Incentivizing Collaboration on Space Sustainability: Detectability, Identifiability, and Trackability of Space Missions

by

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B.S., Computer Science, US Air Force Academy (2020)

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Abstract

The world has increasingly come to rely on satellites to provide services such as navigation, global communications, banking, national security, and weather forecasting. However, as satellites are launched into space at increasing rates, the risk of collision between active payloads or with pieces of debris rises exponentially. One of the initiatives to combat congestion is the Space Sustainability Rating. The Space Sustainability Rating is a rating system commissioned by the World Economic Forum in 2018 that scores a space mission on how sustainable it is for the long-term usability of the space environment, particularly in regards to debris mitigation and collision avoidance. It aims to incentivize more responsible design decisions by satellite operators and encourage the acceleration and establishment of sustainable norms of behavior. One of the six scoring modules in the Space Sustainability Rating is the Detectability, Identifiability, and Trackability (DIT) module. This thesis builds on the earlier work that was done to develop the first version of the DIT module and makes three primary contributions to it. First, it investigates using the previously proposed concept of orbital zip codes for the Identifiability scoring process and then suggests an alternative scoring methodology based on constructing Cypher queries that count the number of similar space objects that could make identifying a given object more difficult. Second, this thesis demonstrates how ASTRIAGraph, a knowledge-graph database that combines data from multiple space data sources, can be used to facilitate parts of the DIT analysis. Finally, it conducts a multi-case study to examine how missions from regions outside of the United States and Europe score in the DIT module and whether there are factors related to the national contexts in which they were developed that impact their scores.

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Group 93 at Lincoln Laboratory, thank you for your support and the freedom to work on whatever interesting project I could find. It's reassuring to know there are such kind people doing the important work you are responsible for.

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1. Introduction

As space technology has matured since the mid-twentieth century, governments, businesses, militaries, and individuals increasingly depend on it for crucial functions that support their way of life. These services include financial transactions, global communication, navigation, weather forecasting, disaster monitoring, and national security. The potential profitability and benefits of these and other novel applications of space technology are motivating both new actors to enter the space domain and already established actors to increase their presence there. As the space environment becomes more congested and competitive, the dangers of this trend also grow more apparent. Losing any of these key services to a collision event in space would be difficult to replace on a meaningful timeline due to the costs and time required to build and launch new assets. Therefore, it is key that meaningful steps are taken both in regards to new technologies and in policy and regulation that incentivize responsible behavior by space operators. One of these initiatives is the Space Sustainability Rating (SSR), a rating system that assigns space missions a score based on how sustainable it is for the long-term usability of the space environment.

1.1 Background

The purpose of this section is to provide high-level context and motivation for key concepts relevant to the work done in this thesis. It is not an exhaustive survey of any of these topics, but more information can be found in the relevant sources [1, 3, 4, 9].

1.1.1 Orbital Debris Problem

The state of the space environment is changing rapidly. Each year, the European Space Agency (ESA) releases a report to provide an overview of current debris mitigation efforts and to raise global awareness of space activities in general. The 2021 report emphasizes the steady increase in the number of objects in space and their combined area and mass, which has led to harmful collisions between operational payloads and debris. In addition, the report explains that despite improvements in sensing capability and thus the size of objects that can be tracked, the orbital debris problem is complicated by the miniaturization of space systems and the deployment of large constellations [1]. A key finding from the report is the evolution of the number and types of objects in space. A definition of each object category can be found in the report, but the most numerous are payload, payload fragmentation debris, rocket fragmentation debris, and unidentified. The report shows that as of 2020 there are close to 30,000 objects of a size that we can track orbiting the Earth. In reality, there are estimated to be 100 million pieces of space debris that are 1 millimeter or larger and even the smallest of these fragments can cause serious damage to spacecraft [1].

There are many significant risks posed by the growing number of objects in space. The most serious of these is the increased likelihood of collisions between active payloads, between a payload and debris, or between two pieces of debris. While the collision itself would likely cause serious or critical damage to the asset, the secondary debris produced by the collision is even more problematic. This is because the new debris then increases the risk to the existing objects. The situation in which the amount of debris orbiting Earth would only create more and more debris because of these fragment-producing events is known as Kessler syndrome [63]. Reaching that point would make space unusable and the critical space-based services we rely on would become unreliable. For example, the 2009 collision between the inactive Russian communications satellite Cosmos 2251 and an active commercial communications satellite operated by Iridium produced almost 2,000 pieces of debris with at least a 4-inch diameter and many thousands of even smaller pieces. Analysis has shown that more than half of the Iridium debris will remain in orbit for at least 100 years [8]. As this example illustrates, collisions of any kind are extremely unsustainable for the space environment and may ultimately prevent our ability to harness the tremendous capabilities derived from space.

Compounding the problem of the amount of debris that already exists is the shifting trend towards launching large constellations of small satellites into LEO. The advantage of this kind of mission plan is that each satellite is cheap and easily replaceable, which spreads out the risk to the operator from potentially losing one satellite. This is contrasted with a traditional mission of one satellite that might cost billions of dollars and decades to produce. However, with large constellations comes added concerns of their impact on space sustainability. One of the most notable examples of this is SpaceX's Starlink mega-constellation that aims to provide low-latency, broadband Internet with global coverage. They already have over 2,000 satellites in orbit and aim to add up to thousands more [2]. Starlink is joined by OneWeb and Amazon, who both have similar goals of launching thousands of satellites [5]. Thus, even if Kessler syndrome is not reached throughout the entire near-Earth environment, these large LEO constellations could create serious challenges for collision avoidance at certain altitude bands, inhibiting the effectiveness of operations and requiring the need for more careful planning [65].

1.1.2 Space Domain Awareness and Space Traffic Management

Addressing the space debris problem requires a holistic, multi-faceted approach combining technical, policy, and regulatory components. In all of these categories related to space sustainability, there are a few important concepts worth defining in the context of this research. The first is space domain awareness (SDA), which has replaced the previously used term of space situational awareness. SDA is "the actionable knowledge required to predict, avoid, deter, operate through, recover from, and/or attribute cause to the loss and/or degradation of space capabilities and services" [3]. It is meant to provide the information necessary for timely and safe decision-making in space operations. Three of the core activities required to build and maintain high-quality space domain awareness are the detection, identification, and tracking of space objects. The definitions of each of these are given and expanded upon in section 1.1.4 below, as they are the three components of the specific Space Sustainability Rating module focused on in this research. SDA is achieved by gathering measurements from sensors, mostly from telescopes and radars on the ground, but also through several other methods. A key provider of free global SDA services has been the U.S. Department of Defense, but a policy is in place to transfer that responsibility to the U.S. Department of Commerce as of Space Policy Directive 3, published by the White House in 2018 [7].

The second key background concept related to addressing space debris is that of space traffic management (STM). Space Policy Directive 3 defines STM as "the planning, coordination, and on-orbit synchronization of activities to enhance the safety, stability, and sustainability of operations in the space environment" [7]. Work has been done to propose what a global STM architecture could look like and also to better understand what emerging space nations and commercial operators would want out of such a system [4]. Regardless of the eventual details of an implemented STM architecture, a commitment to better data sharing and coordination of activities by all types of actors is essential to our future ability to operate in space. Both of these concepts of SDA and STM help to inform the work done in this thesis regarding the Space Sustainability Rating.

1.1.3 Space Sustainability Rating Overview

The Space Sustainability Rating (SSR) is an initiative commissioned by the World Economic Forum through their Global Future Council on Space to create an incentive system describing the sustainability of a given space mission by quantifying how the mission contributes to maximizing debris mitigation and collision avoidance. The SSR could accelerate the establishment and practice of norms of behavior among operators of satellites in all orbital regimes, underscoring safe and sustainable operations, especially as the number of operational satellites in Low Earth Orbit and in constellations is dramatically increasing. The SSR has been designed by a consortium that includes the Massachusetts Institute of Technology, the European Space Agency, the University of Texas at Austin, and Bryce Space and Technology. The World Economic Forum recently announced that the Space Center of the Swiss Federal Institute of Technology Lausanne will lead the operational phase of the SSR [31]. The SSR is comprised of six modules, with each module addressing a different aspect of the mission's sustainability. They include the (a) Mission Index which is used to calculate the Space Traffic Footprint, (b) Collision Avoidance, (c) Data Sharing, (d) Standards and Regulations, (e) the use of External Services, and (f) Detectability, Identifiability, and Trackability (DIT). The Mission Index is the most highly weighted module and it quantifies the level of negative physical interference caused by the planned mission on the space environment. Collision Avoidance emphasizes what operators can do to reduce the risk of collision with debris and other active satellites. Data Sharing quantifies the amount of relevant information operators share with the space community and how that information affects safety in orbit. Standards and Regulations refers to whether a mission adopts published standards that limit debris creation in the congested environment. External Services is relevant only for bonus ratings and focuses on whether a satellite mission is prepared to receive services such as life extension, repair, and deorbiting from a service provider. DIT, which is the subject of this thesis, quantifies how easy it is for an independent operator who does not receive data from a mission operator to detect, identify, and track space objects; these are the three main activities that contribute to space domain awareness. The DIT methodology will be described further in the following sections. Ratings from the SSR are assigned with a tier scoring system, where module scores are weighted and combined to produce a final tier, within a range of Bronze, Silver, Gold, and Platinum. Further information about the Space Sustainability Rating can be found in multiple previous publications [6, 10, 11, 29, 30, 35].

1.1.4 Detectability, Identifiability, and Trackability Definitions

The module of the Space Sustainability Rating that is the subject of this thesis is the Detectability, Identifiability, and Trackability (DIT) module. The definition for each of these terms in the context of the SSR comes from the work done by Steindl in establishing the DIT scoring methodology [6, 11]. All of the analysis done in the DIT module relies on key assumptions that are built into an analysis procedure, particularly regarding the modeling of an assumed ground-based network of radar and optical sensors, defining a standardized SDA capability as a datum for comparisons. For instance, the modeled sensor network is not based on the location of actual space surveillance sensors. It purposefully is much more generous with the number of sensors included and their locations, as real-world geopolitical constraints are ignored. The sensors are generously spread over the surface of the Earth and are of a medium-tier sensing capability. The reason for this is that the Space Sustainability Rating is designed to evaluate the effect of the design decisions and mission plans of satellite operators on the long-term sustainability of the space environment, independent of SSA and sensor capabilities. Therefore, the DIT module aims to, as much as possible, separate evaluating the sustainability of operator decisions from the structure of the network.

Detectability is defined as the likelihood that the mission being scored will be observed by a predefined ground network of optical and radar sensors without utilizing information about the location of the space objects provided by the operators [11]. Detection is important because in order for SDA providers to be able to add the satellite into their catalog and make accurate measurements and predictions about its location they need to be able to detect it. A catalog refers to the collection of space objects being tracked by a given SDA provider. One of the most well-known of these catalogs is that maintained by U.S. Space Command, which releases its unclassified data on Space-Track.org [67]. The Detectability score combines optical and radar sub-scores into an overall score. The optical sub-score is based on the average visual magnitude, or brightness, of the satellite as seen by the ground sensors over the one-month simulation period in Systems Tool Kit (STK). This average visual magnitude is then compared to scoring cutoffs, shown in Table 1.1, and developed by Steindl based on the empirical distribution of space objects to establish the optical score. The radar sub-score is based on the mission's peak probability of detection by the ground sensor network, again over the one-month period simulated in STK. The peak probability of detection is compared to scoring cutoffs derived from empirical analysis of existing satellites, also shown in Table 1.1, to assign the radar sub-score. The justification for the analysis approach is further discussed in the publications by Steindl [6].

Scoring Tier	Optical	Pts.	Radar	Pts.
Difficult to Detect	Vmag greater than 15.0	0.5	$P_{detection}$ less than 50%	0
Detectable	Vmag of 15.0 or lower	1.0	$P_{detection}$ of 50% to 74.9%	0.5
More Detectable	N/A	N/A	$P_{detection}$ of 75% or higher	1.0

Table 1.1 Detectability scoring *cutoffs [6].*

As the use of space increases and changes, so does the problem of satellite identification. It used to be that one large satellite with a dedicated launch vehicle would be launched at a time or that a few smaller payloads would be carried along as secondary payloads. However, with the rise of CubeSats and other small satellites it is possible for multiple satellites to be bundled together for a launch and then inserted into similar orbits over a short period of time. This has led to difficulty in uniquely identifying some satellites in the period after deployment from the launch vehicle. Ambiguity in space object identification is also possible when objects appear to be close to each other in SDA data collection findings. There are certain practices that operators can do to simplify this process for SDA providers. For example, they can coordinate with tracking agencies pre-launch or broadly share Two-Line Element set (TLE) data or other types of data in clear, consistent formats [20]. The decision of satellite operators to follow these practices is accounted for in other parts of the Space Sustainability Rating, specifically in the Data Sharing module [29]. Identifiability in the DIT module is defined as how easy or difficult it would be for a detected satellite to be identified based purely on the information contained in the catalog and from ground-based sensor observations, without any additional orbital information from the satellite operator [11]. This is a useful metric to analyze because having the ability to independently identify and monitor a satellite and associate it with an operator simplifies the process of communicating about collision warnings and possible avoidance maneuvers. The scoring methodology for Identifiability was not clearly defined in the first iteration of the SSR, so scores for it have not been included in any previous beta testing or case studies included in this thesis. Chapter 2 details the work done so far on the methodology and presents a plan for improving the Identifiability approach.

