Improvement of Trajectory Synthesizer for Efficient Descent Advisor

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The Efficient Descent Advisor (EDA) is being developed to provide a decision support tool for controllers to help them issue continuous descent trajectories for arrival traffic. This paper investigates methods for improving the accuracy of the trajectory synthesizer, which is the trajectory engine that supports EDA. The study was motivated by the need to harmonize the trajectories generated by the trajectory synthesizer with those generated by on board Flight Management Systems (FMS's), which are used by pilots to execute continuous descents. An analysis of error sources between predicted and actual continuous descent trajectories shows that thrust and descent speed profiles are the most important parameters affecting the accurate prediction of top of descent location and arrival fix crossing times. While the thrust correction applies to all descents, the descent speed applies to uncontrolled (non-metered) descents. In order to establish the best value for thrust correction for use in the trajectory synthesizer, a limited set of continuous descent trajectories flown by aircraft during regular revenue flights into the Dallas-Fort Worth Airport were recorded and analyzed. In addition to recorded trajectories, controllers also obtained FMS-calculated top-of-descent ranges, crossing times and speed profiles from pilots whenever possible. In post flight analysis the predicted trajectories generated by the Trajectory Synthesizer were compared to the flight test data. It was generally found that the actual (FMS guided) trajectories were flown at shallower descent angles than the predicted trajectories and that actual descent speeds often differed significantly from those programmed into the trajectory synthesizer. A descent thrust correction parameter, normalized to aircraft weight and dependent on aircraft type and airline/operator is introduced to improve trajectory prediction accuracy. It is shown that this parameter, together with updated speeds obtained from pilots prior to descent, increase the accuracy of trajectory prediction significantly.

I. Introduction

Continuous Descent Arrival (CDA)[1–3] refers to a procedure that allows aircraft to approach an airport from cruise altitude at near idle engine power. Compared with typical air traffic arrival procedures, which can include multiple level flight segments prior to reaching the crossing altitude at the arrival fix, CDA reduces fuel consumption, emissions, and noise, thus providing both economic and environmental benefits.

Continuous descent trajectories are typically computed by the Flight Management System (FMS) and are executed automatically by an autopilot or flown manually by the pilot following flight director guidance. At low traffic levels controllers can safely accommodate pilot requests for CDA's. However, as the traffic density increases controllers find it increasingly difficult to handle CDA requests without the help of decision support tools. The Efficient Descent Advisor (EDA)[3,4] is a tool that has been designed to help controllers manage CDA's safely even during busy traffic periods. EDA accomplishes this by computing CDA solutions that conform with time-based metering schedules computed by Traffic Management Advisor (TMA)[5,6] for balancing traffic demand and capacity. By following advisories generated by EDA controllers are able to

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issue CDA clearances while maintaining high traffic flow and avoiding frequent conflicts. A key element in EDA is a function for accurately modeling FMS-generated descent profiles. This function is performed by the Trajectory Synthesizer (TS), which is a component shared between TMA and EDA.

This paper focuses on methods to improve the prediction accuracy of TS. A sensitivity analysis was first conducted to gain an understanding of error sources and their impact on prediction accuracy. The significance of error sources was prioritized based on error magnitudes observed in actual operations. Then methods of introducing updated descent calibrated air speed (CAS) for non-metered flights and a thrust correction factor for all flights were proposed for improving descent trajectory predictions. It should be noted that the application of adjusting CAS is limited to the uncontrolled arrivals or any prediction computed prior to any EDA control. Trajectories from flights that executed the continuous descents into the Dallas Fort-Worth airport were collected for examining the improvements. It is shown that the proposed methods have the potential to reduce the descent trajectory prediction errors to acceptable ranges, thereby improving the prediction accuracy of TS and the performance of EDA.

II. Model of Continuous Descent Trajectory

Typical vertical profiles of CDA's are shown in Fig. 1. Fig. 1(a) and 1(b) present the spatial and temporal altitude profiles. And Fig. 1(c) and 1(d) show the corresponding speed profiles. During continuous descent, an aircraft starts from its cruise altitude and descends with a constant Mach (if the desired descent CAS is greater than the final cruise CAS) until it reaches the pre-defined CAS (point B in Fig. 1(a)). After that, the aircraft continues its descent with the CAS (from point B to C in Fig. 1). Before it reaches the meter fix, the aircraft decelerates to the final CAS. Typically, an aircraft is required to cross the meter fix at an altitude of 10,000 feet with an indicated airspeed of 250 knots, while in Fig. 1 11,000 feet was required.

A trajectory model for calculating descent profiles was developed in the 1980's.[7,8] It typically consists of three segments, an acceleration/deceleration segment to a specified Mach number, followed by a constant CAS segment, and then a deceleration segment. This model not only provides convenience for pilots and controllers but also simplifies the equations of motion to first order differential equations:[8]

$$\dot{V_T} = \frac{T-D}{m} - g\sin\gamma_a - \dot{u}_w\cos\gamma_a \tag{1}$$

$$\dot{x} = V_T\cos\gamma_a + u_w \tag{2}$$

$$\dot{z} = V_T\sin\gamma_a \tag{3}$$

where T and D are thrust and drag, respectively. V_T is the true airspeed, γ_a is the aerodynamic flight path angle, and u_w is the horizontal component of wind and g is the acceleration of gravity. It is assumed that there is no vertical wind. x and z are the horizontal and vertical axis in an earth fixed coordinate system, respectively. From Eqn. 1, γ_a for the constant Mach and constant CAS segments can be expressed as follows, respectively:

$$\gamma_{a(constantM)} = \frac{T-D}{m}[g + V_T(M\frac{da}{dz} + \frac{du_w}{dz})]^{-1} \tag{4}$$

$$\gamma_{a(constantCAS)} = \frac{T-D}{m}[g + V_T(\frac{dV_T(V_{CAS}, z)}{dz} + \frac{du_w}{dz})]^{-1} \tag{5}$$

where a is the speed of sound, M is the Mach number, and V_{CAS} is the indicated airspeed. For idle-thrust descent, γ_a can be obtained by setting T to idle value. Forward and backward integrations are then used for the first and third segments until the conditions of constant indicated airspeed segment are met. Then the complete descent trajectory can be obtained by integrating the segment of constant indicated airspeed. More details of descent calculation can be found in previous works.[7,8]

III. Sensitivity Study of Trajectory Synthesizer

Several trajectory sensitivity studies[9–14] have been conducted in past years. Most of those examine sensitivities for error in arrival times and along-track position. The purpose of this section is to identify the major factors that affect the prediction of descent trajectories in TS. To facilitate comparisons between

