Flight Object -
A Recommendation for Flight Script and Trajectory Description

FAA / EUROCONTROL Action Plan 16
Common Trajectory Prediction Capabilities

October 30, 2006

Table of Contents

1 Overview ... 3
1.1 Purpose and Organization of this Document ... 4
2 Concepts and Related Issues ... 5
2.1 Hierarchy of Trajectories ... 5
2.2 Role of Intent ... 7
2.3 Impact of Client Requirements ... 9
2.4 Sensitivity to Execution ... 13
2.5 Transition and Mixed Equipage ... 15
2.6 High Impact Information ... 16
3 Approach ... 17
3.1 Trajectory Prediction Structure ... 17
4 Derivation of Flight Script Data Elements ... 20
4.1 External Data Assumptions ... 20
4.2 Preparation Process ... 20
4.2.1 Route Conversion ... 20
4.2.2 Constraint Specification ... 24
4.2.3 Path Initialization ... 28
4.2.4 Intent Modeling and Description ... 29
4.3 Trajectory Script ... 39
5 Trajectory Description ... 40
6 Summary, Recommendations and Future Efforts ... 43
7 References ... 48

1 Overview

The Flight Object is intended as the future medium for capturing and sharing the most up-to-date information on any flight. The Flight Object is the single common reference for all systems for information about a flight.
(From Flight Object Concept of Use presented to ICAO FPLSG April, 2006)

The Flight Object (FO) seeks to address a myriad of issues associated with flight information under current operations. The lack of harmonized information between systems, the complexity of changing existing interfaces, and the lack of information protection are but a few areas being addressed through the FO. In conjunction with the FO, System Wide Information Management (SWIM) is envisaged as the distribution network for FO information.

One of the high-level information elements contained within the FO is the trajectory. While trajectory information may be synchronized using higher-level data, it is expected that the flight object will contain one or more trajectories. We define a trajectory as: *A four dimensional (e.g. latitude, longitude, altitude and time) description of an aircraft's flight path and associated information. A trajectory contained within the FO represents a predicted future path of the aircraft*[1]. This last notion allows the FO to contain a collection of trajectories for any given flight, based upon variations in future flight conditions. For example, a single flight may have trajectories based upon a clearance, operator wishes, dynamic constraints, alternative plans, etc.

While multiple trajectories are possible for any given flight, this document focuses on the description of a single trajectory and the information required within the Flight Object to allow the trajectory to be generated via trajectory prediction. This subset of FO information, including intent, required to generate one or more trajectories is labeled the *flight script*. Some information required to generate a trajectory (e.g., aircraft performance models, and atmospheric data) can be external to the flight script.

One driver for Flight Object and Flight Script design is to enable common situational awareness of trajectory prediction across automation systems (air and ground), and another is to facilitate the TP accuracy needed to support client automation systems. Future ATM concepts such as Trajectory-Based Operations and Super-Density Operations will require significantly greater TP precision and accuracy, particularly in the terminal area where 4D trajectory prediction faces the greatest challenge and complexity. Central to the description of the flight script lies the issue of TP performance. As an example,are two aspects: accuracy and computation speed.[2] One can increase the

[1] In a real-time environment, the history of surveillance information represents the actual path flown by the aircraft. This information should be stored in the FO or elsewhere, as it may assist adaptive predictors and provide information for quality assurance purposes.

[2] TP performance requirements are defined by the client automation applications and vary with the nature of specific operational concepts. It is not cost beneficial to improve TP except where needed to meet requirements.

accuracy of a TP by increasing its fidelity (the number and quality of data elements used by a TP), with an associated cost in computational speed and complexity. Similarly, one can decrease the fidelity of a TP to gain speed at the cost of accuracy. Data elements must be chosen in such a manner as to provide sufficient TP performance to support the envisaged automation functions. Since the flight script must support multiple applications with very different requirements on accuracy and computation speed, the flight script data elements must be chosen in such a manner as to allow the requisite tradeoffs to occur by client applications. Otherwise, it will introduce a roadblock to the more advanced applications, particularly those that depend on the integration of, and inter-operability between, air and ground decision support automation systems.

1.1 Purpose and Organization of this Document

This document seeks to provide input from Action Plan 16, Common Trajectory Prediction Capabilities, on the high-level composition of the Flight Script and trajectory description contained in the Flight Object. In developing this document, the goals were as follows:

- Articulate how some choices in Flight Object composition may impact TP performance – these performance requirements are driven by future automation functions
- Make recommendations for specific FO characteristics that support the level of TP performance necessary for future automation systems (this includes discussion of data elements for both the input and output of trajectory prediction)
- Provide additional recommendations that can ensure that the FO will preserve flexibility in future TP requirements

It is recognized that not all issues have been resolved and some additional effort is required to specify data elements. This document should help clarify what areas are in need of additional definition.

The document is organized into the following Sections:

- **Concepts and Related Issues** – This Section describes some of the future concepts incorporating the Flight Object, and the resulting impact on trajectory prediction data requirements. The Section also details how future concepts seek to address poor information quality under current operations.
- **Approach** – This Section describes the method used to identify high-level data elements required in the Flight Script. This approach is based upon a generic TP Structure which defines common elements of trajectory predictors including the preparation process, trajectory script, and trajectory engine. We approached the identification from two directions: a description of elements required for the TP "preparation process" and a description of any additional elements that would be necessary to create a "trajectory script".

- **Derivation of Flight Script Data Elements** – This Section derives the required data elements to implement the preparation process. The trajectory script will be introduced as an unambiguous description for input to the trajectory engine.
- **Trajectory Description** – This Section describes how a 4D trajectory, the output of the trajectory prediction process, is defined by Action Plan 16.
- **Recommendations and Required Future Efforts –** This Section summarizes the recommendations of Action Plan 16, and the areas requiring further investigation to further specify TP-related Flight Object data elements.

2 Concepts and Related Issues

Operational concepts have been proposed over the years with a variety of characteristics related to trajectory prediction. Rather than focus on specific named concepts and the requirements to support those, we discuss the aspects that are relevant to TP. This approach should provide more flexibility, as concepts are likely to evolve.

2.1 Hierarchy of Trajectories

The Flight Object is assumed to contain an element, named the flight script, which seeks to provide all data, or unambiguous references to data, required by the *preparation process* for trajectory prediction. We allow unambiguous references to data with the realization that certain requisite data: surveillance information, aeronautical information, and weather information will not be provided by the flight object, but via alternate "objects". We highlight the fact that the FS provides data required by the preparation process, to be described in Section 4.2. Additional data such as aircraft performance is provided subsequent to preparation.

With regards to trajectory prediction, we do not constrain the flight object to one or any number of flight scripts. This generalization allows us to accommodate a broader range of concepts. There are various reasons one may wish to have multiple flight scripts. If each flight script represents a "plan", the actual plan currently being pursued may represent a compromise plan (e.g., due to resource constraints, weather). Alternative flight scripts could represent other plans such as: an unconstrained user-preferred plan, a plan for possible weather scenarios, or a plan under negotiation. It is also assumed that these various plans can be updated as the situation dictates. In earlier implementations of the FO, it is likely that the plan will be incomplete and the trajectory description will be ambiguous due to assumptions on intent. These will be discussed in Section 4.2.4.

While multiple flight scripts may exist for a flight, only one represents the actual plan being pursued by the flight and should be identified as such. Prior to departure, this one flight script may not contain all information; for example, prior to departure, the departure time will be inaccurate, and the runway may be unknown.

Additional information could be contained in the flight object, external to the flight script, to help various automation systems generate the alternative flight scripts. This

paper does not investigate the details of this information. The kind of information being referred to is that which would be necessary to generate alternative flight scripts including alternative routes of flight (e.g., constraints on routings such as due to minimum equipment lists or ETOPS requirements, preference on turbulence penetration, or preferred alternate airports).

Figure 2-1 illustrates the hierarchy of flight scripts and potential trajectories. Only one flight script would represent the actual plan being pursued (illustrated in red). Each flight script may subsequently yield a collection of trajectories through the trajectory predictor. While each flight script represents a plan, ***each trajectory represents a specific way of executing that plan***. Plans can be highly constrained, thereby limiting all possible ways of executing to one trajectory, or may allow a variety of possible solutions. These various solutions may exist as part of contingency planning within a single system, or across multiple systems. This approach preserves flexibility in concepts, allowing varying levels of flexibility in the planning versus execution.

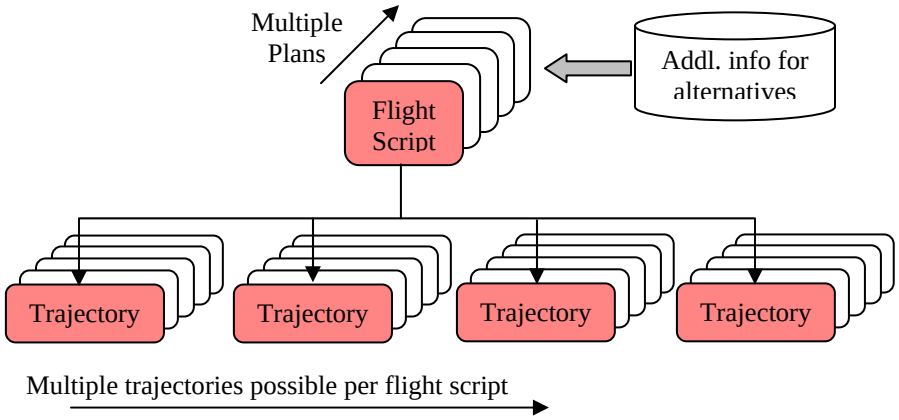

Figure 2-1 Hierarchy of Trajectories

As an example, consider a flight script specifying a route of flight with an altitude constraint at a point along the route. Even with the route specified, multiple vertical profiles can meet that vertical constraint. As more constraints are added to the flight script, (e.g., target descent speeds and modes, top-of-descent, or RTA at crossing constraint) the number of possible vertical and longitudinal profiles is reduced.

