REVIEW DRAFT

White Paper

Common TP Structure and Terminology
in support of
SESAR & NextGen

Eurocontrol/FAA Action Plan 16
Common Trajectory Prediction Capability

Version 1.0, January 29, 2010

EXECUTIVE SUMMARY

The paradigm change towards Trajectory Based Operations (TBO) has led to the deployment or planned deployment of many Air Traffic Management (ATM) decision support tools, across the US and Europe and improvements in airborne Flight Management Systems. Trajectory prediction is fundamental to automation, and the validation and improvement of trajectory predictors lie on the critical paths to success of TBO.

Unless extensive improvements are made, most air service providers view the future of air transport as increasing in demand faster than capacity, making it increasingly difficult to maintain yet alone improve the current levels of safety and efficiency. Decision Support Tools (DSTs) provide support to flight data processing, metering, or conflict prediction functions. The common thread to all these tools is the Trajectory Predictor (TP) that is responsible for predicting the anticipated future path of the aircraft. As a result, the performance of the TP is critical to the success of these DST functions.

The primary purpose of Eurocontrol/FAA Action Plan 16 is to minimize duplication of effort in the many organizations involved in tool and predictor development, thereby reducing costs, reducing time to deployment, and enhancing the quality of the validation and improvement process.

Recent developments in SESAR and NextGen revealed that there is a good deal of confusion between the researchers, developers and organizations when, in many cases, the same term was used with different meanings. Therefore, a common set of terms and definitions is crucial for the specification of architecture, requirements and performance characteristics, as well as the structure for TPs and the communications of this information between related parties.

The objective of this white paper is to address common TP structure and terminology issues, applicable to both airborne and ground based applications, in order to be aligned with the evolution and developments in the SESAR and NextGen systems and to disseminate the proposed terminology and structure to the community, which includes TP developers, DST designers, Flight Data Processing and Flight Data Management system developers and users, Flight Object community, etc.

REVIEW DRAFT

Introduction

Since the 1970's, research on Air Traffic Management (ATM) tools in both Europe and the United States focused on technology that supports Trajectory Based Operations (TBO) rather than the tactical approaches in use today. During the past decade, these ideas have been widely adopted within the ATM community [Ref. 1], leading to international initiatives such as the Single European Sky ATM Research Programme (SESAR) [Ref. 2] in Europe and the Next Generation (NextGen) [Ref. 3] concept of operations in the United States. At both their foundation, these initiatives are based on TBO.

In 2003, European and United States experts joined forces in, what is now referred to as CCOM-Action Plan 16. This Action Plan focuses on all issues related to Trajectory Prediction in airborne and ground based systems. For making progress, it appeared essential to identify the commonalties among the many disparate Trajectory Predictors used in fielded and research applications. The group published a White Paper describing the structure of a generic Trajectory Predictor (TP) using the common terminology that was used at that time to launch several collaborative research initiatives on both sides of the Atlantic [Ref. 4].

With the advent of the SESAR and NextGen as well as the work in defining an ATM Flight Object, several terms that were in common use in the TP community were redefined within the context of these programs. Moreover, it appeared that the common TP structure as published originally by AP16, needed further expansion/decomposition to better support a U.S. initiative at the National Aeronautics and Space Administration (NASA) for capturing the characteristics of disparate, legacy TP's. This work is an essential stepping stone for developing an approach for defining TP performance requirements for the future SESAR and NextGen systems. At the same time it was a kind of validation of the common TP structure.

The sequence of events resulted in a need to review the definition of the common TP structure and to realign the common TP related terminology with the reality of the SESAR, NextGen and Flight Object worlds. The information presented is based on the lessons learned when performing or studying the work reported in the References in Annex A.

The scope of this paper covers the definition of terms required to describe how the trajectory prediction function supports the high level concepts in SESAR and NextGen. It includes the level of detail required to describe the trajectories in an unambiguous way to support the essential system wide synchronization. To that effect the paper proposes a generic structure of the TP that is applicable to airborne and ground based applications. The paper builds on the terminology that is already defined by the SESAR and NextGen concept developers and the working groups addressing the Flight Object. An extensive discussion of TBO vs. TM vs. TP is not within the scope of version 1.0 of this paper but may be considered in subsequent revisions.

The issues addressed in this white paper include:

- The context of Trajectory Prediction in the SESAR and NextGen systems in particular in support of Trajectory Management concepts;
- The interaction between the TP and the Flight Object (FO);
- The definition of a **common, generic** structure for a TP;

REVIEW DRAFT

- The definition of a common terminology for describing the processes, datasets and interfaces of the generic TP that is in line with the terminology used in SESAR/NextGen Concept of Operations (CONOPS) and the work on the Flight Object.

The outline of the paper is as follows:

Part 1 describes the Trajectory Prediction function in the context of the SESAR and NextGen systems.
Part 2 presents the generic TP from a process perspective.
Part 3 presents the generic TP from a data perspective.
Part 4 presents conclusions and proposes next steps.

Annex A: References
Annex B: Related Bibliographie
Annex C: Glossary

Part 1: TP Context

1.1. Trajectory Based Operations

The new ATM concepts proposed by both SESAR and NextGen introduce a paradigm shift from today's, mainly tactical, ATM to a Trajectory Based concept of Operations (TBO). This shift will enable airspace users to plan and execute their operations in collaboration with the ATM service providers by means of 4D trajectories (Business/Mission Trajectory in the SESAR terminology). TBO will lead to a better management of human workload, an increase in productivity and a more efficient leverage of advanced automation capabilities. Thus, the implementation of TBO will require the human actors in the ATM system to rely on advanced Decision Support Tools (DSTs) that will assist them in the execution of Trajectory Management functions whilst keeping the global system human centric.

1.2. Trajectory Management

Trajectory Management (TM) is a fundamental principle of TBO and is at the core of both SESAR and NextGen. The fundamental element in Trajectory Management is the Business/Mission Trajectory. TM is the process by which the Business/Mission Trajectory of the aircraft is established, agreed, updated and revised through Collaborative Decision Making (CDM) processes between the aircraft operator, ATM service providers and Airports (where applicable), except in time-critical situations when only flight crew and controller are involved. TM controls the adjustment of the Business/Mission Trajectories of individual aircraft within a flow to provide efficiency, manage complexity and ensure adherence to safety criteria by resolving potential conflict situations. In the future ATM system, advanced TM functions will be carried out by DSTs.

TM is only imposed when resource contention requires. In that case, the TM process considers any Air Traffic Flow Management (ATFM) constraints and known airspace plans in establishing the best mitigation to resource contention. TM manages the trajectories of aircraft transitioning out of self-separation operations and for aircraft entering or leaving flow corridors. For arrival/departure operations, TM assigns each arriving aircraft to an appropriate runway, arrival stream, and place in sequence. TM supports the Safety Management function through managing the frequency and complexity of potential aircraft conflicts and reduces, but does not eliminate, the need for controller initiated, tactical separation maneuvers. In high-density or high-

REVIEW DRAFT

complexity operations, and especially for climbing and descending aircraft around airports, some potential conflicts may be left to the controller as otherwise the system may become over constrained possibly leading to an underuse of available capacity.

