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Trajectory Specification to Support High-Throughput Continuous Descent Approaches

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Abstract—Continuous descent approaches (CDAs) have demonstrated the ability to reduce aircraft fuel burn and noise, while trajectory-based operations (TBO) have been shown to improve the predictability and throughput of aircraft flows. Prior work has recognized the difficulty of implementing CDAs in high-density terminal-areas due an increase in uncertainty, which can result in a decrease in throughput. This paper investigates whether increased throughput afforded by trajectory-based operations can be combined with continuous descent approach profiles in order to achieve high-throughput CDA operations. Our proposed method first determines a CDA profile, and then locates waypoints with scheduled time of arrival (STA) constraints along this profile, so as to optimize a combination of throughput and fuel burn. For a representative terminal-area descent profile, we find that it is possible to use intermediate waypoints with STAs to increase the throughput by as much as 64%, while incurring an additional penalty of 5 kg per aircraft.

Keywords— *Trajectory Based Operations; Continuous Descent Approaches; High-density terminal areas; Fuel burn; Throughput*

I. INTRODUCTION

Air transportation system modernization efforts are driven by increasing demand, the desire for fuel burn savings, and concerns of environmental impacts. Continuous Descent Approaches (CDAs) or Optimized Profile Descents (OPDs) have been proposed to provide fuel-efficient flight trajectories in the terminal-area. However, the implementation of CDAs in high-density terminal-areas remains a challenge, primarily because of the need to deconflict aircraft and an increase in trajectory uncertainty, which decreases arrival throughput. A key operational concept that can increase throughput and predictability is the shift from open-loop vectoring to trajectory-based control by defining flight trajectories in three spatial dimensions and time, also known as 4D Trajectory-Based Operations (4D-TBO). While 4D-TBO has been shown to improve system

throughput and reduce uncertainty, recent work has demonstrated the possibility of tradeoffs between throughput and fuel burn [1].

Motivated by these observations, this paper investigates whether 4D-TBO can enable high-throughput CDAs. We first determine the optimal CDA profile, and then locate waypoints along this profile. These intermediate waypoints represent locations at which the trajectory is defined using a combination of the geographical position and a scheduled time of arrival (STA) in order to improve predictability and throughput. Finally, we evaluate the impact of the intermediate waypoint locations on the throughput and fuel burn of an aircraft flow along that profile.

A. Continuous Descent Approaches

Conventional descent profiles comprise of multiple level-offs to meet path constraints, and to ensure sufficient spacing between aircraft while managing traffic flows. These profiles are usually achieved by the air traffic controllers assigning altitude and speed adjustments that often achieve maximum runway throughput, but worsen fuel burn and emissions. Furthermore, in high demand scenarios, arriving aircraft may spend long periods of time in holding patterns at low altitudes, incurring even more fuel costs.

In contrast to conventional approach procedures, a Continuous Descent Approach (CDA) maintains idle or near-idle thrust while descending from the cruise altitude to the runway without any level-offs, allowing aircraft to fly at optimal speeds. Numerous studies have demonstrated the potential fuel burn, noise, and emissions benefits of CDAs [2, 3, 4]. CDA profiles can vary due to factors such as weather, decreasing predictability [5]. This decrease in predictability and the resulting decrease in throughput pose a barrier to the practical implementation of CDAs in high-density terminal-areas [6].

B. Trajectory-Based Operations (TBO)

One approach to reducing uncertainty and improving predictability is to specify and manage aircraft trajectories in space and time. Doing so allows a shift from open-loop control to active trajectory management. This concept – known as 4-dimensional (4D) Trajectory-Based Operations (4D-TBO) – can allow for user-preferred trajectories to be flown from gate to gate. A part of 4D-TBO is defining 4D trajectories (4DT), which consist of a series of three-dimensional (3D) waypoints for a flight, each associated with a time (known as the Scheduled Time of Arrival, STA). The Flight Management System (FMS) on an aircraft flying the trajectory then attempts to meet the given STAs (i.e., tries to be at the specified waypoints at the specified times) by appropriately adjusting the aircraft speed. While there are many aspects to the TBO concept, this paper focuses on the ability to specify and manage 4D trajectories.

