

A COLLABORATIVE APPROACH TO TRAJECTORY MODELING VALIDATION

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Abstract

Air service providers view the growth in future air traffic demand exceeding that of capacity, making it increasingly difficult to maintain yet alone improve the current levels of safety and efficiency. Advanced Air Traffic Management (ATM) and flight deck decision support tool (DST) capabilities are seen as the functional enablers of the future ATM concepts needed to increase capacity by two-threefold. Such automation will provide support in flight data, metering, and conflict prediction/resolution functions to name a few. DST capabilities depend directly on the performance of the underlying trajectory predictor(s) (TP) that provide the anticipated future path of the aircraft. The accuracy of the TP is critical to the success of these DST functions.

A joint international effort has begun to develop methodologies and resources for the common development, validation, and improvement of trajectory prediction capabilities. Common methods and resources for TP validation will benefit the ATM automation community at large by providing tools, methods, and validation data that no one organization could afford to develop on their own. A generic TP structure has been constructed and decomposed into individual services that readily map to all the US and European TPs studied. This TP structure enables specific TP elements to be isolated and validated using different types of actual "flown" trajectories from simulation and field/flight observations. A common TP validation strategy has been developed for universal application to each element of the TP structure. The TP validation strategy is complemented by a broad database of actual trajectory recordings posted on a website and formatted in the Extensible

Markup Language (XML). The methodology presented here provides the process for any developer to utilize this database to validate and improve their TP's performance. This paper outlines the TP validation strategy, describes the various types of validation data provided, XML format, and tools developed.

Introduction

Most air traffic service providers (ATSPs) in the United States and Europe anticipate significant growth in air traffic that is expected to out pace the capacity limits of our aviation systems, resulting in greater congestion and inefficiency. Broad advances in ground-based and airborne automation, such as decision support tools (DSTs), are envisioned to mitigate the problem. These tools have many purposes and typically serve to lower the complexity of airspace problems faced by the current human decision makers operating the system. They include tools that serve to predict future conflicts between aircraft, both for ground based controllers or airborne pilots, allowing more strategic separation management of aircraft. Traffic management DSTs include capabilities that forecast where and when traffic workload would stress the system, allowing air traffic supervisors to make more efficient adjustments to either avoid the condition or alter staff and/or airspace accordingly. Such tools also include air traffic metering tools to efficiently sequence aircraft into en route and arrival flows, maximizing the capacity of the system. A common thread in all these DSTs is the accurate and timely modeling of the aircraft's current state and anticipated future path. This function is referred to as the trajectory predictor process or TP. The trajectory is the actual or future four-dimensional path of the aircraft. TP accuracy

can be measured by post flight comparisons of predicted and observed aircraft trajectories. Since the predicted trajectory is the fundamental input that sustains the DST's capabilities and functions, the accuracy of the TP has a direct impact on the DST's overall performance and usability.

While total system performance depends on TP performance (to ensure that specified accuracy requirements are met), the TP validation process can then drive the TP performance toward a targeted level. The objective of this paper is to provide a catalyst for the development of a common TP validation strategy, supporting data, techniques, and tools to improve TP where needed. The goal is to develop a TP validation methodology that is effective, efficient, and useful across the TP community at large.

Overview of Improvement Process

The improvement process is based on a TP validation strategy and a database of generic TP validation data from a multitude of sources. One group of sources, referred to as "derived data," includes aircraft performance model data, flight management system recordings, and flight simulator data. Derived data are available at high levels of accuracy, but can only validate parts of the TP. Operational data, on the other hand, captures a broader set of operational conditions but may lack the detail provided in the derived data sets. Operational data includes aircraft flight data recordings, from experimental flights tests, and air traffic control system recordings.

By utilizing these data sources in a layered approach for validation (first presented in [1]), the TP is dissected into its inner and outer control loops. The inner TP processes are validated first with the derived data sets. As the inner processes are tested, and errors identified, resources can be focused on improvements to the appropriate unit. The broader operational data sets can be used to test the outer processes (as well as re-test the inner processes). Further description of these control loops follow in subsequent sections of the paper. The fundamental characteristic of this approach is the iterative and systematic nature of this process. This approach "bakes down" the errors in an iterative process, increases confidence at each step,

and leads to an improved TP that more closely meets the original DST requirements.

For individual ATSPs developing a specific DST, the cost of assembling this relatively large data set may be prohibitive. However, significant cost reductions may be achieved by the building of a community TP-validation database that leverages contributions from many ATSPs. Under Action Plan 16 (AP16) of the Eurocontrol/FAA R&D Committee and the Eurocontrol CARE/TP Action, validation data is being collected from the FAA, NASA, Eurocontrol, and various European air traffic service providers and stored on a Eurocontrol Internet file server for community use.

By also collaborating and agreeing upon a common set of metrics, the TP's inner and outer control loops can be cross-compared among developers. This would encourage developers to leverage ideas and approaches for improvement as well as the data used to identify them.

This paper is one of a set of papers produced by the AP16 Core Team. The other papers in this set address the proposed structure of a common trajectory predictor [2], the validation metrics to apply [3], a common method for aircraft intent description [4], and an initial comparison of aircraft performance models [5]. This paper presents the AP16 approach to TP validation. The paper begins with the description of a generic TP structure. Trajectory Validation Data Types are then defined and described in terms of their relevance to the Air Traffic Management (ATM) system. The paper then describes the considerations for organizing and accessing the data. The paper concludes with a summary and status of collaborative activities across the U.S. and Europe for implementing¹ the validation database and support tools.