1.3. Flight Object

Key to the success of TBO is the requirement that all stakeholders, including air and ground automation systems, will have a common, synchronized view of the user's Business/Mission Trajectory. This will be achieved through the Flight Object (FO) concept [Ref. 5]. The FO is a single logical entity kept up to date by all parties wishing to share information about a flight. In order to support the sharing of consistent flight data, the FO will be widely and easily available to stakeholders via the System Wide Information Management (SWIM) network, subject to appropriate access controls. Most of the work on the FO to date has focused on internal Air Traffic Control (ATC) interoperability and has only dealt with trajectory synchronization issues between flight data processing systems. However, to achieve the full potential benefits of TBO, an approach for system-wide synchronization of trajectory related information will be required, i.e. including airborne and airspace users' automation systems.

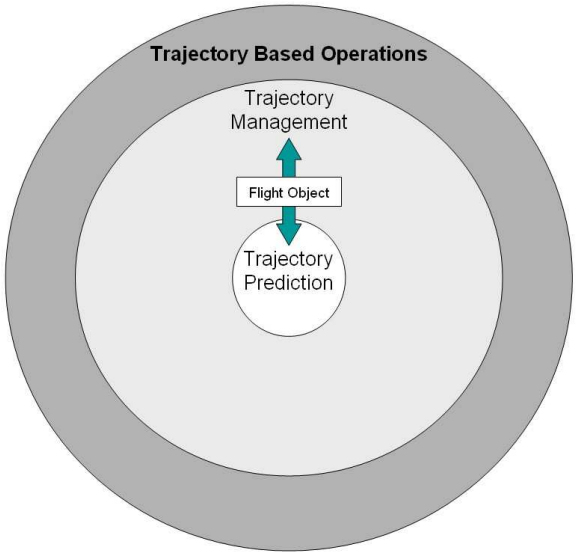


Fig. 1 Trajectory Prediction in the Context of Trajectory Based Operations

1.4. Trajectory Prediction

For the computation and adaptation of the Business/Mission Trajectories, the DST's will rely on the services of Trajectory Predictors (TP). Trajectory Prediction is a function that supports Trajectory Management. In practice, due to the differences in guidance and navigation functions in the air and the multiple trajectory prediction processes in the ground automation systems, it will not be feasible for a DST to make meaningful adjustments to trajectory data directly. Hence, DST's will, instead, adapt the Flight Script of a flight. The Flight Script is one of the key elements of the Flight Object [Ref. 5]. It is intended to include all the flight data needed by a TP to reproduce the intended aircraft trajectory. Fig. 1 illustrates the notional relationship of these key concepts from TP to TBO.

1.5. Terminology

First, a set of common terms is defined, which allows the aviation community to discuss the relations among concepts, TM and TP unambiguously. This issue is exacerbated by the often

REVIEW DRAFT

disparate areas of expertise within the aviation community. To mitigate these issues, it is constructive to specify the definition of a term, explain its meaning in a particular context and to identify the party that manages the definition.

Then, a set of terms is identified that need to be standardized to ensure proper understanding of TP functionality. The references within [..] brackets refer to the group that that has defined the term originally[1].

Trajectory Based Operations (TBO)	Trajectory Based Operations (TBO) refers to the use of 4D trajectories as the basis for planning and executing all flight operations supported by the air navigation service provider. [*Concepts*]
Trajectory Management (TM)	Trajectory Management (TM) is a fundamental principle in the SESAR and NextGen systems. It is the process by which the Business/Mission Trajectory of the aircraft is established, agreed, updated and revised through Collaborative Decision Making (CDM) processes between the aircraft operator, ATM and Airports (where applicable) except in time-critical situations when only flight crew and controller are involved. TM controls the adjustment of the business trajectories of individual aircraft within a flow to provide efficiency, manage complexity and ensure adherence to safety criteria by resolving potential conflict situations. Trajectory Management is effected by Decision Support Tools (DSTs). [*Concepts*] <u>Notes:</u> The term TM describes high level activities within the SESAR and NextGen systems. In this context, the processing performed by a TP to compute a 4D trajectory that, e.g. meets time constraints is not considered a TM function, but an activity <u>supporting</u> TM.
Business Trajectory (BT)	The Business Trajectory (BT) is the representation of an airspace user's intention with respect to a given flight, guaranteeing the best outcome for this flight (as seen from the airspace user's perspective), respecting momentary and permanent constraints [*SESAR*]. <u>Notes:</u> The term Business Trajectory describes a concept of operation, rather than a set of data. It refers at least to two groups of data: • Intent information describing the preferences of the operator, the

[1] Version 1.0 of this White Paper lists, as an example, some of the categories of trajectories that have been identified by SESAR. Later revisions of this paper will extend the categories to include definitions for, e.g. User Preferred trajectories (UPT), Active Trajectories, Provisional Trajectories, etc. These definitions will be compiled in close cooperation with the original “owners” of the terms to ensure global consistency and avoid ambiguities.

