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Trajectory Prediction Accuracy and Error Sources for Regional Jet Descents

Part II—Results of a 2010 Flight Trial at Denver International Airport Using SkyWest Revenue Flights

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Summary

The Efficient Descent Advisor (EDA) controller automation tool generates trajectory-based speed, path, and altitude-profile advisories to facilitate efficient, continuous descents into congested terminal airspace. While prior field trials have assessed the trajectory prediction accuracy for large jet (i.e., Boeing and Airbus) types, smaller (i.e., regional and business) jet types present unique challenges involving different descent procedures and Flight Management System (FMS) capabilities. This paper quantifies the trajectory prediction accuracy for small-jet revenue-flight descents based on SkyWest Canadair Regional Jet 200, 700, and 900 aircraft arrivals to Denver in the fall of 2010. Post-flight-test data analysis and SkyWest pilot interviews uncovered unexpected variations between flight crews due to different interpretations of (1) which fixed flight path angle (FPA) to fly based on the flight trial procedure, and (2) how to fly the descent to achieve the target FPA. Pilot reports were used to select a subset of flights where pilots indicated an FPA according to the flight trial procedure to remove the unexpected variation due to (1) to focus on (2). Results for the subset of en route descents, from prior to top of descent (TOD) to the meter fix 30 to 130 nmi downstream, indicate that aircraft arrived to the meter fix 6 seconds early with about a 12-second standard deviation. Large FPA errors up to 1 degree relative to the EDA flight trial procedure were detected after the flight trial as a characteristic of the unexpected variation. It is recommended that quantitative validation be performed during future flight trials so that experimental procedures can be adjusted if unexpected results are detected.

1. Introduction

Without automated decision support, controllers routinely issue corrective changes in speed, path, and altitude profiles when metering arrivals and maintaining separation during descent. These corrective changes exact a cost in terms of operational efficiency, and their frequency and magnitude can disrupt and, in some cases, overwhelm the metering operation. The Three-Dimensional Path Arrival Management (3D PAM)[1-3] concept for operational deployment of the Efficient Descent Advisor (EDA)[4-7] automation tool addresses this problem by providing controllers with automation that generates advisories—specially formulated for delivery by voice—that are designed to achieve precise meter-fix scheduled times of arrival without the need for corrective changes by controllers, thereby improving the robustness of metering operations. Furthermore, the advisories enable continuous descents during metering operations, which enhance operational efficiency. The 3D PAM descent procedures for large jets were validated in the fall of 2009.[6] Smaller jets, such as business and regional jets, have different Flight Management System (FMS) capabilities, descent procedures, and aircraft performance than large jets. The choice of descent angle for small jets is up to the pilot, and the procedure to select a descent path is generally not standardized.

Part I of this paper[8] describes a flight trial that was conducted in collaboration with the Federal Aviation Administration (FAA) and Boeing in the fall of 2010 using a Bombardier Global 5000 flight test aircraft as a first step in developing procedures, and assessing trajectory prediction accuracy and sources of prediction errors for small jets. The procedures developed for the Global 5000 flight test aircraft were evaluated in preparation for a flight trial of SkyWest Canadair Regional Jet (CRJ) 200, 700, and 900 revenue flight arrivals to Denver International Airport. For both the Global 5000 and SkyWest flight trials, a scripted procedure was used so that pilots selected a fixed flight path angle (FPA) based on a cleared descent speed with a vertical profile anchored at the meter-fix crossing restriction.

This paper quantifies the Center-TRACON Automation System (CTAS)[8-11] trajectory prediction accuracy for small-jet revenue-flight descents based on SkyWest CRJ arrivals to Denver between October 25, 2010, and November 10, 2010. The goal was to estimate trajectory prediction accuracy that could be achievable for small jets in a future EDA deployment. To measure this accuracy, the CTAS trajectory synthesizer component was used to generate predictions that were compared to the flown trajectories in the trials. The data collected to generate predictions included the ground radar tracks, recorded Rapid Update Cycle (RUC) wind data, paper-based pilot reports, and ground observer logs at the center. The predicted time error at the meter fix was quantified, as well as other measures of descent trajectory predictability including FPA, location of top of descent (TOD), location of bottom of descent (BOD), and altitude relative to the predicted trajectory.

This paper is organized as follows: Section 2 describes the flight trial of SkyWest CRJ revenue flight descents, Section 3 presents quantification of trajectory prediction accuracy, and conclusions are presented in Section 4. The appendices contain the flight bulletin issued to SkyWest pilots, anomalies that occurred during descents, frequency distributions of error statistics, and a categorization of typical errors between the flown and predicted trajectories.

2. Flight Trial

The flight trial of SkyWest revenue flights was conducted between October 25, 2010, and November 10, 2010. This section describes the flight trial procedure, including the test matrix and data collected.

2.1. Test Matrix

Each descent followed a fixed FPA defined according to Table 1. Table 1 was developed in collaboration with SkyWest and validated in a piloted simulation at their training facility. The specific values were selected with consideration for a) the ability to fly the descent, b) avoidance of speed brake use or relatively high power settings, and c) fuel efficiency. No winds were considered in the simulation. Controllers issued calibrated airspeeds (CAS) for the descent, and pilots used that speed to select a descent FPA according to Table 1. Because these were revenue flights, no path stretches were issued, and aircraft were assigned to the four Denver arrival gates according to typical operations. The flight crew had the option to reduce CAS during descent or to level off at the meter-fix altitude to meet the generally 250-knot speed restriction. A 230-knot speed restriction was occasionally used for one runway configuration. The meter-fix crossing altitude constraints were FL190 for TOMSN, POWDR, DANDD, and SAYGE, and 17,000 feet for RAMMS, LARKS, QUAIL, and LANDR, with a few exceptions where controllers issued lower crossing altitudes. The flight bulletin issued to flight crews that describes the flight trial is included in Appendix A.

Table 1. Descent FPA by cleared CAS.

Descent CAS (knots)	FPA
250 260	–2.8
270 280	–3.1
290 300	–3.4
320	–3.8

2.2. Data Collection

The data collected during the flight trial were radar tracks recorded at 12-second intervals, RUC wind data, pilot reports, and ground observer logs. Radar track data were occasionally unavailable, including all of November 5, 2010, which reduced the number of trajectories that could be analyzed. The ground observer logs included the flight call sign; time of the EDA clearance; EDA descent speed clearance; whether the clearance was declined by the pilot (e.g., flight crew may not have received bulletin or cancelled for safety reasons) or cancelled by Air Traffic Control (ATC) due to, for example, traffic; and any comments by the observer. According to the ground observer sheets, a total of 1,002 flights were given EDA clearances that were not declined by the pilot or cancelled by ATC. A sample pilot report (SkyWest Airlines EDA Data Collection Form) is included in Appendix A; it contains fields for the pilot to report the flight call sign, aircraft type, tail number, descent-speed clearance, assigned fix, time at TOD and meter fix, aircraft weight, selected FPA, winds, subjective workload rating, if the FMS built a TOD, use of thrust or speed brakes, and crew comments. A total of 501 pilot reports were returned, 320 of which were given an EDA clearance that was not interrupted.

3. Trajectory Prediction Accuracy

CTAS was used to generate a four-dimensional (4D) trajectory prediction (position, altitude, and time) based on the radar track position and ground speed at each run's initial condition. Clearance information recorded by ground observers was unavailable to CTAS during the field trial, so trajectory predictions could not be generated on the same day. Furthermore, uncertainty in the recorded clearance time made it difficult to instruct CTAS to generate trajectory predictions for the issued speed and corresponding FPA. Instead, a superset of trajectory predictions, containing all fixed-FPA descent trajectories listed in Table 1, was generated after the flight test using the atmospheric conditions, flight plan, and meter-fix crossing restrictions that would have been known to the ground automation system at the start of each run. This superset of trajectory predictions was stored in a trajectory archive. A tool was developed to select trajectory predictions from the archive based on the flight identification (ID), clearance time, and descent CAS in the ground observer sheets.

The trajectory selection attempted to pick an initial condition as close to the clearance time as possible. However, the clearance time in the ground observer sheets was recorded to the precision of minutes, and could not be mapped to a unique track point because there were five radar track updates per minute. Furthermore, the clearance time occasionally conflicted with the radar track data, showing clearance time when the flight was already in descent or when the flight had just entered the center boundary. Therefore, a selection process for the initial condition was developed based on the assumption that the clearance was issued shortly before the flown TOD, without directly using the recorded clearance time. The selected initial condition was a track point about 0.5 to 5 minutes before the flown TOD. The selection tool started with a location 0.5 minutes prior to the flown TOD and went back in time until it found a predicted trajectory in accordance with the clearance from the archive. A typical reason why a predicted trajectory could not be generated at 0.5 minute before the flown TOD was due to the actual descent being steeper than the prescribed FPA. Only initial conditions with altitudes at or above 27,000 feet were analyzed to ensure enough length in the descent segment.

The resulting initial condition for the trajectory prediction was about 30 to 130 nmi from the meter fix depending on the ground observer time, cruise altitude, and flown FPA. The distance between the initial condition and the meter fix is shown in Figure 1 in the plot of flown trajectories. Shorter distances occurred when the initial condition was at 27,000 feet, and the aircrew flew a steeper descent (e.g., –3.9 deg) than the procedure, while longer distances between the initial condition and the meter fix occurred when the initial condition was at 39,000 feet and the aircrew flew a shallower descent (e.g., –1.5 deg) than the procedure listed in Table 1.

The modeled descent vertical profile by CTAS was essentially the same as that used for the Global 5000 flight test, except that the CAS deceleration before the meter fix was modeled using a level segment with idle thrust instead of a fixed-FPA descent segment with CAS deceleration.

