FAA/EUROCONTROL COOPERATIVE R&D

ACTION PLAN 16: Common Trajectory Prediction Capability

Common Trajectory Prediction-Related Terminology

EXECUTIVE SUMMARY

Our experience from the US/Europe Technical Interchange Meetings (TIM) on the subject of Trajectory Prediction (TP) revealed a good deal of confusion between researchers and organizations when, in many cases, the same term was used for very different meanings. In order to reduce this confusion, a common set of terms and understanding is essential for the specification of the architecture and performance characteristics of Trajectory Predictors and the transfer of technical information between co-operating partners. Our approach to resolving this issue involved establishing a glossary of common terms through a small-scale drafting group. It is anticipated that comments received as part of future technical interactions will require future updates of this document.

This document presents a glossary of common terms[1] related to trajectory prediction. The document is organized into the following nine sections:

- Air Traffic Management System Items
- Control Theory Items
- Data Items
- Trajectory Items
- TP-related Processes and Services
- Trajectory-Update Process Types
- Intent Items
- Error, Accuracy, and Performance
- Aircraft Performance Items

It is recommended that the community of organizations involved in trajectory prediction research, development and application review the results of the small-scale drafting group presented herein and propose comments. It is anticipated that AP 16 will review and incorporated those comments where applicable. Furthermore, it is recommended that the community refer to this and future version of this document for technical interchange between disparate participants.

[1] "Common terms" are not necessarily terms that are commonly used. Some terms were added to represent common concepts for which no terms existed.

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1 Air Traffic Management System Items

Basic Decision Support Tools (DST) – Basic DSTs do *not* provide suggested controller intent to resolve detected problems. Basic DSTs detect and monitor problems and provide information to the controller.

Advanced Decision Support Tools – In addition to functions provided by basic DSTs, these tools provide controllers with suggested advisories to resolve problems. Since these tools iterate with the trajectory predictor to generate an advisory, they are expected to have more demanding requirements on trajectory predictor performance such as accuracy and computational speed.

Look-ahead time/ Time horizon – Refers to the time for which a trajectory prediction is considered valid relative to a relevant prediction error.

2 Control Theory Items

Closed Loop Control – Systems in which the output quantity has an effect upon the input quantity are called closed-loop control systems. Typically, these systems apply feedback to modify the control inputs to a system such that the system reaches or maintains a desired state

Open Loop Control – Systems in which the output quantity has no effect upon the input quantity are called open-loop control systems. Typically, control inputs to reach a desired system state are pre-computed and applied. These may be pre-computed using a mental, or computational model of the system. The system will respond to disturbances without compensation.

Open Loop Adaptation – The model of the system is altered as a function of the operating condition. When the operating conditions are known in advance, open loop adaptation can be used to schedule the variation of the system as the conditions vary.

Self-Adaptive System – A self-adaptive system is one that has the capability of changing its parameters through an internal process of measurement, evaluation, and adjustment to adapt to a changing environment, either external or internal, to the plant (controlled system) under control. Certain self-adaptation relying on measurement of system outputs are called **closed-loop adaptation**.

Adaptive Trajectory Prediction – Applies feedback of the trajectory prediction error to dynamically modify the aircraft, intent or atmospheric model in an effort to reduce the trajectory prediction error.

3 Data Items

Track Report – A point estimating the position of the aircraft by the automation at a specified time.

Track – 1. A series of points (track reports) that estimate the position of the aircraft by the automation. 2. A track report 3. [ICAO Doc 9569] The projection on the earth's surface of the path of an aircraft, the direction of which is usually expressed in degrees from north (true, magnetic or grid)

Aircraft State/State vector – A set of characteristics or attributes for an aircraft at a given point in time. This term commonly depends on the number of degrees of freedom being used by the aircraft model. In 6 degree-of-freedom applications, the aircraft state can define all degrees of freedom (position, velocity, angular positions and angular velocity). In ATM applications, typically refers to position, velocity and horizontal angular position.