Although 4D-TBO can help improve predictability by having aircraft attempt to conform to STAs, prior work has shown that doing so can cost extra fuel, especially as the number of way points at which STAs are specified (also known as metering points) increase [1]. Consequently, there is a tradeoff between the throughput (which increases with the number of STA waypoints as predictability increases) and the fuel burn. Additionally, there is less controllability during descent than in cruise since there are speed restrictions assigned by Standard Arrival Route (STAR) procedures and airport regulations which become more limiting at lower altitudes.

C. Objective of this Work

The goal of this paper is to investigate whether the specification of additional STAs at multiple intermediate waypoints along a CDA profile can help increase the throughput that it can support in the presence of wind uncertainty, and if so, what the resulting trade-offs with fuel burn would be. Using representative terminal-area scenarios, we find that there is potential value to incorporating multiple intermediate waypoints with associated STAs along a CDA profile: the throughput can be increased by as much as 64%. However, there is a penalty to be paid in terms of fuel consumption, which can increase by as much as 5 kg per flight.

D. Related Work

Prior studies and field trials have considered the combination of CDAs with STAs, and have identified airspace congestion, wind uncertainty, and speed/altitude constraints as the key challenges to practical adoption of TBO for the descent phase of flight [5, 7, 8, 9]. Studies have also considered powered descents or path stretches [10], conflict resolution algorithms [8], guidelines to design STA-compliant CDA trajectories

[9], sensitivity analysis to various factors [11, 9], and other procedures [12, 13]. Much of this work has been focused on implementing only one STA constraint along the trajectory. Although [14] used multiple waypoints, their focus was on monitoring the resulting time errors, and not determining their locations. Finally, [15] used multiple metering points to ensure sufficient spacing between aircraft. This paper fills the gap in the state-of-knowledge by considering the problem of how to optimally locate intermediate STA waypoints along a CDA profile, and the resulting tradeoffs between throughput and fuel burn.

II. TRAJECTORY OPTIMIZATION UNDER WIND UNCERTAINTY

In this section, the methodology for determining a CDA¹ trajectory that minimizes fuel consumption and total time elapsed is presented. Afterwards, a method of calculating the required speed to correct path uncertainties caused by wind forecast errors is described². In practice, the optimized profile will represent the aircraft's planned route, while the speed corrections will occur while executing the planned CDA profile.

A. Optimized CDA Profiles in the Absence of Wind

Several approaches have been proposed in the past to solve this problem with various control and operational parameters. The majority minimize parameters like fuel burn, time, noise and emission costs using control options such as throttle setting, flight path angle, speed brakes deflection and load factor [10, 12, 16, 17, 18]. The optimization problem presented in this research uses elevator-controlled flight path angle (to modulate energy) and engine thrust (to add or subtract energy) as the control options. A scenario is assumed where the pilots have almost completed the cruise portion of the flight and are planning the final descent phase. The cruise portion is included in the optimization problem to determine the top of descent (TOD) and to give enough control authority for the aircraft to meet an assigned time constraint. Based on current piloting procedures, the profile constraints are selected with respect to constant Calibrated Air Speed (VCAS) and Mach number M as shown in Fig. 1. Moreover, the fixed lateral portion of the flight is assumed to be known as determined by Standard Terminal Approach Route (STAR) procedures, while the final time is located at the Initial Approach Fix (IAF).

¹In this paper, we use the terms 'Continuous Descent Approach (CDA) and Optimized Profile Descent (OPD) interchangeably.

²We focus on the wind forecast *errors*, assuming that forecast winds can be accounted for in the initial trajectory optimization. In other words, the wind forecast errors (or wind errors) are the difference between the winds expected during trajectory planning, and those actually experienced.

1) *Aircraft Model*: The Flight Management System (FMS) of an aircraft may use a trajectory predictor to determine the vertical profile to fly by numerical integration of aircraft model equations. To find a balance between accuracy and computational efforts, the selected equations of motion are modelled as a simplified 3-DOF (Degree-of-freedom) point-mass aircraft model represented by nonlinear differential equations:

$$\dot{V} = \frac{T - D}{m} - g \sin \gamma \quad (1)$$

$$\dot{d} = V \cos \gamma + U_w \quad (2)$$

$$\dot{h} = V \sin \gamma \quad (3)$$

$$\dot{m} = -\dot{F}_{fuel}(T, h) \quad (4)$$

where V , d , h , m , and U_w represent true air speed (TAS), along track position, altitude, aircraft mass and horizontal wind respectively. The nominal fuel flow rate \dot{F}_{fuel} , can be written in terms of thrust T and altitude h according to the model in (5), while drag D can be expressed in terms of the state variables and other known parameters (compressibility effects ignored).