Finally, Trackability is defined as how well the already detected and identified satellite can be tracked over time and how well its future location can be estimated [11]. This is a key metric and part of the SDA process because being able to frequently update the catalog of space objects means that their locations and collision predictions will likely be more accurate. In practice, for the SSR Trackability analysis, the score reflects the quality of the ground station access to observe an object and update tracking assumptions. The three metrics used in the Trackability analysis are the average pass duration, average interval duration, and estimated orbital coverage of a satellite over a certain time period. Average pass duration refers to the length of an access opportunity where the satellite can be observed by a sensor. The average interval duration is the length of time between those access opportunities. Finally, estimated orbital coverage indicates approximately what percentage of the orbit can be observed by the sensor network. This is done separately for both radar and optical sensors. Unlike in the Detectability section, the higher of these two scores is then chosen as the overall Trackability score. This is because in practice, radar sensors are usually used to track Low Earth Orbit (LEO) satellites and optical sensors are used for objects in Geosynchronous Orbit (GEO) [23]. Therefore, it would be an unnecessary penalty on the satellite operator to combine these scores when they are likely not both used. These metrics were chosen because the more often the satellite can be observed, and the shorter the interval between these opportunities, the more accurate the tracking capability will be. The scoring cutoffs for each of these metrics are shown in Table 1.2.

Scoring Tier	Average Pass Duration	Average Coverage	Average Interval Duration
Difficult to Track (0pts)	Less than 120s	Less than 10%	More than 12hrs
Trackable (0.25pts)	120s to 179.9s	10% to 24.9%	4hrs to 12hrs
More Trackable (0.5pts)	180s to 399.9s	25% to 59.9%	4hrs or less
Very Trackable (1.0pt)	400s or more	60% or more	N/A

Table 1.2 Detectability scoring cutoffs [6].

The actual mechanics of conducting the scoring analysis for the DIT module are detailed in following chapters. This section introduced the concepts of Detectability, Identifiability, and Trackability and presented a high-level overview of how the scoring methods are set up.

1.2 Research Methods

The research methods used in this thesis can be grouped into two main categories – designing quantitative scoring metrics and performing a case study based around a Systems Architecture Context analysis. The quantitative metrics are those used to assign the Detectability, Identifiability, and Trackability scores for that module of the Space Sustainability Rating. This is done through a Python script that runs an orbit and ground sensor network simulation in Systems Tool Kit, as well as connects to ASTRIAGraph, a knowledge graph database containing information about objects tracked in space. ASTRIAGraph is further explained in Section 3.1 of this thesis. All of these methods are detailed extensively in the following chapters. The case study investigates whether space missions from regions outside of the United States and Europe receive DIT scores comparable to NASA and ESA missions scored previously and whether there might be any factors in the national Contexts in which they were developed relevant to those scores. This is done by assigning scores to one mission each from Thailand, South Africa, and India, and a joint mission from China and Brazil. The case study appears fully in Chapter 4.

1.3 Contributions

The contribution this thesis makes to the methodology and to a better understanding of the DIT module is divided into the four chapters following this one. Chapter 2 describes the current state of the Identifiability section of the DIT module. It begins by summarizing past efforts to define the scoring metrics and then proposes a new version of the metric, as well as provides examples of what that might look like for a few given missions. Chapter 3 is concerned with the integration of ASTRIAGraph as a knowledge management approach into the DIT scoring methodology. It illustrates how this is done for each subsection of the module, the benefits of using ASTRIAGraph in this way, and the current limitations with it. Chapter 4 is the case study of how missions from outside of Europe and the United States score in the DIT module and a Context analysis of how factors in that nation may have affected the score. Finally, Chapter 5 is a detailed guide for how to actually conduct the DIT analysis in its current form, which is important to document as the SSR enters its operational phase. Overall, this thesis contributes to the way that the DIT module operates and is included in the operational SSR, which is a small part of the wider effort to encourage more sustainable operator behavior for the long-term benefit of all actors in space.

2. Identifiability Method and Metrics

As mentioned in the overview of the DIT module in Chapter 1, the Identifiability score aims to quantify how difficult it is to identify a satellite based on ground sensor observations. This is useful because having the ability to identify satellites and match sensor observations with objects in the catalog allows for better coordination among operators and SDA providers, hopefully leading to safer maneuvers and better collision avoidance procedures. The first version of the DIT module, as proposed by Steindl, did not fully solidify the methodology or metrics used for Identifiability so it was not included in the commercial beta testing of the SSR or in the case study in Chapter 4. This chapter summarizes that first proposed method, investigates it further, and then suggests a different way of performing the Identifiability analysis. In this chapter, and throughout the thesis, the term anthropogenic space object (ASO) and satellite or space mission are used interchangeably. ASO simply refers to any human-made object in space.

2.1 Method Description

In the first version of the Identifiability analysis, the main ASO attribute that was considered was the 'orbital zip code', which was based on the specific orbital angular momentum of the ASO. Orbital zip codes are a concept suggested by Dr. Moriba Jah of the University of Texas at Austin, and implemented by Vishnu Nair, who used cluster analysis on the catalog of ASOs to find a physical orbital state-space where ASOs naturally clustered in a way that could be useful for the Space Sustainability Rating and future SDA projects [22]. Nair originally clustered the ASOs into 14 groups, but later separated them further into 35 groups. The orbital zip codes have the potential to be a useful way to quantify the Identifiability of ASOs because they group objects that are in similar orbital neighborhoods and could potentially be confused by ground sensors.

However, further work was done to investigate what a proper number of orbital zip codes would be and whether they made sense as a way to separate ASOs in groups. The first step in doing this was to re-run some of Nair's analysis with the same data he used. There are twelve datasets, where each dataset represents the state of the objects in the catalog on the first day of each month in 2019 as captured using JavaScript Object Notation (JSON). For each ASO in the catalog, there is orbital information such as NORAD ID, launch date, launch country, classical orbital elements, and cartesian coordinates. Nair's code converts each of these JSON datasets into a Python pandas dataframe, and then uses the position and velocity vectors for each object to compute its angular momentum and store it [22].

With these datasets now in a useful format, the next step asked whether using k-means clustering on the angular momentum of the ASOs was an effective way to group and identify something about them. K-means clustering is a method that aims to separate n observations into k clusters, while minimizing the variance (squared Euclidian distance) within each cluster [60]. The angular momentum vectors $\hat{h}$ in the datasets are actually three-dimensional vectors as they were calculated from three-dimensional position and velocity vectors. Therefore, the clusters are also in three dimensions. To determine an appropriate number of clusters for the over 26,000 ASOs in the dataset, the elbow method was used and k values from 1 to 50 were tried. The elbow method is a heuristic in clustering analysis in which the explained variation is plotted as a function of the number of clusters, and the point at the 'elbow' of the curve is chosen as the number of clusters in the data set [66]. The resulting plot is shown in Fig. 2.1. From this, it appears that a k of 7 or 8 would be appropriate for this dataset, as that is where the bend in the curve is relatively distinct. Using a k value of 8, the cluster analysis is performed for the January dataset and then those same cluster centers are used for the remaining eleven months. This is because running the Python k-means algorithm again would result in new cluster centers for each month, so the clusters would be changing throughout the year in an unpredictable way. If the cluster centers are kept the same, theoretically objects that move significantly between clusters are worth investigating for why they exhibit such movement. However, it was found to be the case that when the angular momentum is kept in a three-dimensional space, most of the objects actually change clusters extremely frequently.

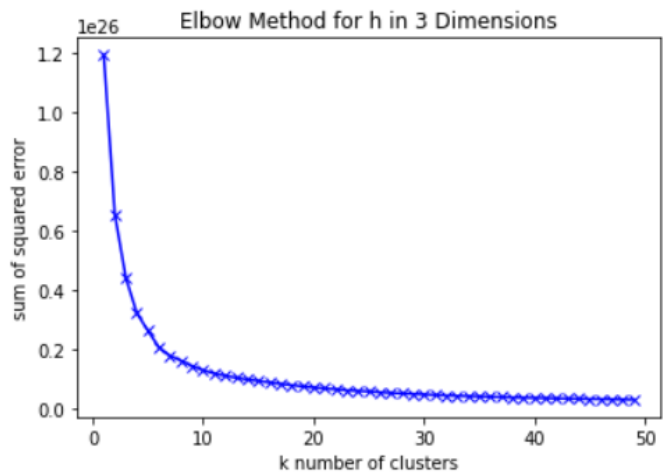

Fig. 2.1 Elbow method plot to find number of clusters for 3-dimensional $\hat{h}$ vectors.

To illustrate this, Fig. 2.2 depicts how many different clusters ASOs were in over the course of the year that the data covers. It is interesting to note that over 10,000 of the objects were put

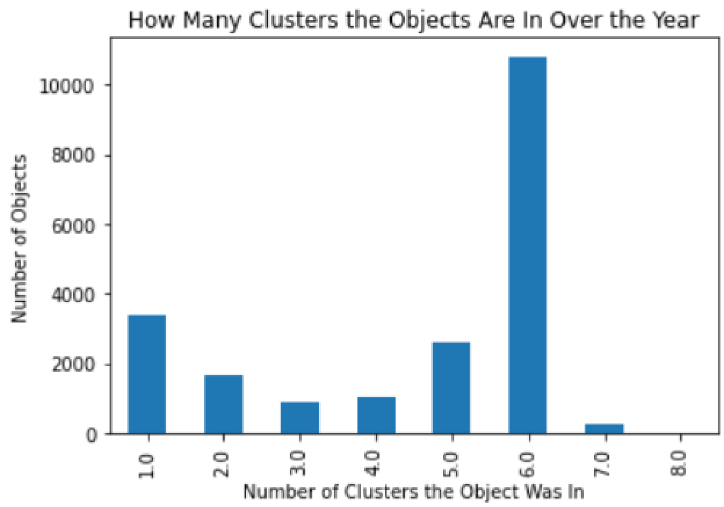

Fig. 2.2 Bar graph showing how many clusters the ASOs were in over the year.

into six out of eight possible clusters at some point in the year. Another way to examine this trend is to look at how the population of each cluster is changing over time, as shown in Fig. 2.3.

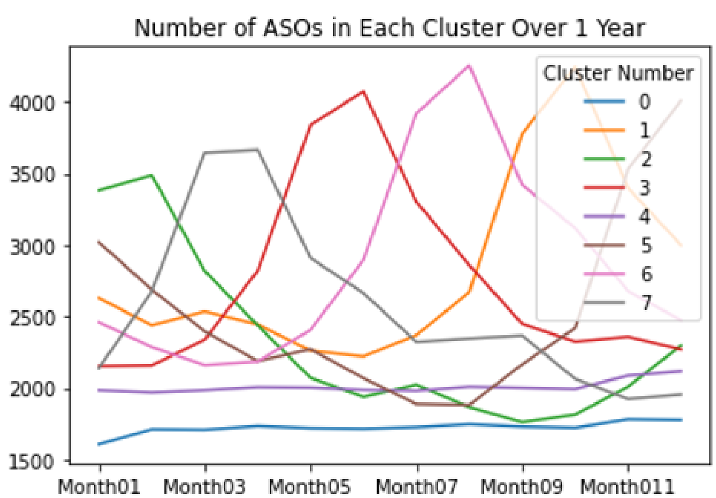

Fig. 2.3 Line chart showing how many ASOs are in each cluster in each month.

From this figure, it appears that the populations of clusters 0 and 7 stay relatively constant, but the other six clusters' populations change in an almost periodic way. More work could be done to understand if the objects in clusters 0 and 7 are similar in some way that makes them different from those in the other clusters, but there was nothing conclusive found at this point. While these trends are interesting, they are concerning for the goal of trying to use the clusters as orbital zip codes in the Identifiability analysis. If the objects that make up a cluster are changing so often, the clusters don't inherently have much meaning or utility for revealing a property of the satellite that is practical for identifying it. The underlying reason for these trends was not explored in conclusive detail because another scoring method for Identifiability was proposed, but one possibility is that the magnitude of the angular momentum stays relatively constant even though the direction of $\hat{h}$ changes throughout the orbit. To test this, a new column representing the magnitude of the angular momentum vector for each object was added to the dataframe of each month. Then, the analysis described above was repeated. First, an elbow plot suggested that the appropriate number of clusters for this metric was only three (Fig. 2.4).

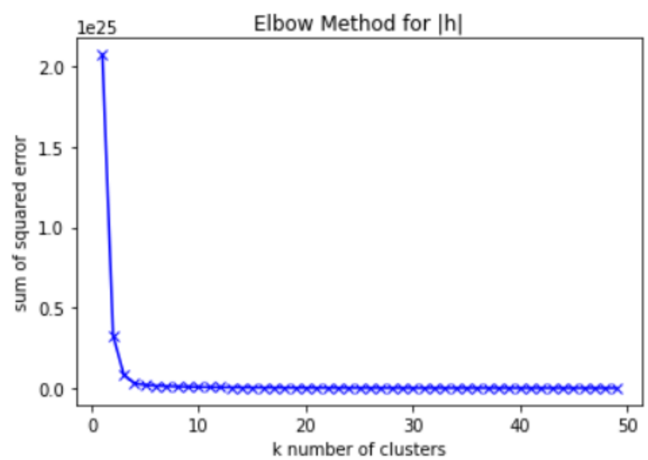

Fig. 2.4 Elbow method plot to find number of clusters for $\hat{h}$ vector magnitude.