Waypoint – A reference location used for navigation. Waypoints may correspond to a specific latitude/longitude or may be *conditional* (also called *floating*). Waypoints can be specified in a variety of manners such as: latitude/longitude, fix-radial-distance, intersection of two radials, etc. A conditional waypoint is conditional on the trajectory (e.g., turn to heading 270 upon crossing 2000 feet). [7100.11a] A predetermined geographical position used for route definition and/or progress reporting purposes that is defined by latitude/longitude.

Airway – [ICAO Doc. 9569] A control area or portion thereof established in the form of a corridor equipped with radio navigation aids.

Route – 1. A combined series of way points and airways, that specifies the *approximate* lateral path to be followed by a flight. The way points are approximate since turn dynamics will result in aircraft flying by, or over, a way point. 2. [RTCA-SC181] (also, host track). The track or route defined by the way points in the active flight plan

Vertical Profile – The altitude of the flight as a function of the distance (or time) along track.

Speed Profile – The speed of the flight as a function of the distance (or time) along track.

Flight Profile – (Deprecated) Use vertical profile or trajectory depending on context.

Trajectory change point (TCP) – Refers to a location in the trajectory at which a characteristic of the aircraft trajectory will change, for example, the top of descent.

Operational Constraints – Something that restricts the trajectory from following a nominal case. Examples are speed, altitude and time constraints. Operational constraints can occur at a point (e.g., AT OR BELOW FL240 at a specified way point) on a leg (e.g., AT MACH 0.78 on a leg), or in a region (e.g., BELOW 250 KCAS when below 10,000 feet). *[Note that operational constraints are distinguished from aircraft performance constraints.]*

Flight Plan – A flight plan consists of intent information that can be used to predict an aircraft's trajectory. This includes, but is not limited to; the origin, destination, route, aircraft type, cruise flight level, cruise speed, and departure time.

Adaptation Data – Adaptation data is information that defines the operating environment for a DST. Two types of adaptation that are used in trajectory prediction are airspace adaptation, which includes definition of airspace elements, and aircraft adaptation, which includes aircraft performance characteristics, pilot models, and company preferences. Airspace adaptation data defines waypoints, airways and operational constraints. Examples include: airway definitions (preferential routes, Standard Instrument Departures (SIDs) and Standard Terminal Arrival Routes (STARs)), fix and airport definitions, center/sector boundaries, special use airspace, planned holding areas, altitude restrictions, speed restrictions, and flow restrictions.

Atmospheric Data – Atmospheric data includes wind, temperature, density and pressure as a function of location (3D) and time. Not all trajectory models will include the effect of all atmospheric data elements on the aircraft trajectory. Atmospheric data may also include ancillary data such as turbulence level, and precipitation.

Company preferences – These are used to represent different behavior of identical aircraft in identical situations belonging to different operators. For example, different aircraft operators may climb or descend identical aircraft differently.

A/c derived data or down linked parameters – Data sent from the a/c to the ground. It could be used in the process of **Adaptive Trajectory Prediction**.

Specific Excess Thrust - The result of the calculation of (Thrust - Drag) / Weight. This term can be used to compute a climb gradient (CGR) when combined with information about the longitudinal acceleration of a flight.

4 Trajectory Items

Trajectory — A four dimensional (e.g., latitude, longitude, altitude and time) description of an aircraft's flight path. A trajectory may be predicted or actual.

4.1.1.1 Flight Path = Trajectory

Actual trajectory – The trajectory that was experienced by a flight

Predicted/Forecast trajectory – An estimate of a flight's future trajectory, multiple predicted trajectories may exist for a flight

Trajectory stability – The degree to which predicted trajectories remain constant as a function of time. A stable trajectory prediction will have small discrepancies between trajectories predicted at successive moments of the flight.