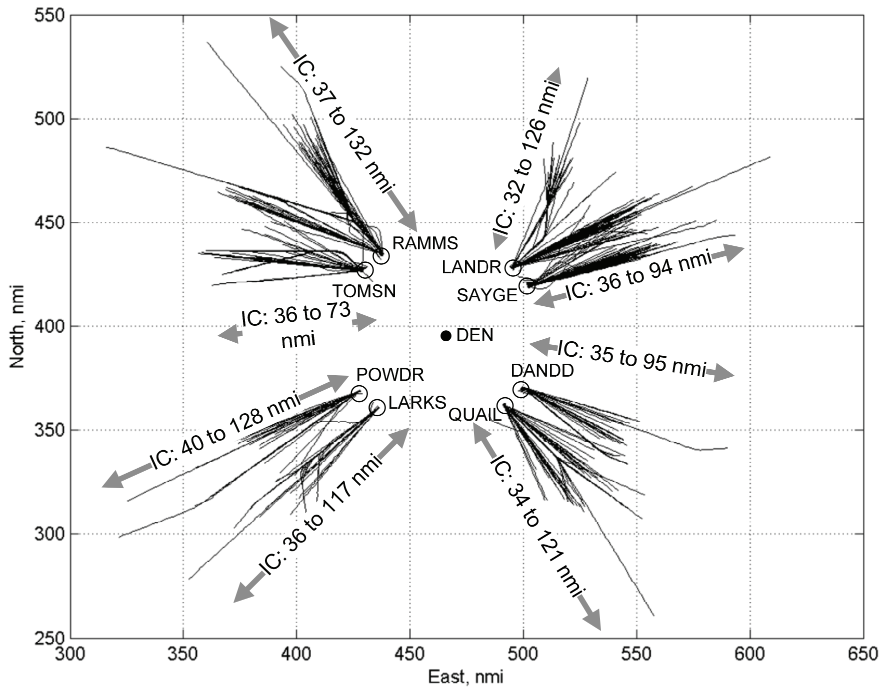

Figure 1. Flown trajectories from the trajectory prediction initial condition (IC) to the eight meter fixes. The range of distances from the IC to the meter fix is also shown. Trajectories for all flights on all days are included.

3.1. Initial Analysis

Initially, analysis focused on 648 flights, with conditions at 27,000 feet or above, for which trajectory predictions could be generated. An additional 11 flights were excluded from the 648 after the CTAS trajectories were generated, bringing the total number analyzed down to 637; these 11 flights did not have enough radar tracks to be analyzed using the MATLAB tools that correlated predicted trajectories to flown trajectories. (The MATLAB tool required more radar track data than CTAS to generate a trajectory prediction.) Comparisons between the radar tracks and predicted trajectories were made at the spatial location (latitude/longitude) along the predicted trajectory closest to each radar track position. The number of flights analyzed with each descent CAS/FPA combination for each meter fix is shown in Table 2. A summary of the initial analysis is shown in the “All Flights” column in Table 3. The “Pilot Reports Correct FPA” column summarizes an analysis of a subset of flights and is discussed in Section 3.2.

The mean (–4.7 sec) and standard deviation (50.8) of the time error at the meter fix indicates a relatively large spread in the time error. This spread is primarily due to the aircraft following a different FPA than specified in the flight trial procedure. The mean (–0.29 deg) and standard deviation (0.59 deg) of the FPA error, and the mean (0.48 deg) and standard deviation (0.46 deg) of the absolute value of the FPA error, are large when considering that the difference between FPAs in the procedure, as shown in Table 1, is 0.3 degrees. Flown FPA was calculated as the angle between the first radar track below 1,000 feet below the TOD, and the last radar track above 1,000 feet above the BOD. These FPA errors result in a trajectory that has large standard deviations for the TOD (9.1 nmi) and BOD (3.4 nmi), and altitude errors.

Altitude error has the largest mean (–670 feet) and standard deviation (1,934 feet) at 4,000 feet below the initial condition. The pilots had the option to reduce CAS during descent or to level off at the meter-fix altitude to reduce CAS to meet the meter-fix crossing speed restriction, which impacts the TOD, BOD, and altitude errors. Examples of both of these behaviors are included in Appendix D. Part I of this paper[8] indicated that a procedure that uses a level segment to reduce CAS is more predictable and would be expected to reduce the predicted error for the BOD location.

Table 2. Number of flights by descent CAS for all flights and those flights where pilot reported FPA according to procedure.

Gate	Fix	Descent CAS	250	260	270	280	290	300	320	Total
		FPA	–2.8	–2.8	–3.1	–3.1	–3.4	–3.4	–3.8	
NE	LANDR	All Flights	8	1	2	33	1	46	4	95
		Pilot Reports	1			1		8	1	11
	SAYGE	All Flights	4	1	2	30	1	33	5	76
		Pilot Reports				5		5	1	11
NW	RAMMS	All Flights	48	1	2	77	1	43	17	189
		Pilot Reports	13			20		12	3	48
	TOMSN	All Flights	13		1	21		25	6	66
		Pilot Reports	4			5		7	1	17
SE	DANDD	All Flights	5		1	10		21	8	45
		Pilot Reports	1			3		4	2	10
	QUAIL	All Flights	13		1	23	3	43	6	89
		Pilot Reports	2			1		6		9
SW	LARKS	All Flights	6	1	2	13		7	5	34
		Pilot Reports	3			3		1	2	9
	POWDR	All Flights	11		1	21		8	2	43
		Pilot Reports	2			6		1	1	10
	Total	All Flights	108	4	12	228	6	226	53	637
		Pilot Reports	26	0	0	44	0	44	11	125

Due to the large FPA errors, an investigation was conducted of anomalies that may cause these large errors. Flights were removed from the analysis set if they exhibited anomalous behavior including (a) the pilot reported that the EDA approach was interrupted, (b) erroneous radar track data, (c) an FPA that was not constant, (d) not targeting the meter-fix altitude constraint, and (e) being handed-off early from en route ATC to the Terminal Radar Approach Control (TRACON). A summary of these and other anomalies is included in Appendix B. Flights were not removed from the analysis based on flown FPA deviation from the Table 1 procedure because the magnitude of the resultant FPA error by itself could not be used to determine if the error would be typical of future EDA operations.

After removing these anomalous flights, the magnitude of the mean time error increased (–6.2 sec) but the standard deviation (13.7 sec) was reduced. The mean (0.40 deg) and standard deviation (0.37 deg) of the absolute value of the FPA remained larger than 0.3 degree, which is the difference between FPAs in the procedure. For this reason, the pilot reports were examined in more detail in an attempt to identify why the aircraft flew an FPA that was very different from that listed in Table 1.

3.2. Analysis of Pilot Reports

A total of 501 flights had pilot reports. Recall that the pilot reports had fields for cleared descent CAS and pilot-reported FPA. Of the 501 pilot reports, 290 indicated an FPA according to the procedure shown in Table 1. Of the remaining 211 pilot reports, 186 correctly filled out the descent CAS but entered an FPA that was not indicated in Table 1, and 25 did not fill out the FPA. This variation was not expected and indicates a range of interpretations of the flight trial procedure to select a descent FPA based on cleared descent CAS. To eliminate this unexpected variation due to interpretation, the analysis focused on

125 flights with a pilot report indicating the correct FPA according to the EDA procedure in the flight bulletin, and that did not contain anomalous behavior.

Table 3. Summary of trajectory prediction errors for all flights and for those flights where the pilot reported FPA according to procedure. μ = mean error and σ = standard deviation of error.

Error Description, units	All Flights		Pilot Reports Correct FPA	
	μ	σ	μ	σ
i) Time error at meter fix, sec	–4.7	50.8	–6.0	12.4
ii) Top of descent location, nmi	0.9	9.1	0.7	3.2
iii) Bottom of descent location, nmi	–1.4	3.4	–0.8	2.5
iv) FPA error, deg	–0.29	0.59	–0.18	0.23
v) Absolute value of FPA error, deg	0.48	0.46	0.22	0.20
vi) Maximum cross-track error, nmi	18.6	1.1	0.3	0.2
vii) Altitude error				
Top of descent, ft	519	1243	248	536
Initial condition – 2,000 ft, ft	–438	1689	–386	1014
Initial condition – 4,000 ft, ft	–670	1934	–392	1069
Initial condition – 6,000 ft, ft	–553	1845	–341	1032
Fix altitude + 4,000 ft, ft	49	1292	–15	935
Fix altitude + 2,000 ft, ft	219	1061	147	877
Bottom of descent, ft	–143	686	–219	443
Meter fix, ft	270	654	100	219

Analysis of trajectory prediction accuracy for the 125 flights with pilot reports indicating an FPA flown according to procedure is shown in the right-hand columns in Table 3. The time error mean (–6.0 sec) and standard deviation (12.4 sec) are roughly comparable to the mean (–15.6 sec) and standard deviation (9.9 sec) for the Global 5000 descents presented in Part I.[8] However, the FPA error is larger than the FPA mean (–0.01 deg) and standard deviation (0.04 deg) for Global 5000 descents by an order of magnitude. A key difference between the Global 5000 and SkyWest flight trials is that the Global 5000 pilots were test pilots accustomed to flying new procedures, while the SkyWest pilots did not typically fly new procedures. Also, the Global 5000 pilots had more interaction with personnel conducting the flight trial, causing training differences between the Global 5000 and SkyWest pilots.

The mean (0.22 deg) and standard deviation (0.20 deg) of the FPA error was large relative to the 0.3-degree difference between descent FPAs. It is possible that some aircraft flew a different flight trial procedure angle (e.g., –3.4 deg vs. –3.1 deg). However, the plot of flown FPAs in Figure 2 does not have most of the data at –2.8 degrees, –3.1 degrees, –3.4 degrees, and –3.8 degrees, which would indicate that behavior. According to Table 2, 91 percent of flights (114 out of 125) had a cleared descent CAS that would correspond to an FPA of –3.4 degrees or less, but Figure 2 shows a significant percentage of flights with a flown FPA steeper than –3.5 degrees. The distribution of FPA error in Figure 3 confirms this trend of most aircraft following a steeper FPA (negative values along x-axis) than would correspond to the descent CAS in Table 1. There were high FPA errors for all descent speeds regardless of the assigned arrival gate.

The flown FPA was as much as 1 degree steeper than the FPA specified in the flight trial procedure, which indicates that the pilot-reported FPA does not reflect what the aircraft flew. Some of the pilot reports indicated that pilots received the descent clearance late, which could have caused the steeper descent. The FMS may have built the TOD behind the current aircraft location, in which case the only way to meet the meter-fix altitude restriction would be for the aircraft to start down immediately following a steeper descent. However, data collection was insufficient to make that determination because the pilot reports only indicated whether or not the FMS built a TOD and not whether the TOD was in front or behind the current aircraft location. Also, the ground-observer-reported descent clearance time was not accurate enough to determine if the clearance was late. Subsection 3.3 describes NASA interviews with SkyWest pilots in an attempt to determine why the pilot-reported FPA did not match the FPA that the aircraft followed. Additional supporting plots for all statistics listed in Table 3 are provided for reference in Appendix C. A selection of flights that illustrate differences between predicted FPA and flown FPA is included in Appendix D.