Trajectory Predictor

An aircraft trajectory prediction refers to the development of an estimate of the future positions of a flight given the aircraft initial conditions, a notional path to be followed by the aircraft,

¹ This work is co-sponsored by Eurocontrol, the FAA Air Traffic Operations Planning office and Technical Center, and NASA's Airspace Systems Program and Advanced Air Transportation Technologies (AATT) project.

environmental information, and aircraft-specific data (such as an aircraft performance model).

Several different approaches exist for aircraft trajectory prediction with differing levels of fidelity and data requirements. However, in almost all cases the following categories of data are required:

- *Initial condition.* This refers to the aircraft state and time at the start of the trajectory calculation. The aircraft state vector will include a greater number of elements in the case of a higher-order model. For example, a full motion simulator would require instantaneous bank angle, whereas a point-mass model would not.
- *Intent information.* This describes the notional path constraints the aircraft will follow in the future. This may be a sequence of control instructions for the aircraft (full control settings schedule), a flight plan, or a simple projection of the velocity vector. Intent information can also include the effect of operational procedures (e.g., how a climb is executed by the flight crew, altitude restrictions, etc.)
- *Environmental information.* This refers to external elements that will affect the aircraft behavior, such as winds and temperature aloft.
- *Aircraft-specific information.* This includes the aircraft performance model and flight-specific data such as weight.

Figure 1 illustrates an example of the trajectory prediction process as applied to a commercial flight already en route. This example refers to a generic trajectory prediction process; some trajectory predictors would require more, different or less information. Increased sophistication in predictors can also lead to intent inferencing, in-flight parameter estimation or trajectory error monitoring and recalibration.

This trajectory predictor will have access to the flight plan containing the flight number (e.g., AAA123), the aircraft type (B-757-200), the filed cruise speed (true airspeed of 450 knots), the desired cruise altitude (31,000 feet), and the route of flight (departure from XXX, now heading to ABC, then DEF, finally to XYZ via the BUC 7 Arrival). Furthermore, the trajectory predictor will have an estimate of the initial condition in terms of

aircraft position, speed, heading/course, and rate of ascent/descent. Prior to conducting trajectory prediction, the flight plan route, expressed as named points, will be converted to a series of geographical points (e.g., latitude and longitude). This process is known as *route conversion* [6].

Once the route is converted, a mechanism for joining the initial condition to the converted route is required. This process of *lateral path initialization* may simply involve the identification of the initial location along the converted route. When the initial condition is off-route, a connection from the initial condition to the route is required. Lateral intent modeling, a more generalized form of this trajectory service, manages the alteration of larger portions of the lateral path (e.g., depending on future traffic density forecasts).

In addition to lateral constraints, the process of *constraint specification* determines the vertical and speed constraints along the route of flight. For example, speed constraints below 10,000 feet may be applied, as well as altitude constraints along an arrival route. The concept of longitudinal intent modeling, while implicit in some trajectory predictors, refers to the addition of speed and altitude considerations to reflect the combined actions of the controller, pilot and aircraft system that control an aircraft's trajectory. Examples include the estimation of the top-of-descent and the planned descent speed profile.

All of the above steps must be conducted prior to the calculation of a trajectory using any physics-based modeling. We refer to this collection of first steps as the *preparation process*. The core part of aircraft trajectory prediction follows from the next step. In this part, the horizontal and vertical profiles (including speed) are computed to follow the converted route, meet specified constraints (such as altitude and speed constraints), follow appropriate aircraft dynamics (such as turns, climbs and descents), and consider environmental and aircraft-specific information. The output of this process is a 4D trajectory prediction.

Trajectory Predictor's Structure

The previously described trajectory prediction process is illustrated schematically in Figure 2. This was first presented in [7] and later in [1].

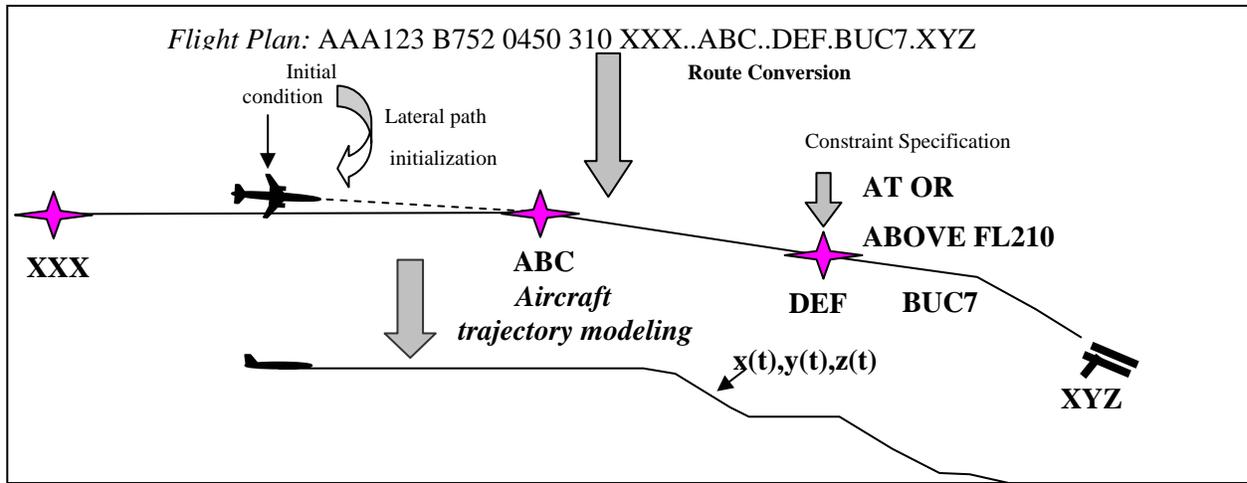


Figure 1: Aircraft Trajectory Prediction – Example in flight [1]

Figure 2 illustrates the generic structure of a wide class of trajectory prediction applications as applied to ATM DSTs (a major category of TP clients). The structure is meant to capture the salient features of many TPs. However depending on the nature of the TP client, some TPs incorporate only a subset of the services listed, while the remainder are either greatly simplified or organized elsewhere (e.g., within the TSP client itself).