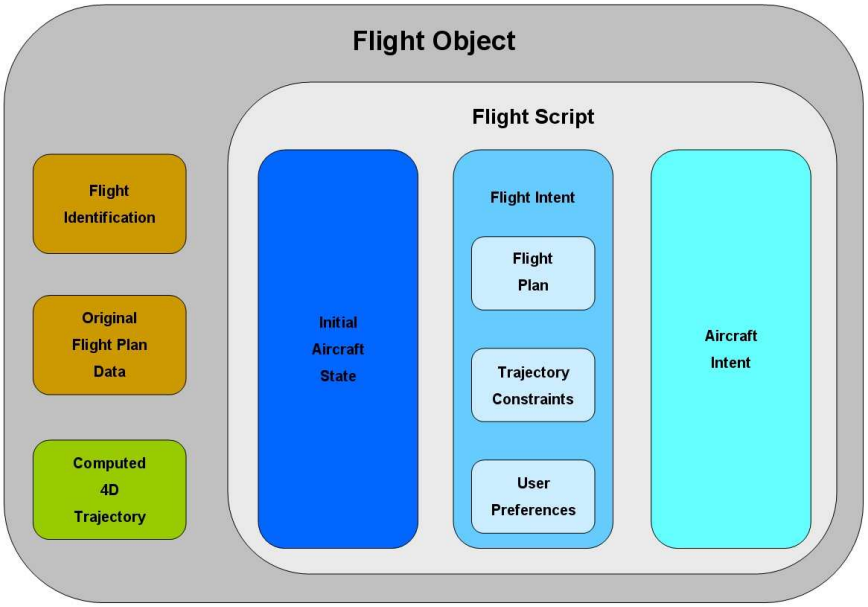
REVIEW DRAFT

	applicable constraints and the operations plan of the aircraft. • Trajectory information, most often expressed as a time-ordered set of trajectory vectors.
Mission Trajectory (MT)	The military Mission Trajectory (MT) is similar, but more complex than a civil Business Trajectory. A military mission trajectory will usually consist of a transit to and from an airspace reservation with mission specific dimensions and characteristics. Outside and inside of an airspace reservation a single trajectory could be used by multiple aircraft (e.g. formation flights, air refueling) demanding increased separation requirements. Additionally, a single airspace reservation could be approached and departed by individual aircraft or formation flights on different trajectories. [*SESAR*]
Reference Business Trajectory (RBT)	The Reference Business Trajectory (RBT) refers to the Business Trajectory during the execution phase of the flight. It is the Business Trajectory which the airspace user agrees to fly and the Air Navigation Service Providers (ANSP) and Airports agree to facilitate (subject to separation provision). [*SESAR*]
Predicted Trajectory	The Predicted Trajectory describes the estimated path a moving aircraft will follow through the airspace. The Trajectory can be described mathematically by a time-ordered set of Trajectory Vectors. [*AP16]* <u>Notes:</u> The predicted trajectory is computed by a Trajectory Predictor on request of a TP client application. The computation is performed based on input data relating to the current state and future intent of the aircraft. It is supported by the underlying models for aircraft performance, meteorological conditions and adaptation data.
Trajectory Vector	A Trajectory Vector is an element of the aircraft trajectory. It comprises a set of trajectory attributes that describes the aircraft state at a given instance of time, possibly enhanced with attributes that describe the environment in which the aircraft is operated (viz. predicted meteorological conditions), information related to quality of the trajectory attributes (viz. uncertainty), information describing the operating modes of the Flight Guidance Systems, etc. [*AP16*] <u>Notes</u>: The Trajectory Vector that is an element of a 4D trajectory has as a minimum four attributes: time, latitude, longitude and altitude.
Decision Support Tools (DST's)	Decision Support Tools are automated functions in air and ground systems that support Trajectory Management. DST's may have many capabilities for detecting and monitoring problems and providing information to pilots or controllers to resolve the problems through Trajectory Management whilst keeping the global system human centric.

REVIEW DRAFT

	[*Concepts*] <u>Notes:</u> Predicted Trajectories constitute the basis of DST operations. These are computed by Trajectory Predictors. In current practice, due to the differences in guidance and navigation functions in the air and the multiple, disparate Trajectory Prediction processes in the ground automation systems; it will not be feasible for a DST to make meaningful adjustments to trajectory data directly. Hence, instead, a DST will facilitate TM by adapting the Flight Script of a flight.
Trajectory Prediction (TP)	Trajectory prediction is the process that estimates a future trajectory of an aircraft through computation. This is performed by a Trajectory Predictor. [*AP16*] <u>Notes:</u> Different DST's may have widely different performance requirements for predicted trajectories, in particular related to accuracy, uncertainty, response times and input data requirements. This results in a situation where multiple, disparate TP's will co-exist within the ATM system. This causes a potential issue for the interoperability among the different automation systems in the air and the ground. The definition of a common, generic description of a TP supported by a common, unambiguous terminology will be a prerequisite for achieving the high level objectives of the NextGen and SESAR systems.
TP Client Application	A TP Client is an application within the ATM system that requires the services of a TP. [*AP16*]. <u>Notes:</u> Often TP clients are related to DST's that support Trajectory Management functions. In many cases they require a capability to consider other trajectories than those that reflect the current flight clearance, i.e. the trajectory data stored in the Flight Object.
Flight Script	The Flight Script contains the flight data required by a TP client to perform a trajectory prediction. It is an element of the Flight Object. [*Flight Object*] <u>Notes:</u> This approach meets the essential interoperability requirements among the various air and ground automation functions. It facilitates the creation of consistent, although not necessarily identical, trajectories for each flight. This makes the Flight Script within the Flight Object, the cornerstone of TBO. If a TM function wishes to adapt the trajectory of the flight, it does so by requesting changes to the Flight Script (typically to add a new constraint), not by proposing changes to the trajectory directly.

REVIEW DRAFT

	The Flight Object working groups have proposed that the flight script comprises: • The Initial Aircraft State, • The Flight Intent. • The Aircraft Intent.  Fig. 2 Flight data contents of Flight Object
Flight Object (FO)	The Flight Object (FO) represents the system instance view of a particular flight that is shareable with other stakeholders. [*Flight Object*] <u>Notes:</u> Flight Object only represents the system instance of a flight that is **<u>shareable</u>** because the system view of a flight in a specific implementation includes also data that is not shared with external systems, like internal events, internal flight plan data used by internal sub-systems, etc). The information in the FO includes aircraft identity, Communications, Navigation and Surveillance (CNS) and related capabilities, flight performance parameters, flight crew capabilities including for separation procedures, and the flight plan (which may or may not be a 4DT), together with any alternatives being considered. Once a flight is being executed, the flight plan in the flight object includes the "cleared" flight profile, plus any desired or proposed changes to the profile, and current aircraft position and near-term intent information. Allocation of responsibility for separation management along flight segments is also likely to be stored. The flight specific information required for trajectory prediction is contained in the Flight Script.

REVIEW DRAFT

	International collaboration on the development of standards for the definition of a flight object is ongoing. (e.g., EUROCAE ED-133, Annex A-5).
Initial Aircraft State	The Initial Aircraft State describes the aircraft state, as input into the TP at the time of the start of the trajectory computation. As a minimum, the Initial Aircraft State needs to comprise the 3D position and time. [*AP16*] <u>Notes:</u> The TP Client application may have a requirement specifying that the Initial Condition of the predicted 4D trajectory is different from the actual Initial Aircraft State, e.g. the Initial Aircraft State, projected onto the planned route.
Flight Intent	The Flight Intent is an element of the Flight Object that describes the constraints and preferences that are applicable to the flight. It describes *WHAT* needs to be achieved. It is the compilation of , inter alia, • The objectives of the aircraft operator; • The constraints from the aircraft characteristics; • The constraints from airport resources; • The constraints from airspace resources; • The constraints from safety requirements. [*Flight Object*] <u>Note:</u> The TBO concept aims at minimizing the constraints that apply to a flight. Hence, most often, there will be multiple trajectories possible that meet the Flight Intent. Consequently, Flight Intent typically constitutes an <u>ambiguous</u> definition of the trajectory.
Aircraft Intent	The Aircraft Intent [Ref. 6] is the aircraft operations plan that defines precisely *HOW* the aircraft intends to meet the constraints and preferences defined in the Flight Intent. [*AP16*] <u>Notes:</u> Aircraft Intent constitutes an <u>unambiguous</u> description of the trajectory, essential to provide interoperability among the stakeholders. The international standardization of the content and formats of Aircraft Intent is a prerequisite for meeting the interoperability requirements of the TBO concept.
User preferences	User Preferences define the conditions of the nominal case, e.g. the aircraft performing “free flight”. They may describe preferred route, take-off and arrival times, cruise level, speeds, cost-index, etc. User preferences are constraints that, if needed, may be relaxed to meet the trajectory constraints. [*Concepts*]

REVIEW DRAFT

	Notes: Examples of User Preferences: • In the FMS defined through cost index • In ground systems User Preferences are currently often extracted from the aircraft model. This is information reflecting a general case and therefore is currently most often NOT user specific.
Trajectory constraints	Trajectory constraints define conditions that may restrict the aircraft from following a nominal case, e.g., performing "Free Flight". [*Concepts*] Notes: Constraints are only defined if conditions require. Over-constraining may lead to loss of efficiency and possibly capacity. In general, multiple trajectories can be defined that meet the constraints. Hence the set of trajectory constraints does NOT define the trajectory unambiguously.