Using this new attribute of angular momentum magnitude and a k value of three, the k-means clustering was run again on the January dataset to establish the cluster centers, and then the ASOs in each month after that were assigned to clusters. With this process as compared to using the angular momentum vectors, the ASOs were much more likely to stay in a single cluster throughout the whole year. Figures 2.5 and 2.6 demonstrate this trend.

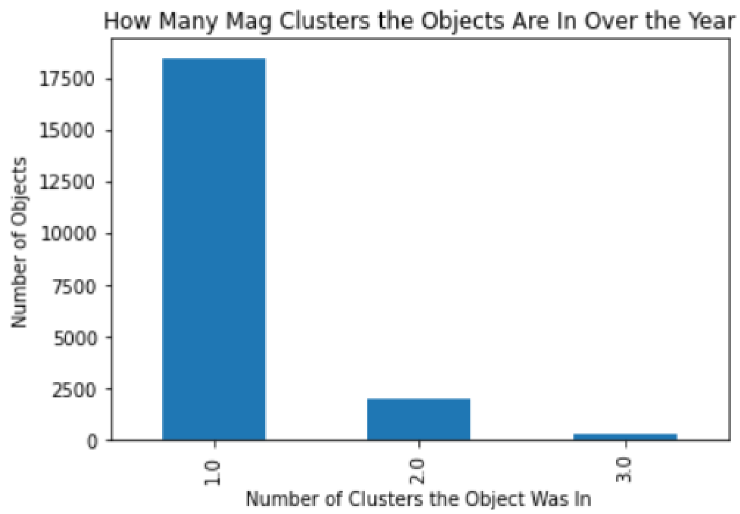

Fig. 2.5 Bar graph showing how many clusters the ASOs were in over the year when clustered based on angular momentum magnitude.

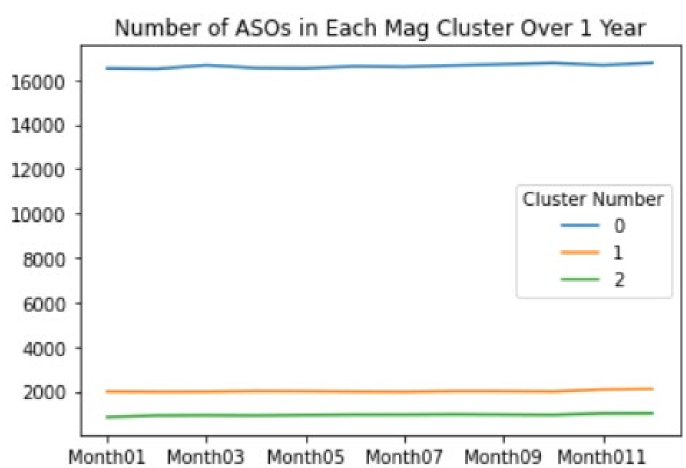

Fig. 2.6 Line chart showing how many ASOs are in each angular momentum magnitude-based cluster in each month.

The relative stability of these clusters when compared to those made based on the three-dimensional vectors is notable and probably more useful for the purpose of separating ASOs into groups to aid in the Identifiability scoring because they aren't constantly moving between clusters. One drawback of using these clusters, however, is that there are only three and the ASOs are very unevenly distributed between the clusters. So, knowing that a satellite is in cluster zero, for example, doesn't actually provide very much information about its orbit or help to distinguish it from many other satellites. While there is still interesting potential for the use of orbital zip codes or some other sort of clustering analysis in the Identifiability section of the DIT module, an alternative scoring methodology is also being developed.

The proposed Identifiability scoring methodology relies on the use of ASTRIAGraph or some similarly functioning database that can compare the attributes of thousands of satellites simultaneously. Essentially, the suggested process is to select characteristics of an ASO that can be observed from the ground and then compare them to those of other ASOs. These can include orbital parameters like altitude, eccentricity, and inclination or physical characteristics of the satellite like size or brightness. Once these characteristics are selected, a query can be constructed that compares each of them to the corresponding characteristic value of the other satellites in the database. The database then returns how many satellites share each of those characteristics or all of the same ones with the satellite being scored. If there are more satellites that share those same properties that can be observed from the ground, it could theoretically be harder to identify that satellite from among those similar to it. To account for the fact that ground sensors cannot observe orbital or physical ASO properties with perfect accuracy, it is possible to include uncertainty around the values in the query. The following subsection lays out some examples of what the queries would look like if using ASTRIAGraph.

2.2 Sample Queries and Results

As mentioned previously, the actual orbital or physical characteristics that would be included in each query and the process for calculating the uncertainty bounds on each value are still being selected, but the method can be demonstrated regardless. The examples will use each ASO's semimajor axis and inclination as the criteria because these are already included in ASTRIAGraph, but these could easily be changed to angular momentum, cartesian coordinates, or other types of parameters that are directly added to ASTRIAGraph or could be calculated from the existing data.

The first example is the International Space Station (NORAD ID 25544), which according to the locally stored, static version of ASTRIAGraph used for this demonstration has a semi-major axis of 6,799.2 kilometers and an inclination of 57.712 degrees. The uncertainty used for these parameters is 50 meters on the semi-major axis and 0.03 degrees on the inclination. These values come from averages of some LeoLabs positional uncertainty on their tracking services observations, but are just meant to be a stand-in for whatever method for estimating uncertainty is eventually used [61]. With these parameter and uncertainty bounds, the following query can be constructed:

MATCH(SO:SpaceObject) –[:has_orbit]->(orb:OrbitalElementsSet) WHERE 57.412 < orb.Inc < 58.012 AND 6799.15 < orb.SMA < 6799.25 RETURN count(DISTINCT SO.NoradId)

This query is written in the Cypher query language, the native language for Neo4j and therefore for ASTRIAGraph [19]. The result is that there are 17 other ASOs that meet the specified criteria and could potentially be confused with the ISS, based solely on semi-major axis and inclination. Of course, this probably isn't realistic for something as unique as the ISS but the parameters can easily be manipulated to include different types of characteristics. Nonetheless, to explore what the results of this query look like for other space objects, it was run for a variety of missions with the same uncertainty bounds. Table 2.1 displays the results.

ASO Name	NORAD ID	# of ASOs that meet query criteria
GRACE	43476	0
Hubble	20580	0
International Space Station	25544	17
THEOS	33396	124
RazakSat	35578	0
NigeriaSat-2	37789	26
Aquarius	37673	16
DirecTV 11	32729	383
GOERGEN	43860	1
YAOGAN 11	37165	18
STSS 1	35937	0
GSAT 8	37605	383
COSMOS 1052	11129	53
QZS-4	42965	0
Mohammed VI-B	43717	30

Table 2.1 List of semi-major axis and inclination query results for variety of ASOs.

2.3 Future Work

While the process described above demonstrates a potential overall flow of the Identifiability scoring and some of the mechanisms needed to implement it, there is still work remaining to be done before it is added to the operational DIT module of the Space Sustainability Rating. This includes finalizing which orbital or physical ASO properties should be included as query parameters and how the uncertainty bins around each value should be calculated. Some of these decisions depend on what data is actually available in ASTRIAGraph. For instance, the download of ASTRIAGraph used for the sample queries does not contain covariance information for the sensor observations so that could not be used as the source for defining the error bars around the query values. Additionally, there is currently not physical characteristic data like radar cross-section or size associated with each ASO in ASTRIAGraph. This type of data exists in sources like DISCOS created by the European Space Agency and could theoretically be added to ASTRIAGraph and then included as a query parameter [24].

Another factor that has not been fully explored in this analysis is where the satellite is in relation to the other similar satellites at the moment of the observation. This could be relevant if the SDA provider has an expectation of where the satellites will be at a certain time so by correlating a time with the ground observation, it is able to rule out many satellites with potentially similar orbits and physical characteristics. Similarly, if there are multiple satellites physically close together in space at the time of the observation, that could make it more difficult to distinguish from those around it in a similar orbit. With the proper data available, this is something that could potentially be included in the scoring considerations. One issue, however, is that missions being evaluated before launch will not be able to be scored on this type of metric.

Beyond these decisions, it is still worth considering whether there are other ways to quantify how hard it is to identify a satellite. One possibility that has been discussed throughout the course of this project is conceptualizing some sort of ‘orbital distance’, or how far apart two orbits are from each other. This could be calculated with a variety of different metrics computed in cartesian, angular momentum, or Keplerian element spaces. These metrics would need to be evaluated for a wide range of representative satellite missions and classes in order to determine whether they should be used for the Identifiability score in the DIT module.

3. Incorporation of ASTRIAGraph

The first iteration of the Detectability, Identifiability, and Trackability scoring methodology developed by Steindl involved manual data input for each mission that needed to be scored. Even for existing missions, the rater would have to input each orbital parameter and physical characteristic needed for the code to then propagate the orbit and compute the DIT metrics [6]. This worked well for developing the methodology but is time-consuming and more prone to error than an automated method. The focus of this chapter, then, is on how ASTRIAGraph, a so-called knowledge-graph database that aggregates and curates orbital and physical characteristic data from multiple space domain awareness providers, can be used to contribute to each step of the analysis in the DIT module of the Space Sustainability Rating. Building the DIT analysis to work with ASTRIAGraph is a powerful example of the kinds of applications that can be built on top of such a knowledge-graph database [35].

3.1 ASTRIAGraph Overview

A knowledge-graph database is designed to emphasize the connections between the data, storing it in the form of a network of nodes and relationships, and whose schema in and of itself provides knowledge. It is intended to curate data in a way that does not restrict it to fitting into a predefined model but can grow and change as new data are added. Curating the data in this connected manner allows for queries to quickly traverse relationships instead of performing a traditional join operation at query time. This is ideal for complex queries that rely on multiple types of data and the relationships between them [12]. One popular available commercial version of a knowledge-graph database is Neo4j, which is a software that functions as a graph database management system [13].

An example of this kind of database is the ASTRIAGraph project, which is a multimodal knowledge-graph database implemented in Neo4j and developed by Professor Moriba Jah and his ASTRIA research program at the University of Texas at Austin in the Texas Advanced Computing Center [14]. ASTRIAGraph combines data about objects in near Earth space from seven different external sources. Because it is implemented as a Neo4j graph database, the data from these different sources can be integrated in a cohesive way through developing relationships between various nodes and classes. The current database schema is depicted in Fig. 3.1 below. The data sources, shown in yellow, are the external sources of information that are collected by the ASTRIA research team. The properties, shown in blue, are curated from the sources and used to describe the different classes of objects, depicted in green. When either a new data source, a new ASO, or new time-sensitive orbital information is collected it can easily be curated and added to the database because graph databases are meant to be scaled in this way. The red nodes in the schema show examples of some of the questions that other researchers have already investigated by querying ASTRIAGraph. The long-term vision of ASTRIAGraph is to build applications on top of it to solve complex problems, answer queries, and address the uncertainty that comes with using diverse, sometimes conflicting data sources [15]. Recently, a company named Privateer announced their work to develop the Wayfinder application, which is building on the capabilities of ASTRIAGraph and is a demonstration of space traffic management tools. It is meant to be useful for operators or companies who are interested in services related to conjunction screenings, satellite servicing, debris removal, or other types of space domain awareness activities [28].

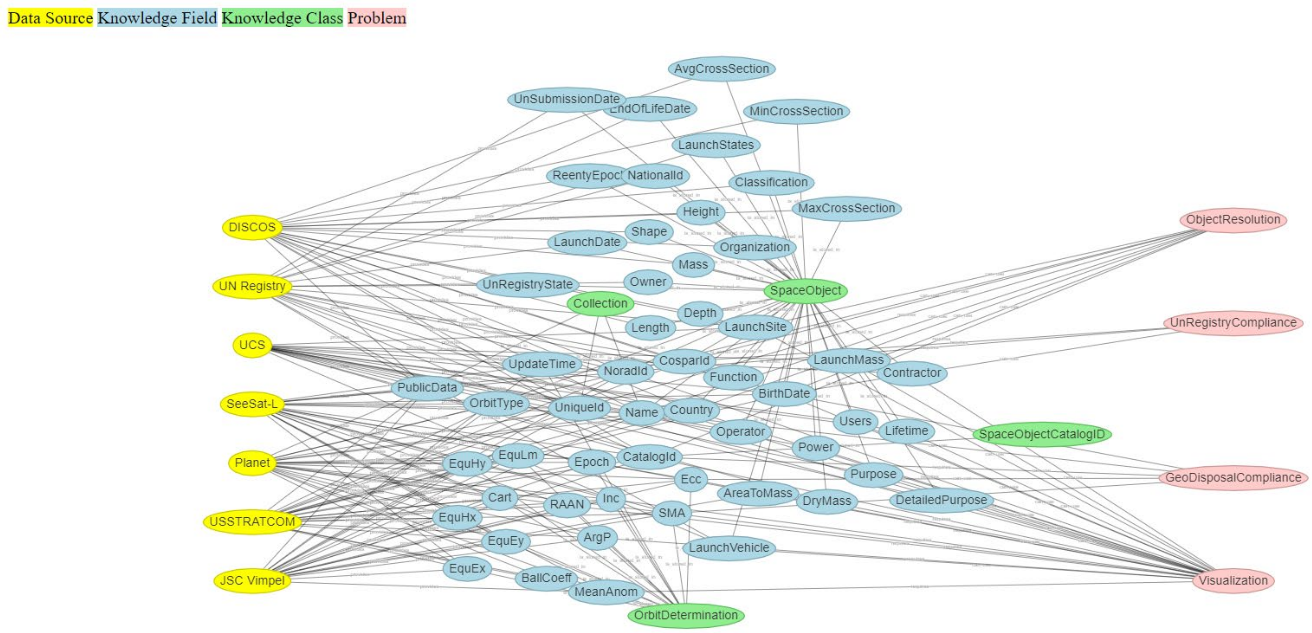

Fig. 3.1 Current ASTRIAGraph schema [16].