In addition to illustrating the preparation process described earlier, sources of data are shown. The output of the preparation process is the *flight script*. The flight script provides the flight-specific information to a *TP engine*. The TP-engine has access to aircraft performance data and meteorological data required to conduct trajectory prediction. The output of the trajectory predictor is a computed trajectory, which can be provided to a variety of *TP export processes*.

The *trajectory update process* is the process whereby the TP re-calculates its trajectory predictions. Trajectory predictors used by DSTs, other than in a user- or automation-initiated trial mode, tend to update the trajectory prediction based upon some trigger. This could be a time-based cycle (e.g., every x seconds), or based upon exceeding an error threshold in the last forecast. This update is in addition to the update required when input information has changed. Upon determination that an update is required, the

trajectory update process will either launch a new preparation process or directly update the flight script and recomputed a new trajectory.

Trajectory Validation Data Types

Validation of trajectory predictors for DST applications relies on data that is available from a variety of sources. For convenience, these sources are categorized as follows:

Derived data – This data is obtained from more accurate and validated models of isolated portions of the aviation system but provides the capability to cover any phase of flight.

- Aircraft performance model data (generated by manufacturer aircraft performance programs)
- Flight simulator and Flight Management System (FMS) data

Traffic (Operational) data – This data can represent a more extensive set of flight conditions. Since this data is obtained from operations, the data will be less controlled than the derived data.

- Aircraft Flight Data Recordings (extracted from aircraft flight data recorders)
- ATC operational data

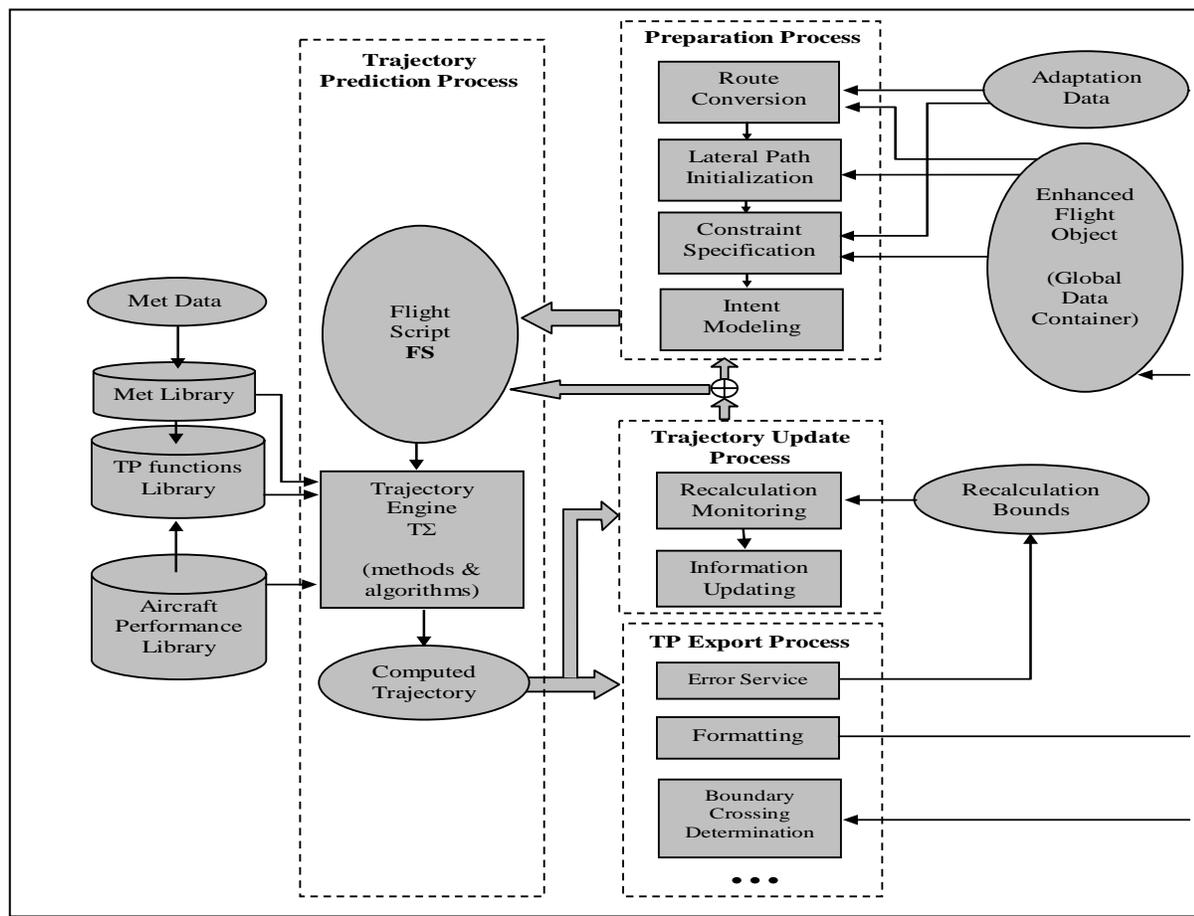


Figure 2: Schematic view of the TP structure (detailed description in [7])

Looking at each one of these data sources within the context of the ATM framework (see [1] and [8]), we can understand which part of the ATM system is being measured. By understanding the relationship between the ATM structure and the TP structure, we can then understand which portions of the TP model can be validated using the different data types. By isolating the TP portions being validated, TP designers, and those responsible for future TP requirements, can understand the performance of various segments of the TP, and which need to be improved to achieve overall performance improvements.

