

Improving Ground-Based Trajectory Prediction through Communication of Aircraft Intent

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The hypothesis that communication of aircraft intent will greatly improve trajectory accuracies as measured by commonly used trajectory prediction metrics is tested by using an anonymous sample flight with an optimized profile descent. The sample flight illustrates two common sources of trajectory prediction uncertainty: Top-Of-Descent uncertainty and an Unknown Lateral Change. The researchers selected two separate trajectory predictors to emulate ground-based trajectory prediction and a trajectory engine for generation of trajectories following aircraft intent communication via the Aircraft Intent Description Language (AIDL). Tests without AIDL produced a root mean square (RMS) of lateral or cross-track error as high as 18 nautical miles, a RMS of vertical error as high as 11,000 feet, and a RMS of time error as high as 70 seconds. With communication via AIDL, these were reduced to 0.3 nautical miles, 170 feet, and 6 seconds.

I. Introduction

In their NextGen Implementation Plan 2009¹, the Federal Aviation Administration (FAA) has identified the next 10 years as "a pivotal time in the history of air transportation, as we begin a transformation that will change the face of aviation." With these words, the FAA has clearly signaled the beginning of the transformation to the Next Generation Air Transportation System (NextGen). The plan cites progress on inter-agency demonstrations, cooperative efforts focused on integrated surveillance and network-enabled operations, headway in transitioning the National Aeronautics and Space Administration's (NASA) air traffic control research to the FAA through new Research Transition Teams, and the National Weather Service's commitment to NextGen Network Enabled Weather. NextGen is moving along and virtually every FAA program is operating in support of its goals.

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Through their extensive interchange with stakeholders and users, the NextGen Implementation Task Force has recognized the need to provide benefit to a wide range of users. "We heard clearly that the Plan must help a broad audience gain a common understanding of NextGen." The message can be extended to include the application of any solutions developed by technical teams, such as the one conducting this study: any solutions developed must have a clear and seamless benefit to users or the solution will never be implemented.

The current implementation plan is focused on equipping or installation of three core avionics capabilities for the midterm (2012-2018): Area Navigation (RNAV) and Required Navigation Performance (RNP), Automatic Dependent Surveillance-Broadcast (ADS-B), and Data Communications. The plan goes into some detail on the subject of communication of aircraft intent...

During flight planning an electronic representation of the operator's intent will be developed. This intent information can be updated as the flight progresses with tactical and strategic information. It will better accommodate operator preferences and optimize resource usage, even to the point of improving scheduling at the destination. The system will provide a full evaluation, including existing limitations and potential limitations, of the intended flight path. Access to flight planning information will be available to authorized users via a secure network and will include a publish/subscribe capability so that users can receive automatic updates when conditions change along the proposed flight path. This will occur both before and after formal filing of a flight plan and includes the time when the flight is active up until the flight is completed and the flight plan closed...If potential conflicts with other aircraft or other constraints, such as weather or homeland security interventions, develop along the path, the NextGen system will identify the problem and provide recommended path trajectory or speed changes to eliminate the conflict.

This is a direct reference to aircraft intent^{2,††} communication similar to that used in this study. It also illustrates an important difference from proposed conflict resolutions in the past. No longer is the ground-based system seen as performing 'what if' scenarios and passing the resolution to the aircraft. The current vision has the operator doing all the negotiating on his own because he has full access to the airspace constraints, thus revealing the potential for allowing an FMS to resolve conflicts on its own.

Similarly, EUROCONTROL has developed the Single European Sky Air Traffic Management Research (SESAR) program. SESAR is aimed at eliminating the fragmented approach to Air Traffic Management and transforming the European Air Traffic Management system to become more efficient, better integrated, more cost-efficient, safer, and environmentally sustainable. The concept of operations proposed by SESAR to achieve these ambitious goals requires an integrated and collaborative system that relies on coordinated, strategic trajectory deconfliction. In this new air traffic management system, the aircraft trajectory becomes the centerpiece of a new set of Trajectory-Based Operations³.

To facilitate reaching their common goals, the FAA, EUROCONTROL, and their commercial partners have established a trend of cooperative research agreements and of standardizing developing technologies. Towards this end, the FAA and the Boeing Company have established a Cooperative Research & Development Agreement (CRDA). The FAA/Boeing CRDA is a five-year collaboration designed to facilitate development in Trajectory-Based Operations. The work done as part of the CRDA is directly applicable to one of the NextGen Implementation Plan 2009 Service Roadmaps; specifically, Initiate Trajectory-Based Operations. The research conducted for this study is the second cooperative publication to come out of this CRDA. This research used the tools and facilities of the Target Generation Facility (TGF) of the FAA William J. Hughes Technical Center (see Konyak and Peters⁴). The communication of the aircraft intent made use of the Aircraft Intent Description Language (AIDL) developed by Boeing Research & Technology Europe (see Gallo & Lopez-Leones⁵).

In the first, a preliminary study published in 2008⁶, the TGF conducted concept demonstration research of AIDL, a promising specification standard. AIDL is a formal language for the unambiguous definition of aircraft trajectories. It is intended as a univocal, rigorous, and standardized manner to interchange aircraft intent information for Air Traffic Management purposes. This follow-up study takes the next logical step by studying the accuracy of trajectory prediction with and without communication of aircraft intent.

II. Experiment Design

It is the duty of ground-based Air Traffic Management to detect and resolve conflicts between aircraft. In the US National Airspace System (NAS), much of that task involves prediction of the aircraft's trajectory using only flight plan data filed with the Host Computer System and the aircraft's existing radar track data. The flight plan filed with the Host Computer System contains only limited information and is dependent on timely and accurate updates from Air Traffic Control. This information gap has given rise to the multitude of trajectory prediction and intent inference

^{††} For the purposes of this study, aircraft intent is as defined in Table 2, page 47 of Mondoloni².

algorithms seen in the literature today. If the track differs significantly from the filed flight plan, the ground-based trajectory predictor becomes little more than a dead-reckoning predictor.

It may be safe to assume that the most accurate source of information about an aircraft's intended trajectory is the aircraft itself; specifically, the Flight Management System (FMS) onboard the aircraft. The FMS has full access to NAS constraints, airline procedures, and aircraft performance capabilities. As an example, if the aircraft is cleared to a certain altitude, the FMS knows the speed and path angle it will use. If an aircraft is vectored to a fix, the FMS knows complete details of the turn. It is possible that if this information (Aircraft Intent) could be communicated to a ground-based Air Traffic Management system, the ambiguity of trajectory prediction could be greatly reduced or removed completely. In a different approach, Wichman, Klooster, et. al. (2008)⁷ showed that communication of the 4DT output from the aircraft's FMS resulted in time of arrival accuracy within seven seconds. In the event that the communicated information is unambiguous (either as a 4DT or as aircraft intent), the task of the ground-based system is changed from a trajectory predictor to a trajectory generator; the ground-based system is no longer "predicting" a path based on ambiguous information, it is re-generating the aircraft's trajectory from unambiguous intent/trajectory information. It follows that conflict-free trajectories are only a step away.

This study takes that step: to show that communication of aircraft intent to a ground-based trajectory predictor greatly improves the predicted trajectory.

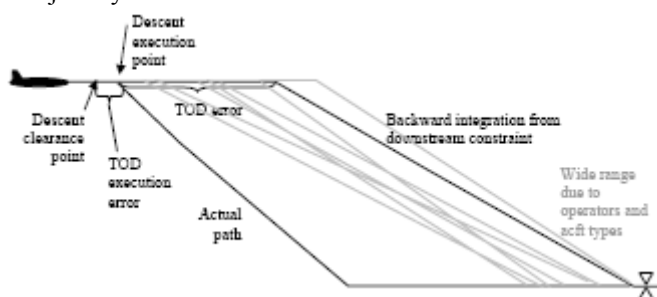


Figure 1: Illustration of top-of-descent error under specific procedure and backward integration prediction. (source: Mondoloni⁸)

In a 2006 study, Mondoloni⁸ identified many aircraft trajectory prediction errors. There are two very common problems noted by experts in the industry of Trajectory-Based Operations. The first is a common source of longitudinal prediction error. It illustrates the ambiguity surrounding climb and descent profiles and the prediction of the bottoms-of-climb and tops-of-descent. Usually, the ground-based system does not have enough information to make an accurate prediction of these points. Mondoloni referred to this as 'Top of Descent Uncertainty' (Figure 1)

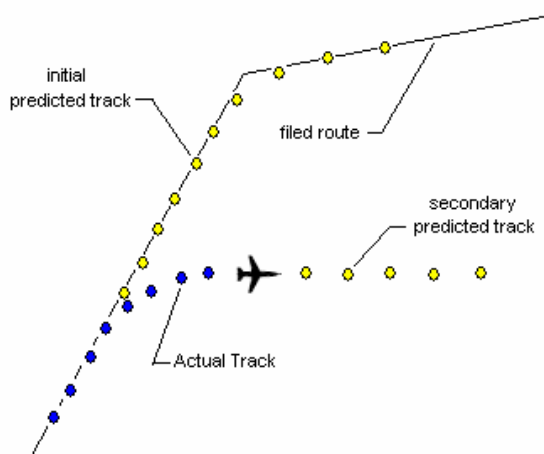


Figure 2: Unknown lateral change as a source of lateral prediction error

The second problem is a common source of lateral prediction error. An example is the case of a locally diverted aircraft in which the diversion details are not entered into the Air Traffic Management system. The ground-based trajectory predictor is unaware of the diversion and continues with predictions along the intended path (Figure 2). Once the ground-based trajectory predictor realizes the filed flight plan is no longer being followed, it is forced to rely on other methods of path prediction. For a trajectory predictor that relies on dead-reckoning, the problem is exacerbated by an inability to predict the point at which the aircraft will turn back to its filed route. While Mondoloni identified this problem as 'Unknown Lateral and Speed Changes,' the cited document did not analyze it.

The objective of this study was to identify an actual flight in the US NAS that illustrated Top of Descent Uncertainty and Unknown Lateral Changes and to apply aircraft intent communication in an attempt to improve on the uncertainty. Once an

appropriate flight was selected as the candidate for the demonstration, the experiment design was broken down as follows:

- emulate the trajectory prediction of the flight by a ground-based system using conventionally available Conflict Detection and Resolution data and tools,
- use the available flight data to reverse engineer the aircraft intent,
- use the aircraft intent to generate the trajectory, and
- compare the accuracy of the predicted and generated trajectories using standard trajectory predictor metrics.

The researchers expected to show that communication of aircraft intent via a standard like AIDL will greatly improve trajectory prediction accuracy.

III. Supporting Data

The anonymous sample flight used for this study is an Optimized Profile Descent of a Boeing 737-300 into Denver International Airport (KDEN) that contains both of the above identified sources of trajectory prediction uncertainty: Top of Descent Uncertainty and Unknown Lateral Changes. The data for this study includes:

- CMS messages of the track, ATC clearances, and flight plans and their amendments;
- notes from the flight crew containing cruise and descent speeds, fuel weights, wind data as measured by the aircraft, and voice communications, including the verbally cleared path stretch.

In the absence of FMS data, the researchers used the available data to reverse-engineer the complete aircraft intent. The aircraft intent was communicated to the TGF trajectory generator to generate a post-AIDL trajectory.

A. Flight Crew Notes

As the anonymous sample flight was used for data collection for another study (entirely separate from this study), pilots and controllers were aware of the intent well before the flight took place. The pilots made intensive notes of the flight and communication with Air Traffic Control that can be used in reverse-engineering the aircraft intent. These notes include

Table 1. Winds in the descent, as recorded for anonymous flight and as modeled in RUC

Encountered Winds			RUC Winds	
FL	Spd (kts)	Brg (deg)	Spd (kts)	Brg (deg)
340	28	256	24	250
330	--	--	23	248
320	25	260	21	241
310	--	--	18	236
300	12	270	17	233
290	--	--	13	187
280	18	60	12	149
270	24	62	12	115
260	27	61	11	103
250	--	--	10	109
240	19	63	8	125
230	6	72	7	160
220	2	360	7	270
210	10	278	9	256
200	15	310	13	275
190	17	342	20	288

- wind data at 1000 foot increments
- top-of-descent point
- path stretch routing
- notes about wind sheer and pilot reaction to maintain airspeed
- cruise speed
- descent profile
- crossing restriction

The aircraft originated at Cleveland International Airport and entered the Denver Center (ZDV) on an approach to the SAYGE SIX Standard Terminal Arrival Route (STAR) while cruising at 34,000 feet pressure altitude and Mach 0.74. The initial leg of the arrival route was given a path stretch. The SAYGE SIX approach plate is shown in Figure 3. A sketch of the approach with the planned path stretch is shown in Figure 7. The aircraft was required to meet the published restriction at the SAYGE waypoint: 19,000 feet and 250 knots indicated airspeed. As indicated on the approach plate, any aircraft on this approach should expect to be vectored upon passing the SAYGE waypoint.

