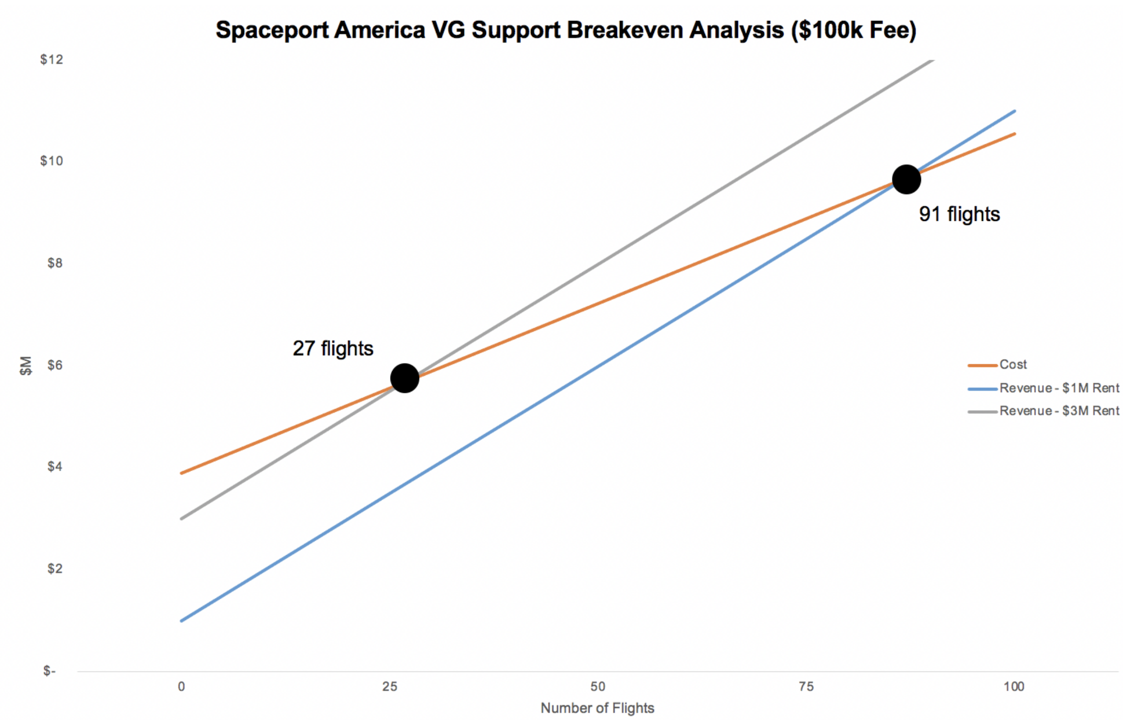


Figure 2-15: Breakeven points for Spaceport America, when earning $100,000 per Virgin Galactic flight.

range of flight cadence for the spaceport to break even, depending on the rent and flight fee paid by VG: it would take 27 to 348 flights to break even.

Despite the significant investment that the state has made into the spaceport, the economic impact of the project remains unclear. One thing is certain: the purpose for which Spaceport America was built, to host suborbital space tourism, has not yet been achieved.

2.2.6 Conclusion

So, is Spaceport America economically viable? That remains to be seen. Supporters suggest that the spaceport has improved STEM education in the state and brought in new business, while critics point out that Virgin Galactic has still not flown a paying customer and that the originally anticipated profit has not been realized. The spaceport's business model has changed significantly over about 15 years of operations, as the spaceport has learned from its attempts to be part of the next big shift in transportation: commercial spaceflight.

Comparing this case to the MARS case reveals general lessons learned and recommendations for commercial spaceports, which can help other policymakers decide whether or not to pursue proposed commercial spaceports, or help to improve existing commercial spaceports.

THIS PAGE INTENTIONALLY LEFT BLANK

Chapter 3

Cross-Case Analysis: Lessons Learned and Recommendations

This chapter summarizes the cross-case analysis for the Mid-Atlantic Regional Spaceport and Spaceport America. An overview of key information about the two cases is shown in Table 3.1. The cross-case analysis includes lessons learned, recommendations, and future work.

3.1 Lessons Learned

This two-case study was designed to conduct a theoretical replication, meaning that the hypothesis was that the results would be different for anticipable reasons (see methodology in Section 1.3). Namely, we expected to see different results for the

Table 3.1: Overviews of the Mid-Atlantic Regional Spaceport and Spaceport America.

Spaceport	Operator	State	Construction Type	Type of Launch Supported	License First Issued
Spaceport America	New Mexico Spaceport Authority	NM	Greenfield	Takeoff/landing methods • Horizontal • Vertical Spaceflight types • Suborbital	2008
Mid-Atlantic Regional Spaceport	Virginia Commercial Space Flight Authority	VA	Federal transitioned to commercial	Takeoff/landing methods • Vertical Spaceflight types • Suborbital • Orbital	1997

Mid-Atlantic Regional Spaceport (MARS) and Spaceport America (SA) because of the different construction types: MARS is a spaceport that transitioned from federal to commercial, such that the commercial spaceport was built from existing infrastructure, whereas SA was a greenfield spaceport, meaning it was built from the ground up (it was also the world's first "purpose-built" commercial spaceport, meaning it was built deliberately to support commercial space launch). However, rather than finding significant differences, the two-case study uncovered many similarities. Across the analyses of finances, business cases, economic impact, and profitability, several common lessons learned emerged:

- Finances
  - A spaceport's revenue per launch (the amount the spaceport charges a launch vehicle provider for using the spaceport) is 2-10% of the market price of the launch vehicle (the amount the launch company charges a customer for the launch)
  - The amount of annual state investment needed to support a commercial spaceport is around $5 to $50 million
  - Without state financial support, a spaceport will not be profitable (it will spend more money than it brings in)
- Business Case
  - Commercial spaceports don't generate sufficient revenue to become financially independent from the state
  - Revenue diversification is important: launch revenue can be augmented by other revenue streams
- Economic Impact
  - Economic impact is notoriously difficult to quantify, and impact analyses often have gaps

- Profitability
  - The launch cadence needed to achieve self-sufficiency is not impossible, but is ambitious

In addition to these similarities, there were a couple differences between the two cases to highlight:

- Finances
  - Cost to build a commercial spaceport: a greenfield construction is more expensive than building from existing infrastructure
- Business Case
  - Some markets within the space industry are riskier than others, which can affect a spaceport. MARS focused on supporting traditional orbital space launch, whereas SA focused on supporting the developing suborbital tourism industry

Each of these trends will be discussed in this section. While this two-case study has revealed several similarities and only a couple differences, the trends would be better supported by additional case studies to either confirm or refute these lessons learned.

3.1.1 Finances

In studying the finances of both MARS and SA, four lessons learned in finances emerged:

- Similarities
  - A spaceport's revenue per launch (the amount the spaceport charges a launch vehicle provider for using the spaceport) is 2-10% of the market price of the launch vehicle (the amount the launch company charges a customer for the launch)

  - The amount of annual state investment needed to support a commercial spaceport is around $5 to $50 million
  - Without state financial support, a spaceport will not be profitable (it will spend more money than it brings in)
- Differences
  - Cost to build a commercial spaceport: a greenfield construction is more expensive than building from existing infrastructure

In both cases, the ratio of launch fee to the market price of the launch vehicle was within a single order of magnitude, ranging from 1.7% to 10%, even though the anchor tenants operate in different launch markets. At MARS, the anchor tenant is Northrup Grumman (NG), who specializes in orbital launches, particularly NASA's cargo resupply missions to the International Space Station. MARS' revenue for each NG launch it supports is $2 million. This revenue comes from a flat launch fee of $1.5 million and a variable commodities fee of $500,000. The launch fee represents 2% of the market price of that launch vehicle. At SA, the anchor tenant is Virgin Galactic (VG). While a customer flight has not yet taken place, spaceport officials have suggested that they will charge VG a flight fee of $25,000-$100,000. With each of six seats on SpaceShipTwo (SS2) selling for $200,000-$250,000, the total price of a SS2 flight is $1.2 million-$1.5 million. Thus, the flight fee paid by VG to SA would be 1.7%-10% of the cost of the vehicle.

The two spaceports also received similar levels of financial support from their states. At MARS, in its years of launch activity (FY 2009-FY 2018), the state of Virginia provided annual financial support in the range of $5 million to $40 million. At SA, throughout its entire history (FY 2008-FY 2019), the state of New Mexico and two nearby counties provided annual financial support in the range of $4 million to $53 million.

Arguably the most important financial lesson learned is that in both cases, the state's financial support kept the finances in the black. Without sustained state support, each spaceport would have sustained losses in every year of operation.

Finally, the main difference in finances between the two cases concerned the spaceport's construction costs. Prior work by spaceport consultant Brian Gulliver estimated the price of a commercial spaceport to be $200 million, but that it could be lower with existing infrastructure available for use [Gulliver et al., 2012]. This two-case study confirmed the ballpark metric and the cost savings from existing infrastructure, with MARS costing about $170 million to build and SA costing about $220 million to build. MARS was built on NASA infrastructure that had been handed off to VCSFA to build a commercial spaceport, whereas SA was built up from an empty plot of land.

3.1.2 Business Cases

From the two-case study, there were three lessons learned about spaceport business cases:

- Similarities
  - Commercial spaceports don't generate sufficient revenue to become financially independent from the state (they have not become "self-sustaining")
  - Revenue diversification is important: launch revenue can be augmented by other revenue streams
- Differences
  - Some markets within the space industry are riskier than others, which can affect a spaceport. MARS focused on supporting traditional orbital space launch, whereas SA focused on supporting the developing suborbital tourism industry

In both the MARS case and the SA case, the spaceport transitioned away from an original goal of becoming self-sustaining (aka self-supporting). Both spaceports defined the same goal (using different terms): generate enough revenue from customers to cover annual operating costs. This did not include covering any infrastructure costs, either the initial construction or any infrastructure expansions, which have occurred at both spaceports. In both cases, the spaceport was not able to achieve this goal, and in recent years had either dropped the goal from its documents or, in the case of SA, leadership had publicly acknowledged that its business plan no longer included a goal to become self-sustaining. This lesson learned is critical for proposed spaceport projects, because policymakers should recognize that a commercial spaceport may continue to rely on annual financial support from its home state, and thus account for that when deciding whether or not to pursue constructing a new spaceport.

Over time, both MARS and SA realized that they were not going to generate enough revenue from supporting launches/flights for their anchor tenants, so both organizations pursued revenue diversification. This included wooing additional tenants as well as introducing new revenue streams like tourism, unmanned aerial systems (UAS) testing, and hosting special events. This is similar to a trend that occurred in air transportation. Over the course of 40 years of commercial airport operations, the nominal airport business model transitioned from just providing transport services, to expanding into a variety of customer services (e.g., retail stores and restaurants), to becoming a "diversified business center" with offices, hotels, and even energy generation hardware in addition to providing transport services [National Academies of Sciences Engineering and Medicine, 2010]. Some spaceport researchers have long advocated for using commercial spaceports as business parks [Matula and Mitry, 2002], and in fact that appears to be the model at the Houston Spaceport. In each case, the organization was spurred toward revenue diversification by an external force. For MARS, diversification was brought about by a Virginia state budget review in FY 2012 that included an analysis of the spaceport's operating agency, the Virginia Commercial Spaceflight Authority (VCSFA). Since then, MARS has aimed to become a multi-user spaceport with revenue streams outside of space launch. They successfully brought on a second tenant, Rocket Lab, and built new infrastructure to support UAS testing and development. For SA, revenue diversification became a necessity after the spaceport's anchor tenant, Virgin Galactic, had a fatal accident that added even more delays to an already-delayed program. SA has always had multiple customers, but since 2015, when they released a new business plan that emphasized revenue diversification, they have increased the number of customers and broadened the launch activities they support. Outside of launch revenue, the spaceport started hosted an annual student rocketry competition called the Spaceport America Cup, opened a new tourist center, began pursuing UAS testing, and hosts special events such as commercial advertising shoots. Despite slightly different situations, both MARS and SA have vigorously pursued revenue diversification in recent years.

Finally, one difference between the two business cases stems from the target market sector: MARS was established around the need to support Orbital ATK's orbital launches to resupply cargo to the ISS, whereas SA was constructed to support Virgin Galactic's suborbital tourism operations. Studying these two cases reveals that the target market can have a serious effect on a spaceport, namely that a riskier market can negatively impact it. SA's focus on suborbital space tourism, an emerging market, has proven difficult for the spaceport's business. They were too reliant on Virgin Galactic as their anchor tenant, which meant that as Virgin Galactic has dealt with continued delays (they still have not launched a single customer), they have not yet begun paying the customer fees that were critical to the spaceport's business model (see Section 2.2). In comparison, MARS made a safer bet by designing the spaceport to support Orbital ATK's ISS cargo resupply missions. ISS cargo resupply missions, and orbital space launch more broadly, are an established market with well-understood activities and technical designs. Although MARS has also had to deal with anchor tenant struggles (namely a 2014 rocket explosion that resulted in $15 million of damage to a pad), they have continued to receive regular payments from Orbital ATK, brought in a second launch tenant, and seem to have a decent path toward achieving the number of flights needed to become profitable 2.1. While SA's risky yet may pay off eventually, MARS' focus on traditional space launch has provided them with a more stable business case.

3.1.3 Economic Impact

Within the topic of economic impact, there was one similar lesson learned for commercial spaceports:

- Economic impact is notoriously difficult to quantify, and impact analyses often have gaps

Economic impact is notoriously difficult to quantify, particularly in cases of public infrastructure being built by governments [Wassmer et al., 2016]. Both MARS and SA have been analyzed for economic impact in multiple reports, and all reports leave something to be desired. A particular challenge for public infrastructure projects is misaligned incentives: the state often gets to select an organization to conduct the economic impact analysis, which gives them the opportunity to ensure the analysis is favorable. Even if the state doesn't attempt to find a favorable analysis, the organizations conducting the analysis are paid by the state, which gives them incentive to report positive results. Regardless of intent and incentives, estimating the dollars of economic impact is highly subjective and therefore not a great metric to rely on.

In comparison to dollars, the number of jobs created is a more objective metric to use for economic impact analysis. However, even this metric needs to be defined and counted carefully: communities with spaceports sometimes complain that the jobs are filled by bringing in talent from outside the region, which may be counter to the goals of the regional government, which usually aims to build up local talent.

3.1.4 Profitability

Finally, for profitability, there was one similar lesson learned across both cases:

- The launch cadence needed to achieve self-sufficiency is not impossible, but is ambitious

Finally, both cases showed that the launch/flight cadence needed to reach breakeven is not impossible, but it is ambitious. MARS would have to host 17 medium class orbital launches to break even on annual operating costs. That number isn't impossibly high, especially since they brought in a second launch tenant, but since the spaceport's record for annual launch cadence is 4, achieving 17 launches in a year is certainly ambitious. For SA, the estimated flight cadence needed to break even is more uncertain. A first estimate, focusing on just Virgin Galactic flights, predicts that the spaceport will need to host somewhere between 27 to 348 flights to break even.

3.2 Recommendations

3.2.1 Existing Commercial Spaceports

Studying the lessons learned from MARS and SA leads to five recommendations for existing commercial spaceports:

1. Plan for sustained state investment
2. Establish metrics to analyze the investment success, i.e., STEM education improvement, jobs
3. Diversify revenue streams, particularly outside of launch support
4. Consider and plan for the worst case scenario
5. Estimate the launch cadence needed to break even and compare to industry launch cadences to determine feasibility

Where commercial spaceports already exist, states should plan for sustained investment of public funds since commercial spaceports have not achieved self-sufficiency in finances.

Policymakers should also establish metrics for analyzing the success of the spaceport. Since the use of public funding for spaceports tends to be justified in terms of economic impact and STEM education, metrics should focus on those two areas. One metric could be the number and type of jobs created and whether they are filled by local or external talent. Another could focus on quantifying the impact on STEM education, including the number of STEM-focused classes offered in K-12 schools and the number of students enrolled in STEM majors at nearby universities.

Commercial spaceport operators should diversify their revenue streams; rather than focusing on supporting launches of an anchor tenant, a spaceport can decrease the risk to revenue by supporting multiple launch customers as well as adding non-launch revenue streams such as UAS testing, tourism, STEM student competitions, and special events (e.g., commercial advertising shoots).

When supporting a commercial spaceport, policymakers should consider and prepare for the worst case scenario, which these cases have shown to include accidents and low revenue. The space industry is high-risk, and accidents are almost inevitable. Policymakers should understand the potential risks involved when supporting a spaceport and develop a plan for managing them. For accidents, this includes preparing for physical damage to infrastructure, as occurred at MARS with the Orbital Sciences Orb-3 accident in 2014 that caused $15 million in damage. Commercial spaceports can prepare by having appropriate insurance and assigning responsibility for managing and paying for accident recovery prior to an accident occurring. Outside of damage to infrastructure, accidents can also harm humans, potentially including loss of life, as occurred with Virgin Galactic's fatal 2014 accident that resulted in co-pilot Michael Alsbury's death. In addition to preparing for accidents before they occur, policymakers also need to prepare for a scenario in which revenues do not live up to projections. This situation happened for both MARS and SA, and the outcome was that both states continued to support annual operating costs for the spaceports rather than the spaceports becoming financially independent of the state.

Finally, policymakers and spaceport operators should estimate the launch cadence needed to break even on operating costs to better understand their financial situation. Breakeven depends on baseline operating costs as well as the marginal cost and revenue for supporting each activity. The outcome of this analysis can help the spaceport develop a solid business plan because they will better understand how to fill the revenue gap with non-launch activities.

3.2.2 Proposed Commercial Spaceports

The lessons learned from this two-case study can also help policymakers analyze new proposed spaceport projects. When considering a proposed spaceport, policymakers should focus on geographical and policy constraints, feasibility of the business plan, whether a spaceport is the best way to achieve the state's goals, and planning for the worst-case scenario. Specifically, policymakers can use these six recommendations:

1. Understand the importance of geography to spaceport siting, including both physical and policy constraints
2. Analyze feasibility of proposed launch cadence and revenue
3. Analyze diversity of revenue streams
4. Plan for sustained state investment
5. Consider and plan for the worst case scenario
6. Clarify the state's goals for supporting the spaceport and determine if there is a lower-risk investment that could meet them

When policymakers first consider a proposed spaceport, they should consider physical and policy constraints on the site. These vary depending on the type of launch being proposed: orbital or suborbital, as well as horizontal or vertical. Regardless of the launch type, spaceports generally require a substantial amount of open space as well as good weather. Open space is needed because any launch activity needs a wide route clear of people or hardware. This is critical for orbital flights, which are required by regulation to clear a wide area both at the launch site as well as down-range in case of an accident. In addition, all spaceports need good weather in order to have good visibility of the vehicle and its flight/launch, as well as warm temperatures to prevent hardware damage (the 1984 Challenger accident occurred in part because of hardware damage caused by unusually cold temperatures for Florida, where it launched). Ideally, a proposed spaceport would have a significant number of sunny days and consistently warm temperatures. It is helpful, but not necessary, for a spaceport to be at a high altitude. For both suborbital flight and orbital flight, a high altitude means the vehicle has to travel a shorter distance to reach its final destination. This is more important for orbital flights because a shorter distance means the vehicle needs less fuel, which saves on the launch mass and thus saves money. Orbital flights have significantly stricter constraints than suborbital flights. As a comparison point between the two types of flight, an orbital flight requires 50 times as much energy as a suborbital flight. For orbital flights, it is important for the launch site to be as close to the equator as possible, so that the vehicle can leverage the spin of the Earth to make it accelerate more quickly to escape velocity (the speed needed to escape Earth's atmosphere and begin orbiting the planet). In the United States, orbital flights must launch over a large body of water because of safety regulations, in order to prevent harm to humans that could be caused by an in-flight accident. Additional safety regulations require a large area to be cleared around the launch vehicle's flight path, which means clearing aviation routes. Thus, it is easier to launch from a spaceport where there is lower density of commercial aviation routes.

In addition to physical constraints, there are also policy constraints to consider. For any space flight, the simple act of crossing a state border could present a problem because of noise, pollution or safety concerns to the local population. Therefore, crossing state boundaries during a flight could pose a political problem. This problem would be amplified by crossing a country boundary, since every country has different policies and laws for spaceflight.

Another point to consider in a proposed spaceport project is the feasibility of the proposed launch cadence and revenue. There is a significant amount of data available about historical orbital launch cadences for different providers, and it should be leveraged as a comparison point. For example, if a company advocating a spaceport be built to support them, and they aim to reach 100 orbital launches in a single year, it would be useful to ask them how they plan to quadruple the record annual launch cadence (26, from 2020) of one of the world's leading launch providers, SpaceX. This analysis is more difficult for suborbital launch providers, since historically there have not been commercial suborbital launch providers. While suborbital launch is less difficult technically than orbital launch, it is not yet clear what a feasible launch cadence is for a suborbital launch provider. In addition to proposed launch cadence, policymakers should compare the proposed revenue to the spaceport for supporting the launch. As discussed in Section 3.1, this two-case study revealed that an estimated ratio of spaceport launch revenue to launch vehicle price is 2%-10%, meaning that it's feasible for a spaceport to make a revenue that represents 2%-10% of the launch vehicle price. If a proposed spaceport plan included numbers outside of normal ranges for launch cadence and spaceport revenue per launch, those numbers should be investigated more closely.

One of the key lessons learned from MARS and SA was that launch revenue is not yet sufficient to cover operational costs, as was expected in both cases. So for new proposed spaceports, policymakers should analyze the diversity of proposed revenue streams to reduce financial risk.

Additionally, studying MARS and SA showed that commercial spaceports rely on state funding to stay afloat financially. Policymakers should therefore expect to provide sustained investment into a spaceport, even if the spaceport plan suggests otherwise.

Policymakers should also consider and plan for the worst case scenario when considering a proposed commercial spaceport. While it's great to be ambitious, it's important to be pragmatic when investing taxpayer dollars. For example, Spaceport America built their business model on the assumption that Virgin Galactic would meet its ambitious goal of flying thousands of customers within the first few years the spaceport was open, but VG has yet to fly a single customer. Policymakers should consider what the worst case scenario could be and determine whether or not the project would survive if that scenario were realized.

Finally, the most important recommendation for policymakers considering a proposed spaceport: clarify your state's goals for supporting the spaceport and determine if there is a lower-risk investment that could meet those same goals. Commercial spaceports require significant and sustained investment, from the $200 million needed for construction to the millions needed each year to support operational costs. While it's exciting to host spaceflight within your state, there are certainly lower-risk ways to be involved with the space industry, such as leveraging existing industrial technology to build components for spaceflight.

3.3 Future Work

This two-case study revealed a significant number of lessons learned for commercial spaceports, which have now existed long enough (about two decades in each case) to see how business plans have shifted to meet the market needs. Future work could expand the study by analyzing more cases, improve the methodology developed in this thesis, or shift analysis to the market level.

Additional cases to study could be selected based on the mini case study in Section 1.3.3 and Appendix A.

Three suggestions for future research to improve on the existing methodology are:

1. Improving profit models for each case: for MARS, once there's sufficient data from Rocket Lab launches and other revenue streams, e.g., UAS testing; for SA, if/when VG starts hosting customer flights

2. Conducting studies of the other nine U.S. commercial spaceports (see Table 1.2 for the full list) would strengthen the findings, either by confirming them or denying/improving them

3. Studying commercial spaceports outside the U.S. to see how different context (e.g., federal policy, markets) changes spaceport outcomes

Future work could also shift the focus of analysis to the market scale. This two-case study provides in-depth analysis and generalized lessons learned for commercial spaceports, whereas a focus on the market level could help to determine current and future demand and estimate the number of commercial spaceports the U.S. needs to meet it. This would address an existing problem of states acting as individual actors when deciding to build a spaceport, which has led to an over-saturated market without enough demand for launches to meet the supply offereed by commercial spaceports. This analysis would also be useful for developing a national spaceport strategy, as discussed in Section 1.3.2.

THIS PAGE INTENTIONALLY LEFT BLANK

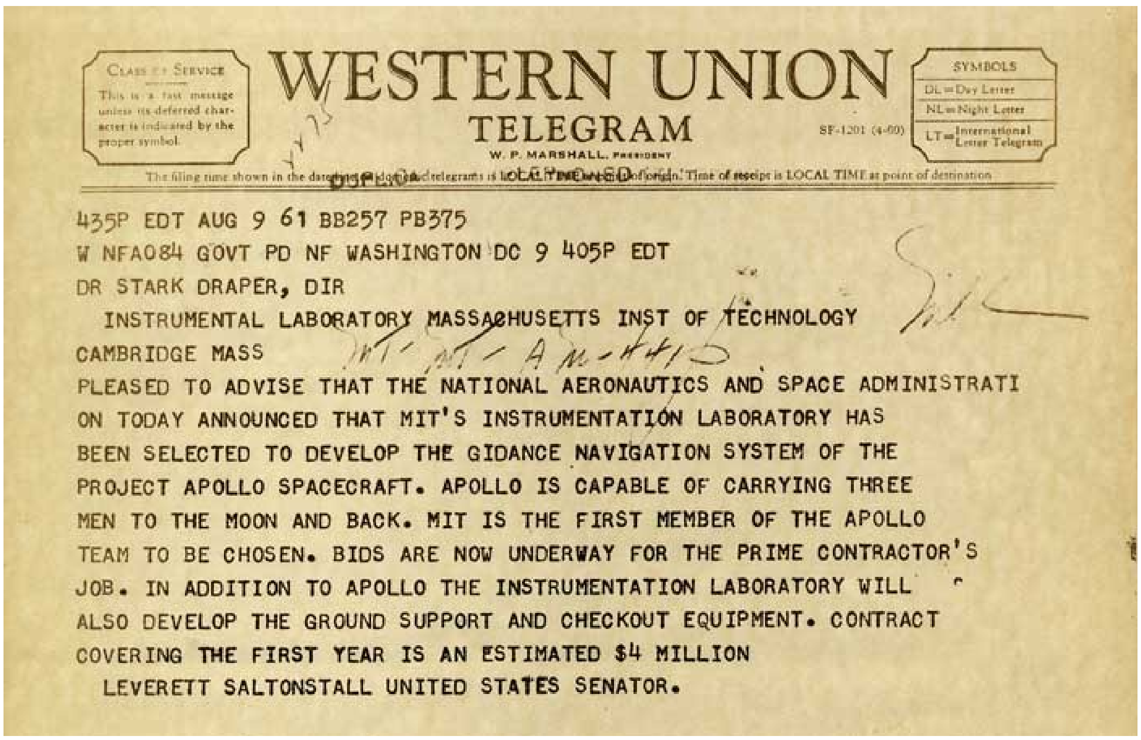
Chapter 4

Introduction to Lunar Surface Exploration

4.1 Motivation

In the past few years, there has been a renewed interest in going to the Moon occurring across the globe. From NASA's Artemis Program, to a recently-announced collaboration between Russia and China to build a joint lunar base, to ESA's longstanding vision for a lunar village, national governments are investing significant financial resources into lunar exploration once again. However, this time is different for two main reasons: 1) there is a growing commercial space sector with significant levels of private financing and 2) there is greater emphasis long-term, sustainable exploration rather than a "flags and footprints" campaign similar to the Apollo Program.

As countries around the world aim to return to the Moon, MIT has an opportunity to leverage its knowledge and resources to be part of the next phase of lunar exploration. MIT has significant experience in lunar science and exploration, from the early days of the Apollo Program to more recent missions like GRAIL (2011) and collaborations with Israel's Beresheet mission (2019). MIT is well poised to leverage both its lunar experience and its science and technology expertise to assist in returning humans to the Moon. At MIT, we're looking to develop our own strategy for this phase of lunar exploration. During the Apollo era, MIT was heavily involved but in a decentralized way, with disconnected projects across the Institute. In fact, MIT received the first contract for the Apollo Program, awarded by NASA to the Instrumentation Lab run by director Charles Stark Draper (aka Doc Draper) [Hardesty, 2009, Waitz, 2009]. The contract is famously short, as shown in Figure 4-1. The Instrumentation Lab would later become the Draper Lab, which is still heavily involved in space exploration efforts. For the Artemis era, we hope to bring together all of MIT's resources to maximize our capabilities and impact to develop something uniquely MIT.



CLASS OF SERVICE
This is a fast message unless its deferred character is indicated by the proper symbol.

WESTERN UNION
TELEGRAM
W. P. MARSHALL, PRESIDENT

SYMBOLS
DL=Day Letter
NL=Night Letter
LT=International Letter Telegram

SF-1201 (4-60)

The filing time shown in the date line on domestic telegrams is LOCAL TIME at point of origin. Time of receipt is LOCAL TIME at point of destination

435P EDT AUG 9 61 BB257 PB375
W NFA084 GOVT PD NF WASHINGTON DC 9 405P EDT
DR STARK DRAPER, DIR
INSTRUMENTAL LABORATORY MASSACHUSETTS INST OF TECHNOLOGY
CAMBRIDGE MASS
PLEASED TO ADVISE THAT THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATI
ON TODAY ANNOUNCED THAT MIT'S INSTRUMENTATION LABORATORY HAS
BEEN SELECTED TO DEVELOP THE GIDANCE NAVIGATION SYSTEM OF THE
PROJECT APOLLO SPACECRAFT. APOLLO IS CAPABLE OF CARRYING THREE
MEN TO THE MOON AND BACK. MIT IS THE FIRST MEMBER OF THE APOLLO
TEAM TO BE CHOSEN. BIDS ARE NOW UNDERWAY FOR THE PRIME CONTRACTOR'S
JOB. IN ADDITION TO APOLLO THE INSTRUMENTATION LABORATORY WILL
ALSO DEVELOP THE GROUND SUPPORT AND CHECKOUT EQUIPMENT. CONTRACT
COVERING THE FIRST YEAR IS AN ESTIMATED $4 MILLION
LEVERETT SALTONSTALL UNITED STATES SENATOR.

Figure 4-1: First Apollo contract, awarded by NASA to the MIT Instrumentation Lab [Waitz, 2009].

This thesis charts the first steps for science and technology planning for the future of MIT lunar exploration, including two main tools: 1) a science traceability matrix and 2) a technology multi-domain matrix. Alongside this work, MIT is pursuing three additional avenues to support lunar exploration: the development of MIT's Lunar Open Architecture, a new graduate course taught in Spring 2021 on "Operating in the Lunar Environment" (cross-listed in the Media Lab and the Department of Aeronautics and Astronautics under course numbers MAS.S60 and 16S.898), and a new cross-Institute framing for a "To the Moon To Stay" MIT mission.

These four strategic planning exercises were coordinated via a collaboration between the MIT Space Exploration Initiative, the MIT Department of Aeronautics and Astronautics, and the MIT Media Lab, and revealed many areas of mutual interest among research groups across multiple departments at MIT. Within the MIT community, there is a broad interest in creating a cohesive, organized strategy for MIT's next steps on the lunar surface. This work will help MIT optimize its efforts toward lunar exploration, maximize investments into lunar research, and develop a cohesive plan for MIT's role in future lunar exploration. This work also serves as a case study for how a large, complex organization can develop a strategic plan for deep space exploration that both leverages its resources while meeting high-level, external science goals. By following the plan laid out in this thesis, MIT can add to its expertise in lunar exploration, gather new scientific knowledge, and be part of the team that lands the first woman and the next man on the Moon.

4.2 Problem Formulation

This thesis develops a a science traceability matrix (STM) and a technology multi-domain matrix (MDM) focused on MIT lunar exploration. Along with the the three other strategic planning exercises listed above, these two outputs can be used to create a cohesive strategic plan for MIT's return to the Moon. These four exercises can also be a tool for building up a community of MIT researchers working on lunar exploration by identifying opportunities for collaboration and optimizing resources. The ultimate goal of this work is to enable the development of a MIT lunar payload that is built as a collaborative effort across the Institute.

4.2.1 Research Questions

In order to align this thesis with the goals of the research group, a few guiding questions set the path forward:

1. How will MIT be involved with the NASA-led initiative to return humans to the Moon?

2. How can we coordinate and collaborate as a community to improve our ability to create new technology and gather new scientific knowledge?

3. What are MIT's areas of technology and science expertise that can be leveraged for lunar exploration?

4. How will this science and technology strategic planning exercise work with the other lunar strategic planning exercises?

With these guiding questions, the following goals were set for the two tools developed in this thesis:

- Science strategic planning for MIT lunar exploration
  - Understand the scientific significance of MIT's lunar-relevant research
  - Identify existing areas of MIT science research that are relevant to lunar exploration
  - Understand how MIT's various lunar-relevant science efforts relate to each other
- Technology strategic planning for MIT lunar exploration
  - Identify existing areas of MIT technology development that are relevant to lunar exploration
  - Understand how MIT's various lunar-relevant technology efforts relate to each other

4.2.2 Rationale

A science traceability matrix (STM) and technology multi-domain matrix (MDM) were selected as the output of this research because they are critical strategic planning tools (see Section 4.4 for more information about STMs and MDMs).

For science analysis, a STM is a standard space mission planning tool used to align community-defined science and exploration goals with detailed goals of a mission. Usually, the detailed goals are mission and instrument requirements, but this work will adapt a standard STM to map to specific research areas at a university.