Aircraft Performance Model Data

This type of data is generated from aircraft manufacturer-provided data, generated by their aircraft performance programs. These programs are used to generate aircraft operating manuals. Only the vertical profile of the aircraft is modeled. These

profiles often use a standard atmosphere and zero winds, but are not limited to this. In some cases, specific temperature profiles can be used. For the Airbus program, PEPC, one can specify wind profiles that accurately model the impact of wind gradient. Multiple profiles may be obtained as a function of weight and target speed with specified power setting, aircraft configuration air bleeds, and all the phases of flight (e.g. very low speed descents) in opposition to operational data. Figure 3 shows the portion of the ATM system being captured by this data. However, even this portion is only captured under a limited set of conditions.

For this type of data, both the lateral and longitudinal intent of the flight are not relevant. The only portion of the system being stressed by application of this data is the vertical profile, the speed change segments and the fuel consumption elements of the TP engine. Regardless of the type of TP engine being used, this data can be used to

validate the vertical performance of the TP engine under controlled conditions. Libraries used by the TP engine to generate the vertical profile can also be validated.

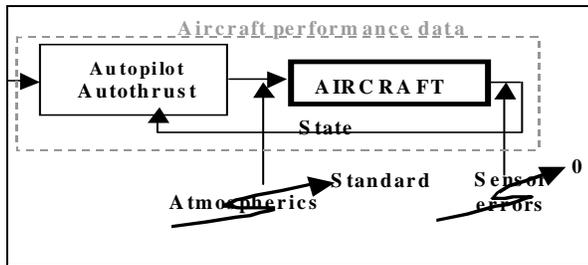


Figure 3: Aircraft Performance Data - Part of ATM

Flight Simulator/FMS Data

This type of data may be obtained from human-in-the-loop flight simulators and from internal Flight Management System (FMS) data. Beginning with FMS data, the Flight Management Computer (FMC) contains an internal model of the aircraft performance and dynamics that are used to generate flight paths used for navigation. Figure 4 illustrates the portion of the ATM system being modeled in the FMS data. Since the data is simulated, sensor errors are not present (unless specifically introduced as an experimental control). Atmospheric data can be specified to the FMC and therefore a broader set of conditions can be investigated than with the prior data type.

By validating against FMS data, the vertical performance of the TP engine can continue to be validated under a broader range of controlled conditions (e.g., wider atmospheric conditions). Since constraints can be specified to the FMS, this type of data can be used to validate the application of constraints within the trajectory engine.

Validation of the lateral performance of the trajectory predictor can be verified using FMS-simulated data. However, this verification is only applicable to flights for which the aircraft is following the FMS-based flight path. When Mode Control Panel (MCP) or manual commands override the Control Display Unit (CDU) command path from the pilot to the aircraft, this validation data is no longer fully applicable.

Pilot-in-the-loop simulations extend the domain further to incorporate almost the entire TP modeling domain (see Figure 4). Pilot intent is now incorporated into the data and the modeling of pilot intent can be validated. Within the TP structure, pilot intent is captured within the lateral intent modeling and vertical/speed intent modeling elements. Under normal operations, this broad term (pilot intent) captures certain pilot decisions such as the timing of certain actions (e.g. initiation of turns or descents), which modes to use (e.g., manual or heading select), and lags in response to commands. If the simulation data includes the pilot inputs (into the CDU, MCP and manual controls) then the actual pilot intent model can be validated directly.

A great advantage of these first two data types is that they facilitate the validation of the TP in areas of the aircraft’s operational flight envelope that are normally difficult to collect operational data (e.g. extreme mass, speeds, altitudes and meteorological conditions).

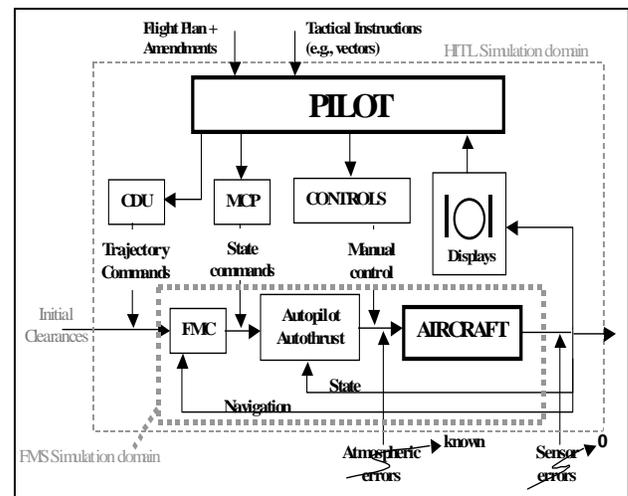


Figure 4: FMS and pilot-in-the-loop simulation data - portion of ATM system

Aircraft Flight Data Recordings

Aircraft flight data recordings are obtained from actual flight operations. The high cost of obtaining this information results in a limited data set of operational cases. When collecting aircraft flight data recording, most if not all of the entire set of ATM control loops are present [1], particularly those related to flight intent. Unlike human in the loop (HITL) simulation data, aircraft data

recordings are subject to actual (uncontrolled yet measurable) atmospheric disturbances and sensor noise. Also, depending on the breadth of data available, greater variation will be present within the data. Aircraft performance will likely vary within aircraft types, aircraft configurations, and pilot procedures will vary due to air carrier policies and pilot differences.

