TRAJECTORY PREDICTOR PERFORMANCE EXPERIMENT USING REQUIRED TIME OF ARRIVAL DURING DESCENT

Mike Paglione, Federal Aviation Administration, Atlantic City, NJ
Ben Musialek and Carl Pankok, General Dynamics Information Technology, Atlantic City, NJ
Dr. Christina Young, CSSI, Inc, Atlantic City, NJ.

Abstract

Most commercial aircraft today have advanced navigation computer systems, referred to as the Flight Management System or FMS. In recent years, the FMS has been increasingly utilized to support a type of performance-based navigation that allows an aircraft to fly a specific path between two defined 3-dimensional points in space. However, current deployed FMS architectures can do even more, calculating a Required Time of Arrival (RTA) at a precise 3-dimensional point in space and then automatically controlling the aircraft's airspeed and rate-of-descent to reach that point within a very small tolerance. This capability could offer increased efficiency for airlines and reduced workload for air traffic control under certain operational concepts such as metering to a transition fix into a terminal area. One challenge is that while RTA clearances are commonly used by en-route controllers when metering, the en-route air traffic automation tools that predict aircraft conflicts do not have the capability to input RTA clearances. The automation depends on flight plan information to generate aircraft trajectories, which are then used to predict conflicts. Adjustments in speed and Top of Descent (TOD) point implemented to meet an RTA would not be known to the automation and therefore not reflected in the trajectories generated. This paper describes an experiment where a real FMS platform was utilized in a simulation environment and simulated flight data was run through the current ground based automation in en route airspace, referred to as En Route Automation Modernization (ERAM). The predicted trajectories were compared under various RTA settings, weather conditions, and flight paths to examine how the current ERAM trajectory predictor performed. The results provide guidance on where additional research is needed and insights into using this FMS capability in current operations.

Introduction

Modern aircraft with sophisticated Flight Management Systems (FMS) equipment have the ability to formulate a Required Time of Arrival (RTA), specifying a time window in which an aircraft will arrive at an assigned waypoint along its flight path. Once an RTA is determined, the FMS can automatically control the aircraft's airspeed and rate-of-descent to achieve a crossing time at an en-route fix within a very tight tolerance (e.g. ±30 sec). The use of RTAs by the FMS would allow controllers to more efficiently control the flow of aircraft into a terminal area.

While en-route controllers commonly use RTA clearances when metering, the RTA information is currently not modeled by the en-route air traffic automation tools for predicting aircraft conflicts. The automation primarily uses the flight plan information to predict aircraft trajectories. Only when the automation senses that an aircraft is not conforming to the flight plan does it update using current surveillance track positions. These short term predictions are only used until the aircraft has returned to the flight plan route. An aircraft's FMS will vary its speed and Top of Descent (TOD) point to meet the RTA time requested. These changes are not transparent to the ground automation, and this lack of aircraft intent affects the conflict probe's ability to accurately predict conflicts.

This paper summarizes a laboratory research simulation to evaluate the accuracy of the current ground automation when an aircraft has been issued a clearance to execute an RTA to a meter fix entry into a terminal area. Using various airborne and ground automation simulators, the research was conducted using actual weather conditions and traffic profiles from the National Airspace System (NAS). The focus of the analysis was to evaluate the differences between the predicted trajectories in the current en route air traffic automation, En Route Automation

Modernization (ERAM), with the simulated flight data of an aircraft flying an RTA constraint under a variety of typical operating conditions.

Experiment Overview

As stated in the Introduction, the objective of this study is to analyze ERAM trajectory prediction accuracy when a flight is assigned various RTA times.

Data Preparation

A review of NAS recordings was performed specifically looking for flights that exhibited a continuous descent profile. A continuous descent represents the most fuel-efficient, idle-thrust descent and is the desired descent profile of most major airline carriers. ZLC was targeted since the ERAM subsystem (ESUB) is currently fully adaptable for that center. Two flights that fit the criteria were identified as well as their associated Rapid Update Cycle (RUC) wind and temperature data, both forecast and actual. Additional RUC data was also collected for alternate days to represent typical variations that could be expected during other weather seasons throughout a given year.

Experiment Design

As described above, the experiment was applied to two distinct flights (Figure 1) covering four weather profiles from two weather seasons utilizing three unique RTA conditions. The descent profiles for both flights are located within the en route control center, Salt Lake City (ZLC) boundary. Flight 1 landed at Wendover Airport (KENV), while Flight 2 landed at Boise Airport (KBOI). Both arrival airports are located in the ZLC center. The three RTA conditions are (1) a nominal target RTA (based on the original ETA of the flight simulator), (2) a positive time RTA set at three minutes after the nominal time, and (3) a negative time RTA set at two minutes prior to the nominal time. These three conditions will be referred to as *Baseline*, *Plus3*, and *Minus2*, respectively. In total, 24 scenarios were simulated encompassing the four weather profiles, three RTA values, and two flights.