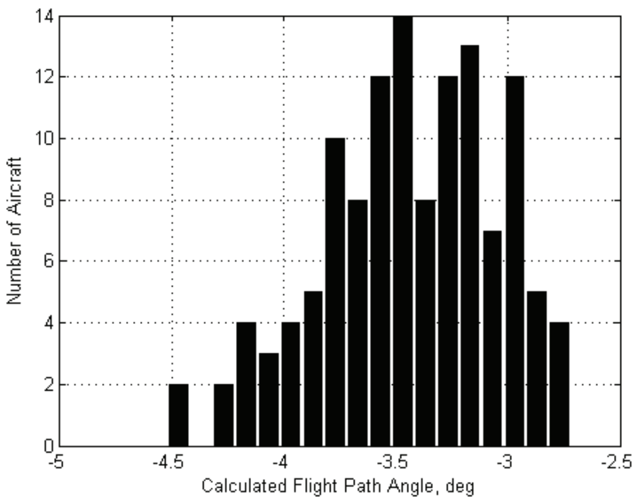

Figure 2. Distribution of flown FPA for flights with pilot reports indicating an FPA in accordance with flight test procedure.

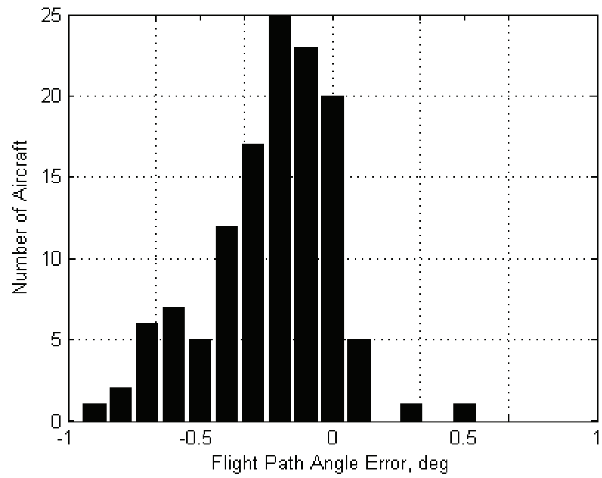

Figure 3. Distribution of FPA error for flights with pilot reports indicating an FPA in accordance with flight test procedure. Negative values indicate that the aircraft followed a steeper descent than was predicted.

3.3. NASA SkyWest Pilot Interviews

NASA consulted with SkyWest pilots in an attempt to identify the source of the larger-than-expected vertical profile errors in Table 3. The pilots indicated that multiple procedures could be followed to achieve a target FPA, and it would be difficult to determine during post-analysis which procedure the pilot was following that caused the FPA error. This indicates a second unexpected variation caused by differences executing the descent procedure to achieve the target FPA. Recall that the first unexpected variation was differences interpreting the flight trial procedure to select a target descent FPA.

4. Conclusions

This paper estimated trajectory prediction accuracy for small-jet revenue-flight descents based on a field trial at Denver International Airport. The predicted trajectory used the CTAS trajectory synthesizer and data known on the ground prior to the aircraft descending approximately 30 to 130 nmi from the meter fix. There was about a 6-second mean and 12-second standard deviation of time error at the meter fix for flights that did not contain anomalous behavior and where the pilot submitted a pilot report indicating the correct FPA as specified in the EDA flight trial procedure. The mean (0.22 deg) and standard deviation (0.20 deg) of the FPA error were an order of magnitude larger than those errors for the Global 5000 descents. However, a key difference between the Global 5000 and SkyWest flight trials is that the Global 5000 pilots were test pilots accustomed to flying new procedures, while the SkyWest pilots did not typically fly new procedures. Also, the Global 5000 pilots had more interaction with personnel conducting the flight trial resulting in training differences between the Global 5000 and SkyWest pilots.

The large FPA errors, which occurred for all descent speeds regardless of arrival gate, were unexpected and were caused by variation between pilots in (1) selection of an FPA according to the flight trial procedure, and (2) executing the descent procedure to achieve the target FPA. Pilot reports and post-flight trial pilot interviews were used to identify this behavior; retaining pilot reporting as a key feature of future flight trials is recommended. It is also recommended that in future flight trials validation be performed during the test by quantifying differences between flown and predicted trajectories. If these differences are large, then pilots should be contacted soon after to determine the cause. Once the cause is found, then the experiment should be adjusted to account for the unexpected results.

Also, it is suggested that the procedure to reduce CAS to meet the meter-fix speed restriction be standardized. A standardized CAS reduction procedure could be based on the aircraft leveling off prior to the meter fix and reducing CAS in a level segment, which is expected to be more predictable than reducing CAS in descent, or the procedure followed during the flight trial, which allowed the pilot to do either.

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Appendix A: Flight Bulletin

3D PAM Flight Trials—DEN

A.1. Background

The purpose of this bulletin is to advise Canadair Regional Jet (CRJ) flight crews of the upcoming flight trials for all SkyWest Airlines flights, in-bound only, into DEN. The flight trials will begin the last week of October and will continue through November 10, 2010.

SkyWest Airlines is participating with the FAA, Boeing, and NASA in a program integrating air carrier operations into the Next Generation Air Traffic system. The program is the Three-Dimensional Path Arrival Management (3D PAM) project. One building block of the 3D PAM is an FAA decision support tool called the Efficient Descent Advisor (EDA), which attempts to meter aircraft over a fix at a specified time. This evaluation represents an incremental step to full 3D PAM implementation. The design intent is to allow a flight to maintain cruise (CRZ) altitude until Flight Management System Top of Descent (FMS TOD), with no step-downs. This benefits SkyWest Airlines and crews—fuel savings for the airlines and less workload for the crews.

Flight crews should expect an EDA clearance from DEN center. If they are unwilling or unable to accept, the crew may decline the clearance and will then receive traditional Air Traffic Control (ATC) clearances. The EDA clearance will provide the flight crew with a CRZ Mach and descent (DES) speed to meet a scheduled time over a metering fix on the arrival. If operational constraints exist, ATC may choose to suspend the EDA flight trials and use traditional ATC clearances.

Crews will not need to reprogram the FMS but they will need to update the flight plan as outlined below. The expectation is to maintain assigned CRZ altitude and speed until FMS TOD. Descent should be via the FMS calculated VNAV PATH (snowflake) when descent clearance is received. Speed should be maintained within 0.02 Mach and +/– 10 knots indicated air speed (IAS) after the Mach/airspeed transition.

An important aspect of this trial is to have valid descent winds available. The flight deck crew will record wind speeds and directions as outlined on the EDA Data Collection Form.

A.2. Assumptions

- Crew has reviewed this bulletin and obtained an EDA Data Collection Form. (Print this bulletin or obtain a copy of the EDA Data Collection Form from your domiciles.)
- The Arrival Procedure will be flown using automation to the greatest extent possible.
- Only the first clearance will state that this is an EDA Clearance. All subsequent clearances will be EDA to the metering fix.
- After the flight crew receive their descent clearance, they are expected to begin the descent at the FMS derived TOD.
- Crew will report leaving last assigned cruise FL or TOD.
- Transition from Mach to IAS in the descent will be conducted by the crew (lack of automation) when assigned Mach = assigned IAS.