This type of data enables the validation process to be extended to operational environments. If a HITL simulation revealed a certain level of performance, validation through application of aircraft flight recordings would reveal its robustness. For example: whether the TP pilot intent model is valid across carriers; whether the aircraft performance is valid in the real-world across multiple airframes (of the same type); and how the aircraft and atmospheric models perform subject to real-world disturbances. As before, it is desirable to have a complete set of control modes and control paths.

Operational constraints will be applied to these flights and the communication of those constraints to the flight deck will likely be known. This data can contribute to the validation of the constraint specification portion of the preparation process (e.g., are the correct constraints being applied to the flight script at the right moment?). Given the operational nature of this data, the influence of controller intent will be present in the clearances that are provided to the flight deck. However, a fundamental difference exists between this data and the information that is often used by an operational TP. Flight data recordings typically include details reflecting most if not all the instructions that are communicated to the flight crew.

Through reverse engineering, it is possible to deduce many if not most air traffic control instructions. However if a change in speed, altitude, power setting, etc. is observed, it may be difficult to trace this to the source (i.e., due to pilot vs. controller decision). For TP validation this is not so critical because in the flight script it also does not matter who triggered the request for change. However, for the Preparation process (Figure 2), the source does matter.

Current real-time TP applications do not have access to this type of data. Thus, part of the TP controller intent modeling involves the inference of

the current clearance (e.g., “is there a vector?”) with the inevitable introduction of inaccuracies (e.g. difficulty in determining the exact moment when the clearance was applied). A second portion of the controller intent modeling involves the inference of future events (e.g., where will the turn-back be?). By having access to the full controller intent, this data can be used to validate the performance of the TP once these instructions have been correctly placed into the flight script.

ATC Operational Data Recordings

This data type can provide more flights than available through other data types. The data elements include radar surveillance data, Air Traffic Control (ATC) clearance instructions, and ground available atmospheric data. As for all operational data, the effects of the full control loops (see [1] for details) are observed in this data. One of the major distinctions between this type of data and the aircraft flight data recordings is the quality and availability of information available per flight.

ATC operational data is subject to significant surveillance errors, sometimes also including the filtering effects of the tracker. Detailed information about the flight is likely to be missing such as:

- Pilot intent (e.g., actual target speed)
- Mode information (e.g. MCP information)
- Aircraft parameters (e.g., aircraft weight)

The full controller intent may also not be known if voice recordings are not available and accurately synchronized. Thus the flight script may not be known for the flights being investigated. However this is not a hard rule for every element of the flight script. Since the quantity of this data is often high, filtering techniques can be employed to focus the analysis on portions of the flight where the flight script is more complete (e.g. see [9]).

While this data type is often limited in extent, in some cases this data closely represents that which is available to some current ground-based decision support tools [10]. For these types of tools, the data can be used to conduct validation of the complete TP under actual operating conditions. The results will provide performance characteristics of the TP under actual situations. If a validation exercise has been conducted on other aspects of the TP, and the

overall performance characteristics of the TP are valid, then we infer that the TP ATC intent model is adequate. More direct evaluation of the ATC intent model may be conducted when voice data is available including all ATC instructions to the flight deck.

Validation Database

As discussed earlier, a collaborative activity has been initiated that includes the collection of a large set of this validation data. The database, being formed, will provide the TP community a common warehouse of aircraft data to apply the proposed validation methodology leading to the improvement of their TPs. These data include recordings of actual 4D trajectory “truth” data along with the environmental “flight description” data. The flight description data is that data necessary to define the operational conditions under which a TP would operate when attempting to predict the actual trajectory (e.g., aircraft and atmospheric state, and flight intent).

To provide the broadest and most effective dissemination of the TP validation database, key design features were considered in its development. First, the data needs to be complete in its description and organization. For example, positional data of the aircraft’s movements must contain the units in which they are expressed, including degrees latitude or nautical miles for the stereographic coordinate frame. If the route of flight is expressed, the data not only is expressed by fix name to the next fix name, but the coordinates of the fix location are included as well. This prevents the need for airspace adaptation for/by the users, minimizing the cost of applying the data. Second, the data needs to be generic for all sources and types. Thus, the team plans publication of an interface requirements document (IRD) with concise definitions of the format of the data files. Third, the data must be organized in such a manner to be easily converted from proprietary formats of TP developers and incorporation into a relational database for full archiving and searching capabilities. Fourth, the data should be formatted and organized to utilize off the shelf utilities wherever possible to minimize the expense of conversion by the suppliers of the data and conversion by the users when applying it to their

individual TPs. Finally, the generic format and organization of the data needs to be easily adaptable and extensible, since it is unlikely that all the particular details will be known during inception and will most certainly need to be modified as new features are needed in the future.

To achieve these design goals, the development of the validation database is composed of three main areas: a relational database that stores the data, a standard format that encapsulates the data, and a browser/export function that allows users access to the data.