For technology analysis, the functions of a R&D portfolio MDM (see Figure 4-2) align well with the goals of this work, which were defined in the previous section:

- Functions of a MDM for a R&D portfolio [de Weck, 2020]
  - Strategic alignment to ensure that the R&D projects being done actually respond to the company's strategy at the top level
  - Identifying and creating synergies between products and business units
  - Avoiding technology blind spots

These two tools will lay the groundwork for future lunar strategic planning at MIT by both collecting useful data and bringing together a community of lunar researchers.

4.3 Research Methodology

As the first step of science and technology strategic planning for MIT's role in lunar exploration, this thesis develops a STM and technology MDM. These two tools are parts of methodologies that turn strategic planning into a methodical exercise, forming strong foundations for future analysis and decision-making based on thorough, quantifiable information. Specifically, the STM and MDM will identify connections between high-level science and technology goals, MIT strategic goals, and MIT research. These two tools also serve as a case study for how MIT's Lunar Open Architecture (LOA) can be used [MIT Media Lab, 2021, Sarang et al., 2020]. From an organizational perspective, the science goals and technology roadmaps embedded in LOA can be connected to an organization's strategic goals and research in order to determine how an organization might be involved with lunar exploration.

The STM and MDM share two similar data sets: MIT strategic goals and current MIT research. The list of MIT strategic goals was compiled from three documents:

- A Global Strategy for MIT (2017) [Lester, 2017]
- MIT Five-year Strategic Action Plan for Diversity, Equity, and Inclusion (2021-2026) - DRAFT (2021) [Dozier et al., 2021]
- MIT Department of Aeronautics and Astronautics 2020 Strategic Plan [MIT Department of Aeronautics and Astronautics, 2020]

As stated by then-Secretary of Defense Ash Carter about thee Department of Defense's (DoD) 2015 cyber strategy, a strategic plan is "a tool for management and communication" that "puts [DoD] on course to capitalize on our strengths, meet our challenges, and fulfill our missions. It therefore sets clear and specific objectives for the Department to achieve over the next five years and beyond" [United States Department of Defense, 2015]. So, strategic plans are a powerful tool for identifying the current state of an organization, defining a vision for the future, and developing a feasible strategy for getting there. However, creating a strategic plan is just a first step: implementing it requires significant and sustained investment of energy and resources. This thesis proposes aligning MIT's strategic goals with its research areas to identify where MIT is meeting its goals as well as areas where it needs to reallocate resources in order to meet goals that are currently not being met. Each of these three documents, described below, can be mapped to MIT's current research portfolio. Applying the lens of lunar exploration in this thesis will help MIT to identify opportunities to be involved in the next phase of exploring the Moon.

The Global Strategy for MIT was a report that analyzed the Institute's current state of international engagement and made recommendations for the future, incorporating feedback from more than 400 MIT community members. The report was the culmination of phases 1 and 2 of the work, which included a "discovery phase" to identify MIT's current activities and the competitive landscape and a "development phase" to bring together ideas and plans. The report mentions a third "implementation phase," but implementation information could not be found.

In response to student demands for improving diversity at the Institute, which stemmed from the 2020 global Black Lives Matter activist movement, the Institute began working on a strategic plan for diversity, equity and inclusion (DEI). In March 2021, the strategic plan's leadership released a draft of the report, titled "MIT Five-year Strategic Action Plan for Diversity, Equity and Inclusion (2021-2026)," which is included in this thesis as the second data source for MIT strategic goals. The Institute is in the process of gathering community feedback on the draft DEI plan, which will be incorporated into a final plan to be released in the future.

The third source of MIT strategic goals come from the 2020 strategic plan development by the Department of Aeronautics and Astronautics (AeroAstro). AeroAstro creates new strategic plans on a regular basis, and the 2020 plan was initiated by a request from MIT's Dean of Engineering [of Aeronautics and Astronautics, 2019]. The goals from this plan are less high-level than the two Institute-wide plans.

These three documents provide a starting point for MIT's strategic goals but leave some gaps. Namely, MIT's DEI plan needs to be finalized and strategic plans from other departments are missing. At a minimum, strategic plans from the Media Lab (ML) and the Department of Earth, Atmospheric and Planetary Sciences (EAPS) should be included since they, along with AeroAstro, make up the three main departments included in this thesis. However, neither ML nor EAPS currently have strategic plans.

As mentioned above, it's important that after investing significant resources in developing strategic plans, that they're actually used in the Institute's operations. This is particularly critical right now as the Institute evaluates the role of diversity, equity and inclusion in our community.

In addition to sharing strategic goals, the STM and MDM also share common data about MIT's research that was gathered during interviews with MIT researchers. The data from these interviews was used in slightly different ways for the STM and MDM, which will be explained in the following sections. For this thesis, interviews were conducted with the following six leaders:

- Department of Aeronautics and Astronautics
    - Professor Jeffrey Hoffman

  - Professor Julie Shah
  - Professor Olivier de Weck

- Media Lab
  - Dr. Ariel Ekblaw
  - Professor Danielle Wood

- Department of Earth, Atmospheric and Planetary Sciences
  - Professor Ben Weiss

For the first phase of data collection to develop the STM and MDM, the author and her research team wanted to include researchers from three key MIT departments: the Department of Aeronautics and Astronautics, the Media Lab, and the Department of Earth, Atmospheric and Planetary Sciences. These departments have all done significant work in space exploration, and all three should be leveraged for their expertise in science and technology progress. Within the departments, numerous individuals were identified who could contribute to lunar research. For the purposes of this thesis, the list was scoped down to six individuals, focusing on researchers that the author and her research team had existing relationships with and thus good access to. Researchers not included in the first round of data collection are listed in Section 6.1 and should be interviewed in a second phase of data collection.

The following sections describe the methodology used to develop MIT's lunar STM and technology MDM, including data sources unique to each tool.

4.3.1 Science Traceability Matrix

A STM is a standard space mission planning tool used to align top science goals to mission investigations and then to instrument and mission requirements. This thesis puts a spin on a standard STM and adapts it to suit a different purpose: aligning top science goals to institutional strategic goals and research capabilities at a university. More information about standard STMs can be found in Section 4.4.3.

Several inputs were needed to construct a MIT Lunar STM. These inputs informed three parts of a STM: top science goals identified by the research community, MIT strategic goals, and MIT "core capabilities" or research areas that would be useful for lunar exploration.

For the science goals, inputs came from two documents:

- NASA's Artemis III Science Definition Report (SDR) [National Aeronautics and Space Administration, 2021]

- The International Space Exploration Coordination Group's (ISECG) Global Exploration Roadmap - Supplement August 2020 (GER) [International Space Exploration Coordination Group, 2020]

These documents were selected because they're from organizations with strong reputations and because they build upon significant community input. The SDR was developed based on substantial lunar analysis and planning, and is a great resource on the American perspective. The GER includes input from 24 countries, making it a good resource for the international perspective.

The SDR is NASA's latest publication about their highest-priority science goals for the next human lunar mission, Artemis III. The report provides deep details about science priorities for the mission, which are based on work conducted by the Artemis III Science Definition Team, which included prominent scientists from across NASA and academia. The team built their work on several decades' worth of lunar exploration plans and specifically incorporated inputs from four lunar documents:

- The 2007 National Research Council "Scientific Context for the Exploration of the Moon Report"

- The NASA Lunar Exploration Analysis Group's (LEAG) Lunar Exploration Roadmap

- The LEAG Advancing Science of the Moon report

- The currently operative Planetary Decadal Survey, Visions and Voyages for Planetary Science in the Decade 2013-2022

Therefore, the SDR is the result of decades of analysis and planning, including significant community input, for human lunar exploration, making it a critical input for MIT's lunar STM.

In addition to the SDR, the GER was also included as an input to the MIT lunar STM. The August 2020 supplement was used instead of the 2018 GER because the supplement focuses on lunar exploration specifically. While NASA is taking a lead role in lunar exploration through the Artemis Program, international collaboration will be essential to achieving the ambitious goals for lunar exploration. The SDR is an excellent resource but focuses on American inputs. In comparison, the GER includes feedback from 24 space agencies: Australian Space Agency (ASA), Brazilian Space Agency (Agência Espacial Brasileira—AEB), Canadian Space Agency (CSA), China National Space Administration (CNSA), Commonwealth Scientific and Industrial Research Organisation (Australia—CSIRO), European Space Agency (ESA), France's National Centre for Space Studies (Centre National D'Etudes Spatiales—CNES), German Space Agency (Deutsches Zentrum für Luft- und Raumfahrt—DLR), Indian Space Research Organisation (ISRO), Italian Space Agency (Agenzia Spaziale Italiana—ASI), Japan Aerospace Exploration Agency (JAXA), Korea Aerospace Research Institute (KARI), Luxembourg Space Agency (LSA), Norwegian Space Agency (NOSA), National Space Agency of Ukraine (NSAU), Polish Space Agency (POLSA), Romanian Space Agency (ROSA), Roscosmos State Corporation for Space Activities (Russia), Swiss Space Office (SSO), Thailand's Geo-Informatics and Space Technology Development Agency (GISTDA), United Arab Emirates Space Agency (UAESA), United Kingdom Space Agency (UKSA), United States' National Aeronautics and Space Administration (NASA), Vietnam National Space Center (VNSC) [Dunbar, 2020]. Including the international perspective is important for MIT planning, since MIT could potentially work with any number of international partners.

As mentioned in the beginning of Section 4.3, and discussed in more detail there, the list of MIT strategic goals was compiled from three documents:

- A Global Strategy for MIT [Lester, 2017]
- MIT Five-year Strategic Action Plan for Diversity, Equity, and Inclusion (2021-2026) - DRAFT [Dozier et al., 2021]
- MIT Department of Aeronautics and Astronautics 2020 Strategic Plan [MIT Department of Aeronautics and Astronautics, 2020]

Finally, MIT's core capabilities were identified through interviews with researchers at the Institute, as mentioned previously. Initial interview questions are listed in Appendix B; additional questions were used as needed for clarification or to gather more information. Interviews served multiple purposes: to collect data for this thesis, to begin building up a community of lunar researchers at MIT, to identify opportunities for collaboration, and to identify potential resource needs.

For the STM, interview data was distilled into research "core capabilities" that became tags in the database. Standardization was the motivation behind turning interview data into tags. In future phases of MIT's development of the Lunar Open Architecture, other organizations could leverage LOA's framework to develop their own STM for planning lunar missions. With standardized research tags, an organization could easily "select" the tags that it is involved with and LOA could auto-generate mapping to high-level science and exploration goals. It is likely that these research tags would need to be refined with additional interviews.

4.3.2 Technology Multi-Domain Matrix

Within technology management strategy, a multi-domain matrix (MDM) is a systems architecture tool that can be used for R&D portfolio management [de Weck, 2020]. More information about multi-domain matrices is in Section 4.4.4. A system model of a R&D portfolio can be built by studying the relationships between the key pieces of a R&D portfolio (strategic drivers, technology roadmaps, figures of merit, and R&D projects), as shown in Figure 4-2. This figure comes from an Advanced Technology Roadmapping Architecture developed for use in industry to study and optimize a company's R&D portfolio. As discussed in Section 4.2.2, the key functions of a R&D MDM are:

1. Strategic alignment to ensure that the R&D projects being done actually respond to the company's strategy at the top level
2. Identifying and creating synergies between products and business units
3. Avoiding technology blind spots

Figure 4-2 shows how strategic alignment is achieved by aligning an organization's strategic drivers with its technology roadmaps, defining targets (aka figures of merit) to benchmark progress along those technology roadmaps, and setting targets for each R&D project to understand how it is progressing the technology. Identifying synergies occurs during analysis of the existing R&D portfolio, where a consolidated project portfolio will reveal projects working on synergistic technologies. Finally, gaps in technology are identified by analyzing the alignment of the existing R&D portfolio to technology roadmaps, which will reveal areas of roadmaps that the organization is not working on.

Several inputs were needed to construct a MIT Lunar Technology MDM. These inputs informed four parts of a MDM: MIT strategic goals, technology roadmaps, figures of merit (FOMs), and MIT research projects.

As mentioned in the beginning of Section 4.3, and discussed in more detail there, the list of MIT strategic goals was compiled from three documents:

- A Global Strategy for MIT [Lester, 2017]
- MIT Five-year Strategic Action Plan for Diversity, Equity, and Inclusion (2021-2026) - DRAFT [Dozier et al., 2021]
- MIT Department of Aeronautics and Astronautics 2020 Strategic Plan [MIT Department of Aeronautics and Astronautics, 2020]

Technology roadmaps were pulled from NASA's Commercial Space Technology Roadmap (CSTR) [MIT Strategic Engineering et al., 2018, de Weck et al., 2018].

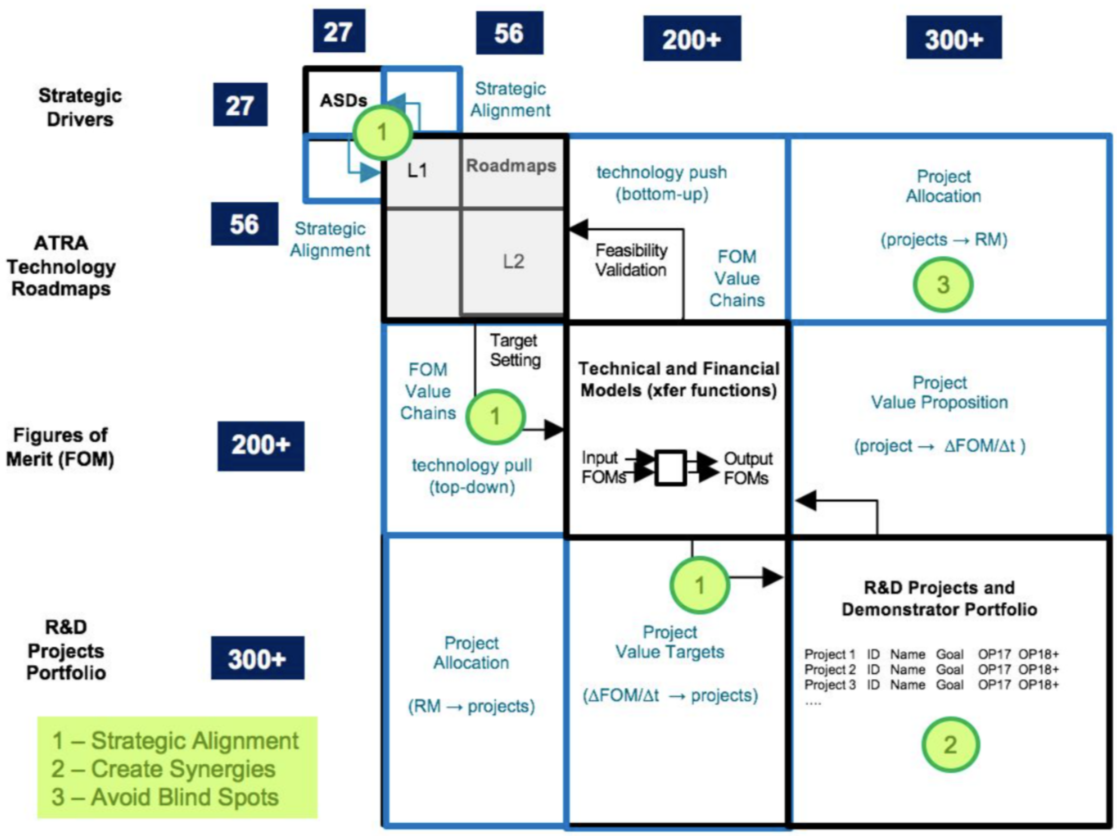


Figure 4-2: A MDM for a R&D portfolio model [de Weck, 2020].

This work specifically used the Level 1 (sector level) roadmaps rather than the Level 2 (subsector level) roadmaps. The CSTR roadmaps were selected over NASA's 2015 roadmaps [National Aeronautics and Space Administration, 2015] because the CSTR roadmaps contain detailed figures of merit since they were created under the leadership of MIT Professor Olivier de Weck, who also designed the R&D portfolio MDM methodology in use here. NASA's technology roadmaps could be incorporated in future work, as discussed in Section 6.1.

The CSTR roadmaps were also the data source of the figures of merit in this technology MDM. However, the CSTR project has only completed roadmaps for five subsectors, so FOMs from the other 24 subsectors are not included in this analysis [MIT Strategic Engineering et al., 2018, de Weck et al., 2018].

Finally, MIT's R&D projects were identified during the aforementioned interviews with MIT researchers. Interviews were conducted with six researchers, and projects from a seventh researcher (Professor Dava Newman, the adviser of this thesis) were added based on the author's knowledge and conversations with students in the lab.

4.4 Literature Review

In this renewed interested in the Moon, there has been a paradigm shift in approach: organizations including NASA are shifting away from the "flags and footprints" approach of the Apollo Program toward establishing long-term settlements on the lunar surface [National Aeronautics and Space Administration, 2020b, Todd et al., 2020, Jones, 2021, Woerner, 2016, European Space Agency, 2021, Blue Origin, 2020]. While the Apollo Program encompassed a race to the Moon between the U.S. and Russia, there were ambitious plans to move to sustained operations on the lunar surface after Apollo 20. However, changes in political priorities led those plans to be cancelled. For decades, committees and groups have convened to think about long-term lunar exploration. So while this phase of lunar exploration is different because it prioritizes long-term operations from the get-go, it is building upon decades of research and planning [National Aeronautics and Space Administration, 2021].

A summary of key references for this work is provided in Table 4.1.

Table 4.1: Overview of Key Literature for Lunar Science and Technology Strategic Planning

Lunar Exploration	STMs	Tech Roadmapping
[David, 2019]	[Feldman, 2019]	[de Weck, 2020]
[National Aeronautics and Space Administration, 2020b]	[National Aeronautics and Space Administration, 2021]	[Eppinger and Browning, 2012]
[National Aeronautics and Space Administration, 2021]		[de Weck et al., 2018]
[International Space Exploration Coordination Group, 2020]		[MIT Strategic Engineering et al., 2018]
[Lunar Exploration Roadmap Steering Committee et al., 2016]		[Sherwood, 2016]

4.4.1 Lunar Exploration

Amongst the plethora of writings that exist about the Moon, veteran space journalist Leonard David's 2019 book, "Moon Rush: The New Space Race," published by National Geographic is a great place for the uninitiated to start [David, 2019]. In the well-written and easily digestible book, David covers the key topics to know about lunar exploration: scientific theories about its origins, the history of the race to land people on the surface, details of the Apollo program, why humans should return, major Moon initiatives from new players (e.g., SpaceX, Blue Origin, China and India), and prominent business cases.

Key lunar strategic planning documents to be familiar with include:

- NASA's Plan for Sustained Lunar Settlement [National Aeronautics and Space Administration, 2020b]
- NASA's Artemis III Science Definition Report (SDR) [National Aeronautics and Space Administration, 2021]

- The International Space Exploration Coordination Group's (ISECG) Global Exploration Roadmap - Supplement August 2020 (GER) [International Space Exploration Coordination Group, 2020]

- The Lunar Exploration Analysis Group (LEAG)'s 2016 Lunar Exploration Roadmap (LER) [Lunar Exploration Roadmap Steering Committee et al., 2016]

As of May 2021, NASA's major contracts for lunar exploration include [Weinzierl and Sarang, 2021, Ridge Bowman et al., 2021]:

- Commercial Lunar Payload Services: contracts to build cargo lunar landers, awarded to around a dozen company [NASA, 2020]

- Gateway Logistics Services: a contract to provide cargo resupply transportation from Earth to a future Lunar Gateway; awarded to SpaceX [Potter, 2021]

- Human Landing System: a contract to build human-rated lunar landers; awarded to SpaceX, under review by the Government Accountability Office [Foust, 2021a]

- Lunar Gateway Power and Propulsion Element (PPE): a contract to build the power and propulsion pieces of the Lunar Gateway, awarded to Maxar Technologies

- Gateway Habitation and Logistics Outpost (HALO): a contract to build "a docking location for Orion, living and working spaces for crewmembers staying less than 30 days, and logistics capabilities;" awarded to Northrop Grumman [Ridge Bowman et al., 2021]

Planning a mission to the moon requires overcome serious exploration challenges, as summarized by retired NASA engineer Ron Creel in Figure [Creel, 2021]. Many of these topic areas are already being researched extensively.

In this new era of lunar exploration, new types of work have emerged, including law, economics and governance of the Moon. In governance, some initiatives include: the Lunar Governance Working Group [Mehak Sarang, 2021], which includes MIT's

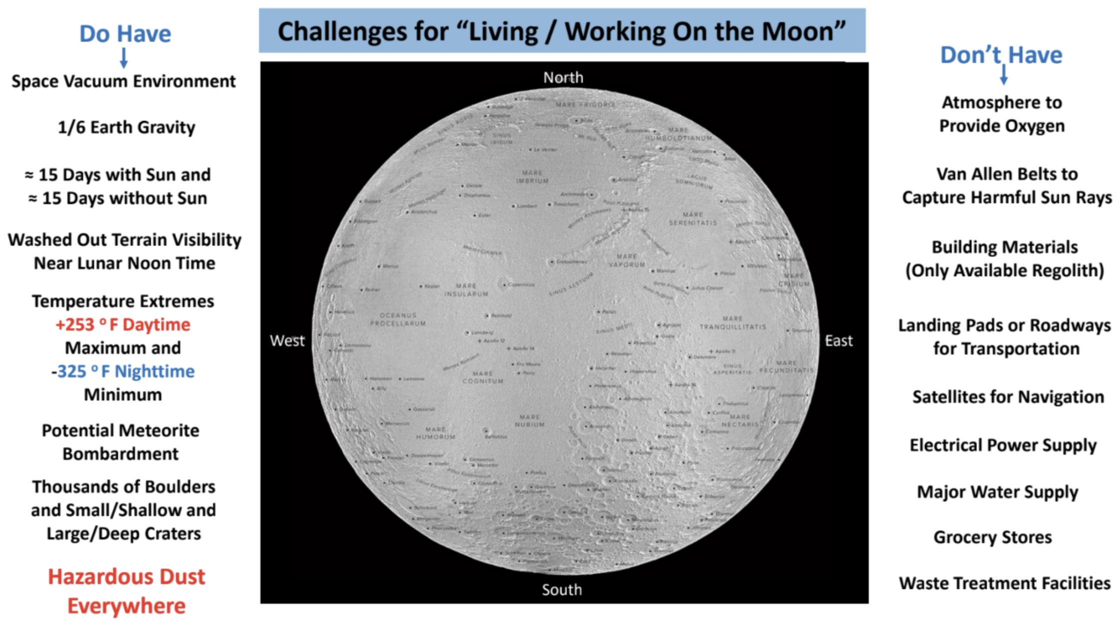


Figure 4-3: Summary of key challenges in lunar exploration [Creel, 2021]

Space Exploration Initiative and Space Enabled Lab as members; For All Moonkind, an all-volunteer international nonprofit group, is working on preservation of human heritage on the lunar surface, including a public Moon Registry that lists all the artifacts left behind on the Moon [CollectSPACE, 2021, For All Moonkind, 2021]; and a Space Sustainability Rating project, led by MIT's Space Enabled research group in collaboration with the World Economic Forum, the European Space Agency (ESA), Bryce Space and Technology, and the University of Texas at Austin [Knight,]. Laws for lunar exploration are currently limited to the Outer Space Treaty of 1967 [United Nations Office of Outer Space Affairs,]. While a Moon Treaty was ratified by the United Nations in 1984, only 18 countries have signed in, not including any of the countries with human spaceflight programs [United Nations, 1984]. NASA is currently leading an initiative to develop the Artemis Accords, which seek to define rules for engagement and peaceful cooperation on the Moon. The Artemis Accords were signed in 2020, but major spaceflight nations Russia and China were not signatories [National Aeronautics and Space Administration, 2020c].

To understand MIT's role in past lunar exploration efforts, refer to an upcoming publication from Elissa Gibson, an undergraduate student in MIT's Department of

Aeronautics and Astronautics who worked as an undergraduate research assistant with the author during the Spring 2021 semester.

4.4.2 Current MIT Lunar Research

MIT has a vast amount of publications relevant to lunar exploration, from papers about missions that went to the Moon (including GRAIL and the Israeli Beresheet) to strategic planning papers and theoretical working papers on governance. Below is a list of publications identified by the author during the development of this thesis.

- Journal/Magazine Articles
  - Professor Maria Zuber on the lunar interior via the NASA Lunar Reconnaissance Orbiter (LRO) mission [Corley et al., 2018][1]
  - Professor Maria Zuber on lunar impact basins via the NASA Gravity Recovery and Interior Laboratory (GRAIL) mission [Andrews-Hanna et al., 2018]
  - Professor Maria Zuber on lunar gravity fields and the implications on structure of the Moon's crust via the NASA Gravity Recovery and Interior Laboratory (GRAIL) mission [Goossens et al., 2020]
  - Professor Maria Zuber on lunar lava tubes via the NASA Gravity Recovery and Interior Laboratory (GRAIL) mission [Chappaz et al., 2017]
  - Professor Maria Zuber on lunar gravity fields and the implications on structure of the Moon's crust and impact basins via the NASA Gravity Recovery and Interior Laboratory (GRAIL) mission [Baker et al., 2017]
  - Research scientist Christopher Carr and Professor Dava Newman on the Apollo number, a metric used to account for spacesuit self-support in lunar gravity that affects human gait [Carr and Mcgee, 2009]

[1] Only five of Prof. Zuber's Moon publications are listed here; a full list of can be found at http://www-geodyn.mit.edu/

  - Graduate students Johannes Norheim and Eswar Anandapadmanaban with Professors Jeffrey Hoffman and Dava Newman on field tests during simulated extravehicular activity of new operational concepts for planetary exploration [Beaton et al., 2020]
  - Professor Ben Weiss on the lunar dynamo [Weiss and Tikoo, 2014]
  - Professor Ben Weiss on the end of the lunar dynamo [Mighani et al., 2020]
  - Professor Ben Weiss on science of Beresheet mission [Aharonson et al., 2020]
  - Graduate students Jessica Todd, George Lordos, Benjamin Martell, Cormac O'Neill and the author on economically viable lunar settlements [Todd et al., 2020]

- Conference Papers
  - Graduate students Cody Paige and Ferrous Ward, undergraduate student Trent Piercy, and Professor Dava Newman on a virtual reality mission operations center for lunar rover missions [Paige et al., 2021b]
  - Graduate students Cody Paige and Ferrous Ward, undergraduate student Trent Piercy, and Professor Dava Newman on integration science instrument data into a virtual reality mission operations center [Paige et al., 2021a]
  - Graduate student Ferrous Ward, undergraduate student Trent Piercy, and Professor Dava Newman on using a virtual reality mission control for closed-loop operations [Ward et al., 2021]
  - Graduate student Aaron Johnson with Professors Jeffrey Hoffman, Dava Newman and Maria Zuber on a traverse planning tool for the Moon [Johnson et al., 2010]
  - Research scientist Christopher Carr and Professor Dava Newman on the use of exoskeletons to support human exploration of the Moon [Carr and Newman, 2017]

- Professor Dava Newman on the use of mixed reality to support planetary extravehicular activity [Beaton et al., 2019]
- Graduate student Johannes Norheim and Professors Jeffrey Hoffman and Dava Newman on testing a traverse planning tool during a Mars analog mission [Norheim et al., 2018]
- Graduate students Skylar Eiskowitz, Sydney Dolan, George Lordos, Matthew Moraguez, Alejandro Trujillo, and Bruce Cameron with professor Olivier de Weck and Ed Crawley on Mars extensibility of lunar propellants systems [Eiskowitz et al., 2020]
- Researchers Mehak Sarang and Dr. Ariel Ekblaw on MIT's Lunar Open Architecture (LOA) [Schingler et al., 2019]
- 2020 MIT BIG Idea Challenge team on MIT's deployable lunar tower [Amy et al., 2020]

- Working Papers
  - Graduate student Carson Bullock on lunar capitalism, [Bullock, 2020]
  - Graduate student Alvin Harvey on the history the Navajo Nation's response to NASA's Lunar Prospector [Harvey, 2021]
  - Graduate student Alvin Harvey on the history the Navajo Nation's response to NASA's Lunar Prospector, discusses the concept of using the Navajo Nation's laws to promote the inclusion of the Navajo in the wider space community [Harvey, 2020]

4.4.3 Science Traceability Matrices

A science traceability matrix (STM) is a space mission planning tool that "shows how science goals and objectives "trace" (flow down) to instrument and mission requirements". They answer three questions [Feldman, 2019]:

1. Does the science address high-level goals?

2. Does the investigation address the science?

3. Does the instrument/mission implement the investigation robustly?

STMs are a required component of major mission proposals, as seen in the Mars 2020 Science Definition Team's final report [Mustard et al., 2013], NASA's Discovery-class Psyche mission [Elkins-Tanton, 2018, Oh et al., 2019], and proposals for Titan-Enceladus missions for ESA [Tobie et al., 2014, MacKenzie et al., 2016, Mitri et al., 2018], just to name a few. They are developed during the early phase of a mission concept design process and become the backbone for organizing and planning the science work of a mission.

4.4.4 Technology Planning

Numerous groups have thought about the technology we need to explore the Moon, both in short-term missions and for longer-term, sustainable settlements. The NASA Artemis III Science Definition Report includes a list of NASA-related lunar strategic planning documents spanning from the 1980s to present [National Aeronautics and Space Administration, 2020b]. NASA has also invested in higher-level strategic planning exercises, as with then-JPL employee (now Vice President of Advanced Development Programs at Blue Origin) Brent Sherwood's paper that designed a strategic, program-level roadmap for exploration ocean worlds, particularly Enceladus [Sherwood, 2016].

In addition to lunar strategic planning, NASA has invested significant resources into technology planning across its organization. Some of the results of this work include the 2015 Technology Roadmaps [National Aeronautics and Space Administration, 2015] and the 2020 Technology Taxonomy [National Aeronautics and Space Administration, 2020a]. NASA also invested in a MIT-led effort to develop a Commercial Space Technology Roadmap [de Weck et al., 2018, MIT Strategic Engineering et al., 2018], which was designed as an industry-focused complement to the 2015 NASA roadmaps. NASA recently awarded funding to a new project at MIT called ASTRA (Advanced Space Technology Roadmapping Architecture), which aims to augment NASA's technology management strategy by aligning strategic goals and technology roadmaps with thorough analysis of valuation and investment [de Weck, 2021].

The ASTRA project will leverage MIT's Lunar Open Architecture for its case study on the Artemis Program. ASTRA's methodology is built on theory covered in an upcoming book by ASTRA principal investigator Olivier de Weck [de Weck, 2020]. In his book, De Weck covers the theory and practice of technology management including topics like the history of technology, technology disruption, and technology R&D portfolio management. As a first step of R&D portfolio management De Weck proposes the use of a system architecture modeling tool called a multi-domain matrix (MDM). A MDM is a more complex version of a design structure matrix (DSM), which is "a highly flexible network modeling method" [Eppinger and Browning, 2012]. At a high level, a DSM identifies connections or dependencies between parts of a system. Functionally, a DSM is a matrix in which the header column and row are the same, and the internal matrix identifies connections between each column and row. An example DSM is shown in Figure 4-4. Generally, a DSM focuses on a particular domain of a system such as product, process, or organization: it maps pieces of a domain to itself to identify dependencies within that domain. Comparison across these domains can also be useful, and can be performed using a domain mapping matrix (DMM), which compares piece of one domain to pieces of another domain. Combining a DSM and DMM into one figure creates a multi-domain matrix (MDM) [Eppinger and Browning, 2012]. Figure 4-5 shows a "periodic table" of DSMs and DMMs (thereby forming a MDM), which is a theoretical mapping of all the types of DSM and DMM combinations, using Eppinger and Browning's five DSM domains (goals, products, processes, organizations, and tools).

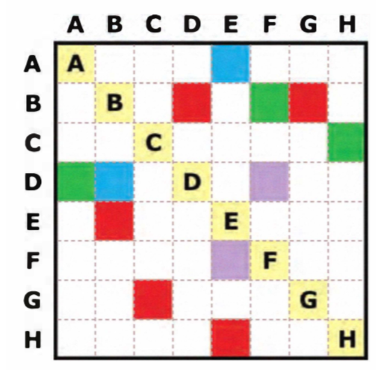


Figure 4-4: Example design structure matrix from Eppinger and Browning [Eppinger and Browning, 2012].

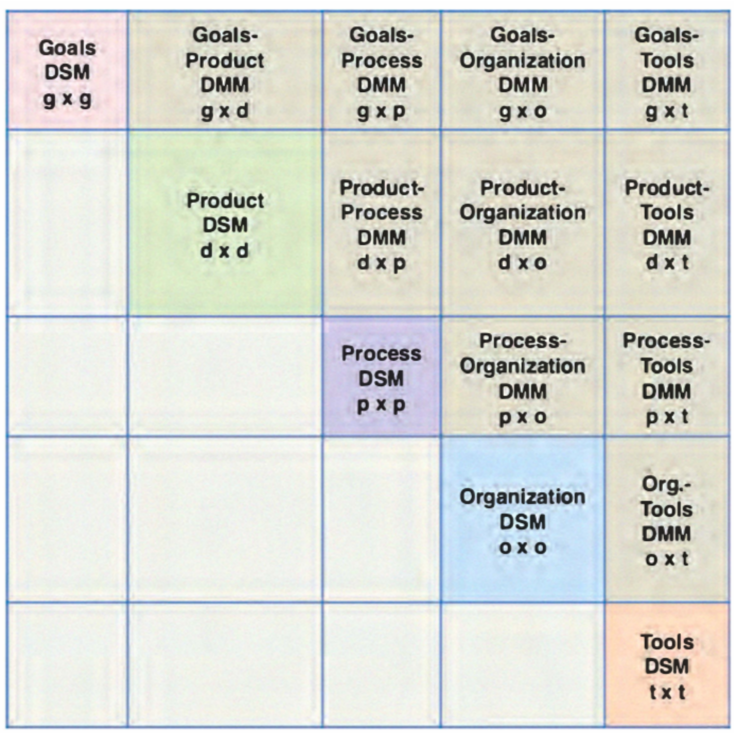


Figure 4-5: The "periodic table" of DSMs and DMMs, resulting in a MDM, from Eppinger and Browning [Eppinger and Browning, 2012].