$$\begin{aligned} \dot{F}_{fuel}(T, h) = & C_{ff,3} \left(\frac{T}{T_0} \right)^3 + C_{ff,2} \left(\frac{T}{T_0} \right)^2 + C_{ff,1} \left(\frac{T}{T_0} \right) \\ & + C_{ff,ch} T h \end{aligned} \quad (5)$$

$$D = C_D \frac{1}{2} \rho V^2 S \quad (6)$$

$$C_D = C_{D0} + k C_L^2; \quad C_L = \frac{mg \cos \gamma}{\frac{1}{2} \rho V^2 S}, \quad (7)$$

where T_0 is the maximum static thrust for at sea-level and C_{D0} , k , S , $C_{ff,1}$, $C_{ff,2}$, $C_{ff,3}$, and $C_{ff,ch}$ are constant coefficients used to model fuel consumption, thrust, and parasite drag functions. The required coefficients are obtained from an open-source aircraft performance model OpenAP [19]. The flight path angle consists of very small values, therefore its change is assumed to be minimal ($\dot{\gamma} \approx 0$). Calm wind conditions are applied ($U_w = 0$) as well as a continuous vertical equilibrium, making the lift force equal to the gravity force.

2) *Trajectory Optimization Formulation*: Finding CDA profiles can be formulated as an multi-phase constrained optimal control problem with dynamic and terminal constraints. In general, an optimal control problem is expressed as [20]:

$$\begin{aligned} \min_{\mathbf{u}(t)} \quad & J := l_f(\mathbf{x}(t_f)) + \int_{t_0}^{t_f} l(\mathbf{x}(t), \mathbf{u}(t), t) dt \\ \text{such that} \quad & \dot{\mathbf{x}} = \mathbf{f}(\mathbf{x}(t), \mathbf{u}(t), t) \\ & \psi(\mathbf{x}(t), \mathbf{u}(t), t) \leq 0 \\ & \phi(t_0, \mathbf{x}(t_0), t_f, \mathbf{x}(t_f)) \leq 0 \end{aligned} \quad (8)$$

where $\mathbf{x} \in \mathbb{R}^4$ is the state vector, $\mathbf{u} \in \mathbb{R}^2$ is the control vector, $[t_0, t_f]$ is the time horizon, and ψ and ϕ consist of

all the algebraic, event and terminal constraints which may be active or inactive. The dynamic constraint $f(\mathbf{x}, \mathbf{u}, t)$ consists of the aircraft model equations of motion listed in (1)-(4). Outputs from the optimization include time histories of the state vector $\mathbf{x} = \{V, h, d, m\}$ and control inputs $\mathbf{u} = \{T, \gamma\}$.

The CDA flight in this optimization begins at cruise level, whose horizontal length $d_{TOD} - d_0$ determines the TOD location. After flying with a cruise Mach, the next phase is restricted by a maximum operational mach (MMO), after with the calibrated speed (VCAS) is limited by a maximum operational speed (VMO) until 10,000 feet (FL100). Below FL100, the aircraft is limited to an indicated air speed of 250 knots (defined by 14 Code of Federal Regulations Title 14 § 91.117 [21]); this is set as the maximum calibrated speed until the end of the profile at the Initial Approach Fix (IAF). For the entire descent phase, the minimum VCAS is set at a green dot speed (GD) [22]. Constraints in VCAS and Mach number for each part of the flight can be written as functions of the TAS and altitude-dependent parameters such as density and pressure. These parameters are calculated using the International Standard Atmosphere model. Initial conditions for the problem are known since the aircraft makes the CDA optimization after previous flight portions have been completed. The numerical values used of the velocity constraints are obtained from the OpenAP model [19]. A schematic of this profile is shown in Fig. 1.

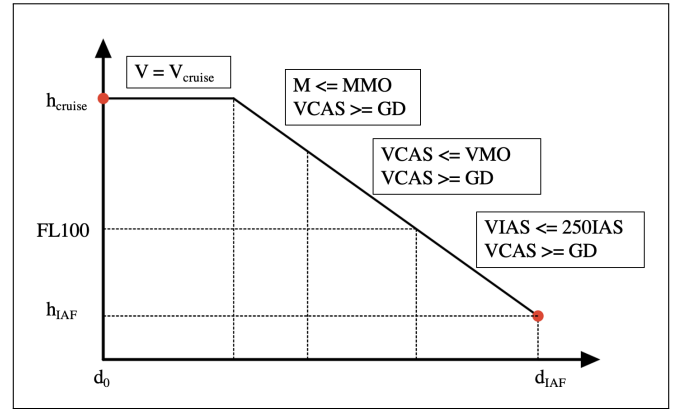


Fig. 1: CDA profile with operational constraints.

