Characterizing Intent Maneuvers from Operational Data – A Step towards Trajectory Uncertainty Estimation

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Many of the future automation concepts to transform the airspace system are likely to require significant improvements to the performance of underlying trajectory prediction algorithms. Where practical considerations may limit the achievable prediction accuracy, the impact of these inaccuracies may be mitigated significantly through the estimation and accommodation of trajectory prediction uncertainty. One approach to developing prediction uncertainty models is through the application of prediction accuracy techniques to identify and size trajectory prediction errors. This approach requires collecting and analyzing vast amounts of operational traffic data. This paper presents methods to analyze these data to automatically identify and categorize intent maneuvers. Intent maneuvers are defined as those required to achieve constraints identified within recorded operational data. The conformity of these maneuvers with observed aircraft maneuvering is crucial to facilitate the appropriate selection of data to support prediction accuracy techniques. Additionally, a searchable database is developed to support the collection of statistically representative data to facilitate error analyses. As a test of this system, operational data, including track data, associated flight plans, and other amending messages, were successfully uploaded into the database and used to test and validate the methods for intent maneuver categorization.

I. Introduction

The growth of air traffic demand will soon exceed the capacity of the Air Traffic Management (ATM) system in the United States and Europe, increasing congestion, delays, and safety-related concerns. Research efforts to mitigate this problem envisage a transformation in the ATM paradigm from current tactical clearance-based operations to future trajectory-based operations, which will require extensive use of ground and airborne automation. The Next Generation Air Transportation System[1] (NextGen) in the United States and the Single European Sky Air Traffic Management Research[2] (SESAR) in Europe advocate for these changes. The automated decision support tools (DSTs)[3,4] that support these trajectory-based operation concepts rely on the prediction of four-dimensional aircraft trajectories (4DTs). The prediction of 4DTs includes position in the horizontal plane, altitude, and time. These tools embrace a broad scope of applications. They include tools for conflict detection and resolution to support both ground controllers and pilots. They also include tools for the metering and sequencing traffic through changes in speed, altitude, and path. Within a more strategic time horizon, they include Traffic Flow Management tools that aim at forecasting the traffic demand for airspace resources to keep the capacity-demand imbalance under limits. A typical trajectory predictor (TP) algorithm requires an estimate of initial aircraft state (e.g., position, altitude, and speed), aircraft intent data (e.g., a flight plan), meteorological forecast data, and models of aircraft performance and pilot procedures. Theoretically, a TP could achieve any desired level of accuracy if input data were sufficiently complete and representative of the aircraft's state, intent, and flight procedures, and the

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prediction algorithm represented the physical aircraft system accurately. However, practical limitations in the accuracy of input data, e.g., meteorological forecast, and in the models used by any TP results in some level of prediction error that every DST must accommodate. One promising method for DSTs to accommodate such error is to estimate the growth/decay of prediction error along the 4DT in real time. This estimated uncertainty is then available to the DST and can be directly factored into its functionality. Estimating and accommodating trajectory uncertainty in real time is a way to improve ATM decision making in the presence of TP errors.

Previous research has proposed the use of several uncertainty models within several DSTs to accommodate prediction error, especially in conflict detection applications. For example, Vink et al.[5] reported the use of protection zones, around predicted trajectory points that linearly grow with the prediction time horizon, by a Medium Term Conflict Detection tool. Karr and Vivona[6] proposed an approach, implemented in the Autonomous Operations Planner system for conflict detection and resolution, to bind the predicted trajectory with Trajectory Prediction Uncertainty Bounds. Those bounds delimit an uncertainty region around a nominal 4D predicted trajectory. Paielli and Erzberger, [7,8] adopted a statistical model of trajectory prediction error, and based on that model, derived an analytical solution for the probability of conflict between two aircraft. Alternative probabilistic models using Monte Carlo simulation have also been developed (Yang and Kuchar,[9,10] Wanke et al.[11]). The implementation of each model requires the estimation of a set of key error parameters, such as the density function of along-track error, its mean, and standard deviation. They are either hypothesized or estimated using prediction accuracy analyses. However, previous work has focused on designing uncertainty methods and validating the uncertainty parameters for a limited set of maneuvers. For example, Paielli[12] validated the along-track error model by using prediction error analysis with real traffic data only applied to straight and level flights.

There is also extensive literature related to prediction accuracy analyses that used actual traffic data[13-19] but each study collected and customized experimental data from flight trials or from passive observation of actual operations to accomplish their specific objectives. As illustrated by the literature, the data required for prediction accuracy analyses are not always easy to obtain and often can be resource intensive, so reusing actual data is advisable. However, reusing this body of data for applications or analyses that differ from the study which captured the data would require a significant amount of effort to identify whether the characteristics of the data meet the new analyses objectives. For example, it is not always easy to identify all the characteristics of data collected from field tests because some of the characteristics are not captured in the data (e.g., experimental pilot procedures.)[13,14] Whether reusing data or collecting new data, selection of data appropriate for the analysis from a large set of data is a challenge. In the literature, some approaches relied on the analyst to manually select data samples adequate for prediction analysis.[16,17] One attempt to automate the process of capturing and classifying operational data as a function of phase of flight was made by Gong and McNally.[18] Whereas their method provided valuable insights within the scope of that study, additional information and data are needed to develop a more general and extensible approach. For example, information on all relevant maneuvers (lateral and vertical) and the ability to identify the succession of these maneuvers is needed.

The main idea pursued in this paper is to develop methods to characterize trajectory data (observed and predicted) and to store them in a searchable database that facilitates the prediction of error bounds over a wide range of aircraft maneuvers to support the development of uncertainty estimation methods. This categorization represents all relevant maneuvers and is not limited by assumptions associated with any particular uncertainty estimation approach or DST application. The database is initially populated with Air Traffic Control (ATC) observed trajectory data (track data and related intent messages) that ultimately will be compared to predicted trajectories to estimate error bounds. These trajectory data are categorized in such a way as to facilitate the proper selection of representative data to support the specific requirements of a desired prediction accuracy analysis. In particular, the characterization of intent maneuvers, in combination with observed maneuvers, is especially significant to the general usability of the database. Intent maneuvers are defined as aircraft maneuvers required to achieve the constraints identified within the intent information. Observed maneuvers are defined as the behavior identified in the observed states of a flight. Because predicted maneuvers are compared against observed maneuvers, one has to ensure that the intent information represented by the constraints used in both the prediction process and the actual flight is the same in order to control intent errors. With the proposed categorization of intent maneuvers, it is possible to identify when the aircraft is not flying consistently with the constraints defined in the aircraft intent information. In addition, the database is intended to allow the analyst to retrieve relevant trajectory information that conforms to multiple required characteristics and that may be restricted to a targeted sub-segment maneuver (e.g., capturing a single phase of flight or a single maneuver within a phase of flight.) These capabilities to isolate intent errors and select data for only those categories of interest are expected to fulfill a wider set of potential analysis requirements and are a key feature for estimating the uncertainty parameters required by real-time uncertainty methods These qualities of the database will also help the analyst reuse the data to fulfill a wide set of analysis needs beyond the original use of the data collected.