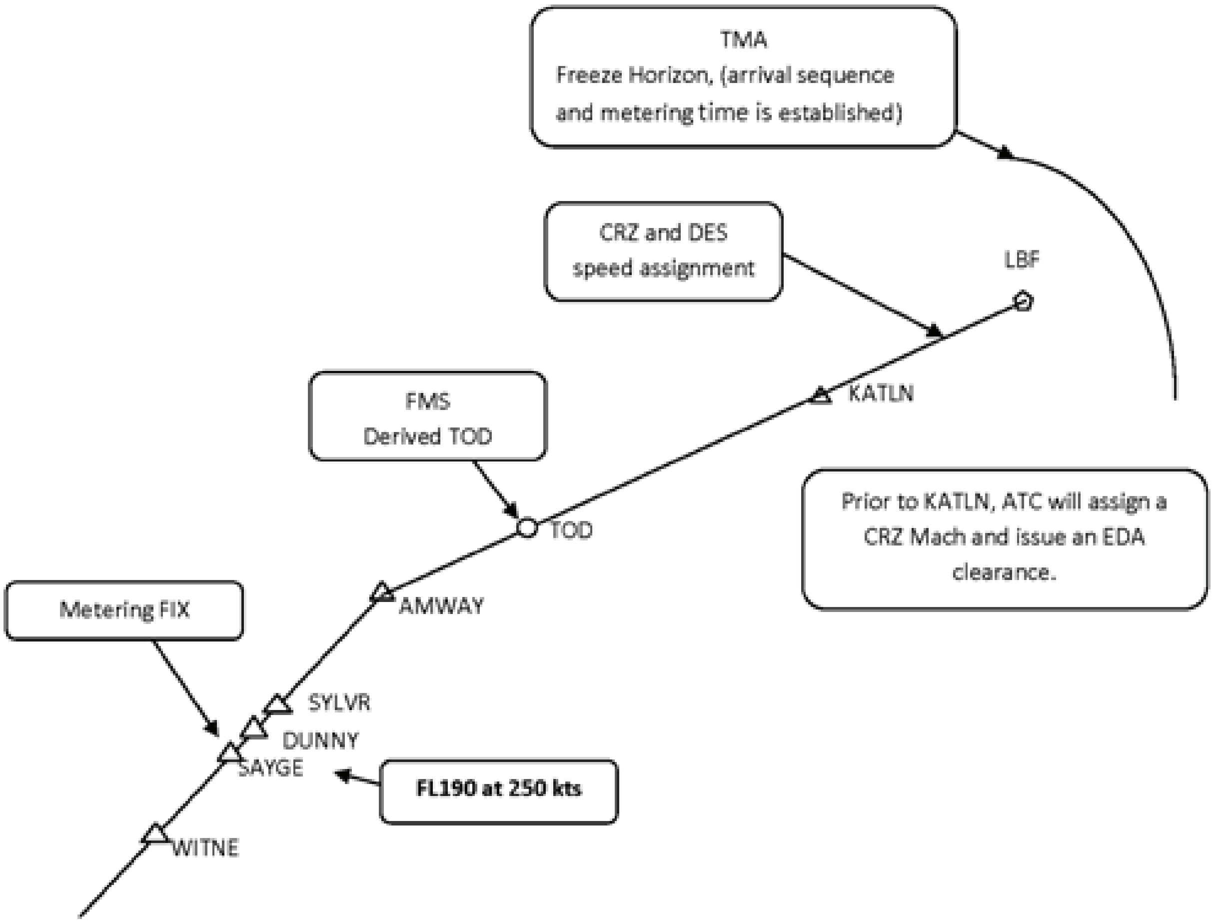
A.3. Procedures and Expectations

- ATC will assign an EDA Clearance unless the crew responds back that they are "unable."
- Upon receiving the EDA clearance, the crew will record the CRZ Mach and CRZ Mach/descent IAS on the EDA Data Collection Form.
- Crews will enter descent winds for CRZ, FL340, FL300, FL240, and FL180 on the EDA Data Collection Form. Wind information will be obtained from the FMS as shown on the multifunction display (MFD) at the altitude listed. Note "NA" for any altitude above current CRZ altitude.
- Maintain CRZ altitude until reaching TOD as calculated by the FMS based on the EDA clearance received. Then set the Flight Control Panel (FCP)**:** Preselect "ALT" to assigned crossing altitude. Enter the crossing altitude and speed, if part of the clearance, in the FMS for the crossing fix. Plan level-off based on winds to ensure crossing the metering fix on speed. Most arrivals have a fix 3 to 8 miles prior to the metering fix. Ensure advisory VNAV is ENABLED. Review the table on the back of the Data Collection Form for best angle based on ground speed and required FPM. If assigned 0.77 M to 300 knots, simulator (SIM) tests have determined that the best angle is 3.4, resulting in minimum use of flight spoilers or thrust. For 0.76 M to 280 knots, the best angle is 3.1, and for 0.74 M to 250 knots, the best angle is 2.8. The angle may be entered in the FMS on the Legs page. There is no need to change the defaults. Enter the angle in the scratchpad and use the Right Line Select Key (RLSK) as required.
- The expectation of ATC is for the flight to begin descent at the FMS-computed TOD. Begin descent and report descent when the FMS initiates TOD. Advise ATC if unable to comply. From SIM tests, it was suggested to start down one dot below the snowflake and set the FPM from the table based on the angle programmed.
- Maintain assigned CRZ Mach until transition to assigned DES IAS. SIM tests found that thrust should be reduced to idle when the transition to IAS is made.
- Crew should use minimal thrust manipulations and/or speed brakes to maintain Mach/IAS tolerances (+/– 0.02 Mach and +/– 10 knots).
- Complete the EDA Data Collection Form, workload permitting.

A.4. Clearance Phraseology Example (Northeast Arrival)

- ATC: The controller may ask you for your Mach speed, which will be used to set up one of four preset combinations: .77/320, .77/300, .76/280, or .74/250.
- Crew: The crew will respond as appropriate to the clearance.
- ATC: SKW 6965, transition to 260 knots in the descent, cross SAYGE at and maintain FL190 at 250 knots.
- Crew: Transition to 260 knots in the descent, cross SAYGE at and maintain FL190 at 250 knots, SKW 6965.
- Crew: (at TOD) SKW 6965 departing FL XXX.
- ATC: SKW 6965, Roger.

A.5. Northeast Arrival Example



A.6. Summary

The last page of this bulletin contains a data tracking form. This form is intuitive, and the crew is requested to complete it as long as it does not interfere with normal flight deck duties. These forms must be given to FLT Operations in DEN (drop boxes) or via COMAT to (name omitted). The forms will be used to evaluate the CRJ using the 3D PAM flight profile. Please pay particular attention to the accuracy and completeness of the data entered on the form.

SkyWest Airlines EDA Data Collection Form

skw r2

Date	Flight # SKW / ATC	Aircraft Type (Circle One)	Tail #	*EDA Clearance CRZ / DES speeds	Meter Fix (Circle One)	
		CRJ 200 CRJ 700 CRJ 900		/	SAYGE RAMMS	LANDR TOMSN

FMS DATA (After EDA Clearance entered in FMS)	Time @ TOD GMT (HH:MM)	Time @ Meter fix GMT (HH:MM)	A/C Wt @ TOD (XXXXX lbs)	A/C Wt. @ Meter fix (XXXXX lbs)
Actual	:	:		

Descent Performance	Angle	GS @ FL250	V/S @ FL250	FF @ FL250	N1 @ FL250

CRZ & DES WINDS	Flight Level	Actual (FMS/MFD) BRG / SPD	Crew EDA Procedure Evaluation 1 – 5 (1 Easy /Intuitive – 5 Difficult / Not Workable)	
CRZ @ TOD	Cruise	/	How hard was it to understand the EDA clearance?	
DES WINDS # 1	FL340	/	How hard was it to fly the EDA?	
DES WINDS # 2	FL300	/	**Circle (Y)es or (N)o**	
DES WINDS # 3	FL240	/	Did the FMS build a TOD for the EDA clearance?	Y N
DES WINDS # 4	FL180	/	Was thrust or speed brakes utilized prior to the meter fix?	Y N

(*EDA – Efficient Descent Advisory)

CREW COMMENTS

EDA Data Collection Form Instructions:

1. Complete first section with data requested. When the EDA is received, complete the CRZ/DES speed section as given in the clearance.
2. Complete the second section as the fixes are crossed. Time is entered as hours and minutes past the hour (GMT). Weight is aircraft current weight (LBS).
3. Complete the third section with the descent angle used and data at FL250 for Ground Speed (GS), Current Vertical Speed (V/S), Total Fuel Flow (FF), and N1.
4. Record wind speed and direction in section four by reading off the MFD. Complete the questions as each phase of the approach is completed.
5. Record any comments that you may have in the crew comments section.
6. The data sheet is no good if it is not given to the appropriate person. Please hand in the completed form.

EDA Checklist

Ground Speed (kts)	–2.8 FPA	–3.1 FPA	–3.4 FPA	–3.8 FPA
600	3000	3300	3600	4000
550	2700	3000	3300	3700
500	2500	2700	3000	3400
450	2200	2500	2700	3000
400	2000	2200	2400	2700
350	1700	1900	2100	2400
300	1500	1600	1800	2000
250	1200	1400	1500	1700

1. EDA Clearance ....Review
2. FCP Setup .... Complete
3. FMS Setup .... Complete
4. Section One of EDA Form.. Complete
5. TOD (Top of Descent) .... Begin descent
6. EDA Data Collection Form..Complete as required in descent
7. Speed..Maintain with minimum use of spoilers or thrust
8. Meter Fix.. Cross on speed and assigned altitude
9. EDA Data Collection Form... Complete and provide to Flight Operations

Appendix B: Anomalies

This section describes the anomalous behavior that affected flights during the field trial. Table 4 summarizes the number of flights identified for each type of anomaly. A flight may have been impacted by multiple anomalies which is why the total anomalies (267) is reported separately from the total unique flights (261) impacted by the anomalies.

Table 4. Number of flights exhibiting anomalous behavior.

Anomaly Type	Flights
B.1. Missing Radar Track Data	6
B.2. Erroneous Radar Track Data on 10/25/2010	12
B.3. Not Targeting Meter-Fix Altitude Constraint	33
B.4. Targets Different Meter-Fix Altitude Than Prediction	5
B.5. Flight Path Angle (FPA) is Not Constant	53
B.6. Flies Different Lateral Path Than Prediction	100
B.7. Prediction Contains Temporary Altitude Level-Off During Descent	12
B.8. Leveled at Correct Meter-Fix Altitude Then Released Early to TRACON	41
B.9. Pilot Report Indicates Interrupted EDA	3
Total Anomalies	267
Total Unique Flights	261

B.1. Missing Radar Track Data

Figure 4 is a vertical profile of SKW6700 on 11/09/2010 showing an example of missing radar track data. The x-axis of the figure is distance along the path where 0 indicates an initial condition approximately 63 nmi from the meter fix, and 63 nmi is the location of the meter fix. The y-axis is the altitude in feet. The missing data starts before the top of descent (TOD) at about 7 nmi on the x-axis, and the radar track does not appear again until approximately two-thirds down the descent segment at about 50 nmi on the x-axis.

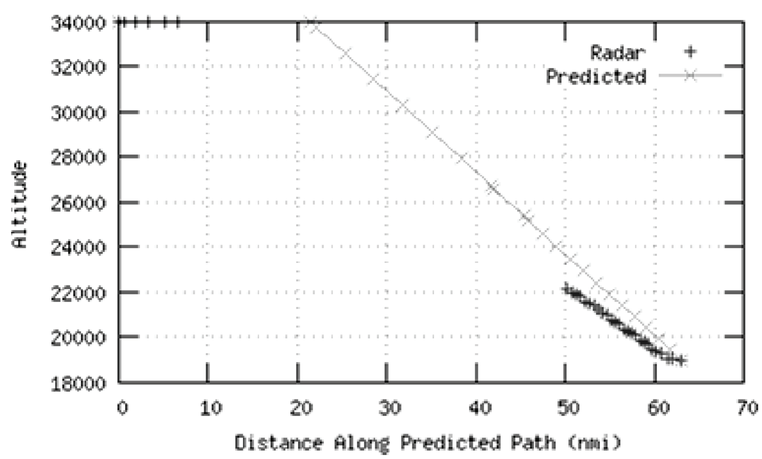


Figure 4. Vertical profile for SKW6700 on 11/09/2010 indicating missing radar track data.

Even though metrics such as arrival-time error could be calculated for these flights with missing radar track data, the flights were excluded because the times associated with the radar tracks were questionable.

B.2. Erroneous Radar Track Data on 10/25/2010

The vertical profile of SKW6136 on 10/25/2010 indicates that the aircraft closely followed both the predicted descent profile and the predicted lateral path. However, SKW6136 arrived to the meter fix approximately 360 seconds (6 minutes) late as shown in Figure 5. The x-axis of Figure 5 is distance along the path, and the y-axis is the corresponding cumulative time.