Airborne Automation

The respective flight plan routes of the two flights were programmed into the General Electric Aviation Simulator (GEAS), which is a real-time desktop FMS simulator. The GEAS system simulates the performance characteristics of a Boeing 737-600 and allows the user to set different RTAs to a waypoint in the flight's route.

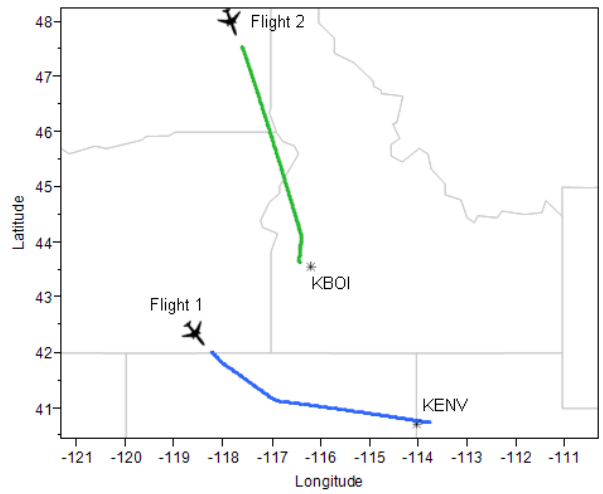

Figure 1: Two FMS Flight Profiles

Modern FMS systems have the ability for the pilot to program an RTA to a meter fix. The pilot simply selects the desired meter fix point and the FMS will instantly calculate three values: the current ETA to the fix, the minimum time to the fix (earliest time the aircraft can arrive), and the maximum time to the fix (latest time the aircraft can arrive). These times are calculated with the assumption that the aircraft will remain on its flight path and will meet the RTA time strictly by adjusting its speed and TOD point.

Additionally, the FMS simulator has the ability to accept both forecast winds and actual winds, which provides a more realistic flight. For each flight flown, the RTA fix was identified as a meter fix and the time to reach this fix was calculated using the capabilities of the simulated FMS software. Once an RTA value was set during the simulation, all the associated track data and RTA results were recorded.

The FMS will then calculate the appropriate TOD point and automatically adjust the speed (throttle) and descent profile (rate of descent) of the aircraft to cross the meter fix at the chosen time using

an idle continuous descent profile. As shown in Figure 2, the TOD position changes considerably for the different selected RTA values. To meet this RTA, the FMS maintains the aircraft within the performance limits based on a common cost index recommended by the FMS manufacturer. In the NAS, the airline would work with the aircraft and FMS manufacturers to select a cost index most appropriate for their specific operations and airframe.

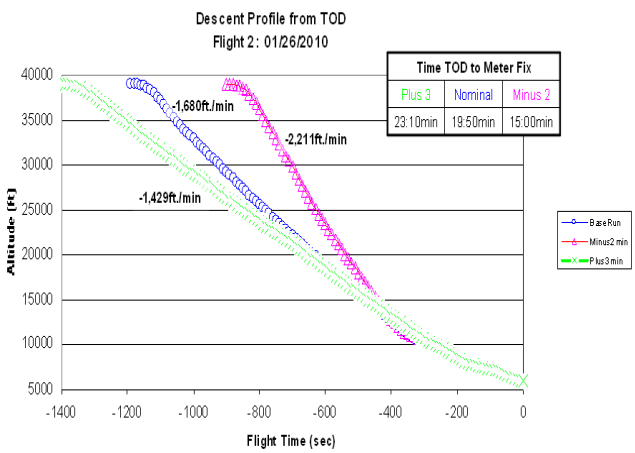

Figure 2: TOD Descent Profiles

The time from TOD to the meter fix, and the rate of descent vary greatly based on the RTA time requested. When the aircraft is requested to meet a later RTA time, the FMS reduces the airspeed so the aircraft will arrive at the assigned fix at a later time. The aircraft also begins the TOD much earlier in the flight, and the rate of descent is lower. Likewise, when an earlier arrival is requested, the FMS delays the TOD and descends at a much higher airspeed with an associated higher rate of descent. Currently the ground based automation does not account for changes in the flight plan caused by the aircraft executing an RTA.

Ground Automation

Track data from the GEAS was converted to radar tracks that were used as input to the ESUB system. This radar position data, along with other inputs, was then sent through the ERAM simulator and the trajectories generated were recorded. Like the FMS desktop simulator, the ESUB system accepts RUC weather data containing wind and temperature forecasts. This helps ERAM predict the most accurate trajectories possible. Upon completion of the ESUB runs, all output data and associated trajectory predictions were collected for analysis.