ATM system trajectory – Extended description of the trajectory. (additional data could be: speed, rates of climb/descent, a/c heading, track heading …)

Maneuver – Instruction on how a change of direction should be performed. (e.g. ARINC424 maneuvers description)

5 TP-Related Processes & Services

The Trajectory Predictor generates an aircraft's forecast trajectory, typically for client applications. The TP is associated with four distinct and closely related processes, the core of which is the trajectory prediction process (see Figure 1). Several of the processes can be further decomposed into "services" (see Figure 2) previously described in the FAA Research Management Plan (RMP) on Common Trajectory Modeling[2].
In practice, many organizations aggregate these processes and services differently. Although Figure 1 provides a universal TP framework, individuals may only be referring to a subset of processes when discussing TP. It is critical, when discussing trajectory prediction, to be clear what processes/services are assumed to be included in "TP".

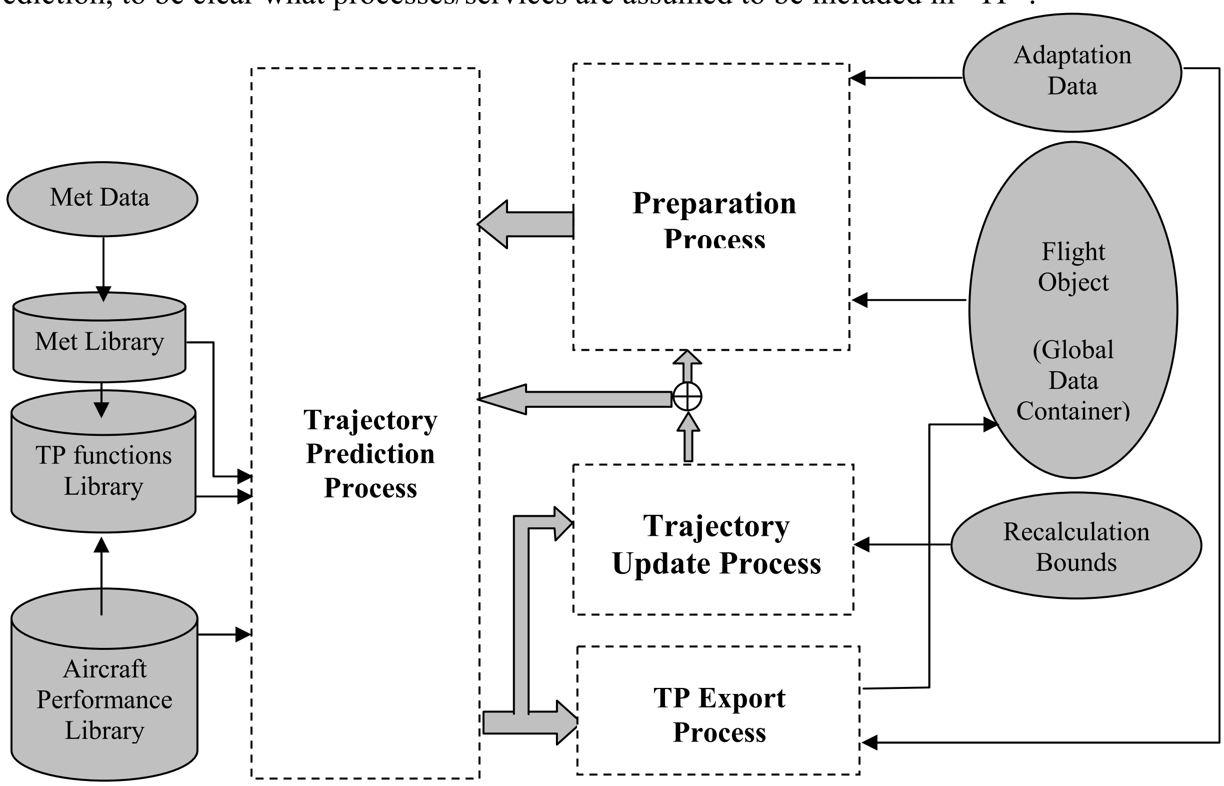

Figure 1. Trajectory Predictor (TP) Related Processes

Preparation process – The process of creating the initial version of the *flight script* (defined below). This process is activated the first time a trajectory needs to be computed for a flight. Input data needs range from flight plan, airline operating procedures, ATC constraints to meteo and aircraft performance. The service will concatenate the data and build a FS describing the flight segment(s) being predicted.