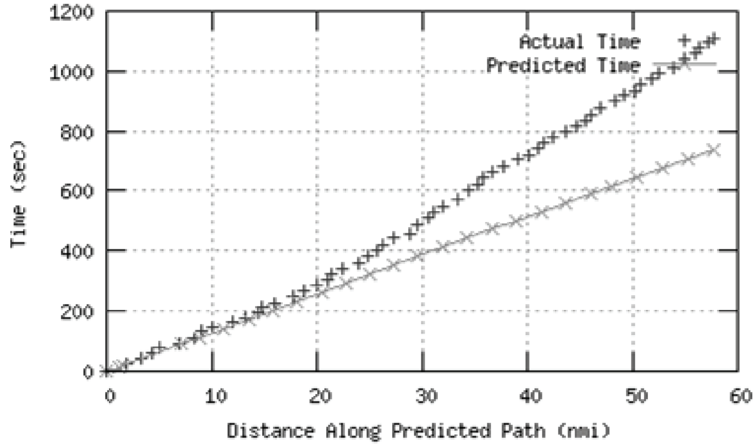


Figure 5. Time profile for SKW6136 on 10/25/2010 indicating the aircraft arrived 360 seconds after predicted time of arrival to meter fix.

Furthermore, even though the predicted speeds were slower than the observed flight speeds, the predicted arrival time at the fix was earlier than the flown arrival time.

The wind magnitudes were determined to be insufficient to produce this arrival-time error. This issue occurred consistently with 10 of the 12 flights on 10/25/2010, so all of the flights on that day were identified as anomalous due an unspecified issue with the actual radar tracks.

B.3. Not Targeting Meter-Fix Altitude Constraint

Flights that did not target the meter-fix altitude constraint were identified as anomalies, because this indicates that the aircraft did not follow the EDA procedure to the meter-fix crossing altitude constraint. An example is shown in Figure 6 where SKW6901 followed the predicted trajectory down to about FL250 while targeting the meter-fix crossing altitude of 17,000 feet. However, SKW6901 changed its FPA below FL250 and no longer targeted 17,000 feet, which indicates that the EDA procedure was interrupted.

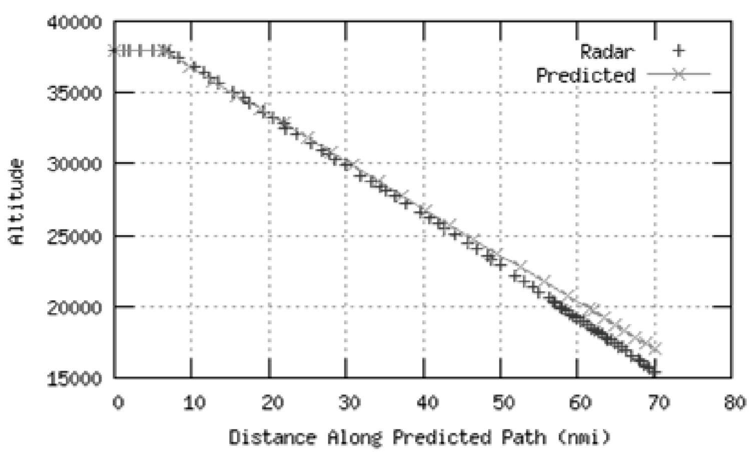


Figure 6. Vertical profile for SKW6901 on 10/31/2010 indicating the aircraft was not targeting the meter-fix altitude constraint.

B.4. Targets Different Meter-Fix Altitude Than Prediction

Figure 8 shows the vertical profile of SKW6896 targeting 17,000 feet as the meter-fix altitude constraint while the prediction uses FL200 as the crossing constraint. This is an example of a case where the prediction and the actual trajectory are targeting different meter-fix altitude constraints. The meter-fix crossing restriction is based on runway configuration and aircraft assignment to a runway within that configuration. This anomaly was due to discrepancies between the CTAS-predicted runway assignment and the assigned runway as flown.

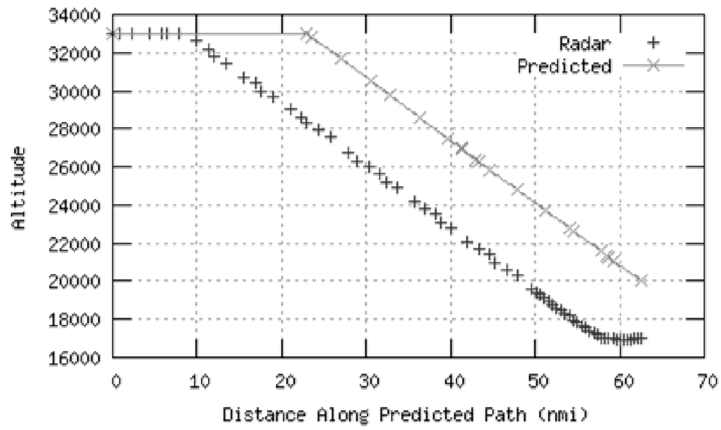


Figure 7. Vertical profile for SKW6896 on 11/10/2010 indicating the aircraft is targeting a different meter-fix altitude (17,000 ft) compared to prediction (FL200).

B.5. FPA is Not Constant

The EDA procedure required aircraft to follow a constant FPA from TOD to the meter-fix altitude constraint. A change in FPA indicates that the EDA procedure was interrupted or otherwise not followed. Such flights are candidates for exclusion. Figure 8 shows an example of initial descent from FL400 to FL350 where there is a temporary level-off, which indicates an interrupted descent. A second FPA is followed from FL350 to FL250, and finally a third FPA is followed from FL250 to the meter-fix altitude constraint.

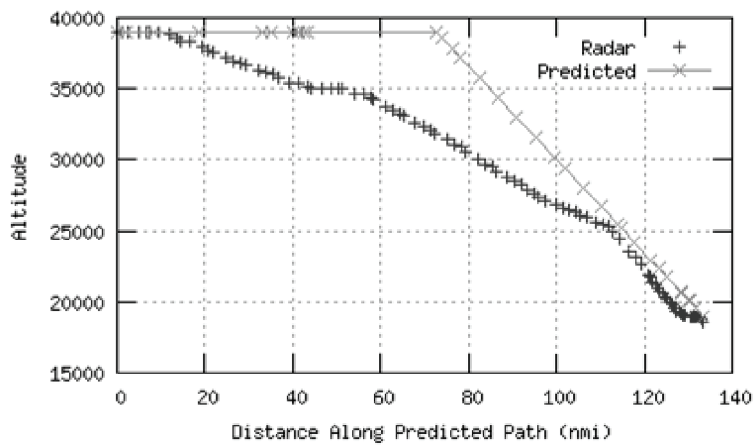


Figure 8. Vertical profile for SKW6762 on 10/31/2010 indicating a level-off and multiple FPAs during descent.

In Figure 9 SKW6590 follows a constant FPA from FL300 to approximately FL220. However, SKW6590 changes FPA below FL220 and adds a deceleration segment at the meter-fix altitude. The pilot had the option of including or not including a deceleration segment at the meter-fix altitude. In order to follow the EDA procedure, the pilot should have made the decision prior to TOD, and selected a TOD and constant FPA that would result in the desired deceleration segment.

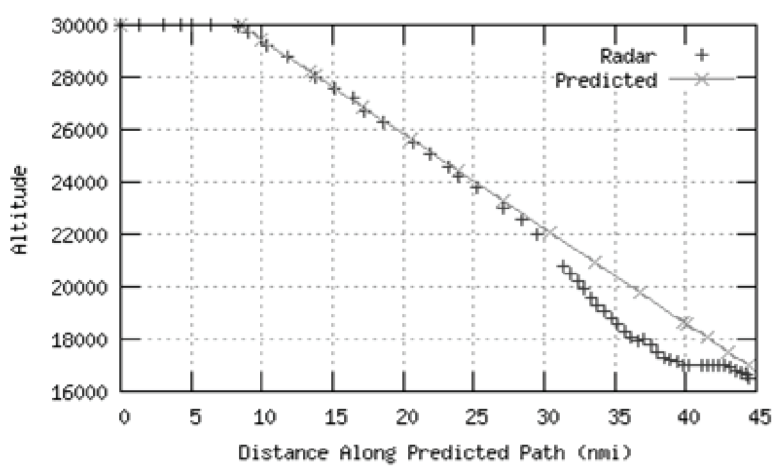


Figure 9. Vertical profile for SKW6590 on 11/02/2010 indicating a change in FPA during descent.

Figure 10 shows an example where the pilot descended early and followed a shallow FPA until the trajectory of SKW7018 intersected with the trajectory corresponding to the EDA clearance with a level-off deceleration segment at the meter-fix altitude. One possible reason for the early descent is that the pilot could have been issued a “descend now” clearance to leave the FL380 altitude at approximately 130 nmi from the meter fix.

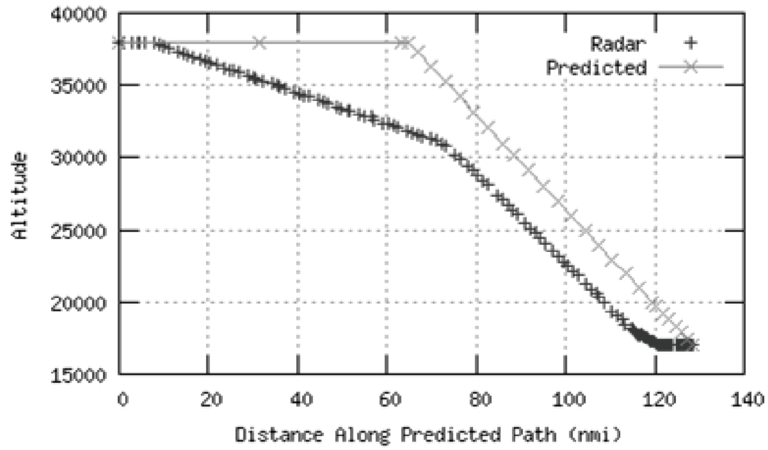


Figure 10. Vertical profile indicating two FPAs during descent.

B.6. Flies Different Lateral Path Than Prediction

Flights with route changes after TOD are anomalies because this indicates an interruption of the EDA procedure. Examples include changes in lateral path near the meter fix, and direct to the meter fix (Figure 11), and vectoring.