The aircraft was given the path stretch PBD (position-bearing-distance) point approximately 48 nautical miles from the North Platte waypoint (LBF). The PBD for this flight was AMWAY051059^{**}. This PBD comes through in the CMS as a flight plan amendment message,

^{**} This syntax means that the added route point is on a bearing 51 degrees from the AMWAY waypoint at a distance of 59 nautical miles

implying that the air traffic controller entered it into the system. The path stretch and flight plan deviation closely resemble a typical, voice-only path stretch clearance (i.e., not entered into the ground automation). Because of this, the researchers removed the flight plan amendment message from the CMS dataset input to the experiment's trajectory predictors to simulate an Unknown Lateral Change. The objective is to see how well the trajectory predictors can predict the lateral path without knowing the path stretch. This portion of the flight occurs at 34000 feet and Mach 0.74, according to the flight crew notes, although the top-of-descent point is encountered prior to the aircraft completely rejoining the route. The following are also known from the flight crew notes:

- The top-of-descent point was 2.9 nautical miles from AMWAY.
- The descent began at a speed of Mach 0.74
- The nominal descent speed was 280 knots calibrated airspeed
- Pilots were to maintain speed within +/- 10 knots
- Encountered wind at 1000-foot increments in the descent (see Table 1)
- The pilots encountered wind shear between FL300 and FL270 that caused an initial speed deviation of - 12 knots, prompting a throttle increase, then a speed deviation of +14 knots prompting speed brakes
- Fuel available was recorded as 13.0 kilo-pounds at LBF, 12.3 at PBD, and 11.7 at AMWAY.

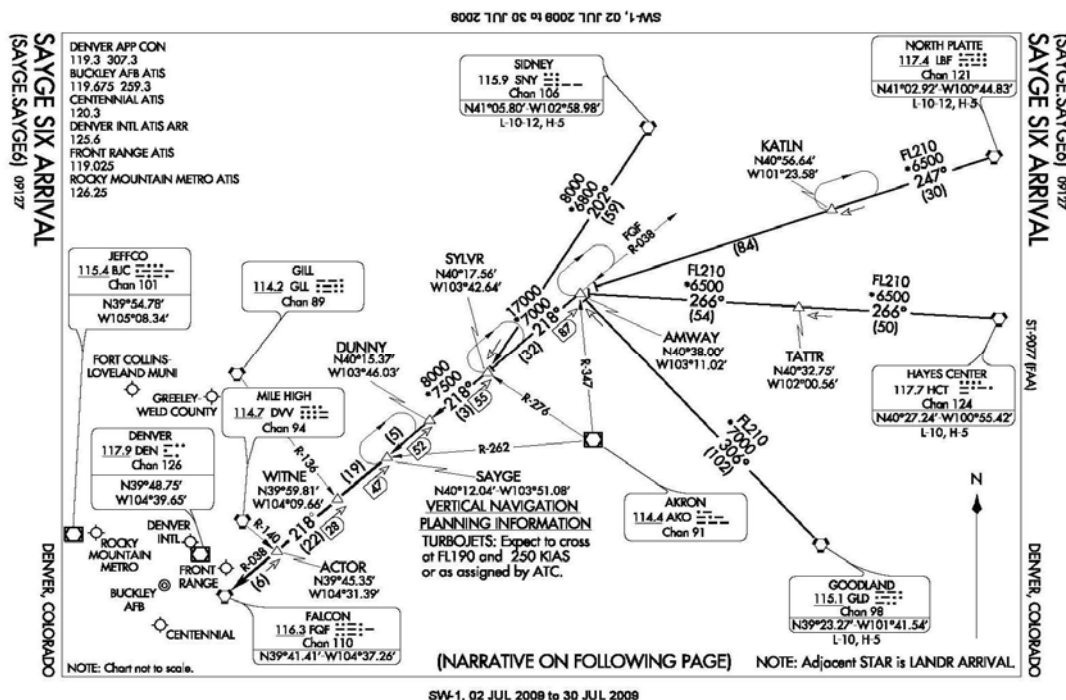


Figure 3. The SAYGE SIX arrival to KDEN. Source: U.S. Terminal Procedures Publication^{§§}.

B. Trajectory Predictor Metrics

Many organizations have established metrics for measuring the accuracy of a predicted trajectory. A commonly used set of metrics was defined by Paglione and Oaks in 2007⁹. These metrics were used to measure the accuracy of the trajectory predictions developed for this work.

Trajectories generated for this study were compared to the actual track data using spatial correlation. Spatial correlation is chosen to accentuate the geometric location of top-of-descent and path stretch point. Each trajectory is illustrated using a map projection and a vertical profile (ie, altitude vs. path distance). Each trajectory is analyzed via plots of cross-track error (lateral path deviation), vertical error (vertical path deviation), and time error (a measure of in-track path deviation). For this study, errors in a state, x , are defined as actual minus predicted.

$$X_{error} = X_{actual} - X_{predicted}$$

^{§§} Available at <http://www.naco.faa.gov/d-tp/0907/09077SAYGE.PDF>

C. Common Message Set (CMS)

The CMS messages are communicated by the Host Centers. There are many different message types to communicate information about aircraft, including flight plan, flight plan amendment, track, and restrictions. A brief yet suitable description of the message types can be found in Paglione and Oaks (2006)¹⁰. The messages of primary concern for this study are the Flight Plan Information and Flight Plan Amendment Information Messages (which provide details of the planned route), Interim Altitude Information Messages (which provide details of altitude clearances and restrictions), and Track Information Messages (which provide actual track data). The reader is referred to the Host Applications Interface Requirements Document¹¹ for greater detail.

Table 2. CMS flight plan and interim altitude messages relevant to flight in the ZDV airspace

GMT (hms)	GMT (sec)	message	notes
22:46:13	81973	flight plan: LBF.SAYGE6.KDEN	
23:00:53	82853	flight plan: LBF..AMWAY.SAYGE6.KDEN	
23:01:41	82901	flight plan: LBF..AMWAY051059..AMWAY.SAYGE6.KDEN	removed for testing
230519	83119	cleared to descend to 19000 feet	

The researchers reduced data from CMS track messages, flight plan messages, flight plan amendment messages, and clearance messages. The track messages were used to generate the actual track for comparison to the trajectories. The remaining message types were used to reverse-engineer the aircraft intent for generation of the trajectories. Table 2 shows the flight plan and interim altitude messages relevant to the ZDV airspace. These are the messages used by this study's trajectory predictors (and by real-time Conflict Detection and Resolution Tools, in general) to develop the lateral and vertical paths. Because the AMWAY waypoint is part of the SAYGE SIX arrival, the second message in the table does not alter the planned route. The third message in the table specifies the path stretch point. This is the message that is removed from the dataset of the trajectory predictors in order to simulate an Unknown Lateral Change.

D. Weather Modeling

The TGF trajectory generator and the URET prototype both used the National Weather Service's Rapid Update Cycle (RUC) 40-km grid weather model¹² (although the implementation of the URET prototype used in this study was not run with weather modeling). This product models wind components and temperature at node points that are approximately 40-km apart and at isobar layers at 25 millibar increments. The researchers recorded the RUC model for the date and time of the test aircraft and used the analysis file representing the 'same hour' model. It may be more appropriate to use forecast models, but a detailed analysis of forecast accuracy is beyond the scope of this work.

The TGF also has the capability to model wind shear layers. Because the pilots reported wind at 1000-foot increment during the descent, the researchers were able to implement those layers into strata for a separate simulation. The wind data from the flight crew notes is shown in Table 1 with corresponding values from the RUC model.

IV. Supporting Tools

A. Trajectory Predictors Used in this Study

The researchers selected two separate conflict probes to emulate the ground-based system: the User Request Evaluation Tool (URET) prototype¹³ trajectory predictor and the FAA Hybrid Merge trajectory predictor. URET was developed at MITRE's Center for Advanced Aviation System Development (CAASD) to assist controllers with timely detection and resolution of predicted problems. It has since been deployed and is fully operational at all 20 en route air traffic control facilities. The FAA Hybrid Merge trajectory predictor merges the heuristic algorithms of the URET prototype with a dead-reckoning predictor. It is strictly for laboratory analyses.

The TGF trajectory generator is used to generate the test flight's trajectory from communicated aircraft intent data. The intent data are communicated via AIDL.

As stated above, the URET prototype is used in this study to generate real-time trajectory predictions in the absence of aircraft intent knowledge. It is a common type of trajectory predictor that analyzes existing track data and predicts future track points. It is constantly analyzing tracks to measure the accuracy of its predictions. As a supplement, this study will compare trajectories from an FAA Hybrid Merge trajectory predictor that combines a

subset of the re-capture algorithms of URET with some alternate recapture algorithms. It includes a dead-reckoning prediction algorithm that is used when an aircraft is off its filed route and does not appear to be attempting to rejoin. The FAA Hybrid Merge trajectory predictor exists solely as a research tool. It was first introduced in Ryan and Paglione¹⁴.

The TGF tool is more of a trajectory engine than a trajectory predictor. It generates trajectories based entirely on flight plans and assumed flight conditions. The TGF trajectory generator is capable of accepting aircraft intent via a standard like AIDL. The accuracy of the intent data is left to the intent-generation tool^{***}. The TGF trajectory generator is not set up to compare predictions to track data in real time, as the predictors are. This means the TGF trajectory generator cannot make accuracy adjustments in flight. As such, the URET prototype and FAA Hybrid Merge are better suited for predicting the trajectory in the absence of intent data, while the TGF trajectory generator is better suited for accepting intent data and generating the trajectory.

B. TGF

The TGF Simulator is a real-time air traffic simulator for fixed wing aircraft. It is intended to support Operational Test & Evaluation, Research & Development, and Air Traffic Management procedure development and validation. Some of the latest FAA technologies in Air Traffic Management, including separation procedures, controller displays, data communication technologies, and traffic routing procedures have been tested at the TGF.

The TGF Simulator is a four degree-of-freedom simulator. Because it is concerned primarily with aircraft trajectories, fast-time dynamic aircraft modes (on the scale of seconds) are not needed and are not modeled. This allows for faster computational speeds and an integration time-step on the scale of half a second.

The TGF Simulator is based on kinematics and dynamics of aircraft and uses a linear feedback control system that adjusts throttle and lift coefficient according to an error vector of speed, altitude, and altitude rate. The error vector is a difference of desired and actual values of the output. The desired values are based on commanded inputs from a simulation pilot, which reflect restrictions imposed by Air Traffic Controllers via voice command. For example, an Air Traffic Controller may command an aircraft to “descend and maintain flight level 230.” A simulation pilot would enter the command and the TGF control system would guide the aircraft to the desired value.

Many aircraft dynamic models with a feedback control system, such as the TGF Simulator, use the assumption of linear behavior in the immediate vicinity of a dynamic state. This implies that dynamic response (e.g., speed, altitude, and bank angle changes) to a control input (e.g., throttle, stick, and even wind gusts) in the vicinity of an equilibrium point (e.g., constant calibrated airspeed climb) can be very closely modeled with linear behavior. Unfortunately, the linear model does not allow large error vectors because they lead to extreme control maneuvers. In response, TGF developers created regions within an aircraft’s flight envelope in which the assumption of linear behavior remains reasonably accurate. The TGF Simulator currently divides an aircraft’s flight envelope into 16 regions and simulated pilot logic (e.g., a maneuver) is applied to guide the aircraft between regions until the desired state is reached. The reader is referred to Peters & Konyak⁴ for details of the TGF Simulator. The TGF trajectory generator used for this study was a simplified version of the TGF simulator that contains an identical dynamic implementation.

C. AIDL

AIDL was developed based on a framework that was identified by COURAGE Consortium. Under the EUROCONTROL-sponsored COURAGE initiative,¹⁵ the team studied and found many similarities in representing aircraft intent, based on which developed a meta-model that generalized the different aircraft intent description methods into a formal rigorous framework. This common framework, with a structure of a formal language, formed the basis for the Aircraft Intent Description Language (AIDL) so it can serve as a common format for the exchange of aircraft intent information between dissimilar trajectory predictors, and to achieve trajectory synchronization in the context of Trajectory-Based Operations.

If the aircraft intent is to be synchronized across different automated Decision Support Tools, it must first be expressed in a common format and then shared via the appropriate communication infrastructure. In general, each trajectory predictor accepts aircraft intent information expressed in a different format, tailored to its requirements. Fortunately, many similarities exist among the different ways of expressing aircraft intent, as they are all different ways of representing the same physical concept. The AIDL has been developed as an aircraft intent metamodel based on these similarities, has the structure of a formal language, and can serve as a “lingua franca” for the exchange of aircraft intent information between heterogeneous trajectory predictors.