Relational Database

The relational database efficiently stores the TP validation data and provides user search capabilities. As illustrated in Figure 5, the validation database is supplied by various sources in selected native formats or using a standard format for the remaining. In most cases, a conversion process is required to translate the native to the standard format. AP16 has developed an initial version of this, which will be presented in the next subsection.

Some elements of the input trajectory data are uniquely specialized and do not lend themselves to standardization. For example, maps or photographs of geographical data often provide detailed specifications of runway configurations at airports. In other cases, industry may have already defined standards, such as weather forecasts under the Rapid Update Cycle (RUC)². For these cases, the information is simply stored electronically for direct retrieval by users.

Generic TP Data Format

To address the design requirements and minimize development of a set of tools for which both suppliers and users can both utilize and build upon, a standard format is required that concisely encapsulates the TP validation data and acts as the main transfer medium of the data from supplier into

² RUC is an operational atmospheric prediction system that provides accurate short-range (0- to 12-hr) numerical forecast guidance for weather-sensitive users. See meted.ucar.edu/nwp/pcu2/rucintro.htm for details.

the database, from database to user, and other external tools (e.g. TP Test Harness).

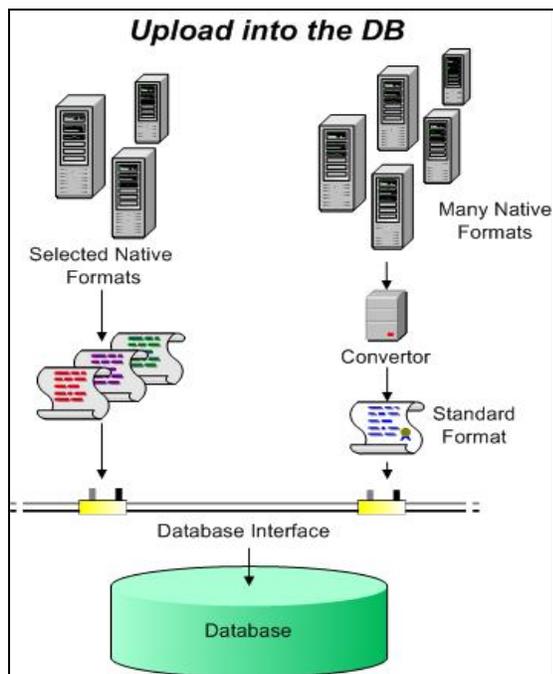


Figure 5: Components for Uploading into DB

The Extensible Markup Language (XML) was utilized to capture the validation data. XML is a World Wide Web Consortium (W3C)³ endorsed standard for document markup and provides a generic syntax used to mark up data with simple, human-readable tags. It provides a standard format for computer documents [11].

Thus, XML is an ideal medium to exchange the trajectory data between TP developers and the suppliers of the data. Based on XML, a standard format has been developed by Titan Corporation supporting AP16. The first release was then tested on a NASA TP on data collected during the 1995 Field Test of the NASA Center TRACON Automation System [12, 13]. This new standard format, called Trajectory Prediction Markup Language (TPML), has five major components that include:

1. Flight Description (FD) provides the requisite information needed by TPs to build the specific flight script each individual TP needs.

2. Initial Condition Data forms the basis of input for trajectory prediction generations along with the FD and atmospheric data; consists of aircraft state information at the beginning of the trajectory to be predicted.
3. Actual (Observed) Trajectory Data represents the actual flight path of the aircraft as reported through radar tracks or some other means (i.e. GPS). Used in the validation of TP results.
4. Predicted Trajectory Data represents TP output and serves as input to the trajectory validation process, offering insights into the overall fidelity of the prediction algorithm(s) from which it came. Note, this component of the standard may not be needed or used by all clients (e.g. they may not have a desire to share their proprietary TP output), but it is part of the standard nonetheless for those who do.
5. Atmospheric (Meteorological) Data represents the observed atmospheric data associated with the airspace in the vicinity of the trajectory to be predicted.

TP Test Harness

The TP Test Harness (TH) application, being developed by Eurocontrol [14, 15], is a validation data driver designed for a generic TP, using Java's graphical user interface from OpenMap⁴. It allows developers to run their specific TP or a number of available TPs on a generic-graphical platform. As a deliverable of the AP16 activities, the TH will be dedicated to the validation of trajectory predictors. It consists of a graphical user interface (GUI) that facilitates the TP "validator" to:

- Define a set of key input data to exercise a TP as indicated in Figure 2. The GUI supports the definition of the adaptation data and information in the enhanced Flight Object, necessary to drive the Preparation process that builds the Flight Script for the specific TP.
- Exercise the selected TP which may reside at a remote location. In effect the communication with the TP is performed through Internet Protocols.

³ See details at <http://www.w3.org>.

⁴ Open Map is an open source Java development toolkit, see <http://openmap.bbn.com/> for details.

- Import the computed 4D trajectory and auxiliary information back into the GUI.
- Extract the required set of reference data from the TP Reference Data Base.
- Compare predicted and reference data to support the application of the validation methodology defined in [1] and metrics defined in [3].
- Provide the validator with a dedicated graphical tool set to study the results.

The TH facilitates the validation (and comparison) of multiple TPs against a consistent set of reference data using a single GUI and a comprehensive set of metrics. As the interface between the GUI and the actual TP software is facilitated through an Internet protocol, it is not necessary to integrate the target TP into GUI. This resolves a lot of potential issues related to intellectual property rights associated with commercial TP distributions. The architecture is illustrated in Figure 6.