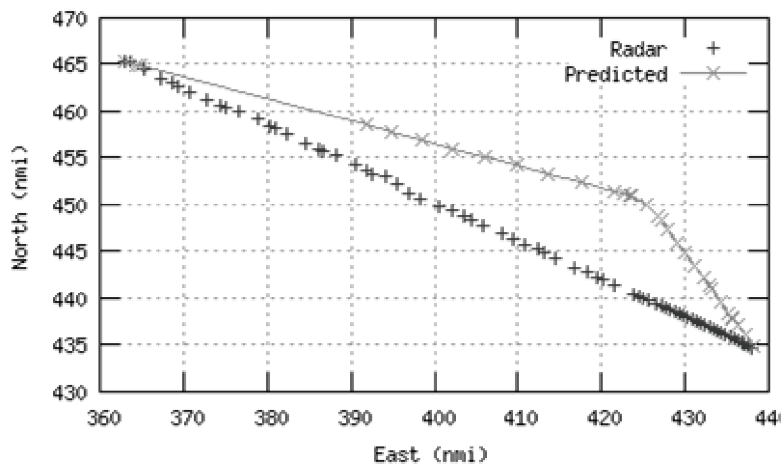


Figure 11. Plan profile for SKW6876 on 11/08/2010 indicating the aircraft follows a more direct route than predicted.

B.7. Prediction Contains Temporary Altitude Level-Off During Descent

All aircraft should follow a constant FPA from TOD down to the meter-fix crossing altitude constraint. Any temporary altitude level-offs between TOD and the meter-fix altitude violates the EDA procedure and should be removed. Figure 12 shows an example where the prediction for SKW6589 contains a temporary altitude level-off in the prediction at FL270.

The level-off was due to a temporary altitude of FL270 issued by the controller prior to TOD and the CTAS initial condition. CTAS generated the prediction based on the information it had at the initial condition, which did not reflect that the controller removed the temporary altitude during descent.

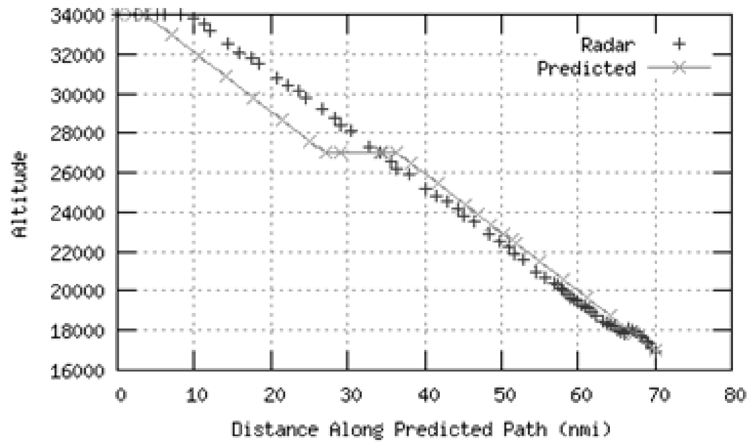


Figure 12. Vertical profile for SKW6589 on 11/03/2010 showing level-off in predicted trajectory during descent.

B.8. Leveled at Correct Meter-Fix Altitude Then Released Early to TRACON

During the flight test, en route controllers were asked not to release aircraft to the TRACON until the aircraft crossed the meter fix. Releasing aircraft to the TRACON is an interruption of the EDA, resulting in invalid arrival-time statistics at the fix. An example of an aircraft that is presumed to have been released early to the TRACON is shown in Figure 13. In this figure, SKW6601 leveled off at the correct meter-fix altitude of 17,000 feet but descended below the meter-fix altitude before crossing the meter fix.

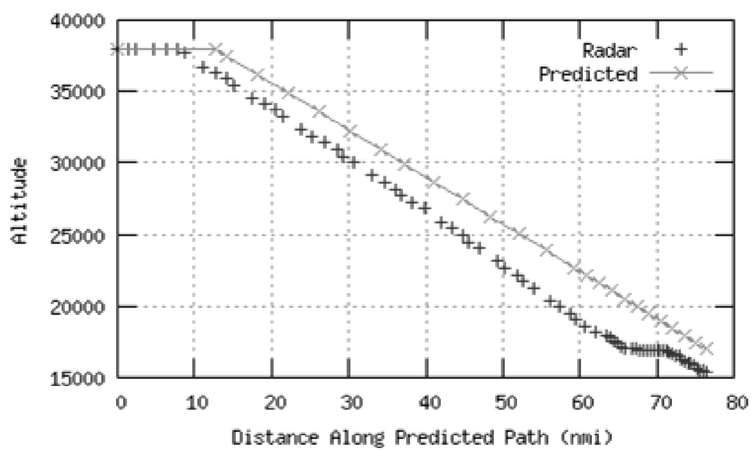


Figure 13. Vertical profile for SKW6601 on 11/02/2010 indicating the aircraft may have been released early to the TRACON.

B.9. Pilot Report Indicates Interrupted EDA

Recall that pilots were asked to fill out the pilot report in Appendix A. If the crew comments' section of this form indicated that the EDA was interrupted, then the flight was classified as an anomaly. Figure 14 shows another example where the SKW6203 crew made the following comment: "EDA was cancelled by approach through FL 210." The corresponding vertical profile for SKW6203 shows a change in FPA at approximately FL 230.

SkyWest Airlines EDA Data Collection Form skw r4

Date	Flight # SKW / ATC	Aircraft Type (Circle One)	Tail #	*EDA Clearance CRZ / DES speeds	Meter Fix (Circle One)
11-3-10	6203	(CRJ 200) CRJ 700 CRJ 900	406sw	.701	(SAYGE) DANDD QUAIL TOMSN LANDR POWDR LARKS RAMMS

FMS DATA ~~(After EDA Clearance entered in FMS)~~	Time @ TOD ~~GMT (HH:MM:SS)~~	Time @ Meter fix ~~GMT (HH:MM:SS)~~	A/C Wt @ TOD ~~(XXXXX lbs)~~	A/C Wt. @ Meter fix ~~(XXXXX lbs)~~
Actual	21 : 38 :	: :	43000	

Descent Performance	Angle	GS @ FL250	V/S @ FL250	FF @ FL250	N1 @ FL250
	3.1	345	2400	706	52%

CRZ & DES WINDS	Flight Level	Actual (FMS/MFD) BRG / SPD	Crew EDA Procedure Evaluation 1 – 5 (1 Easy /Intuitive – 5 Difficult / Not Workable)	
CRZ @ TOD	Cruise	315 / 68	How hard was it to understand the EDA clearance?	
DES WINDS # 1	FL340	NA / NA	How hard was it to fly the EDA?	
DES WINDS # 2	FL300	322 / 62	**Circle (Y)es or (N)o**	
DES WINDS # 3	FL240	305 / 49	Did the FMS build a TOD for the EDA clearance?	Y N
DES WINDS # 4	FL180	/	Was thrust or speed brakes utilized prior to the meter fix?	Y N

(*EDA – Efficient Descent Advisory)

CREW COMMENTS

EDA was cancelled by approach through FL 210

CREW: Place in drop box or COMAT form to Kelvin Hyatt at SLC Hangar	Questions: Contact Kelvin Hyatt x 84518 or 801.694.5991

Figure 14. Pilot report for SKW6203 on 11/3/2010 indicating that the EDA approach was interrupted.

Appendix C: Aggregate Plots

This appendix contains frequency distributions for statistics provided in Table 3 in Section 3.

C.1. Time Error at Meter Fix

Time error is defined as the flown (radar track) time that the aircraft crossed the meter fix minus the time predicted by CTAS for the aircraft to cross the meter fix. Negative values for arrival-time error indicate that the aircraft crossed the meter fix earlier than predicted, while positive values for arrival-time error indicate that the aircraft crossed the meter fix later than predicted. Figures 15 and 16 are the histograms of the arrival-time error for, respectively, all flights, and those flights without anomalies and with a pilot report indicating an FPA according to the procedure. The arrival-time-error histograms show that more aircraft arrived early rather than late to the meter fix.

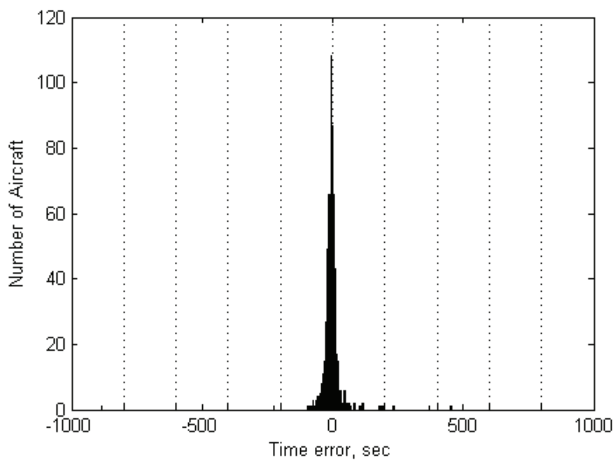


Figure 15. Arrival-time error between flown and CTAS-predicted time crossing meter fix for all flights.

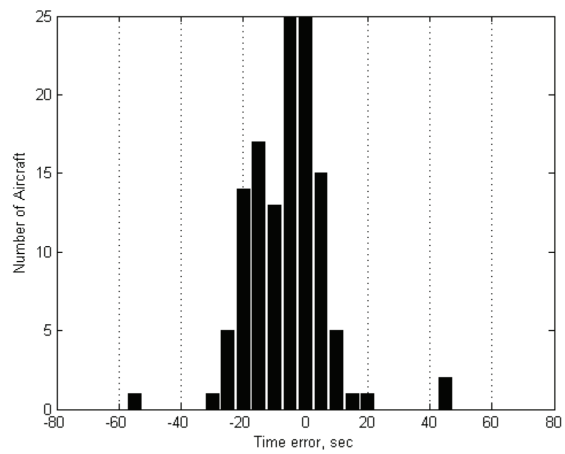


Figure 16. Arrival-time error between flown and CTAS-predicted time crossing meter fix for flights with pilot-reported FPA according to procedure.

C.2. Top-of-Descent Location

The top-of-descent (TOD) location error is the CTAS-predicted distance from the meter fix minus the flown distance from the meter fix where the TOD occurs. Figures 17 and 18 are the histograms of the TOD error for, respectively, all flights, and those flights without anomalies and with a pilot report indicating an FPA according to the procedure.