^{***} It should be noted that intent generation for this study was accomplished manually.

As all formal languages, the AIDL is based on an alphabet and a grammar. The alphabet is a set of symbols with which the language strings or words are composed. In the case of the AIDL, these symbols are known as instructions, and represent the minimal indivisible pieces of information that capture basic commands, guidance modes, and control inputs at the disposal of the pilot or FMS to direct the aircraft behavior. Each instruction closes a degree of freedom in the equations of motion. They can be seen as the minimal indivisible pieces of information regarding the operation of the aircraft that are meaningful to the TE. The instructions must have a mathematical definition that is compatible with the equations of motion employed by the TE.

The grammar comprises the set of rules according to which the symbols of the alphabet can be concatenated into strings belonging to that formal language. In the case of the AIDL, the grammar indicates how the instructions can be combined into valid sequences of aircraft intent. It contains rules governing how to combine instructions both sequentially (instructions with contiguous, non overlapping execution intervals) and simultaneously (instructions with overlapping action intervals). A valid aircraft intent sequence is that which derives into a well posed mathematical problem that, when integrated, results in a unique trajectory. The AIDL grammar rules are based on the instructions features, and are necessary to ensure that the resulting aircraft intent defines the trajectory to be computed in an unambiguous manner and according to the model of the aircraft motion upon which the TE relies.

The AIDL is provided as input to a trajectory engine (TE) in order to unambiguously specify how the aircraft is to be operated during the time interval for which a computed trajectory is required. The TE is responsible for carrying out the trajectory computation process, which consists of generating the trajectory that results from a given aircraft intent. In general, a computed trajectory consists of a series of discrete states describing the time evolution of different aspects of the aircraft motion. The trajectory computation process is based on the integration of a set of equations describing the aircraft motion. The TE relies on a series of resolution strategies and numerical recipes to integrate those equations into a trajectory. In addition, a set of underlying models are also required to support the integration, such as the aircraft performance and weather models.

An instance of aircraft intent is given by a set of instructions combined in the appropriate manner so that the operation of the aircraft is unambiguously defined. Given an instance of aircraft intent as input, the TE computes a unique aircraft trajectory. In other words, the result of integrating the equations of motion used by the TE in conjunction with the mathematical formulation of the instructions contained in the instance of aircraft intent at hand is a unique aircraft trajectory.

The AIDL instructions can be divided into five groups according to the mode in which they influence the aircraft behavior:

- *Set* instructions model target modes that represent the change of a given aspect of the aircraft motion or configuration (path angle, throttle, bank angle, speed brakes, flaps, landing gear) from its initial value towards a target value; this transition is governed by the underlying aircraft performance model as they can not be modeled by means of the equations of motion.
- *Law* instructions model advanced modes of guiding and controlling an aircraft. These flight commands control any given aspect of the aircraft motion (speed, horizontal speed, energy, vertical speed, path angle, altitude, throttle, bank angle, bearing, speed brakes) that can be measured by the aircraft systems, and do so according with specific functions programmed in the FMS or selected by the pilot. The aircraft guidance systems (LNAV and VNAV modes) or the pilot, with cues from the flight instruments, are in charge of continuously adjusting the position of the control surfaces, throttle, and configuration elements to ensure that the desired law is followed according with a certain guiding logic. This logic is embedded in the design of the FMS and the training and experience of the pilot.
- *Hold* instructions model the basic modes of guiding or controlling an aircraft or setting its configuration. These basic modes act as simplified law modes, in which once captured, the desired motion or configuration aspect is maintained constant by the coordinated action of the aircraft control and configuration settings. Any aspect capable of being measured by the aircraft systems or obtained from it (speed, horizontal speed, energy, vertical speed, path angle, altitude, throttle, bank angle, bearing, flaps, speed brakes, landing gear) can in principle be the subject of a hold instruction.
- *Open Loop* instructions model a flight command issued by the pilot that acts directly over the controls (path angle - elevator, throttle, bank angle - ailerons and rudder, speed brakes) at his disposal. Hence, they do not depend on the state variables, just the time.
- *Track* instructions model advanced modes of guiding an aircraft along a predefined track. They specify the bi dimensional (horizontal projection) or tri dimensional geometry of the aircraft trajectory, which the aircraft is required to follow. These instructions do not depend explicitly on time and just contain geometric aspects of the trajectory.

The AIDL described above is a formal language to unambiguously define aircraft trajectories, and can thus be employed as a common format to synchronize different applications that employ aircraft trajectories. The following section describes how AIDL can be employed to act as the input for the TGF.

V. Development of Experiment Hypotheses

When an aircraft is vectored off its filed route via controller voice command only, ground-based trajectory prediction programs have no way of knowing the change. This situation is illustrated in Figure 5. While the aircraft is flying along its filed route, a ground-based trajectory predictor is able to maintain an accurate prediction (as shown in Figure 5 prior to the LBF waypoint). Once the aircraft is vectored off its route, the lateral accuracy of trajectory predictor begins to degrade. Because the trajectory predictor must allow for normal navigation error, it cannot immediately assume the aircraft has been vectored off its route. The URET prototype will not recognize a flight plan deviation until the lateral error approaches 2.5 nautical miles. This is illustrated with a URET conformance box in Figure 5. A detailed diagram of the URET Conformance Bounds is shown in Figure 4. Degradation of lateral accuracy will result in an increase in cross-track error. This leads to the initial hypothesis of this study: (1) if the aircraft communicates to the ground-based trajectory predictor that it has been vectored off route, the cross-track error is greatly reduced.

The second problem trajectory predictors have related to an Unknown Lateral Change is an inability to accurately predict the turn to merge back with the filed route. Many trajectory predictors have complex algorithms for predicting the turn point to merge back with the route, but accuracy varies. The URET prototype typically predicts turn-back within about 1 minute, an expectedly premature estimate, prompting a new trajectory with another one-minute turn-back. The FAA Hybrid Merge trajectory predictor typically defaults to dead-reckoning. This is illustrated in Figure 6. In most cases, the aircraft itself does not know, and so two additional test hypotheses are identified: (2) If the aircraft communicates to the ground-based trajectory predictor when it is sent back to the route, cross-track error is reduced; and (3) If the aircraft knows the turn back point even before the vector-off-route occurs, cross-track error is further reduced.

Regarding the top-of-descent point, any aircraft equipped with a 4D-capable FMS knows the top-of-descent. The Host Computer System messages, while they can be quite accurate with lateral route information, can be poor

URET Detects Conflicts Via Conformance Bounds

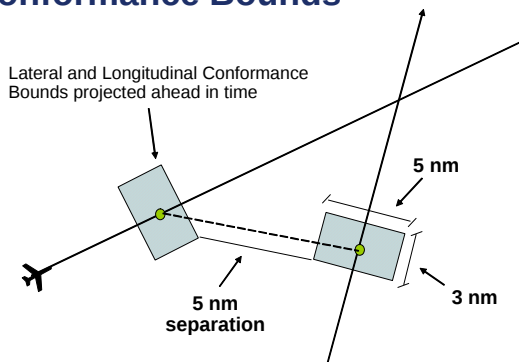


Figure 4. URET Conformance Bounds.
Source: Ref. 13

estimators of the flight's vertical profile. A trajectory predictor that uses only Host Computer System data to predict the vertical path will find gross errors with the actual path. This was illustrated above in Figure 1. The vertical error, speed error, and time error will all increase. The URET vertical conformance bounds present similarly to the lateral conformance bounds. The value varies with configuration and flight level, but is in the vicinity of 1000 feet¹³. A trajectory predictor can use aircraft performance data and NAS constraints to improve the prediction, but accurate prediction of the top-of-descent is still difficult to obtain. But the FMS is the most accurate trajectory predictor for the given aircraft, so if the aircraft communicated this point to the ground-based predictor, trajectory prediction accuracy is greatly improved. This leads to the fourth hypothesis: (4) If the aircraft can communicate the top-of-descent to the ground-based trajectory predictor then time error, vertical error, and speed error will be reduced.

VI. Extracting Aircraft Intent

In order to make comparisons of trajectory predictions before and after communication of aircraft intent, the aircraft intent needs extraction from the flight data. This section is dedicated to reverse-engineering the aircraft intent model to be used in AIDL communication.

A. Assumptions

It is known from analysis of the track data that the aircraft landed on runway 35R at KDEN. It is safe to assume that, by the OBH waypoint, the aircraft knows it is attempting an idle thrust approach, it knows the path stretch, the

top-of-descent, the cruise speed, the descent speed, and the SAYGE restriction (Figure 3). Because it is very common for an aircraft to know its assigned runway shortly after entering the terminal center, it is assumed this is available for communication. The aircraft already knows the arrival route and its associated restrictions, and an FMS can make assumptions about the arrival route vector, the downwind leg, and the turn to final. It is reasonable to assume that the aircraft will itself predict a vector to 230 degrees upon passing the SAYGE waypoint, a downwind leg four miles offset from runway 35R, a heading opposite the runway heading (ie, 170 degrees) for the downwind leg, and a pair of 90 degree turns to final to meet the localizer at 16 nautical miles before the runway. It is also reasonable to assume, because KDEN is a busy airport that requires careful metering, that the aircraft will need to be at 180 knots indicated airspeed and about 4000 feet AGL (above ground level) at the start of the downwind leg, as well as a descent to 2000 feet AGL upon meeting the localizer.

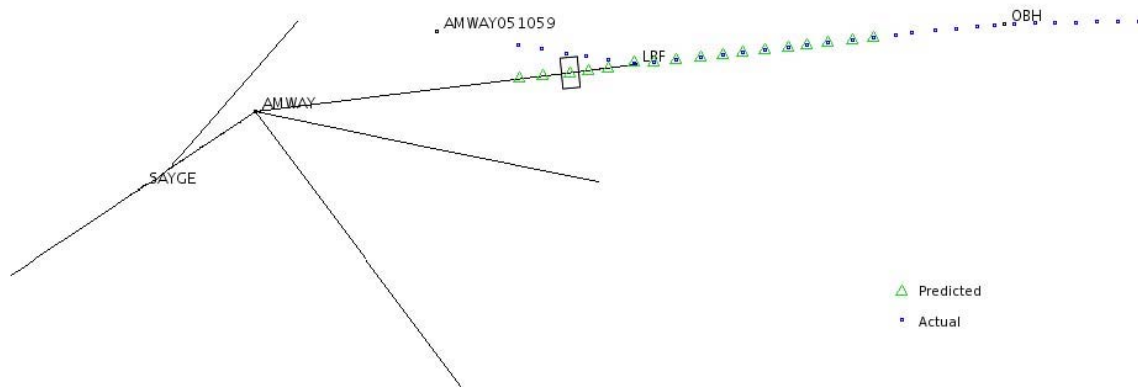


Figure 5. Initial turn from route for controller initiated path stretch. The URET conformance box is shown at the point where the deviation would be identified.

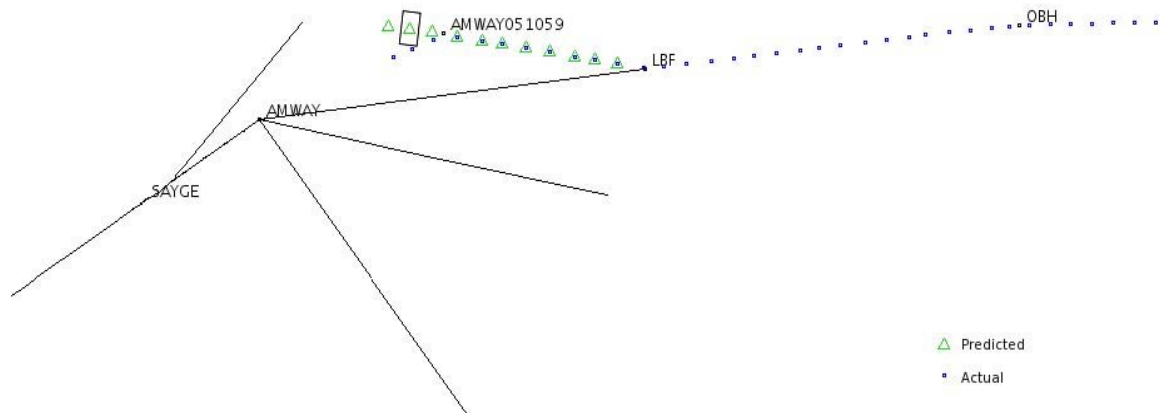


Figure 6. Illustration of turn back to route. The URET conformance box is shown, indicating point at which the turn back is recognized.