Alternatively, flights subject to vectors would have surveillance data not commensurate with the route (heading and location), potentially leading to multiple trajectory possibilities based upon variations in turn-back assumptions (or even no turn-back). This is particularly relevant for traffic transitioning through high-density terminal airspace. As future concepts allow turn-back information to be incorporated into the flight script, the number of potential trajectories diminishes.

2.2 Role of Intent

The prior description of multiple trajectories for any given flight script is related to the level of intent that is known for any given flight. For lower knowledge of intent, multiple trajectories may need to be considered [1], one per intent assumption, in order to plan for the range of situations that may develop. A full discussion of intent can be found in Section 4.2.4; however, we note here that knowledge of one trajectory, even the airborne trajectory, does not necessarily imply full knowledge of intent.

It is assumed that many gross intent errors, such as not knowing the proper route of flight (with the exception of open-ended tactical maneuvers), will be eliminated with the flight object and that the flight script will fully specify these elements now subject to errors. Certain intent errors may remain, at least for initial flight object implementations. However, the flight object must be flexible enough to accommodate future concepts seeking to reduce these errors. One must also consider the time-horizon of the information. For example, a long time prior to departure not all information will be known. Even a flight en route could, depending on the concept, allow for various alternative arrival transitions and runways.

Examples of intent information that may not be known include:

- Initial vector instructions issued by voice and not entered into the automation. The vector would not likely be known far ahead of time.
- Turn-back instruction on a vector including time/location of execution and heading, or capture waypoint/instructions to rejoin a route.
- Temporary altitude clearance not entered into automation, and intended duration of the temporary altitude.
- Top-of-descent would not necessarily be known, depending on the concept for execution of the descent.
- Mode information for the flight such as climb mode during a flight level change, or speed mode during level flight and necessary parameters for the mode.
- Knowledge of guidance algorithms for more complex modes such as those to meet an RTA.

Certain future concepts [2] allow greater knowledge of some intent by facilitating the inclusion of controller instructions into the flight object as soon as the information is known. Prediction would also be enhanced through inclusion of pilot intent through data communication of guidance targets. The flight object should help the viability of these concepts.

Other concepts [3] allow certain regions to exist wherein a trajectory is allowed some bounded flexibility in a “flexibility volume”. Even within the flexibility volume, trajectory prediction would seek the likely paths based upon variations of intent from present position.

There are some situations for which more precise information may be known, but where lack of intent-type information may lead to errors at points where the information is not prescribed. An example of this may exist in a concept relying on an exchange of airborne trajectories with required time of arrival (RTA) information at a waypoint (See Figure 2-2). As illustrated in the figure, the time error may be small at the RTA, but knowledge of how the aircraft is to be actually flown to the RTA would be required to precisely determine even the nominal trajectory's time history. However, modeling this nominal 4D path would require knowledge of specific *algorithms* within the aircraft guidance function assuming the aircraft is under automatic control. These algorithms are not always simply expressible in terms of simple data structures.

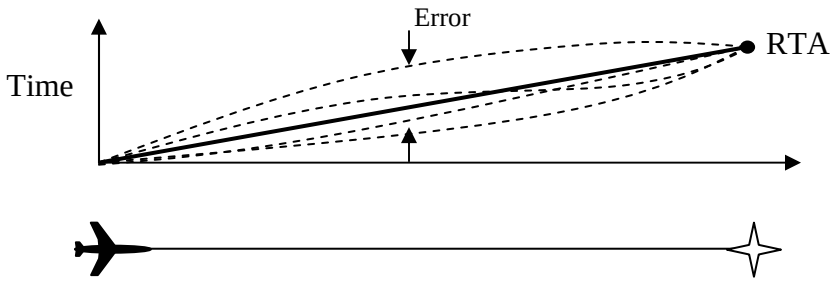

Figure 2-2 Growth of time error to an intended target

Here we separated the nominal trajectory from the actual path flown by the aircraft. In this case, we consider the nominal trajectory as the resulting predicted trajectory assuming no disturbances (e.g. unexpected variations in wind). The nominal may also be used (as within airborne Flight Management Systems) as the target trajectory for the aircraft's guidance system. Note that the nominal trajectory may not vary linearly along its path as the control algorithm may elect to allow excursions early on and implement more control once the aircraft approaches the RTA [4].

The issue is broader than simply cases with a specified RTA. Any trajectory that is specified as a sequence of discrete points will require an interpolation scheme between the points to reconstruct a continuous trajectory. This interpolation scheme may be mathematical or physics-based. A physics-based interpolation scheme requires intent information (such as control algorithms) to model the flight between adjacent points. This remains true whether a human or a machine is flying the aircraft; the exception being that the algorithms for human control will be more difficult to obtain.

For concepts relying on exchange of trajectories between air and ground, certain interoperability issues remain unresolved. The aircraft systems may not actually be controlling to a target trajectory (only airborne Flight Management System-based guidance modes have this capability). This is particularly true for the vertical and longitudinal motion. The airborne system may be operating in a tactical-based flight mode (such as heading or altitude select modes) or closed-loop guidance may tolerate large excursions from a target trajectory. Simply increasing the number of trajectory points transferred between air and ground may reduce interpolation errors between the airborne nominal (active plan) trajectory and the predicted trajectory used by the ground-system, but bandwidth limitations may act as a constraint on the number of points. Intent

errors are also possible when the airborne system is not aware of future changes to be imposed by the ground. Moreover, the ground automation would still need to generate its own what-if trajectory predictions to support ANSP services, particularly separation assurance and tactical trajectory management (e.g., trajectory changes to conform to traffic flow restrictions and assure separation).

In summary:

- *The flight script must be structured in a way that facilitates the inclusion of various types of intent information in the future as this data becomes available.*
- *Multiple trajectories can derive from a single flight script primarily due to variations in intent that are not specified.*
- *Exchange of trajectories between air and ground does not remove interoperability problems.*
    - *Controller intent is often not incorporated into airborne trajectories*
    - *Down link of coarse trajectories due to bandwidth concerns requires interpolation subject to knowledge of intent requirements between points*
    - *The approach does not provide the information for ground-based systems adding constraints or altering the flight path to predict a modified trajectory consistent with the airborne trajectory*
    - *Open-loop guidance is subject to disturbances and information quality concerns on board the aircraft*
    - *Closed-loop guidance may tolerate large excursions from target path depending on the mode*
    - *Intended mode-switches by the pilot will not likely be captured*
- *Certain intent may not easily be codified in terms of data to be included in the flight script, e.g. control laws and algorithms. Investigations are required to determine how to standardize and incorporate this type of information into the flight script.*

2.3 Impact of Client Requirements

A wide variety of automation systems are expected to use the flight object, in particular the flight script, for the purposes of obtaining/generating one or multiple trajectories. The variety of these systems imposes a wide range of potential requirements on trajectory prediction, and as a result, on the flight script. Some of these requirements are discussed below.

- **Accuracy** – Certain applications such as conflict detection / resolution and precise 4D trajectory-based operations (particularly within high-density airspace), or time-based metering require higher accuracy than other applications (e.g. TFM).
- **Computation speed** – Applications requiring trajectory prediction will require a prediction within a specific time-budget. The required computation speed will be higher for control applications and for those applications needing to evaluate a large number of trajectories. It is expected that increases in computation speed,

- **Updates** – Various applications requiring trajectory prediction may operate with different update rates and update schemes. Updates of trajectory prediction can be event-based or time-based (e.g., cyclical). Not all time-based updates will occur at the same frequency. Event-based updates can occur through violation of conformance bounds, changes in flight script information, or the need to perform a function to support ANSP services.
- **Look-ahead horizons** – The temporal extent of trajectory prediction will vary with application. Traffic Flow Management applications typically require very long prediction horizons, whereas conflict detection applications forecast for shorter time-horizons. The required time horizon impacts the computation speed and some applications requiring long horizons expect lower accuracy. Applications with long-range controlled times-of-arrival would require high accuracy with long time horizons.
- **Uncertainty information** – Projections of position uncertainty will likely be required for certain future applications. In particular, TFM applications can benefit from knowledge of prediction accuracy. This may also require the probability of certain choices being made leading to one path over another discrete path.
- **"What-if" scenarios** – Certain applications seeking to investigate required changes to the trajectories (e.g. conflict resolution, implementation of time-based metering, arrival management) require the ability to investigate one or more candidate trajectories. Instead of modifying the trajectory directly, these candidate trajectories are typically obtained by modifying some "control variable(s)" of the flight script (e.g., a candidate path, or a change in altitude constraint) until the resulting trajectory prediction meets the needs of the client automation system. The control variables are typically selected so that they may be communicated to the flight deck for implementation.

The impact of the above requirements on the flight script will depend on the operational concept for use of the flight object by each automation application. We provide several examples to illustrate the potential impacts: data only, trajectory prediction services or uniform trajectory.

In a data only approach, the flight object provides all the necessary data within the flight script to allow automation applications to compute their own trajectory prediction optimized for their own requirements. As shown in Figure 2-3, the flight script would provide data elements, including data quality information, to data subscribers. These subscribers could generate their own prediction subject to their own requirements. For example, the TP for application #1 (TP-1) might use only a subset of information to generate a fast/low-accuracy prediction with a long look-ahead time. This application may require TP updates on a periodic basis and could include uncertainty information. Perhaps TP-1 would have to use a limited set of data in order to deliver the required computation speed for a long look-ahead horizon. A second application may use TP-2 providing a fast/accurate prediction with a short look-ahead. This may be based upon

more information and updated as information changes. TP-2 may also be used for what-if scenarios by evaluating changes to the input, or the imposition of additional constraints.