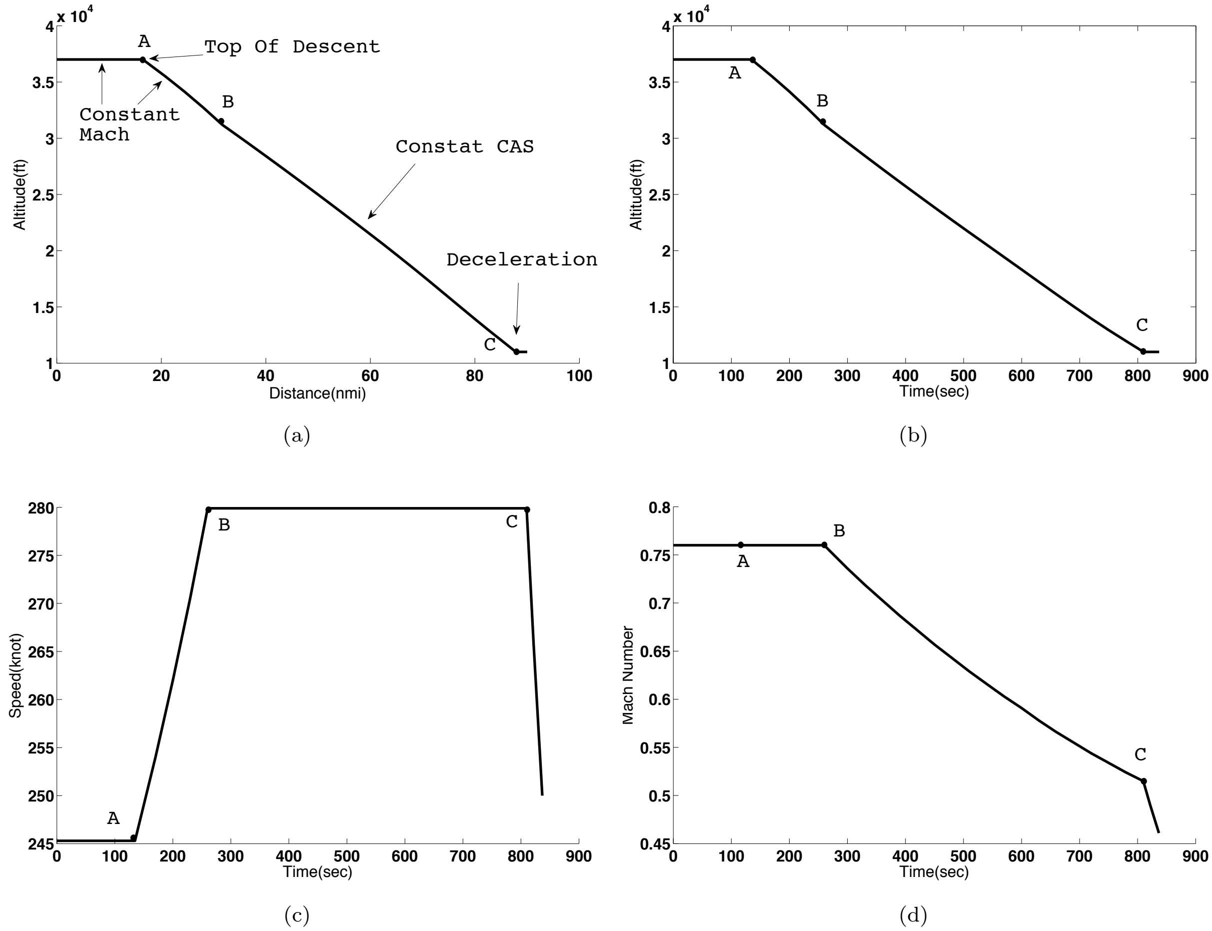


Figure 1. Continuous descent arrival: (a) Spatial profile of altitude (b) Temporal profile of altitude (c) Indicated airspeed (d) Mach Number

trajectories, the descent trajectories are usually treated as two dimensional with horizontal distance to the meter fix and altitude as the two axes.

In this section, the distance from the top of descent (TOD) to the meter fix is called TOD distance, and the time that the aircraft flies from the reference point to the meter fix is recorded as meter-fix crossing time. In this section, three typical error sources — descent weight, wind error, and descent speed — are examined. Without loss of generality B737-800 is used as an example.

A. Descent Weight

Aircraft weight is one of the major concerns in trajectory prediction, especially in the case that datalink is not available or airlines choose not to share the weight. Fortunately, the range of descent weights is much narrower than the range of take-off weights. In nominal situation, assuming descent fuel consumption is negligible, the minimum descent weight can be estimated using Eqn. 6, where W_{OWE} is the Operating Weight Empty (OWE), and F_{res} represents minimum reserve fuel required by Federal Aviation Administration (FAA). The reserve fuel is for cruising to the alternate airport and for 45 minutes of airborne holding. Generally the reserve fuel is set to eight percent of the takeoff weight.[15,16] Assuming no extra fuel would be carried by the aircraft, the maximum descent weight is estimated by Eqn. 7, where W_{MPLD} is the maximum payload allowed for the aircraft, and W_{MLW} is the maximum design landing weight which should not be exceeded. Using B737-800 as an example, the minimum descent weight of B737-800 is about 106,457 lbs, and the maximum descent weight is 146,300 lbs, which corresponds to a load factor of 100%. If an aircraft is executing a long range flight, the maximum possible descent weight should be further reduced, which means the load factor will be less than 100%. Currently, in TS, the default descent weight of B737-800 is 126,720 lbs, corresponding to a load factor of 50%.