Analysis

All 24 simulation runs were completed by the airborne and ground automation and then the data was processed using internal applications developed by the Federal Aviation Administration's (FAA) Simulation and Analysis group. These applications perform two sets of metric calculations. First, an aggregate set of flight metrics were calculated that characterize the entire flight of available trajectory predictions for the en route center under study (ZLC for this study). Second, a set of arrival flight metrics were calculated that characterize each flight's single trajectory prediction before a specified sample time before TOD. Both sets of metrics were used to describe the performance of the flights with different RTAs and weather seasons.

Aggregate Flight Metrics

Aggregate flight metrics are calculated on a sample of trajectories throughout the flight within the ZLC boundaries. The two flights in this study enter ZLC airspace at cruise altitude and then descend to their arrival airports, both within ZLC boundaries. For Flight 1, the aircraft cruises at flight level 310 (FL 310, approximately 31,000 feet) and descends to 10,000 feet crossing a specified meter fix into terminal airspace for destination airport KENV (Wendover). For Flight 2, the aircraft cruises at FL 390 and descends to approximately 5,500 feet crossing a specified meter fix into terminal airspace for destination airport KBOI (Boise).

ERAM trajectory predictor generates a number of trajectory predictions for both flights. For Flight 1, ERAM predicts on average approximately six trajectories, ranging from four to eight for each of the 12 runs. For Flight 2, ERAM predicts on average approximately nine trajectories, ranging from seven to twelve for its 12 runs. Thus, ERAM does make more predictions for Flight 2's longer descent. Flight 1's duration in the ZLC airspace is approximately 33 minutes, while Flight 2's duration is 37 minutes on average.

The aggregate metrics calculation method utilizes a sampling algorithm that has been used over the past decade by the FAA. For example in 1999, two operational trajectory predictors were evaluated using this method [1]. In both [1] and [2], the sampling method and metrics are defined in detail. The sampling algorithm, referred to as the interval based sampling technique (IBST), steps through the ground truth surveillance track positions every parameter sample time (i.e. 30 seconds). At each sample time, the current active trajectory prediction is measured at a set of parameter look ahead times (i.e. 0, 10, 20, … 1200 seconds). These measurements are aggregated into a relational database and later interrogated for both inferential and point statistical analyses.

Two key point metrics utilized in this study are the spatially coincident along track error and time coincident vertical error. Vertical error is the altitude difference between the current surveillance reported altitude and time coincident trajectory predicted altitude. Spatially coincident along track error is calculated by determining the closest lateral position on the trajectory predicted path from the current surveillance track position. It is the longitudinal distance in nautical miles along the trajectory from the time coincident trajectory position to the spatially coincident lateral position projected on the trajectory. For this study, the cross track error (distance lateral from the track projected on the trajectory) is close to zero, since both flights are simulated to fly on their flight plan.