The optimization, originally written in continuous domain is discretized over finite time at a set of collocation points and solved using nonlinear programming tools. Given different constraints assigned to phases of trajectory, Legendre-Gauss pseudo-spectral methods are used to represent the trajectory solution as a linear combination of polynomial functions and solved using MPOPT, a python module that uses an open-source package called IPOPT for solving multiphase nonlinear

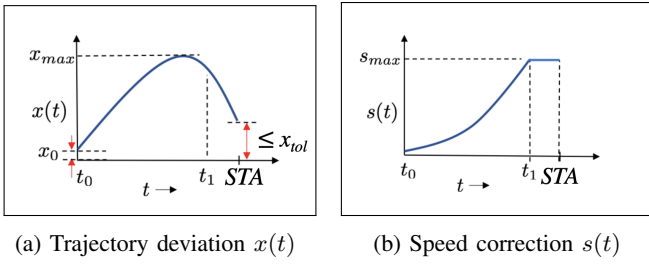


Fig. 2: Speed correction policy and uncertainty profiles [1].

optimization problems [23].

3) *Cost Function*: The Lagrange term in the objective functional and end costs for the optimization problem consider fuel consumption costs formulated as:

$$J = \sum_{k=1}^N \left[\int_{t_0^k}^{t_f^k} \dot{F}_{fuel}^k(\mathbf{x}^k(t^k), \mathbf{u}^k(t^k), t^k) dt \right] \quad (9)$$

where \dot{F}_{fuel}^k is the fuel flow for the k th phase. A time constraint is placed at the end of the trajectory (the IAF) as assigned by the arrival manager.

B. Trajectory Uncertainty Model in the Presence of Wind Forecast Errors

To monitor traffic flows and manage throughput, one or more waypoints with STAs may be placed on a defined trajectory. Given a waypoint with an STA (henceforth referred to as an ‘STA waypoint’), an aircraft is required to arrive at the waypoint at the given STA time, with a specified distance precision. In this case, the FMS initially computes the aircraft’s Estimated Time of Arrival (ETA) at the waypoint, and if different from the assigned STA (due to wind or modeling errors), adjusts its speed to ensure the ETA matches the STA.

It is possible to calculate a speed adjustment profile by employing some sort of optimization algorithm as the last step of the analysis, but to model actual FMS STA functionality operations, we adopt the model for along-track trajectory uncertainty proposed by De Smedt et al. [24]:

$$\frac{dx}{dt} = w(t) - s(t), \quad (10)$$

where $w(t) = U_{w,actual} - U_w$ is the wind forecast uncertainty, $x(t) = X_{actual} - X$ is the flight path uncertainty, and $s(t)$ is the speed correction strategy employed by the aircraft. Here, $X = \sqrt{d^2 + h^2}$ is the magnitude of the flight path in section II-A and $U_{w,actual}$ is the actual wind speed. In this paper, $w(t)$ is set to a constant value w_0 for the entire duration of the profile, which is analogous to assuming a worst case wind uncertainty. Additionally, $x(t)$ is constrained by the distance tolerance x_{tol}

at the STA waypoint, while $s(t)$ is bounded by the available speed correction window, which is in turn evaluated by finding the difference between the airspeed and operational constraints present in the CDA profile. We use a speed correction strategy $s_{cor}(t)$ of the form [24, 1]:

$$s_{cor}(t) = \begin{cases} \frac{x(t)}{STA-t}, & t \leq t_1 \\ s_{cor}(t_1), & t > t_1 \end{cases} \quad (11)$$

$$s(t) = \min(s_{cor}(t), s_{max}) \quad (12)$$

The intuition here is that after the aircraft has accumulated uncertainty due to the wind $w(t)$, a value of $\frac{x(t)}{STA-t}$ has to be subtracted from the slope dx/dt in order to drive $x(t)$ to zero. The time t_1 represents the time at which the current speed correction is sufficient to keep the aircraft remain within the desired tolerance for the rest of the operation. This is illustrated in Fig. 2. Additionally, if the required speed correction exceeds the maximum allowable speed s_{max} as determined by the available speed window, then it is set to this maximum value. The speed correction is employed by flight path angle change which also maintains the altitude profile in a path managed descent. Any speed corrections too large are corrected by additional thrust. We note that this speed correction policy is proportional to the uncertainty and less complex than other optimization-based algorithms, however as shown in [24], it is a very accurate description and bounds the values of actual operations.