The TH can query the large trajectory datasets within the validation database. It also allows the user to make local copies of selected trajectory data and edit them for the developer's specific needs. The only requirement for the TP is it must be adapted to the TH interface.

One of the most salient features of the TH is the ability to graphically deduce the details of the flight maneuvers in the various validation data sets, thus allowing a more detailed flight script to be built. As suggested above, the extension of this feature allows the user to create a local copy of the particular trajectory reference data and alter it based on additional interpretation or focus by the user. This is ideal for testing purposes.

The developer can visually compare the trajectory "truth data" from the database to the trajectory predictions from their TP. This is illustrated in Figure 7. The truth and prediction data is plotted in the horizontal frame with runway and other geographical data is presented. The altitude versus time is also plotted in another window. The two plots are synchronized. This allows the user to select positions along the horizontal path, and then the TH automatically highlights them on the altitude versus time path.

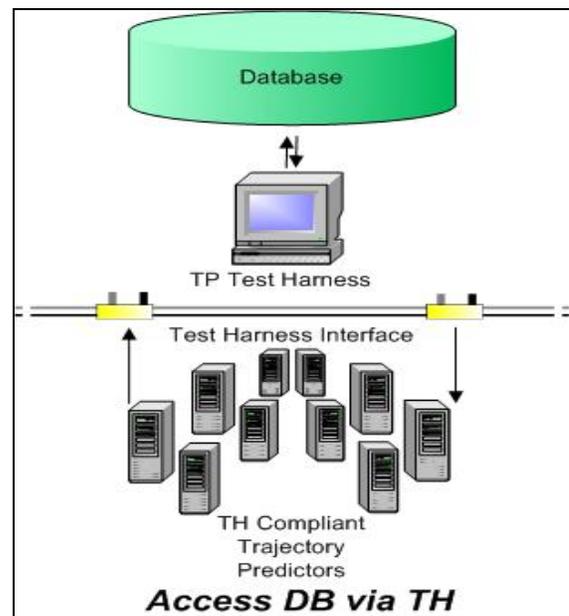


Figure 6: Accessing the Validation Database

Next, the deviations between the truth aircraft positions and the predicted positions by the TP can be explored by applying a suite of tools that calculate metrics and graphically display the results. For example, plots of the speed deviation versus time allow the analyst to visually determine when the prediction deviated from truth occurred. This is illustrated in Figure 8, which shows TH windows of ground speed deviation over time.

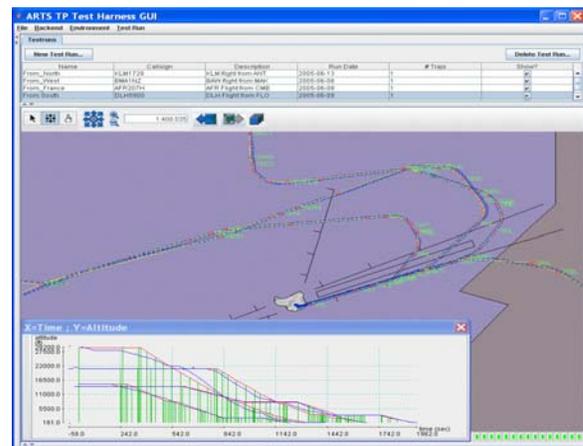


Figure 7: Sample of TH's Graphical Views [15]

Further examination of the speed profiles could show that the flight script was missing a speed change exhibited in the truth data or that it was not correctly, in terms of time, incorporated in the flight script. At this point, the validator can

determine if it is necessary to add this change to the flight script or examine the TP's conformance monitoring capabilities. This could possibly foster the need to perform statistical analyses to determine the frequency of similar events in the larger validation data sets. Thus, the analyst has the ability to determine where an improvement is needed within their particular TP design.

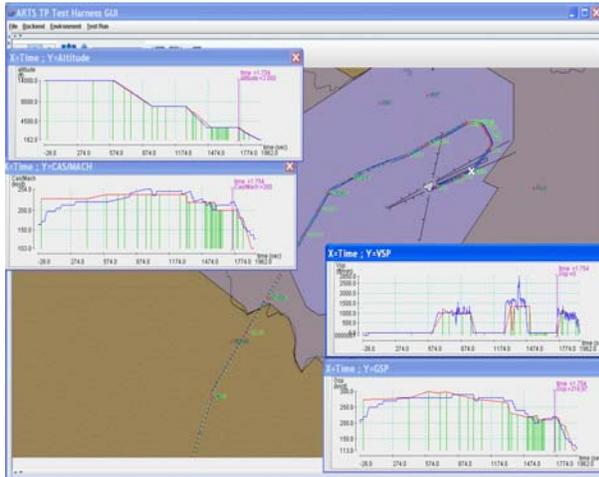


Figure 8: TH Metric Calculation Windows

Summary and Status

An international effort of collaboration has been initiated to foster the development of common capabilities for trajectory prediction and validation. A joint team of researchers from across the United States and Europe have organized under the auspices of FAA/Eurocontrol AP16 to implement these goals. As a part of this effort, the team has developed a methodology for TP validation, based on a generic TP structure, including a validation database, supporting tools, and techniques. This strategy requires a broad validation database, created from a multitude of sources, to minimize the cost to individual sources. These sources includes derived data, such as aircraft performance model data, flight management system recordings, or flight simulators data, which can exercise parts of the TP at high levels of accuracy for a wide set of flight phases. Operational data is also included, such as recordings of flight data from experimental flight tests to actual air traffic operations. This air traffic data contains a broader set of operational conditions but may lack the detail available in the derived data sets.