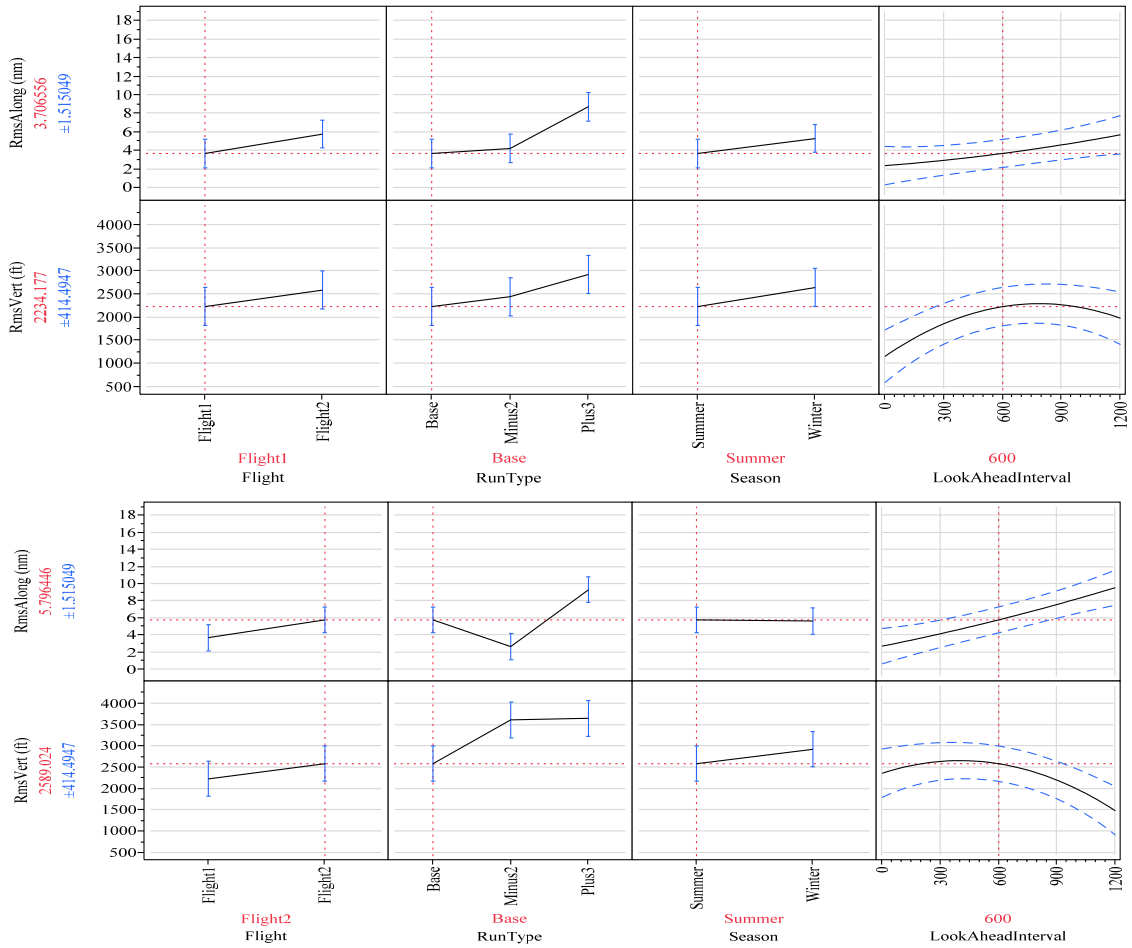

Figure 3: RMS Aggregate Errors - Flight 1 (top) and Flight 2 (bottom)

For all 24 experimental runs, the IBST was employed producing almost 142,000 measurements. The along track and vertical errors were summarized by calculating the square root of the mean of the

squared errors (often referred to as the root mean square error, RMS) for each of the experimental runs. These RMS metrics were then modeled by a multi-regression model that considered the key factors under study: flight (*1 and 2*), RTA type (*baseline, minus2, plus3*), and season (*summer and winter*), using design of analysis techniques modeling both the main and interaction effects of these factors [3,4].

The results of the multi-regression model are summarized in the special contour plots in Figure 3, referred to as a predictor profile produced from the commercial software package, JMP® [5, 6]. The plot illustrates the relationship between flight, run type, and season, as a function of look ahead time (0 to 1200 seconds). Most notably, it shows that Flight 2 has higher RMS errors than Flight 1 at look ahead time 600 seconds and RTA run type of *plus3* has the largest error compared to the other RTA run types for both flights. For Flight 1, *baseline* RTA run type has the lowest RMS along track error, but Flight 2's *minus2* RTA run type has the lowest error. For both flights, the RMS along track error increases almost linearly as a function of look ahead time. However, vertical error is non-linear for both flights, increasing steadily until about 900 seconds for Flight 1 and 600 seconds for Flight 2, where the curve starts to decrease slightly for Flight 1 but sharply for Flight 2. Season has a modest impact on both flights by exhibiting slightly larger error for *winter* over *summer* runs.

The aggregate RMS errors captured by the multi-regression model illustrate the relative effects that the RTA type and season have on the trajectory predictions of ERAM. As shown in Figure 2, it is expected that the RTA type *plus3* that produces the least descent rate and longest descent duration produces the largest errors. ERAM uses nominal descent rates and adjusts its modeled descent rate based on surveillance track reports if beyond a threshold. However, larger and longer differences in the descent are expected to manifest larger errors in along track error as well as vertical error as illustrated by the results. Along track error tends to remain, but vertical error can be compensated for at the longer look ahead times as illustrated by the non-linear vertical errors as a function of look ahead time.

Arrival Flight Metrics

While aggregate flight metrics captured the overall trajectory errors in the experiment because the IBST sampled trajectory predictions throughout the flight profile, the arrival flight metrics sample a single trajectory a parameter time (4 minutes) before the actual TOD and measure the errors from TOD to the meter fix location. The arrival flight metrics illustrate the prediction errors made before TOD where the utility of this flight path forecast is most useful operationally to predict conflicts with other aircraft or metering position among other arriving aircraft. Thus, these metrics are a snapshot of performance for the arrival phase of flight in contrast to the aggregate metrics that characterize the entire flight, capturing the trajectory predictor's processing to auto-correct for errors during the flight.