To illustrate the types of unique problems that ASTRIAGraph and graph databases in general can solve, a group of researchers investigated its capability to quantitatively analyze how well member states of the Convention on Registration of Objects Launched into Outer Space adhere to the provisions of the treaty. They were able to extract country information, launch dates, satellite types, and orbital regimes. From these data, they could calculate the lag

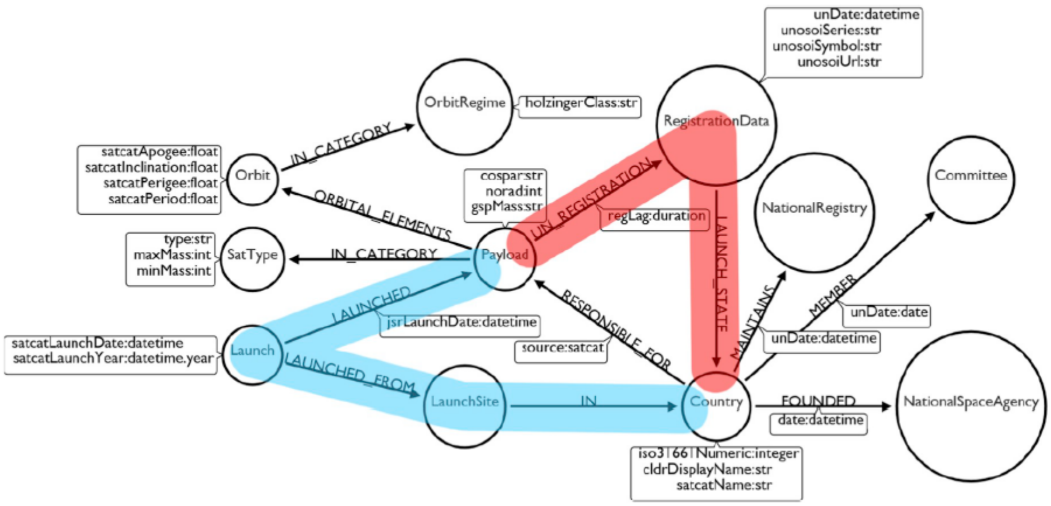

Fig. 3.2 Schema showing the addition of the registration lag to the UN_Registration relationship [17].

between launch date and when the launch was actually registered with the United Nations. Another query was then run that set the calculated registration lag as a property of the relationship between the SpaceObject node and the RegistrationData node [17]. This operation is illustrated in Fig. 3.2. This work on UN registration compliance highlights the ease and robustness with which graph databases can create relationships between multiple types of data to solve complex queries. It also emphasizes the usefulness of having a database that can easily grow and shift structures because once the registration lag is computed, it is pushed back into the database so that other users can access that information as the property of a relationship. Many uses for these kinds of scalable capabilities can be imagined. The one discussed in this paper is how the ASTRIAGraph knowledge-graph database can be used to help compute and then store information about the Detectability, Identifiability, and Trackability of a space mission.

3.2 ASTRIAGraph in DIT Methodology and Scoring

While the primary focus of this chapter is on the benefits of using ASTRIAGraph for the analysis and calculations done in the Detectability, Identifiability, and Trackability module, it is useful to summarize the steps in the scoring methods; the methods and how to conduct them are described in full detail in Chapter 5. The scoring for each section in the module follows a similar overall process. It is initiated by a Python script that writes various Cypher queries to be executed in ASTRIAGraph, runs simulations in Systems Tool Kit (STK), and finally calculates separate metrics for each section, that are then weighted and combined into an overall DIT score [18]. Cypher is the native query language for Neo4j and is similar to SQL but designed specifically for graphs. It is unique in how it provides a way to visually match patterns and relationships in the data with its use of parentheses and arrows in the queries themselves [19]. Each section and ASTRIAGraph's integration into it are broken down in further detail below.

3.2.1 Detectability

The Detectability score approximates how likely it is that a satellite could be detected by both optical and radar ground-based sensors, which is the first step in beginning to track it as part of space situational awareness efforts. The input to this analysis is either the NORAD ID number of an existing space mission in the U.S. Space Command satellite catalog or the orbital information of a proposed mission being evaluated pre-launch, the satellite dimensions, and a radar cross-section (RCS) estimate. A Python script uses the NORAD ID to construct a Cypher query that will request the latest orbital data for the ASO. The query is executed within ASTRIAGraph and the most current available set of orbital elements and other required information in the database is returned to Python. For a mission that is pre-launch, the script instead simply asks the user to input the planned orbital elements, the estimated RCS, and the satellite dimensions. Regardless of which way the information is entered, the script then feeds it into an STK scenario to estimate the satellite's average visual magnitude from an optical sensor and probability of detection by a radar sensor. STK provides a simulation of the orientation of the spacecraft, earth, sun and ground sensor to perform the analysis. The visual magnitude and probability of detection are compared to pre-defined scoring cutoffs so that both an optical and radar score can be calculated. The optical and radar detectability scores are then evenly weighted and combined into an overall score for the Detectability section. Figure 3.3 provides a visual flowchart of this process.

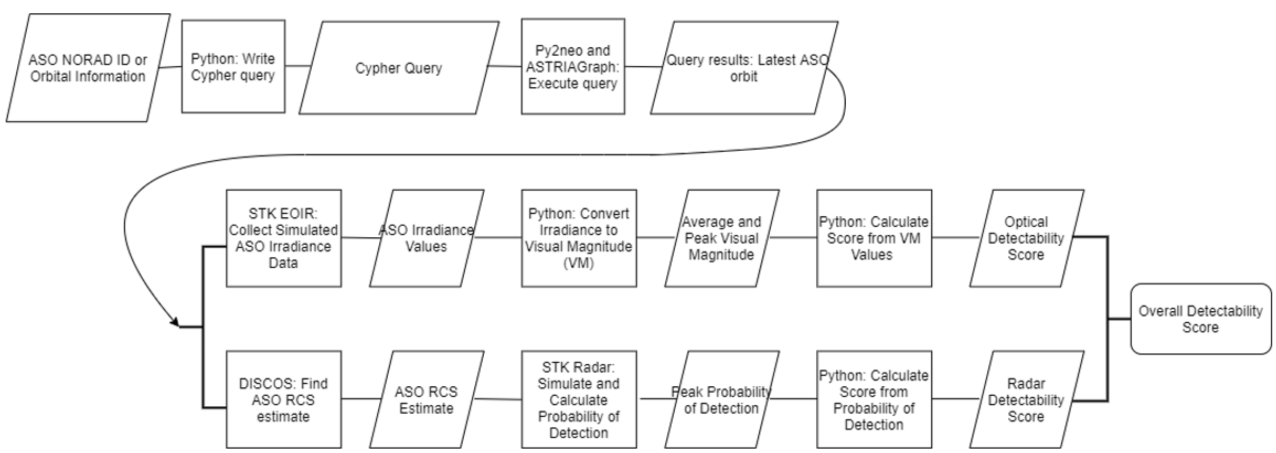

Fig. 3.3 Detectability scoring flow [35].

3.2.2 Identifiability

The Identifiability section of the DIT module tries to quantify how difficult it is to identify a satellite based on the orbital information that would be calculated and stored by tracking agencies and is independent of additional operator input. This information includes general characteristic attributes like approximate radar cross-section (RCS) and visual magnitude, orbital element or state vector data, and derived values such as an ASO's angular momentum. These various data sources and types are evaluated in combination against the rest of the satellite catalog to estimate how unique or identifiable the given satellite is.

The intended uses of ASTRIAGraph align well with the proposed methodology of the Identifiability analysis. When attempting to quantify how identifiable an object is, there are multiple characteristics and types of data that should be considered based on what a ground network of sensors can reasonably determine. ASTRIAGraph brings these data sources together into a central location. The Identifiability scoring process is a Python script that takes in either the NORAD ID of an existing ASO or the proposed characteristic and orbital information of a mission that is pre-launch. The script then constructs a query written in Neo4j's native query language, Cypher, that requests a count of all current ASOs that share similar characteristic and orbital data with the ASO being scored. The query is sent to ASTRIAGraph through a Python Neo4j driver and the results are returned and translated into an Identifiability score [21]. A higher number of similar objects to the ASO being scored would lead to a lower Identifiability score because more objects can be mistaken for the space object under study. This process is depicted in Fig. 3.4 below.

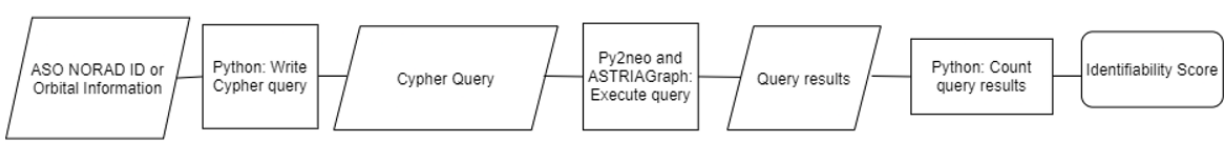

Fig. 3.4 Identifiability scoring flow [35].

3.2.3 Trackability

The Trackability scoring method calculates metrics that quantify how difficult it is to track an ASO over time. It uses the NORAD ID of the ASO being scored to write a Cypher query to ASTRIAGraph that returns its most recent orbital information. For a pre-launch mission, the user simply inputs the planned orbit. Then, the script passes this orbital information and a representation of the previously described simulated sensor network into Systems Tool Kit to calculate the average pass duration, average interval duration, and estimated orbital coverage of an ASO over a certain time period. Average pass duration refers to the length of an access opportunity where the satellite can be observed by a sensor. The average interval duration is the length of time between those access opportunities. Finally, estimated orbital coverage indicates approximately what percentage of the orbit can be observed by the sensor network. This is done separately for both radar and optical sensors. Unlike in the Detectability section, the higher of these two scores is then chosen as the overall Trackability score, for reasons described in section 1.1.4. Figure 3.5 depicts the flow of the Trackability scoring process. These metrics were chosen because the more often the satellite can be observed, and the shorter the interval between these opportunities, the more accurate the tracking capability will be.

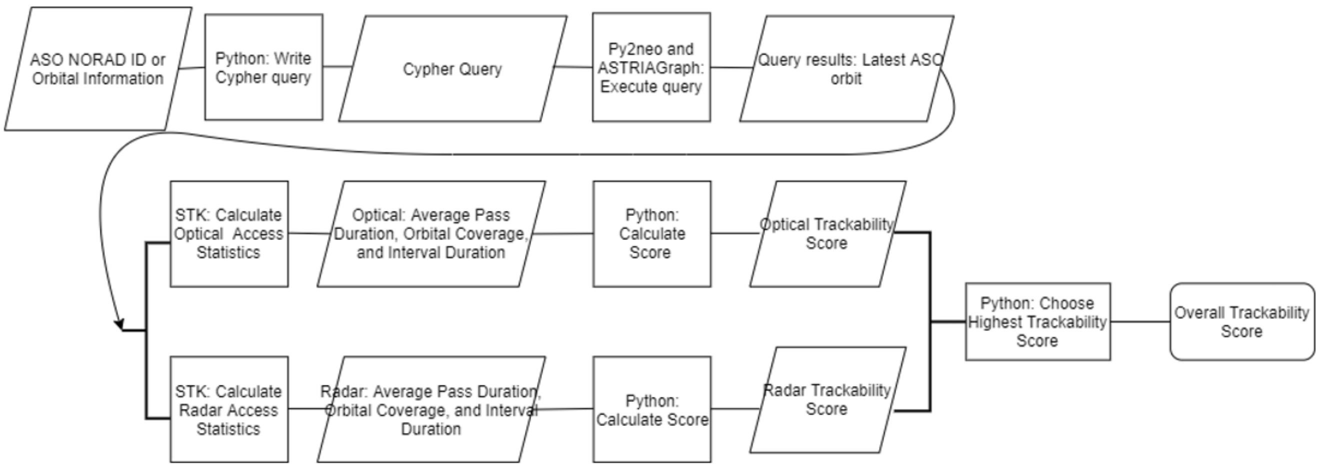

Fig. 3.5 Trackability scoring flow [35].