Part 2: Trajectory Prediction – process view

2.1. Process view

The generation and/or adaptation of trajectory information are performed by a Trajectory Predictor (TP). This function can be considered a service for some client application that provides support for a higher level user in the ATM system, e.g. support for Decision Support Tools that facilitate Trajectory Management. This structure is valid, independently whether the TP function is or is not embedded in the client application.

The trajectory information is the foundation of higher-level processing within the TP client application to achieve the client application's intended purpose and, therefore, does not represent an end in and of itself. Though it is possible to conceive of an automation system that provides trajectory information directly to a system user, it is difficult to envision a useful system that does not provide at least minimal additional processing of the trajectory information to achieve its design purpose.

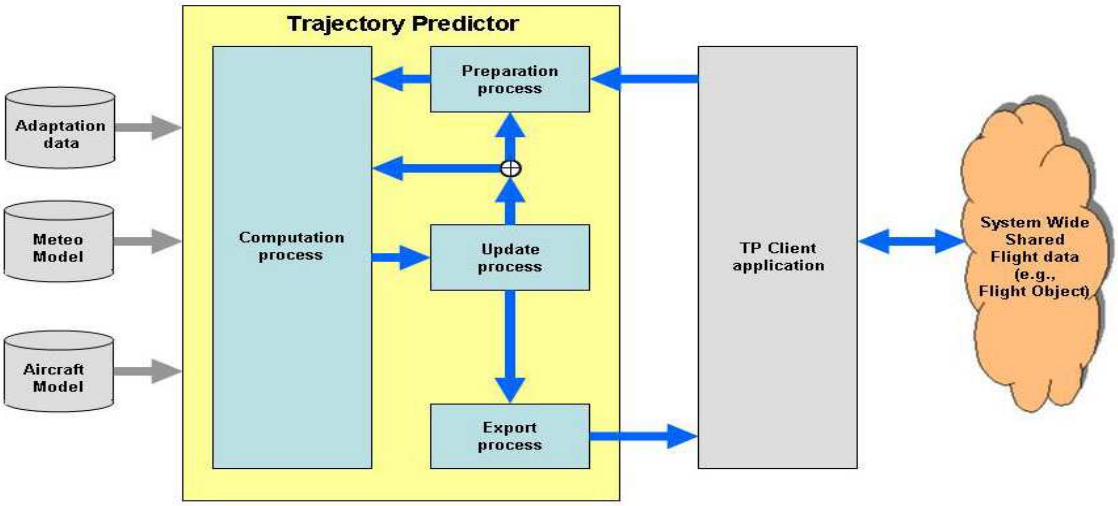


Fig 3 Trajectory Prediction – process view

REVIEW DRAFT

The generic structure of the TP comprises four processes: Preparation, Computation, Update and Export. In this general structure, it is the TP client application that interfaces with the Flight Object, if available, and decides how and when to use the information within the Flight Object to meet its needs. This structure handles all scenarios, including both cases where the client application is or is not involved in data exchange with another automation system via a Flight Object.

2.2. Preparation process

The preparation process builds an initial condition and a Behavior Model from input state and intent information provided by the TP client process.

Behavior Model	The Behavior Model is the ordered list of maneuvers that the aircraft plans to execute. It describes, in an unambiguous way, HOW the aircraft will be operated to meet the trajectory constraints and user preferences. [*AP16*]

In particular in ground based applications, for the case that no applicable Aircraft Intent information is available in the FO, the Behavior Model may be generated from the Initial Aircraft State, Flight Intent information and optimization strategies.

2.3. Computation process

The Computation process computes the predicted trajectory information from the behavior model.

2.4. Update process

The Update process checks the conformance of the computed trajectory with the trajectory constraints specified by the TP client in the Input Flight Intent. In the case of non-conformance, the Update process adapts Behavior Model and/or the Input Flight Intent data. Re-computation of the trajectory should result in a better match. The Processing Strategies defined by the TP client process guide the Update process.

2.5. Export process

The Export process exports the output data of the TP to the TP client process. This includes:

- The predicted trajectory;
- Errors and warning messages informing the TP client on the availability and/or quality of the output data;
- In the case that the initial Behavior Model did not result in a computed trajectory that matches all constraints, an updated Behavior Model is made available to the TP client process, possibly for updating the Flight Script information in the Flight Object;
- In the latter case the TP client process may also want to be informed about the specific preferences and constraints that have been relaxed to compute a matching trajectory.

REVIEW DRAFT

Part 3 Trajectory Prediction – data view

3.1. Data view

The TP-Data View is an expansion of the TP-Process View identifying interfaces and key data sets. It is not intended to represent a software structure. The description is generic, implying that the TP structure is applicable to support airborne as well as ground based automation.