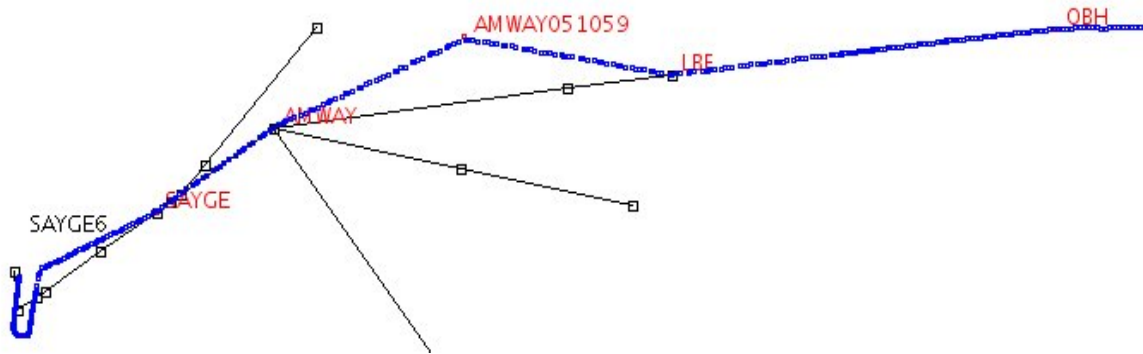


Figure 7. Stereographic projection plot of CMS track of ABC123 with the SAYGE SIX STAR.

B. Analysis of Test Data

Figure 7 shows the complete CMS track data for the test aircraft in the ZDV airspace, along with the SAYGE SIX STAR. One can clearly see the path stretch at the LBF waypoint, the approach vector following the SAYGE waypoint, the downwind leg, and the final approach. Figure 8 is the aircraft's vertical profile. The zero datum corresponds to GMT 22:48:20, or 82100 seconds, 1.4 nautical miles before the OBH waypoint. Figure 9 presents the aircraft's ground speed. Table 3 presents the time and track distance values at several reference points along the test flight's track.

From Figure 8 it is clear to see that the aircraft begins its descent at the 228 nautical mile point. The profile is nearly linear between the top-of-descent and the restriction at the SAYGE waypoint, implying that the pilot was attempting to fly a geometric profile – a common descent method. The bump in the ground speed of Figure 9 shows that the wind shear recorded by the pilot during the descent occurs at about the 250 nautical mile point. The pilot noted a throttle increase and a subsequent speed brakes deployment in reaction to the unanticipated wind shear.

“Speed Performance (+/- Knots): Nominal +/- 2 knots, between FL300 and FL270 due to wind sheer (sic) level you can see the speed deviated -12 knots momentary, I had to prompt the PF to throttle up and maintain +/- 10 knots. The speed deviated +14 knots requiring use of speedbrakes to resume profile speed. The speed deviations were not anticipated by me.”

The pilot's reaction to the wind shear is further implication that he is following a geometric profile and not an airspeed law. The pilot-noted descent speed of 280 knots indicated airspeed was likely a nominal speed for the descent profile built by the aircraft's FMS. A depiction of airspeed data was obtained by using wind models for the descent. Figure 11 shows the indicated airspeed calculated from the ground speed data and two separate wind sources: the associated RUC file and a stratified wind profile built from the pilot-recorded encountered winds. The affect of the wind shear on the indicated airspeed is evident between 20,000 and 25,000 feet. The variation in airspeed during the descent is additional evidence that the aircraft was not attempting to follow a constant indicated airspeed in the descent. It is concluded that the descent law used was idle thrust and geometric path angle.

It should be noted that the pilot-recorded data for the encountered wind is for pressure altitudes 19,000 feet to 34,000 feet. The calculated airspeeds for the encountered wind plot below 19,000 feet in Figure 11 use the 19,000 foot wind. The encountered winds are small at 19,000 feet, resulting in negligible difference between ground speed and true airspeed. Also, there are no data for encountered temperatures and so temperatures of the International Standard Atmosphere were assumed.

Table 3. Test flight time and distance references

GMT (hms)	GMT (sec)	node	Track (nm)
22:48:20	82100	zero datum	0
22:48:32	82112	OBH	1.4
23:05:46	83146	LBF	113
23:14:22	83662	PBD	172
23:22:30	84150	TOD	228
23:23:10	84190	AMWAY	232
29:00:10	84550	SAYGE	272

Figure 10 shows the Mach number in the cruise portion of the flight, calculated from the RUC weather model. It is consistent with the flight crew notes that the aircraft was holding Mach 0.74 during cruise. Figure 12 is a plot of the altitude rate vs. altitude for the test aircraft. Curiously, the data seem to collect at common descent rate points, implying that the pilot is following an altitude rate control law, but, for the initial descent (i.e., between 34,000 and 19,000 feet), the data are scattered enough to be consistent with a geometric path angle control law.

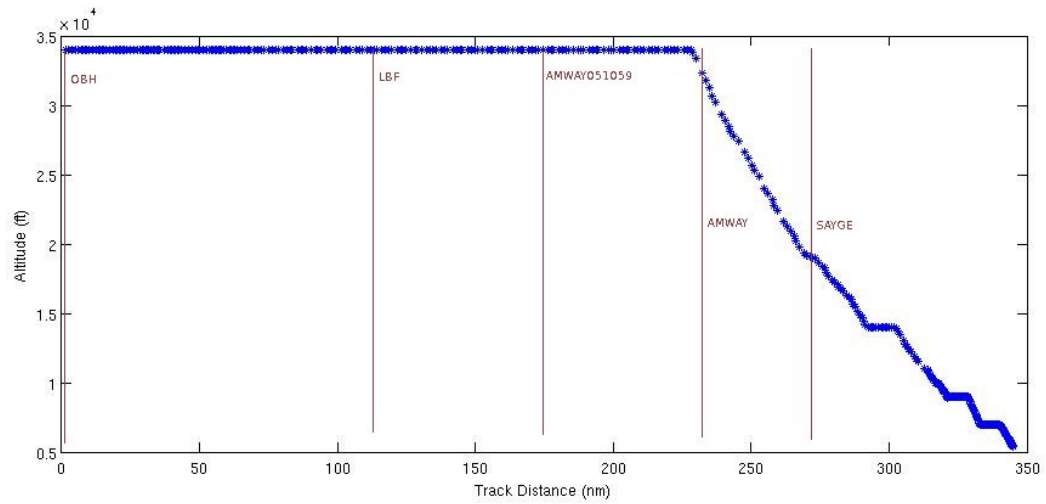


Figure 8. Vertical profile of test aircraft in the ZDC airspace.

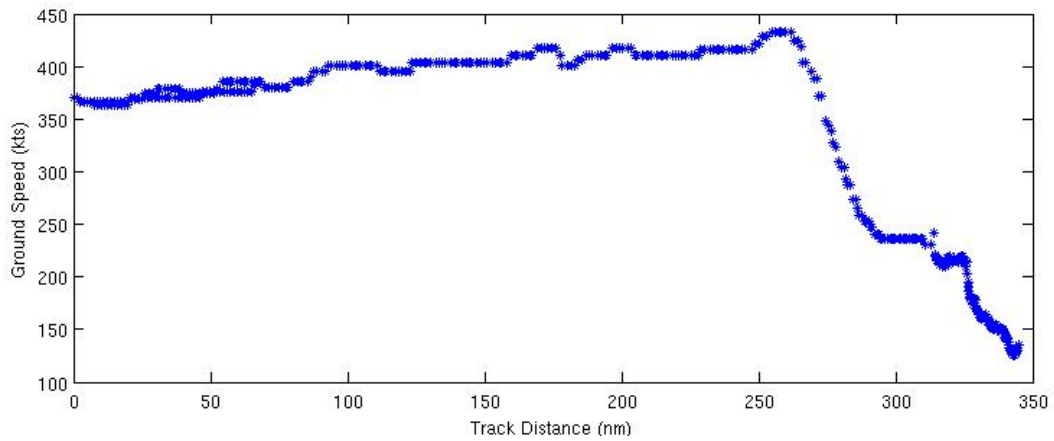


Figure 9. Ground speed profile of test aircraft in the ZDC airspace.

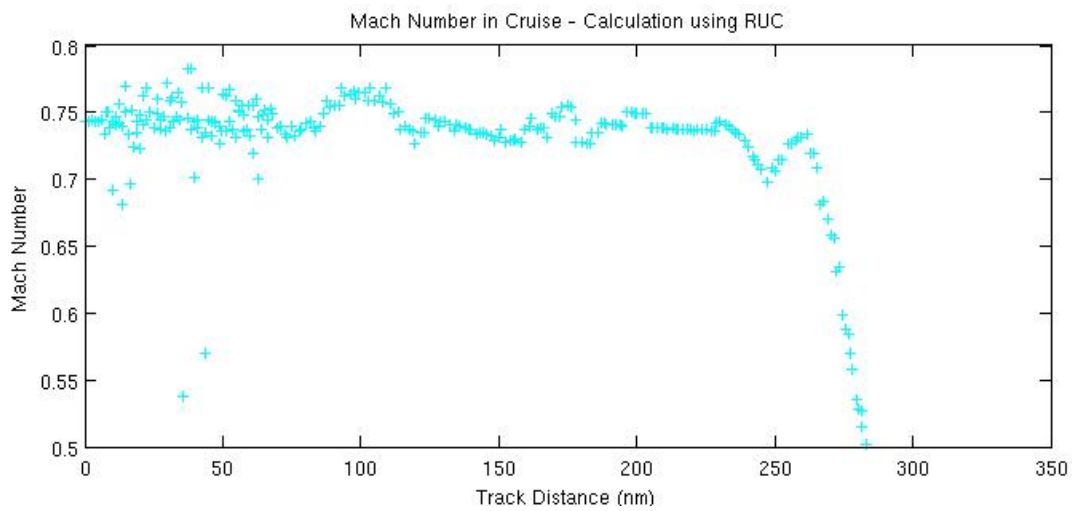


Figure 10. Mach number in cruise calculated from RUC atmospheric model

C. The Aircraft Intent for the Test Aircraft

The aircraft intent of the test aircraft is obtained from analysis of its flight. This section provides a textual description of the aircraft intent, using the threads and terminology of AIDL, as described above. The initial condition (not part of AIDL but required for the integration) shall be: time 22:48:36 GMT, mass 51170 kg, longitude OBH, latitude OBH, altitude 34,000 feet pressure, speed mach 0.74, clean aerodynamics. The mass is estimated from pilot-noted fuel upon reaching the LBF waypoint (13.0 kilo-pounds), the TGF fuel burn model, and from assuming the aircraft is carrying 75% of its payload capacity.

The lateral thread is a succession of route segments (rhumb lines): OBH..AMW051059..AMWAY051004..AMWAY..SAYGE..SAYGE230036..FRONZ152011..FRONZ170010..FRONZ350005.

The first longitudinal thread has the following instructions:

- Hold Mach until reaching AMWAY051004
- Hold geometric path angle connecting AMWAY051004 @ 34000 feet pressure altitude with SAYGE at 19,000 feet pressure altitude until reaching SAYGE
- Hold pressure altitude until reaching 250 knots calibrated airspeed
- Hold geometric path angle of 1.8 degrees until reaching 10,000 feet pressure altitude
- Hold pressure altitude until reaching 170 knots calibrated airspeed
- Hold calibrated airspeed until reaching 7000 feet pressure altitude (2133.6 meters)
- Hold pressure altitude until reaching 140 knots calibrated airspeed (82.31 meters per second)
- Hold calibrated airspeed until reaching FRONZ350005

The second longitudinal thread has the following instructions:

- Hold pressure altitude until reaching AMWAY051004
- Low idle until reaching 9000 feet pressure altitude
- Hold pressure altitude until 23:43:13 GMT
- Low idle until reaching Geometric path angle of -3 [deg] (-0.05236 radians)
- Geometric path angle of -3 [deg] (-0.05236 radians) until FRONZ350005

The speed brakes thread has the following instructions:

- Hold speed brakes (retracted) until AMWAY051004
- Set speed brakes as needed to meet path angle until SAYGE
- Hold speed brakes (retracted) until 23:38:20 GMT
- Hold speed brakes (extended) until 23:41:10 GMT
- Hold speed brakes (retracted) until FRONZ350005

The landing gear thread has the following instructions:

- Hold landing gear (retracted) until reaching 160 knots calibrated airspeed (82.31 meters per second)
- Extend landing gear
- Hold landing gear (extended) until reaching FRONZ350005

The high lift devices thread has the following instructions

- Hold high lift (retracted) until reaching 200 knots calibrated airspeed (102.89 meters per second)
- Extend high lift to 5 deg (position 0.2)
- Hold high lift (5 deg) until reaching 180 knots calibrated airspeed (92.6 meters per second)
- Extend high lift to 15 deg (position 0.4)
- Hold high lift (15 deg) until reaching 160 knots calibrated airspeed (82.31 meters per second)
- Extend high lift to 30 deg (position 0.6)
- Hold high lift (30 deg) until reaching FRONZ 350005