3.3 Advantages of Using a Knowledge-Graph Database for DIT

The process for incorporating ASTRIAGraph into each step of the DIT analysis was described in the preceding section, but it is also important to explain the reasons for doing so. Building on top of a knowledge-graph database like ASTRIAGraph allows for a simpler user interaction with the DIT module, links together data from multiple sources in a way that can be accessed with a single query, ensures that the most current orbital information is used in the STK simulations, and makes it possible to push the results of the analysis back into the database as a node property of the ASO being scored.

For the long-term operation of the SSR as an available service to satellite operators, it is important that the analysis is not overly time-consuming or complex to execute. Before incorporating ASTRIAGraph into the scoring script, the user had to manually input each orbital element as well as an estimate of the radar cross-section. While this still must be done for a mission that is being scored before launch, ASTRIAGraph took away the need for this tedious and error-prone task for any ASO already in orbit. Because all the information in ASTRIAGraph is curated in connected nodes, it is possible to access data from multiple sources by simply entering the NORAD ID of the desired satellite and then the database can draw from rigorously maintained catalogs operated by government agencies.

As briefly discussed previously, another significant advantage that comes from using ASTRIAGraph in the DIT analysis is its scalable, mutable structure. Once they are calculated, the DIT and overall SSR scores can then each be pushed to ASTRIAGraph as yet another node property for any ASO that receives a rating. The DIT module of the Space Sustainability Rating is just one example of the complex, multidimensional types of problems that can be effectively addressed by a graph database.

3.4 Current Limitations of ASTRIAGraph for the DIT Module

The potential benefits of using ASTRIAGraph for the DIT module of the Space Sustainability Rating have been summarized above, but there are currently still some limitations on how effectively it can be incorporated. The first of these is that there is not a fully developed public API that everyone can use to access the database. There was a collaboration between the ASTRIA Research Group at the University of Texas at Austin and IBM's Space Tech team to begin development of an API called the Advanced Research Collaboration and Application Development Environment (ARCADE), but it currently represents only a proof of concept. ARCADE allows developers to retrieve basic information on each ASO such as its name, international identifiers, and most recent ephemeris data [27]. However, it does not facilitate the execution of custom Cypher queries that a user might want to run, such as in the DIT analysis. This functionality is something that could probably be added in the future, but to get around this limitation for the work done in this thesis, a full download of the database was performed and then set up to run locally on the author's computer. Unfortunately, this meant that new ephemeris data and new ASOs are not being added to the local version of ASTRIAGraph but it was an effective way to test the proposed scoring method that utilizes ASTRIAGraph.

The other current limitation in fully incorporating ASTRIAGraph into the DIT analysis is that some space data sources that contain useful information are not yet included in ASTRIAGraph. One example of this is the European Space Agency's Database and Information System Characterising Objects in Space (DISCOS) [24]. DISCOS collects some unique characteristic data such as the ASO's dimensions and radar cross-section that are not commonly found in other space object catalogs. These are particularly useful to the DIT module because the Detectability analysis requires a radar cross-section to estimate probability of detection by a radar sensor and it needs the dimensions to estimate visual magnitude as seen by an optical sensor. Additionally, if DISCOS was included in ASTRIAGraph, it would be possible for the Identifiability queries to include parameters such as radar cross-section and physical dimensions in addition to the ephemeris data that is already being provided by other sources.

4. Case Studies of Diverse Mission Types and Regions

As the Space Sustainability Rating has been evolving since its 2018 inception, the design consortium has worked diligently to ensure that the scoring systems for each module reflect sustainable space practices, not based upon their own views, but those from the community writ large. There have also been several rounds of beta testing with large American or European commercial operators who volunteered to participate, and with several NASA missions for which data were publicly available. However, one objective of the SSR program is to enable the most widespread space operator participation and to then achieve sustainable outcomes for those that follow sound design and operating practices. This includes operators from regions outside of the United States and Europe, some of which are in emerging space nations. Emerging space nations, as defined by Lifson and built on definitions from Wood and Dennerley, are "countries that possess some demonstrated level of national interest and involvement with space, but are not so engaged as to be considered established space actors" [4, 32, 33]. Work has not been done to investigate whether missions in these other regions, and particularly in emerging space nations, face any unique barriers to being able to score a rating on par with large operators from the United States and Europe.

This chapter follows an exploratory multi-case study approach to assess the Detectability, Identifiability, and Trackability (DIT) module scores of the SSR for four missions that represent a diversity of mission types and regions. These missions are the Thailand Earth Observation System (THEOS), the China-Brazil Earth Resources Satellite Program (CBERS), the Indian Regional Navigation Satellite System (IRNSS), and South Africa's SumbandilaSat. The chapter examines both technical features of the missions themselves and aspects of the mission's national Context that might have affected the DIT scores the mission received, such as launch options, financial constraints, or available technical options. The analysis is organized using a Systems Architecture Framework that is further defined below, which includes methods to formally describe and explain the Context, Stakeholders, Forms and Functions of a given system. The factors that potentially influence the DIT scores of these missions that will be investigated are primarily related to the national Contexts in which the selected space missions were developed, as defined from the perspective of Systems Architecture. Contextual factors could include the experience of operator organizations, launch options, financial constraints, or available technical options, among other possible factors. The Context analysis done for each mission will focus around the areas of Technology, Economics, Collaboration, and Policy at the national level, as defined in previous studies using Systems Architecture [62]. Space sustainability is especially important to many of the space actors in these case studies because they are having to deal with the effects of debris created by larger operators, even as they start to operate in the domain.

4.1 Background

One of the concepts being used in this chapter is that of emerging space nations. As the costs of building and operating satellites have decreased with the maturation of CubeSats and other small satellite technology, greater numbers of national and commercial actors have been able to start participating in space [25]. Several scholars have studied this trend, developed definitions for emerging space nations, and created frameworks to use for analyzing the development of the space programs in these nations. Wood and Weigel created a Space Technology Ladder framework and a Space Participation Metric with the purpose of understanding the implementation challenges facing new space actors and how small satellite programs can be leveraged to support national development goals [34]. Wood continued this research by performing six case studies of satellite projects in four developing countries with a Systems Architecture Framework and showed that the case studies can be summarized by three archetypal types of satellite projects [33]. Work on emerging space nations in the context of international regulatory regimes was also done by Dennerley, who listed a specific set of established space nations and then defined emerging nations as those that are not yet established, but have demonstrated an intention to develop space capabilities [32]. Finally, in his study of different stakeholder preferences for space traffic management, Lifson identified a set of countries that "possess some demonstrated level of national interest and involvement with space, but that are not so engaged in space as to be considered established space actors" [4]. This research project draws from these definitions while selecting space missions for the case study analysis, but also considers actors that are more established space nations but still in the regions of interest.

The key method used in this section is that of calculating the Detectability, Identifiability, and Trackability scores for each of the missions solely based on information that is publicly available. In a prior round of testing, the DIT module analysis was performed for a list of missions primarily operated by NASA, but that also included U.S. commercial satellites. These previous beta tests did not examine how the satellites' scores might be affected by their national Contexts. Therefore, this paper will use the same DIT scoring and analysis to assign scores to the case studies being considered but with a focus on how they are affected by the Systems Architecture Contextual analysis for each mission. While research has been done into space programs in emerging space nations and other regional actors and on the Space Sustainability Rating itself, little has attempted to explicitly connect the two. This chapter will examine this connection so that both the designers of the SSR and those considering applying for a rating will have a better understanding of how well the SSR addresses any unique constraints faced by space nations outside of the United States and Europe in the national-level Context of their space programs.

4.2 Research Design

This study uses an exploratory multi-case study approach, a type of research design described by Yin that includes five components: the study's question, propositions, units of analysis, the logic linking the data to the propositions, and the criteria for interpreting the findings [36]. The research question is "How do missions of diverse types and from regions outside of the United States and Europe score in the DIT module of the SSR and what factors might affect those scores?" Because this study is exploratory, there are no explicit propositions. The unit of analysis is a space mission, which could refer to either one satellite or a constellation of satellites, and the study contains four of these cases. The four cases are Thailand's THEOS, Brazil's CBERS, India's IRNSS, and South Africa's SumbandilaSat. These are all described in greater detail in the results section. They were selected because each of these nations are in regions outside of the United States and Europe, which are where previously scored missions have originated. Also, the research team identified adequate publicly available information to analyze these missions. Finally, the criterion for interpreting the findings will be based on comparison of the scores with those of established space actors. The following paragraphs go into further detail on the data sources and analysis methods used.

There are two main types of data sources used in this project. The first is the Detectability and Trackability scores from the DIT module of the Space Sustainability Rating. Even though this represents just one of the six modules that comprise the SSR, it acts as a starting point to analyze how space missions from emerging space nations perform in the SSR's scoring methodology. It was also chosen as the module for this research because the author specializes in performing and enhancing the DIT methodology within the SSR team. Further research could be done on how each mission scores in the other SSR modules.

The second type of data source utilized in these case studies is the academic papers, journals, and articles used to find Contextual information about the nation in which each of the case study missions was developed. A priority is placed on using peer-reviewed and other reputable sources whenever possible. The challenge with this data source is narrowing down the vast amount of information that is available in order to find what is relevant for defining the Context of each mission.

4.3 Systems Architecture Framework

As described previously, the overall method for this chapter is a multi-case study, where each case is a space mission from a different region. For each case, a Contextual analysis was performed, which is the first step in the Systems Architecture Framework (SAF). Systems Architecture is concerned with understanding how the different entities in a system work together and with predicting the emergence that comes from their relationships [37]. Dr. Danielle Wood has adapted a general form of the Systems Architecture Framework based on work by Cameron, Crawley and Selva to analyze many types of space and social systems, including the satellite programs in emerging space nations [64]. This Framework includes six steps: (1) Describe System Context, (2) Identify and Categorize Stakeholders, (3) Describe Stakeholder Needs, Desired Outcomes, and Values, (4) Identify Desired System Objectives, (5) Describe current System Functions and Forms, and (6) Describe proposed System Functions and Forms and evaluate against System Objectives. Before the first step can even be done, she has specified the importance of defining the System Boundary. This is important for making sure the entire System is included in the analysis, but narrow enough that the System's scope can be comprehended by the designer. In this study, the System Boundary is the satellite itself as this is what the Primary Stakeholders are directly controlling.

The Space Sustainability Rating could be modeled with the entire SAF, but this paper is only concerned with the first step of the Framework, which is describing the System Context. The Context includes the factors that are beyond the control of the System's Primary Stakeholders. For a technology-based System, the factors can be grouped into the areas of Technology, Policy, Economics, and Collaboration. The System is actually situated within the different Context levels of organizational, supporting, national, and international, but this research includes only the national level as it focuses on factors specific to nations from different regions [33]. After the DIT scoring and Contextual analysis are completed for each case, the results are summarized and compared to investigate if there are any trends about how Contextual factors in different nations affect a mission's SSR score.

4.4 Results and Analysis

The first section of results is the Detectability and Trackability scores for each of the four space missions being studied. Detectability and Trackability each contain both a radar and an optical score. In practice, low Earth orbit (LEO) missions are tracked typically with radar sensors and geostationary (GEO) missions are typically tracked with optical sensors. These scores, along with the orbital regime of each mission, are summarized in Table 4.1. Each score is out of 1, where 1 represents the highest, most ‘sustainable’ result. Based on previous beta testing done with publicly available data, these scores are relatively on par with missions from NASA and U.S. commercial operators, with the exception of the SumbandilaSat Trackability scores being fairly low [35]. The trends follow what is expected based on the models used in the DIT module. LEO missions tend to receive lower Trackability scores than GEO missions because they are in the sensor fields-of-view for shorter periods of time and have longer intervals between access opportunities. Additionally, when there is a difference between radar and optical Trackability, the radar is higher than optical for LEO missions and vice-versa for GEO; this aligns with the sensor type actually used in practice for tracking. Finally, the radar Detectability scores, other than IRNSS which is a GEO mission, all achieve full marks which is typical for LEO missions of a certain size. The rest of the results section will summarize the Policy, Technological, Collaborative, and Economic national-level Contextual analysis done for each of the four cases in the study.

Mission	Orbital Regime	Radar Detectability	Optical Detectability	Trackability
THEOS	LEO	1.0	1.0	0.5
CBERS	LEO	1.0	1.0	0.42
IRNS	GEO	0.0	1.0	0.83
SumbandilaSat	LEO	1.0	1.0	0.25

Table 4.1 Detectability and Trackability scores for each mission in the case study [62].

For comparison, Table 4.2 below shows the Detectability and Trackability scores for some missions from the United States for which orbital and characteristic data could be publicly found. These scores were calculated as part of a demonstration of using ASTRIAGraph for the DIT module analysis, but can be included as a point of comparison for the missions in this case study from outside of the United States and Europe [35].