Trajectory Prediction Update process – The process of updating the flight script in response to evolving information. Some TPs may do this according to a wall clock, as

[2] FAA/NASA Interagency ATM Integrated Product Team Cross-Cutting Area Work Team. *Common Trajectory Modeling Services for NAS Decision Support Tools – Research Management Plan*. May, 2002.

new state and intent data become available, others in response to events such as conformance monitoring. The update process may result in the generation of a new flight script, or it may modify information and trigger a new preparation process. Externally updated trajectory predictors do not involve an update process, whereas automatically updated trajectory predictors do. Adaptive trajectory predictors use the update process to alter the models used by the trajectory prediction engine. Automatically updating trajectory predictors result in the update process "zeroing" out any errors that have accumulated since the previous trajectory prediction for a flight.

Trajectory Prediction Process – This is the trajectory engine calculation using the information contained in the flight script. Since the interface between the flight script and the TΣ is highly customized and interdependent, these elements are grouped into the trajectory predictor process. From an object-oriented view, the flight script is considered as the data and the engine as the methods.

TP Export Process. This collects all the "output" services of the trajectory predictor.

Flight Script (FS) – The flight script contains all the flight-specific data required by the Trajectory Engine (TΣ) to compute a trajectory. The flight script is formulated to remove all intent ambiguity. The flight script includes "instruction" type data such as how to compute a turn, or how to execute a climb (i.e., the operational constraints on the trajectory segments to be modeled as well as the criteria for transitioning between trajectory segments). Consistency must be ensured between the flight script and the engine so that the engine supports all instructions commanded by the script.

Trajectory Engine (TΣ) – The TΣ is the computer process that computes a predicted trajectory using different types of algorithms and integration process. All the data specific to an individual trajectory prediction is identified within the FS.

The TΣ will also access meteo databases and aircraft performances databases. These databases are used by the TΣ to either compute the impact of met and aircraft performance, or to request the impact directly. For example, a kinetic model would compute the vertical speed, but a kinematic model would obtain the vertical speed for a specific condition.

The trajectory engine also combines the altitude, speed and lateral trajectory specifications into one unified trajectory. This may be accomplished through a variety of methods such as using trajectory break points, or a mapping of the vertical profile onto the lateral path.

TP-Related Services – TP-Related Services represent the abstract functions that are typically related to trajectory prediction. For example, route conversion is considered a TP-related service, since this is a common service that must be provided in many trajectory prediction processes. Services may exist prior to, during and after the calculation of a specific trajectory.