III. A SEQUENCE OF WAYPOINTS WITH STAS

For a 4D trajectory with a sequence of STA waypoints, the uncertainty at prior waypoints affect subsequent ones. The final uncertainty at the preceding waypoint becomes the initial condition for the next, and if not properly managed, can cause future deviations to grow. Furthermore, the distance between consecutive STA waypoints impacts fuel consumption (because of required speed corrections) and throughput. The optimized CDA profile (Sec. II-A) is assumed to be the planned route, with a fixed STA waypoint at the IAF. Our goal is to optimally locate intermediate waypoints along the CDA profile prior to the IAF, taking into consideration the throughput and fuel consumption. Two consecutive STA waypoints are said to be connected by a link.

A. Performance Metrics: Throughput and Fuel Burn

1) *Throughput*: The throughput is defined as the number of aircraft that can pass through a link (connection two points on a trajectory) over a period of time, while satisfying the minimum separation requirements. The time separation t_{sep} at a flight location is the required separation distance between two aircraft, x_{req} , divided by the ground speed, V_{GS} . The required speed correction is added to the uncorrected ground speed $V +$

$U_{w,actual} = V + U_w + w$ which makes the realized ground speed $V_{GS} = V + U_w + w - s$. The throughput of a link can then be computed as the inverse of the maximum time separation required in that link.

$$t_{sep} = \frac{x_{spacing}(t)}{V_{GS}(t)} = \frac{2x(t) + x_{req}}{V(t) + U_w(t) + w(t) - s(t)} \quad (13)$$

$$P_{link} = \frac{1}{\max t_{sep}}, \quad (14)$$

where V is the speed obtained from the CDA optimization problem, and x_{req} is the required minimum separation. This minimum required spacing is set to be 3 NM based on terminal-area aircraft operations, while the $x(t)$ and $s(t)$ profiles are derived from the uncertainty calculation in that link (10)-(12). The term $2x(t)$ is added to the spacing to account for the maximum position uncertainty of two consecutive aircraft following the same profile. This term is necessary because, even though the desired spacing is achieved at the start and end of a link, spacing infringement could occur in-between. For a given link, it can be inferred from the throughput equation that higher minimum speeds and smaller aircraft spacing will result in a larger throughput. Additionally, the shorter the distance between two consecutive STA waypoints, the smaller maximum uncertainty x_{max} of the link, leading to a higher throughput (and vice versa).

2) *Fuel Consumption:* The nominal fuel flow equation given in (5) and is integrated over the entire operation to obtain the total fuel consumption, \mathcal{F} . The actual true airspeed is derived from the ground speed calculation in Equation 13 and the aerodynamic flight path angle is corrected to maintain the descent path. The change both terms will affect the drag and thrust components (7), and ultimately the fuel burn. The fuel consumption of a link that begins at time t_0 and ends at time t_{STA} is computed as:

$$\mathcal{F} = \int_{t_0}^{t_{STA}} \dot{F}_{fuel}(t) dt \quad (15)$$

where $\dot{F}_{fuel}(t)$ is given by (5).

B. Optimal Location of Intermediate STA Waypoints

To determine placement of $N - 1$ intermediate STA waypoints, the descent trajectory is divided into N links, each represented by an duration t_i (i.e., the time-difference between the STAs at the two ends). Each link will have an associated throughput and fuel costs. The objective is to select a set of points that minimizes total fuel burned for the entire trajectory, and maximizes the throughput. This can be represented as the

following optimization problem:

$$\text{minimize } \sum_{i=1}^N \mathcal{F}_i - \alpha \min P_{link,i} \quad (16)$$