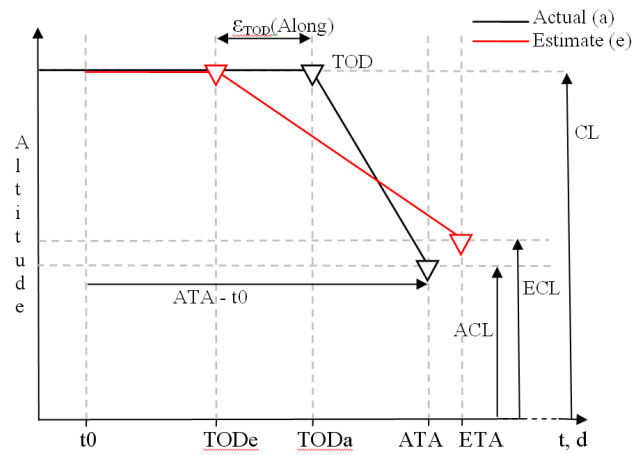

Figure 4: Arrival Flight Metrics' Plot

The arrival flight metrics are defined in Figure 4 graphically. Four key metrics are of interest for this study. They are defined in the following four equations. For (1), $(\varepsilon_{MF})_{ECL}$ is defined as the altitude error at the meter fix in feet. It is determined by subtracting the Estimated Crossing Level (ECL) by the Actual Crossing Level (ACL). For (2), $(\varepsilon_{MF})_{ETA}$ is defined at the relative time error at the meter fix. It is calculated by taking the difference of the Estimated Time of Arrival (ETA) by the Actual Time of Arrival (ATA). It is expressed as a percentage by normalizing by the duration from ATA of the meter fix to time zero (t0), where the active trajectory is selected before the TOD position. For (3), the along track distance is calculated from the estimated TOD position to the actual TOD position in nautical miles.

Finally, for (4), the difference in descent rates (feet per minute) is calculated by subtracting the actual descent rate from the predicted descent rate. The descent rates are calculated individually first by taking the difference in altitude change from the crossing levels (ECL or ACL) at the meter fix to the altitude at TOD cruising level (CL). Next, these differences are divided by the duration in time from TOD to crossing the meter fix. This is expressed as the difference in either ETA or ATA times at the meter fix subtracted by the estimated or actual TOD times. Again, these four metrics are expressed in the following four equations.

$$\left(\varepsilon_{MF}\right)_{ECL} = ECL - ACL\,,\ [\text{ft}] \tag{1}$$

$$\left(\varepsilon_{MF}\right)_{ETA} = \frac{\left(ETA - ATA\right)}{\left(ATA - t0\right)},\ [\%] \tag{2}$$

$$\left(\varepsilon_{TOD}\right)_{Along} = E.TOD_{Along} - A.TOD_{Along}\,,\ [\text{nm}] \tag{3}$$

$$\left(\varepsilon_{Descent}\right)_{Rate} = \left(\frac{ECL - CL}{ETA - E.TOD_{Time}}\right) - \left(\frac{ACL - CL}{ATA - A.TOD_{Time}}\right),\ [\text{ft/min}] \tag{4}$$