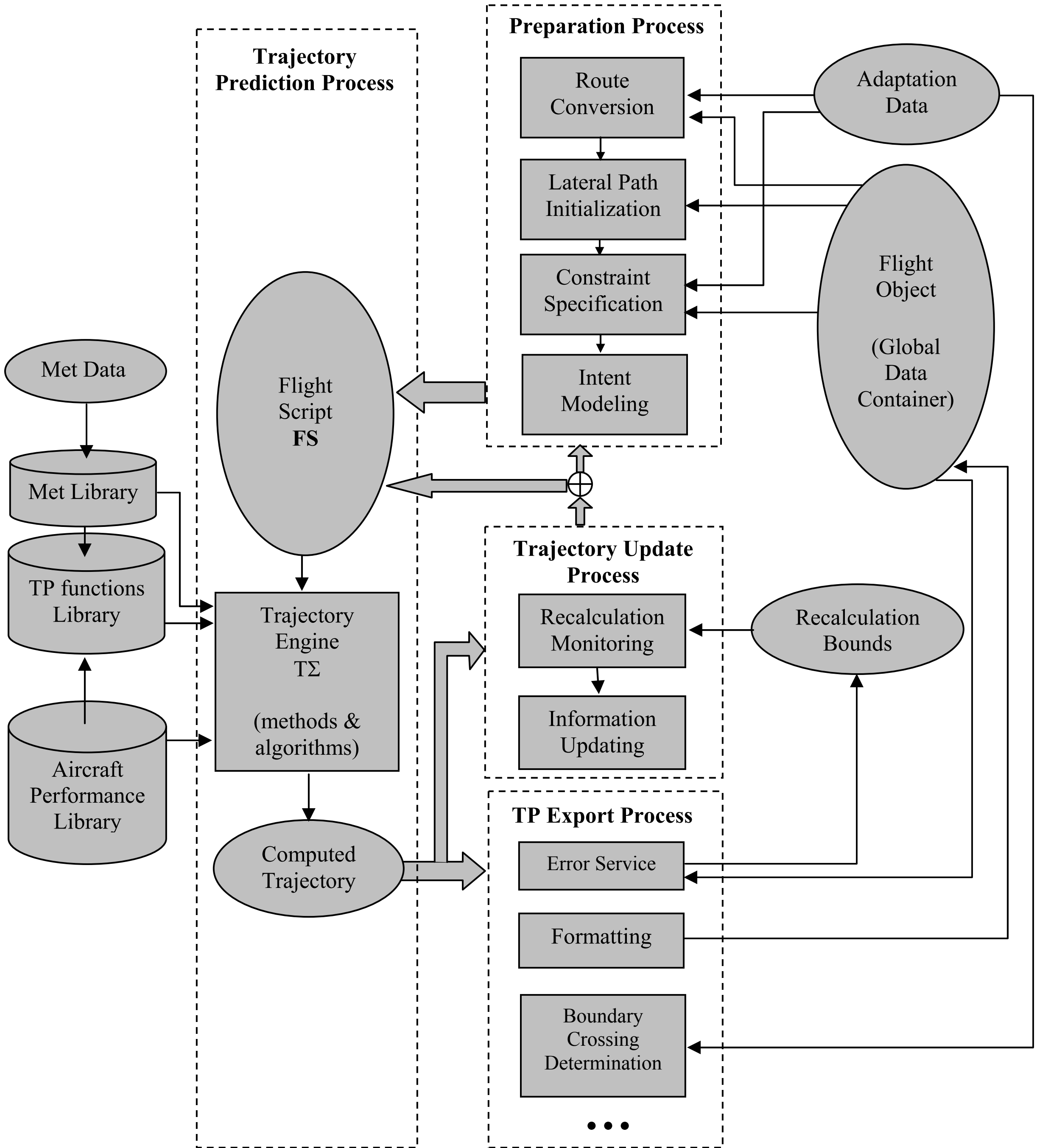

Figure 2 represents a schematic view of the TP structure

TP-Related Services identified within existing TPs – These services have been identified within existing TPs.:

1. Route Conversion
2. Lateral Path Initialization
3. Longitudinal and Vertical Constraint Specification
4. Longitudinal Intent Modeling
5. Altitude, Speed and Turn (if applicable) Modeling
6. Boundary Crossing Determination
7. Formatting
8. Recalculation monitoring
9. Trajectory Information Updating
10. Trajectory Error Service

Route Conversion/ Route Extraction – The process of translating a route, a series of airways and waypoints, into a series of latitudes and longitudes points. Preferential routes may be applied during this process.

Lateral path initialization – This is the process of determining the path from the present position to the route.

Longitudinal and Vertical Constraint Specification – The process of determining needed flight plan constraints. Constraints include assigned altitude and speed, altitude, speed and time restrictions, and interim altitude.

Longitudinal Intent Modeling – The process of specifying how the aircraft will fly, given all available information. For example climbs may be conducted at constant power with loop closure on climb rate or speed. Longitudinal intent modeling covers both speed and vertical degrees-of-freedom. Intent modeling may be explicit, or implicit in the trajectory models.