THIS PAGE INTENTIONALLY LEFT BLANK

Chapter 5

MIT Lunar Science and Technology Planning

To begin planning for science and technology developmental goals for MIT lunar exploration efforts, this chapter takes a first step to define MIT's existing science and technology capabilities. This is achieved through the development of two system-level planning tools: a science traceability matrix (STM) and technology multi-domain matrix (MDM). This thesis incorporates data from seven MIT researchers; in order to develop a complete understanding of MIT's lunar-relevant science and technology ecosystem, input from more researchers would be needed. Once the MIT lunar ecosystem is understood, the Institute can proceed with developing a MIT Lunar Exploration Strategic Plan.

5.1 MIT Lunar Science Traceability Matrix

We propose a twist on a standard science traceability matrix that will focus on mapping science goals to core capabilities within MIT, rather than mapping science goals to mission investigations and instruments requirements/performance. This change stems from a different strategic goal of this work: identifying opportunities and strengths for lunar planetary investigation in the 2020s.

As discussed in Chapter 4 and copied here for reference, the MIT Lunar STM will answer the following research questions:

- Understand the scientific significance of MIT's lunar-relevant research
- Identify existing areas of MIT science research that are relevant to lunar exploration
- Understand how MIT's various lunar-relevant science efforts relate to each other

5.1.1 Data Entry

To build this STM, three distinct data sets were constructed with the following information:

1. Science goals
   - Traceability (source document)
2. MIT strategic goals
   - Traceability (source document)
   - Goal type (recommendation, commitment, thrust or value)
3. MIT lunar research actors
   - Current research areas
   - Past research areas
   - Potential future research areas / research areas of interest

For entry into the STM, science goals/objectives had to be aligned since each document uses different levels of specificity and terminology. From NASA's Artemis III Science Definition Report [National Aeronautics and Space Administration, 2021], the 54 science "goals" (e.g., "1d. Tectonism: Deformation of the Crust and Thermal History") were used. From The International Space Exploration Coordination Group's (ISECG) Global Exploration Roadmap - Supplement August 2020 (GER)

[International Space Exploration Coordination Group, 2020], the 12 science "objectives" (e.g., "Demonstrate human landing/ascent capability to and from the lunar surface") were used. The level of specificity of these goals is obviously different, but this alignment provides a starting point for studying how MIT's core capabilities can address important science goals. Between these two documents, a total of 66 science goals were collected and added into the STM. Table 5.1 shows how the goals from each document were aligned, with the Level 3 alignment used for the STM.

Table 5.1: Aligning science goals from source documents to input into STM.

Source Document	Level 1	Level 2	Level 3	Level 4
NASA Artemis III Science Definition Report (SDR)	Objective	–	Goal	Investigation
The International Space Exploration Coordination Group's (ISECG) Global Exploration Roadmap - Supplement August 2020 (GER)	Goal	–	Objective	–

For MIT's strategic goals, the goal type was recorded for future refinement, to see which types of goals are most useful for mapping to core research capabilities. The usefulness of each type of goal is discussed in Section 5.1.5.

MIT's initial core capabilities were captured through interviews with research leaders and several students at MIT, as discussed in Section 4.3.1.

5.1.2 Mapping

For mapping science goals, MIT strategic goals and, MIT core capabilities, the following guiding questions were used:

- Science goals to MIT core capabilities
  - S1: Is this core capability essential to the achievement of the science goal?
  - S2: Would working on this science goal affect this core capability?
- MIT strategic goals to MIT core capabilities

- M1: Can this core capability be used to work toward this strategic goal?
- M2: Would working toward this strategic goal affect this core capability?

The mapping was conducted using Airtable, a relational database that is a hybrid between a database and a spreadsheet. It automatically updates mappings between items, such that as the two groups of mappings above were completed, the mappings between science goals and MIT strategic goals were automatically filled in.

5.1.3 Static Visualization

The full MIT Lunar Science Traceability Matrix is shown in Table 5.2 in a static form. The table revealed the lack of connections to 19 MIT strategic goals and eight science goals, which MIT could attempt to fill. While this map is useful as a database for studying connections within MIT's lunar research network, it is difficult to digest because of its size. For this reason, an interactive tool was developed to lower the barrier to data exploration and insight discovery, as discussed in the next section.

This static STM established connections between the three data sets of science goals, MIT strategic goals, and MIT lunar research actors. Most importantly, it linked MIT core capabilities to science goals and strategic goals. Studying the connections to MIT's core capabilities will help in developing a strategic plan for lunar exploration that ensures MIT's science research is relevant to both top science goals and to the university's own strategic goals.

Table 5.2: MIT Lunar Science Traceability Matrix

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
1	Demonstrate human landing/ascent capability to and from the lunar surface.	ISECG GER 2020 Supplement	Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Aerospace environmental mitigation and monitori Create an open, diverse, inclusive, and supportiv Become the leading department at MIT in mentor Support academic research, scholarship, and col Critically engage with and empower the MIT com Increase the number of underrepresented gradua Assess and strengthen our recruitment of underr Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Aerospace environmental mitigation and monitori Create an open, diverse, inclusive, and supportiv Become the leading department at MIT in mentor Support academic research, scholarship, and col Critically engage with and empower the MIT com Increase the number of underrepresented gradua Assess and strengthen our recruitment of underr Create an open, diverse, inclusive, and supportiv Become the leading department at MIT in mentor Support academic research, scholarship, and col Critically engage with and empower the MIT com Increase the number of underrepresented gradua Assess and strengthen our recruitment of underr	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	Spacesuits Mobility Technology roadmapping Systems engineering MBSE Multidisciplinary design optimization System architecture Mission modeling Sustainable development Indigenous views of space Green propulsion Antiracism Accessibility Democratization of space AR/VR AI/ML Aerospace biomedicine Industrial design Human-robot interaction Food Waste management	Dava Newman Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Olivier de Weck Danielle Wood Dava Newman Danielle Wood Danielle Wood Danielle Wood Dava Newman Dava Newman Julie Shah Dava Newman Ariel Ekblaw Julie Shah Ariel Ekblaw Ariel Ekblaw	Jeffrey Hoffman Jeffrey Hoffman Olivier de Weck Danielle Wood Danielle Wood	Julie Shah

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT …	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
			Create an open, diverse, inclusive, and supportiv Become the leading department at MIT in mentor Support academic research, scholarship, and col Critically engage with and empower the MIT com Integrate autonomy and humans in real-world sys Integrate autonomy and humans in real-world sys Aerospace environmental mitigation and monitori Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Integrate autonomy and humans in real-world sys Lead development of the College of Computing e Aerospace environmental mitigation and monitori					
2	Demonstrate a range of cargo delivery capabilities on the lunar surface for large surface elements and logistics.	ISECG GER 2020 Supplement	Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Develop new theory and applications for satellite Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Integrate autonomy and humans in real-world sys Aerospace environmental mitigation and monitori Lead development of the College of Computing e Develop new theory and applications for satellite	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	Deployable towers Mobility Technology roadmapping Systems engineering MBSE Multidisciplinary design optimization System architecture Mission modeling Payload development Payload integration Sustainable development AI/ML Industrial design Self-assembling architecture	Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Olivier de Weck Olivier de Weck Benjamin Weiss Ariel Ekblaw Ariel Ekblaw Danielle Wood Dava Newman Dava Newman Julie Shah Ariel Ekblaw Ariel Ekblaw	Jeffrey Hoffman Olivier de Weck	Jeffrey Hoffman Benjamin Weiss

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
3	Demonstrate Extra Vehicular Activity (EVA) capabilities on the lunar surface.	ISECG GER 2020 Supplement	Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Integrate autonomy and humans in real-world sys Integrate autonomy and humans in real-world sys Aerospace environmental mitigation and monitori	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	Spacesuits Mobility Technology roadmapping Systems engineering MBSE Multidisciplinary design optimization System architecture Mission modeling Sustainable development AR/VR Aerospace biomedicine Food Waste management	Dava Newman Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Olivier de Weck Danielle Wood Dava Newman Dava Newman Dava Newman Ariel Ekblaw Ariel Ekblaw	Jeffrey Hoffman Jeffrey Hoffman Olivier de Weck	Julie Shah
4	Demonstrate human long-range traversing capability on the lunar surface.	ISECG GER 2020 Supplement	Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Integrate autonomy and humans in real-world sys Integrate autonomy and humans in real-world sys Integrate autonomy and humans in real-world sys Lead development of the College of Computing e	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	Food Spacesuits Mobility Technology roadmapping Systems engineering MBSE System architecture Mission modeling Multidisciplinary design optimization Waste management AR/VR Aerospace biomedicine Human-robot interaction	Ariel Ekblaw Dava Newman Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Olivier de Weck Ariel Ekblaw Dava Newman Dava Newman Julie Shah	Jeffrey Hoffman Jeffrey Hoffman Olivier de Weck	Julie Shah

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
5	Demonstrate reliability of human long-duration habitation capability and operational procedures on the lunar surface.	ISECG GER 2020 Supplement	Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Strengthen Governance and Operations Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Integrate autonomy and humans in real-world sys Integrate autonomy and humans in real-world sys Lead development of the College of Computing e	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, A Global Strategy for MIT, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	Spacesuits Mobility Habitats Waste management Technology roadmapping Systems engineering MBSE Self-assembling architecture Multidisciplinary design optimization Policy Governance System architecture Mission modeling Sustainable development Aerospace biomedicine Food Human-robot interaction	Dava Newman Ariel Ekblaw Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Ariel Ekblaw Olivier de Weck Dava Newman Danielle Wood Danielle Wood Ariel Ekblaw Olivier de Weck Danielle Wood Dava Newman Dava Newman Ariel Ekblaw Julie Shah	Jeffrey Hoffman Jeffrey Hoffman Jeffrey Hoffman Olivier de Weck	

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
6	Demonstrate crew health and performance sustainability to live and work on the lunar surface for a sufficient duration to validate Mars surface missions.	ISECG GER 2020 Supplement	Strengthen Governance and Operations Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Integrate autonomy and humans in real-world sys Integrate autonomy and humans in real-world sys Aerospace environmental mitigation and monitori Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Integrate autonomy and humans in real-world sys Lead development of the College of Computing e	A Global Strategy for MIT, AeroAstro 2020 Strategic Plan	Spacesuits Mobility Habitats Policy Governance Waste management Technology roadmapping Systems engineering MBSE Self-assembling architecture Multidisciplinary design optimization System architecture Mission modeling Sustainable development AR/VR AI/ML Aerospace biomedicine Food Human-robot interaction	Dava Newman Dava Newman Danielle Wood Danielle Wood Ariel Ekblaw Ariel Ekblaw Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Ariel Ekblaw Olivier de Weck Olivier de Weck Danielle Wood Dava Newman Dava Newman Dava Newman Julie Shah Dava Newman Ariel Ekblaw Julie Shah	Jeffrey Hoffman Jeffrey Hoffman Jeffrey Hoffman Olivier de Weck	Julie Shah

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
7	Demonstrate in-situ resource production and utilisation capability sufficient for crew transportation between lunar surface and Gateway and lunar surface utilisation needs.	ISECG GER 2020 Supplement	Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Develop new theory and applications for satellite Develop new theory and applications for satellite Aerospace environmental mitigation and monitori	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	ISRU Systems engineering MBSE Multidisciplinary design optimization System architecture Mission modeling Technology roadmapping Regolith characterization Sustainable development	Jeffrey Hoffman Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Olivier de Weck Ariel Ekblaw Olivier de Weck Danielle Wood Danielle Wood Dava Newman	Olivier de Weck	
8	Conduct effective global human/robotic cooperative science exploration to perform groundbreaking science.	ISECG GER 2020 Supplement	Integrate autonomy and humans in real-world sys Integrate autonomy and humans in real-world sys Lead development of the College of Computing e Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	AR/VR Human-robot interaction Technology roadmapping Systems engineering System architecture Multidisciplinary design optimization MBSE Mission modeling	Dava Newman Julie Shah Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood	Olivier de Weck	Julie Shah

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
9	Develop infrastructure (e.g., power and communication systems) necessary to achieve the objectives for sustained exploration.	ISECG GER 2020 Supplement	Strengthen Governance and Operations Aerospace environmental mitigation and monitori Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Aerospace environmental mitigation and monitori	A Global Strategy for MIT, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	Habitats Mobility Policy Governance Waste management Deployable towers ISRU Additive manufacturing Technology roadmapping Systems engineering MBSE Multidisciplinary design optimization System architecture Mission modeling Sustainable development	Dava Newman Danielle Wood Danielle Wood Ariel Ekblaw Ariel Ekblaw Jeffrey Hoffman Ariel Ekblaw Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Olivier de Weck Danielle Wood Dava Newman	Jeffrey Hoffman Jeffrey Hoffman Olivier de Weck	Jeffrey Hoffman
10	Engage the public in general and the youth in particular with human/robotic lunar surface exploration by bringing the action to large audiences, making full use of the state-of-the-art technology and through new ways of communication.	ISECG GER 2020 Supplement	Aerospace environmental mitigation and monitori Create an open, diverse, inclusive, and supportiv Become the leading department at MIT in mentor Support academic research, scholarship, and col Critically engage with and empower the MIT com Increase the number of underrepresented gradua Assess and strengthen our recruitment of underr Create an open, diverse, inclusive, and supportiv Become the leading department at MIT in mentor Support academic research, scholarship, and col Critically engage with and empower the MIT com Increase the number of underrepresented gradua Assess and strengthen our recruitment of underr Aerospace environmental mitigation and monitori Create an open, diverse, inclusive, and supportiv Become the leading department at MIT in mentor Support academic research, scholarship, and col Critically engage with and empower the MIT com Increase the number of underrepresented gradua	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, A Global Strategy for MIT, MIT 5-year Strategic Action Plan for DEI, A Global Strategy for MIT, AeroAstro 2020 Strategic Plan, MIT 5-year Strategic Action Plan for DEI, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan,	Antiracism Accessibility Indigenous views of space Democratization of space Citizen science Public engagement Differently-abled astronauts AR/VR Science communication Art Design	Danielle Wood Danielle Wood Dava Newman Ariel Ekblaw Ariel Ekblaw Ariel Ekblaw	Danielle Wood Danielle Wood Danielle Wood Danielle Wood	Danielle Wood Julie Shah

#	High-Level Objective	Objective Traceability		MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
			Assess and strengthen our recruitment of underr Develop new theory and applications for satellite Create an open, diverse, inclusive, and supportiv Become the leading department at MIT in mentor Support academic research, scholarship, and col Critically engage with and empower the MIT com Streamline and strengthen international educatio Critically engage with and empower the MIT com Streamline and strengthen international educatio Lead development of the College of Computing e Reinforce positive interactions among members c Integrate autonomy and humans in real-world sys Create an open, diverse, inclusive, and supportiv Become the leading department at MIT in mentor Support academic research, scholarship, and col Critically engage with and empower the MIT com Increase the number of underrepresented gradua Assess and strengthen our recruitment of underr Integrate autonomy and humans in real-world sys Reinforce positive interactions among members c	MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, AeroAstro 2020 Strategic Plan, MIT 5-year Strategic Action Plan for DEI				
11	Implement new commercial arrangements that stimulate economic prosperity and foster commercial opportunities.	ISECG GER 2020 Supplement	Strengthen Governance and Operations Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite	A Global Strategy for MIT, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	Policy Governance Technology roadmapping Systems engineering MBSE System architecture Multidisciplinary design optimization Mission modeling	Dava Newman Danielle Wood Danielle Wood Ariel Ekblaw Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Olivier de Weck	Olivier de Weck	

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
12	Provide a large number of collaboration opportunities for international partners to contribute to the lunar surface scenario.	ISECG GER 2020 Supplement	Strengthen Governance and Operations Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Create an open, diverse, inclusive, and supportiv Become the leading department at MIT in mentor Support academic research, scholarship, and col Critically engage with and empower the MIT com Increase the number of underrepresented gradua Assess and strengthen our recruitment of underr Develop new theory and applications for satellite Create an open, diverse, inclusive, and supportiv Become the leading department at MIT in mentor Support academic research, scholarship, and col Critically engage with and empower the MIT com	A Global Strategy for MIT, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI	Policy Governance Systems engineering Technology roadmapping MBSE Multidisciplinary design optimization System architecture Mission modeling Accessibility Democratization of space	Dava Newman Danielle Wood Danielle Wood Ariel Ekblaw Olivier de Weck Ariel Ekblaw Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Olivier de Weck	Olivier de Weck Danielle Wood Danielle Wood	

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
13	1a. Formation of the Earth-Moon System	NASA Artemis III	Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Develop new theory and applications for satellite Develop new theory and applications for satellite Advancing the frontiers of knowledge	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, A Global Strategy for MIT	Air-dropped penetrators Remote sensing Technology roadmapping Systems engineering System architecture MBSE Multidisciplinary design optimization Deployable towers Planetary origins Magnetism Regolith characterization Sample analysis	Jeffrey Hoffman Olivier de Weck Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Benjamin Weiss Benjamin Weiss Danielle Wood Benjamin Weiss	Benjamin Weiss	Jeffrey Hoffman

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
14	1b. Differentiation: Magma Oceans, Crust, and Mantle	NASA Artemis III	Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Develop new theory and applications for satellite Develop new theory and applications for satellite Advancing the frontiers of knowledge	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, A Global Strategy for MIT	Air-dropped penetrators Remote sensing Technology roadmapping Systems engineering System architecture MBSE Multidisciplinary design optimization Deployable towers Planetary origins Magnetism Regolith characterization Sample analysis	Jeffrey Hoffman Olivier de Weck Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Benjamin Weiss Benjamin Weiss Danielle Wood Benjamin Weiss	Benjamin Weiss	Jeffrey Hoffman
15	1c. Volcanism: Partial Melting, Eruptions, Flow Sequence and Compositions	NASA Artemis III	Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Develop new theory and applications for satellite Advancing the frontiers of knowledge	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, A Global Strategy for MIT	Air-dropped penetrators Remote sensing Technology roadmapping Systems engineering System architecture MBSE Multidisciplinary design optimization Deployable towers Planetary origins Regolith characterization Sample analysis	Jeffrey Hoffman Olivier de Weck Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Benjamin Weiss Danielle Wood Benjamin Weiss	Benjamin Weiss	Jeffrey Hoffman

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
16	1d. Tectonism: Deformation of the Crust and Thermal History	NASA Artemis III	Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Develop new theory and applications for satellite Advancing the frontiers of knowledge	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, A Global Strategy for MIT	Air-dropped penetrators Remote sensing Technology roadmapping Systems engineering System architecture MBSE Multidisciplinary design optimization Deployable towers Planetary origins Regolith characterization Sample analysis	Jeffrey Hoffman Olivier de Weck Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Benjamin Weiss Danielle Wood Benjamin Weiss	Benjamin Weiss	Jeffrey Hoffman
17	1e. Impact Processes: Basins and Craters, Mixing of the Crust	NASA Artemis III	Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Develop new theory and applications for satellite Advancing the frontiers of knowledge	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, A Global Strategy for MIT	Air-dropped penetrators Remote sensing Technology roadmapping Systems engineering System architecture MBSE Multidisciplinary design optimization Deployable towers Planetary origins Regolith characterization Sample analysis	Jeffrey Hoffman Olivier de Weck Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Benjamin Weiss Danielle Wood Benjamin Weiss	Benjamin Weiss	Jeffrey Hoffman

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
18	1f. The Moon is a Natural Laboratory for Regolith Processes and Weathering on Anhydrous Bodies	NASA Artemis III	Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Develop new theory and applications for satellite Advancing the frontiers of knowledge	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, A Global Strategy for MIT	Air-dropped penetrators Remote sensing Technology roadmapping Systems engineering System architecture MBSE Multidisciplinary design optimization Deployable towers Planetary origins Regolith characterization Sample analysis	Jeffrey Hoffman Olivier de Weck Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Benjamin Weiss Danielle Wood Benjamin Weiss	Benjamin Weiss	Jeffrey Hoffman
19	2a. Determine the Compositional state (elemental, isotopic, mineralogic) and compositional distribution (lateral and with depth) of the volatile component in lunar polar regions.	NASA Artemis III	Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Advancing the frontiers of knowledge	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, A Global Strategy for MIT	Air-dropped penetrators Remote sensing Technology roadmapping Systems engineering System architecture MBSE Multidisciplinary design optimization Deployable towers Regolith characterization Sample analysis	Jeffrey Hoffman Olivier de Weck Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Danielle Wood Benjamin Weiss	Benjamin Weiss	Jeffrey Hoffman

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
20	2b. Determine the source(s) for lunar polar volatile deposits	NASA Artemis III	Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Develop new theory and applications for satellite Advancing the frontiers of knowledge	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, A Global Strategy for MIT	Air-dropped penetrators Remote sensing Technology roadmapping Systems engineering System architecture MBSE Multidisciplinary design optimization Deployable towers Planetary origins Regolith characterization Sample analysis	Jeffrey Hoffman Olivier de Weck Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Benjamin Weiss Danielle Wood Benjamin Weiss	Benjamin Weiss	Jeffrey Hoffman
21	2c. Understand the transport, retention, alteration, and loss processes that operate on volatile materials at permanently shaded lunar regions	NASA Artemis III	Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Develop new theory and applications for satellite Develop new theory and applications for satellite Advancing the frontiers of knowledge	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, A Global Strategy for MIT	Air-dropped penetrators Remote sensing Technology roadmapping Systems engineering System architecture MBSE Multidisciplinary design optimization Deployable towers Planetary origins Regolith characterization Magnetism Sample analysis	Jeffrey Hoffman Olivier de Weck Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Benjamin Weiss Danielle Wood Benjamin Weiss Benjamin Weiss	Benjamin Weiss	Jeffrey Hoffman

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
22	2d. Understand regolith modification processes (including space weathering), particularly deposition of volatile materials in the near surface	NASA Artemis III	Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Advancing the frontiers of knowledge	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, A Global Strategy for MIT	Air-dropped penetrators Remote sensing Technology roadmapping Systems engineering System architecture MBSE Multidisciplinary design optimization Deployable towers Regolith characterization Sample analysis	Jeffrey Hoffman Olivier de Weck Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Danielle Wood Benjamin Weiss	Benjamin Weiss	Jeffrey Hoffman
23	2e. Learn how water vapor and other volatiles are released from the lunar surface and migrate to the poles where they are obsorbed in polar cold traps	NASA Artemis III	Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Develop new theory and applications for satellite Advancing the frontiers of knowledge	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, A Global Strategy for MIT	Air-dropped penetrators Remote sensing Technology roadmapping Systems engineering System architecture MBSE Multidisciplinary design optimization Deployable towers Planetary origins Regolith characterization Sample analysis	Jeffrey Hoffman Olivier de Weck Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Benjamin Weiss Danielle Wood Benjamin Weiss	Benjamin Weiss	Jeffrey Hoffman

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
24	2f. Understand the impact of human exploration on the lunar volatile record across the surface	NASA Artemis III	Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Develop new theory and applications for satellite Advancing the frontiers of knowledge Aerospace environmental mitigation and monitori Aerospace environmental mitigation and monitori Create an open, diverse, inclusive, and supportiv Become the leading department at MIT in mentor Support academic research, scholarship, and col Critically engage with and empower the MIT com Increase the number of underrepresented gradua Assess and strengthen our recruitment of underr Integrate autonomy and humans in real-world sys Lead development of the College of Computing e Aerospace environmental mitigation and monitori	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, A Global Strategy for MIT, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	Air-dropped penetrators Remote sensing Technology roadmapping Systems engineering System architecture MBSE Multidisciplinary design optimization Deployable towers Planetary origins Regolith characterization Sample analysis Spacesuits Mobility Waste management Indigenous views of space Anthropology Human-robot interaction Sustainable development	Jeffrey Hoffman Olivier de Weck Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Benjamin Weiss Danielle Wood Benjamin Weiss Dava Newman Ariel Ekblaw Danielle Wood Ariel Ekblaw Julie Shah Danielle Wood Dava Newman	Benjamin Weiss Jeffrey Hoffman Jeffrey Hoffman	Jeffrey Hoffman

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
25	3a. Test the Cataclysm	NASA Artemis III	Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Develop new theory and applications for satellite Advancing the frontiers of knowledge	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, A Global Strategy for MIT	Air-dropped penetrators Remote sensing Technology roadmapping Systems engineering System architecture MBSE Multidisciplinary design optimization Deployable towers Planetary origins Regolith characterization Sample analysis	Jeffrey Hoffman Olivier de Weck Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Benjamin Weiss Danielle Wood Benjamin Weiss	Benjamin Weiss	Jeffrey Hoffman
26	3b. Understand changes to the Earth-Moon bombardment rate	NASA Artemis III	Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Develop new theory and applications for satellite Advancing the frontiers of knowledge	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, A Global Strategy for MIT	Air-dropped penetrators Remote sensing Technology roadmapping Systems engineering System architecture MBSE Multidisciplinary design optimization Deployable towers Planetary origins Regolith characterization Sample analysis	Jeffrey Hoffman Olivier de Weck Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Benjamin Weiss Danielle Wood Benjamin Weiss	Benjamin Weiss	Jeffrey Hoffman

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
27	3c. Understand the impact history of the landing site	NASA Artemis III	Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Develop new theory and applications for satellite Advancing the frontiers of knowledge	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, A Global Strategy for MIT	Air-dropped penetrators Remote sensing Technology roadmapping Systems engineering System architecture MBSE Multidisciplinary design optimization Deployable towers Planetary origins Regolith characterization Sample analysis	Jeffrey Hoffman Olivier de Weck Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Benjamin Weiss Danielle Wood Benjamin Weiss	Benjamin Weiss	Jeffrey Hoffman
28	4a. Understand the history of the Sun, including the composition and flux of the solar wind	NASA Artemis III	Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Develop new theory and applications for satellite Advancing the frontiers of knowledge	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, A Global Strategy for MIT	Air-dropped penetrators Remote sensing Technology roadmapping Systems engineering System architecture MBSE Multidisciplinary design optimization Deployable towers Planetary origins Regolith characterization Sample analysis	Jeffrey Hoffman Olivier de Weck Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Benjamin Weiss Danielle Wood Benjamin Weiss	Benjamin Weiss	Jeffrey Hoffman

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
29	4b. Understand the record of cosmic rays, gamma-ray bursts, and supernova	NASA Artemis III	Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Develop new theory and applications for satellite Advancing the frontiers of knowledge	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, A Global Strategy for MIT	Air-dropped penetrators Remote sensing Technology roadmapping Systems engineering System architecture MBSE Multidisciplinary design optimization Deployable towers Planetary origins Regolith characterization Sample analysis	Jeffrey Hoffman Olivier de Weck Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Benjamin Weiss Danielle Wood Benjamin Weiss	Benjamin Weiss	Jeffrey Hoffman
30	4c. Understand changing compositions of impactors with time, and the nature of the early Earth.	NASA Artemis III	Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Develop new theory and applications for satellite Advancing the frontiers of knowledge	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, A Global Strategy for MIT	Air-dropped penetrators Remote sensing Technology roadmapping Systems engineering System architecture MBSE Multidisciplinary design optimization Deployable towers Planetary origins Regolith characterization Sample analysis	Jeffrey Hoffman Olivier de Weck Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Benjamin Weiss Danielle Wood Benjamin Weiss	Benjamin Weiss	Jeffrey Hoffman

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
31	4d. Understand the long-term variability in the solar constant	NASA Artemis III	Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Aerospace environmental mitigation and monitori	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	Air-dropped penetrators Remote sensing Technology roadmapping Systems engineering System architecture MBSE Multidisciplinary design optimization Deployable towers	Jeffrey Hoffman Olivier de Weck Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck		Jeffrey Hoffman
32	5a. Astrophysical and Basic Physics Investigations using the Moon	NASA Artemis III	Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	Technology roadmapping Systems engineering MBSE Multidisciplinary design optimization System architecture Mission modeling	Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Olivier de Weck	Olivier de Weck	

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
33	5b. Heliophysical Investigations using the Moon	NASA Artemis III	Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Lead development of the College of Computing e Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	Magnetism Human-robot interaction Spacesuits Mobility Habitats Deployable towers Technology roadmapping Systems engineering System architecture MBSE Multidisciplinary design optimization	Benjamin Weiss Julie Shah Dava Newman Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck	Jeffrey Hoffman Jeffrey Hoffman Jeffrey Hoffman	Jeffrey Hoffman

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
34	5c. Use the Moon as a platform for Earth-observing studies	NASA Artemis III	Critically engage with and empower the MIT com Streamline and strengthen international educatio Lead development of the College of Computing e Reinforce positive interactions among members c Reinforce positive interactions among members c Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Create an open, diverse, inclusive, and supportiv Become the leading department at MIT in mentor Support academic research, scholarship, and col Critically engage with and empower the MIT com Increase the number of underrepresented gradua Assess and strengthen our recruitment of underr Develop new theory and applications for satellite Create an open, diverse, inclusive, and supportiv Become the leading department at MIT in mentor Support academic research, scholarship, and col Critically engage with and empower the MIT com Streamline and strengthen international educatio Integrate autonomy and humans in real-world sys	MIT 5-year Strategic Action Plan for DEI, A Global Strategy for MIT, AeroAstro 2020 Strategic Plan, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, MIT 5-year Strategic Action Plan for DEI, MIT 5-year Strategic Action Plan for DEI, A Global Strategy for MIT, AeroAstro 2020 Strategic Plan	Public engagement Science communication Earth observation Remote sensing Technology roadmapping Systems engineering System architecture MBSE Multidisciplinary design optimization Mission modeling Accessibility Democratization of space Citizen science AR/VR Art Design Industrial design	Ariel Ekblaw Danielle Wood Olivier de Weck Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Dava Newman Ariel Ekblaw Ariel Ekblaw Ariel Ekblaw	Danielle Wood Olivier de Weck Danielle Wood Danielle Wood Danielle Wood	Julie Shah

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
35	6a. Investigate and characterize the fundamental interactions of combustion and buoyant convection in lunar gravity	NASA Artemis III	Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	MBSE Systems engineering System architecture Multidisciplinary design optimization	Olivier de Weck Danielle Wood Olivier de Weck Olivier de Weck Olivier de Weck		
36	6b. Perform tests to understand and possibly discover new regimes of combustion	NASA Artemis III						
37	6c. Investigate interactions of multiphase combustion processes and convection in lunar gravity	NASA Artemis III						
38	6d. Use the unique environment of the lunar surface to perform experiments in the area of fundamental physics	NASA Artemis III						
39	6e. Obtain experimental data to anchor multiphase flow models in lunar gravity	NASA Artemis III						
40	6f. Study interfacial flow with and without temperature variation to anchor theoretical/numerical models	NASA Artemis III						

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
41	6g. Study behavior of granular media in the lunar environment	NASA Artemis III	Aerospace environmental mitigation and monitori Develop new theory and applications for satellite Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	Spacesuits Mobility Habitats Deployable towers Magnetism Regolith characterization Aerospace biomedicine	Dava Newman Benjamin Weiss Danielle Wood Dava Newman	Jeffrey Hoffman Jeffrey Hoffman Jeffrey Hoffman	Jeffrey Hoffman
42	6h. Investigate precipitation behavior in supercritical water in lunar gravity	NASA Artemis III						
43	6i. Investigate the production of oxygen from lunar regolith in lunar gravity	NASA Artemis III	Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	ISRU Systems engineering MBSE Multidisciplinary design optimization Aerospace biomedicine	Jeffrey Hoffman Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Dava Newman		
44	6j. Investigate the behavior of liquid-phase sintering in lunar gravity	NASA Artemis III	Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	ISRU Additive manufacturing Technology roadmapping Systems engineering MBSE Multidisciplinary design optimization	Jeffrey Hoffman Ariel Ekblaw Ariel Ekblaw Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck		
45	6k. Study and assess effects on materials of long-duration exposure to the lunar environment	NASA Artemis III	Strengthen Governance and Operations Aerospace environmental mitigation and monitori Advancing the frontiers of knowledge	A Global Strategy for MIT, AeroAstro 2020 Strategic Plan, A Global Strategy for MIT	Governance Spacesuits Habitats Deployable towers Sample analysis Industrial design Design	Danielle Wood Ariel Ekblaw Dava Newman Benjamin Weiss Ariel Ekblaw Ariel Ekblaw	Jeffrey Hoffman Jeffrey Hoffman Benjamin Weiss	Jeffrey Hoffman