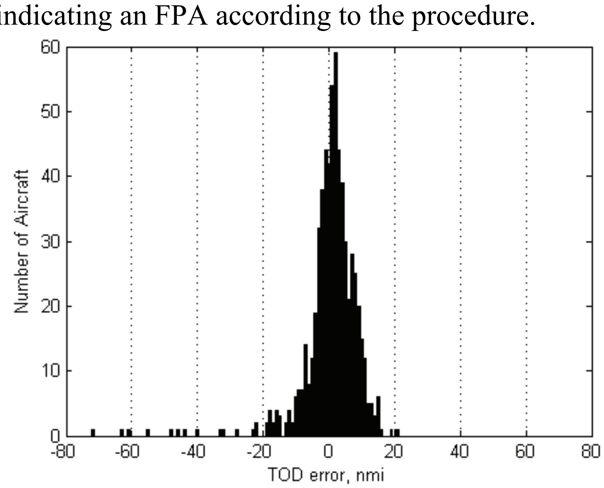


Figure 17. Error predicting TOD location for all flights. Negative values indicate flown distance is further from fix than predicted.

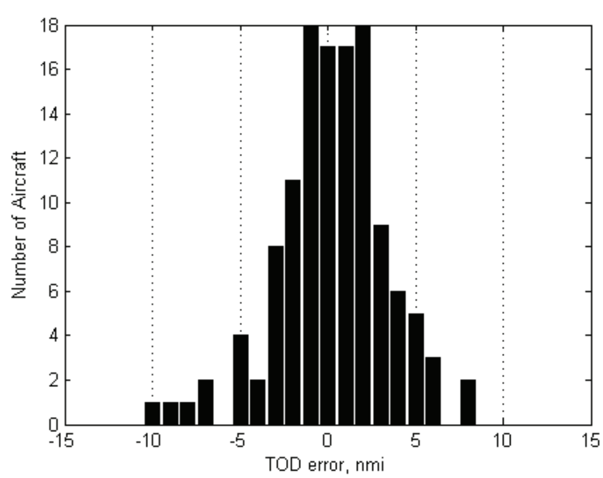


Figure 18. Error predicting TOD location for flights with pilot reported FPA according to procedure.

C.3. Bottom-of-Descent Location

The bottom-of-descent (BOD) location error is the CTAS-predicted distance from the meter fix minus the flown distance from the meter fix where the BOD occurs. Figures 19 and 20 are the histograms of the BOD error for, respectively, all flights, and those flights without anomalies and with a pilot report indicating an FPA according to the procedure.

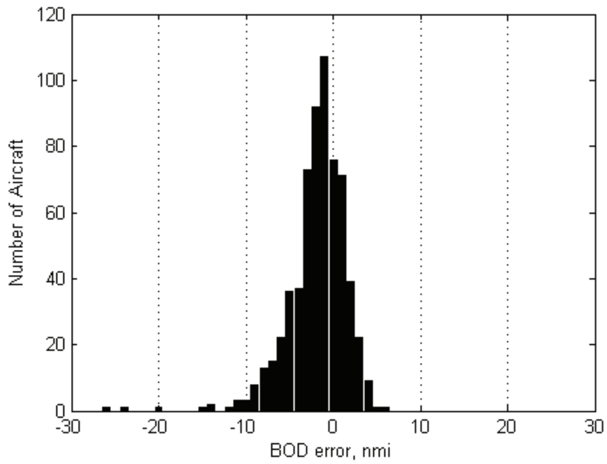


Figure 19. Error predicting BOD location for all flights. Negative values indicate flown distance is further from fix than predicted.

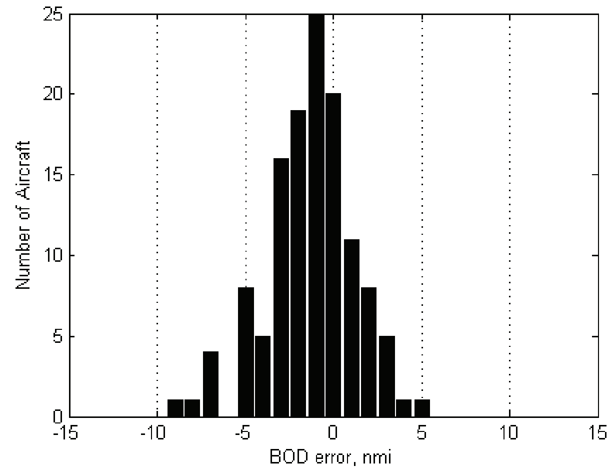


Figure 20. Error predicting BOD location for flights with pilot-reported FPA according to procedure.

C.4. FPA Error

FPA error is the flown FPA minus predicted FPA from 1,000 feet below the TOD to 1,000 feet above the BOD. Figures 21 and 22 are the histograms of the FPA error for, respectively, all flights, and those flights without anomalies and with a pilot report indicating an FPA according to the procedure.

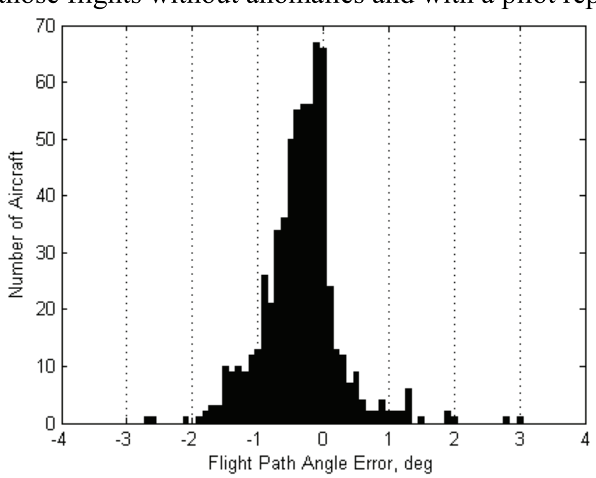


Figure 21. Distribution of FPA error for all flights. Negative values indicate that the aircraft followed a steeper descent than was predicted.

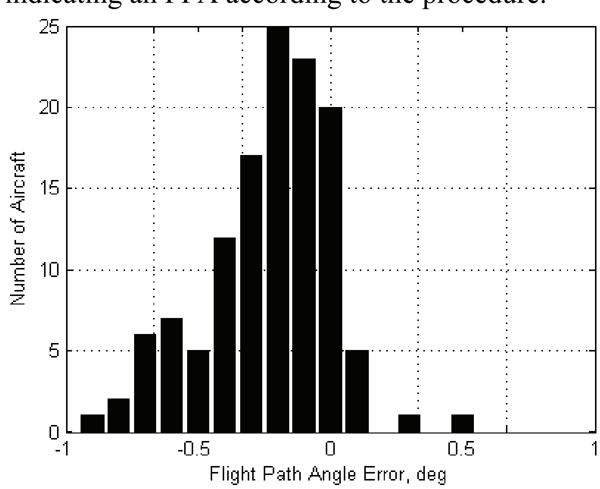


Figure 22. Distribution of FPA error for flights with pilot reports indicating an FPA according to flight test procedure. Negative values indicate that the aircraft followed a steeper descent than was predicted.

C.5. Cross-Track Error

Cross-track error is the lateral offset of the aircraft's flown trajectory from the aircraft's cleared trajectory. A large cross-track error is an indication that the CTAS-predicted trajectory does not reflect the cleared trajectory. These large cross-track errors may be classified as the anomalies described in Appendix B. Figures 23 and 24 are the histograms of the FPA error for, respectively, all flights, and those flights without anomalies and with a pilot report indicating an FPA according to the procedure.

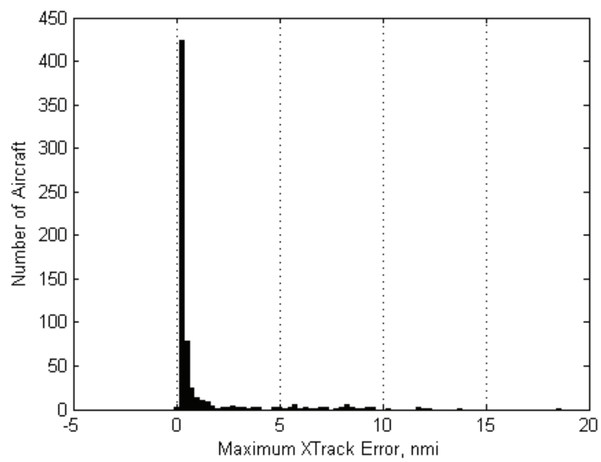


Figure 23. Maximum cross-track error for all flights.

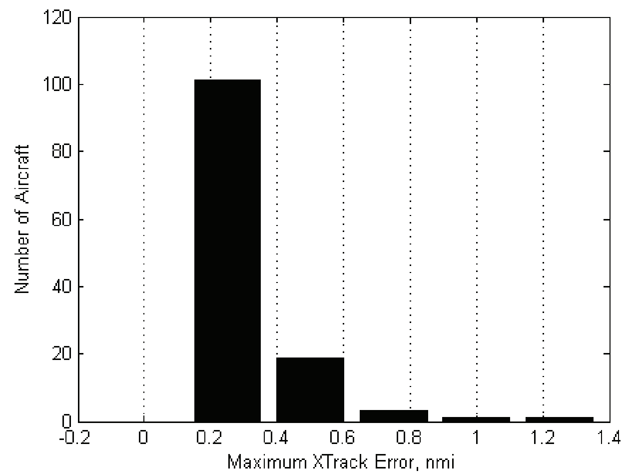


Figure 24. Maximum cross-track error for flights with pilot reports indicating an FPA according to flight test procedure.

C.6. Altitude Error

Figures 25 and 26 show the altitude error between the initial condition (IC) and the meter fix (MF) as the difference between the altitudes along the CTAS-predicted trajectories (dashed line) and the altitudes along the flown trajectories. The mean difference is indicated by triangles with error bars located one standard deviation above and below the mean using the scale in the upper right of the plot. Altitude errors are shown at the initial condition (IC), top of descent (TOD), initial altitude minus 2,000 feet (IA – 2K), initial altitude minus 4,000 feet (IA – 4K), initial altitude minus 6,000 feet (IA – 6K), final altitude plus 4,000 feet (FA + 4K), final altitude plus 2,000 feet (FA + 2K), bottom of descent (BOD), and meter fix (MF).