$$\text{such that } \sum_{i=1}^N t_i \leq t_{total} \quad (17)$$

$$P_{link,i} \geq D, \forall i = 1, \dots, N \quad (18)$$

$$t_{min} \leq t_i \leq t_{max} \quad (19)$$

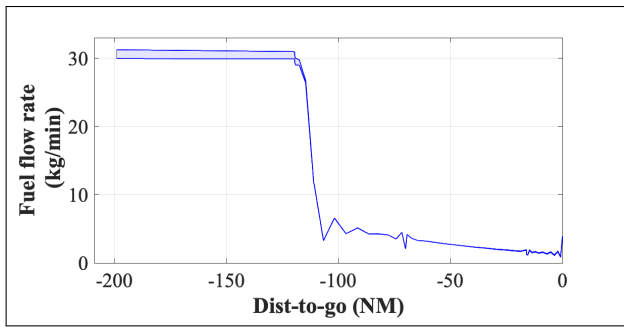
where α is the relative weight placed on throughput relative to fuel burn in the objective function, t_i is the duration of link i , D is the demand for the entire CDA operation, $P_{link,i}$ is the minimum throughput for link t_{i-1} to t_i , f_i is the corresponding total fuel burn, t_{min} and t_{max} are the minimum and maximum allowable values of t_i , and t_{total} is the total flight time to the IAF.

The number of variables in the optimization problem are specified by the number of STA waypoints defined during the planned trajectory. For example, a single intermediate STA waypoint will correspond to two links of length t_1 and t_2 : the first from the initial point to an intermediate STA waypoint, and the second from the intermediate STA waypoint to the IAF. The time durations t_i must sum to total time given by the planned CDA trajectory, this explains constraint (17). The average throughput for each link is also required to be greater than the given demand (18), and the intermediate constraints are bounded by the smallest achievable STA duration (19). These values depend on how much speed control authority is available: if the STA is too small, the speed correction needed will be too high to complete the operation. The `surrogateopt` tool in MATLAB is used to solve this optimization problem.

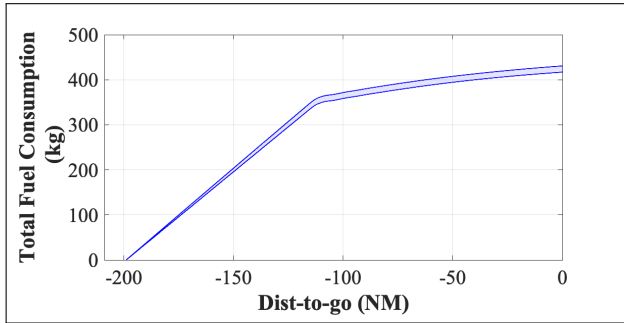
IV. RESULTS

In the analysis that follows, the constraints for the CDA profile optimization (8) are derived from a study that investigated energy-neutral CDAs for an A320 aircraft [25]. STAR procedure waypoints and minimum throughput demand are determined to approximate the ones considered in [26]. We assume that aircraft begin their descent from a cruise altitude of 37,000 ft at a distance of 200 NM from the airport, and reach the Initial Approach Fix (IAF) at 5,000 ft. For the trajectory uncertainty, the initial deviation is set to 1.3 NM in cruise, and the minimum required separation is set to be 3 NM.

The factors affecting fuel burn can be investigated over a CDA flight which has a single STA located at the IAF. Fig. 3b shows how the fuel flow rate and total consumption change over the trajectory. The upper and lower bounds of the blue shaded area represent the range of values (since the wind errors



(a) Fuel Flow Rate



(b) Fuel consumption

Fig. 3: Fuel burn rate and cumulative fuel consumption along the trajectory, given a single STA waypoint located at the IAF.

can be positive or negative). The fuel flow rate is higher during cruise and decreases as the aircraft descends to the airport. Most of accumulation of uncertainty occurs when the flight is 200 NM to 75 NM away from the airport, which is the region where more speed control is available and more changes in the thrust can be made.

To understand the effect of adding intermediate STA waypoints, we vary the number of such points, and solve the optimization problem (16)-(19). The scaling factor α between the two costs is varied to increase or decrease the weight placed on throughput, and can be adjusted based on user preferences. A higher value of α reflects a scenario where more throughput is needed at the expense of some fuel expenditure; the amount of such additional fuel is what is being explored here. Fig. 4 shows an example of the optimal location of two intermediate STA waypoints along a CDA profile (i.e., $N = 3$).