Section II sets the context in which the categorization methods and database are developed. It describes, at a high level, a proposed methodology that extends trajectory prediction accuracy analyses and techniques to support the development of real-time uncertainty estimation. A brief description of the database development and categorization of trajectory categories is presented in Section III. Special interest is given to the identification of intent maneuvers from actual ATC operational data, described next in Section IV. Finally, concluding remarks and the next steps in the research are presented in Section V.

II. Research Approach and Methodology

This section starts by introducing some terms and definitions. Some of these terms do not have universally accepted definitions. An overview of the uncertainty estimation development methodology is given next to provide the context for the development of the database and trajectory categories. The methodology extends prediction accuracy techniques to the development of uncertainty estimation models. Only those aspects of the proposed methodology that impact the development of the database and trajectory categorization are described in detail. The full methodology is described in Enea et al.[20]

A. Definition of terms

- **4D Trajectory:** Series of aircraft states in four dimensions (position in the horizontal plane, altitude, and time). They may be actual aircraft states **(observed trajectory)**, either from actual operations (e.g., radar tracks recorded at an ATC facility or sensor data recorded onboard the aircraft) or from field tests, and predicted aircraft states **(predicted trajectory.)**
- **Run:** Single instance of trajectory data retrieved from the database, e.g., a portion of a flight, that reflects a set of trajectory characteristics specified by an analyst.
- **Trajectory Prediction:** The process of estimating the future states of individual aircraft on the basis of the current aircraft state, estimation of pilot and controller intent, expected environmental conditions, and computer models of aircraft performance and procedures.
- **Intent:** Information required to describe the behavior of an aircraft's future motion. This includes constraints that aircraft will follow, sequence of control instructions, e.g., full control settings schedules, a flight plan, and operational procedures, e.g., how a climb is executed by the flight crew.
- **Observed maneuver:** A change in the flight path inferred by the observation of actual aircraft states.
- **Intent maneuver:** A change in the flight path required to achieve the constraints identified within an intent. In this paper, intent is defined by the constraints identified within ATC data from actual operations. It is worth noting that a collected intent may be only part of the existing intent that directs the aircraft behavior, thus, the intent maneuver may differ from the observed maneuver.
- **Prediction Accuracy:** Quantification of the prediction error given by the difference between a predicted trajectory and the observed trajectory.
- **Prediction Uncertainty:** The range of potential prediction error for a predicted trajectory. Prediction uncertainty typically varies over the length of a predicted trajectory.

B. Methodology to Extend Prediction Accuracy to Uncertainty Estimation

The literature review on current uncertainty estimation methods has shown that, to apply any of these methods, a set of uncertainty modeling parameters have to be first estimated. A methodology, described in detail in Enea et al.,[20] and summarized below, has been proposed to identify and quantify these uncertainty modeling parameters. This methodology, which focuses on using trajectory prediction accuracy metrics and techniques to estimate modeling parameters, consists of four main steps, as illustrated in Fig. 1 (adapted from Ref. 20.)

The first step consists of capturing predicted and observed trajectory data for populating a database from simulations, field test studies, or ATC real-world data. The database has been developed with a structure that is flexible enough to retrieve candidate runs, using different trajectory categories as search criteria to meet the needs of an analyst. More details are provided throughout the paper, as the methods to characterize data are the main theme of this paper. It is, however, worth noting the important role a flexible database plays within the methodology to provide statistically representative data needed to estimate the modeling parameters of various uncertainty estimation methods.

The second step consists of identifying the specific uncertainty estimation method to be used by the DST. This is mainly a function of the requirements imposed by the DST capabilities (e.g., conflict detection and resolution, TFM application).

The third step consists of identifying the required uncertainty modeling parameters as a function of predicted trajectory segments. Segmentation of the predicted trajectory is used because the error propagation (growth or decay) along path typically varies with the characteristics of the predicted aircraft maneuver(s) associated with segments, such as climb/descent rate, speed profile, and lateral path (straight vs. turn segments.) Each segment may require its own modeling parameters to estimate the uncertainty along that segment. Prediction accuracy techniques, such as visualizing the growth and decay of errors along a predicted trajectory, are used to identify these parameters. The database is a useful tool to identify as many data as required by these prediction accuracy techniques. For example, run data with intent maneuvers that match the predicted maneuvers within a segment being analyzed can be quickly identified and retrieved. In this step and the next, the use of prediction accuracy techniques includes choosing an appropriate set of metrics and defining an algorithm for quantifying them. However, it is unlikely that a single prediction accuracy technique or set of techniques can be defined to support the identification of the key parameters for all uncertainty estimation methods. This is why the prediction accuracy techniques are described as a toolbox in Fig. 1, from which the developer must choose the proper tool to meet the specific project objectives, as detailed in Enea et al.[20]

Finally, the fourth step consists of quantifying the key uncertainty model parameters. Statistical prediction accuracy analyses are used to quantify the appropriate metrics.

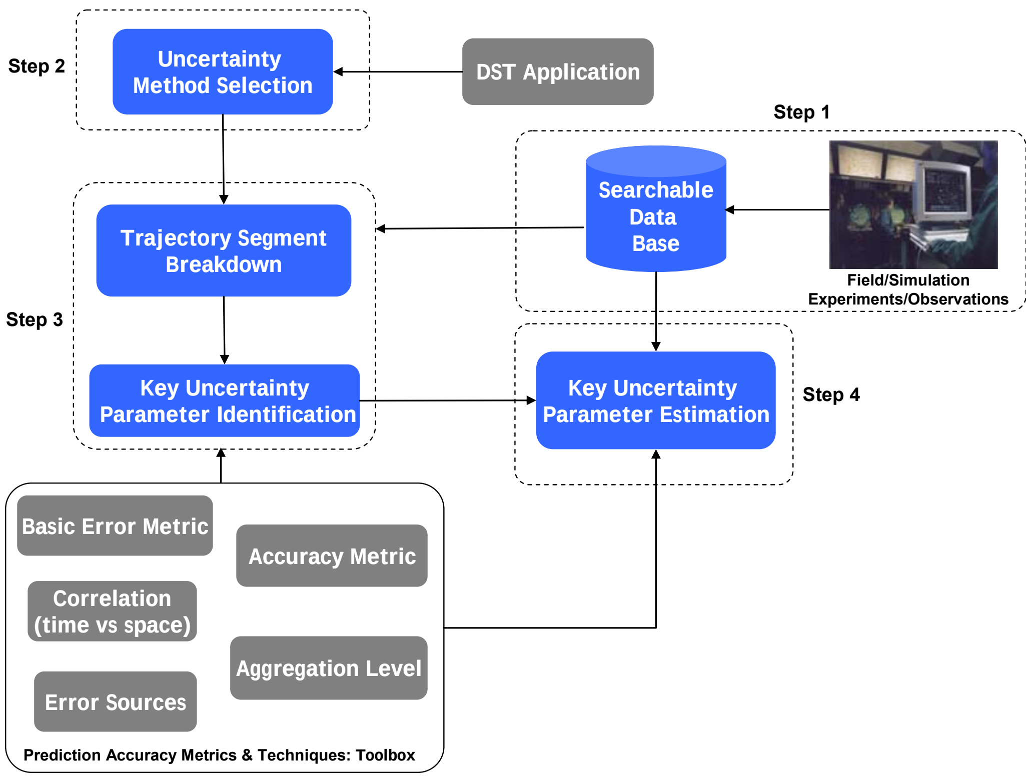

Figure 1. Overall approach for extending prediction accuracy techniques to uncertainty estimation methods

III. A Searchable Database using Trajectory Categories

Any prediction accuracy analysis requires the comparison of predicted trajectories against observed trajectories. Due to the large amount of data required for statistically significant analyses and the wide range of analyses of potential interest, it is desirable to develop a database that facilitates a flexible retrieving of trajectory data to meet the needs of the analyst. By defining and populating data from a wide range of trajectory categories (i.e., characteristics of the data that are of analyst's interest,) the utility of available data is maximized. One advantage of the approach is that it makes the greatest use of available data by enabling the effective reuse of data captured during previous efforts, which are often difficult to obtain. Such a database can support a range prediction accuracy related activities, including uncertainty estimation modeling and TP validation.