$$W_{min} = W_{OWE} + F_{res} \tag{6}$$

$$W_{max} = min\{W_{OWE} + F_{res} + W_{MPLD}, W_{MLW}\} \tag{7}$$

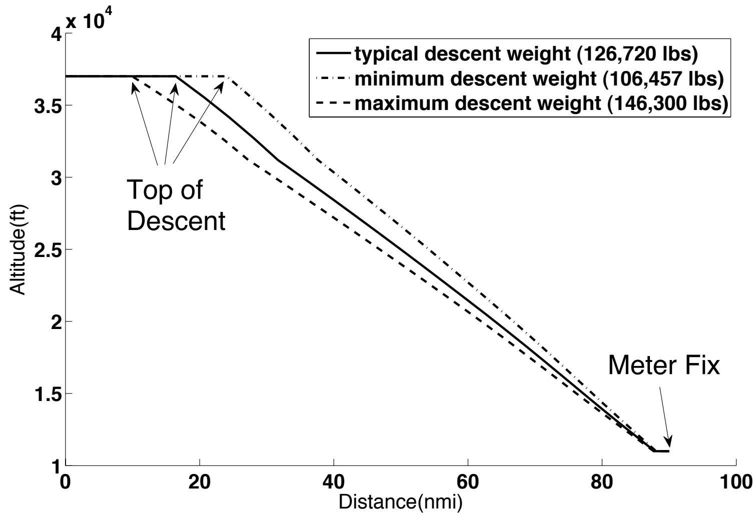


Figure 2. Impacts of weight on descent trajectory

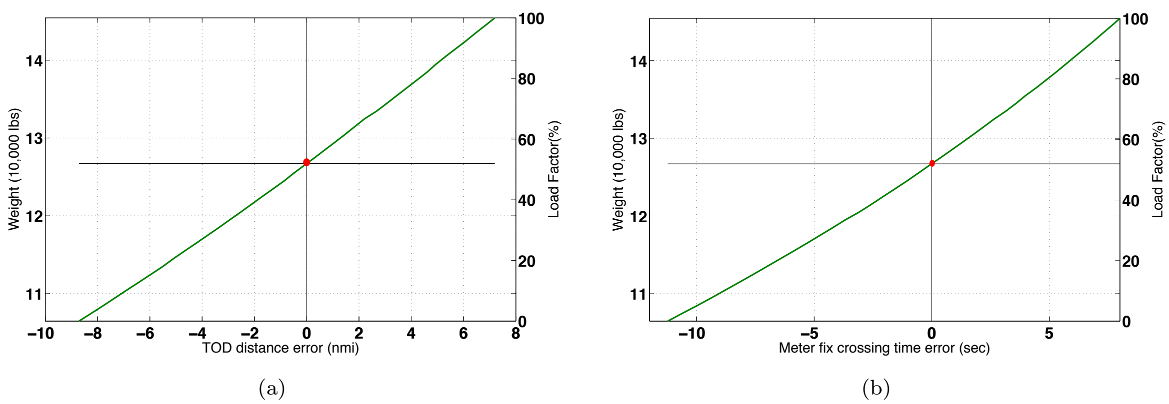


Figure 3. Impacts of weight on (a) TOD distance (b) Meter-fix crossing time.

Figure 2 shows the different descent trajectories associated with different descent weights for CAS 280 and standard day without wind. The middle trajectory corresponds the typical descent weight used by TS, the steep one is based on minimum descent weight, and the shallow profile results from maximum descent weight. It is noted that heavily loaded aircraft fly shallower descents with idle thrust than do lightly loaded aircraft. Figure 3(a) shows the difference in TOD range can be as large as 16 nmi from empty payload (load factor 0) to full payload (load factor 100%), which means TOD will be 4.1 nmi further from meter fix for each 10,000 lbs increase in weight. The default weight in the TS is shown as a red dot in the figure, which denotes load factor 50%. The difference in meter-fix crossing time over the weight range is small as shown in Fig. 3(b). To serve the purpose of this paper, it is assumed that the requirement of meter-fix crossing time accuracy is 30 seconds. For the entire range of descent weights, the difference is only about 20 seconds. For each 10,000 lbs increase in weight, the increase in meter-fix crossing time is less than 5 seconds. According to the analysis conducted by the International Air Transport Association (IATA), the average load factor for commercial airlines is about 70%. This further narrows the range of weight and reduces the difference in TOD distance to around 3 nmi. Thus, the prediction errors might be tolerable given the fact that the aircraft descent weight can be well estimated. Since even in actual operations, it is unlikely to obtain aircraft weight information, it is useful to compute accurate descent prediction without weights reported from pilots or airlines.

B. Wind Speed

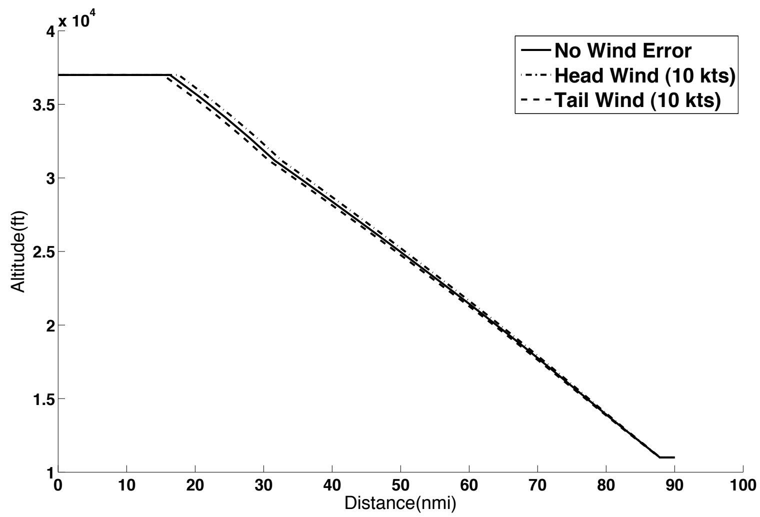
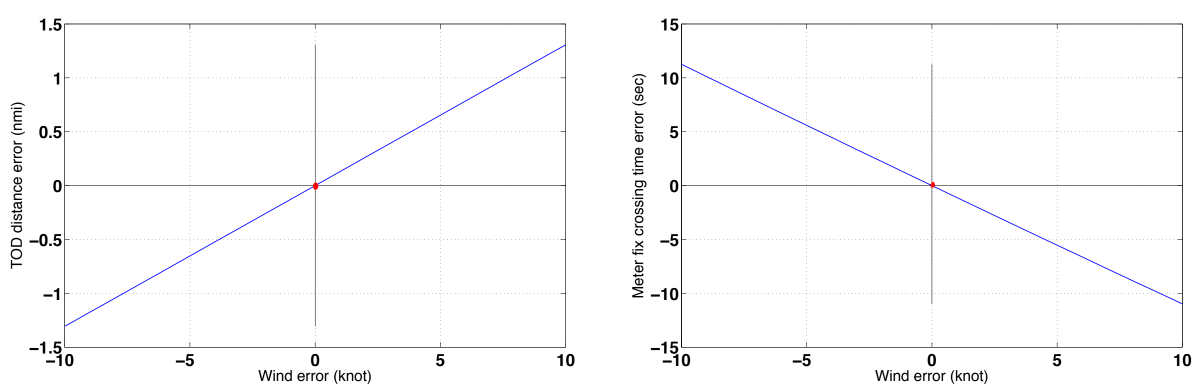


Figure 4. Impacts of wind on descent trajectory



(a) (b)

Figure 5. Impacts of wind on (a) TOD distance. (b) Meter-fix crossing time.

Wind speeds can be as high as 150 knots at high altitudes and are therefore critical to the trajectory calculation. Wind speed error exists due to the inaccurate wind forecast. Although the magnitude of wind speed is high, the error is usually less than 10 knots.[14,17] Figure 4 shows the trajectories with different wind speeds. The steep trajectory results from a strong head wind, while the shallow trajectory corresponds to a strong tail wind. Strong head wind shortens the TOD distance to the meter fix. Figure 5(a) presents the different TOD distances due to wind errors. It can be seen that the shift of TOD distance caused by wind speed error is small. The error of 10 knots only corresponds to 1.3 nmi difference in TOD distance. Figure 5(b) shows the effect of wind error on arrival time, typically 11 seconds for every 10 knots.