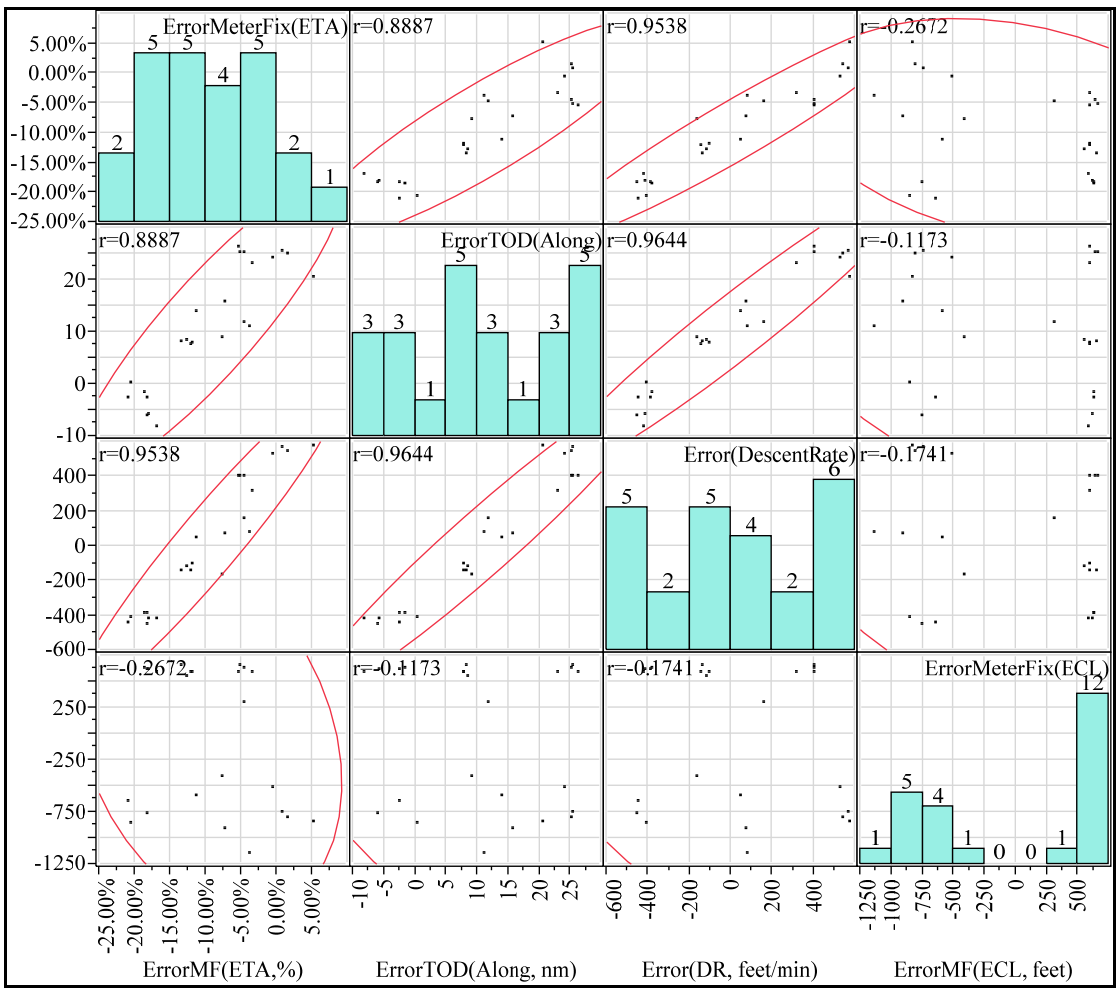

Figure 5: Arrival Metric Correlations and Histograms

All four metrics were calculated for the 24 runs of the experiment and cross compared by correlation ratio (statistic measuring the linear relationship between variables). The results are illustrated in Figure 5 where each arrival metric are compared to each other. It is clear that three of the four metrics

have high positive correlations from 0.88 to 0.96 indicating that if one metric increases the other increases as well. These were $(\varepsilon_{MF})_{ETA}$, $(\varepsilon_{TOD})_{Along}$, and $(\varepsilon_{Descent})_{Rate}$, while the $(\varepsilon_{MF})_{ECL}$ metric exhibits very low correlations between the other three metrics. Figure 5 also illustrates the histograms with frequency count listed for all four of the distributions of metric calculations.

Like the aggregate metrics, a multi-regression model was fit to the 24 runs of data. However, with the first three metrics exhibiting high positive correlations, only two of the four will be examined in detail, since the basic trends should be consistent. Descent rate error and altitude error at the meter fix were selected and a set of surface plots were generated to illustrate the effect of flight, RTA run type, and season on these metrics. A full listing for the four metrics on all 24 runs is presented in Table 1 in Appendix I.