Mission	Orbital Regime	Radar Detectability	Optical Detectability	Trackability
GRACE	LEO	1.0	1.0	0.33
Hubble	LEO	1.0	1.0	0.42
ISS	LEO	1.0	1.0	0.33
TESS	HEO	0.5	0.0	0.83

Table 4.2 Detectability and Trackability scores for selected NASA missions [35].

4.4.1 Thailand Earth Observation System (THEOS)

THEOS is an Earth observation mission with the primary goals of providing Thailand with affordable access to space and using the experience to develop personnel capability and infrastructure within the country for future space missions. It was launched in 2008 with a mass of 715 kg and a volume of 8 m^3 to an altitude of 725 km and is still active. It uses an optical instrument for applications in the fields of land use, agriculture, forestry management, coastal zone monitoring, and flood risk management. It also reduces the cost of purchasing satellite images from other countries [38]. Because the Detectability and Trackability scores for THEOS are typical for what the SSR consortium has seen for other LEO Earth observations missions, the Contextual analysis is done briefly. Technologically, Thailand was an early adopter of satellite communication technology and was also receiving earth imagery data from many foreign sources at the time of the THEOS project. A university and a Thai ministry had previously collaborated with foreign organizations on satellite hardware projects, but THEOS was the first remote sensing satellite project at the national level [33]. Economically, the Thai government was anticipating a potential severe budget deficit in the years of the THEOS project but the economy remained relatively stable [39]. In terms of policy, Thailand has long been a party to the Outer Space Treaty, but has not yet enacted a master law governing space affairs and activities. In 2000, they established the Geo-Informatics and Space Technology Development Agency

(GISTDA) as a public organization to unify their development of satellite-related technology [40]. Finally, in the area of collaboration, Thailand worked closely with France on THEOS. France provided capabilities such as launch, ground control, spacecraft hardware, and training of Thai engineers [33, 39]. This brief Contextual analysis demonstrates that Thailand likely had all the pieces in place to have success with the THEOS program. Even though they are less experienced than some more established space actors, Thailand’s national-level factors did not affect the mission’s scores in a noticeable way as compared to those of other nations.

4.4.2 China-Brazil Earth Resources Satellite Program (CBERS)

CBERS is a technological collaboration program between China and Brazil that was established in 1984. Together, they have launched six satellites between 1999 and 2019, all of which are Earth observation satellites for applications in agriculture, geology, hydrology, and the environment. The satellite payloads include multiple sensors with different spatial resolutions and data collecting frequencies [41]. Even though China is not considered an emerging space nation based on the definition found in the literature review, CBERS was selected as a case study because it is an interesting example of international collaboration with an established space nation outside of the United States and Europe. CBERS-4A, the most recent satellite in the program, was launched in 2019 with a mass of 1980 kg and a volume of 38 m^3 to an altitude of 628 km and is still active. It received Detectability and Trackability scores on par with missions from the U.S. and other large operators. Regardless, performing a brief Contextual analysis for CBERS could still help to show any relevant factors that enabled them to achieve these scores.

The four areas of the national-level Contextual analysis are complicated by the fact that both China and Brazil are relevant and directly involved in this mission. However, because this paper is concerned mostly with emerging space nations, Brazil will be the focus of the Technology, Economics, and Policy sections, but China will be included in the area of Collaboration. CBERS-4A was launched on a Chinese Long March 4 rocket from Taiyuan Satellite Launch Center, but it is important to mention that the Brazilian Space Agency also operates launch sites at Alcantara Space Center and Barreira do Inferno [42, 43]. They have also worked on several launch vehicle projects in the past that ended up failing to launch or even exploding on the launchpad, and now continue their efforts to develop launch capability [44]. So, even though CBERS uses a lot of Chinese hardware and systems, Brazil has managed to advance quite far in the field of space technology. Economically, Brazil and China contributed the same amount of money to the project, demonstrating the equality of their partnership in the project [45]. Politically, Brazil has gone through a lot of transition and unrest over the course of the CBERS project. In the years leading up to the launch of CBERS-4A, there were waves of protest over poor public services, a corruption scandal around the state oil company, a former president was imprisoned for corruption, and far-right politician Jair Bolsonaro was elected [46]. These events, especially the changes in national leadership, affect the budget and priority given to different government projects and groups, to include the Brazilian Space Agency. Finally, Brazil's collaboration with China for CBERS-4A is the key element of this Context analysis. Both countries have benefited from the partnership over the years it has been active. Brazil gained the chance to develop larger, more advanced satellites at a time in the history of its space program when it was only capable of building small 100 kg satellites. China received an international partner that posed no military threats and allowed it to gain more international relevance as it came out of its period of internal reform. The two countries have exchanged important technical information and visited each other's facilities, renewing the agreement two times so far [47]. After examining the four Context areas of Policy, Technology, Economics, and Collaboration for Brazil and the CBERS program, there seem to be a few factors indicated that might positively affect their Detectability and Trackability scores in Table 4.1. The biggest of these is that the long-term collaboration between China and Brazil on this project demonstrates a commitment to the development of their space programs and capabilities, realized in the launch of larger, more expensive and reliable satellites than some of the other countries in this case study.

4.4.3 Indian Regional Navigation Satellite System (IRNSS)

India does not meet the definition of an emerging space nation established earlier in this chapter. One reason for this is that the Indian Space Research Organization (ISRO), India's national space agency, is one of six government space agencies in the world that possess full launch capabilities [48]. However, this mission is useful to include because it is still from a different region of the world and is a geostationary (GEO) constellation, unlike the other case studies which are all in low Earth orbit. This then provides a greater variety of mission types for the research question. The Indian government approved the Indian Regional Navigation Satellite System (IRNSS) project in 2013 because access to foreign government-controlled navigation systems is not guaranteed. IRNSS is made up of 8 geosynchronous satellites and provides a standard positioning service for civilian use and an encrypted service for military use. The last satellite was launched in 2018 with a mass of 1425 kg and a volume of 3.6 m^3 to an altitude of 35,786 km and is still operational [49].

The Detectability and Trackability scores received by IRNSS are on par with other GEO missions in the previous beta testing [35]. The radar Detectability is zero because GEO satellites are so much farther away than LEO satellites that radar sensors are not practically used for tracking them. Instead, optical sensors are used, which is reflected in the scoring. Additionally, the Trackability scores are higher than those of the LEO missions. This is because at a higher altitude, the GEO satellites spend more time in the field of view of the sensors and thus, are easier to track. For the Technology Context analysis, as was mentioned previously, India already has full launch capability. This suggests that the state of their space technology sector is far more developed than that of a typical emerging space nation. In fact, having the capability to launch a satellite to GEO puts India all the way at Level 13 of the Space Technology Ladder proposed by Wood as a framework for understanding the technical capability and autonomy of a nation's space program [33]. Economically, ISRO has played an important role in the socio-economic development of India, supporting fields such as disaster management, navigation, telemedicine, and engineering. Their annual budget is approximately 1.9 billion USD [50]. This mission's national-level Political Context is highly related to India's desire to be independent from relying on navigation data from foreign countries' satellites. In 1999, the United States denied the Indian's military request for GPS data for the Kargil region [51]. Their goal with the IRNSS mission is to have complete Indian control of the ground and space segments and to have the user receivers all being built in India [52]. Finally, in terms of Collaboration, in the past India was a part of Interkosmos, a Soviet program for space cooperation, and used Soviet launch services for its first satellites [53]. However, they have been operating essentially independently for a couple of decades now, including for the development of IRNSS. This brief Contextual analysis demonstrates that India is fully capable of achieving high Detectability and Trackability scores for a GEO mission.

4.4.4 South Africa SumbandilaSat

SumbandilaSat is South Africa's third satellite project. Launched in 2009, it is a micro Earth observation satellite with the primary mission of collecting data to monitor disasters such as flooding, oil spills, and fires in South Africa. It has a mass of 81 kg and a volume of 0.32 m^3. The key organizations in constructing it were the University of Stellenbosch, SunSpace which is a South African Space company, and the Council for Scientific and Industrial Research's Satellite Application Centre [54]. As seen in Table 1, SumbandilaSat received lower Trackability scores than the other LEO Earth observation missions tested in this and in previous work [35]. Based on the structure of the SSR DIT model, this lower Trackability score means that the assumed ground sensor network has shorter access opportunities and longer intervals between access opportunities. This is usually a function of altitude, as satellites that are further from Earth spend more time in the field of view of the sensors. SumbandilaSat was damaged by a solar storm in 2011 in such a way that the power supply to the onboard computer stopped working and images were no longer being sent back to Earth. SunSpace decided to write it off as a loss and stop trying to operate or repair SumbandilaSat [55]. The orbit then slowly decayed to below its intended operational altitude and the set of orbital elements from ASTRIAGraph used to calculate its Trackability scores show the satellite with a semimajor axis of only 6,611 kilometers, making it even lower than the International Space Station [56]. This alone can explain the lower Trackability scores.

A Contextual analysis of South Africa's space program at the time of building SumbandilaSat shows a few factors that might have contributed to this performance. Technologically, SumbandilaSat was built from commercial off-the-shelf equipment that did not have adequate radiation hardening. Part of the reason for the satellite's failure in 2011 can be contributed to this outdated technology. This is not particularly surprising as the mission was meant primarily to be a technology demonstrator that provided experience for the construction of future national satellites. Economically, the satellite was built for approximately one-tenth of what NASA spent on a satellite of a similar size. This slim budget, according to the head of business development at Sunspace, was the reason that more money could not be spent on better radiation hardening [55]. In the area of Policy, SumbandilaSat ended up sitting on the shelf for three years before it was launched due to “political reasons”. A new launch had to be negotiated after years of frustrating delays [57]. Also, South Africa was facing a national-level transition for their space policy as they adopted a new National Space Policy that changed the structure and priorities of their space industry [58]. Finally, the Collaboration surrounding this project came mostly in the form of a partnership between university, commercial, and government agency groups. This approach allowed for extremely valuable capability building, sharing of knowledge and experience, and set strong foundations for future South African space projects, which made the mission a resounding success in terms of what it set out to do [59]. Taking these four Contextual areas into consideration, there are some clear factors that contributed to the risk of the satellite being damaged and failing. The most important are the tight budget that led to the use of outdated technology with poor radiation hardening and political factors that delayed launch. These factors, though still possible, are less prominent in the programs of established space actors like the United States.

4.5 Implications

In conclusion, this research project showed that in many cases, space missions from a diversity of regions achieve Detectability and Trackability scores that are on-par with missions from the United States and Europe. When there are score discrepancies, as was the case with South Africa's SumbandilaSat, an investigation revealed that the score was lower because of damage that the satellite received on-orbit. This degraded the orbit in such a way that it could no longer be tracked as easily by the simulated ground sensor network. The Contextual analysis showed that a slim budget and tight time constraints led to the use of outdated technology and a lack of radiation hardening on SumbandilaSat which increased the risk from solar radiation. Additionally, political issues plagued the scheduled launch date so much that it had to be delayed and renegotiated for three years, while the satellite was just sitting in storage. These factors, while maybe not always unique to emerging space nations, can be very impactful to them because they have a fewer number of satellite projects and less overall experience in dealing with these challenges.

The DIT module was chosen for testing these missions in this project for the sake of accessibility and simplicity, but in practice, the DIT scores are related almost solely to the orbit chosen for the mission and the satellite's size and shape. For this reason, it might not be the best SSR module to illustrate the impact of national-level Contextual factors on missions in emerging space nations. Further work should be done to investigate how these emerging space nation missions score in other modules like Mission Index, Collision Avoidance, and Data Sharing as they have the potential to yield greater differences in scores and more interesting trends.

The ideas explored in this paper are important for two groups of stakeholders. First, it is a chance for the designers and operators of the Space Sustainability Rating to gain a better understanding of unique challenges faced by missions outside of the United States and Europe. This could motivate greater dialogue with them so that, if necessary, the SSR can continue to be refined to make sure that it accurately reflects both sustainable operating behaviors and the interests of all types of operators and space actors. Secondly, this research demonstrates to programs in different regions that participating in the SSR can be beneficial to them. Because their scores can be on-par with more established actors, at least in the DIT module, receiving a rating could be a way to boost reputation and publicity for emerging space nations. Ultimately, it is the hope that this piece of research contributes to greater efforts for sustainability in space that will enable long-term access and benefits for all types of actors.

5. User Manual to Implement DIT for Operational Use

As the Space Sustainability Rating transitions to an operational phase where the Space Center of the Swiss Federal Institute of Technology Lausanne (EPFL) will issue ratings to operators who apply for a rating, it is important that the models and scoring methodology are well documented so that everything is executed in a consistent way. This chapter aims to provide that documentation for the Detectability, Identifiability, and Trackability module.

5.1 Step-by-Step Guide

Before explaining the process of actually conducting the analysis, all of the software and files required for the DIT module are listed and described below. The software version numbers used by this author are provided, but earlier or later versions may also be acceptable; they have not been thoroughly checked for compatibility.