C. Descent Speed

Descent speed is another important factor for descent trajectory calculation. Usually, descent speeds are selected by airlines or pilots for those un-delayed (non-metered) flights. Fig. 6 presents the impacts of descent speed on descent trajectory, and Fig. 7(a) and 7(b) show TOD distances and meter-fix crossing times corresponding to different descent speeds. It was found that descent CAS has the dominant impact due to the length of the segment. A 10 knots difference in CAS causes the differences of 3.2 nmi in TOD distance and 18.1 seconds in meter-fix crossing time. Cruise Mach number has minimal effect of 2.4 seconds and 0.5 nmi per 0.01 Mach. It is noticed that descent CAS in actual operations is different from the default CAS in TS. For instance, the trajectory synthesizer of EDA uses a default descent speed of 280 knots for B737-800, [a] whereas flights from the actual operational data, which will be discussed in next section, descended at 310 knots. This mismatch alone will cause 9 nmi error in TOD distance and 51 seconds error in meter-fix crossing time, which makes the trajectory prediction unacceptable. Based on this finding, it is strongly recommended that pilot-preferred descent speeds be acquired prior to descent in order to make initial trajectory predictions acceptable.

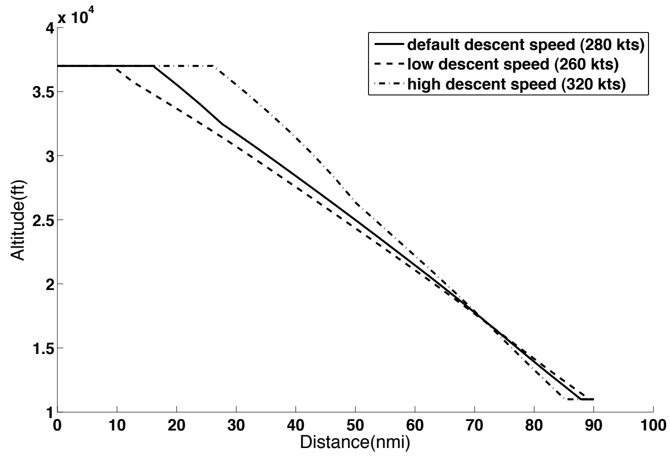
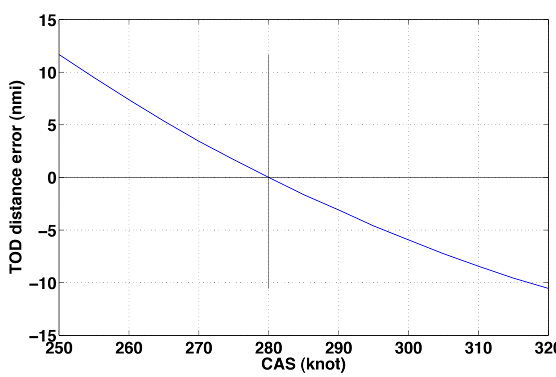
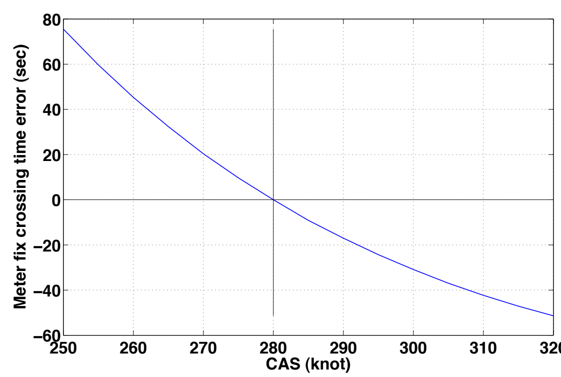


Figure 6. Impacts of descent speed on descent trajectory



(a)



(b)

Figure 7. Impacts of decent speed on (a) TOD distance (b) Meter-fix crossing time.

[a]EDA uses the default speed for the initial, un-delayed trajectory calculation only, once EDA advises a speed profile and controller accepts, descent CAS is no longer an error source

IV. Methods for Improving Prediction Accuracy

Based on the impact on the error magnitude and the accessability of the information, the first recommendation for improving un-delayed/initial prediction is to acquire the descent CAS prior to descent. Here it is proposed that the intended descent CAS can be acquired via down linked communication from the aircraft to the air traffic control center. If the intended CAS can NOT be down-linked, the default descent speeds in EDA need to be revised based on the actual operations.

Furthermore, a thrust correction factor, which is dependent on aircraft type and airlines, is proposed to mitigate the TOD prediction errors. The thrust correction factor is referred to as τ in Eqns. 8 and 9. It is defined as a function of nominal aircraft weight W, and a dimensionless tuning parameter c_τ is selected to minimize prediction errors.

$$\dot{V}_T = \frac{T + \tau - D}{m} - g\sin\gamma_a - \dot{u}_w\cos\gamma_a \tag{8}$$

$$\tau = c_\tau \cdot W \tag{9}$$

Before applying the thrust correction, the impact of thrust changes on the trajectories needs to be understood. Figure 8 shows the impact of a 1.5% thrust correction factor on descent trajectory. A positive thrust correction factor makes the shallow descent trajectory, and the dash-dot line results from a negative thrust correction factor. Figure 9(a) and 9(b) plot the change in TOD location and meter-fix crossing time over a range of ±1.5% thrust correction, which roughly corresponds to ±15 nmi in TOD and ±20 seconds for meter-fix crossing time, respectively.

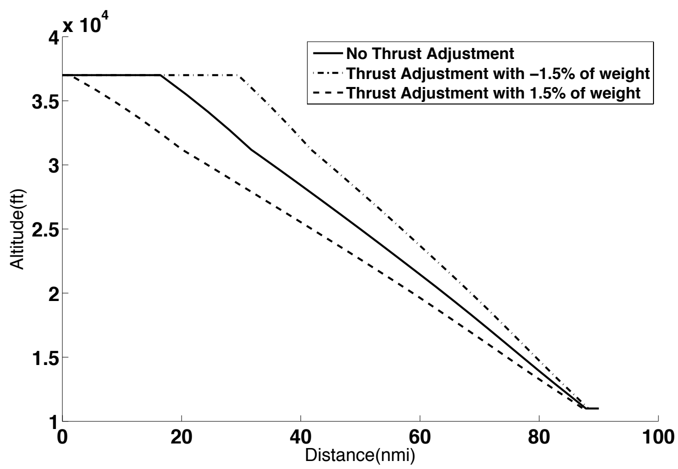


Figure 8. Impacts of thrust correction on descent trajectory

V. Experiments and Results

In order to examine above methods, a limited set of continuous descent trajectories flown by aircraft during regular revenue flights into the Dallas-Fort Worth Airport were recorded and analyzed. Based on the request from NASA, on Feb. 25-26, 2011, controllers acquired FMS-calculated top-of-descent ranges, crossing times and intended descent CAS from pilots who were willing to fly CDA's during light traffic. Prior to such requests, controllers determined that flights had enough space for executing CDA's. There were no pilot briefing or training prior to the short experiment. Meanwhile, the flight track information including aircraft position, altitude, ground speed, and heading was recorded at the NASA's North Texas Experimental Facility, co-located at the Fort Worth Center. The associated wind forecasts were also recorded.