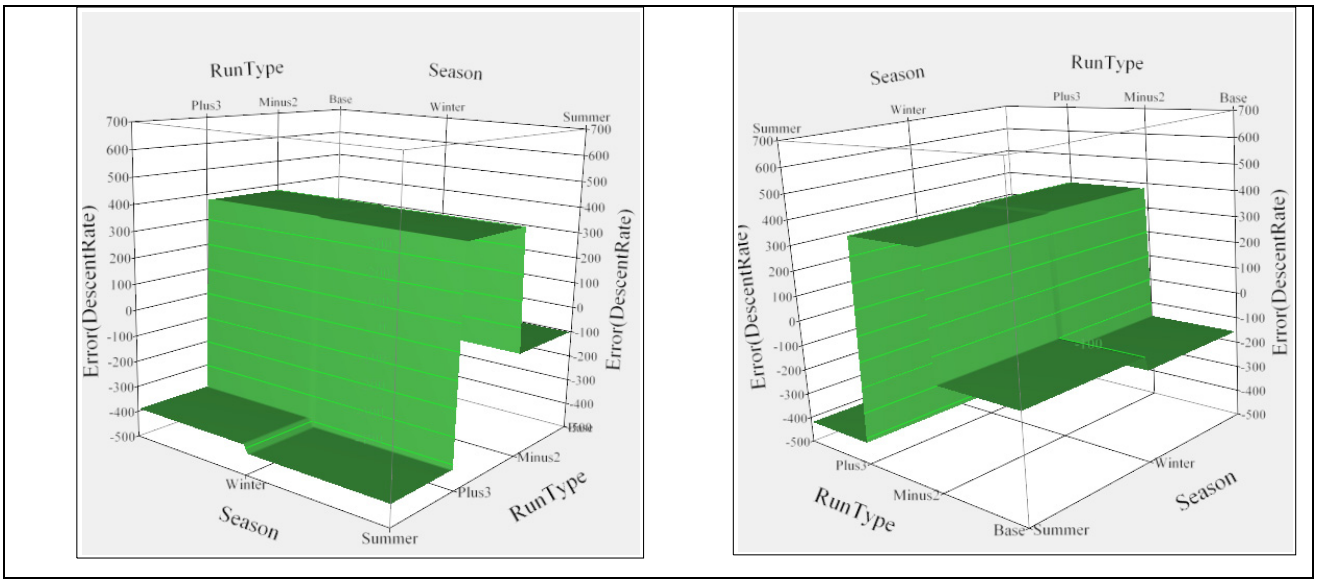

Figure 6: Flight 2's Descent Rate Error by Run Type Front (left) and Back View (right)

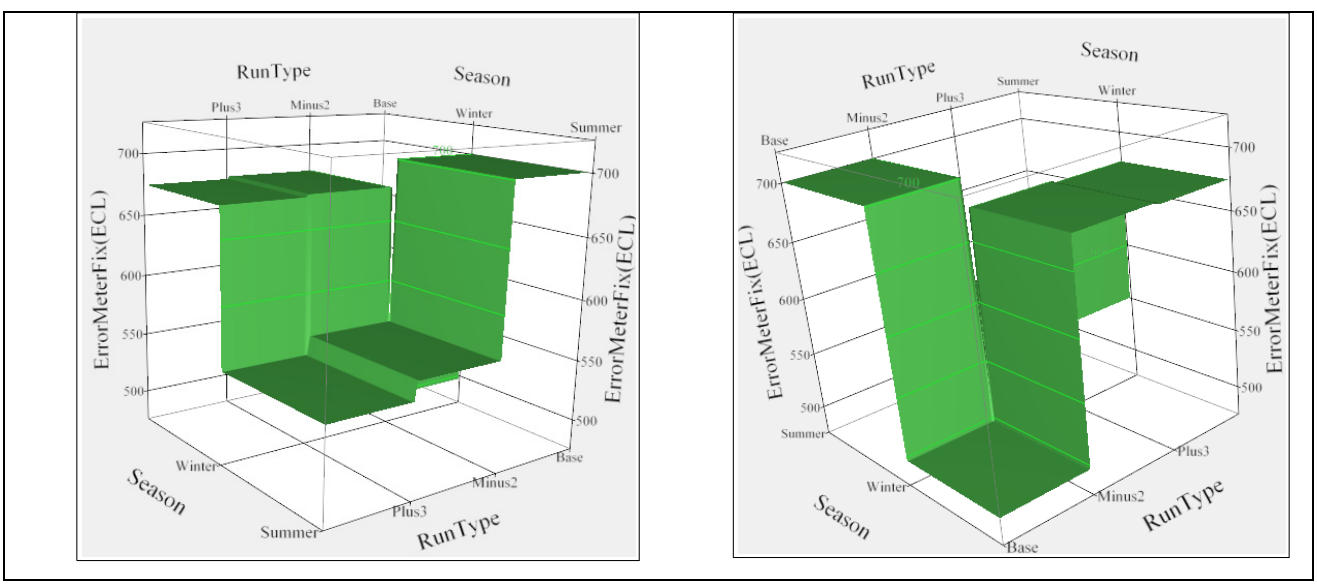

Figure 7: Flight 2's Meter Fix Altitude Error by Run Type Front (left) and Back View (right)

Figure 6 presents the surface for Flight 2's descent rate error (see Equation (4) for details) as modeled and fit for the flight's 12 experimental runs. Figure 7 presents the surface similarly for the altitude error at the meter fix (see Equation (1) for details). Similar to the aggregate metrics the season factor only exhibits a minor effect on descent rate error. However, for the altitude error at the meter fix the season factor seems to interact with the RTA run type exhibiting differences in altitude error of approximately 100 to 200 feet.

In summary, for Flight 2's descent rate there is only a slight difference by season, but RTA run type's have large differences. The experimental RTA run level of *plus3* demonstrates the largest impact in terms of vertical rate change, with the next largest being the *minus2* level, and nominal baseline run in between. The results for Flight 1 are not illustrated but all data listed in Table 1 in Appendix I indicate the trends are very similar in terms of descent rate.