The database accommodates as many types of data sources and formats as possible (e.g., recording of raw ATC operational flight data and/or simulation data) and groups the data into as many useful categories as needed. Data categories and queries can be changed with minimal development effort. Fig. 2 illustrates the conceptual use of the database as conceived by the first step of the methodology described in Section II. The analyst defines the subset of data categories of interest and retrieves a set of runs that meets the query requirements. Each run can be independently analyzed using the predicted vs. actual trajectory data. Finally, the accuracy analysis aggregates the error results over a set of runs.

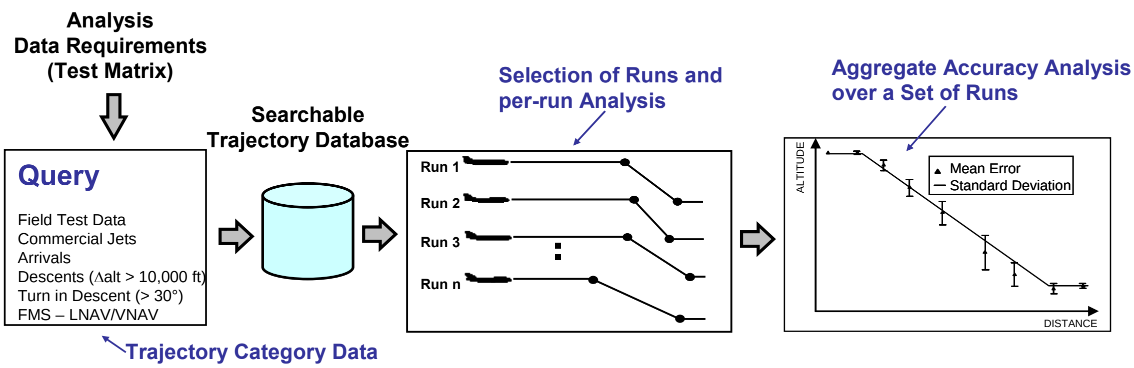

Figure 2. Conceptual use of the database to retrieve information

A. Searchable Database Development

The database is designed to store observed actual trajectory data (e.g., radar tracks), predicted trajectory data, aircraft intent data, and atmospheric data (among other necessary data). These data are conceptually related as shown in the example of Fig. 3. In the example, the observed trajectory consists of the aircraft's first observed state (A), its last observed state (B), and a series of intermediate observed states represented by the dots along the line from A to B. In addition, two aircraft intents, represented by the rectangles labeled "Intent 1" and "Intent 2," which have been applied at some points along the observed trajectory, are also stored. These "intents" represent changes on the flight intent at specific events, e.g., due to a revised ATC clearance instruction. Furthermore, some predicted trajectories that have been generated for this flight (grey lines starting at states C, D, and E) are also stored in the database. Multiple trajectories may have been predicted from a single intent by the same TP at different instances in time. The trajectory is predicted at different initial states (represented by the predicted trajectories starting at C and D). The database may also contain data modeling the physical environment (indicated as "Atmospheric Conditions") consisting of snapshots of the forecast atmosphere (at a relevant set of grid points of the region) taken at discrete instants in time. When predicted trajectories are not available, they can be obtained running a TP off-line with information captured during the data collection. At a minimum, the required data to be stored in the database are the observed aircraft states, atmospheric data and intent information needed to be able to post-run predictions using an off-line TP.

The current version of the database was populated with raw data samples from CTAS operational data recordings and data from the 1994 and 1995 Descent Advisor Field Tests[13,14] converted to a generic data format called the Trajectory Prediction Markup Language (TPML).[21] CTAS operational data consists primarily of observed radar tracks from the FAA Host Computer System and intent information (in the form of flight plans and amendments), and Rapid Update Cycle (RUC) formatted atmospheric data.[22] The TPML data include observed radar tracks, predicted trajectories from CTAS, intent, and atmospheric modeling data at the predicted points for a series of en-route cruise and descent cases. The automated characterization of maneuvers that is detailed in Section IV is only applicable to CTAS operational data.

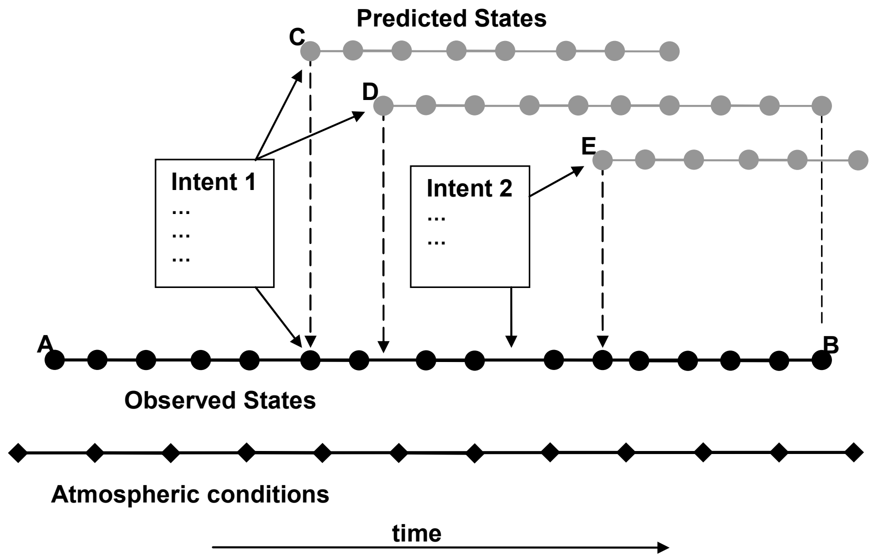

Figure 3. Types and relationship of stored data

B. Trajectory Categories

This section lists and defines the set of trajectory categories included in the database to support the selection of data needed to meet the analyst needs for estimating modeling-uncertainty parameters. Two principles guided the definition of the trajectory categories. The first principle was that trajectory categories represent the fundamental nature of trajectory error source. In other words, although the categories are developed to support prediction accuracy analyses and then estimations of key uncertainty parameters, the design of the categories does not presume any specific error analysis. The second principle was that category definitions are not assumed to be complete. It will always be possible to create new categories to add to the database.