The data-only approach provides an improvement over current operations by ensuring consistency in the quality of input data used by TP applications. However, the interoperability of the output from these multiple TPs remains an open issue. The various predictions would incur differences due to: different update cycles, different computation algorithms, and use of different input data.

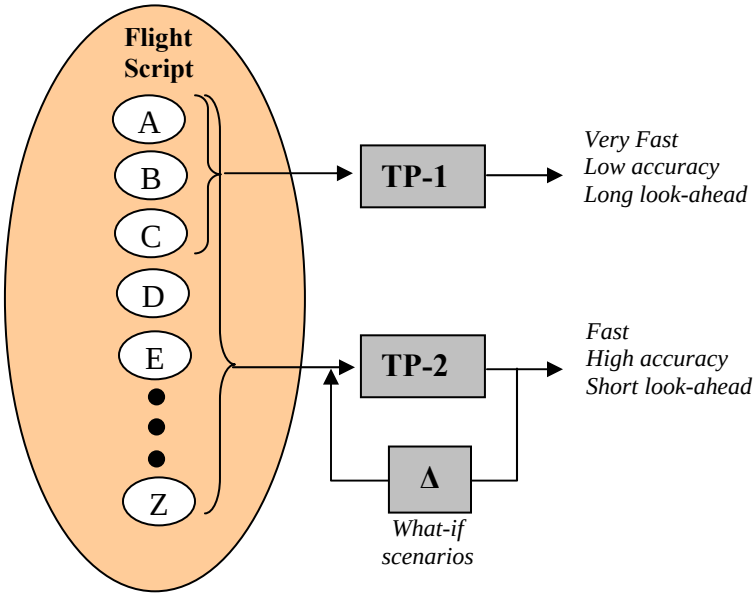

Figure 2-3 Illustration of the data-only approach

In the trajectory prediction services approach, the flight object could deliver a trajectory prediction "service" to requesting applications. A TP service would imply that an application would request a prediction from the FO with some parameters specified. Requesting applications might specify certain requirements such as: level of accuracy, computation speed, look-ahead times, and update criteria. Allowing parametric variation of inputs to the trajectory could be used to accommodate what-if scenarios. While this approach allows harmonization of prediction algorithms (as they can essentially be a single application), it is likely that the problems described for the data-only model would occur in this situation as well. If quality-of-service (e.g., accuracy, computation time) is to be specified in the request, relevant measures for these items would have to be developed in addition to mechanisms for altering the predictions as a function of these measures.

Support for multiple trajectories per flight script implies that the trajectory prediction service would require a precise specification of the flight intent in order to deliver a trajectory prediction. Client applications would then require the ability to provide these precise intent assumptions given a flight script. The flight object would provide

information to a client that the client would supplement with specific intent information necessary to allow trajectory prediction for that client's purposes.

The uniform trajectory approach requires the flight object to obtain and disseminate a single uniform trajectory, given identical flight intent assumptions, to all requesting applications. This approach would likely represent a compromise approach whereby consistency is achieved through the production of a centralized prediction compromised to adequately meet the needs of potential users. Several approaches to obtaining this trajectory can be developed:

- The flight object might request a prediction from a client trajectory predictor upon any change to flight script information
- The flight object might obtain a predicted trajectory from the airborne side, potentially representing the target trajectory for guidance.

This candidate approach also has issues in dealing with the requirements. With regards to computation speed, the approach would always be able to provide a trajectory within the time budget. However, the trajectory could potentially be "stale" leading to a different type of accuracy degradation. Analysis is required to determine if this would be suitable for most applications.

The uniform trajectory approach would allow applications to select their own update schemes, and as the entire trajectory would be specified, look-ahead would not be an issue. When investigating "what-if" scenarios, the uniform trajectory approach needs to be detailed.

- A uniform trajectory approach with a supporting TP service might be used to evaluate "what-if" scenarios if the same TP service can be used by the application and can deliver the performance required by the "what-if" application. Use of a different TP would add potential trajectory discrepancies.
- Use of airborne-obtained information would require flight script information for what-if evaluation on the ground. Agreement between the airborne trajectory information and the ground-based output will not be guaranteed.

The uniform trajectory approach would typically provide only one trajectory per flight script, although nothing precludes this approach from having multiple uniform trajectories under a set of canned intent assumptions. In the case of a single trajectory obtained from the aircraft, the flight script used for what-if evaluation *should* contain a level of intent that allows for close reproduction of the down linked trajectory.

In addition to the issues above, the centralized prediction approaches must also consider the impact on system architecture, response time, and bandwidth requirements. Distributed approaches, on the other hand, can tailor the performance to the client application but may lead to inconsistency. For these, these inconsistencies must be dealt with. With multiple trajectories possible to any given flight script, the approaches are not mutually exclusive. For example, a uniform approach may be used to represent a nominal trajectory, with a data-only approach used by certain systems for evaluation of alternative plans.

In summary:

- *Regardless of approach, a flight script is required with the amount and quality of information tailored to the application that has the highest accuracy requirement.*
- *It is likely that uncertainty on data elements in the flight script will be required to be able to compute an uncertainty on trajectories used for some applications. This uncertainty would likely be only on the high-impact elements.*
- *An improved understanding of application requirements is necessary to be able to determine which approach is best. For all approaches, a tradeoff exists between the meeting of disparate requirements and the degree of harmonization between trajectories. One research issue that needs to be addressed is which one is more important under various circumstances?*

2.4 Sensitivity to Execution

An issue related to intent is the sensitivity in the initial execution of a "do it now" type of maneuver. This includes the impact of latency in the execution of the maneuver in addition to certain effects that are not typically modeled by prediction (these may appear to an observer as latency).

An instruction may be provided via voice or data communication to the flight deck. A trajectory predictor will typically not be aware of the precise execution time of that instruction. There may be exceptions to this if the instruction is specified in a manner that correlates execution with an external event (e.g., upon crossing XYZ, climb to and maintain FL 310). While the execution may be delayed from the instruction due to flight deck response time, simplifying assumptions in trajectory modeling may lead to the perception of execution latency. Two examples illustrate this point: roll-in during a turning maneuver and execution of top-of-descent.

Providing the flight deck with an instruction to "turn now" to a particular heading will result in the aircraft initiating a turn in short order. When the turn begins, the aircraft will first roll into the turn, then perhaps fly a fixed radius turn, then roll out of the turn and continue on the new heading. An application that is conducting what-if analysis to issue the instruction might simplify the situation to not include the roll-in and roll-out maneuvers (i.e., model the entire turn as a constant radius turn). This may be necessary because the parameters of the turn are not known a priori. Figure 2-4 illustrates the impact on the error in turn for a very specific case. Had the application conducting the calculation considered the rolling maneuvers, the instruction would have been issued at the proper time to capture the desired path.

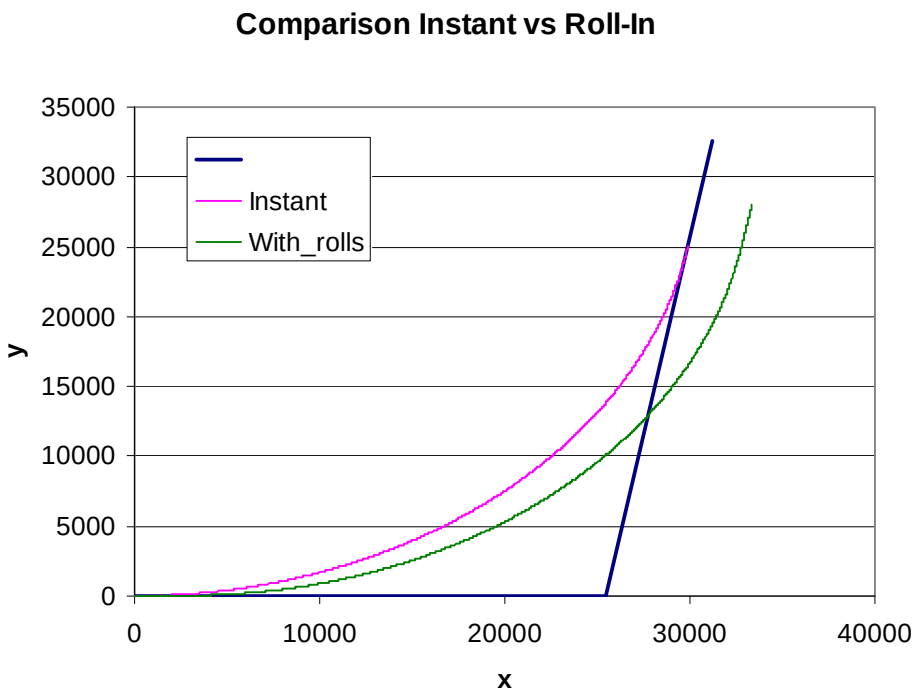

Figure 2-4 Comparison of turns with instant bank versus 3 degree-per-second roll to/from the bank angle. Assumed turns start at same location.

An issue similar to initiation of the turn occurs at top-of-descent if a TP does not model detailed behavior at the top-of-descent. Instructions to execute a descent can result in the flight crew "rounding-out" the descent profile for passenger comfort.[3] Figure 2-5 illustrates the case. Depending on the guidance mode during descent, the actual descent may attempt to capture the predicted path.