- Python 3.9 - programming language used for the primary DIT analysis script; run by this author in the PyCharm Integrated Development Environment but can be executed in other Python shells
- Py2neo 2021.1.5 - Python library for working with Neo4j from within Python applications
- Neo4j 4.2.1 - graph database management system that is used to build ASTRIAGraph
- Neo4j Desktop 1.4.1 - local development environment for managing Neo4j projects
- Systems Toolkit 12.1.0 - 3D modeling software for simulating satellites, orbits, and ground sensors; needs to include license for Electro-Optical Infrared (EOIR) and Integration toolkits

- MATLAB R2020b - programming language used to compute the radar cross-section of a satellite
- Solidworks 2018 - computer-aided design (CAD) application used to build simplified 3D models of satellites if not provided by the operator

There are also several files required to execute the DIT analysis. These are listed and briefly summarized below. They can be found in a GitHub repository at https://github.com/mercush/UROPsatellites.

- DT.py - Python script that calculates the radar Detectability and radar/optical Trackability scores for a given satellite
- I.py - Python script that writes and executes the sample query shown in Chapter 2 for the proposed Identifiability analysis for a given satellite
- rcs_calculation.m - MATLAB function that calculates the radar cross-section of a satellite from a .STL 3D model file of it
- ASTRIAGraph data - download file of all the data stored in ASTRIAGraph; only required if running a local version of the database; not included in GitHub repository
- DetectabilityTesting.sc - STK scenario file containing the assumed ground stations and sensors for the Detectability scoring
- SSR operator inputs - an Excel file given to operators applying for a rating that contains the required mission parameters; not included in GitHub repository

The first steps to set up the environment for the DIT analysis are to open the DetectabilityTesting.sc file in Systems Toolkit and to start the local instance of ASTRIAGraph with the download file and Neo4j desktop so that the database is active. Once these actions are accomplished, they should look like the screenshots shown in Figs 5.1 and 5.2. The processes described in the subsections below are all based on the data currently available in ASTRIAGraph and the existing functionality of the Python scripts as of the time of this thesis's completion, but likely will change as more data is added or additional functionality becomes available in future work. Also, the radar Detectability and optical and radar Trackability scores are all currently calculated with a single execution of the DT.py script, but the appropriate lines could be commented out to just receive whichever score is desired.

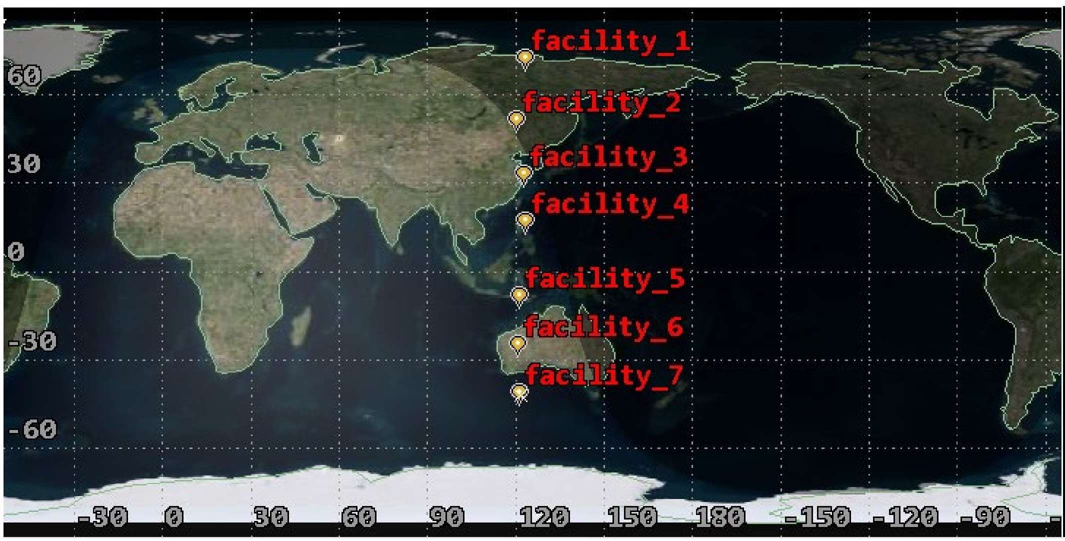

Fig. 5.1 DetectabilityTesting.sc opened in Systems Toolkit (STK).

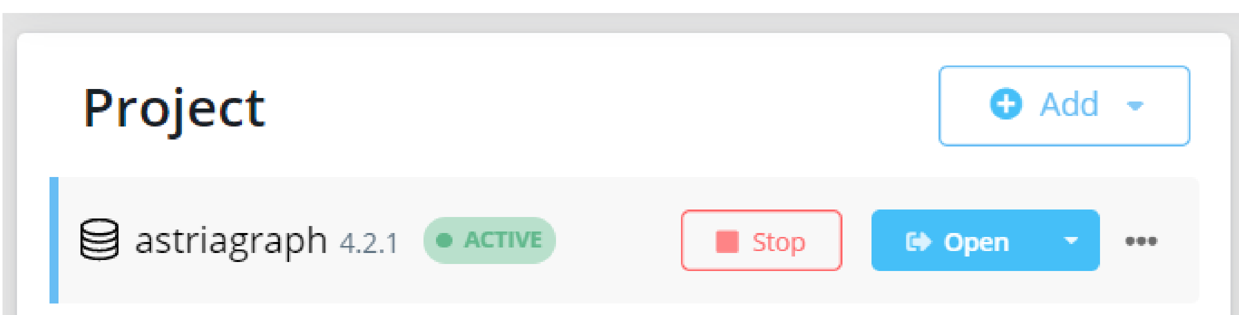

Fig. 5.2 ASTRIAGraph database running locally in Neo4j desktop.

5.1.1 Detectability

First, the process for calculating the radar Detectability score will be described. The inputs to this analysis are the classical orbital elements of the satellite's orbit and the radar cross-section of the satellite. If the radar cross-section is not provided by the operator or it is not an existing mission whose radar cross-section can be found in a source like DISCOS, it must be calculated. This is done by creating a simplified 3D model of the satellite in Solidworks, based on the rough dimensions provided by the operator. The model should be saved with meters as the units and as a .STL file. An example of one of these 3D models is shown in Fig 5.3.

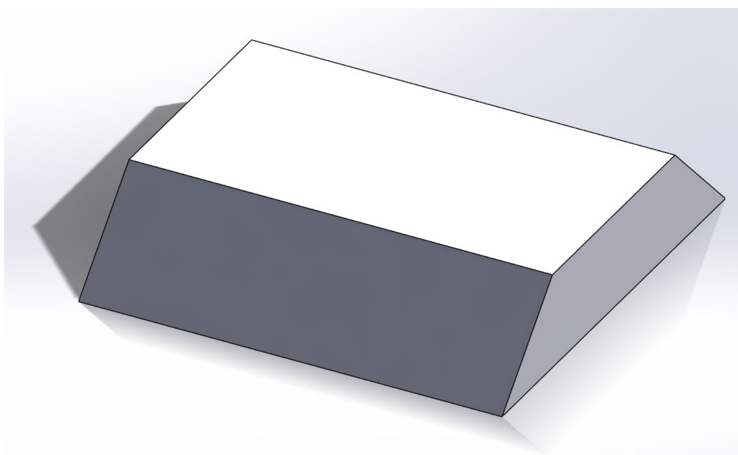

Fig. 5.3 Simplified 3D model of NASA GRACE mission.

Then, the rcs_calculation.m script can be used to calculate the radar cross-section, where that 3D model file is the input and the mesh parameter in line 26 should be changed to half the value of the shortest dimension of the satellite in meters. An output of this script for the GRACE 3D model is provided in Fig 5.4. The output shows a plot of the RCS for a full 360-degree simulation, the peak RCS, and an average RCS estimate. More detail about this estimation method can be found in Steindl's publications [6, 11].

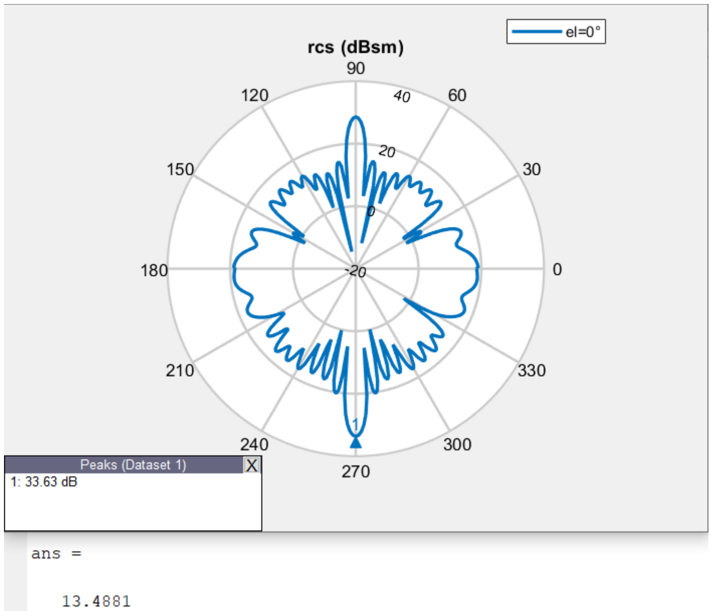

Fig. 5.4 Outputs of rcs_calculation.m script for NASA GRACE mission.

Next, the DT.py file should be executed. Following the prompts in the terminal, the user should input a 1 if the satellite is an existing mission or a 2 if it is a pre-launch mission not yet in the maintained satellite catalog. If option 1 is selected, the script will ask for the NORAD ID and radar cross-section, then retrieve the orbital elements from ASTRIAGraph. With option 2, the script will ask for the NORAD ID, the radar cross-section, and the orbital elements from the SSR inputs sheet to be inputted by the user. The script will use this information to construct a representation of the satellite and its orbit in STK, propagate it over the course of a month, calculate the access between the radar ground sensors and the satellite, and find the maximum probability of detection by the radar sensors. Finally, the script outputs the results of this calculation and the associated score that the probability of detection score receives for the SSR. An example of this output is in Fig. 5.5.

```
MATCH(SO:SpaceObject)-[:has_orbit]->(orb:OrbitalElementsSet) WHERE SO.NoradId='43476' RETURN SO, orb
Enter the ASO's estimated radar cross-section in m^2: 22.3
                         Metric  Value            Tier  Score
0  Max Probability of Detection    1.0  More Detectable    1.0
```
Fig. 5.5 Radar Detectability scoring output in Python script for GRACE mission.

The optical Detectability scoring process is more complex as the script does not yet have the functionality to do it automatically and requires manual use of the STK Graphical User Interface (GUI). After the radar Detectability is computed, the STK scenario should still show the 7 ground stations and the ASO and its orbit. The user should uncheck the boxes next to all of the facilities in the left pane of STK except for the EOIR sensor at one of the facilities that has access to the ASO during its orbit. For a polar orbit, this could be any of the facilities but a lower inclined orbit might only be accessible by one of the sensors closer to the equator. Next, the user should right click on the ASO in the left pane and go to its Properties. In the EOIR Shape page under the Basic menu, the user should put in the proper shape and dimensions in meters of the ASO and change its reflectance to 17.5%. Also, in the Sun page of the Constraints menu, the user should ensure that the lighting box is checked and the option is set to Penumbra or Umbra. These changes to the properties should be applied. The rationale behind all of these settings can be found in Steindl's thesis [6]. Next, the user should right click on the EOIR sensor of the facility being used and go to its properties. In the Pointing menu under Basic, the ASO should be switched from the Available Targets list to the Assigned Targets list by selecting it and then clicking the arrow to move it to the right side of the list. This change should also be applied.

Then, with the EOIR sensor still selected, the Access tool from the toolbar (looks like a small yellow square connected to a larger green square) can be chosen. The "Access for:" line should show the EOIR sensor of the chosen facility. The user should click on EOIR and then compute. The access opportunities between that sensor and the satellite will be calculated. The user can click Access under the Reports section to see the access report. Figure 5.6 shows an example of what the first part of this report looks like for the GRACE mission.

```
FOR UNFUNDED EDUCATIONAL USE ONLY
Place-facility_1-Sensor-EOIR-To-Satellite-ASO:  Access Summary Report


EOIR-To-ASO
-----------
                  Access        Start Time (UTCG)           Stop Time (UTCG)        Duration (sec)
                  ------    ------------------------    ------------------------    --------------
                       1    26 Oct 2020 17:01:00.203    26 Oct 2020 17:04:11.188           190.984
                       2    26 Oct 2020 18:35:17.190    26 Oct 2020 18:35:50.824            33.634
                       3    27 Oct 2020 07:09:33.069    27 Oct 2020 07:10:19.806            46.737
                       4    27 Oct 2020 08:43:50.055    27 Oct 2020 08:47:04.235           194.180
                       5    27 Oct 2020 10:18:07.041    27 Oct 2020 10:23:44.733           337.692
                       6    27 Oct 2020 11:52:24.027    27 Oct 2020 11:59:28.344           424.317
                       7    27 Oct 2020 13:26:41.013    27 Oct 2020 13:33:54.632           433.619
                       8    27 Oct 2020 15:00:58.000    27 Oct 2020 15:07:02.802           364.802
                       9    27 Oct 2020 16:35:14.986    27 Oct 2020 16:39:06.503           231.517
                      10    27 Oct 2020 18:09:31.972    27 Oct 2020 18:10:43.242            71.270
```

Fig. 5.6 STK EOIR access report from facility 1 to GRACE mission.