Using one flight as an example, here is how the experiment was conducted: On Feb. 26, 2011, at 22:29 GMT (4:29 pm local time), per controller's request, the pilot reported that they were 10 nmi prior to the FMS-calculated TOD, their intended descent CAS was 261 knots, and their arrival time to meter fix YEAGR

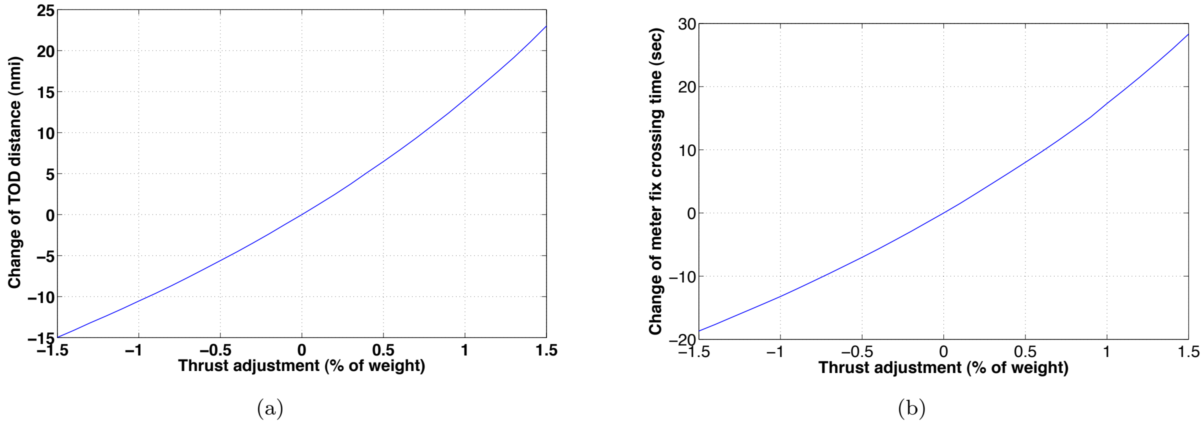


Figure 9. Impact of thrust correction on (a) TOD distance (b) Meter-fix crossing time.

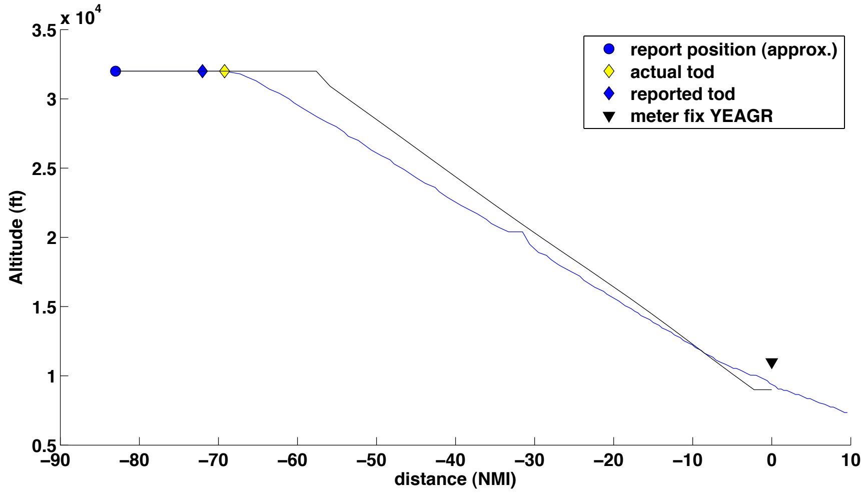
was estimated to be 22:57 GMT. At 22:46 GMT, the flight was cleared to descend to YEAGER with final speed 250 knots and altitude 9,000 ft, respectively.

Overall 14 flights from two major airlines — Airline A and S — were collected and analyzed. They comprised four B737-700 from Airline S, and seven B737-800, two B757-200, and one B737-700 from Airline A.

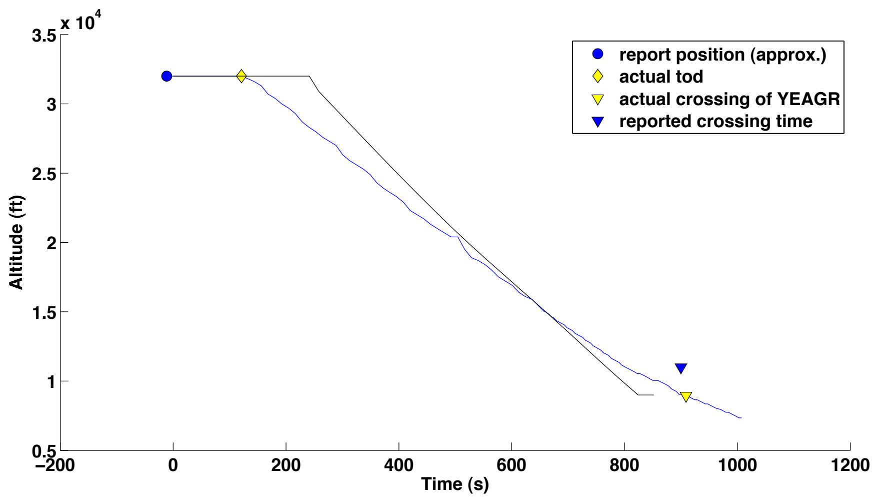
A. Speed and thrust corrections

In TS, the default descent CAS for a B737-700 is 280 knots, quite different from 261 knots reported by pilots in Airline S cases. Thus, speed correction was conducted in TS. Fig. 10(a) and 10(b) show spatial and temporal profiles calculated by default TS for flight S101. And Fig. 11(a) and 11(b) show spatial and temporal profiles computed by TS after the speed correction. The blue curves are radar-recorded actual descent trajectories and associated blue dots are the positions where pilots reported their TOD, time, and speed. Blue diamonds and triangles are TOD positions and meter-fix crossing times, respectively, calculated by the onboard FMS and reported by pilots. Yellow diamonds and triangles are actual TOD positions and actual meter-fix crossing time retrieved from radar-recorded track information. Black curves are trajectory predictions as calculated by TS. Temporal profiles show that before speed correction, there is about a 50 second difference between TS prediction (the low end of black curve) and actual crossing time, and actual and FMS crossing times are very close. After speed correction, the difference between TS calculation and actual becomes negligible for this particular set of flights and aircraft type.