The approach to developing the categories began with an assessment of the FAA/EUROCONTROL Action Plan 16 effort to establish common trajectory prediction capabilities.[3,4] In addition, previously published prediction accuracy studies for the 1994 and 1995 Descent Advisor Field Tests[13,14] were reviewed. A first list of potential categories was developed by evaluating the characteristics of data required to support these analyses. Other analyses were also reviewed to extend the initial list. [15,16,17,19]

Nine categories were finally created (a definition is provided in following paragraphs): Fidelity-Based Data Type, Flight Domain, Vertical Maneuver Type, Lateral Maneuver Type, Maneuver Characteristics, Aircraft Characteristics, Lateral Guidance Characteristics, Vertical Guidance Characteristics, and Environment Characteristics. Fig. 4 illustrates the main categories and subcategories. Additional lower level subcategories are provided in Appendix.

These categories include attributes related to data quality, type of intent maneuver, and aircraft characteristics, guidance mode, and environmental conditions. Database population scripts were developed to identify the values for each category and to fill in the database, if enough information is known. Yet not all information will be known for all types of data. For example, specific maneuver characteristics (e.g., descent Indicated Air Speed) are typically not found in ATC operational data.

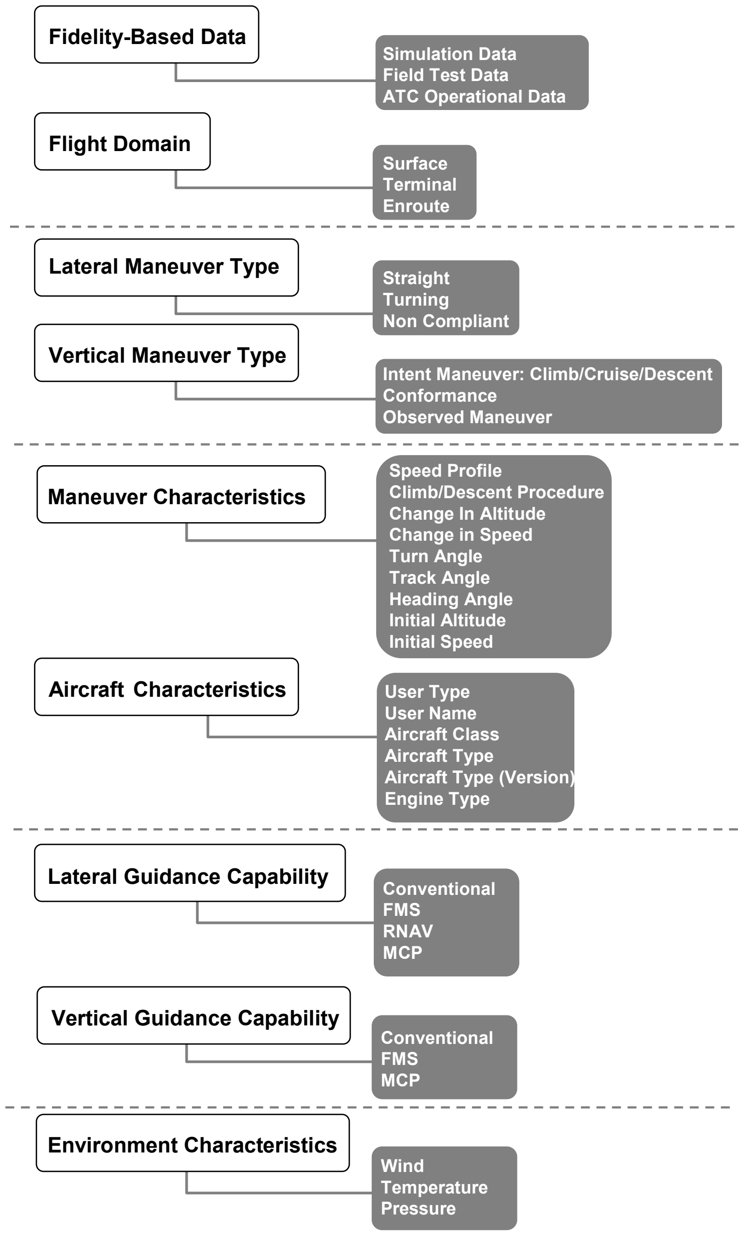

Figure 4. Trajectory Categories and main Subcategories

Flight Domain characterizes the domain of the ATC facility controlling the flight over the relevant portion of the run. This category enumerates three main values, although additional ones may be added, as necessary. First, *Surface* includes aircraft operations from the gate to the runway (Outbound) or from exiting the runway to the gate (Inbound). Second, *Terminal* includes airborne operations in airspace controlled by a Tower or a TRACON. Finally, *En Route* includes operations in airspace controlled by an Air Route Traffic Control Center (ARTCC). Additional sub-levels based on the location of the origin and destination airports respect to the facility that collected the data are also included (see table in Appendix.)

Lateral Maneuver Type characterizes the horizontal movement the aircraft needs to perform to achieve the aircraft's intent, i.e., the horizontal intent maneuver, and its relation to the observed horizontal states. Similar to vertical maneuvers, the maneuvers depend on the observed states of the aircraft and its intent. There are three basic types. First, *Straight Maneuver* is a type for which the aircraft does not perform a specified course (or heading) change in the lateral path.[§] This includes the straight segments of a strategic path (e.g., a flight plan route), straight segments of route capture maneuvers, and straight segments of tactical guidance modes. Second, *Turning Maneuver* is a type for which a turning lateral maneuver is performed to capture a new, specified course (or heading) for the aircraft. This includes turns defined at waypoints within a specified route or tactical turning maneuvers initiating at a given aircraft state. Finally, *Non Conformance Lateral Maneuver* is a type for which the intent lateral maneuver does not conform to the observed maneuver. More details are provided in Section IV.

Vertical Maneuver Type characterizes the vertical movement that an aircraft needs to perform to achieve the aircraft's intent, i.e., the vertical intent maneuver, and its relation to the observed vertical states. The characterization depends on the observed states of the aircraft and its intent information. There are three high level types: *climb*, *cruise*, and *descent*. Detailed characterization is provided and expanded in Section IV.

Maneuver Characteristics provide detailed information about a lateral and vertical intent maneuver (e.g., descent speed profile, change in altitude, or turn angle.) This information often complements the maneuver type category and is not meant to be searched independently from the maneuver type.

Aircraft Characteristics provide detailed information about the type of aircraft represented in the selected run. These characteristics are needed for the analyses that study the variations in behavior across different aircraft types, or even for different operations for a given type. The values captured here include: *User Type* (e.g., Commercial, Military); *User Name* (e.g., American Airline – different users may use different pilot procedures)*; Aircraft Class* (e.g., Jet, turboprop – ATC procedure may differ for them); *Aircraft Type* (e.g., B757)*; Version* (e.g., B757-200); and *Engine Type* (e.g., PW JT9D.)