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
46	6l. Study the production of lunar concrete samples in the lunar environment	NASA Artemis III	Advancing the frontiers of knowledge	A Global Strategy for MIT	ISRU Sample analysis Industrial design Design	Jeffrey Hoffman Benjamin Weiss Ariel Ekblaw Ariel Ekblaw	Benjamin Weiss	
47	6m. Study material flammability in the lunar environment	NASA Artemis III	Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	MBSE Spacesuits Habitats Aerospace biomedicine Industrial design Design	Olivier de Weck Danielle Wood Dava Newman Dava Newman Ariel Ekblaw Ariel Ekblaw	Jeffrey Hoffman Jeffrey Hoffman	
48	6n. Study the conversion of water-ice to gaseous hydrogen and oxygen, and liquefaction of gasses for propellant storage	NASA Artemis III	Develop new theory and applications for satellite Aerospace environmental mitigation and monitori	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	Green propulsion	Danielle Wood		
49	6o. Study the water management in lunar plant growth systems	NASA Artemis III			Food	Ariel Ekblaw		
50	6p. Study pool and flow boiling in the lunar environment	NASA Artemis III						
51	6q. Study two phase adiabatic flow in the lunar environment	NASA Artemis III						
52	6r. Perform tests of lunar resource recovery of O, Al, Fe or Mg using ionic liquids	NASA Artemis III			ISRU	Jeffrey Hoffman		

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
53	6s. Perform tests of biofilms on various materials and the effect of biocide surface coatings on biofilms	NASA Artemis III	Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	Habitats Aerospace biomedicine Self-assembling architecture Design Industrial design	Dava Newman Ariel Ekblaw Ariel Ekblaw Ariel Ekblaw	Jeffrey Hoffman	
54	7a. Study the fundamental biological and physiological effects of the integrated lunar environment on human health and the fundamental biological processes and subsystems upon which health depend	NASA Artemis III	Integrate autonomy and humans in real-world sys	AeroAstro 2020 Strategic Plan	Aerospace biomedicine Anthropology	Dava Newman Ariel Ekblaw		
55	7b. Study the key physiological effects of the combined lunar environment on living systems and the effect of pharmacological and other countermeasures	NASA Artemis III	Integrate autonomy and humans in real-world sys	AeroAstro 2020 Strategic Plan	Aerospace biomedicine Anthropology Food	Dava Newman Ariel Ekblaw Ariel Ekblaw		
56	7c. Evaluate consequences of long-duration exposure to lunar gravity on the human musculoskeletal system	NASA Artemis III	Integrate autonomy and humans in real-world sys Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	Aerospace biomedicine Anthropology Spacesuits Habitats MBSE	Dava Newman Ariel Ekblaw Dava Newman Olivier de Weck Danielle Wood	Jeffrey Hoffman Jeffrey Hoffman	
57	7d. Study the effects of lunar radiation on biological model systems	NASA Artemis III	Integrate autonomy and humans in real-world sys Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	Aerospace biomedicine Anthropology MBSE	Dava Newman Ariel Ekblaw Olivier de Weck Danielle Wood		
58	7e. Use biological model specimens to conduct single and multigenerational studies on the long term effects of the lunar environment and transportation to and from the Moon on biological processes	NASA Artemis III	Integrate autonomy and humans in real-world sys Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	Aerospace biomedicine MBSE	Dava Newman Olivier de Weck Danielle Wood		
59	7f. Understand the effects/interactions of lunar gravity and the transitions between lunar gravity, microgravity, and Earth-normal gravity on reproduction and development, genetic stability, and aging	NASA Artemis III	Integrate autonomy and humans in real-world sys Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	Aerospace biomedicine Anthropology MBSE	Dava Newman Ariel Ekblaw Olivier de Weck Danielle Wood		

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
60	7g. Study the influence of the lunar environment and its effects on short- and long-term plant growth, productivity (as a food source), palatability, and nutrition	NASA Artemis III	Integrate autonomy and humans in real-world sys Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Aerospace environmental mitigation and monitori	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	Food Aerospace biomedicine MBSE Waste management	Ariel Ekblaw Dava Newman Olivier de Weck Danielle Wood Ariel Ekblaw		
61	7h. Evaluate the use and effectiveness of model plants in ecological life support systems	NASA Artemis III	Integrate autonomy and humans in real-world sys Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	Aerospace biomedicine Anthropology MBSE	Dava Newman Ariel Ekblaw Olivier de Weck Danielle Wood		
62	7i. Study the effect on microbes of long-duration exposure to the lunar environment	NASA Artemis III	Integrate autonomy and humans in real-world sys	AeroAstro 2020 Strategic Plan	Aerospace biomedicine	Dava Newman		
63	7j. Assess the effect on plants of long-duration exposure to the lunar environment	NASA Artemis III			Food	Ariel Ekblaw		
64	7k. Understand lunar dust behavior, particularly dust dynamics	NASA Artemis III	Develop new theory and applications for satellite Develop new theory and applications for satellite	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	Magnetism Regolith characterization	Benjamin Weiss Danielle Wood		
65	7l. Understand lunar electrodynamics	NASA Artemis III	Develop new theory and applications for satellite	AeroAstro 2020 Strategic Plan	Magnetism	Benjamin Weiss		

#	High-Level Objective	Objective Traceability	MIT Strategic Goals (from Related MIT Research Areas)	MIT Goal Traceability (from Related MIT Research Areas)	Enabling MIT Research Areas	Current Researchers (from Related MIT Research Areas)	Past Researchers (from Related MIT Research Areas)	Interested Researchers (from Related MIT Research Areas)
66	7m. Monitor real-time environmental variables affecting safe operations, which includes monitoring for meteors, micrometeors, and other space debris that could potentially impact the lunar surface	NASA Artemis III	Integrate autonomy and humans in real-world sys Lead development of the College of Computing e Develop new theory and applications for satellite Aerospace environmental mitigation and monitori Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Lead development of the College of Computing e Integrate autonomy and humans in real-world sys Develop new theory and applications for satellite Develop new theory and applications for satellite Integrate autonomy and humans in real-world sys	AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan, AeroAstro 2020 Strategic Plan	Habitats Spacesuits Human-robot interaction Mobility Remote sensing Systems engineering System architecture MBSE Multidisciplinary design optimization Technology roadmapping Anthropology Industrial design Design Aerospace biomedicine	Dava Newman Julie Shah Olivier de Weck Olivier de Weck Olivier de Weck Olivier de Weck Danielle Wood Olivier de Weck Ariel Ekblaw Olivier de Weck Ariel Ekblaw Ariel Ekblaw Ariel Ekblaw Dava Newman	Jeffrey Hoffman Jeffrey Hoffman Jeffrey Hoffman	

5.1.4 Interactive Visualization

While the static STM is a useful tool, it is difficult to digest such a large amount of data in a table. As an alternative way to visualize and explore the data, a relationship map (shown in Figure 5-1) was also created using the online tool Kumu. This relationship map shows the connections between the four main data types: science goals (shown in blue), MIT strategic goals (shown in pink), MIT lunar research actors (shown in yellow), and MIT core capabilities (shown in pink).

The ring of unconnected dots around the network highlights the 19 MIT strategic goals that don't map to any science goals or MIT core capabilities, as well as the eight science goals that don't map to any MIT strategic goals or MIT core capabilities. The map highlights the gap of connections to these goals, which could be targeted by MIT as a gap to fill.

- MIT strategic goals
  - A Global Strategy for MIT [Lester, 2017]
    - Build new MIT Partnerships for a Better World
    - Expand MIT's global classroom
    - Develop a new MIT Global Leaders program
    - Review the cap on international undergraduate admissions
    - Encouragement of discovery, intellectual risktaking, and creative problem-solving
    - Honesty and integrity in all professional and personal dealings
    - Respect for others
    - A commitment to diversity
    - Fairness in the treatment of all individuals and groups
    - An open, respectful approach to discourse
    - Reliance on facts and reason-based objective inquiry
    - Freedom of expression, communication, and movement of people

    - A commitment to excellence in all that we do
  - MIT 5-year Strategic Action Plan for DEI [Dozier et al., 2021]
    - Close achievement gaps and advance equity in all forms of success among underrepresented undergraduate students, graduate students, postdocs, staff, and faculty at MIT.
  - AeroAstro 2020 Strategic Plan [MIT Department of Aeronautics and Astronautics, 2020]
    - Develop education for digital natives and digital immigrants
    - Make innovation a key component in MIT AeroAstro leadership
    - Ethics and integrity
    - Lead through excellence in research and education
    - Succeed together
- Science goals (all from NASA Artemis III Science Definition Report [National Aeronautics and Space Administration, 2021])
  - 6b. Perform tests to understand and possibly discover new regimes of combustion
  - 6c. Investigate interactions of multiphase combustion processes and convection in lunar gravity
  - 6d. Use the unique environment of the lunar surface to perform experiments in the area of fundamental physics
  - 6e. Obtain experimental data to anchor multiphase flow models in lunar gravity
  - 6f. Study interfacial flow with and without temperature variation to anchor theoretical/numerical models
  - 6h. Investigate precipitation behavior in supercritical water in lunar gravity
  - 6p. Study pool and flow boiling in the lunar environment

– 6q. Study two phase adiabatic flow in the lunar environment

To analyze the data points with the strongest connection to the rest of the network, the degree of centrality was calculated, with the top 12 strongest connectors (also called "hubs") shown in Figure 5-2. This figure also shows how a user can explore the interactive STM: in this case, the user is focused on the MIT core capabilitity of model-based systems engineering (MBSE) and can see all the connections to it. From the centrality analysis, the top 10 MIT core capabilities with the strongest connections to the rest of the MIT lunar science network are listed in Table 5.3. The centrality analysis showed that the systems-type core capabilities (including model-based systems engineering aka MBSE, systems engineering, multidisciplinary design optimization, technology roadmapping, and system architecture) have the strongest connection to the network. This makes sense because systems analysis can be applied to virtually any type of research.

The centrality analysis also revealed the top 5 science goals with the strongest connection to the network, listed in Table 5.4 with their source documents (GER = the International Space Exploration Coordination Group Global Exploration Roadmap August 2020 Supplement [International Space Exploration Coordination Group, 2020], SDR = NASA's Artemis III Science Definition Report [National Aeronautics and Space Administration, 2021]). Since these science goals have the strongest connections to the MIT lunar science network, they may serve as useful goals to bring together different MIT researchers into a new, collaborative project.

The centrality analysis showed that the top 5 MIT strategic goals with the strongest connections to the lunar science (shown in Table 5.5) had weaker connections in comparison to the MIT core capabilities and science goals. This reveals the need to improve the implementation of MIT's strategic plans in order to ensure that at an operational level, MIT is pursuing its stated goals. AeroAstro's departmental goals [MIT Department of Aeronautics and Astronautics, 2020] had the strongest connections to the MIT lunar science network, followed by the MIT DEI plan [Dozier et al., 2021] and the MIT global plan [Lester, 2017].

Exploration of the connections across this map will be essential to developing a

Table 5.3: MIT core capabilities with the strongest connections to the MIT lunar science network.

MIT Core Capability	# Connections
Model-based systems engineering	49
Systems engineering	40
Multidisciplinary design optimization	39
Technology roadmapping	38
System architecture	37
Deployable towers	26
Remote sensing	24
Regolith characterization	23
Sample analysis	22
Aerospace biomedicine	21

MIT strategic plan for lunar exploration because it will allow MIT to identify gaps and synergies, and discover connections between different researchers that may have been overlooked.

5.1.5 Discussion

As discussed in Section 4.3, the MIT core capabilities included in this section encompass the work of seven MIT researchers, most of whom work more on engineering-focused projects than on science-focused projects. As a result, there are 8 key science goals (out of 66 total) in the STM that were not mapped to MIT core capabilities. However, more work needs to be performed identifying core capabilities of other researchers at MIT in order to finish mapping MIT's existing research to science and exploration goals.

In addition, the types of strategic goals had varying utility for mapping to science

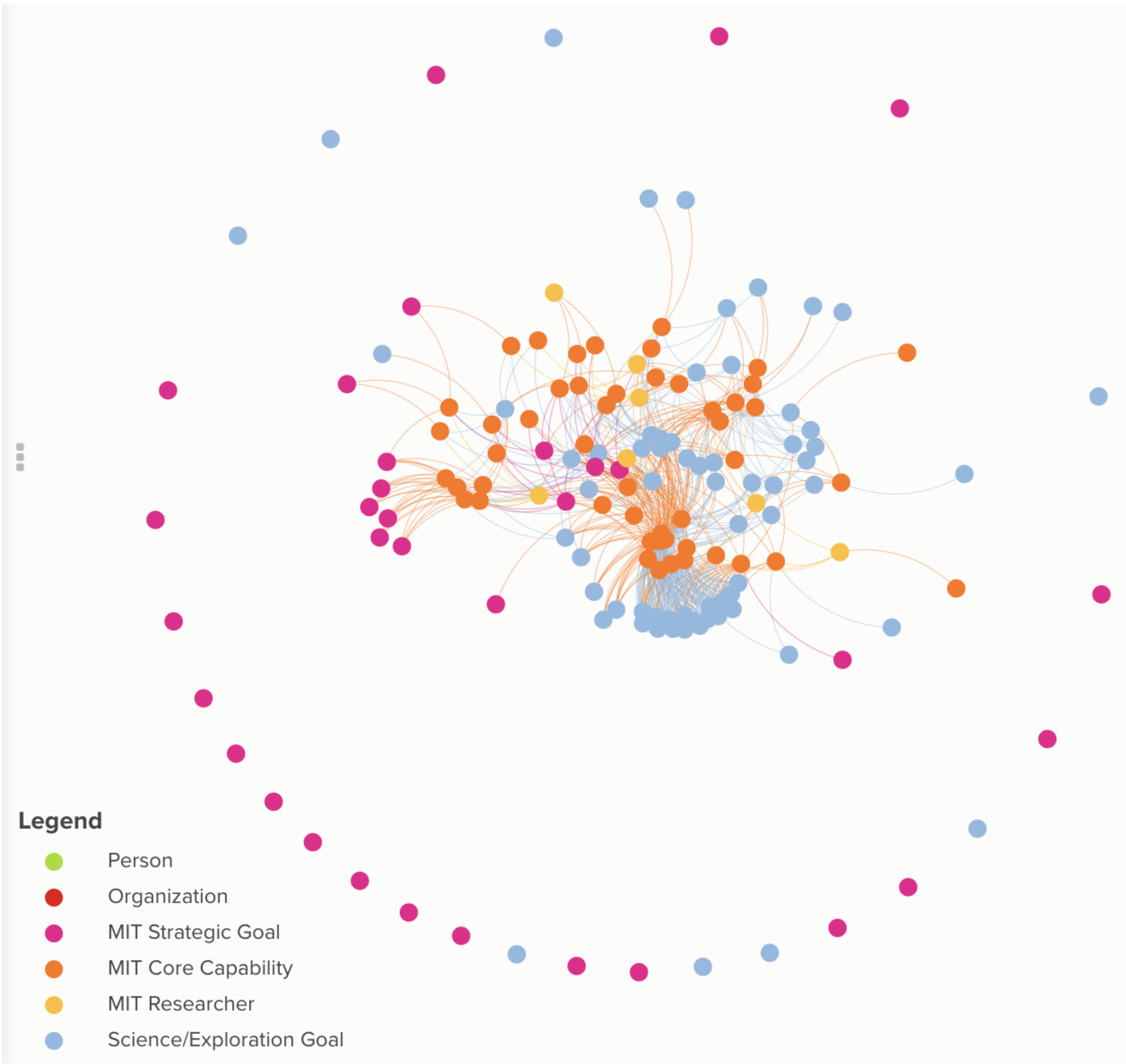


Figure 5-1: Relationship map of the STM data, using the online tool Kumu.

Table 5.4: Science goals with the strongest connections to the MIT lunar science network.

Science Goal	# Connections	Source
Demonstrate human landing/ascent capability to and from the lunar surface.	21	GER
Demonstrate crew health and performance sustainability to live and work on the lunar surface for a sufficient duration to validate Mars surface missions.	19	GER
2f. Understand the impact of human exploration on the lunar volatile record across the surface	18	SDR
5c. Use the Moon as a platform for Earth-observing studies	17	SDR
Demonstrate reliability of human long-duration habitation capability and operational procedures on the lunar surface.	17	GER

and exploration goals and MIT core capabilities. As discussed in Section 4.3, MIT strategic goals were pulled from two Institute-level strategic plans (one for global engagement and one for diversity, equity and inclusion) and one department-level plan (for Aeronautics and Astronautics). The higher-level nature of the MIT-wide plans resulted in goals that were more difficult to map core capabilities and science goals to. In addition, the "values" included in each plan were more difficult to map to than the "recommendations" (from the global engagement plan) and the "commitments" (from the DEI plan) because they are vague by nature. This is not to say that the MIT-wide goals should not be used; in fact, the author believes that considering MIT-wide strategic plans at the operational level, as done in this thesis, is critical to the successful implementation of the plans. This takeaway simply highlights a gap in science and technology planning that can (and arguably should) be filled, at least from the MIT perspective. In comparison, the strategic thrusts from the AeroAstro plan were easy to map to because they were more specific and also more relevant to lunar science and exploration goals. Overall, higher-level strategic goals are more

Table 5.5: Science goals with the strongest connections to the MIT lunar science network.

MIT Strategic Goal	# Connections	Source
Develop new theory and applications for satellite constellations and swarms	18	AeroAstro
Aerospace environmental mitigation and monitoring	12	AeroAstro
Integrate autonomy and humans in real-world systems	10	AeroAstro
Critically engage with and empower the MIT community on the value of diversity, equity, and inclusion.	6	MIT DEI
Support academic research, scholarship, and collaborations regarding diversity, equity, inclusion, social justice, and related topics at MIT.	5	MIT DEI

difficult to map to science goals and science research, and values are the most difficult to map to.

A centrality analysis will be essential to exploring the data and identifying potential collaborations for MIT lunar research, as discussed in section 5.1.5. In particular, understanding which science goals have the strongest relevance to MIT's science research will help identify goals to coalesce the MIT community around.

5.1.6 Conclusion

With input from just seven researchers at MIT, it is already clear that there are numerous lunar science and exploration goals that MIT's existing research is applicable to. The STM also shows that in pursuit of lunar goals, MIT can simultaneously pursue its own organizational strategic goals. The MIT Lunar Science Traceability Matrix begins to chart a path forward in which MIT can strategically plan its research projects to pursue its own strategic goals and science goals, while also identifying areas for collaboration at MIT so that the Institute can leverage the full extent of its

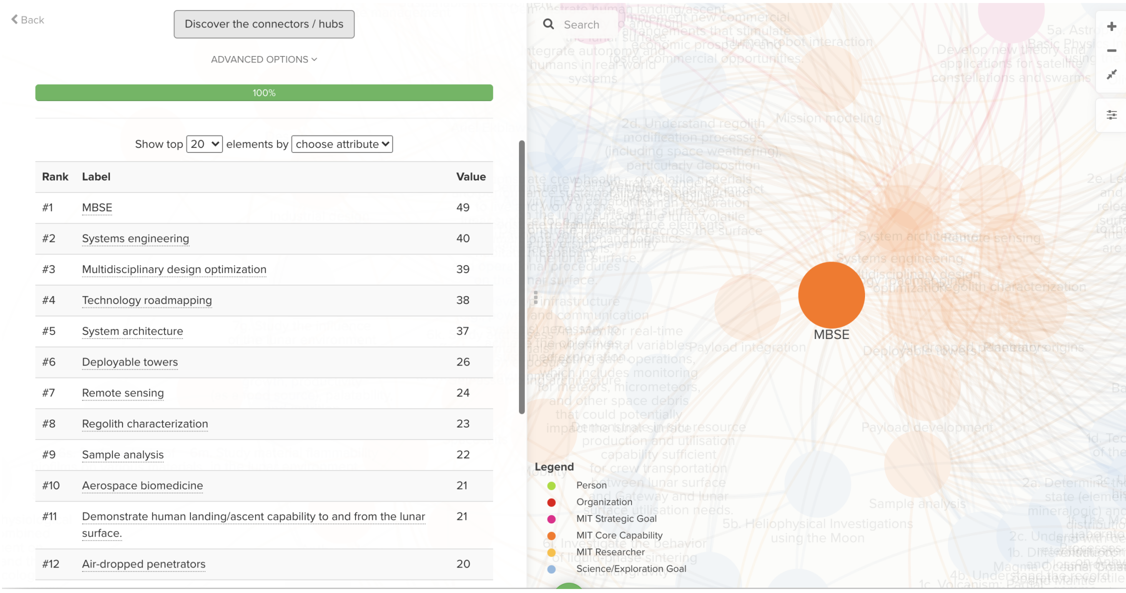


Figure 5-2: Exploration of the interactive STM, focused on the main hub in the network: the MIT core capability of model-based systems engineering (MBSE).

expertise as we work to return humans to the Moon.

5.2 MIT Lunar Technology Multi-Domain Matrix

This section encompasses the development of MIT's Lunar Technology Multi-Domain Matrix (MDM), which will allow MIT to identify relationships between its strategic goals, technology roadmaps, figures of merit, and MIT R&D projects. This exercise will help MIT develop a strategic plan for lunar exploration in which thee Institute will continue working at the edge of technology development while also being part of the global effort to explore the lunar surface.

Following the MDM R&D portfolio methodology described in Section 4.3.2, an overview of the MDM model of MIT's lunar R&D portfolio is shown in Figure 5-3.

As discussed in Chapter 4 and copied here for reference, the MIT Technology MDM will answer the following research questions:

- Identify existing areas of MIT technology development that are relevant to lunar exploration

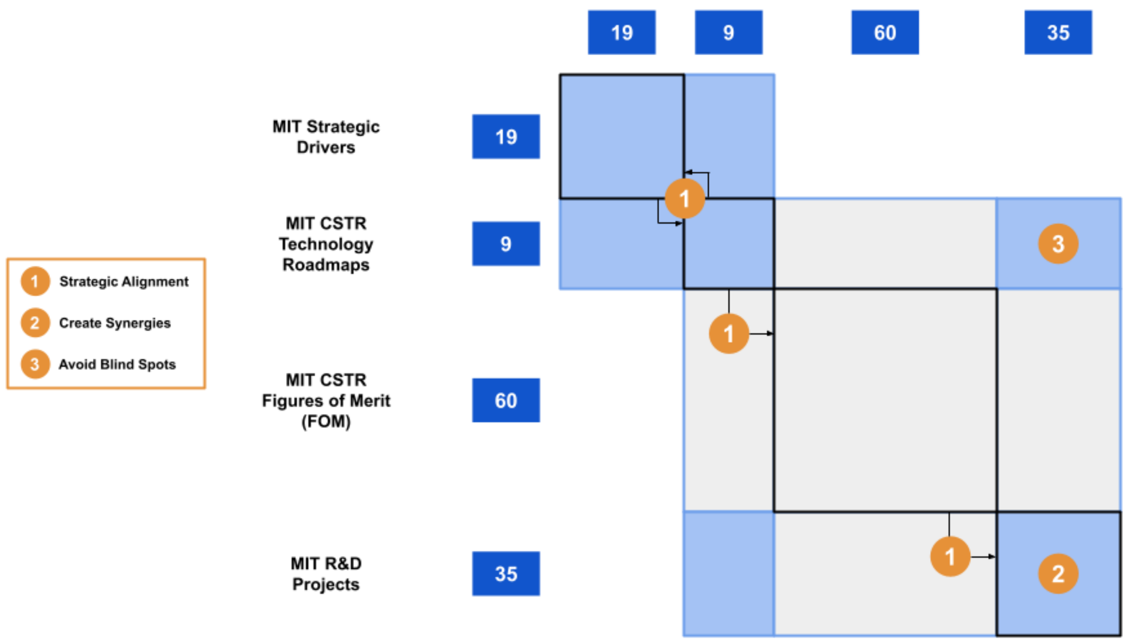


Figure 5-3: Overview of the MDM model for MIT's lunar R&D portfolio, adapted from de Weck [de Weck, 2020].

- Understand how MIT's various lunar-relevant technology efforts relate to each other

5.2.1 Data Entry

Data sources used in the MDM were outlined in Section 4.3. This section describes how the data were used in the MDM.

Since the STM mapping exercise revealed that mapping to MIT values was less useful than mapping to recommendations and commitments, the values are not included in the MDM. A list of MIT's values is in Table B.2.

Broadly, relationships were identified between a row and a column by answering the question "can this row be an input to this column?" This was particularly important for the strategic drivers design structure matrix (DSM) because the mapping exercise identified ways in which MIT's own strategic drivers impact each other, showing strategic overlap. Additional guiding questions for mapping include:

- DSM for R&D projects

  - Q1: Are they led by the same principal investigator?
  - Q2: Can the first project affect the second project?

- DMM for strategic drivers and technology roadmaps
  - Q3: Can this strategic goal be an input to developing this technology?
  - Q4: Will developments in this technology affect this strategic goal?

- DMM for technology roadmaps and R&D projects
  - Q5: Can this project be an input to developing this technology?
  - Q6: Will developments in this technology affect this project?

As discussed in Section 4.3.2, DSM mapping includes directionality, meaning that rows are inputs to columns. Therefore, DMMs of the same two domains (e.g., technology roadmaps to strategic drivers DMM and strategic drivers to technology roadmaps DMM) may not be exact mirrors. A difference arises if the relationship between two items was not circular, meaning that one could input to the other but not vice versa.

5.2.2 Static Visualization

MIT's lunar technology multi-domain matrix (MDM) contains 12 matrices, seven of which are included in this thesis. Within the seven matrices, there are three design structure matrices (DSMs) and four domain mapping matrices (DMMs). As discussed in Section 4.4.4, a DSM is a matrix in which a single domain (e.g., strategic drivers) is mapped to itself to identify how the pieces relate to each other. A DMM is a matrix in which two distinct domains (e.g., strategic drivers and technology roadmaps) are mapped. The seven matrices included here are:

- DSMs
  - 1: MIT strategic drivers (shown in Figure 5-4)
  - 2: Technology roadmaps (shown in Figure 5-5)

– 3: MIT R&D projects (shown in Figure 5-6)

- DMMs

  – 4: MIT strategic drivers –> technology roadmaps (shown in Figure 5-7)

  – 5: technology roadmaps –> MIT strategic drivers (shown in Figure 5-8)

  – 6: technology roadmaps –> MIT R&D projects (shown in Figure 5-9)

  – 7: MIT R&D projects –> technology roadmaps (shown in Figure 5-7)

Due to time constraints in this research investigation, only seven of the 12 matrices were mapped. The mapped matrices are displayed as blue in Figure 5-3; the unmapped matrices are displayed as grey.

		Build new MIT Partnerships for a Better World MITG1	Expand MIT's global classroom MITG2	Streamline and strengthen international educational assistance/institution-building programs MITG3	Develop a new MIT Global Leaders program MITG4	Review the cap on international undergraduate admissions MITG5	Strengthen Governance and Operations MITG6	Increase the number of underrepresented graduate students, postdocs, staff, and faculty at MIT. MITD1	Assess and strengthen our recruitment of underrepresented undergraduate students. MITD2	Critically engage with and empower the MIT community on the value of diversity, equity, and inclusion. MITD3	Reinforce positive interactions among members of the MIT community to foster and promote an enduring sense of belonging. MITD4	Support academic research, scholarship, and collaborations regarding diversity, equity, inclusion, social justice, and related topics at MIT. MITD5	Close achievement gaps and advance equity in all forms of success among underrepresented undergraduate students, graduate students, postdocs, staff, and faculty at MIT. MITD6	Integrate autonomy and humans in real-world systems AA1	Develop new theory and applications for satellite constellations and swarms AA2	Aerospace environmental mitigation and monitoring AA3	Lead development of the College of Computing education programs in autonomy and computational science and engineering AA4	Develop education for digital natives and digital immigrants AA5	Become the leading department at MIT in mentoring, advising, diversity, and inclusion AA6	Make innovation a key component in MIT AeroAstro leadership AA7
Build new MIT Partnerships for a Better World	MITG1		X				X	X	X	X										
Expand MIT's global classroom	MITG2						X			X		X								
Streamline and strengthen international educational assistance/institution-building programs	MITG3	X	X				X		X											
Develop a new MIT Global Leaders program	MITG4	X	X				X		X	X										
Review the cap on international undergraduate admissions	MITG5	X		X			X	X		X										
Strengthen Governance and Operations	MITG6	X	X	X	X	X				X	X									
Increase the number of underrepresented graduate students, postdocs, staff, and faculty at MIT.	MITD1								X	X									X	
Assess and strengthen our recruitment of underrepresented undergraduate students.	MITD2	X	X					X											X	X
Critically engage with and empower the MIT community on the value of diversity, equity, and inclusion.	MITD3							X	X		X		X						X	X
Reinforce positive interactions among members of the MIT community to foster and promote an enduring sense of belonging.	MITD4							X	X			X	X						X	
Support academic research, scholarship, and collaborations regarding diversity, equity, inclusion, social justice, and related topics at MIT.	MITD5	X		X	X			X	X	X	X		X	X	X	X	X	X	X	X
Close achievement gaps and advance equity in all forms of success among underrepresented undergraduate students, graduate students, postdocs, staff, and faculty at MIT.	MITD6				X			X	X	X	X						X	X	X	X
Integrate autonomy and humans in real-world systems	AA1	X	X	X	X							X				X	X	X		
Develop new theory and applications for satellite constellations and swarms	AA2	X	X	X	X							X				X		X		X
Aerospace environmental mitigation and monitoring	AA3	X	X	X	X							X		X	X			X		X
Lead development of the College of Computing education programs in autonomy and computational science and engineering	AA4			X				X	X	X	X	X	X	X						X
Develop education for digital natives and digital immigrants	AA5	X		X						X	X	X	X	X	X	X			X	X
Become the leading department at MIT in mentoring, advising, diversity, and inclusion	AA6							X	X	X	X	X	X					X		X
Make innovation a key component in MIT AeroAstro leadership	AA7	X	X									X		X	X	X	X	X	X	

Figure 5-4: DSM of MIT strategic drivers.

5.2.3 Discussion

In the methodology for using a MDM to define a R&D portfolio, the strategic drivers are not mapped to figures of merit (FOMs) or R&D projects (see Figure 5-3). Mapping strategic drivers to FOMs would not be useful to the research questions. However,

		Space Transportation and Access	Spacecraft Development and Manufacturing	Ground Sites	On-Orbit Services	Telecommunications Services	Navigation and Positioning Services	Remote Sensing Services	Space Resource Extraction	Support Industries
		CSTR1	CSTR2	CSTR3	CSTR4	CSTR5	CSTR6	CSTR7	CSTR8	CSTR9
Space Transportation and Access	CSTR1		X		X	X	X	X	X	X
Spacecraft Development and Manufacturing	CSTR2	X			X	X	X	X	X	
Ground Sites	CSTR3	X	X		X	X	X	X		
On-Orbit Services	CSTR4	X	X			X	X	X	X	
Telecommunications Services	CSTR5	X		X					X	X
Navigation and Positioning Services	CSTR6							X		
Remote Sensing Services	CSTR7								X	
Space Resource Extraction	CSTR8	X			X					
Support Industries	CSTR9	X	X	X	X	X	X	X	X	

Figure 5-5: DSM of technology roadmaps.