By utilizing all these data sources in a layered approach as first presented in [1], the TP is dissected into its inner and outer control loops and tested with the various data sources. The inner TP processes are validated first with the derived data sets. As these inner processes are validated and errors are identified, resources can be focused to the appropriate unit and improvements made. Once these inner processes are improved, the broader operational data sets can be implemented to test the outer processes and re-test the inner processes. The fundamental characteristic of this approach is the process is iterative and systematic. The approach will serve to “bake down” the errors in an iterative process, increase confidence at each step, and lead to an improved TP that more closely meets the original DST requirements.

For any single air traffic provider developing a specific DST, the cost of assembling this relatively large data collection could be prohibitive. However, the cost is significantly less by leveraging among many air traffic providers and building a community TP validation database. Under AP16, the validation database has been populated starting with data collected from NASA Ames field trials from the mid 1990s. Eurocontrol has also initiated an ambitious effort to populate the site with flight data recordings collected from operational traffic and operational systems within Europe. This data is expected to be available at or before early next year.

To minimize the investment from both suppliers and users, a standard format was developed that concisely encapsulates the TP validation data and acts as the main transfer medium of the data from supplier into the database, from database to user, and to other external tools. This new standard format, Trajectory Prediction Markup Language (TPML), has been tested on the NASA CTAS TP and applied to the first (current) dataset in the validation database derived from the past NASA field trials.

Eurocontrol is constructing web based tools to query and output all data from the validation database into the TPML format. The schedule for deployment of these tools has not been finalized but is expected for January 2006. Eurocontrol is also constructing the TP Test Harness (TH), currently available as a prototype. It is a graphical user interface that can access the validation database and

run an interface compliant TP. This allows the analyst to utilize the full set of available validation data and perform the methodology proposed by AP16. In the end, the community will have an infrastructure to explore their TP's performance, cross compare results, and make improvements accordingly. Unlike the current environment, this new approach leverages the activities of TP developers across both Europe and the United States, to minimize the costs of such a major undertaking.

References

- [1] Mondoloni, S., M. Paglione, S. Swierstra, C. Garcia-Avello, S. M. Green, October 2004, A Structured Approach for Validation and Verification of Aircraft Trajectory Predictors, 23rd DASC, Salt Lake City, Utah.
- [2] Mondoloni S., S. Swierstra, 2005, Commonality in Disparate Trajectory Predictors for Air Traffic Management Applications, 24th DASC, Washington, D.C.
- [3] Mondoloni S., S. Swierstra, 2005, Assessing Trajectory Prediction Performance - Metrics Definition, 24th DASC, Washington, D.C.
- [4] Vilaplana M., E. Gallo, F. Navarro, S. Swierstra, 2005, Towards a Formal Language for the Common Description of Aircraft Intent, 24th DASC, Washington, D.C.
- [5] Garcia-Avello C., H Idris, R. Vivona, S. Green, 2005, Common Aircraft Performance Modeling Evaluation Tools and Experiment Results, 24th DASC, Washington, D.C.
- [6] Lindsay, K. S., S. M. Green, S. Mondoloni, M. Paglione, 2004, Common Trajectory Modeling for National Airspace System Decision Support Tools, Air Traffic Control Quarterly.
- [7] FAA/EuroControl Cooperative R&D Action Plan 16 Common Trajectory Prediction Capability, 2004, Common Trajectory Prediction-Related Terminology, Version 2.0.
- [8] Reynolds, Tom G., R. John Hansman, June 2000, Analysis of Separation Minima Using a Surveillance State Vector Approach, 3rd USA/Europe Air Traffic Management R&D Seminar, Naples, Italy.
- [9] Gong, C., McNally, D., August 2004, A Methodology for Automated Trajectory Prediction Analysis, AIAA-2004-4788, AIAA Guidance, Navigation, and Control Conference, Providence, RI.
- [10] Kerns, Karol, A. L. McFarland, 1998, Conflict Probe Operational Evaluation and Benefits Assessment, 2nd USA/Europe Air Traffic Management R&D Seminar, Orlando, FL.
- [11] Harold, E. R. and W. S. Means, 2002, XML in a Nutshell, 2nd Edition, O'Reilly & Associates, Inc.
- [12] Vivona, R. A., DePascale, S. M., T. C. Hsu, 2005, Trajectory Prediction Markup Language Standard for the Publication of Trajectory Predictor Data, Version 1.0, Titan Corporation.
- [13] Williams, D. H., and S. M. Green, 1998, Flight Evaluation of the Center / TRACON Automation System Trajectory Prediction Process, NASA/TP-1998-208439.
- [14] Petre, E. June 2005, TP Test Harness Rationale, presented at FAA WJHTC Speaker Series.
- [15] Petre, E. June 2005, Using the TP Test Harness, Working Draft, Eurocontrol Directorate ATM Strategies Air Traffic Services.
- [16] Green, S. M., S. Swierstra, S. Mondoloni, R. Irvine, C. Garcia-Avello, M. Paglione, June 2003, Common Methodology and Resources for the Validation and Improvement of Trajectory Prediction Capabilities, A Proposed Plan for Action.
- [17] FAA/EuroControl Cooperative R&D Action Plan 16 Common Trajectory Prediction Capability, 2004, Validation Data Methodology, Version 1.0.

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