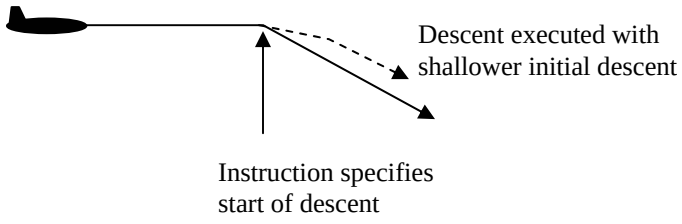

Figure 2-5 Comparison of descent prediction near TOD

[3] This is typically performed as a constant vertical rate to capture a VNAV descent path and is built into some FMS VNAV modes. This is another case illustrating when the nominal aircraft trajectory is used as input to the guidance system and does not represent the prediction of actual flight behavior. An instantaneous TOD is calculated as part of the nominal trajectory, but the "rounding" of the path is executed as part of the guidance law relative to the nominal TOD location.

Impact on Flight Object:

- *Depending on design, advanced applications seeking to provide certain instructions to the flight deck may be sensitive to some very detailed parameters. Active Decision Support Tools (DSTs), such as those that actively provide controllers with clearance/instruction advisories, represent one example of an advanced application. These applications may impose requirements on the flight object to contain these detailed parameters, or may impose requirements on altering the control instructions provided to the flight deck.*

2.5 Transition and Mixed Equipage

One area common to most concepts is the need to accommodate transition from current operations to a future state. For concepts requiring additional capabilities on board the flight deck, a mixed equipage scenario may be necessary for some period (if uniform equipage is not mandated). A situation may also develop in which ground systems are improved in certain localities. What this implies for the flight script is the need to accommodate situations in which certain data elements are either missing, of lower quality, or no longer required due to higher-quality alternatives. This is likely to persist for some time into the future, as modernization continues and new capabilities are constantly being developed.

As an example of this situation, equipped aircraft broadcasting speed intent could provide a different level of accuracy compared to aircraft that do not. However, both the TP and the FO must handle both situations. Furthermore, the accuracy of the output will be impacted. Systems relying on the output of trajectory prediction must be robust to these circumstances.

As another example, consider the deployment of a system that enhances surveillance information including speed and bank angle. This system may initially be deployed locally and require airborne equipage. Trajectory prediction based upon this information will have a different accuracy relative to prediction based upon traditional tracker output. It is likely that knowledge of these differences would be important to clients of the TP. For this reason, information quality measures may need to be included.[4]

In summary:

- *During transition, information quality measures are important to be able to determine the types of applications that may rely on the provided information.*
- *The flight script will have to accommodate differences in data elements being provided.*
- *Information of low quality, or missing, in the flight script may have to be accommodated in a preparation process that provides input to the trajectory predictors.*

[4] It is recognized that surveillance information may be separate from the FO. However, the information on present position and speed is critical to trajectory prediction and must be available. There are many implementation approaches to ensuring the flight script has access to this information.

2.6 High Impact Information

As part of activities preceding AP-16 on common trajectory prediction, a U.S. team was assembled to determine information that impacts trajectory prediction accuracy. The focus was on items that are currently of poor quality, or are available for today's TPs. Future concepts, including TMA-2010 (Europe) and the Next Generation Air Transportation System (US) among others, will require access to quality measures of most if not all of the information listed in Table 1. The table presents a matrix describing these data, with an assessment of the level of impact along several dimensions as follows:

- Impact – The impact the information quality is likely to have on trajectory prediction accuracy
- Frequency – The frequency with which modeling accuracy is impacted by poor information quality
- Control – The timeframe during which the information quality can be improved. Note that this was judgment based upon the situation existing in the US at the time, and may not apply globally.

Table 1 Description of information quality impact

Information	Impact	Frequency	Control*
Intent – Information entered into automation regarding vectors	high	frequent	Far
Intent – Knowledge by automation of top-of-descent time and location	high	frequent	Far
Intent – Information entered into automation regarding interim altitudes	high	frequent	Far
Intent – Knowledge of aircraft speed target and speed mode	high	frequent	Far
Intent – Knowledge of crossing restrictions within TP	high	frequent	Near
Intent – Knowledge of aircraft mode of control and targets	high	frequent	Far
Aircraft Performance Model quality	high	frequent	Near
Atmospheric predictions	high	frequent	Near
Aircraft weight	med.	frequent	Near
Surveillance information (including state)	med.	frequent	Far
Departure time	high	some apps	Far
Intent – Pilot deviations	high	Rare	Far
Intent – Instruction for best climb/descent	high	Rare	Far
Time to exit hold	med	Rare	Far
Time lags (execution and entry into automation)	low	frequent	Far
Intent – turn knowledge (e.g. fly-by/over)	med	frequent	Far
Configuration information (intended and current)	high	some apps	Far

*Expresses judgment of difficulty of implementation within the US NAS. Different nations may have differing implementation horizons.

Section 2.2 discussed the issue of intent information and some concepts that address the issues of improving intent information. Certain information described in the table such as improved atmospheric prediction or improved surveillance information will be provided by communities of interest outside of the Flight Object domain. The aircraft performance model quality will be the responsibility of trajectory prediction and is only impacted by the flight object if the object provides TP services with a dedicated TP. For much of the remaining information, issues of how to get good information as a forecast (e.g. departure time, hold exit time) can be directly related to the predictability of the overall system. In addition, systems do not currently exist that can provide all the information described.

3 Approach

The derivation of information requirements for the flight script was approached via an investigation of the individual functions required to prepare information for input into a trajectory prediction "engine." We first describe a structure, developed as part of Action Plan 16 activities, that was used to generalize the functions performed for trajectory prediction. One key element in the structure, the "trajectory script" is described in greater detail. The emphasis is meant to ensure that all necessary information is available to support the production of the trajectory script.

3.1 Trajectory Prediction Structure

As part of activities related to the definition of common terms for Action Plan 16, a structure (see Figure 3-1) was defined that helped clarify some of the common elements of trajectory predictors. This common structure greatly facilitated discussions, as prior endeavors did not start with a common understanding of the TP. The structure itself has been described in detail in [5]. Here we focus on a few of the elements that are required to understand the role of the Flight Object and Flight Script.

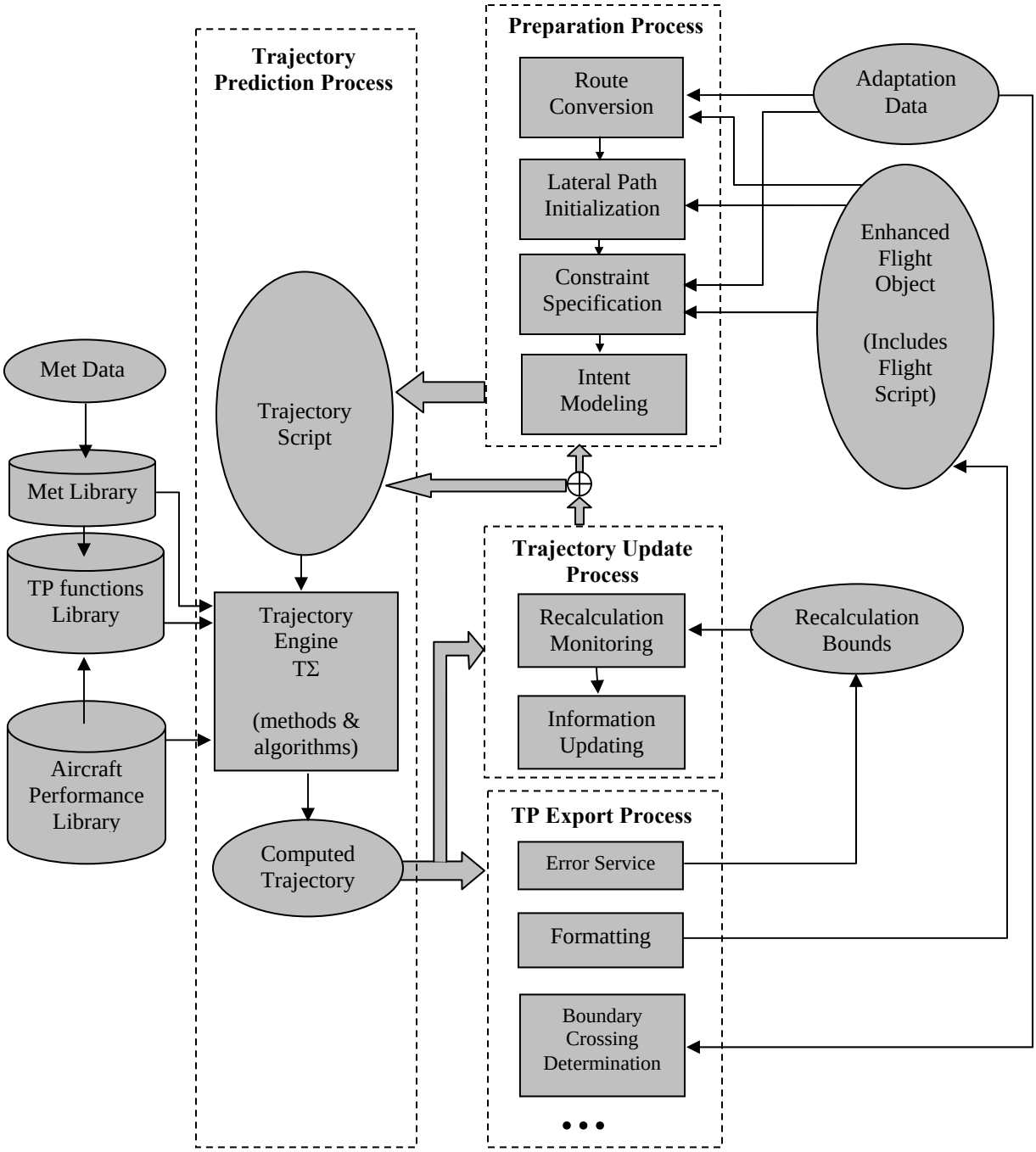

Figure 3-1 TP structure

When the TP structure was developed, our focus was on ensuring that we could replicate the trajectory prediction process as described by various TP developers. However, the structure supports, but does not explicitly highlight certain features such as:

- As illustrated in Figure 2-1, multiple Flight Scripts can be supported if we realize that for each flight script the process gets repeated.
- Multiple trajectory scripts are possible from any given flight script *under various modeling assumption*s. For example, some DSTs will simultaneously generate multiple trajectories using a collection of intent assumptions.
- The trajectory update process is expressed in a generic manner, but this process may occur on a fast or slow cycle with very different purposes. A DST may be making several to many simultaneous predictions as part of an iterative process (e.g. metering and conflict-free metering conformance). Alternatively, a predictor may be used to analyze traffic for potential problems (e.g., conflict detection), or adapt a performance model as new track update information becomes available.