		MOXIE	Antarctic air-dropped penetrators	Deployable lunar tower	Lunar open architecture	Extrusion additive manufacturing	Telemetron	Zenalith	Astronaut ethnography project	TESSERAE	Fermentation closed-loop food ecosystem	Zero-G Tasting Menu	Interplanetary Cookbook	The Space Governance Collaborative	Space Freedoms	Microgravity research flights	Psyche magnetometer	Lunar dynamo	Beresheet magnetometer	Mars 2020 Returned Sample Science	Advanced Space Technology Roadmap Architecture (ASTRA)	ROAMS: Reconfigurable on-Orbit Adaptive Maneuverable Satellites	PEARL: Platform for Expanding AUV exploRation to Longer ranges	Space Sustainability Rating	Passive collection of lunar regolith dust	Candlewax propulsion	Accessibility of the microgravity research ecosystem	Socioeconomic behavior of humans in space	Indigenous views of space	Vida Decision Support System	RESOURCE	Science and technology strategic planning for MIT lunar exploration	Gravity Loading Countermeasure Skinsuit	Biosuit	Electrical neuromuscular stimulation as a bone loss countermeasure	Neural control of soft actuators for applications in exoskeleton design
		P01	P02	P03	P04	P05	P06	P07	P08	P09	P10	P11	P12	P13	P14	P15	P16	P17	P18	P19	P20	P21	P22	P23	P24	P25	P26	P27	P28	P29	P30	P31	P32	P33	P34	P35
MOXIE	P01		X	X		X				X										X	X				X	X					X	X				
Antarctic air-dropped penetrators	P02	X		X																												X				
Deployable lunar tower	P03	X	X													X															X	X				
Lunar open architecture	P04			X		X	X	X	X	X	X	X	X	X	X	X		X	X		X			X	X	X		X	X		X	X				
Extrusion additive manufacturing	P05			X	X		X	X	X	X	X	X	X	X	X	X					X			X	X	X	X					X				
Telemetron	P06				X	X		X	X	X	X	X	X	X	X	X											X	X				X				
Zenalith	P07			X	X	X	X		X	X	X	X	X	X	X	X											X	X				X				
Astronaut ethnography project	P08				X	X	X	X		X	X	X	X	X	X	X											X	X			X	X				
TESSERAE	P09				X	X	X	X	X		X	X	X	X	X	X					X	X		X	X		X	X				X				
Fermentation closed-loop food ecosystem	P10				X	X	X	X	X	X		X	X	X	X	X					X						X	X				X				
Zero-G Tasting Menu	P11				X	X	X	X	X	X	X		X	X	X	X											X	X				X				
Interplanetary Cookbook	P12				X	X	X	X	X	X	X	X		X	X	X												X				X				
The Space Governance Collaborative	P13			X	X	X	X	X	X	X	X	X	X		X	X								X	X	X	X	X	X		X	X				
Space Freedoms	P14				X	X	X	X	X	X	X	X	X	X		X												X				X				
Microgravity research flights	P15			X	X	X	X	X	X	X	X	X	X	X	X						X	X	X		X	X	X	X	X		X	X	X	X	X	X
Psyche magnetometer	P16																	X	X	X												X				
Lunar dynamo	P17			X	X												X		X	X	X											X				
Beresheet magnetometer	P18			X	X											X	X	X		X	X				X		X				X	X				
Mars 2020 Returned Sample Science	P19	X			X	X											X	X	X		X				X			X	X		X	X				
Advanced Space Technology Roadmap Architecture (ASTRA)	P20		X	X	X	X				X				X		X		X	X	X		X	X	X	X	X	X				X	X	X	X	X	X
ROAMS: Reconfigurable on-Orbit Adaptive Maneuverable Satellites	P21									X				X		X					X		X	X			X			X		X				
PEARL: Platform for Expanding AUV exploRation to Longer ranges	P22																				X	X										X				
Space Sustainability Rating	P23	X		X	X	X	X	X	X	X	X	X	X	X		X	X	X	X	X	X	X			X	X	X	X	X	X	X	X	X	X	X	X
Passive collection of lunar regolith dust	P24			X	X	X				X				X		X					X			X		X	X	X	X	X	X	X				
Candlewax propulsion	P25				X	X								X		X					X	X		X	X		X	X	X	X		X				
Accessibility of the microgravity research ecosystem	P26			X	X	X	X	X	X	X	X	X	X	X	X	X					X	X		X	X	X		X	X	X	X	X	X	X	X	X
Socioeconomic behavior of humans in space	P27				X				X		X	X	X	X	X									X	X	X	X		X	X		X				
Indigenous views of space	P28	X		X	X		X	X	X	X	X	X	X	X	X	X					X			X	X		X	X		X	X	X		X		
Vida Decision Support System	P29																							X				X	X			X				
RESOURCE	P30			X	X									X							X				X							X	X	X	X	X
Science and technology strategic planning for MIT lunar exploration	P31			X	X	X	X	X	X	X	X	X	X	X	X	X			X		X	X		X	X	X	X	X	X		X		X	X	X	X
Gravity Loading Countermeasure Skinsuit	P32	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X		X	X	X
Biosuit	P33				X					X						X					X						X					X	X		X	X
Electrical neuromuscular stimulation as a bone loss countermeasure	P34				X				X					X		X					X						X	X				X	X	X		X
Neural control of soft actuators for applications in exoskeleton design	P35				X				X					X		X					X						X	X				X	X	X	X	

Figure 5-6: DSM of MIT R&D projects.

		Space Transportation and Access	Spacecraft Development and Manufacturing	Ground Sites	On-Orbit Services	Telecommunications Services	Navigation and Positioning Services	Remote Sensing Services	Space Resource Extraction	Support Industries
		CSTR1	CSTR2	CSTR3	CSTR4	CSTR5	CSTR6	CSTR7	CSTR8	CSTR9
Build new MIT Partnerships for a Better World	MITG1	X	X	X	X	X	X	X	X	X
Expand MIT's global classroom	MITG2	X	X	X	X	X	X	X	X	X
Streamline and strengthen international educational assistance/institution-building programs	MITG3	X	X	X	X	X	X	X	X	X
Develop a new MIT Global Leaders program	MITG4	X	X	X	X	X	X	X	X	X
Review the cap on international undergraduate admissions	MITG5									
Strengthen Governance and Operations	MITG6									
Increase the number of underrepresented graduate students, postdocs, staff, and faculty at MIT.	MITD1									
Assess and strengthen our recruitment of underrepresented undergraduate students.	MITD2									
Critically engage with and empower the MIT community on the value of diversity, equity, and inclusion.	MITD3									
Reinforce positive interactions among members of the MIT community to foster and promote an enduring sense of belonging.	MITD4									
Support academic research, scholarship, and collaborations regarding diversity, equity, inclusion, social justice, and related topics at MIT.	MITD5	X	X	X	X	X	X	X	X	X
Close achievement gaps and advance equity in all forms of success among underrepresented undergraduate students, graduate students, postdocs, staff, and faculty at MIT.	MITD6	X	X	X	X	X	X	X	X	X
Integrate autonomy and humans in real-world systems	AA1	X	X	X	X	X	X	X	X	X
Develop new theory and applications for satellite constellations and swarms	AA2		X	X	X	X	X	X	X	X
Aerospace environmental mitigation and monitoring	AA3	X	X	X	X			X	X	X
Lead development of the College of Computing education programs in autonomy and computational science and engineering	AA4									
Develop education for digital natives and digital immigrants	AA5									
Become the leading department at MIT in mentoring, advising, diversity, and inclusion	AA6									
Make innovation a key component in MIT AeroAstro leadership	AA7	X	X	X	X	X	X	X	X	X

Figure 5-7: DMM mapping MIT strategic drivers to technology roadmaps.

		Build new MIT Partnerships for a Better World	Expand MIT's global classroom	Streamline and strengthen international educational assistance/institution-building programs	Develop a new MIT Global Leaders program	Review the cap on international undergraduate admissions	Strengthen Governance and Operations	Increase the number of underrepresented graduate students, postdocs, staff, and faculty at MIT.	Assess and strengthen our recruitment of underrepresented undergraduate students.	Critically engage with and empower the MIT community on the value of diversity, equity, and inclusion.	Reinforce positive interactions among members of the MIT community to foster and promote an enduring sense of belonging.	Support academic research, scholarship, and collaborations regarding diversity, equity, inclusion, social justice, and related topics at MIT.	Close achievement gaps and advance equity in all forms of success among underrepresented undergraduate students, graduate students, postdocs, staff, and faculty at MIT.	Integrate autonomy and humans in real-world systems	Develop new theory and applications for satellite constellations and swarms	Aerospace environmental mitigation and monitoring	Lead development of the College of Computing education programs in autonomy and computational science and engineering	Develop education for digital natives and digital immigrants	Become the leading department at MIT in mentoring, advising, diversity, and inclusion	Make innovation a key component in MIT AeroAstro leadership
		MITG1	MITG2	MITG3	MITG4	MITG5	MITG6	MITD1	MITD2	MITD3	MITD4	MITD5	MITD6	AA1	AA2	AA3	AA4	AA5	AA6	AA7
Space Transportation and Access	CSTR1	X	X	X	X							X		X		X	X			X
Spacecraft Development and Manufacturing	CSTR2	X	X	X	X							X		X	X	X	X			X
Ground Sites	CSTR3	X	X	X	X							X		X	X	X	X			X
On-Orbit Services	CSTR4	X	X	X	X							X		X	X	X	X			X
Telecommunications Services	CSTR5	X	X	X	X							X		X	X		X			X
Navigation and Positioning Services	CSTR6	X	X	X	X							X		X	X		X			X
Remote Sensing Services	CSTR7	X	X	X	X							X		X	X	X	X			X
Space Resource Extraction	CSTR8	X	X	X	X							X		X	X	X	X			X
Support Industries	CSTR9	X	X	X	X							X		X	X	X	X			X

Figure 5-8: DMM mapping technology roadmaps to MIT strategic drivers.

		MOXIE	Antarctic air-dropped penetrators	Deployable lunar tower	Lunar open architecture	Extrusion additive manufacturing	Telemetron	Zenalith	Astronaut ethnography project	TESSERAE	Fermentation closed-loop food ecosystem	Zero-G Tasting Menu	Interplanetary Cookbook	The Space Governance Collaborative	Space Freedoms	Microgravity research flights	Psyche magnetometer	Lunar dynamo	Beresheet magnetometer
		P01	P02	P03	P04	P05	P06	P07	P08	P09	P10	P11	P12	P13	P14	P15	P16	P17	P18
Spacecraft Development and Manufacturing	CSTR2	X	X	X	X	X	X	X		X	X	X		X		X	X		X
Ground Sites	CSTR3	X		X	X					X				X		X	X		X
On-Orbit Services	CSTR4				X	X				X				X					
Telecommunications Services	CSTR5			X	X									X					
Navigation and Positioning Services	CSTR6		X	X	X									X					
Remote Sensing Services	CSTR7			X	X									X			X	X	X
Space Resource Extraction	CSTR8	X	X	X	X									X					
Support Industries	CSTR9	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

		Mars 2020 Returned Sample Science	Advanced Space Technology Roadmap Architecture (ASTRA)	ROAMS: Reconfigurable on-Orbit Adaptive Maneuverable Satellites	PEARL: Platform for Expanding AUV exploRation to Longer ranges	Space Sustainability Rating	Passive collection of lunar regolith dust	Candlewax propulsion	Accessibility of the microgravity research ecosystem	Socioeconomic behavior of humans in space	Indigenous views of space	Vida Decision Support System	RESOURCE	Science and technology strategic planning for MIT lunar exploration	Gravity Loading Countermeasure Skinsuit	Biosuit	Electrical neuromuscular stimulation as a bone loss countermeasure	Neural control of soft actuators for applications in exoskeleton design
		P19	P20	P21	P22	P23	P24	P25	P26	P27	P28	P29	P30	P31	P32	P33	P34	P35
Spacecraft Development and Manufacturing	CSTR2	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Ground Sites	CSTR3	X	X	X		X	X		X		X	X	X	X				
On-Orbit Services	CSTR4		X	X		X			X		X			X				
Telecommunications Services	CSTR5		X			X					X	X		X				
Navigation and Positioning Services	CSTR6		X	X		X					X	X		X				
Remote Sensing Services	CSTR7		X	X		X					X	X		X				
Space Resource Extraction	CSTR8	X	X			X	X				X	X	X	X				
Support Industries	CSTR9	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

Figure 5-9: DMM mapping technology roadmaps to MIT R&D projects.

		Space Transportation and Access	Spacecraft Development and Manufacturing	Ground Sites	On-Orbit Services	Telecommunications Services	Navigation and Positioning Services	Remote Sensing Services	Space Resource Extraction	Support Industries
		CSTR1	CSTR2	CSTR3	CSTR4	CSTR5	CSTR6	CSTR7	CSTR8	CSTR9
MOXIE	P01		X	X					X	X
Antarctic air-dropped penetrators	P02		X						X	X
Deployable lunar tower	P03		X			X	X	X	X	X
Lunar open architecture	P04	X	X	X	X	X	X	X	X	X
Extrusion additive manufacturing	P05	X	X		X				X	X
Telemetron	P06		X							X
Zenalith	P07		X							X
Astronaut ethnography project	P08									X
TESSERAE	P09	X	X		X					X
Fermentation closed-loop food ecosystem	P10	X	X							X
Zero-G Tasting Menu	P11	X	X							X
Interplanetary Cookbook	P12	X								X
The Space Governance Collaborative	P13	X	X	X	X	X	X	X	X	X
Space Freedoms	P14	X								X
Microgravity research flights	P15	X	X	X						X
Psyche magnetometer	P16		X					X	X	X
Lunar dynamo	P17								X	X
Beresheet magnetometer	P18		X					X	X	X
Mars 2020 Returned Sample Science	P19		X						X	X
Advanced Space Technology Roadmap Architecture (ASTRA)	P20	X	X	X	X	X	X	X	X	X
ROAMS: Reconfigurable on-Orbit Adaptive Maneuverable Satellites	P21		X	X				X	X	X
PEARL: Platform for Expanding AUV exploRation to Longer ranges	P22	X	X							X
Space Sustainability Rating	P23	X	X	X	X	X	X	X	X	X
Passive collection of lunar regolith dust	P24		X						X	X
Candlewax propulsion	P25	X	X		X					X
Accessibility of the microgravity research ecosystem	P26	X	X	X						X
Socioeconomic behavior of humans in space	P27	X				X		X	X	X
Indigenous views of space	P28	X		X	X			X	X	X
Vida Decision Support System	P29		X	X		X		X		X
RESOURCE	P30	X	X	X			X	X		X
Science and technology strategic planning for MIT lunar exploration	P31	X	X	X	X	X	X	X	X	X
Gravity Loading Countermeasure Skinsuit	P32	X	X							X
Biosuit	P33	X	X							X
Electrical neuromuscular stimulation as a bone loss countermeasure	P34	X	X							X
Neural control of soft actuators for applications in exoskeleton design	P35	X	X							X

Figure 5-10: DMM mapping MIT R&D projects to technology roadmaps.

strategic goals were mapped to MIT core capabilities in the MIT Lunar STM in Section 5.1, and their dependencies are studied there.

Studying the MDM reveals a few key takeaways:

- MIT's global engagement goals have minimal overlap with AeroAstro's departmental thrusts
- MIT's DEI goals have low relevance to technology roadmaps and vice versa
- MIT's existing R&D projects are most relevant to MIT's CSTR roadmaps 9, 2 and 1 (in decreasing order of relevance)
  - CSTR9: Support Industries
  - CSTR2: Spacecraft Development and Manufacturing
  - CSTR1: Space Transportation and Access

The strategic drivers DSM (see Figure 5-4) reveals that the commitments from MIT's DEI strategic plan have minimal overlap with AeroAstro's departmental thrusts. AeroAstro does include a thrust about DEI (AA7, "Become the leading department at MIT in mentoring, advising, diversity, and inclusion"), but this gap shows that AeroAstro may need to ensure that DEI is incorporated into its more technology-focused thrusts.

In addition, MIT's DEI commitments and AeroAsto's DEI strategic thrust have low relevance to the CSTR technology roadmaps, as seen in the strategic drivers/technology roadmaps DMMs (see Figures 5-7 and 5-8). This is not a surprising revelation, since technology roadmaps don't usually include DEI work, but this again highlights the need to carefully consider how DEI goals will be incorporated into technology development.

Finally, MIT's existing R&D projects are most relevant to CSTR roadmaps 9, 2 and 1 (see Figures 5-9 and 5-10). Table 5.6 summarizes the number of MIT R&D projects that could be inputs to each technology roadmap.

Table 5.6: Tally of MIT R&D projects relevant to each CSTR technology roadmap.

ID	Roadmap	# Projects
CSTR1	Space Transportation and Access	22
CSTR2	Spacecraft Development and Manufacturing	29
CSTR3	Ground Sites	12
CSTR4	On-Orbit Services	9
CSTR5	Telecommunications Services	8
CSTR6	Navigation and Positioning Services	7
CSTR7	Remote Sensing Services	13
CSTR8	Space Resource Extraction	17
CSTR9	Support Industries	35

5.2.4 Conclusion

Developing this MIT Lunar Technology MDM marks the first step toward understanding MIT's lunar R&D portfolio, which is essential to developing a strategic plan for MIT lunar exploration. The MDM revealed that every identified R&D project at MIT is pushing development in some area of critical space technology (as identified in the technology roadmaps). It also revealed that some strategic goals will be easier to work toward during lunar exploration efforts than others, but this does mean that they shouldn't all be incorporated. The MDM also shows which areas in space technology MIT is putting its most resources toward, which is important when developing a optimal R&D portfolio. Ultimately, the development of this MDM concludes the first step toward developing a full technology R&D portfolio for MIT's lunar exploration efforts.

5.3 Key Takeaways

This initial analysis of MIT's lunar science and technology research, conducted through the creation and analysis of a MIT lunar science traceability matrix (STM) and MIT lunar science technology multi-domain matrix (MDM) reveals both opportunities to capture and gaps to fill in order to develop a comprehensive MIT strategy for lunar exploration:

- Opportunities
  - Coalesce new MIT collaborations around science goals and technology roadmaps with strong relevance to existing MIT research
- Gaps
  - Improve the connections between MIT strategic goals and MIT research, particularly for DEI strategic goals
  - Fill research gaps: study the science goals and technology roadmaps that don't link to any MIT research and potentially start new projects to fill those gaps

5.3.1 Opportunities

The main opportunity presented in this research is the potential to coalesce new MIT collaborations around science goals and technology roadmaps with strong relevance to existing MIT research. As shown in Table 5.4 and discussed in Section 5.2.3, the science goals and technology roadmaps with the strongest connections to existing MIT research are (in order of strongest to weakest connection):

- Science goals
  - Demonstrate human landing/ascent capability to and from the lunar surface (GER)

  - Demonstrate crew health and performance sustainability to live and work on the lunar surface for a sufficient duration to validate Mars surface missions (GER)
  - 2f. Understand the impact of human exploration on the lunar volatile record across the surface (SDR)
  - 5c. Use the Moon as a platform for Earth-observing studies (SDR)
  - Demonstrate reliability of human long-duration habitation capability and operational procedures on the lunar surface (SDR)

- Technology roadmaps
  - CSTR9: Support Industries
  - CSTR2: Spacecraft Development and Manufacturing
  - CSTR1: Space Transportation and Access

These five science goals and three technology roadmaps offer opportunities to identify and establish new projects at MIT that bring together researchers from across the Institute.

5.3.2 Gaps

In addition to the main opportunity presented by the MIT lunar STM and technology MDM, there are two key gaps that could be filled.

First, MIT should work to improve the connections between its strategic goals and its research, particularly for DEI strategic goals. Analysis in Sections 5.1.5 and 5.2.3 revealed that MIT's research currently does not connect strongly to the Institute's strategic goals. This is problematic because without operational implementation of its goals into its daily activities, MIT will not be able to reach its goals.

Second, MIT should work to fill its research gaps: there are eight science goals (discussed in Section 5.1.4 and copied below) that don't link to any MIT research. While some of these gaps could be filled by adding more research to the STM, further analysis is needed to understand whether there are true gaps between MIT's research and key science goals. Once the STM is fully mapped to all of MIT's research, the Institute can identify its true research gaps and potentially start new projects to fill those gaps.

- 6b. Perform tests to understand and possibly discover new regimes of combustion
- 6c. Investigate interactions of multiphase combustion processes and convection in lunar gravity
- 6d. Use the unique environment of the lunar surface to perform experiments in the area of fundamental physics
- 6e. Obtain experimental data to anchor multiphase flow models in lunar gravity
- 6f. Study interfacial flow with and without temperature variation to anchor theoretical/numerical models
- 6h. Investigate precipitation behavior in supercritical water in lunar gravity
- 6p. Study pool and flow boiling in the lunar environment
- 6q. Study two phase adiabatic flow in the lunar environment

5.3.3 Conclusion

This initial analysis of MIT's lunar science and technology research revealed one key opportunity and two key gaps to address for developing a comprehensive MIT strategic plan for lunar exploration. Expanding this analysis to MIT's entire research portfolio will improve understanding of opportunities and gaps and help MIT become a leader in the next phase of lunar exploration.

THIS PAGE INTENTIONALLY LEFT BLANK

Chapter 6

Next Steps for MIT Lunar Exploration

As discussed in Section 4.1, this thesis is one part in a broader MIT effort to be involved in the latest phase of lunar exploration. Including this thesis, the four lunar strategic planning efforts currently being pursued include:

1. Science and technology strategic planning (this thesis)
2. Development of MIT's Lunar Open Architecture (LOA)
3. Graduate course taught in Spring 2021 on "Operating in the Lunar Environment" (course numbers MAS.S60 and 16S.898)
4. Cross-Institute framing for a "To the Moon To Stay" MIT mission

This chapter discusses the next steps for MIT's involvement in lunar exploration, including future work to expand on this thesis, incorporation of this thesis work into MIT's Lunar Open Architecture (LOA), and development of MIT lunar payloads (including one for a cross-Institute mission).

6.1 Expanding on This Thesis (Future Work)

Through creation of a lunar STM and technology MDM, this thesis established a framework for aligning MIT's work with science and technology goals and priorities. This work can be expanded in three key ways: 1) improving the STM and MDM, 2) taking the next steps in science and technology planning, and 3) taking the next steps for lunar strategic planning. Potential work in pursuit of these three ways are summarized below.

- Improving the STM and MDM
  - Improve tech MDM by mapping the figures of merit, aka FOMs (see the grey boxes in Figure 5-3)
  - Expand data collection
  - Refine mapping through community feedback
  - Improve tech MDM by adding more technology roadmaps and figures of merit
- Next steps for MIT lunar science and technology planning
  - Analyze tools to identify gaps and synergies.
  - Conduct mission and technology sensitivity analysis to determine targets for technology development
  - Conduct scenario-based technology valuation
  - Perform technology portfolio valuation, optimization and selection
- Next steps for MIT lunar strategic planning
  - Use existing strategic plans to guide MIT's research
  - Develop an interactive analysis tool and a strategic plan for MIT lunar exploration

  - Use LOA to understand what other actors are working on to ensure MIT isn't duplicating work
  - Identify lessons learned from MIT's and Draper's history of involvement with lunar exploration

For improving the STM and MDM, the first step would be conducting the mapping of FOMs for the tech MDM. As highlighted in Figure 5-3, this includes the FOMs DSM, the FOMS <–> technology roadmaps DMMs, and the FOMs <–> MIT R&D projects DMMs. These were not included in this thesis because of time constraints.

Another way to improve the STM and tech MDM would be to expand the data collection effort. For this thesis, seven MIT researchers were interviewed (as discussed in Section 4.3:

- Department of Aeronautics and Astronautics
  - Professor Jeffrey Hoffman
  - Professor Julie Shah
  - Professor Olivier de Weck
- Media Lab
  - Dr. Ariel Ekblaw
  - Professor Danielle Wood
- Department of Earth, Atmospheric and Planetary Sciences
  - Professor Ben Weiss

However, there are numerous other researchers at MIT who can contribute to lunar exploration efforts. Some people identified during work on this thesis could make up a second phase of data collection:

- Department of Aeronautics and Astronautics

  - Professor Dava Newman [1]
  - Professor Ed Crawley
  - Professor Kerri Cahoy
  - Dr. Afreen Siddiqi

- Department of Earth, Atmospheric and Planetary Sciences
  - Professor Maria Zuber
  - Professor Richard Binzel
  - Dr. Rona Oran (recommended by Ben Weiss)
  - Dr. Jodie Barker Ream (recommended by Ben Weiss)
  - Professor Sara Seager

In addition to these researchers, there are likely other individuals at MIT whose work would be relevant to lunar exploration.

Next, the STM and MDM should be refined by soliciting detailed feedback on mapping. The tools' most significant contribution is identifying connections between pieces of MIT's lunar system architecture. While the author is quite familiar with lunar efforts at the Institute, mapping should be refined via discussions and an interactive session with MIT researchers. MIT's Space Exploration Initiative (who funded this work in part) has substantial experience in community feedback workshops that could be leveraged to refine the STM and MDM.

The MDM specifically could be augmented by incorporating additional technology roadmaps and figures of merit (FOMs). For this thesis, nine roadmaps from the Commercial Space Technology Roadmap (CSTR) were used [de Weck et al., 2018, MIT Strategic Engineering et al., 2018]. All 60 existing FOMs from the CSTR work were included. However, the CSTR project has only identified FOMs for 5 of the 29 sub-sectors included in the 9 roadmaps. If CSTR work continues and more FOMs are identified, they should be added. In addition, NASA's 15 technology roadmaps from

[1] Some information about Prof. Newman's work was included but an interview would provide more thorough coverage of her work

2015 could be added, along with FOMs listed in those roadmaps [National Aeronautics and Space Administration, 2015].

In addition to improving the STM and MDM developed in this thesis, future work can be done on next steps for MIT lunar science and technology planning. First, extensive analysis of the data in the STM and MDM should be conducted in order to identify gaps and synergies. Gaps illuminate areas in which MIT may to expand its capabilities or find external partners. Synergies can show potential collaborations within the Institute, which would be useful in developing a cross-MIT mission (see Section 6.3 for more information). For the MDM, a MIT-led textbook and website about design structure matrices (DSMs) identify analysis methods [Eppinger and Browning, 2012, DSM, 2021]. After conducting initial analysis on the STM and MDM, further analysis of MIT's R&D portfolio should be conducted. Following the method laid out in the NASA-funded Advanced Space Technology Roadmap Architecture (ASTRA) [de Weck, 2021], the next steps would include 1) conducting mission and technology sensitivity analysis to determine targets for technology development, 2) conducting scenario-based technology valuation, and 3) performing technology portfolio valuation, optimization and selection. Upcoming publications from the ASTRA team will likely cover the methodology in more detail. Additional information about R&D portfolio management and technology valuation can be found in Chapters 16 and 16 of ASTRA principal investigator Olivier de Weck's upcoming book on technology roadmapping and development [de Weck, 2020]. Conducting all of this analysis of the STM and MDM will lead to a cohesive, data-based plan for science and technology for MIT lunar exploration.

Following the science and technology planning, MIT should continue its lunar exploration efforts by conducting additional lunar strategy work. First, MIT should use its existing strategic plans [Lester, 2017, MIT Department of Aeronautics and Astronautics, 2020, Dozier et al., 2021] to guide investments for lunar exploration. Substantial effort and resources went into developing these plans, but implementation of them is difficult. Incorporating them into science and technology investments should be part of the implementation plan, to ensure that strategic goals are incorporated throughout all operations at the Institute. This is particularly important for DEI commitments and values, since the current versions of these strategic goals were difficult to map to in the STM and MDM. In addition, MIT should develop a strategic plan for lunar exploration. While this would require significant effort, it would optimize MIT's efforts, incentivize new collaborations, and maximize MIT's impact. An example to study for strategic planning is Brent Sherwood's roadmap for exploration the ocean world Enceladus [Sherwood, 2016]. While this thesis can become an input into MIT's Lunar Open Architecture (see Section 6.2), the relationship is circular because LOA can also be an input into lunar strategic planning. As LOA develops, it should be used to analyze the work of other actors in order to ensure MIT isn't duplicating work and to potentially identify collaborators. Finally, MIT should identify lessons learned from its history of involvement in lunar exploration both to avoid past mistakes and to pursue efforts recommended by past efforts. Upcoming work from MIT undergraduate researcher Elissa Gibson will summarize MIT's history of involvement with lunar exploration, which will be a key resource for historical lessons learned. If MIT invests sufficiently in the next steps of lunar strategy development, it will optimize resources and maximize impact as we work to return humans to the lunar surface.

6.2 Incorporation into LOA

The work in this thesis was developed in collaboration with the team developing MIT's Lunar Open Architecture (LOA), such that this work was optimized to align well with LOA.

This thesis serves as a case study for future features of LOA: a science traceability matrix (STM) and technology multi-domain matrix (MDM). LOA "is the first open-source, collaborative, and dynamic roadmap for lunar exploration." It "captures the subjective, tacit information" that is "characteristic of the space industry" [MIT Media Lab, 2021, Sarang et al., 2020]. It will leverage objective technology roadmaps (such as the CSTR roadmaps used in this thesis) and augment them with subjective actor analysis to add context. This thesis showed how existing information about science/exploration goals and technology roadmaps (which are incorporated into LOA) can be leveraged to develop strategic science and technology planning tools (STM and MDM) for an organization like MIT. In the future, LOA could be expanded to include automatic creation of these two tools based on its existing databases and some input from a user. If a user could enter their organization's core research capabilities and existing R&D projects, LOA could automatically generate the structures for the STM and MDM and even some of the mapping, saving a significant amount of time. Human validation of these mappings will always be necessary: for the STM, even though standard "tags" of core capabilities were developed, it is possible that a user may want to insert a new tag or create a new mapping that doesn't already exist; for the MDM, R&D projects aren't standardized, so the mapping exercise would still need to be performed by the user. Using MIT's LOA to automatically generate a lunar STM and lunar technology MDM would be a powerful first step toward an organization's science and technology planning for lunar exploration.

Although an organization could develop their own STM and MDM with leveraging LOA's databases, using LOA will add depth and credibility because LOA captures an enormous amount of data about lunar exploration and is constantly updating as new information is released. In addition, the LOA project is partnering with highly regarded experts in industry to ensure quality of its data, so users can feel confident in the quality of data in the LOA databases. LOA will save users time that would normally be spent on data collection and cleaning, and will also help them conduct strategic planning for their own organization.

6.3 MIT Lunar Payload Development

As the work continues on MIT's four strategic planning exercises for lunar exploration, MIT is also actively seeking flight opportunities to the Moon. Four payloads are currently in development, listed below. More information is available on the public page for the graduate class "Operating in the Lunar Environment":

https://tothemoon.pubpub.org/payload-project-teams. In addition, MIT is gathering resources to develop a MIT-wide payload under the umbrella of the "To the Moon to Stay" mission. All payload concepts require refinement, fundraising, and hardware/software development before achieving flight readiness.

- The Lunar Tower Team, aka Multifunctional Lunar Lightweight Tall Tower (MELLTT; note the thesis author is also the Integration and Test Lead for MELLTT) Team, was created to respond to NASA's 2020 BIG Idea Challenge for students [Amy et al., 2020]. Over the course of 1.5 years in the challenge, the students progressed from concept to TRL 4 with funding from NASA and advisers from MIT, NASA and industry (including a CLPS provider). The team is in the process of transitioning into a permanent project at MIT, including a collaboration with NASA Langley Research Center. MELLTT is pictured in Figure 6-1.

- The Resource Exploration and Science of OUR Cosmic Environment (RESOURCE) project, led by Professor Dava Newman as the MIT principal investigator and conducted in collaboration with NASA Ames Research Center, addresses ISRU needs through a structured program directly linking science and exploration. The goal of RESOURCE is to characterize potential resources on SSERVI Target Bodies through scientific investigation. The MIT component of RESOURCE focuses on the optimization of the robotic and human interactions for missions to prospect for resources and conduct lunar ISRU as well as future manned missions to planetary surfaces. RESOURCE is affiliated with NASA's Volatiles Investigating Polar Exploration Rover (VIPER) mission, which is targeting a 2023 launch and will test RESOURCE's tools for enhancing science and human-robotic interaction via a mixed reality mission operations center.

- Passive Regolith Collector: The Space Enabled Research Group of the MIT Media Lab is investigating methods of passive regolith collection on the Lunar surface, where passive is defined as not requiring any additional moving parts or electrical components. The current focus of the project is the employment of regolith collection receptacles mounted between rover wheel grousers which may or may not include paraffin or other waxes as a "sticky material" for attracting regolith. The work is currently in a conceptual phase with initial experimental tests conducted on subcomponents.

- The Lunar Wireless Sensor Network (LunarWSN) is composed of multiple miniature (5cmx5cmx5cm), modular sensor nodes that can be ballistically deployed on the lunar surface from a rover or lander or can be dropped by a spacecraft flyby. The host central station on the rover or lander serves as the data collection station and position references. After being deployed on the lunar surface, the sensor nodes can automatically set-up a localization and communication network and start the sensing mission.

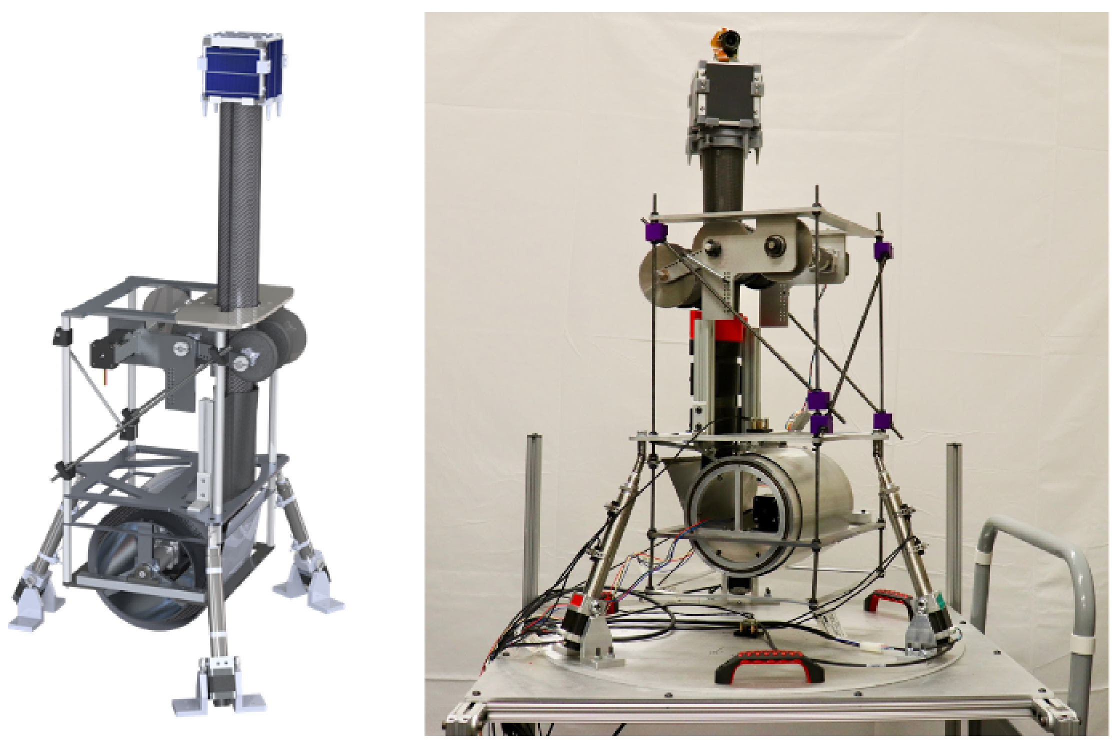


Figure 6-1: Side-by-side comparison of a rendering and a photo of MIT's MELLTT.