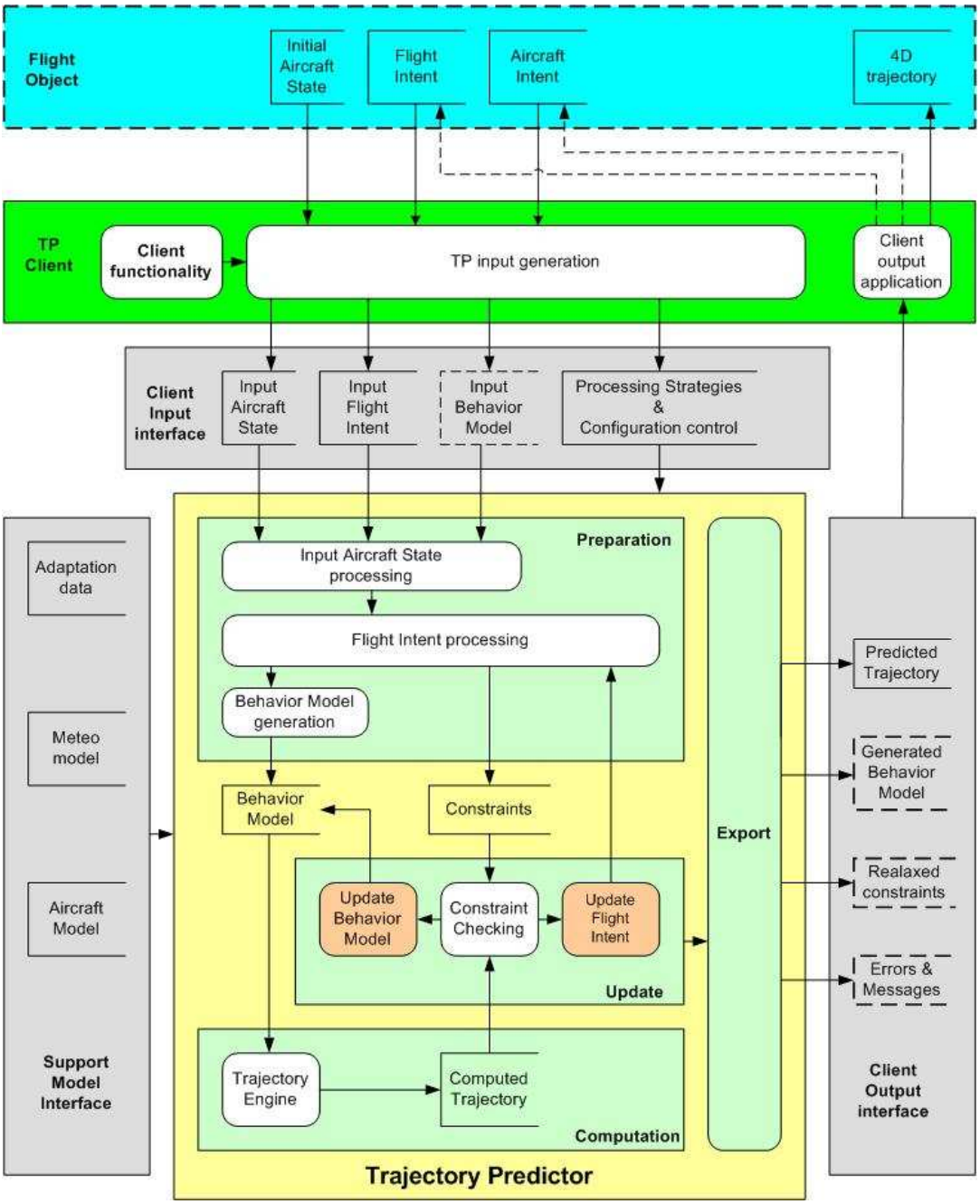


Fig. 4 Trajectory Prediction – Data view

REVIEW DRAFT

In the diagram the “closed” boxes refer to generic processes, whereas the “open” boxes identify data containers. Dashed lines indicate optional data paths and system elements. The structure is generic in that it describes the data containers and processes that may exist in a TP. Whether a specific process of data container can actually be identified in a specific TP depends on the implementation for the specific use case. In fact a process depicted in the diagram may, in practice, very well be a “no-operation” if the functionality is not required in a specific implementation, e.g. not all TP’s will need to have the capability to compute a trajectory that meets an Estimated Time of Arrival. Nevertheless it is key to identify and define these generic elements to facilitate unambiguous system performance specifications and the subsequent validation processes.

3.2. Flight Object

The synchronization of flight data among stakeholders in the ATM system is ensured through the Flight Object. Stakeholders that are not actively involved in Trajectory Management functions may not require the services of a TP function. Hence they may use the 4D trajectory information contained in the FO directly. Stakeholders, actively involved in the TM processes, may require adaptation of the trajectory information to meet their specific requirements. These stakeholders are considered TP clients.

The Flight Object is shared system wide through SWIM. Standards are required to specify the content and format of the Flight Script, viz. Initial Aircraft State, Flight Intent and Aircraft Intent.

3.3. TP Client

The TP Client is any function in the SESAR and NextGen system that requires the support of a Trajectory Predictor, e.g. DST’s on the ground and FMS in airborne applications.

The TP Client function is the interface between the TP and the higher level services in the ATM system. The interface between TP Client and TP is very often governed by implementation issues, e.g. the TP may or may not be embedded within the TP Client function. Hence the interface specification may be specific to the system developer. The definition of unambiguous TP performance requirements is key to ensure that the TP client will be capable of meeting its own higher level performance requirements. AP16 work has indicated that a common, generic structure for a TP can be defined that is applicable to all TP’s and their interfaces. This was a prerequisite for facilitating the unambiguous definition of TP performance requirements that will also lead to improved global interoperability and a reduction in development and maintenance costs.

The TP client may use, if available, the trajectory information contained in the Flight Script of the FO to request the TP to compute a trajectory. It may want to adapt the constraints defined in the Flight Script, e.g. to ensure a safety level, manage a departure or arrival stream, etc. This is performed by the TP input generation process. Aircraft Intent information may be converted into an Input Behavior Model. Aircraft Intent and the Behavior Model are similar in information content but the level of detail and the formats may be different.

The TP Client specifies in the Processing Strategies how the TP should perform the matching of the Predicted Trajectory to the constraints and preferences specified in the Input Flight Intent. Through Configuration Control the TP Client may define processing characteristics of the TP, e.g. select a specific integration method, aircraft performance model, functionality of the export function, etc.

REVIEW DRAFT

The TP Client may use the computed output information from the TP for internal processing, e.g., "What-iffing" and/or, in the case that it has the authority, to update the information in the Flight Object. In that case the Client Output Interface converts the implementation specific formats of the TP output format to the standardized formats of the FO.

3.4. TP-Preparation process

3.4.1. Input Aircraft State processing

This process generates the Initial Condition for the TP-Computation process. In the simplest case, the Initial Condition is just set equal to the Input Aircraft State. Other examples include projecting the Input Aircraft State information onto a route defined by the constraints in the Input Flight Intent to create an Initial Condition that starts on this route. The Input Aircraft State processing covers any processing required to generate the Initial Condition for trajectory generation.

3.4.2. Flight Intent processing

Two operating modes can be distinguished:

- The TP Client requests a trajectory prediction based on the Input Behavior Model information. In this case, the Flight Intent processing does not perform any significant operations.
- The TP Client has not defined an Input Behavior Model. In that case the Behavior Model needs to be created from the Initial Condition and Input Flight Intent information.

The Flight Intent processing evaluates the Initial Condition, both laterally and vertically, against the set of constraints defined in the Input Flight Intent. The goal is to identify missing constraints (i.e., missing intent information) that require definition prior to integration. Common examples are flight plan route expansion, definition of climb / descent speeds, procedures to connect the Initial Condition with the planned route, etc.

The output of the Flight Intent processing is the Initial Condition and the complete set of constraints that must be met during trajectory generation.

3.4.3. Behavior Model Generation

The Behavior Model Generation builds the Behavior Model from the Initial Condition and the completed Input Flight Intent information.

3.5. Behavior Model

The Behavior Model consists of one or more ordered list of maneuvers, starting at the Initial Condition, which the aircraft will perform to meet the trajectory constraints. It describes unambiguously HOW the aircraft will be operated to meet the constraints and preferences. The Behavior Model is a dataset internal to the TP of which the contents and the formats are implementation specific. They are tuned to the requirements and the capabilities of the Trajectory Engine function in the TP-Computation process.