As shown in Fig. 10(b) and 11(b), after speed correction there still exists a significant gap between the TS-calculated TOD locations and FMS/actual TOD locations. Thus a unified thrust correction factor must be applied on all four B737-700s from Airline S. The thrust correction parameter τ was manually identified as 0.7%. Figure. 12(a) and 12(b) present the temporal and spatial profiles after introducing thrust correction for flight S101, which is similar to other Airline S flights as well. It can be seen that the TS prediction of TOD location has been improved significantly after adjustment. Table 1 lists the statistics for all four Airline S flights using the same thrust correction factor τ. The prediction accuracy desired for EDA operations is for TOD and meter-fix crossing time errors to stay within 5 nmi and 30 seconds, respectively. It appears that these error rates are achievable with the proposed methods.

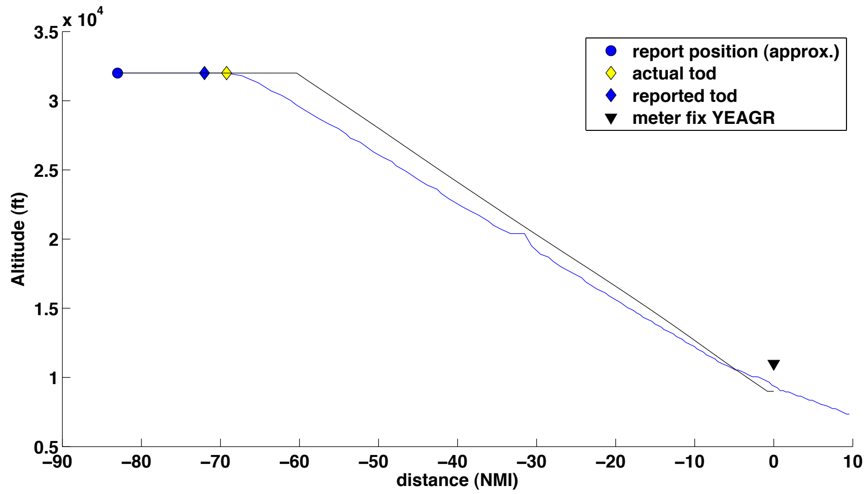


(a)



(b)

Figure 10. Flight S101 actual trajectory and default TS calculation (a) Spatial profiles (b) Temporal profiles



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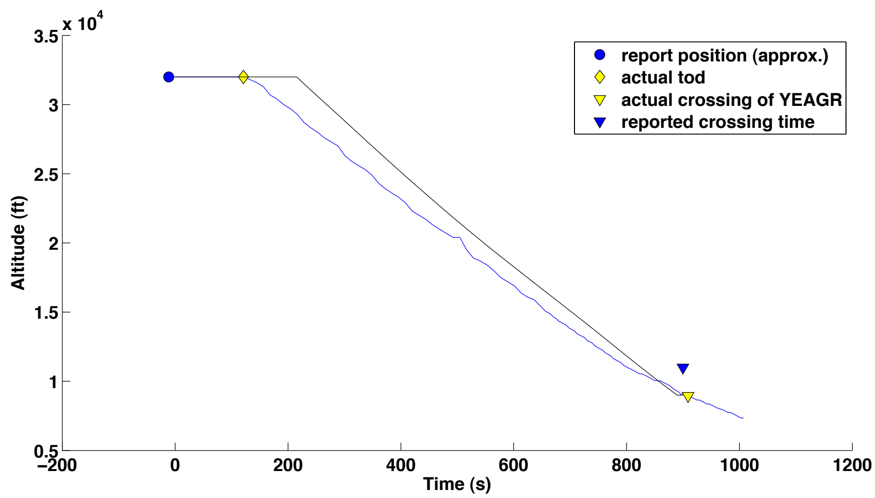


(b)

Figure 11. Flight S101 actual trajectory and TS calculation with updated CAS (a) Spatial profiles (b) Temporal profiles

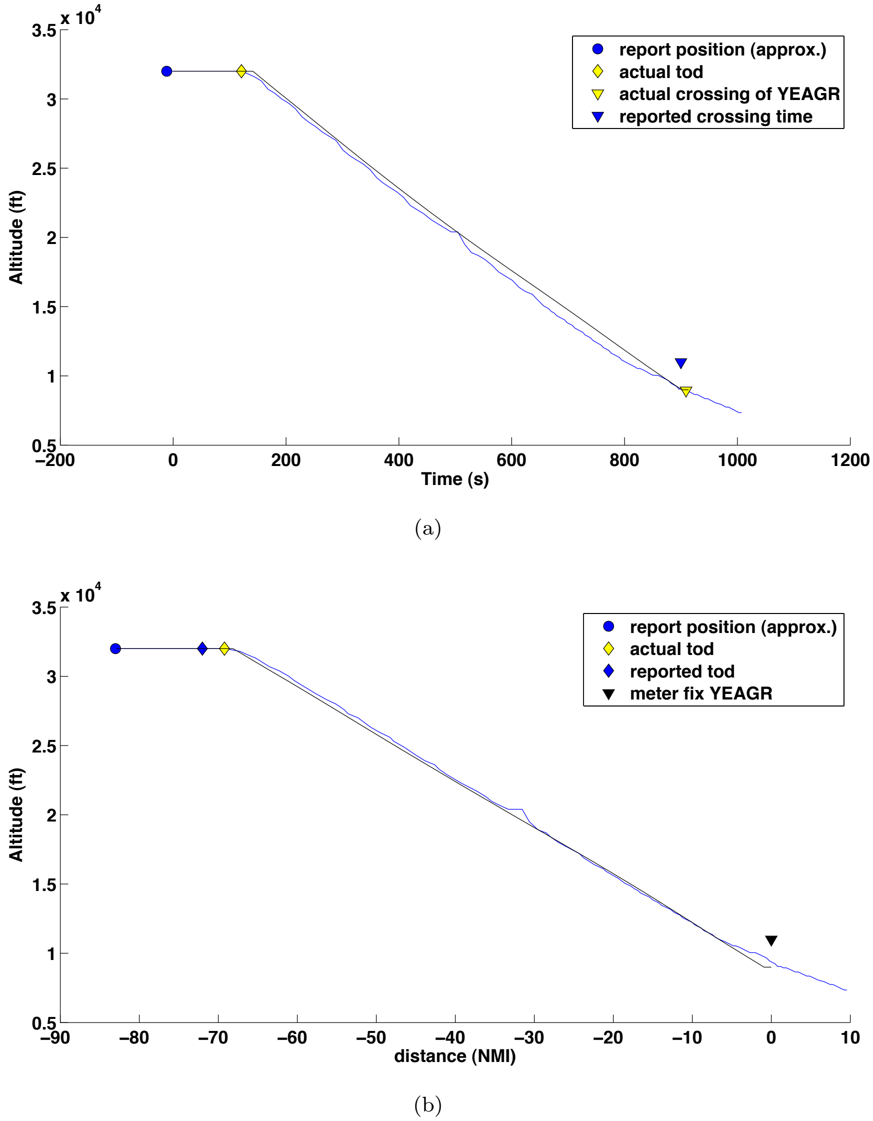


Figure 12. TS profiles with constant thrust correction for flight S101 (a) temporal (b) spatial