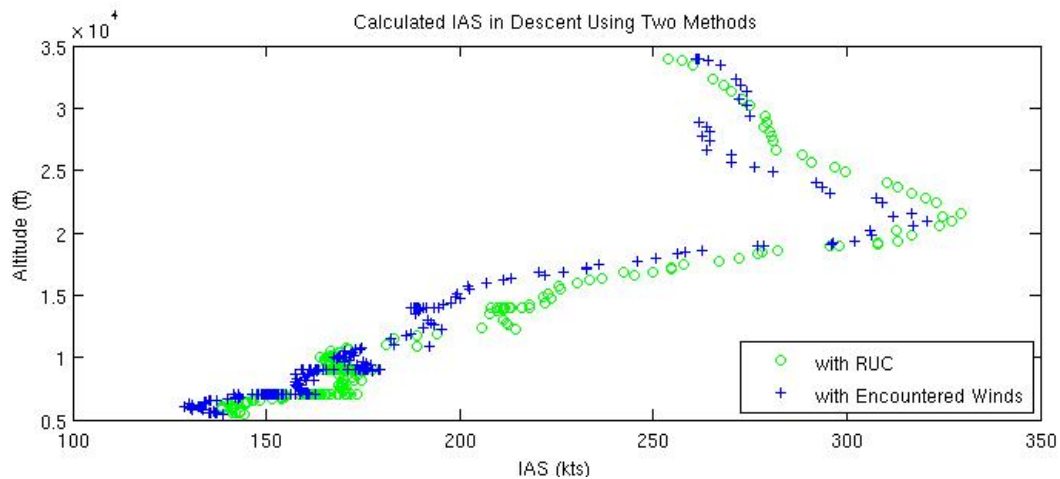


Figure 11. Indicated airspeed in the descent

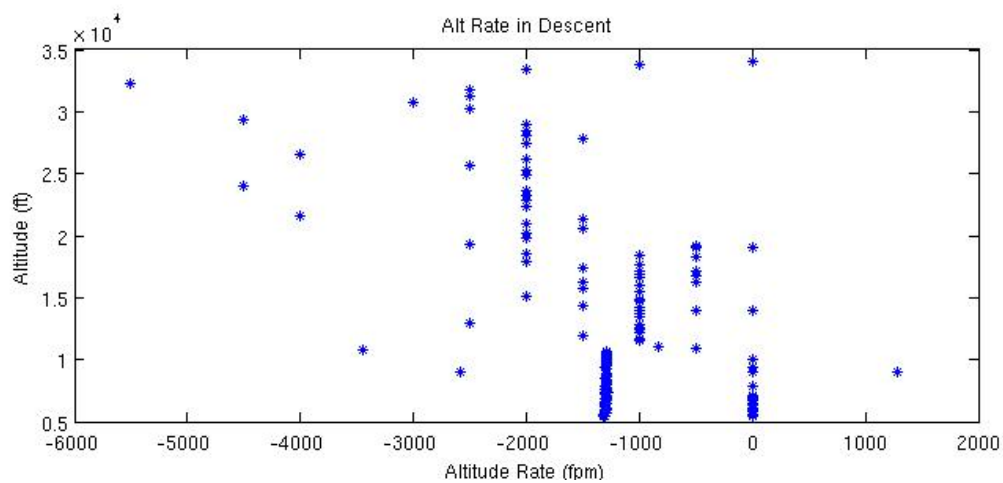


Figure 12. Altitude Rate during the descent

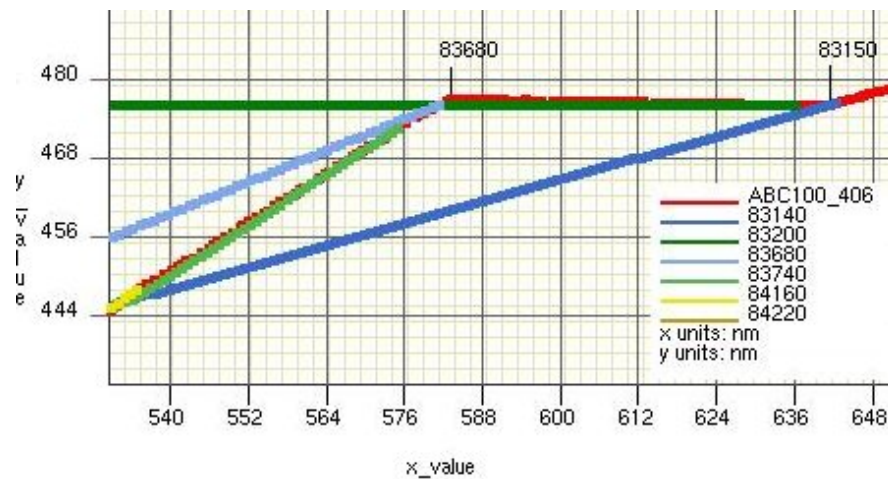


Figure 13. Stereographic plot of FAA Hybrid Merge trajectories generated for path stretch

VII. Results

A. FAA Hybrid Merge Trajectory Predictor

Figure 13 is a stereographic plot of trajectories generated by the FAA Hybrid Merge trajectory predictor for the path stretch phase of the test flight. Figure 14 is a plot of the error metrics for the same trajectories. The FAA Hybrid Merge trajectory predictor generates new trajectories every 60 seconds. For example, in the 17 minutes it takes for the test aircraft to travel between the OBH and LBF waypoints, the FAA Hybrid Merge trajectory predictor generates 17 new trajectories, and during this time, the aircraft is on route (with cross track error less than 0.5 nautical miles) and holding speed and altitude (with negligible vertical error). In the figure, the 5-digit numbers in the legend are the FAA Hybrid Merge trajectory build times, in seconds. Time tags on the actual track are shown for clarity. Referring to Table 3, the test aircraft reached the turn of the LBF waypoint at 83146 seconds and the turn back point at 83662 seconds.

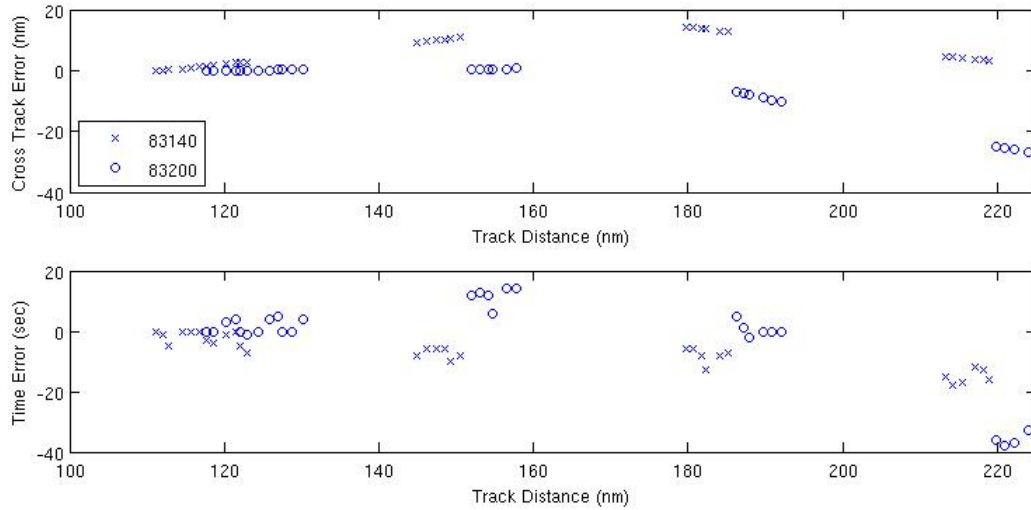


Figure 14. Error metrics of FAA Hybrid Merge trajectories generated for path stretch

The FAA Hybrid Merge trajectory predictor was run without weather modeling. Even though this trajectory predictor estimates ground speed from existing track data, inaccuracies in the wind implementation still manifest into the time error. This is illustrated in the time error plots. Time errors will result from uncertainties in predicted ground speed, wind, vertical speed, and lateral path.

At 83140 seconds, just before reaching the turn point at the LBF waypoint (which occurs at 113 nautical miles in track distance), the FAA Hybrid Merge generates a new trajectory. The trajectory predictor expects that the aircraft is following the filed route and the path stretch is unknown. The cross-track error increases to about 4 nautical miles beyond the LBF waypoint. At 83200 seconds (now beyond the turn point) the trajectory predictor generates a new trajectory and it is clear that the trajectory predictor recognizes that the aircraft is no longer following the route. The predictions are clearly based on dead-reckoning, and the trajectories continue well beyond the turn-back point. Referring to Figure 14, the cross-track error of 83200 is significantly better than 83140 up until the turn back point (at 172 nautical miles track distance). Every 60 seconds along this segment (although they are not shown in the figures), the trajectory predictor generates a new dead-reckoned trajectory that has improved cross-track accuracy prior to the turn-back point, but fails beyond it, continuing, as 83200 does, in a straight, dead-reckoned path beyond the turn-back point. These trajectories have lower cross-track errors than the URET prototype trajectories prior to the turn-back point (see Figure 18). Ryan and Paglione¹⁴ pointed out that the FAA Hybrid Merge trajectory predictor has superior cross-track prediction capabilities at short look-ahead times. The time error varies from -40 to +20 seconds during the path stretch.

Referring again to Figure 13, at 83680 seconds, the FAA Hybrid Merge trajectory predictor generates a new dead-reckoned trajectory in the middle of the aircraft's turn back to the route. The trajectory predictor fails to recognize that the aircraft is turning to rejoin the route, generating a trajectory that continues along the current heading in the turn. At 83740 seconds, the trajectory predictor generates a trajectory that successfully predicts the rejoin and, once again, this reflected in the reduced cross-track error (Figure 14).

Figure 15 shows the vertical profile of the FAA Hybrid Merge trajectories. Even though the Host Computer System broadcast an altitude restriction to 19,000 feet when the aircraft was in the vicinity of the LBF waypoint (near 83200 seconds), none of the FAA Hybrid Merge trajectories attempt a descent until the trajectory generated at 84160 seconds. Although they are not shown in Figure 15 or Figure 16, every trajectory generated between 83200 and 84160 holds constant altitude. At 84160 seconds, the trajectory predictor recognizes that the aircraft is in a descent, but, apparently because the descent has only just begun, the descent rate of the prediction is inaccurate. The descent of the next generated trajectory (at 84220 seconds) is considerably more accurate. The error metrics for the descent are shown in Figure 16. While the vertical error of the earlier two trajectories grows quickly, the vertical error of the trajectory generated in mid-descent is quite accurate, never rising above 400 feet in magnitude. The time error is relatively small, less than ten seconds, during the descent begins, indicating that the FAA Hybrid Merge does fairly well at predicting the ground speed. It isn't until the test aircraft increases its deceleration rate near the SAYGE waypoint that the time error grows above 10 seconds.

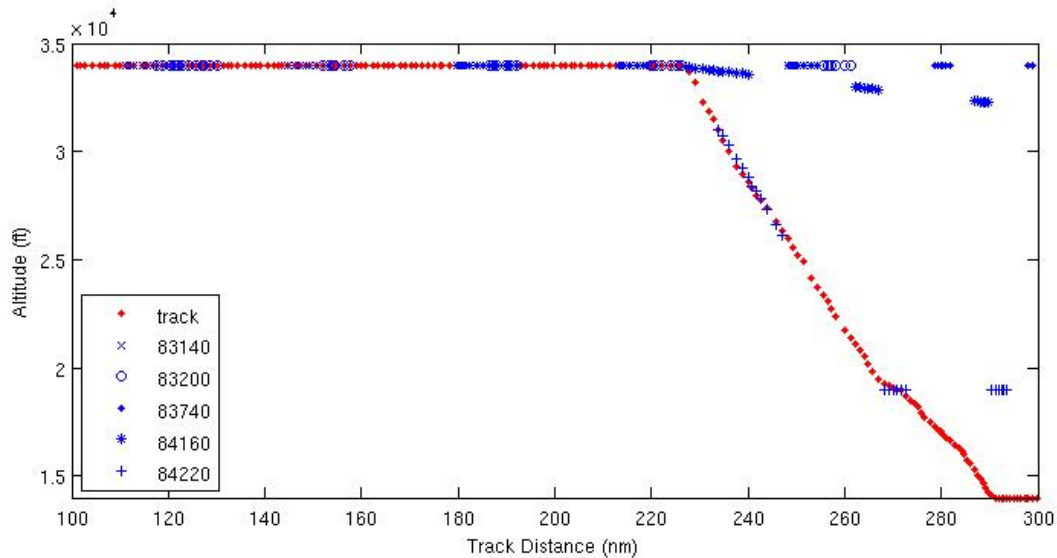


Figure 15. Profile of FAA Hybrid Merge trajectories generated for initial descent