Guidance Characteristics indicate the guidance system being used by the pilot during a specific maneuver. Depending on the TP's application, this can significantly change the prediction accuracy when a TP attempts to model the aircraft behavior. Two categories have been identified. *Lateral Guidance Capability* defines whether the aircraft is using FMS-based, MCP-based, RNAV-based or no advanced lateral guidance capabilities to fly the lateral path. *Vertical Guidance Capability* defines whether the aircraft is using FMS-based, MCP-based, or no advanced vertical guidance capabilities to fly the vertical path.

Finally, **Environment Characteristics** describe atmospheric information. The values represented by the atmospheric model vary throughout the airspace. Under certain experimental conditions (i.e., simulations,) these values are known and controlled, such that the values do not vary or vary in a defined way. This category captures those variations. If the environment characteristics are not controlled, this category should store the model that was used by the TP (as in real-world RUC meteorological forecast model). Values to enumerate are *winds* and *temperature aloft* characteristics.

The categorization of vertical and horizontal maneuvers is critical, because it is key in selecting representative trajectory data for accuracy prediction analyses. The next section describes the method to characterize vertical and horizontal maneuver types when using operational data recorded by CTAS. However, the characterization of maneuvers is general and extensible to other types of raw data.

IV. Automated Maneuver Characterization from CTAS-recorded Operational Data

This section focuses on the algorithms implemented in the database to automatically characterize intent maneuvers from recording of ATC operational data captured by CTAS during the data population process. The CTAS operational data recordings used during the development and validation of the database were captured at NASA's North Texas Research Facility. These data files contain recordings based on the track data and other intent messages (e.g., flight plans, flight plan amendments, and interim altitudes) received from the FAA's ARTCC Host Computer System of Fort Worth Center.

Among other things, the TP's prediction accuracy is a direct function of the specific maneuver or combination of maneuvers being modeled. As such, prediction accuracy analyses often spend considerable time evaluating the accuracy of a TP for an isolated set of lateral and vertical maneuvers. Therefore, identifying the type of maneuver is critical in prediction accuracy analysis. In particular, maneuvers where an aircraft is not flying consistently with the constraints defined by the intent information are relevant because intent errors would be then introduced in the

[§]The distinction here is that a course change is not specified, though this does not mean that the aircraft's course will not vary. A great circle path or constant heading is considered "straight" even though ground track may vary.

analysis. These maneuvers can be identified by comparing the conformance of intent maneuvers with observed maneuvers. The algorithms used to populate the database characterize intent maneuvers incorporate this information.

Observed trajectory data from operational and field test recording rarely contain explicit information about the actual intended maneuvers, but they are often implied by the aircraft's intent information (e.g., flight plan.) For example, a climbing maneuver after departure could contain actual tracks at the same altitude, indicating a level-off. However, this leveling-off could either be an interim altitude or the beginning of the cruise phase. The additional information needed to add to the maneuver is only discernible after comparing the leveling-off altitude with the intent information (cruise altitude or an interim altitude message). In addition, if this leveling-off altitude is not equal to any available intent information this means that the aircraft intent changed but the system did not register it. Therefore, the prediction based on the last known intent has an intent error for which the analyst must decide if it is relevant for their desired analysis or not.

Some maneuvers may be subdivided if the uncertainty estimation process requires such segmentation. For example, a climb maneuver with an interruption at an intermediate altitude before reaching the cruise flight level can be subdivided in three smaller maneuvers: an initial climb, followed by a level-off at the intermediate altitude and a final climb towards the cruise flight level. Although the classification of maneuvers captures very general maneuver categories, the database design allows the analyst to retrieve smaller subdivisions of maneuvers and associated trajectory points.

A. Vertical Maneuver Tagging Process and Classification

The process to characterize maneuvers from Host data begins with the tagging of each observed state (i.e. radar track) as belonging to one type of intent maneuver or another, based on the sequence of intent messages, actual position values, and the preceding and following observed aircraft states. The objective was to identify those intent messages within Host data that identify types of intent maneuvers and the observed aircraft states that correlate to those maneuvers. It is worth noting that this correlation is less well defined at the beginning and at the end of each maneuver. It is up to the analyst to decide how to refine the association between maneuvers and observed states, being able to extend and reduce the range of states belonging to a determined maneuver.

Each observed aircraft state was tagged with four names that define the vertical maneuver (see Fig. 5.) The first two names characterize the vertical intent maneuver as defined by the intent messages available. The third name refers to the conformance of the intent maneuver and the observed maneuver. The fourth name indicates the observed maneuver as defined by the trend of the observed states. The vertical maneuvers are divided into three main categories (1^{st} name): *climb*, *cruise*, and *descent*. A vertical maneuver is defined as *climb* and *descent* before the Top of Climb (TOC) and after the Top of Descent (TOD),[**] respectively; any altitude change between these two points (TOC and TOD) is classified as a *cruise altitude change* (a sub-maneuver to *cruise*.) However, TOC and TOD are not explicitly available. To tag an aircraft state (i.e., an observed trajectory track derived from radar data) as belonging to one of these three high level maneuver categories, the altitude of the aircraft state and its relationship with the intent cruise altitude and the altitude of preceding aircraft states are compared. For a climb, the altitude of an observed aircraft state should be lower than the flight plan cruise altitude and the preceding trajectory aircraft states should have never achieved the cruise altitude. A tolerance value of ±100 ft is used around a target cruise altitude in order to consider a flight flying at that altitude value. Once one aircraft state altitude achieves the cruise altitude, the subsequent observed aircraft states belong to a *cruise* maneuver until an intent message to initiate the descent is received. Since such a message is not explicitly available in the radar tracks, a *descent* is considered to be initiated if only an intent flight altitude change message is recorded with a difference in altitude higher than a threshold. In the CTAS recording, this is given by a flight plan amendment message or an interim altitude QQ message. The altitude difference threshold used was 6000 ft[††] from the altitude of the state at the time the message is received.

[**] The actual beginning of the descent maneuver starts when the descent clearance is issued. This can result in a "short" cruise segment prior to TOD (e.g., for decelerating to the descent speed), which is actually considered part of the descent maneuver.

[††] This value was estimated from a sample set of aircraft with altitude changes in the cruise phase that were always lower than 6000 ft. If further data shows that this value is too restrictive or conservative, it can be quickly changed in the algorithm of the database.

The first set of sub-values of vertical maneuvers (2^{nd} name) indicates if the aircraft leveled off during the climb/descent maneuver or if the maneuver was uninterrupted. In addition, it indicates if the cruise altitude changed, requiring a climb or descent to the new altitude. This characteristic of the maneuver provides a powerful functionality in the search capability of the database. The analyst is able to choose whether to retrieve trajectories with interrupted climb maneuvers, or even has the ability to choose maneuvers that did not receive any interim altitude messages during the climb or descent[‡‡]. The defining criterion for this characteristic is the occurrence of any intent change message during the duration of a high-level intent maneuver, i.e., climb, descent, or cruise. Note that these first two names are dependent primarily on the intent information present in the data.