One must consider these aspects when investigating the required content in the Flight Script.

The relationship between the Flight Script (FS) and the trajectory prediction process is straightforward. The FS provides input to the *preparation process* that is used to create one or more *Trajectory Scripts* in support of specific DST client needs. The trajectory script unambiguously describes how an aircraft will be operated, for the purposes of trajectory prediction, including tactical and procedural ATC constraints. The preparation process is divided into a collection of four services:

- **Route Conversion** – This service translates a route, a series of airways and waypoints, into a series of latitude and longitude points. When necessary, ANSP preferential routes may be applied by this service.
- **Lateral Path Initialization** – This service determines the path from present position to the route.
- **Longitudinal and Vertical Constraint Specification** – This service determines needed flight plan constraints. Constraints include assigned altitude and speed, altitude, speed and time restrictions, and interim altitudes.
- **Intent Modeling** – This service specifies how aircraft operations will be modeled, 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 altitude degrees-of-freedom. Intent modeling may be explicit or implicit in the trajectory models.

Stepping through each service described above and summarizing what elements are required to perform the service was the approach used to define the elements of the flight script. The results of this approach are presented in Section 4.2.

4 Derivation of Flight Script Data Elements

This Section describes some relevant assumptions regarding data, and applies the approach described in Section 3 in order to derive the requirements for data content within the flight script.

4.1 External Data Assumptions

The Flight Object is but one type of information that we expect to exist in the future information architecture. We assume that certain information, of relevance to trajectory prediction, will exist and will be provided via alternative information sources.

- **Weather and atmospheric information** – Atmospheric information including winds, temperature and pressure are all important information elements for the trajectory prediction problem. The flight object is not expected to provide this information.
- **Aeronautical information** – Information about the locations of airspace structures such as airways, waypoints, preferential routes, known constraints on routes, airport location, SIDs/STARs are required. The flight object will not provide this type of information; however, the flight object is expected to make valid references to this type of information.
- **Surveillance data** – Knowledge about the present position of a flight, and the state information (e.g. accurate speed information) associated with it will be provided through a separate information source. Since this information is required by TP, the flight script must be able to refer to the correct surveillance information. The ability to ensure consistency between the surveillance data and the flight object will be necessary.
- **Aircraft Performance** – Trajectory prediction is expected to have access to valid aircraft performance models suitable for the trajectory prediction engine. The flight script must describe the aircraft model in a manner suitable to identify the correct aircraft performance model. Additional data, such as precise aircraft weight can help with accuracy of certain performance models.

4.2 Preparation Process

This section steps through the elements of the preparation process, using the approach discussed in Section 3.1.

4.2.1 Route Conversion

Route conversion is “the process of transforming the route string in a flight plan or amendment into an equivalent set of points in some two-dimensional coordinate system” [6].

4.2.1.1 The Situation Today

Current trajectory predictors rely on route information contained in a flight plan and subsequent amendments as input to the route conversion service. Route information used by current route conversion services require the following information:

- Departure aerodrome – departure runway information is currently not incorporated.
- Standard Instrument Departure (SID) may be included. However, these are often described in a manner not suitable for automation (e.g., "Climb runway heading to 3000 feet. Thence, via vectors to assigned route. Expect clearance to filed altitude 10 minutes after departure.") The application of RNP/RNAV departure routes can remove ambiguity and provide precision for lateral paths.
- Fixes and airways – The route of flight is described as a series of fixes and airways. Adaptation data is used to convert these into a series of latitude and longitude points to be followed by the flight.
- Standard Terminal Arrival Routes (STAR) – As for the route, these define a lateral path that can be obtained using adaptation data. Information along the STAR may include speed and altitude *expectations* (e.g. "turbojet aircraft expect to cross at FL180"). As for the SID, information does not define the route fully ("expect radar vectors to final approach").
- Arrival aerodrome – The arrival runway information is not included.
- Amendment information to the route field would alter the elements in the above information. – It is important that amendments to lateral paths be entered into automation; this is not always the case today.

We concern ourselves strictly with the lateral path based upon information supplied to the route conversion process. Systems may be in place to verify the validity of the route with regards to adapted preferred routes, Special Use Airspace, and consistency of the supplied elements (e.g., does the flight have the equipment/performance necessary to be able to fly the route). It is assumed that these systems will have operated on the data prior to flight script information being provided to route conversion for trajectory prediction.

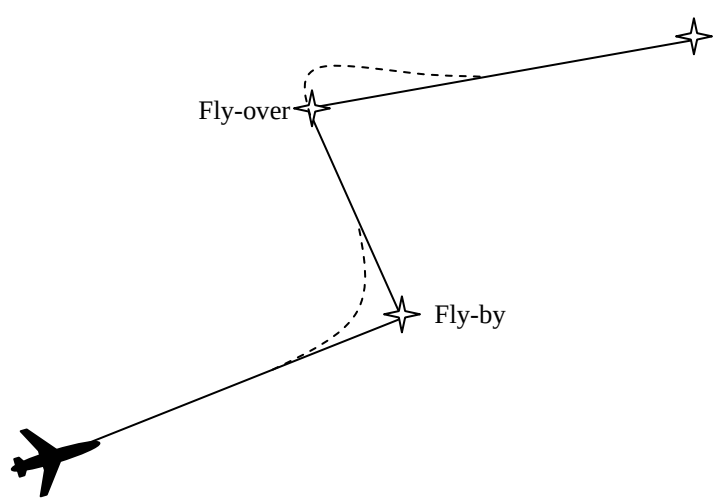

Figure 4-1 Impact of type of turn on lateral path

In addition to the issues identified above, aircraft may be vectored off-path or may deviate for weather. The former will have a significant impact on the lateral path if trajectory prediction is not provided this information along with the intentions for resuming the flight. When aircraft are subject to airborne holding, trajectory prediction must be aware of the route to enter and exit the hold-stack, in addition to parameters on the hold stack (presumably within the airspace information data).

The lateral route as defined above can include relatively coarse information on the lateral path to be taken by an aircraft. For example, legacy TPs often describe the lateral path as a series of straight lines between a series of waypoints. More precise trajectory prediction can occur if the route includes a series of maneuvers rather than just waypoints. As an example, consider a TP modeling the turn dynamics of a flight. These must incorporate assumptions regarding the turn dynamics at any given waypoint, which can be adapted or specified with the route. For example, a waypoint may be adapted as, inter-alia, a fly-by or fly-over waypoint (see Figure 4-1). Knowledge of this behavior can affect both the lateral and longitudinal accuracy.

4.2.1.2 Looking to the Future

It is clear that the future seeks to have the capability to more accurately represent the aircraft flight path. With the more widespread application of RNP/RNAV routes, higher precision in the lateral dimension will become more prevalent. Information requirements for route conversion in this type of environment include:

- Departure information – Knowledge of the pushback time, taxi path and departure runway can enhance the ability to forecast the departure time, a significant source of uncertainty. Runway information can also improve forecasts of the initial flight path, depending on airport configuration and additional information provided (e.g. SID).
- Departure route information – Removal of route ambiguity on departure (e.g. “via vectors”) will lead to greater precision in forecasting. This includes a more widespread application of RNP/RNAV departure routes from the runway or indications of the nominal vector plans/procedures for each departure/runway option. In the longer-term, a flight-by-flight specification of lateral path from the runway may be desired. It is recognized that an ability to tactically “path-stretch” flights may be required. In the medium-term, some concepts rely on a set of pre-coded alternative routes (e.g., [7]) to allow a discrete choice of paths (see Figure 4-2). This allows the automation (both ground and air) to select a consistent plan for execution with very little manual input required. Prediction on departure can also be important for concepts using time/path control to meter aircraft into congested en route airspace.
- Fixes and airways – The route of flight must continue to be defined in a manner that allows conversion to a series of latitude and longitudes. However, additional data at each waypoint, including expected turn types, should likely be included as well. For the purposes of route specification, the ARINC 424 leg types provide one method of specifying the lateral path including this level of detail. Note that for some leg types, coupling is introduced between the lateral, vertical and longitudinal profiles. More discussion will follow in the Section on constraints.

- Arrival route information – As for the departure route information, a more precise definition of route to runway is required. Near-term applications include RNP/RNAV routes, with flight-by-flight routes defined in the future. Pre-coded alternative routes can be incorporated as well.
- Arrival – Knowledge of arrival runway can help decision support tools seeking to develop a planned trajectory to a time over the threshold. The flight may also be executing a continuous descent arrival while seeking to avoid conflicts.
- Amendment information – In the near term, route information can be structured in a manner that facilitates the inclusion of amendment information. This includes clearances to pre-coded alternative routes, which can be more easily entered by an operator, and the ability to also enter minor route amendments without triggering undesirable side effects such as the unnecessary reposting of flight strips. In the long-term, integration of aeronautical data link services with decision support tools can help automate the process and ensure greater compliance.