The user will now step through various time intervals to simulate the brightness, or irradiance, of the satellite over the course of its orbit. They can do this by right clicking on the start time of the access opportunity and selecting Start Time, then Set Animation Time. Then the user should click on the EOIR Configuration button on the toolbar, which looks like an orange circle with a settings symbol. They should move the ASO from the Available STK Objects box to the Selected Targets box and click OK. Then, they can select the EOIR Sensor Scene tool on that same toolbar that looks like a telescope. This brings up a window displaying what the EOIR sensor shows during the simulated time. Right click on that window and click Details; this displays a window with the details of the scene, including the irradiance of whatever object in the scene is selected. Because the sensor is pointing at the ASO, the ASO will always be in the middle of the scene, which is centered at Pixel X 64, Pixel Y 64 and fills a few surrounding pixels as well. The Details window shows which location in the scene is selected and the name of the object, as well as the irradiance of that object. The value of interest from this window is the

Inband Irradiance. An example of the EOIR Sensor Scene and Details window for the GRACE mission is shown in Fig. 5.7 below.

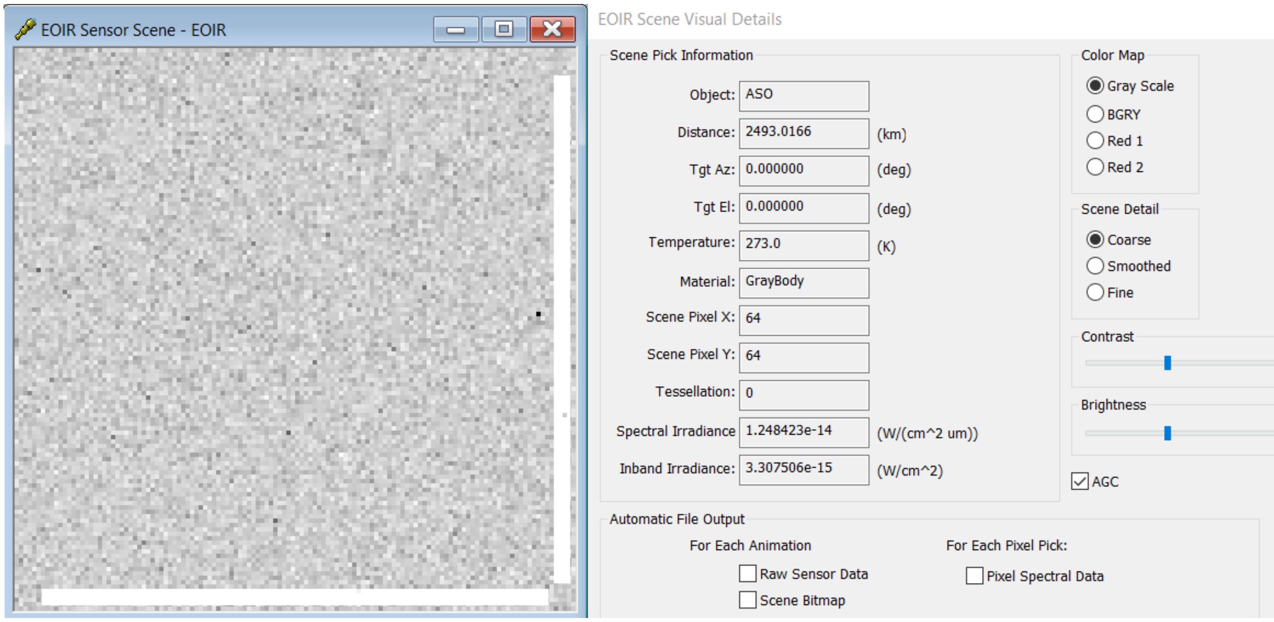

Fig. 5.7 EOIR Sensor Scene and Details window for GRACE mission at facility 1.

Once the user copies this Inband Irradiance value and stores it in a spreadsheet or some other form of managing the data, they can select Step Forward on the toolbar that controls the time in the STK scenario. This will step the time forward by 60 seconds, where the user can collect another irradiance value. Once one access opportunity is fully simulated, the user can right click on another start time in the access report and set the scenario start time to it. While conducting this process, the user might notice that some of the irradiance values are extremely small, around an order of magnitude of 10^{-40}. Steindl has defined that this means the ASO is essentially not observable by the EOIR sensor [6]. It typically happens at the beginning or end of a pass when the ASO is near the horizon and not at a proper elevation angle to be in the field-of-view of the sensor. When the ASO actually becomes visible, there is a dramatic shift in the order of magnitude of the irradiance value. It jumps to around 10^{-21} or larger. For the purposes of this analysis, only these values that are greater than 10^{-21} meet the cutoff to be included in the collected irradiance values [6]. Once 50 of these irradiance values are collected from over the course of the simulated orbit, they can be turned into visual magnitude numbers with a logarithmic equation also found in Steindl's work [6]. An example of what the visual magnitude values look like for the GRACE mission are shown in Fig. 5.8. Each curve of values follows how the ASO becomes brighter and dimmer throughout the course of a single pass as it gets closer and further from the sensor. The multiple curves represent different access opportunities that were measured and simulated during the orbit. The average visual magnitude is used to assign the object an Optical Detectability score for the DIT module.

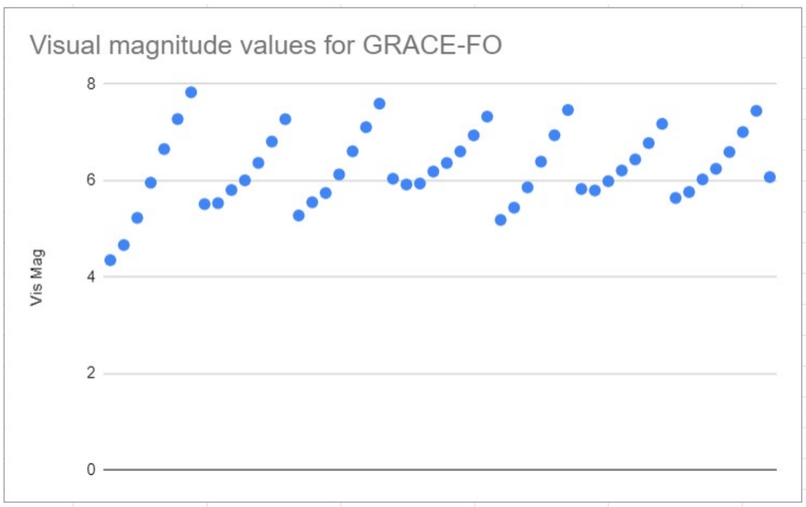

Fig. 5.8 Visual magnitude values for GRACE mission simulated with STK EOIR.

5.1.2 Identifiability

At the time of this thesis, the Identifiability analysis is run in a separate file from the Detectability and Trackability because it has not been incorporated into the operational SSR. The first step is to ensure that a local version of ASTRIAGraph is running in Neo4j. The process for this is described in section 5.1.1. Then, the I.py file can be executed in PyCharm or another

Python terminal. The inputs to I.py are actually quite similar to DT.py - either a NORAD ID for an existing mission, or the orbital parameters for a mission being evaluated pre-launch. The script will then use these inputs and hardcoded uncertainty bounds to construct a Cypher query, such as the one shown in Fig 5.9 for the THEOS mission. The query is executed in ASTRIAGraph and the results are returned. The ASO characteristics and orbital elements, along with the uncertainty values, can all be changed in the script when a final methodology is proposed, tested, and confirmed for the Identifiability subscore of the DIT module.

```
MATCH(SO:SpaceObject)-[:has_orbit]->(orb:OrbitalElementsSet)
WHERE 1.7161010883284635 < orb.Inc < 1.7261010883284633
AND 7197617.081149996 < orb.SMA < 7197713.081149996 RETURN count(DISTINCT SO.NoradId)

Number of ASOs in same Inc and SMA range: 124
```

Fig. 5.9 Sample Identifiability Cypher query and result for THEOS mission.

5.1.3 Trackability

As explained briefly above, DT.py actually calculates the radar Detectability and both Trackability scores simultaneously. So, to conduct the Trackability analysis, the same steps for inputting the data should be followed as described for the radar Detectability in section 5.1.1, making sure that the Trackability functions in lines 80-93 of DT.py are uncommented. The script adds the full network of ground stations into the STK scenario, propagates the satellite's orbit for a month, and computes the access opportunities between each ground station and the ASO. The three Trackability metrics of average pass duration, average interval duration, and percentage of the orbit observed (orbital coverage) are calculated and displayed, along with the resulting SSR scores. The output for both optical and radar Trackability scores for NASA GRACE is shown in Fig 5.10. The higher score out of optical and radar is actually used in the final SSR scoring.

```
              Metric       Value            Tier  Score
0      Avg Pass (s)  163.953641       Trackable   0.25
1      Avg Coverage    0.148393       Trackable   0.25
2  Avg Interval (s)  940.905694  More Trackable   0.50

Overall T Radar Score: 0.3333333333333333

              Metric        Value                Tier  Score
0      Avg Pass (s)   162.305062           Trackable   0.25
1      Avg Coverage     0.090169  Difficult to Track   0.00
2  Avg Interval (s)  1637.694938      More Trackable   0.50

Overall T Optical Score: 0.25
```

Fig. 5.10 Radar and optical Trackability sample scores for NASA GRACE mission.

6. Conclusion

The Space Sustainability Rating is an incentive system commissioned by the World Economic Forum, designed by a consortium that includes the European Space Agency, the Massachusetts Institute of Technology, the University of Texas at Austin, and Bryce Space and Technology, and is now operated by the Space Center of the Swiss Federal Institute of Technology Lausanne. It rates a given space mission on how sustainable it is for the space environment in regards to how it contributes to debris mitigation and collision avoidance. The rating tier that the mission receives is based on a weighted combination of the scores it earns in the six modules. One of these modules is the Detectability, Identifiability, and Trackability (DIT) module. DIT aims to quantify how difficult it is to detect, identify, and track a satellite. These three actions are critical for maintaining high-quality space domain awareness and allowing for safer operations in space. Thus, including an evaluation of a mission's performance in the DIT module as part of the SSR demonstrates the importance of operators designing their satellites in a way that is mindful of how well SDA providers will be able to track it and to provide accurate collision warnings if necessary. Operators can improve their scores in the DIT module in several different ways. In terms of Detectability, they can consider whether the satellite will be large and bright enough in its planned orbit to be detectable by radar and optical ground sensors, while still being careful about the potential effects of light pollution for astronomers. For Identifiability, operators can examine the density of the planned orbit and how close the satellite will be to other similar objects or whether there are any unique characteristics they can add to their satellite. They can also determine whether the deployment plan from the launch vehicle has the potential to immediately make the satellite unidentifiable from the others launched with it, as sometimes happens when multiple satellites are deployed simultaneously. For Trackability, the operator can plan the satellite's orbit in a way that maximizes how long it can be observed by ground stations, depending on the orbital regime of the mission. These are considerations for the DIT module specifically, but there are also many other design decisions relevant to raising the mission's score in other modules of the SSR, especially related to collision avoidance capabilities and the mission lifecycle plan.

The work in this thesis focused on improving and extending the first version of the DIT module. It evaluated the feasibility of using cluster analysis and 'orbital zip codes' for the Identifiability scoring methodology, and then proposed a different process that relies on creating queries in ASTRIAGraph that use the ASO's physical and orbital characteristics to find how many other ASOs in the space catalog might be similar to the one being scored and thus, could make it difficult to identify. This thesis also explained how ASTRIAGraph can be integrated into each step of the DIT scoring analysis, and described the potential benefits and limitations of doing so. Utilizing a source such as ASTRIAGraph demonstrates the potential value for the space community of sharing data across catalogs. It is just one example of the kind of technical tool that can be spurred by the adoption of such practices among operators. Finally, it presented a case study of four space missions of different types and from regions outside of the United States and Europe, evaluated their DIT scores, and examined the national contexts in which the missions were developed. This case study emphasized that operators of all sizes and from many different regions are doing important work in the space sector that should be recognized. They may not always be the loudest contributors in the space community when compared to the large commercial operators and national programs in established space nations, but the nature of space as a common environment means that their ability to operate is disproportionately impacted by the irresponsible behavior of others.

The hope of this work and of the Space Sustainability Rating as a whole is that it will motivate more responsible, sustainable design and operating behavior for all types of satellite operators. Additionally, there is the potential for it to encourage more dialogue and cooperation between commercial, government, military, and academic space sectors as the risk to their assets grows with the more widespread, contested use of space. The SSR was developed as a practical tool but it also motivates academic research by posing policy and technical questions about how certain practices will impact the space environment. As new technologies are developed, the operating environment changes, and policy and law are implemented, research must continue to be done to refine what it looks like to operate in a sustainable, safe manner. The DIT module, in particular, will be a publicly available capability so that other academic colleagues and scholars can improve on it and perhaps use it for applications outside of the SSR if that would be informative. The issue of space sustainability is only becoming more important and urgent and while the Space Sustainability Rating is a worthwhile initiative to address it, it is vital that there are also focused advances in the realms of technology, policy, and law surrounding space sustainability.

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