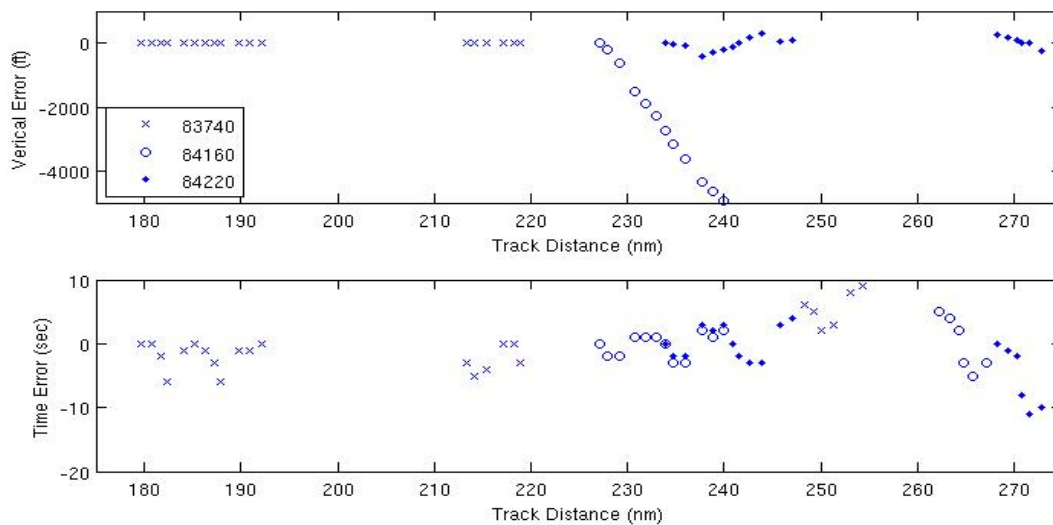


Figure 16. Error metrics of FAA Hybrid Merge trajectories generated for initial descent

B. URET Prototype Trajectory Predictor

Figure 17 shows the trajectory predictions of the path stretch using the URET prototype. It is repeated here that, for purposes of testing the hypotheses, prior knowledge of the path stretch was removed from the filed route to simulate a controller-initiated vector.

It is evident that the URET prototype generates trajectories that attempt to rejoin the filed route at some downstream fix. The path selected by the URET prototype trajectory predictor is the result of a heuristic algorithm that is dependent on the geometry of the problem at hand. In the figure, the 5-digit numbers in the legend are the URET prototype trajectory build times, in seconds. Time tags on the actual track are shown for clarity. Referring to Table 3, the test aircraft reached the turn of the LBF waypoint at 83146 seconds and the turn back point at 83662 seconds. The URET prototype trajectory at 83218 seconds was the first trajectory to recognize the path deviation. The reader may recall the discussion above of the URET conformance bounds. Each time the track exceeded the conformance bounds, a new trajectory was generated. This resulted in the subsequent trajectories at 83338 seconds, 83458 seconds, and 83578 seconds.

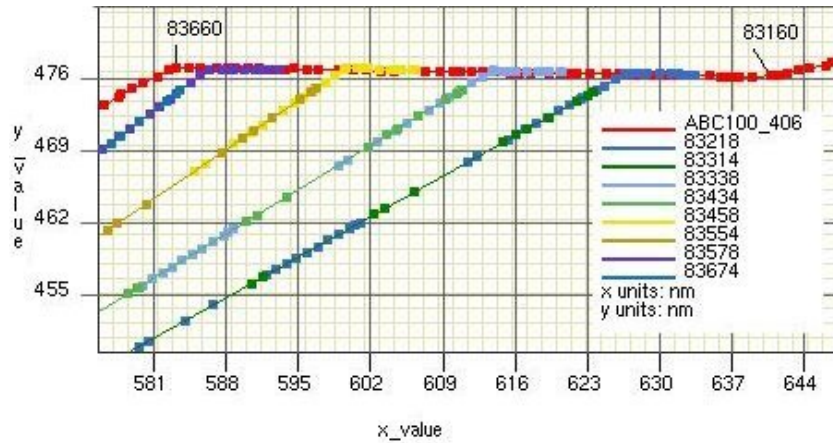


Figure 17. Stereographic plot of URET prototype trajectories generated for path stretch

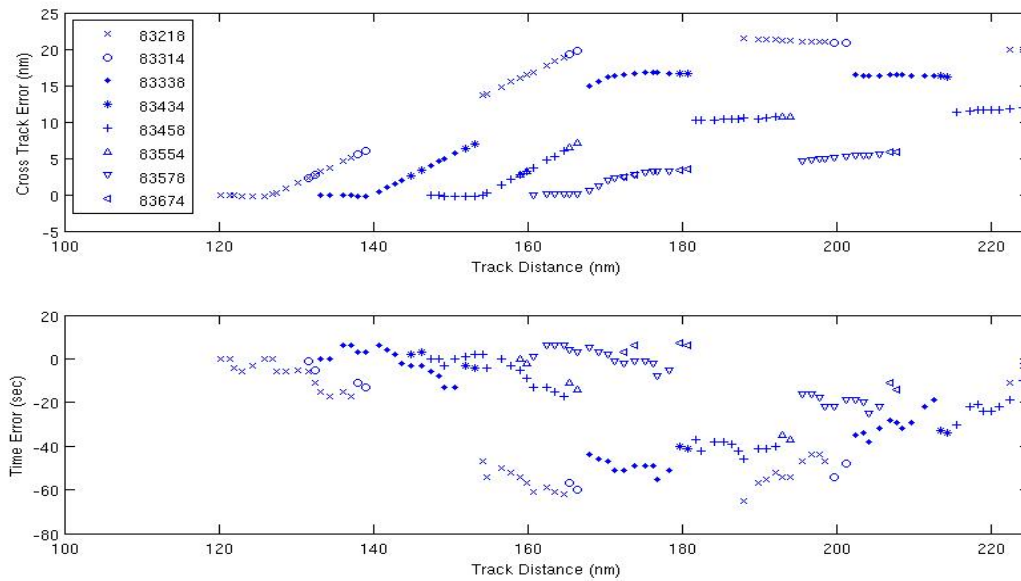


Figure 18. Error metrics of URET prototype trajectories generated for path stretch

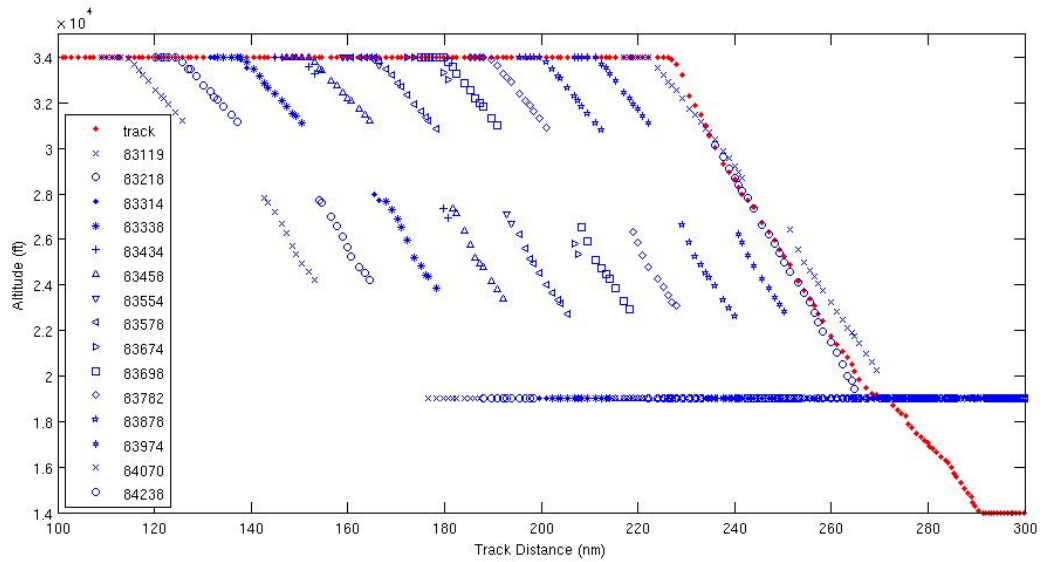


Figure 19. Profile of URET prototype trajectories generated for initial descent

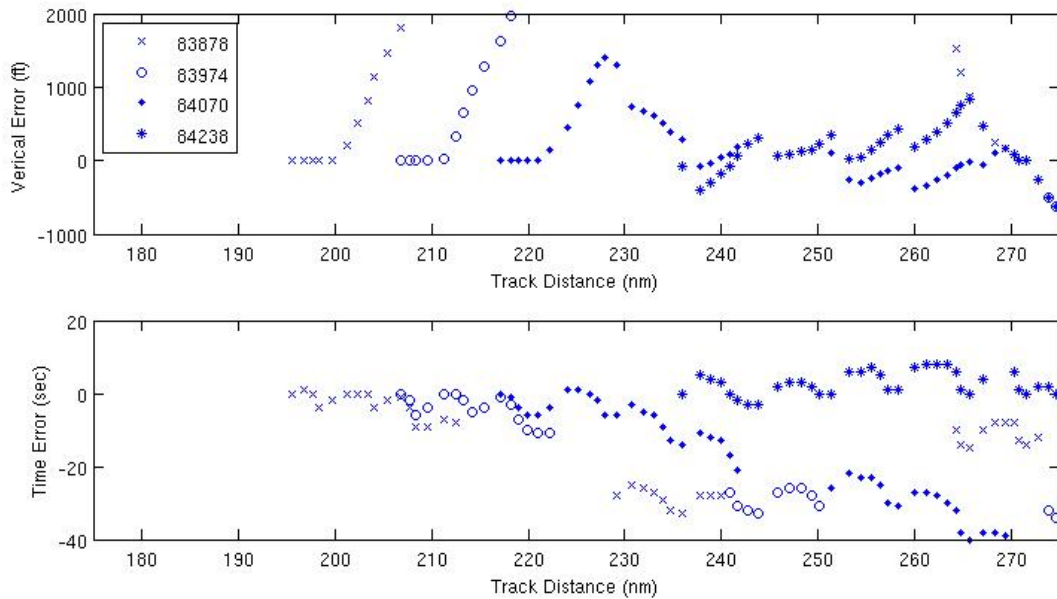


Figure 20. Error metrics of URET prototype trajectories generated for initial descent

Figure 18 is a plot of the error metrics for the URET prototype path stretch trajectories. As seen in the stereographic plot of Figure 17, the cross-track error is negligible for about 50 seconds, at which point the URET prototype has predicted a turn-back to the filed route, and this is where the cross-track error begins to grow. When the cross-track error is greater than the URET conformance boundary, a new trajectory is generated. The time errors are noticeably greater than the trajectories of the FAA Hybrid Merge.

From the Host Computer System record (see Table 2), it is known that at 83119 seconds, the Host Computer System broadcast an interim altitude clearance to 19,000 feet. At that point, the URET prototype began generating descent trajectories. These are illustrated in Figure 19, a plot of profiles for the URET prototype trajectories of the initial descent. Recalling that the URET vertical conformance boundary is 1000 feet, one can explain the periodic generation of new trajectories. This also explains the interim trajectories seen in the stereographic plot of Figure 17.

Because the URET prototype trajectory predictor is attempting to correct the lateral path at the same time as meeting the new interim altitude clearance, it becomes difficult to attribute the generation of the new trajectories to the vertical or lateral URET conformance boundary violations. Trajectory 84070 began its descent only a few seconds before the actual descent and its descent profile matches quite well. Trajectory 84238 is initiated in the descent, also matching the descent profile quite well. All the URET prototype trajectories remain at 19,000 feet pressure altitude for the duration of the flight, presumably because the Host Computer System never broadcast another altitude clearance for this flight.

Figure 20 is a plot of the error metrics for the URET prototype trajectories generated for the initial descent. As the first URET prototype descent trajectories generated at 83119 seconds and 83782 seconds are well before the top-of-descent of the actual track and their associated errors grow quickly off scale, they are not shown. The vertical error for trajectory 83878 is off scale for the time range shown until the actual track meets the altitude that the trajectory had attained nearly 300 seconds earlier. The vertical error of trajectory 83974 demonstrates the pattern of its predecessors in underestimating the top-of-descent and quickly attaining a vertical error greater than 2000 feet. Trajectory 84070 misses the top-of-descent by only a few seconds. Still, its vertical error tops out at 1500 feet before falling back below 500 feet. The smallest vertical error is owned by trajectory 84238, which was begun during the descent. Its vertical error stays below 1000 feet reaching its highest error value near the SAYGE waypoint. And, once again, the time errors are noticeably greater than for the FAA Hybrid Merge trajectories, approaching -40 seconds.