Comparisons are made with respect to the to the baseline trajectory ($N = 1$) which uses single STA waypoint (at the IAF) for the entire descent profile. Fig. 5 shows how the total fuel burn and throughput change with number of STA waypoints, for both maximum and minimum speed profiles caused by negative and positive wind errors (the left and

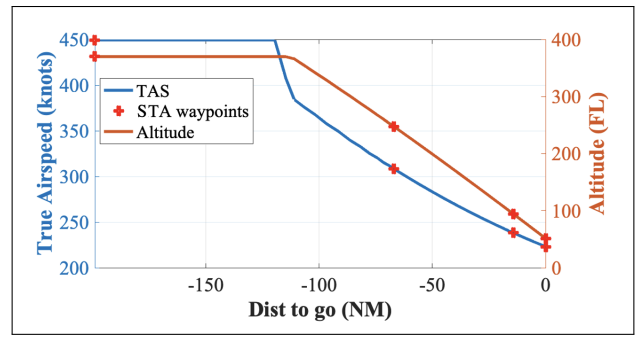


Fig. 4: Optimal intermediate STA waypoint locations for $N = 3$.

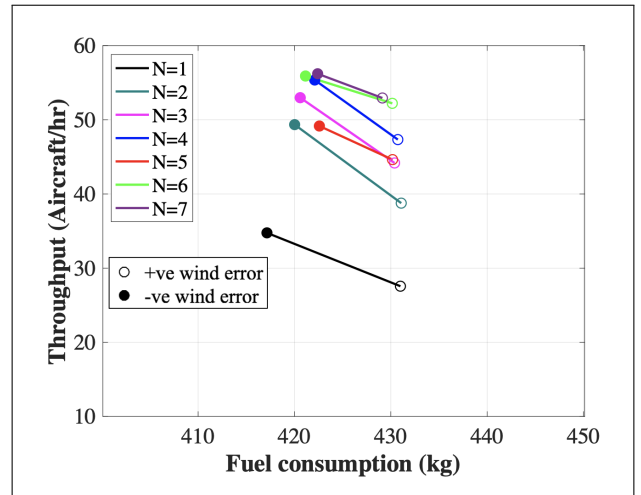


Fig. 5: Throughput vs. fuel consumption, for varying number of STA waypoints, N . The solid markers denote negative wind errors, and the unfilled markers denote positive wind errors. $\alpha = 10$.

right points, respectively). The analysis shows that higher throughput can indeed be achieved by increasing the number of points, but is accompanied by an increase in fuel consumption (especially when the wind errors are negative). This is to be expected: as the number of STA waypoints increases, the aircraft makes more speed corrections to meet the STAs, incurring fuel costs. However, more STA waypoints yields better predictability and increased throughput. The reduction in difference between the minimum and maximum velocity parameters also reflects the fact that predictability is improved with higher N . This is also seen in Fig. 6, where the final deviation of the aircraft trajectory decreases as the number of STA waypoints increases.

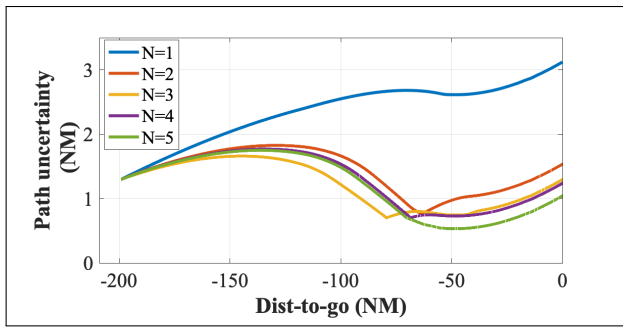


Fig. 6: Trajectory spatial (path) uncertainty along the descent profile, for varying number of STA waypoints, N .

V. CONCLUSIONS

This paper presented an approach to optimally locating intermediate waypoints with associated time-constraints (called STA waypoints) along a Continuous Descent Approach (CDA) profile, in order to balance throughput and fuel consumption. Doing so allows us to leverage the increased predictability of Trajectory-Based Operations (TBO) to overcome the potential loss in throughput of CDA operations due to increased uncertainty. Consequently, this method is a step toward enabling CDAs in high-density terminal-areas. We found that adding intermediate STA waypoints can increase throughput and predictability, but at the expense of additional fuel costs in the presence of wind uncertainty. Furthermore, the throughput can be improved by as much as 64% at an additional fuel cost of up to 5 kg per flight.

An interesting next step is a similar analysis for conventional step-down approaches. Furthermore, a few simplifications made could be relaxed such as using drag models that consider compressibility effects and extending the dynamic equations to include 6 degrees of freedom. Finally, the incorporation of more sophisticated wind models or other sources of uncertainty is an important direction for further investigation.

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