Initial Condition	The Initial Condition in the trajectory prediction process describes the assumed initial aircraft state at the start of the trajectory computation. [*AP16*] Note: It may be different from the Initial Aircraft State to meet requirements

REVIEW DRAFT

	from the TP client, e.g., it may result from projecting the Initial Aircraft State information onto a route defined by the constraints in the Input Flight Intent to create an Initial Condition that starts on this route.
Maneuver	A Maneuver is a specific event with a *beginning* and an *end* that defines a change in control parameters of an aircraft in one or more dimensions, e.g., set thrust, climb, turn, etc. [*AP1*6] <u>Note:</u> In the Behavior Model, Maneuvers can be specified as Component Maneuvers or Aggregate Maneuvers.
Component maneuver	A Component Maneuver is a Maneuver consisting of • a single Control Action, and, • one or more Triggers that activate or de-activate the Maneuver. [*AP1*6]
Aggregate Maneuver	An Aggregate Maneuver is a maneuver definition that describes a set of Component Maneuvers. [*AP16*] <u>Note:</u> An Aggregate Maneuver can be decomposed into one of more lists of Component Maneuvers, e.g., a "climb" Maneuver can be decomposed in Altitude maneuver(s), Speed maneuver(s), Thrust maneuver(s), Flaps maneuver(s), etc.
Control Action	A Control Action is an element of a Maneuver definition. It defines the change of a control parameter of the aircraft, e.g. "change altitude", "maintain speed", "change flaps", etc. [*AP1*6]
Trigger	A Trigger is an element of a Maneuver definition. It defines the condition or conditions that either activates the next maneuver in the Maneuver Profile or de-activates the current Maneuver. [*AP1*6] <u>Notes:</u> The Trigger definition can be simple or complex depending on the characteristics of the Trajectory Engine used in the TP-Computation process. For example the explicit Trigger condition "*At the computed aircraft Altitude = FL 300*" could be used directly to switch Maneuvers in the Maneuver Profile defining "speed" from "*maintain climb speed*" to "*change to cruise speed*". In contrast, an implicit Trigger definition often involves reverse trajectory computation, e.g., the Trigger definition that is used for switching Maneuvers in the Maneuver Profile defining "Altitude" from "*maintain cruise level*" to "*change altitude to FL 100*" could be defined as "*At the computed aircraft position = the ToD position"* where the ToD position is defined implicitly as *"the aircraft position on the horizontal profile that results in the last Maneuver of the altitude profile to end at the touch-down point on the landing runway*".

REVIEW DRAFT

Maneuver profile	A Maneuver Profile is an ordered list of Component Maneuvers, e.g., "speed" maneuvers, "altitude" maneuvers, "thrust" maneuvers, etc. A Maneuver Profile is an element of the Behavior Model. [*AP16*]
Maneuver Switching	Maneuver Switching refers to the action of activating / de-activating successive Maneuvers in a Maneuver Profile. The switching is controlled through the processing of Capture Conditions. *[AP16*] <u>Notes:</u> At any one time there is <u>always</u> only a <u>single</u> Maneuver "active" in every Maneuver Profile of the Behavior Model, e.g. an Altitude Maneuver profile could not specify that the aircraft is at the same time "changing" and "holding" altitude. It is possible that Maneuvers in a Maneuver Profile can be skipped in the execution sequence, but the switching may never result in reverting to a Maneuver specified earlier in the sequence.
Capture Condition	Capture Conditions are information used <u>internally</u> in the Trajectory Engine of the TP-Computation process to manage the switching of Maneuvers in the Maneuver Profiles. [*AP16*] <u>Note:</u> Capture Conditions relate a Trajectory Attribute to a specified value , e.g. "*At computed aircraft Altitude = FL 300*". In that respect they are similar to explicit definitions of Trigger conditions. In the case implicit Trigger condition definitions, the value needs to be resolved through reverse trajectory computation within the Trajectory Engine.

3.5.1. Behavior Model vs. Aircraft Intent

The Behavior Model as well as the Aircraft Intent describes unambiguously the operations plan of the aircraft. However, in practice, the contents and formats may differ significantly.

The Behavior Model uses contents and formats that are specific to a given TP implementation. They are affected by the complexity of the Trajectory Engine and Aircraft Model used. TP Client performance requirements may force the TP developers to choose specific logic for the Trajectory Engine and a specific Aircraft Model to meet the performance criteria of the TP Client application for, e.g., Accuracy and Response Time.

In contrast the contents of and formats of Aircraft Intent are independent of any implementation and must meet the interoperability requirements for system wide trajectory synchronization serving airborne and ground based applications. To that effect it is a requirement to define an international standard for describing Aircraft Intent. The decomposition of Aircraft Intent in Maneuver Profiles and the vocabulary and grammar of the Intent Definition Language must be sufficiently detailed and flexible that these support the requirements of the most demanding Trajectory Predictors in the SESAR and NextGen systems, e.g. those used in FMS's and advanced AMAN's. The current work on Aircraft Intent Description Language (AIDL) is a promising path forward (Annex A – 6).

REVIEW DRAFT

A future implementation of a TP in which the content and the format of the Behavior Model would be similar to that of the Aircraft Intent would require significantly less processing for data conversion whilst leading to maximum flexibility and accuracy.

3.6. TP-Computation process

The trajectory computation is performed by the Trajectory Engine on the basis of the Behavior Model, the underlying models for meteorological information and aircraft performance and the Processing Strategies and Configuration Control as defined by the TP Client application. The output consists of the Computed Trajectory data and a set of Messages & Warnings that summarizes the degree of success of the trajectory computation. If the trajectory computation completed successfully, then the computed trajectory data will be further processed by the Export function of the TP for delivery to the TP Client.

The structure of the Trajectory Engine depends on the specific implementation. In many cases it consists of one Trajectory Engine kernel as presented below. However, in order to meet specific TP client performance requirements, e.g., for response time and/or accuracy, the Trajectory Engine process may consist of multiple Trajectory Engine Kernels, each optimized to compute a specific segment of the trajectory, e.g. Climb-Cruise, Cruise, Cruise-Descent, etc. In the case that the Trajectory Engine consists of multiple Trajectory Engine kernels, additional processing is required to merge the trajectory segments into a single, consistent trajectory before it can be exported to the TP Client application

REVIEW DRAFT

3.7. Trajectory Engine kernel

The generic structure of the Trajectory Engine kernel is depicted below.