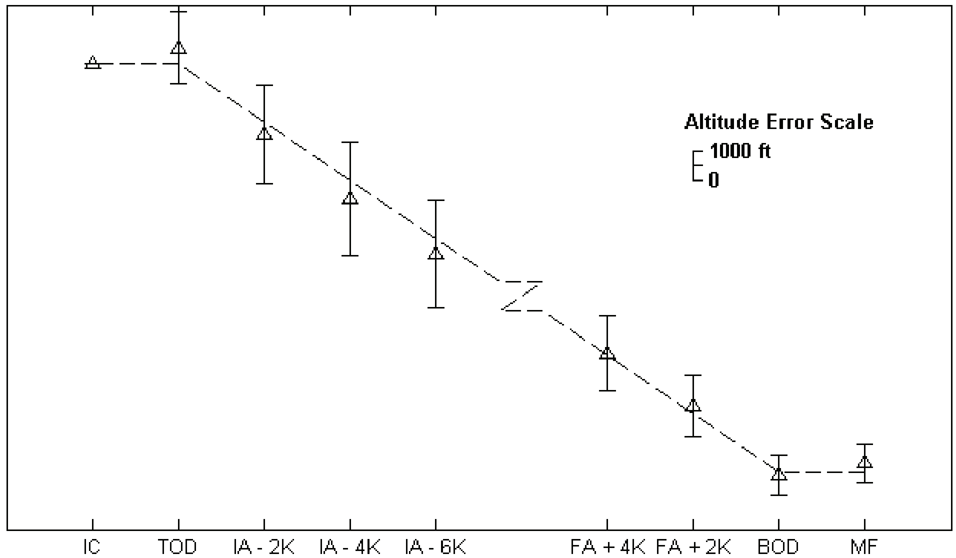


Figure 25. Altitude error for all flights.

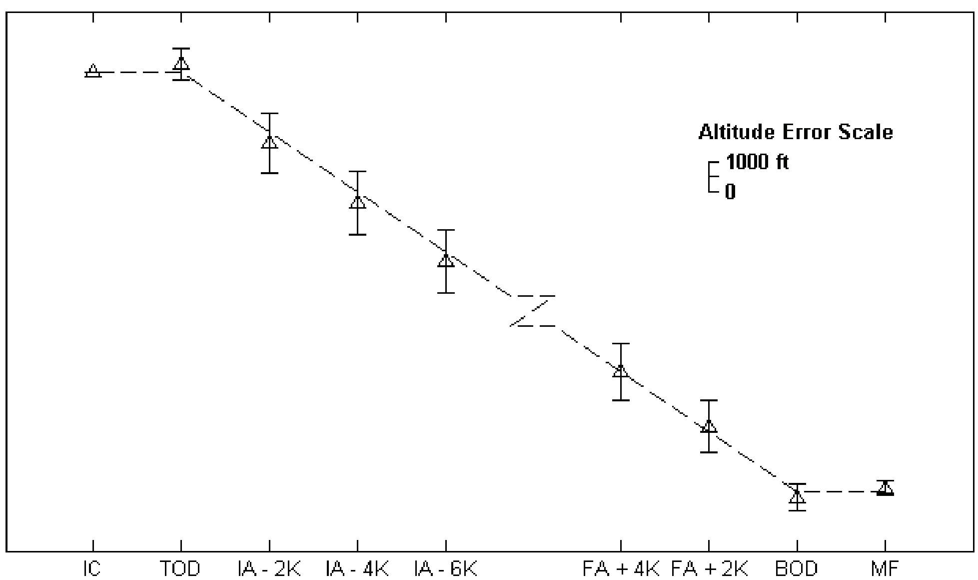


Figure 26. Altitude error for flights with pilot reports indicating an FPA according to flight test procedure.

Appendix D: Typical Differences Between Predicted and Flown Descents

This appendix contains a range of typical differences between the predicted and flown descents for flights without any anomalies listed in Appendix B. Figures 27 and 28 are examples of typical flown descents that are steeper than predicted. Figures 29 and 30 are examples of typical flown descents that are shallower than predicted. Figures 31 and 32 are examples of differences between the flown and predicted behaviors to meet the 250-knot meter-fix crossing speed restriction.

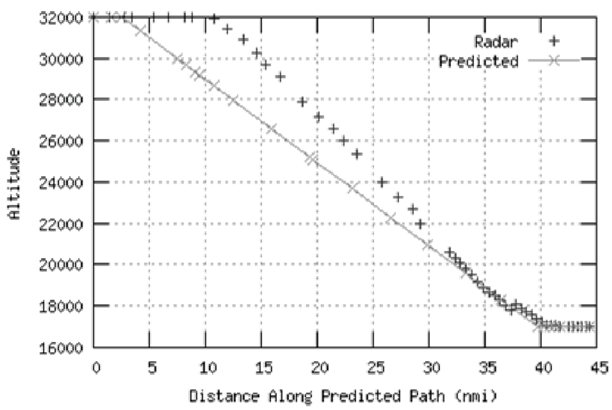


Figure 27. Example flight SKW6447 following a steeper descent (–5.2 deg) than the procedure FPA (–3.8 deg) for a descent CAS of 320 knots. Steeper descent is associated with a flown TOD closer to the meter fix than predicted. Flown and predicted level-off deceleration at the meter fix is similar.

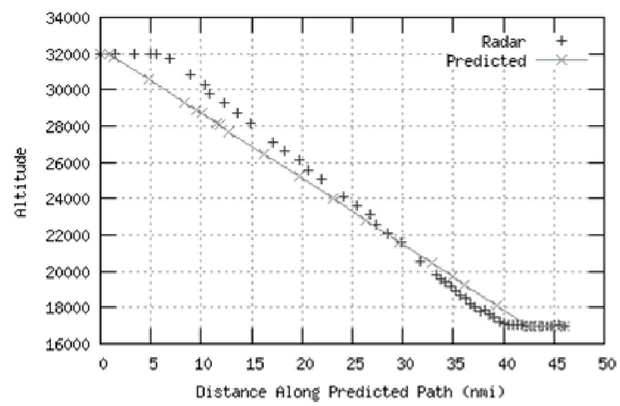


Figure 28. Example flight SKW6627 following a steeper descent (–4.3 deg) than the procedure FPA (–3.4 deg) for a descent CAS of 300 knots. Steeper descent causes flown TOD to be closer to the meter fix than predicted. A longer flown level segment deceleration at the meter fix than predicted causes BOD to be further from the meter fix than predicted.

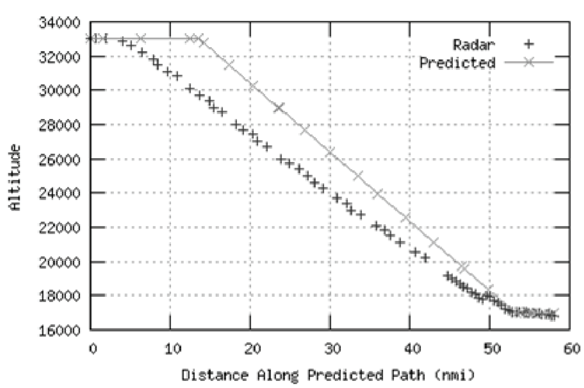


Figure 29. Example flight SKW6129 following a shallower descent (–3.2 deg) than the procedure FPA (–3.8 deg) for a descent CAS of 320 knots. A shallower descent causes the flown TOD to be further from the meter fix than predicted. Flown and predicted level-off deceleration at the meter fix is similar.

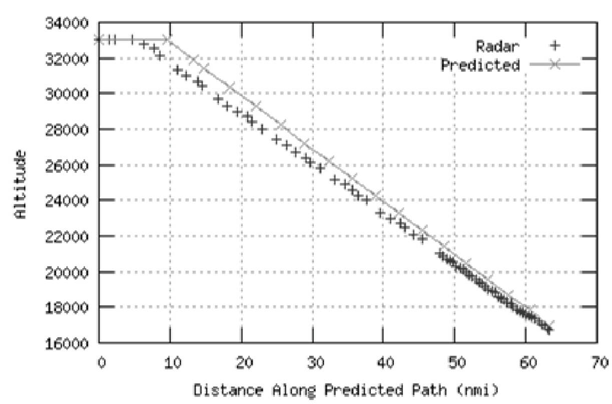


Figure 30. Example flight SKW6698 following a shallower descent (–2.7 deg) than the procedure FPA (–2.8 deg) for a descent CAS of 250 knots. A shallower descent causes the flown TOD to be further from the meter fix than predicted. Because there is no deceleration, the location of the BOD is the same for the flown and predicted descents.

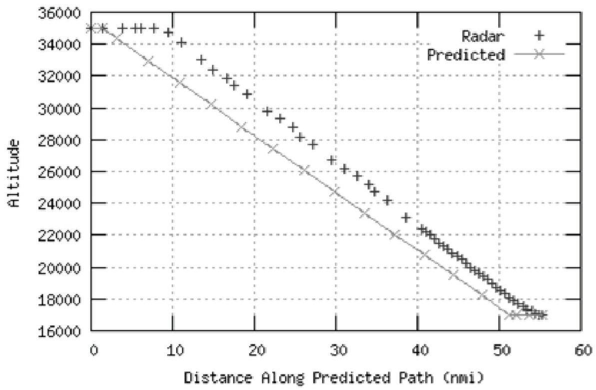


Figure 31. Example flight SKW6130 that decelerates from 300 knots to the 250-knot crossing restriction during descent rather than the predicted behavior of leveling off and decelerating at the meter fix. This behavior causes both the flown TOD and flown BOD to be closer to the meter fix than predicted.

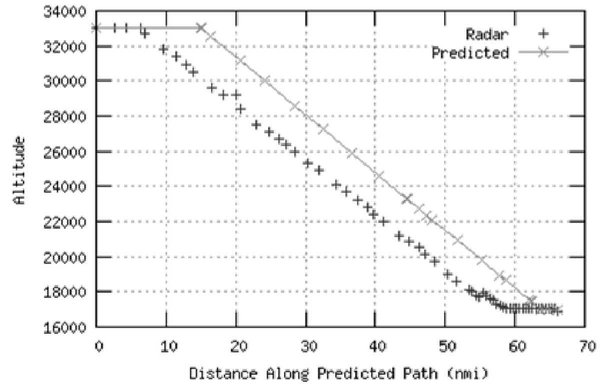


Figure 32. Example flight SKW6399 that decelerates from 280 knots to the 250-knot crossing restriction using a longer level segment deceleration than was predicted. This behavior causes both the flown TOD and flown BOD to be further from the meter fix than predicted.