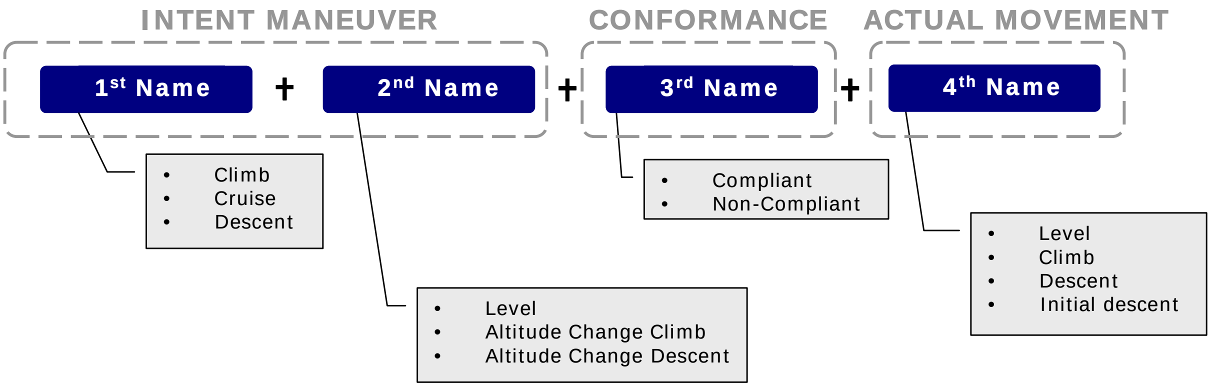

Figure 4. Vertical Type of Maneuvers

The other sub-values of the vertical maneuver provide information about the observed maneuver and its conformance with the intent maneuver. The observed maneuver is a key element for choosing the appropriate runs required by the analyst. However, it is not obvious how to determine the movement with the information provided by observed states. To determine whether the aircraft is climbing, descending, or leveling off, the altitude of the aircraft current state is compared against the altitude of one prior state and three subsequent states.[§§] This is implemented in an algorithm that contains a sequence of three steps:

- First, the logic determines if the aircraft is leveled off by sequentially checking if the observed state is the continuation of a level-off. A level determination requires that the prior state was leveled and the altitude difference between the current state and the altitude associated with the state at the "beginning of the level-off" was equal or lower than 100 ft. If greater than 100 ft, the algorithm then checks if the state is the beginning of a level-off. The beginning of a level-off is determined if the three states ahead are within 100 ft altitude with respect to the current state altitude.
- Second, if none of the first conditions are met, the logic checks if the state belongs to a descent maneuver. This requires two conditions: the aircraft is not level and its current altitude is greater that the altitude of the third state ahead of it.
- Finally, if conditions one and two are not met, the state is considered in a climb.

This logic provides the tag of the 4^{th} name and the conformance (3^{rd} name) is deduced by direct comparison with the intent maneuver. Two examples of actual trajectory data and their identified intent maneuvers from the database are presented next.

Fig. 6 illustrates a plot of the trajectory categories extracted from the database for flight 49042 which descends from cruise to an altitude crossing restriction. Intent information is given by the flight plan message (blue circle) received by the Host at the time 6268 sec from the reference clock. This flight plan is valid for the entire trajectory

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‡‡ Interim altitudes might be received along the climb maneuver within QQ messages; the aircraft may or may not level off at that altitude depending on whether the intent is overridden by additional QQ messages received before reaching that altitude either containing a higher altitude or clearing the interim altitude.

§§ The minimum altitude resolution between consecutive radar tracks is 100 ft, if data are stored by an En-Route Center.

through to the meter fix and was not changed – the solid blue line represents the time interval of validity of the flight plan altitude. At approximately time 7500 sec, the flight enters the center airspace and the radar tracks start to be recorded. At this point the first segment is tagged as "cruise-level-compliant –level", according to the algorithm above. At time 8384 sec the controller of the high altitude sector issues the clearance to descend to the bottom of that sector (FL240) where operational procedures require the hand-off to occur before. An interim altitude (QQ message) is received to start the descent. Interim altitude messages are represented by red triangles in the plot. At this point, the intent maneuver changes from cruise to descent (note that the altitude difference is greater than 6000 ft). A new segment is tagged as "descent-level-compliant-initial descent" for just two tracks. This segment accounts for a lag in the response of the flight to start descending. Moreover, a message introduced into the system by the controller does not typically coincide with the time the clearance is issued to the pilot. As soon as the flight starts the descent, the flight starts descending to the given clearance, and the segment is tagged as "descent-altitude change-compliant-descent."

During the descent, the higher sector hands off the flight to the lower sector. In normal situations, this happens before the flight actually reaches that target altitude, and the receiving controller instructs the flight to continue the descent towards the altitude constraint restriction. This can be interpreted in the graph by the second interim altitude (11000 ft) that is received at 8835 sec. At this time the altitude intent (illustrated by the red line between triangles) changes from FL240 to 11000 ft. In this case, the flight continues descending towards that altitude without interruption. When the flight reaches the altitude crossing restriction, it levels off at 11000 ft, and the segment radar tracks change to "descent-level-compliant-level." Finally, after the flight is handed off to the TRACON facility, it receives the clearance to approach the airport. No intent message is received by the Host reflecting this fact because these data are stored by the en route center, and the TRACON messages are not recorded. The last segment is, therefore, tagged as non-compliant. It is worth noting that there is a distinctive change in vertical descent rate around the time the second interim altitude message is received. However, the reason for that change is unknown since none of the trajectory data gives a clear indication of a required maneuver change.