C. Post-AIDL-Communication Trajectories Using the TGF Trajectory Generator

Figure 21 shows the error metrics of the post-AIDL trajectory predictions of the path stretch generated from the initial point of clearance to the path stretch using the TGF trajectory generator. (The difference from the actual track seen in a map projection is trivial and so is not presented.) In this case, with the path stretch point and the turn back point communicated, the cross-track error maximum is about 0.5 nautical miles - significantly smaller than the pre-AIDL trajectories. There is a peak in the lateral error at 172 nautical miles track distance, the location of the turn back. This is due to errors in the modeling of that turn. Prior to the LBF waypoint (at 113 nautical miles track distance), the speed error is significant and time error quickly grows to 20 seconds in less than 20 minutes of flight. Because flight crew notes indicate that the cruise speed is Mach 0.74, these errors are attributed entirely to errors in the weather model. Mondoloni⁸ analyzed the effect of wind uncertainty on trajectory prediction errors and showed how, even when airspeeds are known, small root mean square (RMS) values of wind uncertainty can propagate into significant along-track error, an effect seen in Figure 21, although presented as time error. The time errors shown in Figure 21 are not inconsistent with Mondoloni's findings. Klooster, Wichman, and Bleeker¹⁶ reported similar problems with wind model accuracy.

Figure 22 shows the post-AIDL trajectory predictions of the path stretch generated from 10 nautical miles beyond the LBF waypoint using the TGF trajectory generator. Because the accumulation of time error seen in Figure 21 slows significantly at this point, the wind error must be small. While the difference in cross-track error between the two trajectories is negligible, the wind model is more accurate over this section of the flight and so the time error is less than 5 seconds. The discovery of the importance of an accurate weather model for accurate trajectory predictions is repeated in this study.

Figure 23 shows the profile of the post-AIDL trajectory predictions of the top-of-descent using the TGF trajectory generator and the RUC weather model, as compared to the actual profile. In this case, with the top-of-descent point communicated directly to the TGF trajectory generator, the top-of-descent is accurately predicted. Figure 24 shows the error metrics for the descent. Because the aircraft is flying a geometric path angle and adjusting speed to correct for errors in the forecast winds, the speed error is significant; however, the time error maximum is only 10 seconds. As pointed out in Klooster, Wichman, and Bleeker,¹⁶ flying to a geometric path angle serves to prevent variations in the profile while allowing for speed adjustments to compensate for errors in the forecast winds (at the expense of fuel burn). Consequently, the vertical error maximum is only 500 feet, with a RMS of less than 200 feet. And with the vector to the downwind leg communicated ahead of time, the post-AIDL trajectory predictor was able to predict the trajectory with considerable accuracy and a cross track error of less than 0.5 nautical miles.

It should be noted that Figure 23 and Figure 24 cover the duration of the flight from the top-of-descent at 34,000 feet to landing, as predicted using the TGF trajectory generator, even though this section of the flight was not tested with the FAA Hybrid Merge and URET prototype trajectory predictors. The aircraft intent used for the trajectory made the assumption that the complete flight object, including aircraft intent and flight intent, was known prior to the descent. This includes the approach vectors and the removal of altitude restrictions. It illustrates that if the complete flight object is known and can be communicated, trajectory prediction can attain accuracy within 0.3 nautical miles RMS in cross-track error, 6 seconds RMS in time error, and 170 feet RMS in vertical error.

A general trend in the behavior of trajectory predictors is illustrated in this collection of figures. While the aircraft is following a steady-state maneuver (i.e., non-turning or steady descent), these trajectory predictors predict the trajectory with accuracy comparable to a trajectory generator using aircraft intent. Once the aircraft deviates from the steady-state, it takes the trajectory predictors as long as a minute to recognize the deviation and correct the predicted path. Frequent monitoring from the trajectory predictor is required to maintain tolerable accuracy. With the trajectory generated from aircraft intent knowledge, the predicted path is not likely to change until there is a change in the aircraft intent. And because the aircraft is following the correct lateral and vertical path, the trajectory is less susceptible to wind uncertainty.

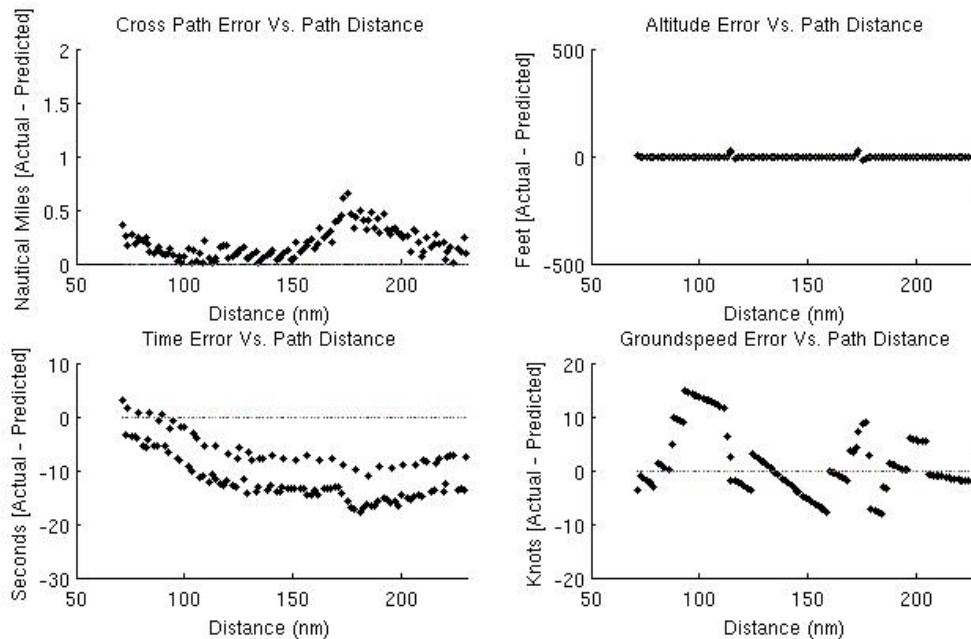


Figure 21. Error Metrics of Post-AIDL trajectory generated from path stretch clearance to AMWAY

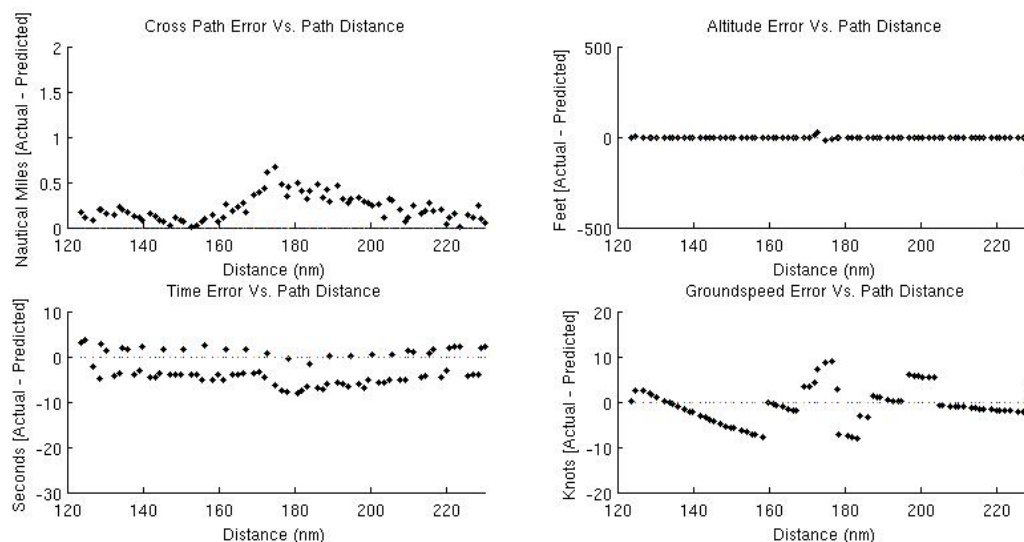


Figure 22. Error Metrics of Post-AIDL trajectory generated from LBF - AMWAY

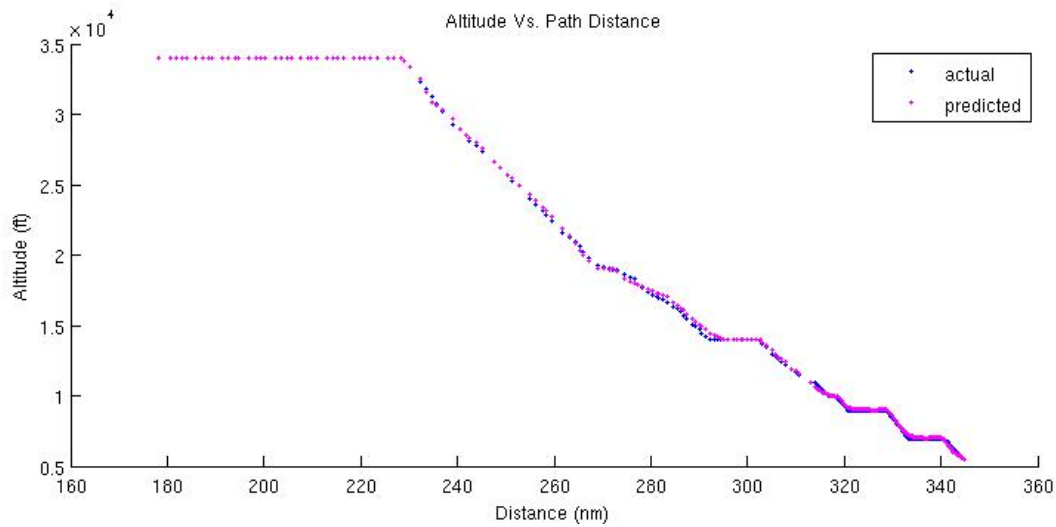


Figure 23. Descent profile of actual track compared with post-AIDL predicted trajectory

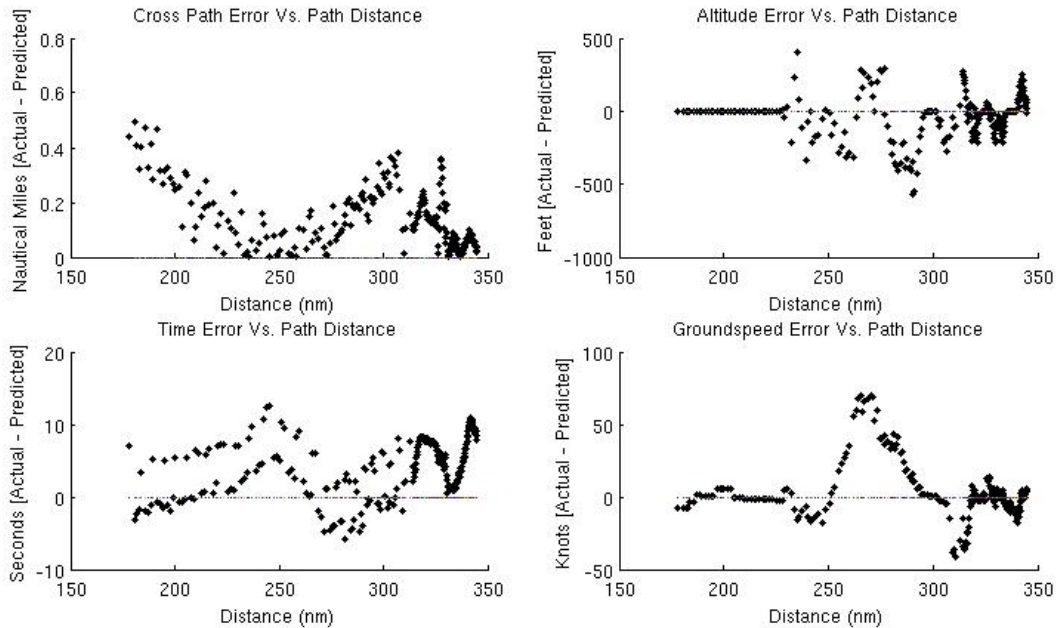


Figure 24. Trajectory error metrics of post-AIDL predicted trajectory

Table 4 presents the RMS error for some selected trajectories in this study. For calculating the path stretch RMS, the trajectories were reduced to points that were spatially correlated to track points between the LBF and AMWAY waypoints. For calculating the initial descent RMS, the trajectories were reduced to points that were spatially correlated to track points between a point 20 nautical miles before the AMWAY waypoint and 5 nautical miles beyond the SAYGE waypoint. There are two consequences of this approach: 1) trajectories generated near the end of the flight phase are not predicting the portion of the flight that deviates from the steady-state condition, and so their RMS values are small, and 2) trajectories generated near the end of the flight phase have smaller look-ahead times to the end of the phase and, as many trajectory prediction analysts have pointed out, trajectory errors typically increase with trajectory look-ahead time. It is easy to see that the pre-AIDL trajectories were much better at predicting the path stretch phase of the flight once the flight was beyond the turn-back point. Similarly, the pre-AIDL trajectories were much better at predicting the descent once the aircraft was near the top-of-descent or actually in the descent. The post-AIDL trajectories have shown that the flight can be accurately reproduced well before any

Table 4. Root Mean Square Errors of Selected Trajectories

	Build Time	Path Stretch			Initial Descent		
		xTrack (nm)	Time (sec)	Vert (ft)	xTrack (nm)	Time (sec)	Vert (ft)
URET Prototype	83119	18.3	43.4	10997	20.8	27.6	11431
	83218	14.6	35.8	10269	16.4	35.2	10219
	83698	1.6	12	6117	3.1	15.9	8896
	83782	2.2	16.7	6340	3.5	20.5	7968
	84070	0.6	3.8	904	1.8	19.1	612
	84238	-	-	-	2.4	4.2	319
FAA Hybrid Merge	83080	9.5	10.8	0	3.1	18.6	5405
	83140	8	8.9	0	2.8	11.7	6442
	83200	12.5	16.9	0	39.4	70.2	8179
	83680	3.7	5.7	0	15.2	28.9	8244
	83740	0.3	2.9	0	0.4	4.8	6442
	84100	0.1	3.6	286	3.2	5	6738
	84160	0.1	1.6	379	2.5	2.6	7675
	84220	-	-	-	0.1	4.5	185
postAidl		0.3	4.3	0	0.1	5.8	170

deviation is recognized and new trajectories are generated. It can be concluded that if the aircraft communicates to the ground-based trajectory predictor that it has been vectored off route, the cross-track error is greatly reduced.