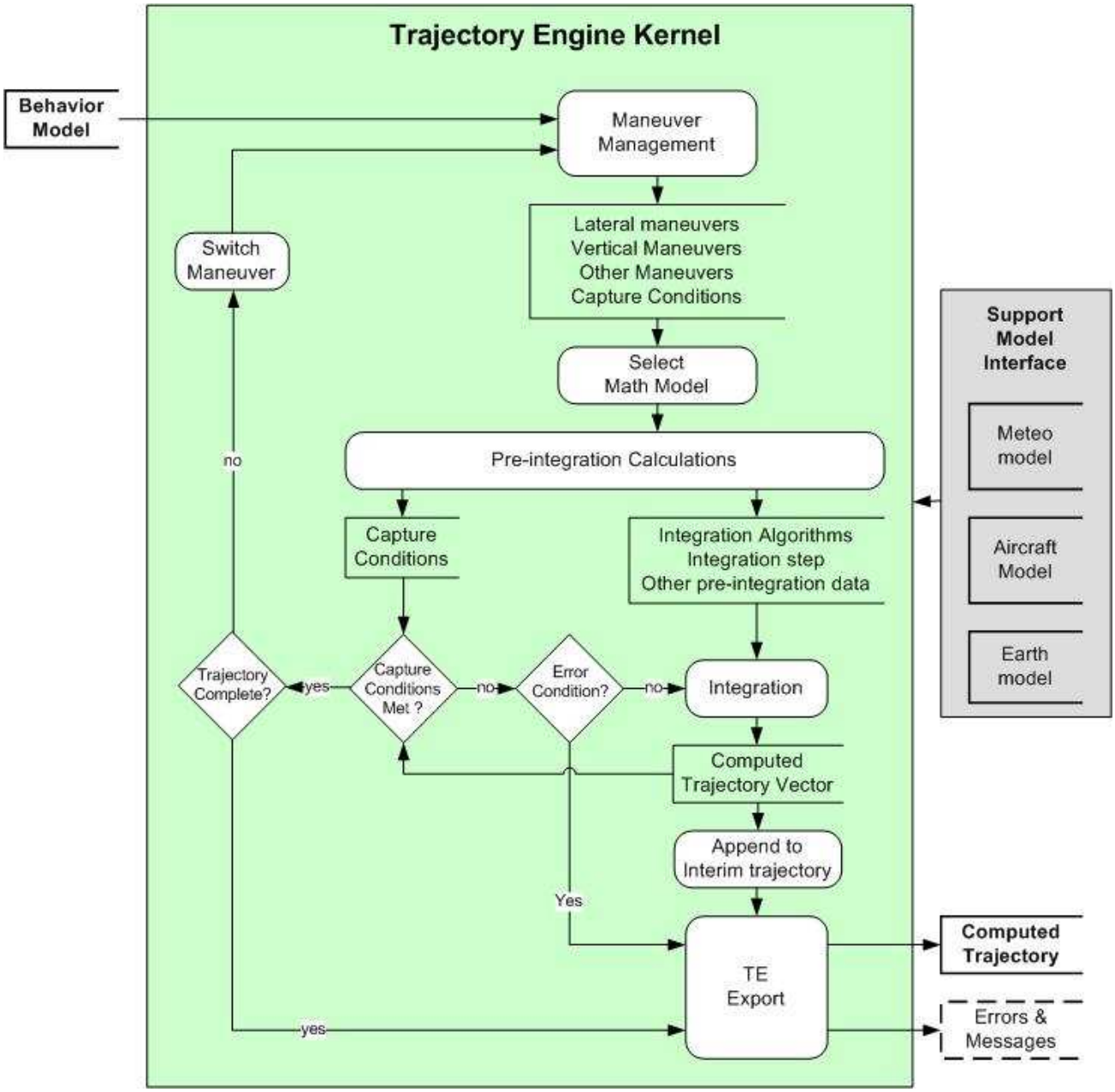


Fig. 5 Generic Trajectory Engine Kernel

3.7.1. Maneuver Management

The Maneuver Management identifies for each Maneuver Profile in the Behavior Model the currently active Maneuver and extracts the explicitly defined Capture Conditions.

REVIEW DRAFT

3.7.2. Selection Mathematical Model

There are many forms the mathematical models can take, including:

- A single set of equations of motion that, when integrated, generates all dimensions of the trajectory;
- A mixture of lateral and vertical equations of motion and other mathematical simplifications that are integrated in parallel;
- A mixture of geometric calculations that approximate one or more dimensions of the trajectory and equations of motion used to integrate the remaining dimensions (e.g., approximating the geometric horizontal path and integrating speed and altitude equations of motion along this path).

3.7.3. Integration preparation

This process performs the multiple operations that are required before the actual integration can be performed, including (the list is not exhaustive):

- The set of algorithms that the integration process will apply;
- The definition of the dimension and extent of the integration step;
- In the case that the Behavior Model includes Maneuvers using implicit Capture Conditions, e.g. related to "conditional" constraints, these need first to be resolved to explicit definitions to facilitate Maneuver Switching.
- The computation of any geometrically defined dimension of the trajectory, e.g. the computation of geometric horizontal path.

3.7.4. Integration

The Integration process adds one Trajectory Vector to the interim trajectory. The process is supported by the data from the Aircraft Model and the Meteorological Model.

3.7.5. Capture Conditions check

The last computed Trajectory Vector data are checked against the Capture Conditions. In the case that a Capture Condition is met, this will result in either the switching of one or more Maneuvers or the completion of the Trajectory Computation process.

"Conditional" constraints in the Behavior Model may result in explicit Capture Conditions that are not met before a default "end-of-trajectory" capture condition is met, e.g. a maximum prediction time, distance flown, or another exceptional condition. Such occurrences cannot be avoided as the validity of the Capture Conditions related to "conditional" constraints can only be assessed during Trajectory Computation. In such a case the trajectory prediction process is terminated and appropriate messages are generated for the Update process.

3.7.6. TE Export

When the integration stops, the Trajectory Engine Kernel exports the Interim Trajectory and generated Messages and Warnings for further processing. In the case that the Trajectory Engine consists of multiple Trajectory Engine Kernels, Interim trajectories need to be merged before being formatted and exported to the TP Client application.

3.8. TP-Update process

The functionality of the Update process is threefold:

- It checks the conformity of the computed trajectory, if successful, against the set of constraints compiled by the Flight Intent processing.
- In the case of non-conformance, the Update process adapts the Behavior Model and/or the constraints in the Flight Intent information.
- In the case of conformance, it triggers the Export process.

REVIEW DRAFT

The functionality of the Update process is controlled by the TP Client through the definition of Processing Strategies and Configuration Control. The type of non-conformance detected and the Processing Strategies define whether the Behavior Model can be updated directly or if the Behavior Model requires regeneration. Adaptations that do not need a redefinition of the maneuver lists in the Behavior Model can be directly introduced, e.g. a change of climb rate, cruise and/or descent speed, expedite descent, etc.. Adaptations that require a change in the maneuver lists require a regeneration of the Behavior Model, e.g. an adaptation of the planned route, introducing a holding circuit, etc.. Such an adaptation will be processed by the Preparation process.

The functionality in the Update process affects to a large extent the capability of the TP to support some TM tasks of the TP Client. For example the Update process may include the capability for adapting the Behavior Model to ensure that the computed trajectory meets a set of time constraints.

3.9. TP-Export process

The Export process completes the processing in the TP. It provides the TP client with:

- the Predicted Trajectory information;
- Optionally, a Generated Behavior Model that is associated with the predicted trajectory. This information is provided in the case that the Preparation process had used the Input Behavior Model and that this did not resulted in a Predicted Trajectory that matched the constraints in the Input Flight Intent;
- Optionally, information on the constraints that have been relaxed to complete the trajectory computation successfully;
- Optionally, a set of error and/or warning messages that provides information to the TP client on the quality of the predicted trajectory.

3.10. Underlying models

The TP process uses underlying models for adaptation, aircraft and meteorological data. A TP implementation may choose a version of the model that facilitates the TP to meet specific TP user requirements in an optimum way.