For meter fix altitude error, Flight 2 demonstrates the interaction between season and RTA run type. For RTA run type at *plus3* and *minus2* levels, Figure 7 shows that under *winter* runs the experiment produces meter fix altitude errors between 600 to 700 feet, while for *summer* runs the error drops between 500 to 550 feet on average. However, for *baseline* RTA run type the opposite trend is produced. Under *baseline* RTA runs, the *winter* runs are approximately 500 feet, while the *summer* runs are much larger at 700 feet.

Conclusions

The simulation study presented in this paper was designed to evaluate the effect on ERAM trajectory prediction when a flight is following an RTA. Two types of metrics were calculated; the aggregate trajectory error metrics show the effects of the correction for flight plan deviation and subsequent trajectory rebuilds in the automation, and the arrival metrics provide a detailed view of the performance of one particular trajectory (i.e. 4 minutes before TOD) which is assumed to be operationally important. Unexpectedly, the results demonstrated a large difference in TOD for a small change in RTA. Even though the differences in RTA were only a few minutes, the resulting changes by the FMS were very significant, manifesting into large prediction errors by the ground-based TP at both the TOD and metering fix. Although the ERAM trajectory predictor would compensate over time, correction was not possible before the TOD as illustrated in the arrival flight metrics. For example, using an RTA of minus 2-minutes produced errors in predicting the TOD up to 26 nautical miles longitudinally.

This was an initial study evaluating the impact of RTAs on ground automation, illustrating that RTAs significantly impacted the TOD and metering fix predictions. If RTA, TOD, and descent rate from airborne automation could be entered into ERAM, the trajectory prediction performance would improve. From past experience when the TP improves so does the conflict probe [7]. The authors recommend a follow-up study, where the TP is updated to utilize this intent data, and the resulting performance on the conflict probe is analyzed (e.g. missed/false alerts).

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Email Addresses

Mike M. Paglione: Mike.Paglione@faa.gov

Ben Musialek: Benjamin.CTR.Musialek@faa.gov

Christina Young: Christina.M-CTR.Young@faa.gov

Appendix I

Table 1 provides a full listing of the arrival flight metrics for all 24 runs of the experiment, including flights, seasons, run dates, and most importantly RTA run types.

Table 1: Complete Set of Arrival Flight Metrics

Flight	Run Type	Season	Simulation Date	Error Meter Fix (ETA, %)	Error TOD (Along, nm)	Error (Descent Rate, fpm)	Error Meter Fix (ECL, ft)
Flight1	Base	Winter	26-Jan-10	-11%	13.95	45	-595
Flight1	Base	Winter	27-Jan-10	-4%	11.12	81	-1139
Flight1	Base	Summer	9-Jul-10	-7%	15.8	71	-905
Flight1	Base	Summer	25-Jul-10	-5%	11.82	159	307
Flight1	Minus2	Winter	26-Jan-10	-1%	24.12	530	-513
Flight1	Minus2	Winter	27-Jan-10	5%	20.62	573	-836
Flight1	Minus2	Summer	9-Jul-10	1%	25.08	542	-808
Flight1	Minus2	Summer	25-Jul-10	1%	25.47	565	-747
Flight1	Plus3	Winter	26-Jan-10	-8%	9.07	-166	-413
Flight1	Plus3	Winter	27-Jan-10	-18%	-5.98	-452	-757
Flight1	Plus3	Summer	9-Jul-10	-21%	-2.53	-446	-648
Flight1	Plus3	Summer	25-Jul-10	-21%	0.29	-411	-851
Flight2	Base	Winter	26-Jan-10	-13%	8.23	-140	656
Flight2	Base	Winter	27-Jan-10	-12%	7.73	-142	591
Flight2	Base	Summer	9-Jul-10	-12%	7.82	-104	598
Flight2	Base	Summer	25-Jul-10	-13%	8.43	-120	551
Flight2	Minus2	Winter	26-Jan-10	-5%	25.31	400	661
Flight2	Minus2	Winter	27-Jan-10	-5%	26.28	399	592
Flight2	Minus2	Summer	9-Jul-10	-5%	25.19	402	637
Flight2	Minus2	Summer	25-Jul-10	-3%	23.03	316	596
Flight2	Plus3	Winter	26-Jan-10	-18%	-5.86	-415	614
Flight2	Plus3	Winter	27-Jan-10	-17%	-8.18	-421	586
Flight2	Plus3	Summer	9-Jul-10	-18%	-2.53	-390	625
Flight2	Plus3	Summer	25-Jul-10	-19%	-1.69	-383	627