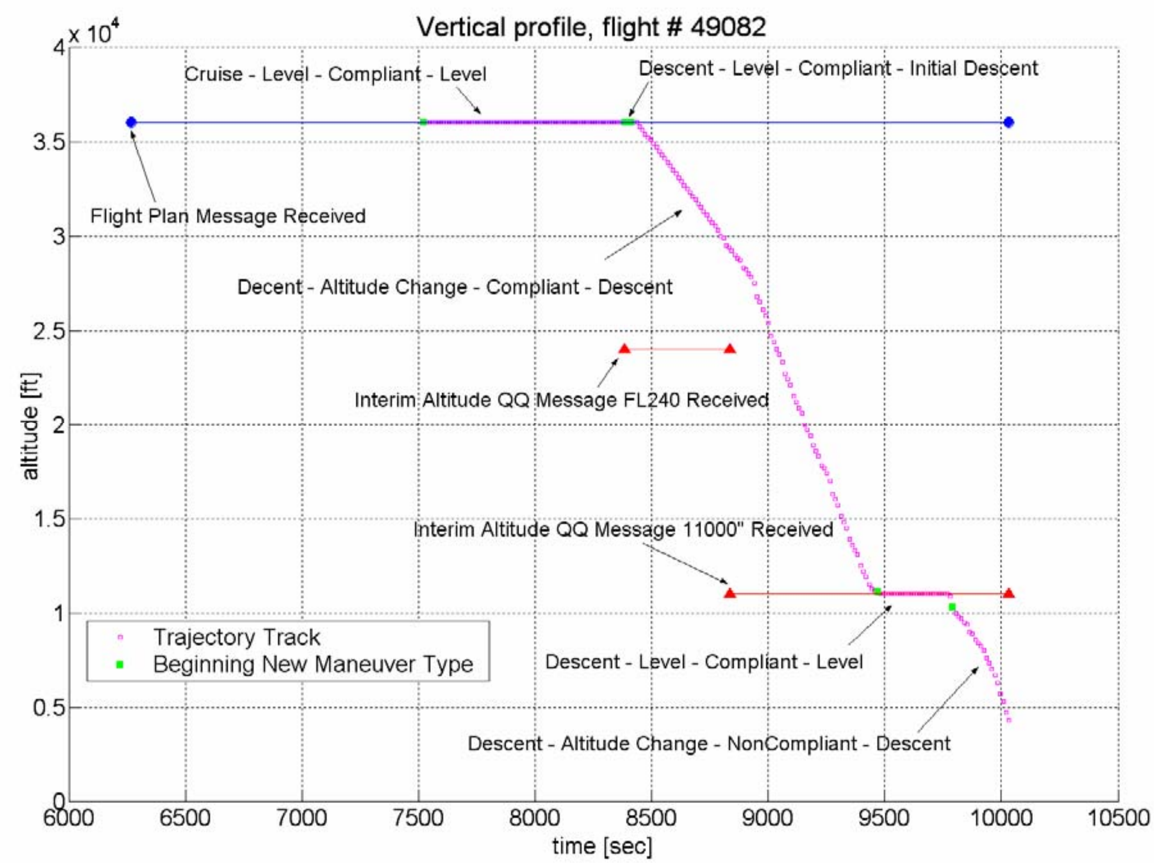

Figure 5. Example of Processed Vertical Maneuvers along a Descent

Fig. 7 presents a second example of the vertical intent maneuver types extracted from the database based on flight 49436 climbing toward its cruise altitude. This example illustrates the case of an interrupted climb maneuver. At 8277 sec the flight plan is received with a cruise altitude of FL390. The initial segment of the climb is processed as “climb-altitude change-compliant-climb.” The flight levels off at FL270, possibly due to a verbal clearance by the controller, but no intent information was introduced into the system or recorded. This segment of the maneuver is not compliant, because the intent maneuver (climb towards the last known intent FL370) does not match the actual observed maneuver (level-off at FL270). This type of interim clearance occurs frequently due to operational requirements.

At time 9098 sec, the controller clears the flight to climb to a new interim altitude below the cruise altitude, and this is captured by the system with the reception of a new intent QQ message. The maneuver (until that point) is stored in the database as “climb-altitude change-compliant-climb.” The flight reaches the target altitude and levels off. This maneuver segment is processed as “climb-level-compliant-level.” This may reflect operational situations where a potential conflict with traffic at a higher altitude was foreseen. In that case, the receiving controller in the higher sector would have stopped the climb until the situation is cleared and then clear the continuation of the climb towards the cruise altitude. At 9522 sec, a QQ message (with a -999999 value) to clear the altitude was recorded. This means that the interim altitude clearance is removed and the aircraft is cleared to continue towards its cruise altitude. The maneuver changes to “climb-altitude change-compliant-climb.” Finally, the aircraft reaches the target cruise altitude and the maneuver switches from climb to a cruise maneuver. A portion of the cruise maneuver at constant altitude is represented in the figure as “cruise-level-compliant-level.”

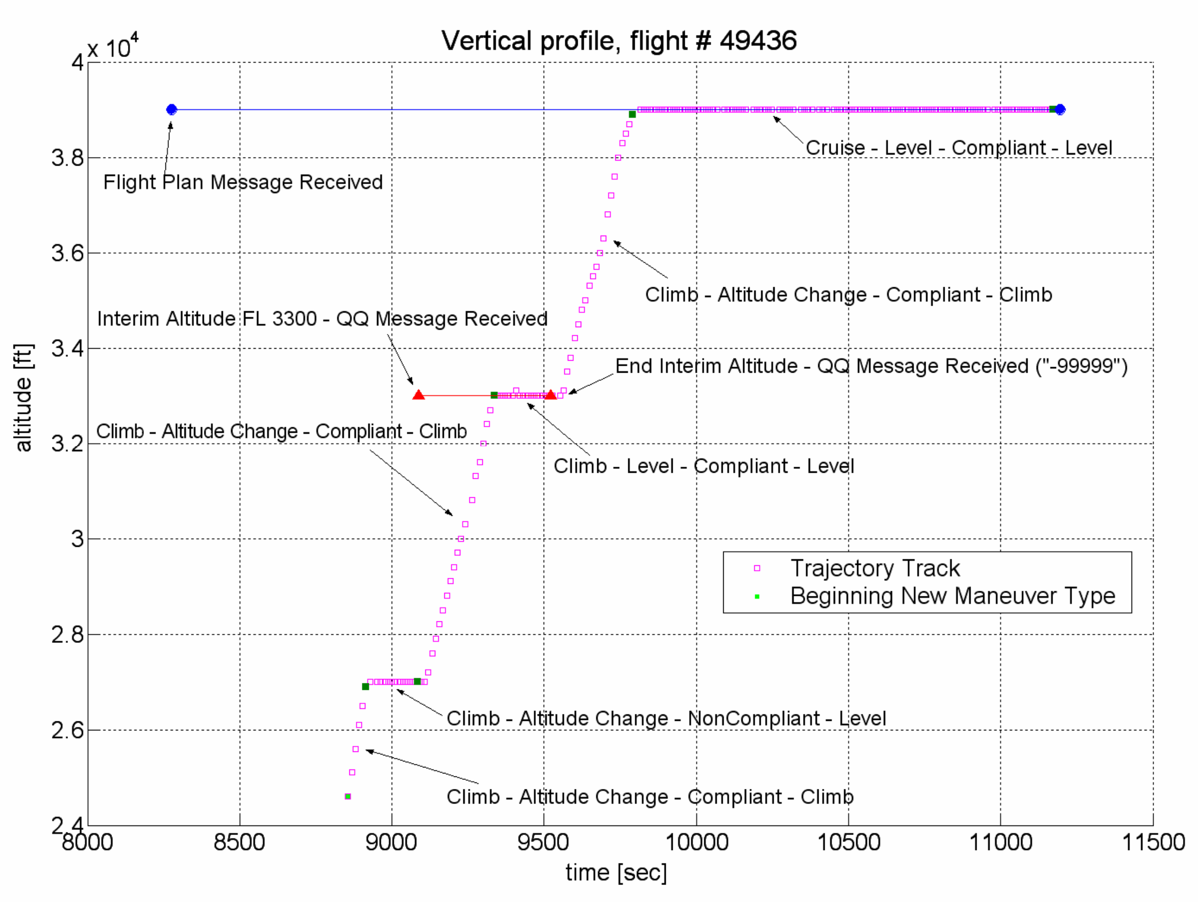

Figure 6. Example of Processed Vertical Maneuvers along a Climb

B. Horizontal Maneuver Tagging Process and Classification

The horizontal path is defined as a sequence of straight maneuvers and inside turn maneuvers at every waypoint.[***] It is worth noting that the maneuvers might overlap (see Fig. 8).[†††] In this figure, it can be observed that trajectory points in turn maneuvers are captured analyzing their spatial position relative to circles of variable radius (x_i). The radius of these circles is calculated as a function of the flight speed (V), type of aircraft (a/c), and the change in course angle (ψ) (see Garcia-Chico and Vivona[23] for justification and formula). Each circle is centered on each waypoint (WP_i) of the flight plan. Only waypoints where the course angle varies by more than 5 degrees are considered as turns (if there is no change in course greater than this value, no turn maneuver is stored for that waypoint). Straight maneuvers are captured by rectangles with sides parallel to the course of the trajectory, i.e., the line that links two consecutive waypoints, 2.5 nmi apart from the center line, assuming airways are RNP-2;[24] perpendicular ends of the rectangle are built at the waypoints. The path is given in the Host flight plan message and any further amendment, and is decomposed into a string of waypoints WP_i. If actual trajectory data are left outside these shapes, the observed data points are tagged as belonging to a Non Conformance Lateral Maneuver. This indicates that the aircraft if flying out of the ATC assigned course.