In addition to these four existing payload projects, MIT also seeks to develop a cross-MIT payload that leverages expertise from around the university. The STM and MDM developed in this thesis would be a useful input tool for identifying shared scientific and exploration interests that could lead to a payload concept. To develop new concepts and ultimately down-select to the most feasible ones, MIT can employ the NASA Jet Propulsion's Laboratory mission concept generation methodology [Sherwood and McCLeese, 2013].

As MIT works to develop a cross-Institute mission, it can use the lunar STM and MDM to guide concept generation and refinement as well as proposal development and submission. Proposals will benefit most from leveraging the STM, which is a required component for NASA missions.

Finally, MIT can continue building a community of lunar researchers. Lunar community connections began to be established through the four lunar strategic planning exercises, but MIT should leverage the space industry's momentum to return to the Moon to pursue opportunities for community-building and collaboration across the Institute. Building and maintaining this community is essential to developing a truly MIT-wide mission.

Bringing together this thesis, MIT's other three lunar strategic planning exercises, and MIT's scientific and technological expertise for lunar exploration, along with building a community of lunar researchers, will put MIT in a strong position to make a significant contribution to lunar exploration and science, all while strengthening MIT itself. MIT played an essential role as a contractor in the Apollo program (see Chapter 4), conducting work in guidance and navigation, computers, and human physiology that made the missions successful. With proper planning and investment, MIT can play this role once again in the new Artemis Program.

6.4 Concluding Thoughts

This thesis focused on two main research topics: 1) the economic viability of commercial spaceports and 2) science and technology planning for lunar exploration.

Through the development of a two-case study on commercial spaceports in the United States (focused on the Mid-Atlantic Regional Spaceport in Virginia and Spaceport America in New Mexico), this thesis uncovered important lessons learned and created recommendations for existing and proposed commercial spaceports across the topics of finances, business case, economic impact and profitability. The cross-case analysis could also be an essential input into the development of a national spaceport strategy, an initiative that is currently under way.

The creation of a MIT lunar science traceability matrix and a MIT technology multi-domain matrix revealed gaps and opportunities for MIT to pursue in order to develop a comprehensive strategic plan for MIT's lunar exploration. Leveraging decades of experience with the Moon (including a lead role in the Apollo Program) and MIT's cutting-edge science and technology work, MIT can once again be a key player in lunar exploration as NASA's Artemis Program aims to send the first woman and the next man to the Moon within the decade.

THIS PAGE INTENTIONALLY LEFT BLANK

Appendix A

Commercial Spaceport Mini Case Study

This appendix encompasses the full commercial spaceport mini case study, including the summary provided in Section 1.3.3 as well as brief overviews of all 11 commercial spaceports in the United States.

In order to select the two cases for in-depth study, a mini case study was conducted. This involved a brief analysis of each commercial spaceport in the United States, culminating in a summary table for all 11 US commercial spaceports.

In the United States, there are 11 commercial spaceports (as shown in Figure A-1) [FAA/AST, 2020], using the term "commercial spaceport" to mean a non-federal launch site that is licensed by the Federal Aviation Administration (FAA). The mini case study focused on answering several questions for each commercial spaceport:

- What was proposed?
- Who proposed it and why?
- Who opposed it and why?
- What impacts/risks were raised and by whom?
- What regulators were involved and why/how?

- Who are the other key stakeholders?

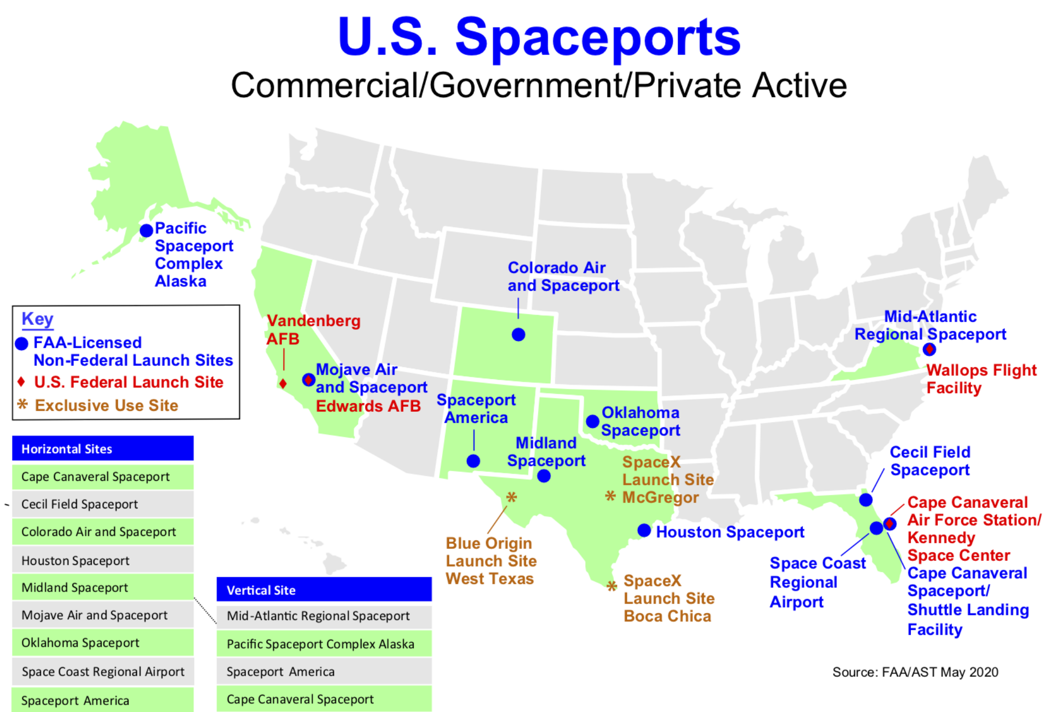


Figure A-1: Map of all spaceports in the United States [FAA/AST, 2020]

Figure A.1 (augmented from two FAA tables [FAA Office of Commercial Space Transportation, 2018]) provides an overview of the 11 commercial spaceports in the United States, incorporating key information for selecting the final two case studies. From column 2 alone, six spaceports are eliminated from the running because they have not yet supported a space launch (although they may have supported other launch activities, such as a captive carry test). The remaining five cases are:

- Mojave Air and Space Port
- Spaceport America
- Cape Canaveral Spaceport
- Pacific Spaceport Complex Alaska
- Mid-Atlantic Regional Spaceport

Table A.1: Overview of all active U.S. commercial spaceports, last updated in July 2020

Spaceport	Supported Space Launch?	Operator	State	Construction Type	Type of Launch Supported	License First Issued
Cecil Field Spaceport	No	Jacksonville Airport Authority	FL	Augmented airport	Takeoff/landing methods • Horizontal Spaceflight types • Suborbital • Orbital	2010
Midland International Air and Space Port	No	Midland International Airport	TX	Augmented airport	Takeoff/landing methods • Horizontal Spaceflight types • Suborbital	2014
Mojave Air and Space Port	Yes	East Kern Airport District	CA	Augmented airport	Takeoff/landing methods • Horizontal • Vertical Spaceflight types • Suborbital	2004
Spaceport America	Yes	New Mexico Spaceport Authority	NM	Greenfield	Takeoff/landing methods • Horizontal • Vertical Spaceflight types • Suborbital	2008
Cape Canaveral Spaceport*	Yes	Space Florida	FL	Federal transitioned to commercial	Takeoff/landing methods • Horizontal • Vertical Spaceflight types • Suborbital • Orbital	1999
Pacific Spaceport Complex Alaska	Yes	Alaska Aerospace Development Corporation	AK	Greenfield?	Takeoff/landing methods • Vertical Spaceflight types • Suborbital • Orbital	1998
Colorado Air and Space Port	No	Adams County	CO	Augmented airport	Takeoff/landing methods • Horizontal Spaceflight types • Suborbital	2018
Mid-Atlantic Regional Spaceport	Yes	Virginia Commercial Space Flight Authority	VA	Federal transitioned to commercial	Takeoff/landing methods • Vertical Spaceflight types • Suborbital • Orbital	1997
Oklahoma Spaceport	No	Oklahoma Space Industry Development Authority	OK	Augmented airport	Takeoff/landing methods • Horizontal Spaceflight types • Suborbital	2006
Houston Spaceport	No	Houston Airport System	TX	Augmented airport	Takeoff/landing methods • Horizontal Spaceflight types • Suborbital	2015
Space Coast Regional Air and Space Port	No	Titusville-Cocoa Airport Authority	FL	Augmented airport	Takeoff/landing methods • Horizontal Spaceflight types • Suborbital • Orbital	2020

** Throughout this mini case study, the Cape Canaveral Spaceport encompasses two FAA launch site operator licenses: the Cape Canaveral Spaceport/Shuttle Landing Facility and the Cape Canaveral Air Force Station.*

From these five cases, the author had unique access to information about the Mid-Atlantic Regional Spaceport (MARS), so it became the pilot case for the in-depth case studies. The access came from a class taught by MIT Hunsaker Visiting Professor Dave Thompson, retired founder and CEO of Orbital ATK, which is the anchor tenant at MARS.

From conversations with industry experts, it became clear that the Mojave Air and Space Port is a unique case that people should not attempt to recreate. Mojave is world-renowned as an experimental aerospace vehicle development facility; it has significant activity, but it is already filling the need for experimental facilities and should not be copied. Since this work aims to do a two-case study in order to facilitate broader generalizations, a unique case should not be included. Based on this information, Mojave was removed as a candidate.

Of the remaining three cases, the mini case study research resulted in Spaceport America emerging as the second case for in-depth study. Although Cape Canaveral Spaceport is perhaps the most famous launch site in the world, it is unique in its prominence and in its operation, which is shared by Space Florida (a space-focused economic development agency for the state of Florida), NASA, and the US Air Force. While Pacific Spaceport Complex Alaska provided an interesting case, Spaceport America was ultimately selected because it is a greenfield construction, similar to the proposed Azores spaceport, and because it is one of the most highly publicized commercial spaceports in the world. This research is being funded by the MIT Portugal Program, so studying a spaceport that most closely represents the Azores spaceport was of interest. In addition, it provides a comparison point for the Mid-Atlantic Regional Spaceport (MARS) in terms of construction type, because MARS is a federal site that transitioned to commercial operator. Spaceport America is also one of the most prominent commercial spaceports in the United States, and industry experts agreed it would be difficult to have a comprehensive spaceport case study without including it. Using MARS and Spaceport America as the two cases follows the theoretical replication logic discussed in Section 1.3.1. Here, the theoretical replication means that the author anticipates different results from each case because of the different in construction type (federal transitioned to commercial vs. greenfield, respectively).

In summary, this thesis conducts a holistic two-case study of the Mid-Atlantic Regional Spaceport and Spaceport America.

Following are brief overviews of all 11 commercial spaceports in the U.S. in alphabetical order.

Cape Canaveral Spaceport/Shuttle Landing Facility

The Cape Canaveral Spaceport (CCS) in Jacksonville, FL is a unique case because of its extensive integration into massive existing federal infrastructure. Cape Canaveral Spaceport doesn't just encompass the FAA-licensed Shuttle Landing Facility. Rather, it represents Florida's vision for all of the facilities at NASA's Kennedy Space Center and the US Air Force's Cape Canaveral Air Force Station to be overseen by Space Florida, the state's economic development agency, in order to streamline operations and expand commercial activity [Space Florida, 2017, Seedhouse and International Space University, 2017]. While Space Florida is still in the process of enacting this vision to coordinate all of the facilities at Cape Canaveral, it currently oversees operations at Exploration Park (an industrial park), the Space Coast Integration Facility, Space Launch Complex (SLC) 20, SLC-46, SLC-41, SpaceX Launch Complex 39A, and the Shuttle Landing Facility [Space Florida, 2019]. Space Florida holds two separate FAA commercial launch licenses for facilities at Cape Canaveral, including the Shuttle Landing Facility [Federal Aviation Administration, 2018] and the Cape Canaveral Air Force Station [Federal Aviation Administration, 2015]. The Cape Canaveral Spaceport is part of a larger Space Florida initiative to establish a network of spaceports across the state [Space Florida, 2017, Seedhouse and International Space University, 2017, Space Florida, 2019]. CCS has been largely supported by Florida's Congressional delegation, including former U.S. Senator and new NASA Administrator Bill Nelson, U.S. Senator Marco Rubio, current U.S. senator and former Florida Governor Rick Scott, and U.S. Representative Bill Posey [Dean, 2014, Harwood, 2015]. However, while the Shuttle Landing Facility hosted numerous landings of NASA's Space Shuttle, it has yet to host a single commercial launch or landing [Foust, 2019d]. In addition to the wide scope of current activities, Cape Canaveral Spaceport builds upon decades of history of American spaceflight. Originally established during the Cold War to develop intermediate and long-range ballistic missiles, the site expanded significantly during the 1960s as part of the race to the Moon and then was altered to support Space Shuttle launches in the 1970s [Space Florida, 2017]. Although Cape Canaveral has been home to every launch of humans from the United States [Roberts, 2019b], concern began to grow about the future of the site with the planned retirement of the Space Shuttle and no alternative American launch vehicle, so Space Florida began to develop the plan for a network of spaceports that could support a growing commercial space sector [Space Florida, 2017, Robert, 2017, Foust, 2019g]. The first use of the term Cape Canaveral Spaceport was in the 2002 CCS Master Plan developed by NASA KSC, the USAF's 45th Space Wing, and the Florida Space Authority (the predecessor to Space Florida) [Space Florida, 2017]. Cape Canaveral Spaceport can now support both horizontal and vertical launches and landings [FAA/AST, 2020, Federal Aviation Administration, 2018, Federal Aviation Administration, 2015], despite opposition to attempted spaceport development. Space Florida attempted to pursue development of a Shiloh Launch Facility north of Kennedy Space Center, but there was significant pushback because of environmental concerns [Dean, 2014]. In addition, Space Florida has proposed commercial launch sites within the existing NASA and USAF facilities. Even though NASA and USAF have expressed support of expanding commercial operations, the USAF is concerned about an independent facility being operated within their existing jurisdiction [Dean, 2014]. There have also been concerns about developing commercial facilities within the existing NASA and USAF infrastructure because national security missions will always take priority over commercial missions, and there are increasing regulations of the site that may be burdensome to commercial companies [Dean, 2014]. Other stakeholders in the Cape Canaveral Spaceport are aerospace consultants AECOM [Space Florida, 2019], who are referenced throughout the 2017 spaceport master plan [Space Florida, 2017]; and the US Fish and Wildlife Service and the National Park

Service (both of which are agencies in the US Department of the Interior), who manage portions of CCS for conservation and conditional use public access [Space Florida, 2017]. CCS is home to many customers, including SpaceX and Blue Origin.

Cecil Field Spaceport

The Cecil Field Spaceport is a joint civil-military airport and spaceport operated by the Jacksonville Aviation Authority, located in Jacksonville, Florida. The site is licensed by the FAA to host horizontal takeoffs and landings, both suborbital and orbital [Space Florida, 2018]. The idea to transform the airport into a spaceport stemmed from a long-standing interest from Space Florida in establishing another spaceport outside of the Cape Canaveral launch complex. An initial feasibility study considered Titusville (which has recently become a licensed commercial spaceport) as an alternate location to Jacksonville, but Jacksonville was deemed the better option. With support from the Jacksonville mayor and other local leaders, a plan begin to develop to turn the Cecil Field airport into a commercial spaceport. Consultants RS&H have been involved with developing master plans for the site. The FAA granted a license in 2010, and later granted the site a Space Transportation Infrastructure Matching Grant to the tune of 100,000. Leadership looked into Virgin Galactic, XCOR and Stratolaunch as tenants, but was not able to secure an agreement with any of those companies. Rocketplane Global (who was also involved with the Oklahoma Spaceport) became the first company to sign up as a tenant and planned to open a visitor's center similar to the one at KSC, but they later left and are now working with the Michigan proposed spaceport. No launches have been hosted at Cecil Field Spaceport, but some testing has occurred. [Foust, 2010, RS&H, 2020, Federal Aviation Administration, 2010, Messier, 2010, Foust, 2019g, Dixon, 2020]

Colorado Air and Space Port

The Colorado Air and Space Port, located in unincorporated Adams County, CO, started as a local airport that was six miles from the Denver International Airport and wasn't getting much use. Regional and state leadership, led by then-Governor (current U.S. senator) John Hickenlooper, proposed extending the site to support horizontal space launch. The governor was joined by the entire Colorado delegation in U.S. Congress in supporting the proposed spaceport, and the leadership cited the potential economic development as well as providing additional legitimacy to the Colorado space sector by having a spaceport. The economic development could come from suborbital space tourism initially, and later from point-to-point transportation. Locals have expressed dissatisfaction with the project because they have not been included in the planning, and raised concerns about both the risks of an in-flight failure as well as consequences of airspace closure on crop dusting or emergency helicopter flights. Jonathan Goff, the president and CEO of locally-based Altius Space Machines, raised several relevant concerns, including that the spaceport was relying on too few tenants, a lack of clarity about the effect on airspace surrounding Denver International Airport (DIA), the highly speculative nature of the point-to-point transportation concept, and an inability to support rockets that take off vertically. Despite some concerns from these groups, the FAA licensed the spaceport in 2012 after a letter written to them by the entire Colorado Congressional delegation. Since then, UK company Reaction Engines has spent a couple million dollars developing an engine test facility, and three architectural firms were shortlisted as potential consultants on the project. Japanese-based PD Aerospace signed a letter of intent with the spaceport to explore opportunities for PD Aerospace to work at the site. The spaceport has looked into attracting Sierra Nevada Corporation (SNC's) and XCOR as tenants, but SNC Dream Chaser spaceplane is still in development and XCOR has gone bankrupt. The spaceport accommodates horizontal, suborbital launches [Colorado Air and Space Port, 2020]. Colorado claims to have the highest per capita aerospace employment of any state in the U.S. [Kohler, 2020]. [Avery, 2011, Rodriguez, 2018, David, 2012, The Associated Press, 2018, Aguilar, 2018]

Houston Spaceport

The Houston Spaceport was established at the site of the Ellington Airport in Texas in 2015, when the site received a spaceport operator license from the FAA [Fly2Houston, 2015]. The license was renewed in 2020 [Federal Aviation Administration, 2020a]. Ellington Airport was created in 1917 to support World War I, but closed shortly thereafter because the war ended. It was reactivated as a military site in 1940 to support WWII, and became the site of pilot training. It was transitioned to an Air Force Base in 1949, and then to the Air National Guard in 1975, continuing decades of pilot training. The site supported early NASA efforts, hosting lunar landing training. The city of Houston purchased it for $1 in 1984 from the federal government, who wanted to divest from the site, making it part of the Houston Airport System. Beginning in 2011, Mario Diaz, the Director the Houston Airport System, began discussing the idea of turning the airport into a commercial spaceport [Fly2Houston, 2015, Moran and Collier, 2012, Collier, 2013] and enlisted consultants RS&H to conduct a feasibility study [Gulliver et al., 2012, Yazell and AIAA Houston, 2012, Moran, 2012]. While there was some skepticism about the idea from industry [Seedhouse and International Space University, 2017], local business leaders, policymakers [Moran and Collier, 2012], and even the editorial board of the Houston Chronicle [Editorial Board, 2014], over time the idea garnered broad support. It seemed that the city of Houston was worried about the shift in the space industry from NASA to commercial players. Local leaders wanted to make sure that Houston stayed a hub of space work, and believed having a spaceport could help achieve this [Berger, 2013]. The spaceport supports horizontal reusable launch vehicles (RLVs) [Fly2Houston, 2015], but cannot support vertical launches because of its proximity to a city [Leinfelder, 2019]. The site already had three runways, and Diaz proposed spending on the order of 100M [Moran, 2012] to update the site to support space launches. While the spaceport has the ability to support horizontal launches, the operators recognized that there is not enough demand to make money on launches in the near future, so they are focused on establishing a business hub at the site [Foust, 2019a], bringing in partners from industry, academia, and research [Alexander and Machuca, 2015, Foust, 2019c]. The site now has three tenants: Intuitive Machines (working on a lunar lander for NASA), San Jacinto College (creating an aerospace workforce training center), and FlightSafety International (building an aeronautical training facility, with 10-12 flight simulators) [Leinfelder, 2019]. Ellington is also home to NASA's fleet of T-38 aircraft, which they use for astronauts' flight training. The spaceport is focused on diversification in order to maximize profitability, appearing to follow the airport revenue model [Collier, 2013]. They emphasized economic development when they hosted the first Global Spaceport Alliance meeting in 2019 [Foust, 2019a]. In addition to tenants, they are pursuing partnerships with several other organizations, including Catapult Satellite Applications, the Rice Space Institute, Boeing, and CASIS [Seedhouse and International Space University, 2017, Alexander and Machuca, 2015]. The spaceport also pursued and achieved the relocation of the Lone Star Flight Museum from nearby Galveston airport to the spaceport [Yazell and AIAA Houston, 2012].

Mid-Atlantic Regional Spaceport

A full case study of the Mid-Atlantic Regional Spaceport is covered in Section 2.1.

In 1945, the National Advisory Committee for Aeronautics (NACA) and the Navy started working at a beach on Wallops Island in Maryland for rocket testing. The testing eventually expanded to supersonic vehicle research, and NASA bought the site to establish a permanent research center there. Over time, the work at Wallops (which became part of NASA's Goddard Spaceflight Center) became less important, and in 1995, NASA decided to close the facility. Maryland Senator Barbara Mikulski, a prominent U.S. Senator and Congressional advocate for space exploration, protested the decision to close Wallops and eventually saved the center. As part of NASA's plan to keep the center, they began to work to commercialize parts of it, resulting in Virginia's establishment of the Virginia Commercial Spaceflight Authority (VCSFA) and the licensing of a commercial spaceport at Wallops. The commercial spaceport was originally envisioned as a joint operation between Virginia and Maryland, but is run only by Virginia. NASA Goddard center director Joseph Rothenberg helped Virginia gain the FAA license to establish the Mid-Atlantic Regional Spaceport (MARS), which supports vertical takeoff and landing for suborbital and orbital launches [Space Florida, 2018]. The strong support from Mikulski, as well as other senators including Mark Warner (VA), Chuck Robb (VA), and Paul Sarbanes (MD), has been integral to both NASA Wallops and MARS. Although state legislators and the spaceport originally planned for the spaceport to become self-sufficient, that business model did not play out; instead, MARS continues to receive state funding for operations and acts as a mediator between launch operators and NASA. For a while, MARS' only tenant was Northrup Grumman (formerly Orbital ATK, formerly Orbital Sciences), which has launched every Cygnus International Space Station resupply mission from MARS. Since Virginia and MARS resolved the issue regarding funding, the spaceport has worked to diversify revenue sources, bringing in Rocket Lab as a second tenant and expanding to support UAV testing. VCSFA partners with the Virginia Economic Development Partnership, Old Dominion University, NASA, Virginian's Center for Innovative Technology, and private industry. It is overseen by a board appointed by the state governor. NASA was involved with MARS following Orbital Sciences' rocket accident in 2014, after which members of Congress got involved to pressure NASA to pay for some of the damages. The NASA Inspector General seemed unhappy at this development, since he originally believed that NASA would not be responsible for damages to infrastructure at MARS. MARS has become one of the more active commercial spaceports in the United States and maintains moderate support from the state. [Pappalardo, 2019, Gulliver et al., 2012, Tinoco, 2018, Handberg, 2002, Wright, 2004, Thompson and Browder, 2019, Eberly and Browder, 2020]

Midland International Air and Space Port

A former civil airport and Army air field, this commercial airport in Midland, TX was licensed to support horizontal takeoff space vehicles when it received its spaceport operator license from the FAA in 2014 [Federal Aviation Administration, 2014]. The spaceport was proposed by the Midland Development Corporation, who planned to start by leveraging existing facilities at the airport to support horizontal launch vehicles, specifically XCOR's Lynx spaceplane (the Lynx program was eventually cancelled and XCOR went bankrupt), and then expand to include a business park and eventually support other types of launch vehicles. During the original development of the spaceport, the local community raised concerns about the spaceport's required safety range to protect people and infrastructure from flight failures, which could prohibit the expansion of housing or business near the airport, which was a major concern since the city was experiencing significant growth during an oil boom [Gleason, 2014]. The Midland Development Corporation gave a contract for spaceport operations to Silverwing Enterprises [Doreen, 2018], and worked with consultants Kaplan Kirsch & Rockwell LLP on a land use compatibility study [Gleason, 2014]. The first two tenants at the spaceport were XCOR (who was developing a space vehicle called Lynx) and Orbital Outfitters (who was developing spacesuits for the Lynx) [Messier, 2011]. XCOR and Orbital Outfitters later went out of business, but only after the state of Texas had awarded the Midland spaceport $2M from the Spaceport Trust Fund to develop the site [Pappalardo, 2019]. The Midland Development Corporation had also lost investments, having spent $8M on incentives and facilities for Orbital Outfitters [Hawes, 2018] plus $11.5M on incentives and facilities for XCOR [Basco, 2014]. While there had mostly been support from local leadership during the original process of licensing, after XCOR and Orbital Outfitters went out of business, there was controversy within the city council when one councilman strongly opposed renewing a contract to operate the spaceport because of its lack of success. However, another council member was strongly in favor of the spaceport and the operating contract renewal passed 6-1 [Doreen, 2018, Pappalardo, 2019]. Since XCOR and Orbital Outfitters left, the Midland Development Corporation has attracted two new tenants to take over their facilities: Avellan Space Technology & Science (who is working on space-based cellular broadband [AST and Science, 2021]), and Kepler Aerospace Ltd (who is working satellite and propulsion technology [Kepler Aerospace, 2021]) [Doreen, 2020].

Mojave Air and Space Port

The Mojave Air and Space Port in Mojave, CA developed from an existing civilian and military airport, which was purchased by aviation enthusiast and farmer Dan Sabovich in 1972, with the help of key members of U.S. Congress, including Barry Goldwater, Jr. Sabovich established a civilian test flight center, inspired by the nearby Edwards Air Force Base and Naval Test Pilot School [Pappalardo, 2019]. Aerospace vehicle development has taken place there since famous aerospace designer Burt Rutan first set up shop at Mojave in 1974; Rutan went on to found or co-found several companies, including the Rutan Aircraft Factory, Scaled Composites, Mojave Aerospace Ventures, and The Spaceship Company. The Mojave spaceport primarily focuses on experimental vehicle development, including the development of SpaceShipOne, which won the $10M Ansari X-Prize. Mojave became the first licensed inland spaceport and the first commercial spaceport when the FAA licensed it for horizontal launch vehicles in 2004 [International Space University, 2008]. In addition to flight testing and vehicle development, Mojave also provides aircraft maintenance and storage services. Because of the region's long-standing history with flight testing, there was virtually no opposition to making it into a spaceport. However, controversy has come to the spaceport from two fatal accidents resulting in five deaths: a Scaled Composites test for SpaceShipTwo that killed three employees in 2007, and the crash of Virgin Galactic's SpaceShipTwo during a flight test that killed one of the two pilots. Mojave Air and Space Port is often credited as igniting a trend of airports considering adding spaceport facilities [Gulliver et al., 2012]. While Mojave is one of the most active commercial spaceports in the US, industry experts strongly advise against anyone attempting to duplicate their business model, saying that it's impossible to copy and that Mojave is already fulfilling the demand for experimental vehicle development facilities.

Oklahoma Spaceport

The Oklahoma Spaceport in Burns Flat, OK was born out of a decommissioned military air base. Previously used by both the Navy and the Air Force, the spaceport later became an operational civil airport with one of the country's longest runways. Since the Air Force left the facility a few decades ago, there have been multiple attempts to commercialize the facility, including transforming the infrastructure to be an industrial park. In the late 1990s, Oklahoma legislators joined several other states in the competition to attract reusable launch vehicles (RLVs) by establishing the Oklahoma Space Industry Development Authority (OSIDA). OSIDA wanted to attract the RLVs being developed for NASA, which would have used horizontal takeoff and landing (HTOL). The state created a tax incentive to attract NASA's RLVs in development. Eventually these RLV programs were cancelled, but the state retained the incentives in the hopes that OSIDA could find other customers. However, the facility is limited in that it can only support HTOL, rather than vertical takeoff and landing (VTOL), forcing VTOL launch vehicle developers to seek other spaceports. OSIDA did succeed in attracting three companies: Rocketplane Global, Armadillo Aerospace and TGV Rockets. When Rocketplane came to the spaceport, they got involved with the remaining tax incentives and were "instrumental" in passing the legislation" that was designed to encourage RLV development, similar to the more famous Ansari X-Prize. Rocketplane won the so-called "O Prize" to the tune of 18M and had hired several dozen employees for development, but later went bankrupt [Lauer, 2007]. Armadillo and TGV went out of business. Support at the state level seems mixed, with some legislators in favor and others opposed. Former Gov. Mary Fallin initially opposed the spaceport but changed her stance after taking office. Local officials have lost confidence in the spaceport, particularly after the state lost 18M to the Rocketplane failure. People are concerned about both the facility's limitation to only support HTOL, as well as competition from other spaceports. The FAA licensed the facility as a spaceport in 2006 with the ability to support HTOL suborbital launches [Space Florida, 2018], and renewed the license in 2016. The Oklahoma Spaceport makes the majority of its money from aviation activities and federal grants, rather than from space activities. Rocketplane, which was a vocal supporter of the spaceport, who established an office in the area, and who was actively involved in lobbying, has reemerged from bankruptcy and is now supporting a proposed spaceport project in Michigan. [Foust, 2004b, Foust, 2004a, Beery, 2012, Pound, 2016, McNutt, 2010, Palmer, 2010, Federal Aviation Administration, 2016, Lauer, 2007]

Pacific Spaceport Complex Alaska

In 1991, the state of Alaska created Alaska Aerospace Development Corporation in order to expand and promote aerospace development in the state. The focus of the organization shifted to constructing a new launch site on the west coast, which eventually became one of the first four state spaceports and the only one of the four "not collocated on a federal range" [Alaska Aerospace, 2018, Handberg, 2014]. The spaceport, now named Pacific Spaceport Complex Alaska (PSCA) and located in Kodiak Island, AK, can launch to several orbits (polar, low Earth, sun synchronous, highly elliptical), launches over open water, and has easy access by water because its on an island [Handberg, 2002, Alaska Aerospace,]. Although it is currently one of the most active commercial spaceports [Carey, 2019], having supported five launches (three at PCSA and two for Rocket Lab in New Zealand) in fiscal year 2018 [Alaska Aerospace, 2018], the local community has raised concerns about negative environmental impacts, harm to the integral fishing industry when waterways are shut down for launches, and the fact that the high-skill jobs at the site are usually imported rather than sourced locally [Finnerty, 2019, Foust, 2019f]. The site focuses on small launch vehicles [Handberg, 2002]. The FAA licensed the spaceport in 1998, and the site can accommodate both suborbital and orbital launches, and supports vertical launches [FAA Office of Commercial Space Transportation, 2018, Handberg, 2014, Alaska Aerospace, 2020]. Architecture and engineering design firm BRPH has been involved with the spaceport since it was a concept, conducting the site feasibility analysis as well as the design and construction of facilities [Waite and DeLuna, 2012]. PSCA has benefitted from the support of state legislators and the federal government, including financially [Handberg, 2014, Handberg, 2002]. Alaska Aerospace, who operates PSCA, has looked into expansion with another site in Hawaii, but significant community opposition has stalled those plans [Finnerty, 2019, Wilkinson, 2019]. PCSA hosts launches for the U.S. Air Force, the U.S. Missile Defense Agency (MDA) and private company Astra [Alaska Aerospace, 2018, Gray, 2020].

Space Coast Regional Airport

The Space Coast Regional Airport in Titusville, FL, also called the Space Coast Regional Air and Space Port [Kelly, 2020], is the newest site to receive an FAA commercial spaceport license, which was granted in May 2020 [Federal Aviation Administration, 2020c]. The airport was constructed in 1943 and is operated by the Titusville-Cocoa Airport Authority (TCAA) [56]. As the closest commercial airport to NASA's Kennedy Space Center, it is often used to transport KSC personnel and spacecraft [Kelly, 2020]. The spaceport has two existing runways from airport operations (although they may not be long enough for some space vehicles), is licensed to host horizontal takeoff and landing of spacecraft, and will be capable of hosting up to 50 launches per year—although it does not yet have agreements with any launch operators [Kelly, 2020, Foust, 2019b]. In addition to its existing infrastructure, the 400-page report submitted to the FAA for the spaceport license included plans for a 400,000 square-foot hangar for spacecraft development and storage, as well as significant supporting infrastructure like a parking lot, an apron between the hangar and taxiway, and new roads [Kelly, 2020]. The spaceport is being developed by Space Florida as part of it and the state of Florida's plan to develop a state spaceport system that can support future growth in the space industry. Plans for the spaceport have been in development since 2013, when the state legislature made the Space Coast Regional Airport part of the Florida spaceport territory [Space Florida, 2018]. Spaceport consultants at RS&H completed a spaceport feasibility study of the site [Gulliver et al., 2012]. Thus far, there has not been significant pushback to the newly licensed spaceport.