Aircraft model	The aircraft model is a support function for the TP. It describes the characteristics of the aircraft required for trajectory prediction. It delivers: • Aircraft specific constraints, e.g. the certification limits for speeds, altitudes, weights, etc.; • The performance of the aircraft; • Optionally, the nominal speed, altitude, thrust setting, configuration and bank angle profiles used. <u>Note:</u> Different aircraft models exist with different data content, fidelity and complexity. The TP may have the capability to interface to multiple aircraft models to better match the TP Client performance requirements, e.g., compare the requirements of an ATFM function with a conflict detection function.
Meteorological model	The meteorological model is a support function for the TP. It

REVIEW DRAFT

	generates the predicted information describing the state of the air mass in which the aircraft is operated. <u>Note:</u> Different models may use different source data, e.g., in the FMS predicted meteorological data is merged with onboard observations resulting in a de-facto inconsistency among meteorological data used for trajectory prediction in different aircraft. This is one of the reasons leading to the situation where duly synchronized, unambiguous Aircraft Intent information will nevertheless lead to differences in computed trajectories. This can be managed system wide through uncertainty management. Reversely, if under these conditions, the trajectory data would have been synchronized, this would lead to inconsistent Aircraft Intent information among stakeholders.
Adaptation data	Adaptation data is a set of data used to configure a given TP to a particular operational environment. The three main categories of adaptation for trajectory prediction are : • **airspace adaptation**, which includes the definition of airspace elements. Airspace adaptation data defines waypoints, airways and some specific trajectory 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. • **aircraft adaptation**, which includes aircraft characteristics, pilot models, and company preferences. • **Earth model** that defines magnetic declination, earth radius (e.g. WGS84), Projection method used, gravitational constants, etc.

REVIEW DRAFT

Part 4 Conclusions and ways forward

A terminology that is common to all layers of concept designers, system developers and, ultimately, users of the NextGen and SESAR systems is key to facilitate the unambiguous definition of performance requirements and validation and verification processes. This White Paper presents the definition of terms required to describe how the trajectory prediction function supports the high level concepts SESAR and NextGen. It includes the level of detail required to describe the trajectories in an unambiguous way to support system wide synchronization. To that effect the paper proposes a generic structure of the TP that is applicable to airborne and ground based applications. The paper builds on the terminology that is already defined by the SESAR and NextGen concepts developers and the working groups addressing the Flight Object.

The issues addressed in this white paper include:

- The context of Trajectory Prediction in the SESAR and NextGen systems in particular in support of Trajectory Management concepts that facilitate Trajectory Based Operations;
- The interaction between TM, TP and the Flight Object (FO);
- The definition of a **common, generic** structure for a TP;

As a follow up of this work, it is desirable to investigate critical use cases in the SESAR and NextGen systems to further validate the proposed terminology and structure and to complete the set of common terms that unambiguously describes the relations among TBO, TM and TP. The road towards the definition of unambiguous performance requirements for TP will require developing a common framework for metrics. All this work will need to be performed in close cooperation of all parties concerned.

REVIEW DRAFT

Annex A: References

1. **Global ATM Operational Concept**
   ICAO Doc 9854 AN/458 First edition, 2005
   *(*http://ap16.atmrt.org *– library / 2005)*

2. **ATM Target Concept**,
   SESAR Joint Undertaking, deliverable D3, September 2007
   *(*http://ap16.atmrt.org *– library / 2007)*

3. **Next generation Air Transport System - NextGen - Concept of Operations**
   Version 2, June 2007
   *(*http://ap16.atmrt.org *– library / 2007)*

4. **White Paper on Common TP related terminology**,
   AP16, April 2004
   *(*http://ap16.atmrt.org *– library / 2004)*

5. **Flight Object Interoperability specification**,
   EUROCAE doc ED-133, June 2009
   *(*http://ap16.atmrt.org *– library / 2009)*

6. **Flight Script Specification**
   ASIS Deliverable D-6, September 2009
   *(*http://ap16.atmrt.org *– library / 2009*

REVIEW DRAFT

Annex B: Related Bibliographie

1. **REACT project,** Synchronizing Business Trajectories in the future ATM system, June 2008, Seville, Spain
   *(*http://ap16.atmrt.org *– library / 2008)*

2. **Description of Trajectory Prediction in the ARETA AMAN/DMAN support tool**, R. Verbeek, NLR report NLR-CR-2002-166, March 2002
   *(*http://ap16.atmrt.org *– library / 2002)*

3. **Abstraction Techniques for Capturing and Comparing Trajectory Predictor Capabilities and Requirements**
   Robert A. Vivona, AIAA – AF2008098
   *(*http://ap16.atmrt.org *– library / 2008)*

4. **Cross-Comparison of Aircraft Trajectory Prediction Technologies: CTAS, ERAM, FACET, FMS,**
   Robert A. Vivona, NASA-Ames,
   (POC steven.m.green@nasa.gov)

5. **The ASIS Initiative: Towards an open testbed for the study of Trajectory Synchronization in the future ATM system**
   J. Lopez et al, 2009,
   *(*http://ap16.atmrt.org *– library / 2009)*

6. **Validation Data Methodology**
   AP16 deliverable, September 2004.
   (http://acy.tc.faa.gov/cpat/tjm/Validation_Data_Methodology.pdf)

7. **Assessing Trajectory Prediction Performance – Metrics Definition**
   S. Mondoloni et al., 2005,
   (http://acy.tc.faa.gov/cpat/tjm/3c1.pdf)

8. **Implementation and Metrics for a Trajectory Prediction implementation Validation Methodology,**
   M. Paglione et al., 2007,
   (http://acy.tc.faa.gov/cpat/docs/AIAA-2007-6517-848.pdf)

9. **Effectiveness of Pairing Flights when evaluating the accuracy of a conflict probe** ,
   M. Paglione et al, 2009,
   (http://acy.tc.faa.gov/cpat/docs/AIAA-2009-6079-103.pdf)

REVIEW DRAFT

Annex C: Glossary

3D	3 Dimensional
4D	4 Dimensional
4DT	4 Dimensional Trajectory
AMAN	Arrival Manager
ANSP	Air Navigation Service Provider
AIDL	Aircraft Intent Description Language
AP16	Action Plan 16
ASIS	Aircraft Intent Synchronization Infrastructure for SESAR
ATC	Air Traffic Control
ATFM	Air Traffic Flow Management
ATM	Air Traffic Management
BT	Business Trajectory
CCOM	Co-ordination Committee
CDM	Collaborative Decision Making
CNS	Communications, Navigation and Surveillance
CONOPS	Concept of Operations
DST	Decision Support Tool
EUROCAE	European Organization for Civil Aviation Equipment
FAA	Federal Aviation Authority
FL	Flight Level
FMS	Flight Management System
FO	Flight Object
MT	Mission Trajectory
NASA	National Aeronautics and Space Administration
NextGen	Next Generation
RBT	Reference Business Trajectory
SESAR	Single European Sky ATM Research
SID	Standard Instrument Departure
STAR	Standard Terminal Arrival Route
SWIM	System Wide Information Management
TBO	Trajectory Based Operations
TM	Trajectory Management
ToD	Top of Descent
TP	Trajectory Prediction/Predictor