Altitude, Speed and Turn (if applicable) Modeling – This service is contained in the trajectory engine.

Boundary Crossing Determination – This is the service of identifying the points where the computed trajectory crosses specific volumes of airspace. This service operates after the trajectory has been computed.

Formatting – This is the service of packaging a predicted trajectory for the requisite client application.

Recalculation Bounds – This parameter determines under which circumstances a trajectory must be recalculated. This parameter may be a specified maximum allowable trajectory prediction error (lateral, longitudinal and/or vertical error) that triggers re-calculation. Alternatively, if the trajectory is on a time cycle, the recalculation bounds may be a simple time step. Recalculation bounds may be computed dynamically through the error service, or specified as fixed.

Recalculation Monitoring – This is the process of monitoring information to determine if a new trajectory must be calculated. One approach monitors the trajectory prediction errors to determine if re-conformance is required. (Note this is distinct from the conformance monitoring function performed by the controller to monitor flight plan conformance.)

Trajectory Information Updating – Trajectory information updating is the initial step required to re-calculate a trajectory when indicated by the recalculation monitoring service. This may be accomplished through modification of the flight script, or through initiation of a new preparation process. The updating of information is critical for automatic trajectory updates and adaptive trajectory predictors as described under the *Update Process.*

Trajectory Error Service – This service monitors the aircraft state and prior predictions to provide measures of trajectory prediction accuracy. These may be used by the recalculation monitoring service. Depending on the design of the trajectory predictor, this service may provide data such as: a trajectory prediction error, a forecast error, historical errors, or error thresholds.

6 Trajectory-Update Process Types

The update process can be classified into two general types of updates: external and automatic. This distinction may be used to differentiate trajectory predictors that have bundled the update process as part of the trajectory predictor from those that have not. If the update process is not bundled with the trajectory predictor, the trajectory update process is external. DST applications may also have different types of update processes built-in. For example, a DST with manual trial planning would have an external trajectory update process, as would the corresponding TP. A DST updating with every new track hit would have automatic trajectory updates in the DST, but the TP would likely have an external trajectory update process.

The most current information (e.g., state and intent) is always used to calculate a predicted trajectory.

External Trajectory Updates – External trajectory updates occur when the prediction of a trajectory is triggered in response to external events or requests.

Automatic Trajectory Updates – Automatic trajectory updates involve the prediction of a trajectory and the continuous updating of that prediction. The updating of the predicted trajectory may be time-based, or based upon an event such as the exceeding of a conformance bound or getting new radar position updates. One may further compare automatic updates according to the frequency with which the updates are conducted.

7 Intent Items

Ground Automation Intent – The behavior of the aircraft that is expected by the ground automation (e.g. flight plan and amendments provide long-term intent, interim altitudes provide medium-term intent)

Controller Intent – Desired behavior by the controller that will have an impact on the aircraft trajectory. The controller intent may not be entirely observable or quantifiable. For example, a controller may vector an aircraft by assigning a heading, the controller intent includes a turn-back, but the precise magnitude and timing of that maneuver may not be known a priori.

Aircraft Intent – Behavior by the aircraft that will have an impact on the aircraft trajectory.

Pilot Intent – Desired behavior by the pilot that will have an impact on the aircraft trajectory. An example includes the placement of the top-of-descent during descents at the pilot's discretion.

Intent error – Discrepancies between the intent used by the TP and the combined controller, pilot and aircraft intent. For example, a TP using ground automation intent would suffer intent errors due to discrepancies between ground automation intent and the combined controller, pilot and aircraft intent.

Pilot models – These incorporate the effect of predictable pilot behavior on the aircraft trajectory. An example would be the latency in the execution of a maneuver after a clearance is granted and read-back.

8 Error, Accuracy, Performances

Instantaneous trajectory prediction error – The difference between the actual aircraft position at a particular time and the forecast position along a predicted trajectory at the same time.