Table 1. TS predictions errors for Airline S B737-700

	TOD Error (nmi)		Time Error (sec)	
	average	std.	average	std.
Default TS	20.3	16.1	38.9	13.0
Speed correction	5.6	3.1	5.4	2.7
Thrust correction	1.8	1.5	9.4	7.2

B. Early descent phenomenon

Although five out of ten Airline A flights behaved similarly to Airline S flights and TS predictions for these flights can be significantly improved by same means, there exists an interesting phenomenon - "early descent" for five Airline A flights. Figure 13 and Fig. 14 present such an example, which shows the comparisons before and after applying thrust correction for a B737-800 of Airline A. The constant thrust correction factor is 1.6%, which was set for all seven Airline A B737-800s. From the figure, it is noticed that although the TS predicted TOD does not match the actual TOD it is a good match for FMS TOD (the blue diamond). Apparently, pilots didn't follow their FMS calculations and chose to descend almost 30 nmi earlier than FMS TOD location. At the end of the early descent segment, the descent trajectory merges with the FMS calculated idle thrust trajectory.

Without a debriefing of the pilots after the experiments, the exact reasons for early descents could not be ascertained. However, according to FMS experts, pilots frequently choose the "descend now" option on the FMS before the aircraft reaches the FMS calculated TOD location. The primary reason for pilots selecting "descend now" instead of flying the FMS-calculated idle-thrust descent is to make passengers comfortable.

The early descent phenomenon suggest the need to coordinate the descent procedures of airlines with the ground-based EDA tool. Then, the TS in EDA can be adapted to correct for early descent procedure, thereby improving prediction accuracy.

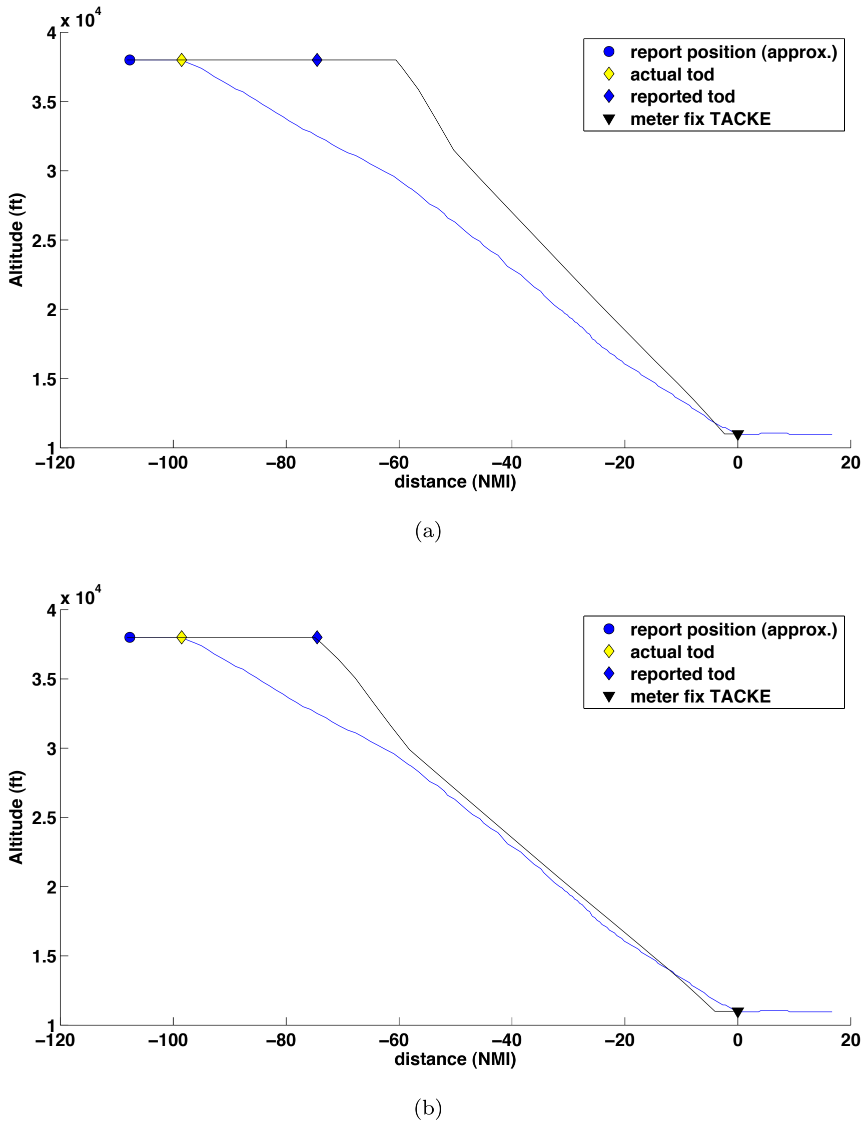
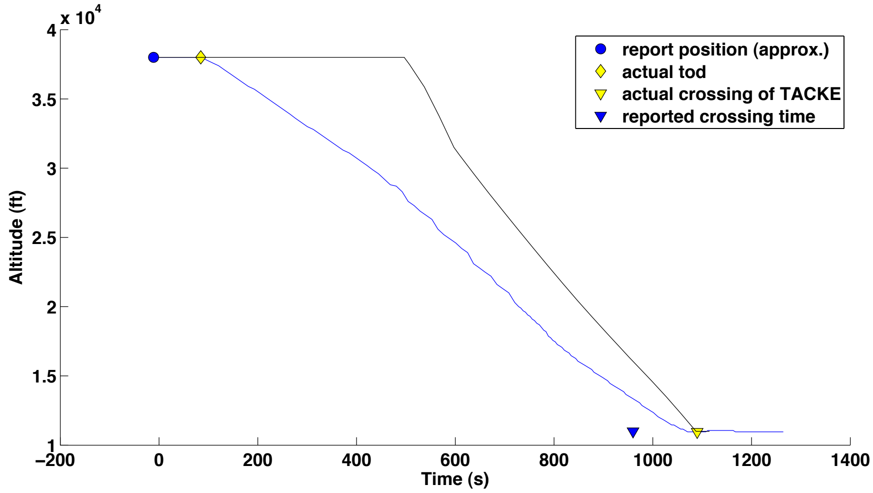