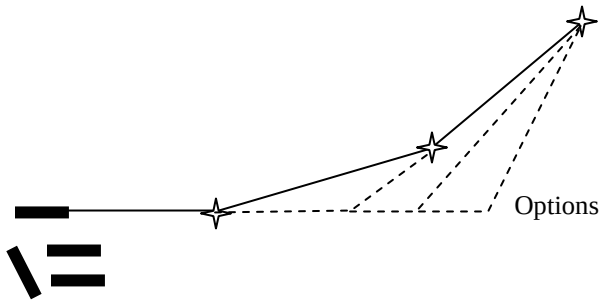

Figure 4-2 Pre-computed optional paths on departure route

Much of the information described above is expected to be dynamic. For example, the pushback time will be an estimate, under constant revision, until it materializes. The arrival runway will not likely be known for most of the flight, but will become known as one approaches the destination. An improving estimate still allows for improvements in uncertainty and significant accuracy improvements for shorter (more tactical) decision making.

Just as pre-computed optional paths can be considered and described in the flight object, options for airborne holding can also be described. This includes parameters for holding in addition to the routes that allow paths to be computed to ingress and egress the hold stack. Note that this information may be specified in the flight object, or in adaptation data that can be obtained via information in the route.

For the long term, certain concepts [3] allow the incorporation of flexibility in the definition of a four-dimensional trajectory. Care must be taken with the definition of "trajectory" as used within that concept since the concept accommodates varying levels of flexibility within the definition of a 4-D trajectory. At some locations and times, the flexibility would be reduced to impose tight four-dimensional constraints. When one considers the analogous route conversion process in this particular concept, the lateral

path must include the specification of a nominal path, together with a measure of flexibility (not to be confused with accuracy) around that nominal path.

4.2.2 Constraint Specification

Constraint specification is defined as:

> *The process of determining needed flight plan constraints. Constraints include assigned altitude and speed, altitude, speed and time restrictions, and interim altitude(s).*

4.2.2.1 The Situation Today

Current generation trajectory predictors may incorporate altitude and speed constraints within adaptation data. These are based on letters-of-agreement (LOA) between facilities or standard operating procedures (SOP). As an example, these static constraints may allow the inclusion of altitude constraints when transfer between facilities requires certain aircraft types to be transferred at specified altitudes and speeds. The information that is adapted is disparate, difficult to obtain and some constraints are frequently applied based upon controller experience rather than a published procedure.

While the constraints can be incorporated by current TPs, the constraints act as point constraints and can be executed in a variety of different ways. For example, a flight required to cross a waypoint at FL240 during descent may be descended in a variety of different manners (see Figure 4-3). While the figure illustrates different paths, there can be variations in speed of descent and times of arrival as well. This example illustrates the impact of intent, rather than a direct impact of constraints. This shall be described further in a description of intent modeling.

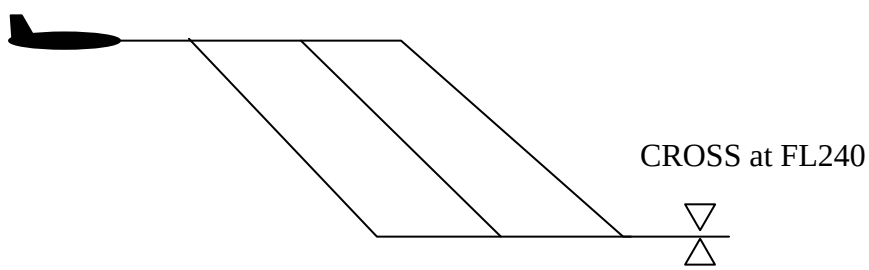

Figure 4-3 Ambiguous application of constraints

Interim constraints can also be applied by controllers for a variety of reasons. These include the management of flow and the resolution of conflicts. Speed control can be imposed to manage flow and interim altitudes can be imposed as flights vertically transit through a sector. Consider a flight climbing through a sector with a ceiling at FL 240. The controller may initially clear the flight to FL 240 and will clear the flight to climb into the next sector when transfer-of-control can be accomplished. This can depend on controller workload or the speed with which the flight reached the flight level in the first place. Trajectory predictors are not aware of either the constraint, or the duration of the constraint.

Constraints on time-of-arrival at waypoints are currently not imposed through communication of the time-of-arrival constraint to the flight. Controllers using time-based-metering tools are provided with a scheduled time-of-arrival for each impacted aircraft; however, these times are targeted by the controllers and instructions are provided to the flight deck in the form of speed control and vectors. These instructions add to the trajectory prediction challenge due to the unknown lateral and speed intent.

Flight Management Systems are currently capable of incorporating constraints into the active route. However, not all combinations of constraints will be imposed in a manner that is both predictable and known to the ground automation. Combinations of constraints include the application of both altitude/time constraints at a single waypoint, and the impact of constraints on multiple waypoints. One FMS model may construct a combination of performance and geometric paths between multiple constraints in a different manner than another FMS. While the application of constraints by the FMS would be considered "intent", ground systems performing "what-if" analysis through the application of constraints must be acutely aware of the impact of multiple constraints on an aircraft's trajectory.

It is possible to over-constrain the flight path. For example, the imposition of an AT OR ABOVE constraint followed by an AT OR BELOW constraint may not be reachable for certain aircraft models (of specified weight, given the atmospheric parameters). Thus, the ability to ensure that over-constraining does not occur is necessary when conducting ground-based "what-if" analysis. Certain TPs will have methods for providing the best trajectory available for the over-constrained situation, whereas others will just return an error.

Certain constraints lead to what is referred to as a "conditional waypoint". An example of this is the Course to an Altitude (CA) leg type in ARINC 424 (see Figure 4-4). A "constraint" on the altitude determines the point at which transition to the next leg will take place. As a result, coupling between the lateral path and the longitudinal path will likely follow (depending on the subsequent leg).

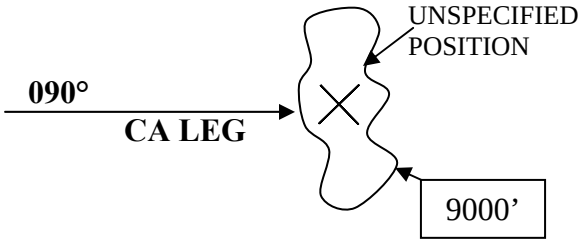

Figure 4-4 ARINC 424 CA Leg type

4.2.2.2 Looking to the Future

In the near term, migration towards RNP/RNAV routes, even with optional paths, will lead to broader knowledge of constraints and publication of those constraints. The objective should be to ensure that the automation is aware of constraints that are imposed in a routine matter to separate flights from flow or terrain. The specification of optional paths (see Figure 4-2) can include waypoints with constraints. The inclusion of these constraints can enable certain paths. For example a path may only be possible with altitude constraints for terrain avoidance.

More widespread application of RNP/RNAV routes with constraints can allow these routes to be input into the FMS and flown using guidance to these paths. The application of optional routes can facilitate the execution of these alternatives if they are pre-loaded into the FMS.

Migrating towards the longer-term future, dynamic and tailored routes with constraints are developed for individual flights. Prior to getting to this point, trajectory predictors need to be capable of ensuring that aircraft can meet the combination of constraints that are provided. Furthermore, separation from flows and terrain must be considered *real-time*. The ability of the ground system to compute the impact of constraints to a desired level of accuracy is dependent on, *inter alia*:

- Accurate aircraft performance models for each flight. This includes aircraft performance models that cover the range of relevant operational conditions. For example, a descent above idle thrust requires performance data at the thrust levels in use.
- Knowledge of aircraft weight.
- Knowledge of intent information such as speed targets, control modes and the manner in which these modes impact the trajectory.
- Manner in which the constraints are implemented. This may require knowledge of specific FMS behavior, control modes being used onboard the flight deck or company policy.
- Knowledge of additional company policies. For example, some air carriers may require earlier stabilization on final than others. Application of reduced thrust climbs are another example.

One future concept that has been discussed is the idea that an aircraft can downlink a 4D trajectory to the ground system. When necessary, the ground system would provide constraints to assure separation and manage flow. However, if the ground system is to provide these functions, the ground must still be capable of accurately computing the impact of constraints in order to assess alternative trajectories for separation assurance and flow management. The result is identical to the prior situation; the ground system still requires the information previously described to obtain an accurate assessment of the impact of constraints. Downlinked trajectories may support nominal ANSP analyses (e.g., conflict probe, estimating traffic demand), and then only if the trajectory is still valid.

[For the above operations, it is assumed that the FMS has wind information loaded in order to compute a proper target trajectory (this is not yet the case in current operations).]

The ability of a future system to remove the impact of interim constraints is highly dependent on the procedures used to implement a future concept. As an example, consider a flight climbing through a sector subject to an interim altitude clearance (see Figure 4-5). Knowledge of the level-off altitude is essential to be able to capture the level-off segment. When/where the aircraft intercepts the interim altitude can be improved through better prediction of the climb profile. This can be accomplished through knowledge of the items described above for the application of constraints. Knowledge of the duration of any level-off segment (including no level-off at a previously assigned interim altitude) can, in theory, be achieved through the specification of an altitude constraint at the end of the segment. However, operationally one must determine how this constraint could be known. For example, the constrained trajectory may have been the output of a system performing de-confliction or load-balancing. Even with such an active decision support tool, the performance of the tool must be such that the instructions are implemented a large percentage of the time, in a timely manner and communicated to all TPs. Otherwise, it is unlikely that the duration would be accurately known to a TP unless the automation is able to accept controller inputs (and the controllers input the information).