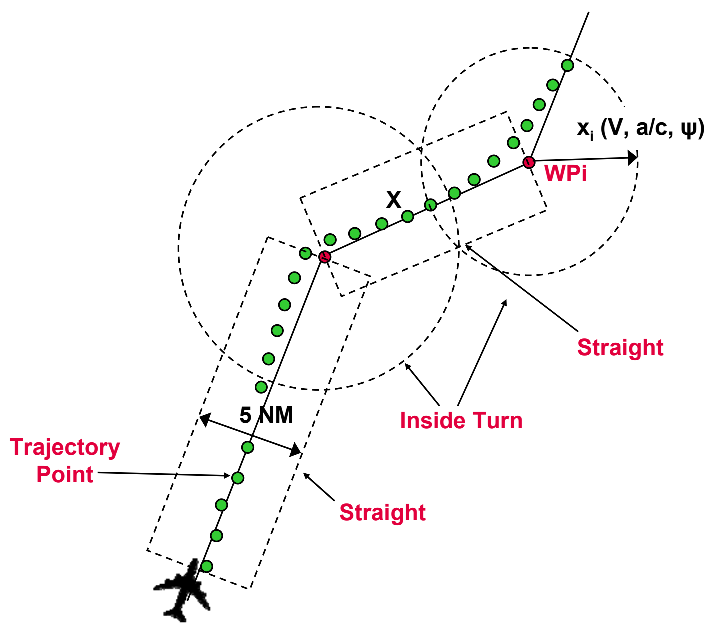

Figure 7. Horizontal maneuvers- straight and turn segments

V. Concluding Remarks and Future Work

The design and effectiveness of any DST is conditioned by the error in its underlying trajectory prediction. Estimating and accommodating trajectory uncertainty in real time is a critical factor to support decision making. Methodologies are being developed with the community to estimate uncertainty model parameters with prediction accuracy techniques. This can only be achieved if statistically representative samples of trajectory data are used to obtain error measurements. Towards this end, an automated process to characterize intent maneuvers from operational data and then to store these data in a searchable database was presented.

In many analyses, it is paramount to select comparable trajectories (observed and predicted) based on the same intent to identify and eliminate intent errors. The algorithms developed here provide this capability and enough flexibility to choose trajectory data according to a wide set of analysis requirements. The database will facilitate the

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[***] Other types of lateral paths are certainly possible, but an aircraft following its flight plan route was determined to be the initial case to be studied.

[†††] The overlap of straight and turning maneuvers was created to ensure sufficient data retrieved for aircraft that do not accurately follow the flight plan route. It is left to the analyst to determine how to appropriately “trim” the excess points for his/her analysis.

analysis of large and representative trajectory data from different sources. Although the current version of the database contains only two types of data (a sample of CTAS operational data recordings and NASA field test data recordings), the database structure and trajectory categories were designed to facilitate the addition of other data formats from different sources. Some additional development may be required to process the raw data and store them into the database. The database will be a powerful tool for storing and retrieving trajectory data from different sources and to serve multiple prediction accuracy analysis requirements.

The methods to characterize intent maneuvers were developed in the context that extends prediction accuracy to uncertainty estimation. This methodology has been applied to a hypothetical climb scenario, identifying what are the parameters that need estimation. Future work will make use of the database to demonstrate the approach using several uncertainty methods applied to an actual climb maneuver. This will demonstrate the flexibility of the characterization and the database's ability to adequately retrieve statistically representative trajectory data. Storing a larger sample of Host data recordings spanning 24 hours is planned to provide an adequate amount of actual operational trajectory data. Specific statistical methods and computing algorithms by which trajectory data extracted from the database will be combined, plotted, analyzed, and prototyped in a suitable programming environment.

VI. Appendix: Trajectory Categories

Category / Characteristic	Values	Sub-Values
Fidelity-Based Data Type	Simulation Data Field Test Data ATC Operational Data	N/A
Flight Domain	Surface	Inbound Outbound
	Terminal	Departure Arrival Satellite Tower EnRoute
	En Route	Overflight Departure Arrival Satellite
Lateral Maneuver Type	Straight (compliant)	Constant Track Constant Heading Direct: Capture Waypoint Capture Route
		Follow Route: Track to Fix Follow Radial
	Turning (compliant)	Waypoint Defined: Turn Inside Start Turn At End turn At
		State Defined: Capture Heading Capture Track Turn to Fix
	Non Compliant	N/A
Vertical Maneuver Type	Climb	Alt Change - Compliant Level - Compliant Alt Change - NonCompliant - Level Alt Change - NonCompliant - Descent
	Descent	Alt Change - Compliant Level - Compliant - Initial Descent Level - Compliant Alt Change - NonCompliant - Level Alt Change - NonCompliant - Climb
	Cruise	Level - Compliant Level - NonCompliant - Descent Level – NonCompliant - Climb Alt Change Climb - Compliant Alt Change Climb - NonCompliant - Level Alt Change Climb - NonCompliant - Descent Alt Change Descent - Compliant Alt Change Descent - NonCompliant - Level Alt Change Descent - NonCompliant - Climb

Category / Characteristic	Values	Sub-Values
Maneuver Characteristics	Speed Profile	Mach and/or IAS values
	Climb/Descent Procedure	Idle Thrust Near-Idle Thrust 3:1 Glide Slope Constant Vertical Rate Max Climb Thrust
	Change In Altitude	Delta altitude value
	Change in Speed	Delta speed value (Mach or IAS)
	Turn Angle	Turn value
	Track Angle	Value of ground track
	Heading Angle	Value of heading
	Initial Altitude	Altitude value
	Initial Speed	Speed value
Aircraft Characteristics	User Type	Commercial Military Test Aircraft
	User Name	Specific user name
	Aircraft Class	Jet Turboprop Prop
	Aircraft Type	Specific aircraft value
	Aircraft Type (Version)	Specific version of that aircraft type
	Engine Type	Specific engine type
Lateral Guidance Capability	Conventional	None
	FMS	LNAV
	RNAV	None
	MCP	Heading/Track Hold Heading/Track Select
Vertical Guidance Capability	Conventional	None
	FMS	VNAV
	MCP	V/R Hold Altitude Hold FPA Hold FLCH
Environment Characteristics	Wind	Zero
		Non-Zero: Magnitude Direction
	Temperature	Standard Non-Standard
	Pressure	Standard Non-Standard

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