Figure 13. Early descent phenomenon: (a) Spatial profiles with NO thrust correction (b) Spatial profiles with thrust correction



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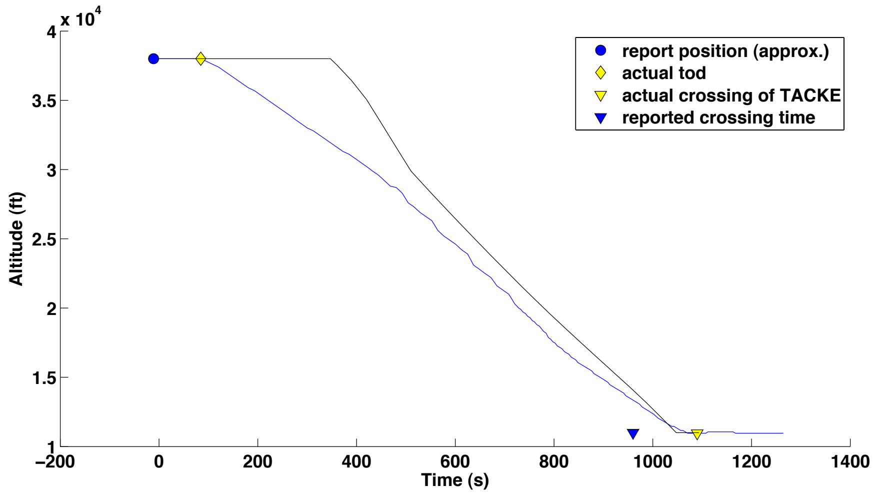

(b)

Figure 14. Early descent phenomenon: (a) Temporal profiles with NO thrust correction (b) Temporal profiles with thrust correction

C. Overall results

Table 2. TS predictions errors for all flights

	TOD Error (nmi)		Time Error (sec)	
	average	std.	average	std.
Default TS	19.0	12.2	22.1	15.5
Speed correction	16.1	11.7	10.1	9.3
Thrust correction	7.3(1.7)	8.1(1.4)	7.8	7.1

Table 2 shows the overall comparisons between TS prediction and actual track. In the table, the errors shown in parentheses are the errors between the TS calculation and the onboard FMS (instead of actual).

(Recall that, in early descent cases, TS prediction can still match on board FMS calculations.) The table shows that with speed correction, the meter-fix crossing time errors can be halved to 10 seconds with a standard deviation of 9 seconds. With further thrust correction, the TOD location errors can be reduced from 19 nmi to 1.7 nmi (if taking away the impact of early descents), which is similar to what was found in Airline S cases.

D. Discussion

Although it was proposed above that a constant thrust correction factor should be pre-defined based on aircraft type and airlines/operator, the thrust correction can be applied in two different ways: 1) If the FMS-calculated TOD location and meter-fix crossing time can be down-linked from an aircraft through Data-link, then in real-time for an individual flight, a thrust correction factor may be calculated based on the down-linked TOD and crossing time. Therefore, an accurate 4D descent trajectory can be calculated by TS, which is required for reliable conflict detection and resolution when flying continuous descent approaches; 2) If the FMS-calculated TOD location and meter-fix crossing time can NOT be down-linked from an aircraft, the thrust correction factor can be used in the way proposed in previous sections: For a given type of aircraft and a given airlines/operator, determine a constant thrust correction factor from analysis of a set of previously recorded descent trajectories. Both methods can improve TS prediction accuracy for continuous descents. However, down-linked information has the advantage in accuracy. It has to be acknowledged that the small sample set is not statistically significant. Additional modification needs to be made in TS, so a large amount of on-line experiments can be conducted in TS for validating the proposed methods. Regarding the early descents, while the TS is architected to model multiple descent segments based on different parameters (e.g. thrust, fixed flight path angle, or rate of descent), efforts are needed to identify appropriate parameters for early descents and to develop methods to obtain such intent.

VI. Conclusion

In order to handle continuous descent procedures during busy traffic conditions, controllers using decision support tools, such as EDA, require accurate prediction of descent trajectories. The prediction function is performed by the trajectory synthesizer (TS). This paper investigated the sensitivity of TS prediction accuracy to various parameters and proposes methods for improving its accuracy based on actual operational flight data.

During the sensitivity analysis, the significance of error sources was prioritized based on error magnitudes in actual operations. Assuming that the prediction accuracy requirements of TOD location and meter-fix crossing time are 5 nmi and 30 seconds, respectively, it was found that for the range of expected wind speed and weight errors prediction errors remained within acceptable limits. Since aircraft descent weight lies within a relatively narrow range in practice, it may be acceptable to use an estimated descent weight if the actual weight is not available prior to descent. The FMS-selected descent speed has a significant impact on arrival time prediction for those non-metered flights and should be correctly entered into TS for each aircraft-FMS combination prior to descent. It is suggested to acquire the FMS-selected descent speed for trajectory prediction prior to any EDA speed assignment. At least, the nominal descent speeds in TS need to be calibrated based on actual airline policies. As actual descent trajectories were typically shallower than TS predicted trajectories even after the descent speed correction, a thrust correction factor was introduced to achieve the desired prediction accuracy.

Data were collected from a limited set of flights that executed the continuous descents into DFW airport. Analysis shows that introducing a constant thrust correction factor and intended descent CAS correction has the potential to reduce the descent trajectory prediction errors to acceptable/desired ranges. The descent CAS mainly corrected the meter-fix crossing time and the thrust correction factor mainly improved the TOD prediction. These corrections could be achieved by the aircraft down-linking critical FMS parameters prior to the descent. If only descent CAS can be down-linked, a thrust correction factor parameter can be identified based on aircraft type and airlines/operator for future prediction. If TOD locations and meter-fix crossing time can also be down-linked from an aircraft, a thrust correction factor could be computed in real time for accurate 4D trajectory calculations. In both cases, the accuracy of descent trajectories required for reliable conflict detection and resolution will be significantly improved. It is suggested that additional modification can be made in TS such that a large amount of on-line experiments can be carried for further validation.

It was also determined, in order to model early descents, appropriate parameters need to be identified for multiple descent segments in the TS model and methods should be developed to obtain the intents of early descents.

VII. Acknowledgement

The authors gratefully acknowledge the contribution of Mr. Paul Borchers of NASA and Mr. Keenan Roach of University of California Santa Cruz at NASA/FAA Northern Taxes Research Station. They coordinated with air traffic controllers at DFW airport and collected actual operations data for the flights that executed continuous descent arrivals at the airport.

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