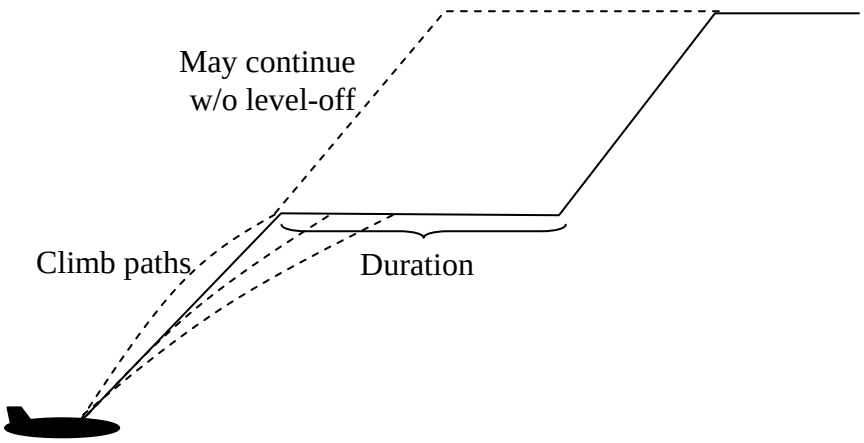

Figure 4-5 Interim altitude constraint effects

Many future concepts rely on time-of-arrival constraints at waypoints. The flight script must support the ability to impose a time-of-arrival constraint on a waypoint in addition to any type of constraint definition required for chosen operational concepts. When combined with altitude and speed constraints, the ability to determine whether an aircraft will meet all constraints becomes more complex. Furthermore, multiple 4D-trajectory solutions may be found for meeting a time constraint. These multiple solutions can be considered part of the intent description problem (i.e., introducing ambiguity as to the intended trajectory) and are discussed in a subsequent section.

4.2.3 Path Initialization

Path initialization describes the process of determining the path from the present position to the route.

4.2.3.1 The Situation Today

The aircraft's present position is obtained through surveillance data. This surveillance data is typically sampled at a fixed rate to provide a lateral position and a reported altitude. From a sample of this information, ground speed, air speed and course can be *inferred*, albeit with limited precision.

In order to conduct path initialization, a trajectory predictor must obtain the surveillance information, determine where the information maps onto the route defined during the route initialization process, decide if the present position is on- or off-path, and compute a path from present position back onto the route if off-path. This process is illustrated in Figure 4-6. The trajectory predictor must consider the present location of the aircraft, together with additional information (estimated course, intercept angle to next waypoint, distance off-path).

Aircraft can be off-path for a variety of reasons, leading to varying logic for lateral-path initialization. Below are some nominal cases for being off the flight-plan route.

- Flight technical error (FTE) – the aircraft can be off-path within some narrow bounds. Depending on the mode of flight navigation used (e.g., LNAV, heading-select, hand flown), the aircraft and pilot may seek to "capture" and/or track the original route in different manners.
- Flight in a turn – the aircraft may be executing a turn. The flight would not be exactly on the route, but would still be following the original route.
- Flight on a vector – the aircraft may have been given a vector off-path and will be vectored back at some point. This may be to a next waypoint or back to intercept the original route.

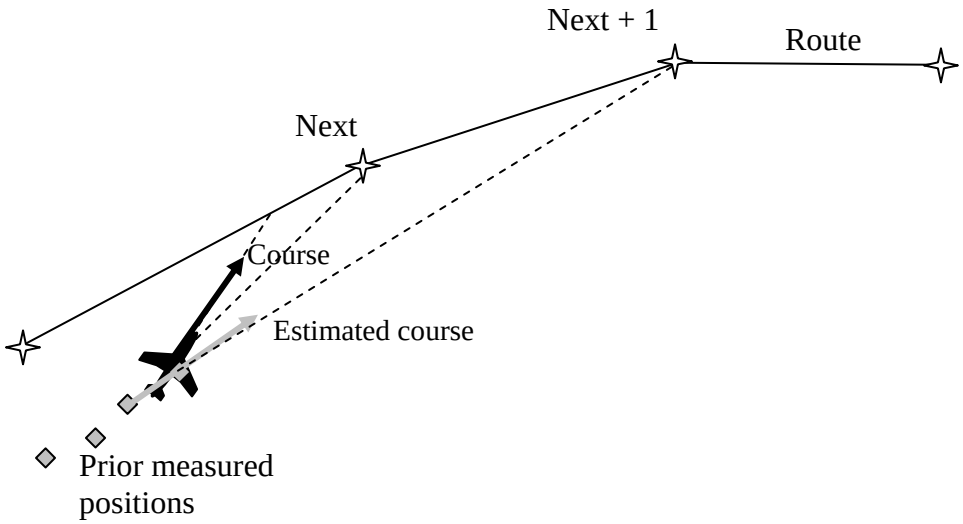

Figure 4-6 Path initialization

Additional cases can exist when the flight route being flown is not known to the TP, or the flight crew has blundered and the flight is out of conformance with a reference trajectory.

Given the information present in current automation systems, the estimated speed and course may have a substantial error from the actual speed and course. Lack of knowledge of aircraft navigation/control modes also prevents lateral path initialization from determining short-term intent. For flights that are on an initial vector, prior to a "turn-back", the system does not know the exact initial course, nor the point or heading for a turn-back. In some systems, the controller may be able to enter these clearances into the automation.

4.2.3.2 Looking to the Future

The introduction of improved surveillance information (e.g., ADS-B or modern radar tracking algorithms will allow automation systems to have knowledge of speed and course information with greater accuracy. This information can be used during path initialization to better estimate an intercept course to the original route of flight. With this information, turn detection would also be improved. The reader should understand that proposed approaches for the future improve the situation, but may not necessarily address all errors.

The application of RNP/RNAV routes with optional paths for path-stretch vectoring can remove the lack of intent in cases when a flight would have been vectored off-path. For these situations, the flight would never even be considered off-path since the "path stretching" on the optional path would have been input into the automation as a new route.

In the far-term, knowledge by a TP of aircraft state information, current aircraft control modes, and inclusion of TP models of the aircraft control modes would help reduce uncertainty associated with the initial path. Depending on the future concept, the issuance of a new path via data link services may replace vectors thereby eliminating the need for path initialization in this case. This assumes that the new path is conveyed to the TP.

4.2.4 Intent Modeling and Description

As the last step to be described in the preparation process, intent modeling directs the manner in which a plan (expressed by the flight script) is executed. Recall that we described a situation in which multiple trajectories could stem from a single flight script. These multiple trajectories can stem from various assumptions about intent.

Intent modeling can be decomposed in several ways. Along the degrees-of-freedom being considered: longitudinal and lateral intent modeling. If we consider all the actors/agents involved in the definition of intent, intent can be decomposed into ground automation, controller, pilot, and aircraft intent. Some have also discussed the concept of flight intent (see [8]) as a separate concept.

Longitudinal intent modeling is defined as:

> *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.*

Lateral intent modeling covers the lateral degrees-of-freedom. Some lateral intent modeling has been described as part of the route conversion process and the lateral path initialization process.

In order to understand intent modeling, one must recognize that each actor in the system has one or multiple expectation(s) of how a specific flight will behave. The automation system may build a specific trajectory based upon information available to it. The controller may have a mental model of behavior based upon expectations of his/her own actions and the expected response of the pilot/aircraft. A pilot intends to fly the aircraft in a specific manner, including guidance targets and control modes. Separately, the aircraft guidance and navigation functions will respond to what is specified by the pilot, but the pilot may not be entirely aware of all the execution details. Furthermore, human errors may lead to discrepancies, and each agent may have multiple plans based upon future events.