Lateral (cross-track) error – 1. The cross-track error is the component of the instantaneous trajectory prediction error that is perpendicular to the actual aircraft ground track. 2. [RTCA-DO236A] The perpendicular deviation that the airplane is to the left or right of the desired path. This error is equal to the cross-track component of the *total system error*.

Longitudinal (along-track) error – The along-track error is the component of the instantaneous trajectory prediction error that is parallel to the actual aircraft ground track.

Vertical error – The vertical error is the vertical component of the instantaneous trajectory prediction error.

Speed error – The speed error is the difference between the instantaneous speed of the aircraft and the predicted one.

Heading error – The heading error is the difference between the instantaneous heading of the aircraft and the predicted one.

Accuracy – [From ICAO Doc 9613, RTCA/DO-208] The degree of conformance between the estimated, measured or desired position and /or the velocity of a platform at a given time and its true position or velocity. Radio navigation performance accuracy is usually presented as a statistical measure of system error and is specified as:

a) Predictable. The accuracy of a position in relation to the geographic or geodetic coordinates of the earth.
b) Repeatable. The accuracy with which a user can return to a position whose coordinates have been measured at a previous time with the same navigation system.
c) Relative. The accuracy with which a user can determine one position relative to another position regardless of any error in their true positions.

Note that this is a general definition of accuracy, and it must be placed in a specific context in order to be applied

Calculation time – Time required by the TP to compute a trajectory. (The time to calculate *one* integration step could also be considered)

9 Aircraft Performance Items

Kinetic – Trajectory modeling using a kinetic approach is concerned with modeling the forces on the aircraft (thrust/drag, lift/weight) and deriving the acceleration using Newton's first law. For ATM applications, kinetic models use a point-mass model of the aircraft and longitudinal forces are modeled on the point mass (thrust/drag and lift/weight).

Kinematic – Kinematics is the study of motion without reference to mass or force. Trajectory modeling using a kinematic approach uses parametric models of acceleration and speed. These parametric models may depend on a small or large number of parameters.

Turn Dynamics – The aircraft state vector evolution during a turn. Both kinematic and kinetic models may incorporate or exclude models of the turn dynamics.

Aircraft Performance Constraints / Flight Envelope – In the ATM arena, these refer to the limits of maneuvers that are expected from aircraft operating in the system. The limits not only include physical limits to performance, but also acceptability to the flight crew and even may take into account passenger comfort. These limits include limits on climb rate, descent rate, turn rate, speeds, altitudes and acceleration/deceleration.

Aircraft Performance Data – Aircraft performance data required for trajectory prediction will depend on the type of model used (kinematic/kinetic). These data will include aircraft performance constraints, and data required by the model to compute the aircraft accelerations. In a kinetic model, force and mass data would be required (e.g., thrust, drag and weight). For example drag may be a function of configuration, lift coefficient, and Mach number. In a kinematic model, acceleration data is required (e.g., climb rate as a function of temperature and altitude).

Aircraft Performance models characteristics/classification – Aircraft performance models exist in a variety of forms and as the result of different techniques used in their development. **Classes** refer to the type of aircraft performance model being used and the **level** refers to the quality (see "some remarks", below) of the reference data being used.

Aircraft performance models supporting kinetic trajectory modeling

> **Class A a/c performance model** – Supports a full six degree-of-freedom trajectory calculation. This approach models the forces and moments (loads) affecting the airframe along all axes of motion as a function of the aircraft state and control settings. Accurate functional relationships between the loads and state/control values are typically obtained from the aircraft and engine manufacturers. These relationships are frequently expressed in tabular form as they are derived from empirical

measurements. Furthermore, since the aircraft is controlled through operation of control surfaces and engines, this model requires knowledge of the control laws for determining the control settings. Various analytical techniques exist for obtaining lower fidelity models of aircraft loads as a function of airframe geometry and technology-level (e.g. supercritical airfoils).