The RMS of the cross-track error of the post-AIDL trajectory in the vicinity of the turn back to the filed route is about 0.3 nautical miles. The FAA Hybrid Merge trajectory predictor appears to be using dead-reckoning and the cross-track errors of its trajectories grow to 2.5 nautical miles before the turn back is recognized and new trajectories are generated. The URET prototype is continually trying to predict the turn back to the route. In the immediate vicinity of the turn back point, the cross-track errors of the URET prototype's most recent trajectories are small (less than one nautical mile) but the earlier trajectories have cross-track errors similar to (and sometimes larger than) the FAA Hybrid Merge. Errors increase significantly at look-ahead times above one – two minutes. It can be concluded that if the aircraft communicates to the ground-based trajectory predictor when it is sent back to the route, the cross-track error is greatly reduced.

The RMS of the cross-track error of the post-AIDL trajectory over the entire path stretch phase of the flight is about 0.3 nautical miles. The RMS of the cross-track error of the FAA Hybrid Merge trajectories is as high as 12.5 nautical miles. The RMS of the cross-track error of the URET prototype trajectories is as high as 18.3 nautical miles. Cross-track errors for the trajectories of both predictors increase significantly at the higher look-ahead times. It can be concluded that if the aircraft can communicate the path stretch and the turn back point to the ground-based trajectory predictor even before the path stretch begins, the cross-track error is greatly reduced.

The RMS of the vertical error of the post-AIDL trajectory over the initial descent phase of the flight is about 170 feet while the RMS of the time error is less than six seconds. The RMS of the vertical error of the FAA Hybrid Merge trajectories and for the URET prototype trajectories over the same section of the flight is about 8000 feet and the RMS of the time error is as high as 35 seconds for the URET prototype and 70 seconds for the FAA Hybrid Merge. The FAA Hybrid Merge and URET prototype predictors have smaller RMS at shorter look-ahead times (i.e., vertical error RMS below 1000 feet and time error RMS below six seconds) but the errors increase significantly at higher look-ahead times. It can be concluded that if the aircraft can communicate the top-of-descent to the ground-based trajectory predictor then time error and vertical error will be reduced.

The fourth test hypothesis outlined in the experiment design predicted that communication of the top-of-descent would greatly reduce speed error. The study has shown that uncertainty in the wind field can produce speed errors as high as 80 knots (Figure 24) even while time errors remain in the vicinity of 10 seconds. This was a consequence of flying a flight path angle descent instead of a speed profile. Nevertheless, this was considered a significant speed error and so further examination of the test hypothesis was abandoned.

deviations from steady flight. The post-AIDL trajectories were generated as much as 20 nautical miles (approximately 10 minutes) before the steady-flight-deviations with a cross-track RMS of less than 0.3 nautical miles, a time RMS of less than 6 seconds, and vertical RMS of less than 170 feet. Consequently, the large error increases typically seen with large look-ahead times in trajectory prediction have been greatly reduced.

D. Examining the Test Hypotheses

The RMS of the cross-track error of the post-AIDL trajectory in the vicinity of the initial turn to the path stretch (i.e., at the LBF waypoint) is about 0.3 nautical miles. The cross-track errors of the URET prototype trajectories grow to 2.5 nautical miles and of FAA Hybrid Merge trajectories to 4 nautical miles before the

VIII. Conclusion

This study used flight data from an anonymous commercial flight performing an optimized profile descent into Denver International Airport to test the hypothesis that communication of aircraft intent via a standard like AIDL will greatly improve trajectory accuracies as measured by commonly used trajectory prediction metrics. The flight contained two common sources of trajectory prediction uncertainty: Top-Of-Descent uncertainty and an Unknown Lateral Change. The researchers selected two separate trajectory predictors (the URET prototype and the FAA Hybrid Merge) to emulate ground-based trajectory prediction and the TGF trajectory generator to serve as the trajectory generator after aircraft intent communication. Communication of aircraft intent was facilitated via the Aircraft Intent Description Language (AIDL).

1. If the aircraft communicates to the ground-based trajectory predictor that it has been vectored off route, the cross-track error is greatly reduced. This study has shown that the cross-track error resulting from a voice-only, controller-initiated path stretch is 2.5 nautical miles with a ground-based trajectory predictor before the turn is recognized and only 0.3 nautical miles with the TGF trajectory generator using AIDL to communicate the known path stretch.
2. If the aircraft communicates to the ground-based trajectory predictor when it is sent back to the route, cross-track error is reduced. Once the path stretch was recognized by the URET prototype and the FAA Hybrid Merge trajectory predictors, the RMS of the cross-track error was still as high as 14.6 nautical miles with the URET prototype, 12.5 nautical miles with the FAA Hybrid Merge, and only 0.3 nautical miles with the TGF trajectory generator using AIDL to communicate the known path stretch. The URET prototype's errors in predicting the turn-back point grew significantly with look-ahead time.
3. If the aircraft communicates to the ground-based trajectory predictor the turn back point even before the vector-off-route occurs, cross-track error is greatly reduced. Over the entire path stretch phase of the flight, the RMS of the cross-track error of the FAA Hybrid Merge trajectories is as high as 12.5 nautical miles. The RMS of the cross-track error of the URET prototype trajectories is as high as 18.3 nautical miles. Cross-track errors for the trajectories of both predictors increase significantly at the higher look-ahead times.
4. If the aircraft can communicate the top-of-descent to the ground-based trajectory predictor then time error and vertical error will be reduced. The RMS of the vertical error of the post-AIDL trajectory over the initial descent phase of the flight is about 170 feet while the RMS of the time error is less than six seconds. The RMS of the vertical error of the FAA Hybrid Merge trajectories and for the URET prototype trajectories over the same section of the flight is about 8000 feet and the RMS of the time error is as high as 35 seconds for the URET prototype and 70 seconds for the FAA Hybrid Merge. The FAA Hybrid Merge and URET prototype predictors have smaller RMS at shorter look-ahead times (i.e., vertical error RMS below 1000 feet and time error RMS below six seconds) but the errors increase significantly at higher look-ahead times.
5. Improvements in the speed error were not realized, illustrating that accurate weather modeling is important to accurate trajectory prediction.
6. A general trend in the behavior of trajectory predictors was revealed in this study. While the aircraft is following a steady-state maneuver (i.e., non-turning or steady descent), the trajectory predictors predict the trajectory with accuracy comparable to a trajectory generator using aircraft intent. Once the aircraft deviates from the steady-state, it takes the trajectory predictors as long as a minute to recognize the deviation and correct the predicted path. Frequent monitoring from the trajectory predictor is required to maintain tolerable accuracy. With the trajectory generated from aircraft intent knowledge, the predicted path is not likely to change until there is a change in the aircraft intent. And because the aircraft is following the correct lateral and vertical path, the trajectory is less susceptible to wind uncertainty.

Appendix

Figure 25 shows a sample of an XML (Extensible Markup Language) implementation of AIDL. XML has become widely-used as a data interchange format. Its flexibility and its simplistic basis permit the direct sharing of information between different kinds of computers, applications, and organizations.

The figure presents the XML implementation of the first longitudinal thread of the aircraft intent extracted from the test flight used in this study. The first lines introduce the AIDL and identify the format. This is followed by the identification of the first longitudinal thread. The first instruction of the thread specifies mach speed control for the cruise portion of the flight (this instruction is held for about 230 nautical miles of the flight). The cruise speed and altitude (Mach 0.74 and 34,000 feet) will have been specified in a separate file. The second instruction specifies the

geometric path angle control law along with the geometric parameters of the path angle. The auto-trigger between the instructions is determined by the intersection in the geometry. The ending altitude of the instruction (19,000 feet) is specified in meters. The next instruction is constant altitude, followed by another geometric path angle. The remaining instructions carry the flight beyond the portion analyzed for this study and so are not detailed here. The actual XML implementation used for this study contains the second longitudinal thread, the lateral thread, and the configuration threads as detailed in Section VI, paragraph c.

<pre> <?xml version="1.0"?> <aidl:aircraft_intent xmlns:aidl="http://www.boeing.com/XSD/AIDO/v1.3.1" xmlns:obj="http://www.boeing.com/XSD/COIN/v1.0" xmlns:cc="http://www.boeing.com/XSD/BIZCO/v1.0" xmlns:mp="http://www.boeing.com/XSD/GEN_COMP/v1.0"> <aidl:long1_thread> <aidl:hs specifier="mach"> <aidl:linked_trigger id="1" href="2"/> </aidl:hs> <aidl:pal specifier="geo"> <aidl:constraint> <cc:constraint class="latitude"> <mp:variable variable="gamma"/> <mp:units units="rad"/> <mp:function class="constant" value="-0.08934"/> </cc:constraint> </aidl:constraint> <aidl:floating_trigger id="3"> <aidl:condition> <cc:condition class="altitude"> <mp:scalar value="5791.2"/> <mp:units units="m"/> <mp:function class="static" variable="Hp"/> </cc:condition> </aidl:condition> </aidl:floating_trigger> </aidl:pal> <aidl:ha specifier="pre"> <aidl:floating_trigger id="4"> <aidl:condition> <cc:condition class="speed"> <mp:scalar value="128.611"/> <mp:units units="mps"/> <mp:function class="static" variable="cas"/> </cc:condition> </aidl:condition> </aidl:floating_trigger> </aidl:ha> <aidl:pal specifier="geo"> <aidl:constraint> <cc:constraint class="latitude"> <mp:variable variable="gamma"/> <mp:units units="rad"/> <mp:function class="constant" value="-0.0314159"/> </cc:constraint> </aidl:constraint> <aidl:floating_trigger id="5"> <aidl:condition> <cc:condition class="altitude"> <mp:scalar value="3048"/> <mp:units units="m"/> <mp:function class="static" variable="Hp"/> </cc:condition> </aidl:condition> </aidl:floating_trigger> </aidl:pal> </aidl:long1_thread> </aidl:aircraft_intent> </pre>	<pre> </cc:condition> </aidl:condition> </aidl:floating_trigger> </aidl:ha> <aidl:hs specifier="cas"> <aidl:floating_trigger id="7"> <aidl:condition> <cc:condition class="altitude"> <mp:scalar value="2133.6"/> <mp:units units="m"/> <mp:function class="static" variable="Hp"/> </cc:condition> </aidl:condition> </aidl:floating_trigger> </aidl:hs> <aidl:ha specifier="pre"> <aidl:floating_trigger id="8"> <aidl:condition> <cc:condition class="longitude"> <mp:scalar value="4.45685"/> <mp:units units="rad"/> <mp:function class="static" variable="lambda"/> </cc:condition> </aidl:condition> </aidl:floating_trigger> </aidl:ha> <aidl:pal specifier="geo"> <aidl:constraint> <cc:constraint class="latitude"> <mp:variable variable="gamma"/> <mp:units units="rad"/> <mp:function class="constant" value="-0.0523599"/> </cc:constraint> </aidl:constraint> <aidl:linked_trigger id="9" href="10"/> </aidl:pal> </aidl:long1_thread> </aidl:aircraft_intent> </pre>
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Figure 25. Sample XML implementation of AIDL showing the first longitudinal thread of the extracted aircraft intent of the test aircraft of this study

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