Spaceport America

A full case study of Spaceport America is covered in Section 2.2.

Spaceport America was the first spaceport built for private launch providers, not as an additional to an existing airport or military base. The spaceport was the brainchild of New Mexico Governor Bill Richardson and Virgin Galactic owner Richard

Branson—the spaceport and Virgin Galactic signed an agreement for VG to become the anchor tenant. Construction of the spaceport was financed through state appropriations and taxes on two surrounding counties, coming to a total of $200M. A third county voted down the proposed tax to pay for the spaceport. Although the spaceport expected VG to fly before construction on the facility was completed [Foust, 2014], VG faced setbacks and delays (including the loss of a pilot to an in-flight explosion in 2014), such that they have yet to fly a paying customer, although in the last few months, they have moved a significant amount of staff to NM (from Mojave spaceport in CA) and started conducting test flights from SA. When VG first faced delays, the spaceport began looking for alternative revenue sources; but some people weren't happy with the lack of progress, and one state senator even introduced a bill to sell the spaceport [Boyle, 2015a]. While state legislators and the spaceport originally planned for the spaceport to become self-sustaining, the last executive director of the spaceport (Dan Hicks) said in a state legislative hearing that the spaceport now plans for state funding to become an even greater portion of its budget. Some state legislators (including the last governor, Susana Martinez), as well as some local leaders and members of the community, opposed the spaceport because it was financed by one of the less wealthy states, and in particular two of the poorest counties in the country, to pay for wealthy individuals to take tourist flights on board a spaceship built by a billionaire's company. People in favor of the spaceport seemed to support it because of the promise of job creation and increased tourism, although the benefits remain to be seen. The FAA licensed the spaceport for both horizontal and vertical takeoff and landings, and the site's proximity to White Sands Missile Range gives it access to restricted airspace that is favorable for space flights. When originally under consideration, the spaceport's economic impact was analyzed by Futron consultants, which projected an economic impact of $550M by 2020 [Futron Corporation, 2005]. A January 2020 economic impact analysis by consultants Moss Adams stated that the spaceport had generated $33M in economic impact through FY2019, and projected an economic impact of $118M by 2029 [Moss Adams LLP, 2020a, Moss Adams LLP, 2020b].

THIS PAGE INTENTIONALLY LEFT BLANK

Appendix B

STM Interview Information and Supporting Databases

This appendix covers supporting information for the Science Traceability Matrix developed in Section 5.1, including details abut the interviews for data collection, the MIT actors database (a direct output of the interviews) developed as an input to the STM, and the MIT strategic goals database that was also developed as an input to the STM.

B.1 Details About MIT Researcher Interviews

As discussed in the methodology section (Section 4.3.1), interviews were conducted with seven MIT researchers (listed below) to gather data for the science traceability matrix and technology multi-domain matrix.

- Department of Aeronautics and Astronautics
  - Professor Jeffrey Hoffman
  - Professor Julie Shah
  - Professor Olivier de Weck
- Media Lab

    - Dr. Ariel Ekblaw
    - Professor Danielle Wood

- Department of Earth, Atmospheric and Planetary Sciences
    - Professor Ben Weiss

Initial interview questions are listed below; additional questions were used as needed for clarification or to gather more information. Interviews served multiple purposes: to collect data for this thesis, to begin building up a community of lunar researchers at MIT, to identify opportunities for collaboration, and to identify potential resource needs. The output of the interviews informed the development of a MIT Actors database, which is shown in Section B.2.

- Q1: What topics do you research?
- Q2: Are there any research topics you're interested in learning more about or getting more involved with?
- Q3: Do you want/need support in your work? If yes, what do you want help with/what support do you need?
- Q4: Would your research benefit from lunar exploration?
- Q5: Are there any research projects or space missions you're particularly interested in?
- Q6: Do you have any projects (past, present or future) that are relevant to lunar exploration?
- Q7: Do you know anyone at or affiliated with MIT who has expertise in or is working on lunar exploration?
- Q8: Are there any people you're interested in collaborating with?
- Q9: Is there anyone else (faculty, students, etc.) you think I should talk to?

B.2 MIT Actors Database

This section shows the MIT actors database, which was developed based on the interviews with MIT researchers discussed in Section B.1 and used as an input to the Science Traceability Matrix.

Table B.1: Database of MIT researchers, used as an input to the MIT Lunar Science Traceability Matrix

#	Name	Current Research	Past Research	Interested in Research	Department
1	Jeffrey Hoffman	ISRU Air-dropped penetrators	Spacesuits Mobility Habitats	Deployable towers	Department of Aeronautics and Astronautics
2	Ariel Ekblaw	Additive manufacturing Waste management Technology roadmapping Industrial design Anthropology Self-assembling architecture Food Payload integration Science communication Payload development Art Design Governance			Media Lab
3	Julie Shah	Human-robot interaction AI/ML		AR/VR	Department of Aeronautics and Astronautics Computer Science and Artificial Intelligence Lab
4	Olivier de Weck	Technology roadmapping Remote sensing Systems engineering MBSE Multidisciplinary design optir Satellite constellations Reconfigurable satellites Payload development System architecture	Mission modeling		Department of Aeronautics and Astronautics

#	Name	Current Research	Past Research	Interested in Research	Department
5	Benjamin Weiss	Planetary origins Magnetism Payload development Sample analysis	Sample analysis	Payload development	Department of Earth, Atmospheric and Planetary Sciences
6	Danielle Wood	Governance Regolith characterization Indigenous views of space Sustainable development Green propulsion Earth observation Antiracism MBSE Policy	Accessibility Democratization of space Citizen science Public engagement	Differently-abled astronauts	Department of Aeronautics and Astronautics Media Lab
7	Dava Newman	Spacesuits Policy AR/VR AI/ML Sustainable development Aerospace biomedicine			Department of Aeronautics and Astronautics Media Lab

B.3 MIT Strategic Goals Database

This section shows the MIT strategic goals database, which was developed as an input to the Science Traceability Matrix. The data was compiled from three MIT strategic plans listed below, as discussed in Section 4.3.

- A Global Strategy for MIT (2017) [Lester, 2017]
- MIT Five-year Strategic Action Plan for Diversity, Equity, and Inclusion (2021-2026) - DRAFT (2021) [Dozier et al., 2021]
- MIT Department of Aeronautics and Astronautics 2020 Strategic Plan [MIT Department of Aeronautics and Astronautics, 2020]

Table B.2: Database of MIT's strategic goals, used as an input to the MIT Lunar Science Traceability Matrix

#	MIT Strategic Goal	Traceability	Goal Type
1	Build new MIT Partnerships for a Better World	A Global Strategy for MIT	Recommendation
2	Expand MIT's global classroom	A Global Strategy for MIT	Recommendation
3	Streamline and strengthen international educational assistance/institution-building programs	A Global Strategy for MIT	Recommendation
4	Develop a new MIT Global Leaders program	A Global Strategy for MIT	Recommendation
5	Review the cap on international undergraduate admissions	A Global Strategy for MIT	Recommendation
6	Strengthen Governance and Operations	A Global Strategy for MIT	Recommendation
7	Advancing the frontiers of knowledge	A Global Strategy for MIT	Value
8	Encouragement of discovery, intellectual risktaking, and creative problem-solving	A Global Strategy for MIT	Value
9	Honesty and integrity in all professional and personal dealings	A Global Strategy for MIT	Value
10	Respect for others	A Global Strategy for MIT	Value

#	MIT Strategic Goal	Traceability	Goal Type
11	A commitment to diversity	A Global Strategy for MIT	Value
12	Fairness in the treatment of all individuals and groups	A Global Strategy for MIT	Value
13	An open, respectful approach to discourse	A Global Strategy for MIT	Value
14	Reliance on facts and reason-based objective inquiry	A Global Strategy for MIT	Value
15	Freedom of expression, communication, and movement of people	A Global Strategy for MIT	Value
16	A commitment to excellence in all that we do	A Global Strategy for MIT	Value
17	Increase the number of underrepresented graduate students, postdocs, staff, and faculty at MIT.	MIT 5-year Strategic Action Plan for DEI	Commitment
18	Assess and strengthen our recruitment of underrepresented undergraduate students.	MIT 5-year Strategic Action Plan for DEI	Commitment
19	Critically engage with and empower the MIT community on the value of diversity, equity, and inclusion.	MIT 5-year Strategic Action Plan for DEI	Commitment
20	Reinforce positive interactions among members of the MIT community to foster and promote an enduring sense of belonging.	MIT 5-year Strategic Action Plan for DEI	Commitment

#	MIT Strategic Goal	Traceability	Goal Type
21	Support academic research, scholarship, and collaborations regarding diversity, equity, inclusion, social justice, and related topics at MIT.	MIT 5-year Strategic Action Plan for DEI	Commitment
22	Close achievement gaps and advance equity in all forms of success among underrepresented undergraduate students, graduate students, postdocs, staff, and faculty at MIT.	MIT 5-year Strategic Action Plan for DEI	Commitment
23	Integrate autonomy and humans in real-world systems	AeroAstro 2020 Strategic Plan	Thrust
24	Develop new theory and applications for satellite constellations and swarms	AeroAstro 2020 Strategic Plan	Thrust
25	Aerospace environmental mitigation and monitoring	AeroAstro 2020 Strategic Plan	Thrust
26	Lead development of the College of Computing education programs in autonomy and computational science and engineering	AeroAstro 2020 Strategic Plan	Thrust
27	Develop education for digital natives and digital immigrants	AeroAstro 2020 Strategic Plan	Thrust
28	Become the leading department at MIT in mentoring, advising, diversity, and inclusion	AeroAstro 2020 Strategic Plan	Thrust
29	Make innovation a key component in MIT AeroAstro leadership	AeroAstro 2020 Strategic Plan	Thrust
30	Ethics and integrity	AeroAstro 2020 Strategic Plan	Value

#	MIT Strategic Goal	Traceability	Goal Type
31	Lead through excellence in research and education	AeroAstro 2020 Strategic Plan	Value
32	Succeed together	AeroAstro 2020 Strategic Plan	Value
33	Create an open, diverse, inclusive, and supportive community	AeroAstro 2020 Strategic Plan	Value

Bibliography

[DSM, 2021] (2021). The Design Structure Matrix (DSM).

[Aerospace Corporation, 2020] Aerospace Corporation (2020). A National Spaceport Strategy. Technical report, United States Space Force.

[Aguilar, 2018] Aguilar, J. (2018). Rural residents on Colorado's Eastern Plains wary of launch issues related to planned spaceport at Front Range Airport.

[Aharonson et al., 2020] Aharonson, O., Russell, C. T., Head III, J. W., Wieczorek, M., Garrick-Bethell, I., Weiss, B. P., Smith, D. E., Rowe, K., Grosz, A., Amrusi, S., Novoselsky, A., Nahaman, N., Grossman, Y., Shimoni, Y., and Gomez, A. (2020). The science mission of SpaceIL's Beresheet lander. *Planetary and Space Science*, 194:1–8.

[Alaska Aerospace,] Alaska Aerospace. From the Last Frontier to the Final Frontier - Comprehensive Launch Capabilities.

[Alaska Aerospace, 2018] Alaska Aerospace (2018). Rockets n Roll'n - Alaska Aerospace 2018 Annual Report. Technical report, Alaska Aerospace.

[Alaska Aerospace, 2020] Alaska Aerospace (2020). Spaceports.

[Alba Soular, 2013] Alba Soular, D. (2013). Virgin Galactic takes step toward flight license, outlook revised for first flights.

[Alexander and Machuca, 2015] Alexander, D. and Machuca, A. (2015). Houston, we have a Spaceport. *Room: The Space Journal*, (3).

[Amy et al., 2020] Amy, C., Bégin, M.-A., Browder, B., Chan, M., Dawson, C., do Vale Pereira, P., Hank, T. J., Hinterman, E., Lordos, G., Martell, B., Miller, A., Padia, V. J., Stamler, N., Todd, J., Wang, N., Newman, D. J., de Weck, O., and Hoffman, J. A. (2020). Autonomously Deployable Tower Infrastructure for Exploration and Communication in Lunar Permanently Shadowed Regions. In *AIAA ASCEND*, pages 1–22. American Institute of Aeronautics and Astronautics.

[Anderson, 2013] Anderson, C. (2013). Legislative Finance Committee. Technical report, Spaceport America.

[Andrews-Hanna et al., 2018] Andrews-Hanna, J. C., Head, J. W., Johnson, B. C., Keane, J. T., Kiefer, W. S., McGovern, P. J., Neumann, G. A., Wieczorek, M. A., and Zuber, M. T. (2018). Ring faults and ring dikes around the Orientale basin on the Moon. *Icarus*, 310:1–20.

[Arrowhead Center at New Mexico State University, 2005] Arrowhead Center at New Mexico State University (2005). Southwest Regional Spaceport Business Plan. Technical report, New Mexico Economic Development Department.

[Associated Press, 2006] Associated Press (2006). Virginia spaceport's first launch succeeds.

[AST and Science, 2021] AST and Science (2021). AST and Science.

[Augustine Commission et al., 2009] Augustine Commission, Augustine, N., Austin, W., Bejmuk, B., Chiao, L., Chyba, C., Crawley, E. F., Greason, J., Kennel, C., Lyles, L., and Ride, S. (2009). Summary Report of the Review of U.S. Human Space Flight Plans Committee. Technical report.

[Avery, 2011] Avery, G. (2011). Colorado officials eye spaceport at Front Range Airport.

[Baker et al., 2017] Baker, D. M., Head, J. W., Phillips, R. J., Neumann, G. A., Bierson, C. J., Smith, D. E., and Zuber, M. T. (2017). GRAIL gravity observations of the transition from complex crater to peak-ring basin on the Moon: Implications for crustal structure and impact basin formation. *Icarus*, 292:54–73.

[Basco, 2014] Basco, J. (2014). MDC to pay $1.5 million for XCOR improvements.

[BBC, 2008] BBC (2008). Branson unveils space tourism jet.

[BBC, 2019] BBC (2019). Experts cast doubt over Highlands spaceport plan.

[Beaton et al., 2019] Beaton, K., Menzies, A., Young Kim-Castet, S., Abercrombie, S., jplnasagov Victor Luo, Chappell, S., and Lim, D. (2019). Immersive Mixed Reality Capabilities for Planning and Executing Exploration Extravehicular Activity. In *70th International Astronautical Congress*, number 5, Washington D.C., United States. International Astronautical Federation.

[Beaton et al., 2020] Beaton, K. H., Chappell, S. P., Menzies, A., Luo, V., Kim-Castet, S. Y., Newman, D., Hoffman, J., Norheim, J., Anandapadmanaban, E., Abercrombie, S. P., Kobs Nawotniak, S. E., Abercromby, A. F., and Lim, D. S. (2020). Mission enhancing capabilities for science-driven exploration extravehicular activity derived from the NASA BASALT research program. *Planetary and Space Science*, 193.

[Beery, 2012] Beery, J. (2012). State, capital and spaceships: A terrestrial geography of space tourism. *Geoforum*, 43(1):25–34.

[Berger, 2013] Berger, E. (2013). Plans envision spaceport at Ellington.

[Bergin, 2010] Bergin, C. (2010). NASA's Senate Bill passes after dramatic debate and vote in Congress.

[Bernstein et al., 2004] Bernstein, R. D., Darmody, B., Melissaratos, A., Stoltzfus, L., Travis, E. W., Schewel, M., Cooke, Jr., F. B., Boles, V. C., Parker, B., and Rerras, N. (2004). Mid-Atlantic Regional Spaceport (MARS) Implementation Plan. Technical report, Joint Maryland and Virginia Working Group on Regional Spaceport Implementation.

[Blue Origin, 2020] Blue Origin (2020). NASA Selects Blue Origin National Team to Return Humans to the Moon.

[Boyle, 2015a] Boyle, A. (2015a). After Virgin Galactic's Tragic Setback, Spaceport America Goes to Plan B.

[Boyle, 2015b] Boyle, A. (2015b). Spaceport America Launches a Tourist Operation That's Down to Earth.

[Boyle, 2018] Boyle, A. (2018). SpaceShipTwo rocket plane pushes the envelope in third supersonic test flight.

[Boyle, 2019] Boyle, A. (2019). Virgin Galactic signs deal to bring spaceflights to Italian spaceport.

[Browder and Newman, 2019] Browder, B. and Newman, D. (2019). How to Build a Spaceport: Analyzing Spaceport Feasibility via Financial Analysis. In *70th International Astronautical Congress*, pages 1–10. International Astronautical Federation.

[Browder and Newman, 2020] Browder, B. and Newman, D. (2020). Economic Viability of Commercial Spaceports: A Case Study of the Mid-Atlantic Regional Spaceport. In *TECHPRES-10 On-Earth Spaceports and Launch Systems*. ASCEND.

[Brown, 2021] Brown, K. (2021). NASA's SpaceX Crew-2 Astronauts Headed to International Space Station.

[Bryce Space and Technology, 2019] Bryce Space and Technology, L. (2019). 2018 Orbital Launches Year in Review. Technical report.

[Bryce Space and Technology LLC, 2020] Bryce Space and Technology LLC (2020). Start-Up Space 2020: Update on Investment in Commercial Space Ventures. Technical report, Bryce Space and Technology, LLC.

[Bullock, 2020] Bullock, C. (2020). Lunar Extractive Capitalism: Identification of Objectives and Anticipation of Consequences.

[Burrington, 2018] Burrington, I. (2018). New Mexico's Sad Bet on Space Exploration.

[Carey, 2019] Carey, B. (2019). Spaceport Integration Is A Work In Progress.

[Carr and Mcgee, 2009] Carr, C. E. and Mcgee, C. E. (2009). The Apollo Number: Space Suits, Self-Support, and the Walk-Run Transition. *PLoS ONE*, 4(8):1–7.

[Carr and Newman, 2017] Carr, C. E. and Newman, D. J. (2017). Exoskeleton Energetics: Implications for Planetary Extravehicular Activity. In *IEEE Aerospace Conference*, pages 1–14. Institute of Electrical and Electronics Engineers (IEEE).

[Chappaz et al., 2017] Chappaz, L., Sood, R., Melosh, H. J., Howell, K. C., Blair, D. M., Milbury, C., and Zuber, M. T. (2017). Evidence of large empty lava tubes on the Moon using GRAIL gravity. *Geophysical Research Letters*, 44(1):105–112.

[Clarke, 2013] Clarke, S. S. (2013). Severance Tax Bonding Program and Severance Tax Permanent Fund. Technical report, New Mexico State Board of Finance.

[CollectSPACE, 2021] CollectSPACE (2021). 'Moon Registry' catalogs human heritage left behind on lunar surface.

[Collier, 2013] Collier, K. (2013). Airport chief: Ellington spaceport 'definitely doable'.

[Colorado Air and Space Port, 2020] Colorado Air and Space Port (2020). Colorado Air and Space Port.

[Commercial Space Transportation Advisory Committee (COMSTAC), 2021] Commercial Space Transportation Advisory Committee (COMSTAC) (2021). COMSTAC Innovation and Infrastructure Working Group National Spaceport Authority Report. Technical report, Commercial Space Transportation Advisory Committee (COMSTAC).

[Commonwealth of Virginia Auditor of Public Accounts, 1998] Commonwealth of Virginia Auditor of Public Accounts (1998). Virginia Commercial Space Flight Authority Report on Audit for the Year Ended June 30, 1998.

[Commonwealth of Virginia Auditor of Public Accounts, 1999] Commonwealth of Virginia Auditor of Public Accounts (1999). Virginia Commercial Space Flight Authority Report on Audit for the Year Ended June 30, 1999.

[Commonwealth of Virginia Auditor of Public Accounts, 2000] Commonwealth of Virginia Auditor of Public Accounts (2000). Virginia Commercial Space Flight Authority Report on Audit for the Year Ended June 30, 2000.

[Commonwealth of Virginia Auditor of Public Accounts, 2001] Commonwealth of Virginia Auditor of Public Accounts (2001). Virginia Commercial Space Flight Authority Report on Audit for the Year Ended June 30, 2001.

[Commonwealth of Virginia Auditor of Public Accounts, 2002] Commonwealth of Virginia Auditor of Public Accounts (2002). Virginia Commercial Space Flight Authority Report on Audit for the Year Ended June 30, 2002.

[Commonwealth of Virginia Auditor of Public Accounts, 2003] Commonwealth of Virginia Auditor of Public Accounts (2003). Virginia Commercial Space Flight Authority Report on Audit for the Year Ended June 30, 2003.

[Commonwealth of Virginia Auditor of Public Accounts, 2004] Commonwealth of Virginia Auditor of Public Accounts (2004). Virginia Commercial Space Flight Authority Report on Audit for the Year Ended June 30, 2004.

[Commonwealth of Virginia Auditor of Public Accounts, 2005] Commonwealth of Virginia Auditor of Public Accounts (2005). Virginia Commercial Space Flight Authority Report on Audit for the Year Ended June 30, 2005.

[Commonwealth of Virginia Auditor of Public Accounts, 2006] Commonwealth of Virginia Auditor of Public Accounts (2006). Virginia Commercial Space Flight Authority Report on Audit for the Year Ended June 30, 2006.

[Commonwealth of Virginia Auditor of Public Accounts, 2007] Commonwealth of Virginia Auditor of Public Accounts (2007). Virginia Commercial Space Flight Authority Report on Audit for the Year Ended June 30, 2007.

[Commonwealth of Virginia Auditor of Public Accounts, 2008] Commonwealth of Virginia Auditor of Public Accounts (2008). Virginia Commercial Space Flight Authority Report on Audit for the Year Ended June 30, 2008.

[Commonwealth of Virginia Auditor of Public Accounts, 2009] Commonwealth of Virginia Auditor of Public Accounts (2009). Virginia Commercial Space Flight Authority Financial Report for the Year Ended June 30 2009.

[Commonwealth of Virginia Auditor of Public Accounts, 2010] Commonwealth of Virginia Auditor of Public Accounts (2010). Virginia Commercial Space Flight Authority Financial Report for the Year Ended June 30 2010.

[Commonwealth of Virginia Auditor of Public Accounts, 2011] Commonwealth of Virginia Auditor of Public Accounts (2011). Virginia Commercial Space Flight Authority Financial Report for the Year Ended June 30, 2011.

[Commonwealth of Virginia Auditor of Public Accounts, 2020] Commonwealth of Virginia Auditor of Public Accounts (2020). Auditor of Public Accounts Report Finder.

[Corley et al., 2018] Corley, L. M., McGovern, P. J., Kramer, G. Y., Lemelin, M., Trang, D., Gillis-Davis, J. J., Taylor, G. J., Powell, K. E., Kiefer, W. S., Wieczorek, M., and Zuber, M. T. (2018). Olivine-bearing lithologies on the Moon: Constraints on origins and transport mechanisms from M3 spectroscopy, radiative transfer modeling, and GRAIL crustal thickness. *Icarus*, 300:287–304.

[Creel, 2021] Creel, R. (2021). Lunar Roving Adventures: Dust, Dust, Everywhere - What Are We Going To Do?

[D'Ammassa, 2020a] D'Ammassa, A. (2020a). Spaceport America CEO Dan Hicks placed on administrative leave.

[D'Ammassa, 2020b] D'Ammassa, A. (2020b). Spaceport America's former CFO accuses CEO Dan Hicks of abusing authority.

[David, 2012] David, L. (2012). Potential Colorado Spaceport Plan Gaining Steam.

[David, 2019] David, L. (2019). *Moon Rush*. National Geographic Partners, LLC, Washington, DC.

[Davidian, 2016] Davidian, K. (2016). Do "commercial" Space Companies Exist? *New Space*, 4(4).

[de Gregorio, 2016] de Gregorio, Z. (2016). Economic Impact for New Mexico.

[de Weck, 2020] de Weck, O. (2020). *Technology Roadmapping and Development [DRAFT]*. Springer Nature.

[de Weck, 2021] de Weck, O. (2021). Advanced Space Technology Roadmapping Architecture (ASTRA).

[de Weck et al., 2018] de Weck, O., Siddiqi, A., Moraguez, M., Trujillo, A., Lordos, G., and Sarang, M. (2018). Project Report: Development of a Commercial Space Technology Roadmap. Technical report, Strategic Engineering Research Group at the Massachusetts Institute of Technology.

[Dean, 2014] Dean, J. (2014). Lawmakers fire up alternatives for Shiloh complex.

[Decamp and Gibbons, 2005] Decamp, D. and Gibbons, T. J. (2005). IS SPACE IN CECIL'S FUTURE? State and City Officials Have Been Quietly Building a Case for Luring a Spaceport for Months.

[Dickerson, 2015] Dickerson, K. (2015). Watch the incredible first test flight of Jeff Bezos's mysterious new rocket.

[Dixon, 2020] Dixon, D. (2020). Jacksonville's Cecil Spaceport is counting down to 'liftoff'.

[Dixon Hughes Goodman LLP, 2012] Dixon Hughes Goodman LLP (2012). Virginia Commercial Space Flight Authority Financial Report for the Year Ended June 30, 2012.

[Dixon Hughes Goodman LLP, 2013] Dixon Hughes Goodman LLP (2013). Virginia Commercial Space Flight Authority Financial Statements Year Ended June 30, 2013.

[Dixon Hughes Goodman LLP, 2014] Dixon Hughes Goodman LLP (2014). Virginia Commercial Space Flight Authority Financial Statements Year Ended June 30, 2014.

[Dixon Hughes Goodman LLP, 2015] Dixon Hughes Goodman LLP (2015). Virginia Commercial Space Flight Authority Financial Statements as of and for the Year Ended June 30, 2015, and Independent Auditors' Report.

[Dixon Hughes Goodman LLP, 2016] Dixon Hughes Goodman LLP (2016). Virginia Commercial Space Flight Authority Financial Statements Year Ended June 30, 2016.

[Dixon Hughes Goodman LLP, 2017] Dixon Hughes Goodman LLP (2017). Virginia Commercial Space Flight Authority Financial Statements Year Ended June 30, 2017.

[Dixon Hughes Goodman LLP, 2018] Dixon Hughes Goodman LLP (2018). Virginia Commercial Space Flight Authority Financial Statements Year Ended June 30, 2018.

[Doreen, 2018] Doreen, S. (2018). Council to talk about spaceport's future.

[Doreen, 2020] Doreen, S. (2020). MDC board approves deal with spaceport prospect.

[Dozier et al., 2021] Dozier, J., Kirkbride, M., and Jamison, T. (2021). MIT Five-year Strategic Action Plan for Diversity, Equity, and Inclusion (2021-2026) - DRAFT. Technical report, Massachusetts Institute of Technology.

[Drake, 2019] Drake, N. (2019). Want to be a space tourist? Here's what to expect.

[Dreier, 2020] Dreier, C. (2020). NASA's Commercial Crew Program is a Fantastic Deal.

[Dunbar, 2020] Dunbar, B. (2020). International Space Exploration Coordination Group.

[Eberly and Browder, 2020] Eberly, K. and Browder, B. (2020). Personal Interview with Kurt Eberly.

[Editorial Board, 2014] Editorial Board (2014). Spaceport: One small step.

[Eiskowitz et al., 2020] Eiskowitz, S., Dolan, S., Latyshev, K., Lordos, G., Moraguez, M., Trujillo, A., Cameron, B., De Weck, O., and Crawley, E. (2020). Quantifying the Impact of Cryo-Management, ISRU, and Fuel Cell Lunar Technology Infusion to a Notional Mars LOX/LH2 Architecture. In *71st International Astronautical Congress (IAC) – The CyberSpace Edition*, pages 1–10. International Astronautical Federation.

[Elkins-Tanton, 2018] Elkins-Tanton, L. (2018). Planning to measure an unknown asteroid.

[Eppinger and Browning, 2012] Eppinger, S. D. and Browning, T. R. (2012). *Design structure matrix methods and applications.* MIT Press.

[European Space Agency, 2021] European Space Agency (2021). ESA engineers assess Moon Village habitat.

[FAA Office of Commercial Space Transportation, 2018] FAA Office of Commercial Space Transportation (2018). The Annual Compendium of Commercial Space. Technical report, Federal Aviation Administration.

[FAA Spaceport Categorization ARC, 2019] FAA Spaceport Categorization ARC (2019). Spaceport Categorization ARC Final Report. Technical report, Federal Aviation Administration, Washington, DC.

[FAA/AST, 2020] FAA/AST (2020). U.S. Spaceports – Commercial/Government/Private Active. Technical report, Federal Aviation Administration.

[Federal Aviation Administration, 2008] Federal Aviation Administration (2008). Commercial Space Transportation License, License Order No. LSO 08-011 - New Mexico Spaceport Authority.

[Federal Aviation Administration, 2010] Federal Aviation Administration (2010). FAA Issues First-Ever Spaceport Grants to Strengthen Commercial Space Activities.

[Federal Aviation Administration, 2012] Federal Aviation Administration (2012). Commercial Space Transportation License, License Number LSO 02-007 (Rev 2) - Virginia Commercial Space Flight Authority.

[Federal Aviation Administration, 2014] Federal Aviation Administration (2014). Commercial Space Transportation License, License Order No. LSO 14-015A (Rev 1).

[Federal Aviation Administration, 2015] Federal Aviation Administration (2015). Commercial Space Transportation License, License Order No. LSO 10-014A (Rev 2) - Cape Canaveral Air Force Station.

[Federal Aviation Administration, 2016] Federal Aviation Administration (2016). Commercial Space Transportation License, License Number: LSO 06-010 (REV 2).

[Federal Aviation Administration, 2017] Federal Aviation Administration (2017). Spaceport Categorization Aviation Rulemaking Committee Charter. Technical report, Federal Aviation Administration.

[Federal Aviation Administration, 2018] Federal Aviation Administration (2018). Commercial Space Transportation License, License Number LSO 18-018.

[Federal Aviation Administration, 2020a] Federal Aviation Administration (2020a). 2020 Houston Renewal Order.

[Federal Aviation Administration, 2020b] Federal Aviation Administration (2020b). Active Licenses.

[Federal Aviation Administration, 2020c] Federal Aviation Administration (2020c). Commercial Space Transportation License, License Number LSO 20-019.

[Feldman, 2019] Feldman, S. (2019). The Science Traceability Matrix. Technical report, NASA PI Launchpad Workshop.

[Filer, 2019] Filer, L. (2019). The Economic Impact of the Wallops Aerospace Cluster. Technical report, Old Dominion University.

[Finger and Gulliver, 2009] Finger, G. W. and Gulliver, B. (2009). Design of Operationally Responsive Launch Sites. In *47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition*, pages 1–12, Orlando, Florida. American Institute of Aeronautics and Astronautics.

[Finger and Gulliver, 2010] Finger, G. W. and Gulliver, B. (2010). Economic Factors for Launch Complex Development in Current Economy. In *48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition*, pages 1–8, Orlando, Florida. American Institute of Aeronautics and Astronautics.

[Finger et al., 2007a] Finger, G. W., Keller, D. L., and Gulliver, B. (2007a). Launch Site Infrastructure Cost Trends. In *AIAA SPACE 2007 Conference and Exposition*, pages 1–5, Long Beach, California.

[Finger et al., 2008] Finger, G. W., Keller, D. L., and Gulliver, B. (2008). Public-Private Spaceport Development. In *SpaceOps 2008 Conference*, pages 1–8, Heidelberg, Germany. European Space Agency, EUMETSAT, American Institute of Aeronautics and Astronautics.

[Finger et al., 2007b] Finger, G. W., Kercsmar, J. C., Hammett, R. C., Keller, D. L., Endicott, P. K., and Gulliver, B. (2007b). State Spaceports-If You Build It, Will They Come?

[Finnerty, 2019] Finnerty, R. (2019). Alaska Residents Urge Caution to Hawai'i Officials Considering Spaceport.

[Fly2Houston, 2015] Fly2Houston (2015). Houston Airport System plans for spaceport approved by FAA.

[For All Moonkind, 2021] For All Moonkind (2021). For All Moonkind Moon Registry – Human Heritage on the Moon.

[Foust, 2004a] Foust, J. (2004a). Little spaceport on the prairie.

[Foust, 2004b] Foust, J. (2004b). Oklahoma is OK for suborbital.

[Foust, 2010] Foust, J. (2010). The maturing NewSpace industry.

[Foust, 2014] Foust, J. (2014). A spaceport in limbo.

[Foust, 2015] Foust, J. (2015). House Passes Commercial Space Bill.

[Foust, 2016] Foust, J. (2016). Waiting for liftoff.

[Foust, 2017] Foust, J. (2017). House passes NASA authorization bill.

[Foust, 2018] Foust, J. (2018). A trillion-dollar space industry will require new markets.

[Foust, 2019a] Foust, J. (2019a). Commercial spaceports increase focus on economic development.

[Foust, 2019b] Foust, J. (2019b). Florida airport seeks spaceport license.

[Foust, 2019c] Foust, J. (2019c). Foust Forward | How to succeed in spaceports without really launching.

[Foust, 2019d] Foust, J. (2019d). How many spaceports are too many?

[Foust, 2019e] Foust, J. (2019e). LEO commercialization studies show wide range of markets and demand.

[Foust, 2019f] Foust, J. (2019f). Spaceports seek ways to deal with public opposition.

[Foust, 2019g] Foust, J. (2019g). The spaceport glut.

[Foust, 2019h] Foust, J. (2019h). U.K. to fund development of spaceport facilities for Virgin Orbit.