Class B a/c performance model – Supports a point mass model. This approach models the a/c as a point and only requires the modeling of the resulting longitudinal forces affecting this point – Thrust and Drag (it is assumed that the lift compensates for the weight). If required, fuel flow can be modeled as a function of Thrust. Thrust, drag and fuel flow data can be expressed in tabular or polynomial form. The reference data required to produce such a model needs to be thrust data (e.g. installed net thrust), drag data (e.g. for high/low speeds and for each a/c configuration) and thrust specific fuel consumption. However as this data is difficult to obtain, profile data (e.g. altitude vs. time) may be used. These data represent the motion of the aircraft as a result of the combination of all the forces affecting it ((thrust-drag)/weight). In order to differentiate individual forces from this set of integrated reference data, a large set of profile data must be used covering the whole flight envelope and the associated operating regime (e.g. climb thrust, idle, etc.).

Aircraft performance models supporting kinematic trajectory modeling

Class C a/c performance model – This approach models the macroscopic behavior of the a/c (e.g. rate of climb/descent, rate of acceleration/deceleration) as a polynomial function of a set of input parameters affecting that behavior (e.g., altitude, temperature). In order to cope with discontinuities in the a/c performance, multiple polynomials can be used to model unique behavioral characteristics.
The reference data required for the modeling process is limited to a/c rates of change and does not require the availability of thrust and drag data.

Class D a/c performances model – Similar as Class C but the tabular data approach is used as modeling method. Basically nothing differentiates a Class C – level 2 model from a class D model. The reason for preserving this naming convention is historical. Tabular models of Class D are a very simple approach giving rates of climb/descent for a few altitude bands without taking into account any other significant parameters.

Some examples

Class A, level 1 – A/c flight simulators dedicated to pilot training

Class A, level 2 – Six degree-of-freedom research a/c flight simulators using aircraft performance data obtained from engineering formulations of stability derivatives (e.g., from airframe geometry).

Class B, level 1 – Based on Thrust, Drag and TSFC reference data and using the tabular data approach: INFLT from Boeing, PEPC from Airbus, OPAL from former MDD and FOS from ATR.

Class B, level 2 – Based on profile reference data and using the polynomial approach: BAse de Donnees Avion (BADA) model.

Class C, level 1 – Based on rates of change (climb, descent, acceleration and deceleration) reference data and using the polynomial approach. Includes a model of the complete flight envelope: General Aircraft Modeling Environment (GAME) model.

Class D (equivalent to Class C, level 2) – Based on rates of change (climb and descent) reference data and using the tabular data approach (no weight or speed impact). The Central Flow Management Unit (CFMU) model used for TP in flow management.

<u>Some remarks</u>

Independent of the approach used and the mathematical method used, the accuracy/fidelity of the resulting model is heavily affected by several quality aspects of the reference data used to produce the model:

- Granularity of the reference data (e.g., number of data points per profile)
- Accuracy of the reference data (e.g., times to climb rounded to the minute)
- Suitability of the reference data (e.g., profile data is not suitable to model thrust and drag forces)
- Flight envelope coverage of the reference data.

For any modeling approach selected, the number of input parameters taken into account by the model (sensitivity analysis applied to a/c performances modeling) as well as how accurately their impact is modeled (granularity of tabular data, type and degree of polynomials used) will heavily affect the fidelity/accuracy of the resulting model.

The validation of any a/c performance model produced needs to be performed not only against the reference data used to generate the model itself, but against reference data covering the complete flight envelope.

10 Recommendations to the Community

A collection of common terms and a common TP framework has been presented in this document. The consensus achieved in this document represents the views of several disparate agencies and participants. We encourage readers involved in the trajectory prediction community to respond with comments and feedback to the FAA/Eurocontrol Action Plan 16. All your comments will be reviewed thoroughly by the team and responded to. Subsequent versions of the paper will incorporate received comments. Please use the attached comment form (file name: "ActionPlan16Comments01.doc") and mail to: tim-tp@cena.fr by October 25, 2004.