[Foust, 2020a] Foust, J. (2020a). Report concludes former Spaceport America director violated state law.

[Foust, 2020b] Foust, J. (2020b). Virgin Galactic prepares for low-key first spaceflight from New Mexico.

[Foust, 2021a] Foust, J. (2021a). Dynetics protests NASA HLS award.

[Foust, 2021b] Foust, J. (2021b). Starliner test flight scheduled for July 30.

[Futron Corporation, 2002] Futron Corporation (2002). Space Tourism Market Study: Orbital Space Travel and Destinations with Suborbital Space Travel. Technical report.

[Futron Corporation, 2005] Futron Corporation (2005). New Mexico Commercial Spaceport Economic Impact Study. Technical report.

[Gerstein, 2020] Gerstein, M. (2020). Spaceport board removes former CEO.

[Gleason, 2014] Gleason, R. (2014). Spaceport could limit city's growth options.

[Goossens et al., 2020] Goossens, S., Sabaka, T. J., Wieczorek, M. A., Neumann, G. A., Mazarico, E., Lemoine, F. G., Nicholas, J. B., Smith, D. E., and Zuber, M. T. (2020). High-Resolution Gravity Field Models from GRAIL Data and Implications for Models of the Density Structure of the Moon's Crust. *Journal of Geophysical Research: Planets*, 125(2):e2019JE006086.

[Gould, 2020] Gould, J. (2020). Allegations of criminal acts part of CEO probe, spaceport official says.

[Gould, 2019] Gould, J. E. (2019). Spaceport: Time to boost staff, infrastructure.

[Graham and Bergin, 2014] Graham, W. and Bergin, C. (2014). Orbital's Antares fails seconds after launch.

[Gray, 2020] Gray, T. (2020). Astra launches on first orbital test; fails in first stage flight.

[Grush, 2020] Grush, L. (2020). Virgin Galactic aborts first powered spaceflight from New Mexico spaceport.

[Gulliver, 2016] Gulliver, B. (2016). Commercial Spaceports: Where We Are and Where We Are Going. pages 1–6. Kimley-Horn and Associates, Inc., International Conference on Transportation and Development.

[Gulliver et al., 2017] Gulliver, B., Barden, J. P., and Valentine, B. D. (2017). Seeing is Believing-Improving Spaceport Planning and Public Outreach Through Visualization. In *AIAA SPACE and Astronautics Forum and Exposition*, pages 1–7, Orlando, Florida. American Institute for Aeronautics and Astronautics.

[Gulliver and Finger, 2010] Gulliver, B. and Finger, G. W. (2010). Can Your Airport Become a Spaceport? The Benefits of a Spaceport Development Plan. In *48th Annual AIAA Aerospace Sciences Meeting Including New Horizons Forum and Aerospace Exposition*, pages 1–9, Orlando, Florids. American Institute for Aeronautics and Astronautics.

[Gulliver and Finger, 2014] Gulliver, B. and Finger, G. W. (2014). Spaceport Infrastructure Cost Trends. In *AIAA SPACE 2014 Conference and Exposition*, page 8, San Diego, California. American Institute of Aeronautics and Astronautics.

[Gulliver et al., 2009] Gulliver, B., Finger, G. W., and Curtis, C. J. (2009). Aerospaceports - Economic and Schedule Guidelines. In *AIAA Proceedings*, Hilton Head, South Carolina. American Institute of Aeronautics and Astronautics.

[Gulliver et al., 2012] Gulliver, B., Finger, G. W., Ibold, K. R., and Sandifer, W. C. (2012). From Airports to Commercial Spaceports. pages 1–10, Pasadena, California. AIAA SPACE 2012 Conference and Exposition.

[Gulliver et al., 2014] Gulliver, B., Ibold, K. R., Rogers, R. M., and Finger, G. W. (2014). Financial Aspects of Aerospaceport Implementation and Operation. In *AIAA SPACE 2014 Conference and Exposition*, pages 1–9, San Diego, California. American Institute of Aeronautics and Astronautics.

[Handberg, 2002] Handberg, R. (2002). Creating transportation infrastructure through state spaceport initiatives: Florida and other examples. *Technology in Society*, 24(3):225–241.

[Handberg, 2014] Handberg, R. (2014). Building the new economy: "NewSpace" and state spaceports. *Technology in Society*, 39:117–128.

[Hardesty, 2009] Hardesty, L. (2009). Apollo's Rocket Scientists. *MIT Technology Review*.

[Harvey, 2020] Harvey, A. (2020). Ashes to Ashes | łeeshchih dah łeeshchih.

[Harvey, 2021] Harvey, A. (2021). Lunar Prospector and the Navajo Response.

[Harwood, 2015] Harwood, W. (2015). Jeff Bezos plans to boost humans into space from Cape Canaveral.

[Harwood, 2020] Harwood, W. (2020). SpaceX launches secret NRO satellite, its record-setting 26th launch of the year - CBS News.

[Haussamen, 2017] Haussamen, H. (2017). Is Spaceport America taking flight?

[Hawes, 2016] Hawes, T. (2016). Despite XCOR setback, space industry in Midland continues to grow.

[Hawes, 2018] Hawes, T. (2018). MDC terminates agreement with Orbital Outfitters.

[Hilburg, 2020] Hilburg, J. (2020). SpaceX reveals it's building a luxury spaceport in a small Texas town.

[Hughes, 2018] Hughes, T. (2018). Small rockets, big dreams: More spaceports are taking root across the U.S.

[International Space Exploration Coordination Group, 2020] International Space Exploration Coordination Group (2020). Global Exploration Roadmap Supplement August 2020: Lunar Surface Exploration Scenario Update. Technical report, International Space Exploration Coordination Group.

[International Space Station (ISS) Cooperative Agreement Independent Review Team, 2020] International Space Station (ISS) Cooperative Agreement Independent Review Team (2020). A Strategy for the Future of the International Space Station (ISS) National Laboratory (ISSNL) and Commercial Low-Earth Orbit (LEO) Development. Technical report.

[International Space University, 2008] International Space University (2008). FuturIST: Future Infrastructure for Space Transportation Final Report. Technical report, International Space University.

[Johnson et al., 2010] Johnson, C., Hoffman, J., Newman, D., Mazarico, E., Zuber, M., Johnson, A. W., Hoffman, J. A., Newman, D. J., Mazarico, E. M., and Zuber, M. T. (2010). An Integrated Traverse Planner and Analysis Tool for Planetary Exploration Terms of Use Creative Commons Attribution-Noncommercial-Share Alike 3.0 An Integrated Traverse Planner and Analysis Tool for Planetary Exploration. In *AIAA SPACE 2010 Conference and Exposition*, pages 1–28, Anaheim, CA. American Institute of Aeronautics and Astronautics.

[Jones, 2021] Jones, A. (2021). China, Russia enter MoU on international lunar research station.

[Kagan and Uradu, 2020] Kagan, J. and Uradu, L. D. (2020). Severance Tax Definition.

[Kelly, 2020] Kelly, E. (2020). Space Coast airport wants to launch and land spacecraft in Titusville.

[Kepler Aerospace, 2021] Kepler Aerospace (2021). About – Kepler Aerospace.

[Klamper, 2010] Klamper, A. (2010). Garver, Bolden Urge Passage of NASA Authorization.

[Knight,] Knight, H. Creating a Space Sustainability Rating.

[Kohler, 2020] Kohler, J. (2020). Colorado's aerospace industry not slowing down in pandemic.

[KPMG Corporate Finance LLC, 2011] KPMG Corporate Finance LLC (2011). Virginia Commercial Space Flight Authority Governance, Organization and Competitive Landscape Review. Technical report, KPMG Corporate Finance LLC.

[Kubota, 2019] Kubota, L. (2019). Big Island residents say no to the idea of a rocket launching facility.

[Landers, 2018] Landers, M. (2018). Public comments slam coastal Georgia spaceport proposal.

[Lauer, 2007] Lauer, C. J. (2007). The XP spaceplane: A near term multi-purpose suborbital RLV. *Acta Astronautica*, 61(1-6):432–437.

[Leinfelder, 2019] Leinfelder, A. (2019). Houston Spaceport inks deal with its third tenant.

[Lemon et al., 2017] Lemon, N. K., Gulliver, B., and West, C. L. (2017). Analysis of Utilizing Existing Runways for Horizontal Commercial Space Launch and Reentry. In *AIAA SPACE and Astronautics Forum and Exposition*, pages 1–6, Orlando, Florida. American Institute of Aeronautics and Astronautics.

[Lester, 2017] Lester, R. K. (2017). A Global Strategy for MIT. Technical report, Massachusetts Institute of Technology.

[Logsdon and Nye, 2018] Logsdon, J. M. and Nye, B. (2018). *The Penguin book of outer space exploration: NASA and the incredible story of human spaceflight.*

[Lunar Exploration Roadmap Steering Committee et al., 2016] Lunar Exploration Roadmap Steering Committee, Abell, P., Bailey, B., Beaty, D., Beinhoff, D., Bell, M. S., Duke, M., Eckert, P., Eppler, D., Gruener, J., Jones, J., Kelso, R., Klaus, K., Kring, D., Lawrence, S., Lester, D., Mackwell, S., Neal, C., Neitzel, P., Peach, L., Pellis, N., Ramsey, M., Rayl, N., Reiss-Bubenheim, D., Rice, J., Sanders, G., Sacksteder, K., Schmidt, G., Shearer, C., Snook, K., Spann, J., Spudis, P., Tahu, G., Taylor, J., Taylor, L., Volosin, J., and Wargo, M. (2016). The Lunar Exploration Roadmap: Exploring the Moon in the 21st Century: Themes, Goals, Objectives, Investigations, and Priorities, 2016. Technical report, A Community Endeavor Coordinated by the Lunar Exploration Analysis Group (LEAG).

[MacKenzie et al., 2016] MacKenzie, S. M., Caswell, T. E., Phillips-Lander, C. M., Stavros, E. N., Hofgartner, J. D., Sun, V. Z., Powell, K. E., Steuer, C. J., O'Rourke, J. G., Dhaliwal, J. K., Leung, C. W., Petro, E. M., Wynne, J. J., Phan, S., Crismani, M., Krishnamurthy, A., John, K. K., DeBruin, K., Budney, C. J., and Mitchell, K. L. (2016). THEO concept mission: Testing the Habitability of Enceladus's Ocean. *Advances in Space Research*, 58(6):1117–1137.

[Macvean and Hernandez, 2019] Macvean, K. and Hernandez, B. (2019). Is the time right for Arizona to build a spaceport?

[Martin, 2019] Martin, F. (2019). Houston Spaceport Groundbreaking, First Company Tenant Expected Within Weeks.

[Matula and Mitry, 2002] Matula, T. L. and Mitry, D. J. (2002). Spaceports as Multi-Use Industrial Facilities – A Marketing Approach to Spaceport Development. In *Space 2002: The 8th International Conference on Engineering, Construction, and Operations in Space*, pages 1–6, Albuquerque, NM.

[McKay, 2018] McKay, D. (2018). Spaceport bill clears key Senate committee.

[McNutt, 2010] McNutt, M. (2010). Spaceport bill passes Oklahoma House day after failing.

[Mehak Sarang, 2021] Mehak Sarang (2021). The MIT SEI Space Governance Collaborative.

[Messier, 2010] Messier, D. (2010). Rocketplane Global Expects to Begin Suborbital Space Tourist Flights in 2013.

[Messier, 2011] Messier, D. (2011). Commercial Spacesuit Companies Compete for Market Share.

[Messier, 2019a] Messier, D. (2019a). 2018 Was Busy Year for Suborbital Flight Tests.

[Messier, 2019b] Messier, D. (2019b). A Brief History of Spaceport America.

[Messier, 2019c] Messier, D. (2019c). Spaceport America and Virgin Galactic: The Numbers Never Added Up.

[Mighani et al., 2020] Mighani, S., Wang, H., Shuster, D. L., Borlina, C. S., Nichols, C. I. O., and Weiss, B. P. (2020). The end of the lunar dynamo. *Science Advances*, pages 1–74.

[MIT Department of Aeronautics and Astronautics, 2020] MIT Department of Aeronautics and Astronautics (2020). To Look Ahead, Look Up: Strategic Plan 2020. Technical report, Massachusetts Institute of Technology.

[MIT Media Lab, 2021] MIT Media Lab (2021). Overview: Lunar Open Architecture.

[MIT Strategic Engineering et al., 2018] MIT Strategic Engineering, de Weck, O., Siddiqi, A., Moraguez, M., Trujillo, A., Lordos, G., and Sarang, M. (2018). Commercial Space Technology Roadmap. Technical report, NASA Emerging Space Office.

[Mitri et al., 2018] Mitri, G., Postberg, F., Soderblom, J. M., Wurz, P., Tortora, P., Abel, B., Barnes, J. W., Berga, M., Carrasco, N., Coustenis, A., Paul de Vera, J. P., D'Ottavio, A., Ferri, F., Hayes, A. G., Hayne, P. O., Hillier, J. K., Kempf, S., Lebreton, J. P., Lorenz, R. D., Martelli, A., Orosei, R., Petropoulos, A. E., Reh, K., Schmidt, J., Sotin, C., Srama, R., Tobie, G., Vorburger, A., Vuitton, V., Wong, A., and Zannoni, M. (2018). Explorer of Enceladus and Titan (E2T): Investigating ocean worlds' evolution and habitability in the solar system. *Planetary and Space Science*, 155:73–90.

[Moran, 2012] Moran, C. (2012). City aviation director envisions spaceport at Ellington.

[Moran and Collier, 2012] Moran, C. and Collier, K. (2012). Airport boss supports international flights at Hobby.

[Moss Adams LLP, 2020a] Moss Adams LLP (2020a). Spaceport America Economic and Fiscal Impact Analyses. Technical report, Moss Adams LLC.

[Moss Adams LLP, 2020b] Moss Adams LLP (2020b). Spaceport America Economic and Fiscal Impact Analyses: Executive Summary. Technical report, Moss Adams LLC.

[Mustard et al., 2013] Mustard, J., Adler, M., Allwood, A., Bass, D., Beaty, D., Bell III, J., Brinckerhoff, W., Carr, M., Des Marais, D., Drake, B., Edgett, K., Eigenbrode, J., Elkins-Tanton, L., Grant, J., Milkovich, S. M., Ming, D., Moore, C., Murchie, S., Onstott, T., Ruff, S., Sephton, M., Steele, A., and Treiman, A. (2013). Report of the Mars 2020 Science Definition Team. Technical report, Mars Exploration Program Analysis Group (MEPAG).

[NASA, 2020] NASA (2020). Commercial Lunar Payload Services.

[NASA Administrator, 2013] NASA Administrator (2013). Maj. Gen. Robert White, Former X-15 pilot, Dies at 85.

[NASA Glenn Research Center, 2020] NASA Glenn Research Center (2020). Microgravity Research Flights.

[National Academies of Sciences Engineering and Medicine, 2010] National Academies of Sciences Engineering and Medicine (2010). *Airport Revenue Diversification*. The National Academies Press, Washington, DC.

[National Aeronautics and Space Administration, 2015] National Aeronautics and Space Administration (2015). 2015 NASA Technology Roadmaps (Archive).

[National Aeronautics and Space Administration, 2019] National Aeronautics and Space Administration (2019). NASA Plan for Commercial LEO Development. Technical report, National Aeronautics and Space Administration.

[National Aeronautics and Space Administration, 2020a] National Aeronautics and Space Administration (2020a). 2020 NASA Technology Taxonomy.

[National Aeronautics and Space Administration, 2020b] National Aeronautics and Space Administration (2020b). NASA's Plan for Sustained Lunar Exploration and Development. Technical report, National Aeronautics and Space Administration.

[National Aeronautics and Space Administration, 2020c] National Aeronautics and Space Administration (2020c). The Artemis Accords: Principles for Cooperation in the Civil Exploration and Use of the Moon, Mars, Comets and Asteroids for Peaceful Purposes. Technical report.

[National Aeronautics and Space Administration, 2021] National Aeronautics and Space Administration (2021). Artemis III Science Definition Team Report. Technical report, National Aeronautics and Space Administration.

[New Mexico Office of the State Auditor,] New Mexico Office of the State Auditor. Audit Report Search.

[New Mexico Spaceport Authority and Axiom Certified Public Accountants and Business Advisors LL New Mexico Spaceport Authority and Axiom Certified Public Accountants and Business Advisors LLC (2016). New Mexico Spaceport Authority Financial Statements Year Ended June 30, 2016. Technical report, New Mexico Spaceport Authority.

[New Mexico Spaceport Authority and Axiom Certified Public Accountants and Business Advisors LL
New Mexico Spaceport Authority and Axiom Certified Public Accountants and Business Advisors LLC (2017). New Mexico Spaceport Authority Financial Statements Year Ended June 30, 2017. Technical report, New Mexico Spaceport Authority.

[New Mexico Spaceport Authority and Axiom Certified Public Accountants and Business Advisors LL
New Mexico Spaceport Authority and Axiom Certified Public Accountants and Business Advisors LLC (2018). New Mexico Spaceport Authority Financial Statements Year Ended June 30, 2018. Technical report, New Mexico Spaceport Authority.

[New Mexico Spaceport Authority and Clifton Gunderson LLP, 2011] New Mexico Spaceport Authority and Clifton Gunderson LLP (2011). New Mexico Spaceport Authority Financial Statements June 30, 2011. Technical report, New Mexico Spaceport Authority.

[New Mexico Spaceport Authority and CliftonLarsonAllen LLP, 2012] New Mexico Spaceport Authority and CliftonLarsonAllen LLP (2012). New Mexico Spaceport Authority Annual Financial Report for the Year Ended June 30, 2012. Technical report, New Mexico Spaceport Authority.

[New Mexico Spaceport Authority and CliftonLarsonAllen LLP, 2013] New Mexico Spaceport Authority and CliftonLarsonAllen LLP (2013). New Mexico Spaceport Authority Financial Statements June 30, 2013. Technical report, New Mexico Spaceport Authority.

[New Mexico Spaceport Authority and CliftonLarsonAllen LLP, 2014] New Mexico Spaceport Authority and CliftonLarsonAllen LLP (2014). New Mexico Spaceport Authority Financial Statements June 30, 2014. Technical report, New Mexico Spaceport Authority.

[New Mexico Spaceport Authority and CliftonLarsonAllen LLP, 2015] New Mexico Spaceport Authority and CliftonLarsonAllen LLP (2015). New Mexico Spaceport Authority Financial Statements Year Ended June 30, 2015. Technical report, New Mexico Spaceport Authority.

[New Mexico Spaceport Authority and Meyners + Company, 2008] New Mexico Spaceport Authority and Meyners + Company, L. (2008). New Mexico Spaceport Authority Financial Statements for the Year Ended June 30, 2008. Technical report, New Mexico Spaceport Authority.

[New Mexico Spaceport Authority and Meyners + Company, 2009] New Mexico Spaceport Authority and Meyners + Company, L. (2009). New Mexico Spaceport Authority Financial Statements for the Year Ended June 30, 2009. Technical report, New Mexico Spaceport Authority.

[New Mexico Spaceport Authority and Meyners + Company, 2010] New Mexico Spaceport Authority and Meyners + Company, L. (2010). New Mexico Spaceport Authority Financial Statements for the Year Ended June 30, 2010. Technical report, New Mexico Spaceport Authority.

[New Mexico Spaceport Authority and Patillo, Brown and Hill, 2019] New Mexico Spaceport Authority and Patillo, Brown and Hill, L. (2019). New Mexico Spaceport Authority Financial Statements Year Ended June 30, 2019. Technical report, New Mexico Spaceport Authority.

[New Mexico State Legislature, 2018] New Mexico State Legislature (2018). Commercial Aerospace Protection Act.

[Norheim et al., 2018] Norheim, J., Hoffman, J., Newman, D., Cohen, T. E., Lees, D. S., Deans, M. C., and Lim, D. S. (2018). Architecture of a surface exploration traverse analysis and navigational tool. In *IEEE Aerospace Conference Proceedings*, volume 2018-March, pages 1–11. IEEE Computer Society.

[of Aeronautics and Astronautics, 2019] of Aeronautics, M. D. and Astronautics (2019). MIT AeroAstro Strategic Plan 2019. Technical report, Massachusetts Institute of Technology.

[Oh et al., 2019] Oh, D. Y., Collins, S., Drain, T., Hart, W., Imken, T., Larson, K., Marsh, D., Muthulingam, D., Steven Snyder, J., Trofimov, D., Elkins-Tanton, L. T., Johnson, I., Lord, P., and Pirkl, Z. (2019). Development of the Psyche Mission for NASA's Discovery Program. In *36th International Electric Propulsion Conference*, pages 1–29, Vienna, Austria.

[Oklahoma Space Industry Development Authority, 2019] Oklahoma Space Industry Development Authority (2019). Oklahoma Space Industry Development Authority - About.

[Ompusunggu, 2017] Ompusunggu, M. (2017). Indonesia to talk with China, Russia about spaceport project.

[Ortegon, 2014] Ortegon, J. (2014). Special Report: What does Virgin Galactic crash mean for Spaceport America?

[Paige et al., 2021a] Paige, C., Haddad, D. D., Ward, F., Piercy, T., Heldmann, J., Lim, D., Colaprete, A., Cook, A., and Newman, D. J. (2021a). Lunar instrument data integration into the Virtual Reality Mission Simulation System for Decision Making and Situational Awareness. In *50th International Conference on Environmental Systems*.

[Paige et al., 2021b] Paige, C., Ward, F., Piercy, T., and Newman, D. J. (2021b). A virtual reality mission simulation system for lunar rover missions. In *SpaceCHI Conference*.

[Palmer, 2010] Palmer, J. (2010). No spaceships at Oklahoma's spaceport but they are welcome.

[Pappalardo, 2019] Pappalardo, J. (2019). *Spaceport Earth*. Abrams Press, New York, New York.

[Patricio Ruiloba Rep Tomás Salazar et al., 2016] Patricio Ruiloba Rep Tomás Salazar, R. E., William Soules Sen Joseph Cervantes, S. P., Rep David Adkins Rep Patricia A Lundstrom Sen Nancy Rodriguez Rep Patricia Roybal Caballero Sen John C Ryan Rep Monica Youngblood, C. E., Jacob Candelaria Rep George Dodge, S. R., Rep Brian Egolf Rep Roberto, J., Gonzales Sen Stuart Ingle Rep Sarah Maestas Barnes Sen Bill O, J. B., and Sen William Payne Sen Clemente Sanchez, N. H. (2016). Minutes of the Fourth Meeting of the New Mexico Finance Authority Oversight Committee. Technical report, New Mexico Finance Authority Oversight Committee, Las Cruces, NM.

[Plait, 2012] Plait, P. (2012). A Grasshopper's Leap. *Slate*.

[Potter, 2021] Potter, S. (2021). NASA Awards Artemis Contract for Gateway Logistics Services.

[Pound, 2016] Pound, J. (2016). The space wait continues for Oklahoma town.

[Public Affairs Office,] Public Affairs Office, W. S. M. R. White Sands Missile Range – More Than Missiles Fact Sheet.

[Raymond and Browder, 2021] Raymond, J. and Browder, B. (2021). Personal Interview with General John Raymond.

[Raymond, 1997] Raymond, M. J. W. (1997). Airports and Spaceports: A Historical Comparison. Technical report, Air Command and Staff College.

[Reagan, 2019] Reagan, M. (2019). UPDATE: SpaceX conducts first tests requiring closures at Boca Chica Beach.

[Reimold, 2018] Reimold, D. (2018). U.S. Commercial Space Transportation Regulations. Technical Report January, Federal Aviation Administration Office of Commercial Space Transportation.

[Reimold and Sloan, 2017] Reimold, D. and Sloan, J. (2017). Commercial Space Transportation Overview. Technical report, Federal Aviation Administration Office of Commercial Space Transportation, Arlington, Virginia.

[Ridge Bowman et al., 2021] Ridge Bowman, James Smith, Benjamin Patterson, Lauren Suls, and Paul K. Martin (2021). Artemis Status Update. Technical report, NASA Office of Inspector General.

[Robert, 2017] Robert, A. (2017). States Bet On Spaceports, Future Economic Benefits.

[Roberts, 2019a] Roberts, T. G. (2019a). History of the NASA Budget - Aerospace Security.

[Roberts, 2019b] Roberts, T. G. (2019b). Spaceports of the World. Technical report, Center for Strategic and International Studies.

[Rodriguez, 2018] Rodriguez, J. (2018). Colorado just got approval for a spaceport. Here's what that actually means.

[RS&H, 2020] RS&H, I. (2020). Cecil Field Spaceport - RS&H, Inc.

[Rubel, 2016] Rubel, W. (2016). Spaceport head says bill would shutter facility.

[Ryba, 2012] Ryba, J. (2012). NASA - Kennedy History Quiz.

[Sarang et al., 2020] Sarang, M., Robinson, C., and Ekblaw, A. (2020). Towards a Lunar Open Architecture: facilitating transparency and collaboration in the new era of lunar exploration. In *71st International Astronautical Congress (IAC)*, Virtual. International Astronautical Federation (IAF).

[Schingler et al., 2019] Schingler, J. K., Guglin, J., Sarang, M., and Ekblaw, A. (2019). Lunar Mission Actor Analysis: Open Information Architecture for International Collaboration. In *70th International Astronautical Congress (IAC)*, pages 1–12. International Astronautical Federation (IAF).

[Scoles, 2018] Scoles, S. (2018). America's Spaceport Boom Is Outpacing the Need to Go to Space.

[Seedhouse and International Space University, 2017] Seedhouse, E. and International Space University (2017). *Spaceports Around the World, A Global Growth Industry*. Springer.

[Seymour, 2020] Seymour, D. (2020). Spaceport revenue claims don't add up.

[Sherwood, 2016] Sherwood, B. (2016). Strategic map for exploring the ocean-world Enceladus. *Acta Astronautica*, 126:52–58.

[Sherwood and McCLeese, 2013] Sherwood, B. and McCLeese, D. (2013). JPL innovation foundry. *Acta Astronautica*, 89:236–247.

[Sloan, 2020] Sloan, K. (2020). Spaceport Authority board approves $20 million in "urgently required critical infrastructure developments" despite Spaceport's lack of a strategic business plan.

[Smith and Zervos, 2010] Smith, G. and Zervos, D. V. (2010). *A New European Spaceport: Law and Politics in Spain*. PhD thesis, International Space University.

[Space Florida, 2017] Space Florida (2017). Cape Canaveral Spaceport Master Plan January 2017. Technical report, Space Florida.

[Space Florida, 2018] Space Florida (2018). Florida Spaceport System Plan 2018. Technical report, Space Florida.

[Space Florida, 2019] Space Florida (2019). Dare to Dream - Space Florida 2019 Annual Report. Technical report, Space Florida.

[Spaceport America, 2015] Spaceport America (2015). Spaceport America Business Plan. Technical report.

[State of New Mexico and New Mexico Spaceport Authority, 2019] State of New Mexico and New Mexico Spaceport Authority (2019). Request for Proposals (RFP): Spaceport America Economic Impact Study. Technical report, State of New Mexico.

[Staten, 2020] Staten, M. (2020). Spaceport America Discusses Search For New CFO And More With Legislative Finance Committee.

[Stone, 2012] Stone, C. (2012). Perception vs. reality in NASA's commercial crew and cargo program.

[Tennant, 2008] Tennant, D. (2008). NASA destroys rocket shortly after launch at Wallops Island.

[The Associated Press, 2015] The Associated Press (2015). Revenue plan for Spaceport America gets go-ahead.

[The Associated Press, 2018] The Associated Press (2018). Spaceport Colorado sells the future.

[The Guardian, 2010] The Guardian (2010). NASA budgets: US spending on space travel since 1958.

[The Performance Management Group in the L. Douglas Wilder School of Government and Public Af
The Performance Management Group in the L. Douglas Wilder School of Government and Public Affairs at Virginia Commonwealth University (2011). Competitive Analysis of Virginia's Space Industry. Technical report.

[The Planetary Society et al., 2020] The Planetary Society, Lal, B., Dreier, C., and Kaplan, M. (2020). Space Policy Edition: A Trillion-Dollar Space Economy?

[The State of New Mexico State Auditor and The McHard Firm, 2020] The State of New Mexico State Auditor and The McHard Firm (2020). Audit Report Details - New Mexico Spaceport Authority 2020. Technical report, The State of New Mexico State Auditor.

[Thompson and Browder, 2019] Thompson, D. and Browder, B. (2019). Personal Interview with David Thompson.

[Tinoco, 2018] Tinoco, J. K. (2018). Public-Private Partnerships in Transportation: Lessons Learned for the New Space Era. Technical report.

[Tobie et al., 2014] Tobie, G., Teanby, N. A., Coustenis, A., Jaumann, R., Raulin, F., Schmidt, J., Carrasco, N., Coates, A. J., Cordier, D., De Kok, R., Geppert, W. D., Lebreton, J. P., Lefevre, A., Livengood, T. A., Mandt, K. E., Mitri, G., Nimmo, F., Nixon, C. A., Norman, L., Pappalardo, R. T., Postberg, F., Rodriguez, S., Schulze-Makuch, D., Soderblom, J. M., Solomonidou, A., Stephan, K., Stofan, E. R., Turtle, E. P., Wagner, R. J., West, R. A., and Westlake, J. H. (2014). Science goals and mission concept for the future exploration of Titan and Enceladus. In *Planetary and Space Science*, volume 104, pages 59–77. Elsevier Ltd.

[Todd et al., 2020] Todd, J., Lordos, G., Browder, B., Martell, B., and O'Neill, C. (2020). Ensuring Economically Viable Lunar Settlements. Technical report, ASCEND.

[United Nations, 1984] United Nations (1984). Moon Agreement.

[United Nations Office of Outer Space Affairs,] United Nations Office of Outer Space Affairs. The Outer Space Treaty.

[United States Department of Defense, 2015] United States Department of Defense (2015). The DoD Cyber Strategy. Technical report, United States Department of Defense.

[Villagran, 2014] Villagran, L. (2014). Senator wants to limit Spaceport tax fund use.

[Virginia Commercial Space Flight Authority, 2012] Virginia Commercial Space Flight Authority (2012). Virginia Commercial Space Flight Authority Strategic Plan 2012-2017. Technical report, Virginia Commercial Space Flight Authority.

[Virginia Commercial Space Flight Authority, 2016] Virginia Commercial Space Flight Authority (2016). Virginia Commercial Space Flight Authority Strategic Plan 2017-2022. Technical report.

[Wade, 2008] Wade, M. (2008). Wallops Island LA0A.

[Waite and DeLuna, 2012] Waite, A. C. and DeLuna, A. T. (2012). Kodiak Launch Complex (KLC) aka Alaska Orbital Launch Complex (AOLC) History and Lessons. In *The 12th International Conference on Space Operations*, pages 1–15, Stockholm. SpaceOps 2012.

[Waitz, 2009] Waitz, I. A. (2009). Perspective is everything. *MIT AeroAstro Magazine*.

[Wall, 2017] Wall, M. (2017). President Obama's Space Legacy: Mars, Private Spaceflight and More.

[Ward et al., 2021] Ward, F., Piercy, T., Heldmann, J., Lim, D. S., Colaprete, A., Cook, A., and Newman, D. J. (2021). A Virtual Reality Mission Simulation System (vMSS) Supporting Closed-Loop Mission Control. In *50th International Conference on Environmental Systems*.

[Wassmer et al., 2016] Wassmer, R. W., Ong, R. S., and Propheter, G. (2016). Suggestions for the Needed Standardization of Determining the Local Economic Impact of Professional Sports. *Economic Development Quarterly*, 30(3):252–266.

[Wattles, 2018] Wattles, J. (2018). Meet the pilots of Virgin Galactic's first flight to space.

[Weinzierl et al., 2021] Weinzierl, M., Newman, D., Browder, R., and Acocella, A. (2021). Spaceport America, Public Sector Risk-Taking, and Political Accountability.

[Weinzierl and Sarang, 2021] Weinzierl, M. and Sarang, M. (2021). The Lunar Gateway, Moon vs Mars, and the Commercialization of Human Space Activities (Draft).

[Weinzierl and Acocella, 2016] Weinzierl, M. C. and Acocella, A. (2016). Blue Origin, NASA, and New Space.

[Weiss and Tikoo, 2014] Weiss, B. P. and Tikoo, S. M. (2014). The lunar dynamo. *Science*, 346(6214):1–11.

[Whittle, 2018] Whittle, P. (2018). Group envisions Maine's former air bases as spaceport for tiny satellites.

[Wilkinson, 2019] Wilkinson, M. (2019). Michigan, we have a problem: Gretchen Whitmer kills $2.5M rocket plan pushed by Rick Snyder.

[Woerner, 2016] Woerner, J. (2016). Moon Village: A vision for global cooperation and Space 4.0.

[Wright, 2004] Wright, R. (2004). Joseph H. Rothenberg Oral History.

[Wyland, 2021] Wyland, S. (2021). New Mexico spaceport's new director hopes to launch new era.

[Yazell and AIAA Houston, 2012] Yazell, D. and AIAA Houston (2012). Ellington Field, Ellington Spaceport, and The Lone Star Flight Museum. *Horizons*, 12:22–23.

[Yin, 2014] Yin, R. K. (2014). *Case Study Research: Design and Methods*. SAGE Publications, Inc., 5 edition.