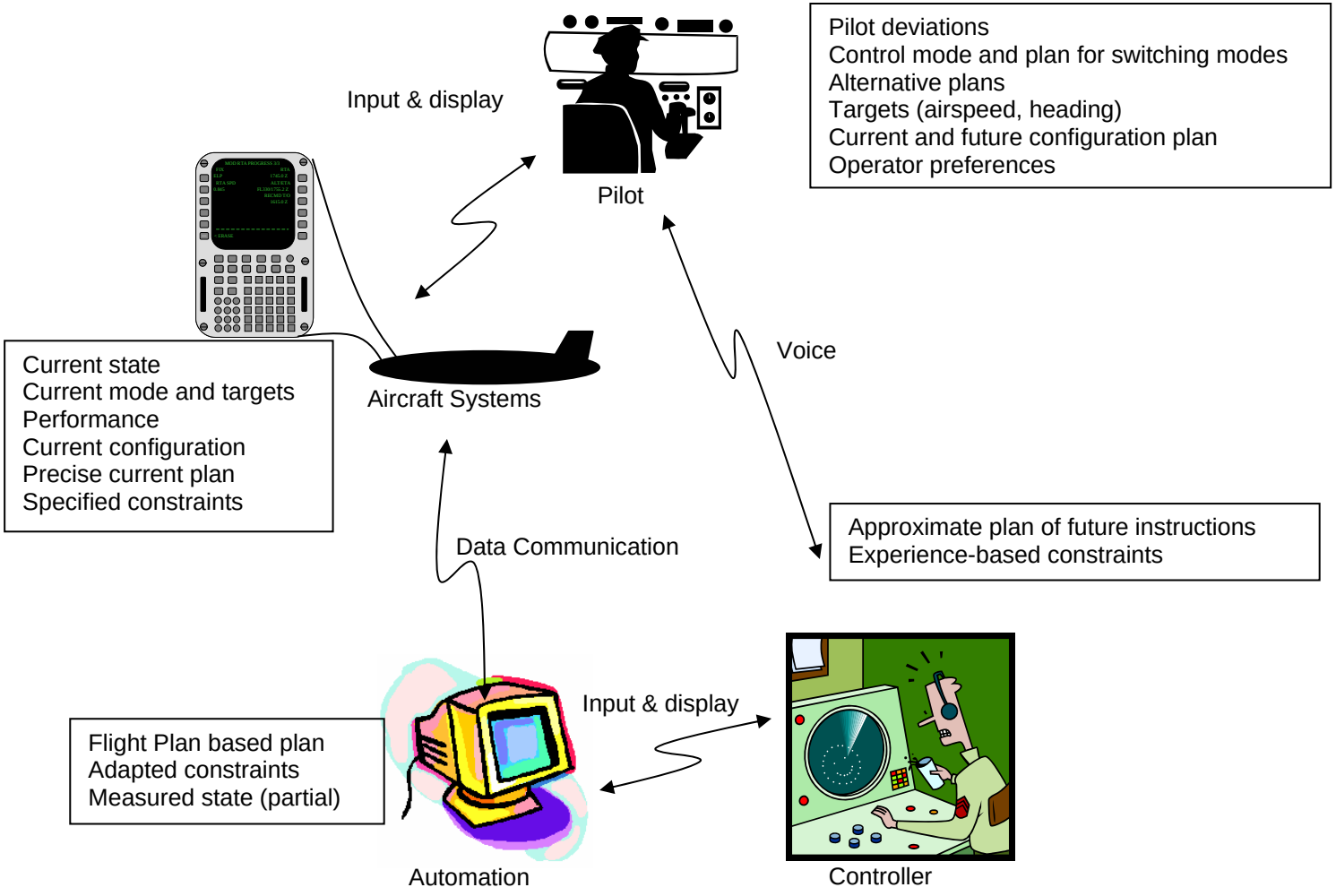

Figure 4-7 Intent knowledge by actor

4.2.4.1 The Situation Today

We describe the current situation of intent by categorizing intent according to the degrees-of-freedom being considered, and according to the actors within the degree-of-freedom. A high-level sketch of the intent situation is described in Figure 4-7.

4.2.4.1.1 Lateral

Ground Automation – Lateral intent is primarily known to ground automation through the route that is specified to automation and adapted navigation data. Depending on the accuracy of the surveillance system, the estimation of the current course may be subject to substantial error. Automation is not aware of lateral path changes (i.e., vectors or pilot deviations) unless the controller specifically provides such input. Even then, such inputs are severely limited by current flight data processing systems (at least in the U.S.), and are rarely used (primarily due to poor human-machine interface design and undesirable side effects. When an aircraft is off the route of flight, automation must make assumptions to get the aircraft back onto the route. One example is that of a flight on a vector with unknown timing and magnitude of turn-back. Details of turn-dynamics may not always be known to automation, and assumptions must be made to estimate the aircraft behavior. Some waypoints may be adapted as fly-by or fly-over waypoints. Details of turn dynamics include: the timing of turn execution, actual turn rates (and lower-level parameters to obtain these), and roll-in/out rates.

Controller – Controller intent will also include knowledge by the controller of planned changes to the route of flight. This includes the expectation to issue direct routings, and the *approximate* timing and magnitude of lateral instructions for both separation assurance and conforming to traffic flow restrictions (e.g., meeting scheduled time-of-arrival constraints).

Pilot – Like the automation, the pilot does not have awareness of all the lateral controller intent until it is communicated to him/her. Once communicated, the pilot will execute the instructions, but these may still not be known to ground automation. The pilot is aware of pilot deviations, and can have precise information (e.g. selected heading) on short-term lateral intent typically necessary for path initialization. The pilot intent includes events at which pilot-initiated mode switching will occur (such as following LNAV versus being in heading-select mode or hand flying the aircraft).

Aircraft – The aircraft systems execute the commands provided by the pilot. These include levels of detail that precisely define the motion, but may be obscured to the pilot. For example, aircraft operating in LNAV mode will execute a turn with roll-in/out to capture the next leg. Guidance also corrects for perturbations due to wind variations. However, the knowledge horizon of aircraft systems may be limited due to pilot intent. In most cases the intent of the pilot to switch modes will not likely be known to aircraft systems ahead of the timing of the mode switch.

4.2.4.1.2 Speed

Ground Automation – In present systems, some speed intent is known to ground automation through the speed that is provided to it. This includes adapted speed restrictions, filed speed in the flight plan, or speed as amended. Other speed intent that is not typically available to the ground today is the speed profile planned for climb, cruise, and descent segments. Measurement of current ground speed is an inference of intent. The speed intent known to automation due to flight plan filing is only the true airspeed during cruise (FAR §91.153, §91.169). Upon reaching their filed cruise level; flights are required to conform to their filed speed within the greater of 5% or 10 knots, or report the change (AIM 5-3-3e). When the controller has issued a speed instruction, "the pilot is expected to maintain a speed within plus or minus 10 knots or 0.02 Mach number of the specified speed" (AIM 4-4-11). Controller instructions are provided in terms of indicated airspeed or Mach number. Only if the controller enters the instruction into automation will the automation be aware of the speed intent.

Under current operation, there is substantial variability allowed in the target speeds. Furthermore, speed targets are not known to automation in all phases of flight. If an aircraft is operating to a speed target in climb or descent, these speeds are not known to automation. The aircraft control mode is also not known to ground automation. Ground automation may be aware of an estimation of the current ground speed; however, depending on the accuracy of the surveillance data, the current ground speed may be subject to substantial error. Attempts to infer target airspeeds from computed ground speed are subject to additional error from wind modeling errors. Wind models are required within ground automation systems to convert between target air speeds and ground speeds used to compute a trajectory.

Controller – The controller may issue speed instructions to the aircraft. Automation is only aware of these instructions if entered by the controller. The controller may also be aware of planned speed instructions prior to issuance or execution. The application of a vector to obtain separation, and the speed to maintain it, leads to speed control being expected by the controller before the instruction is provided. A controller may also issue speed control for the purposes of meeting specific targets (e.g. metering).

Pilot – The pilot is aware of the mode of control and the speed target, if applicable. Under many circumstances, the pilot is the initiator of the speed target, particularly when the speed target is left to pilot discretion. Events leading to switches in mode are known to the pilot and may not be known by the aircraft systems. Certain modes of control (e.g., specified cost-index, using RTA functionality), may lead to the pilot not being precisely aware of the target speeds throughout the flight.

Aircraft – The aircraft systems have precise information on the <u>current</u> mode of control and speed targets, if applicable. It is important to note that the speed target does not necessarily mean that the target will be met. Aircraft subject to fluctuations in wind will experience a dynamical response with transient speeds. Transients in speed during transition between modes and changes in speed targets can be known by aircraft systems. The aircraft system would have a prediction for the speed target as the flight progresses

when operating at a fixed cost index (or RTA if so equipped). If a vertical speed target and thrust settings are specified, then the aircraft may use speed as a control variable. In this case, speed is an outcome.

4.2.4.1.3 Altitude

Ground Automation – Under current operations, automation is in possession of the planned cruise altitude from the flight plan. Cleared and temporary flight levels are available to the automation, assuming this information has been entered into the automation via amendment. Information on duration of stay at interim flight levels is not known to automation. In certain airspace (e.g. Oceanic) flight plan information may also include desired step climb points and flight levels. Certain altitude restrictions may be known to automation in the case of restrictions that have been adapted.

Controller – The controller maintains knowledge of the instructions provided to the flight, and likely has a plan for future altitude instructions (e.g., future changes in cleared altitude). These may be conditional, or based upon events (e.g., for separation assurance). These include the end to an interim altitude clearance, or the issuance of a descent instruction. The controller intent, regarding the current or future altitude instructions, may not be communicated to either the automation or the flight deck. Through clearances, the controller limits the altitude band in which the aircraft operates but does not typically control how the aircraft meets the next altitude target.

Pilot – With regards to altitude, the pilot may have knowledge of planned future events that will lead to mode-switches. For example, the pilot may desire a step climb at a future time. The pilot intent is to request this step climb from the controller when desired; however, neither the controller or ground systems would have this information. Some current-generation FMS implement a manual process by the pilot to compute the optimal flight level including winds. Thus, unless separately entered by the pilot, the aircraft systems may also not be aware of this intent. During transition (climb/descent), the pilot is aware of the mode that will be applied to implement the maneuver. This can lead to a fast/slow climb that is not initially known to the ground actors.

When the pilot is provided instructions that allow discretion, the pilot will maintain the knowledge of how/when the altitude transition will be conducted.

Aircraft – The aircraft systems have knowledge of the current altitude targets for the aircraft and the current mode that the aircraft is operating in. The aircraft systems may also have a plan in the FMS for implementing altitude constraints, specifying desired top-of-descent or reaching top-of-climb. During transition, in certain modes, a path may have been constructed that is used as a target for altitude. This plan is only known to the aircraft systems. Whether this plan is followed is entirely dependent on the pilot's intent to use specific flight modes. The aircraft systems have information on the climb and descent performance of the specific aircraft during transition.

4.2.4.1.4 Control Inputs

Ground Automation – Under current operations, the automation has no information on the control modes, power setting or configuration of the flight. This information, if modeled within certain TPs is based on adapted data that is inferred from measurement of other values (e.g. speed and weight). For example, assumed procedures may specify configuration as a function of speed.

Controller – Like the automation, the controller does not possess information on control modes.

Pilot – The pilot has knowledge of the current and anticipated future settings of control inputs. This information can be based upon company-specific procedures or anticipation of mode switching based upon pilot preference. For example, the pilot is aware of an approach procedure and at which point (based on speed) various flap settings will be imposed. However, the deployment of spoilers may be based on the response to uncertainty. For example, an aircraft subject to higher than expected tailwinds will remain above path during descent. Use of VNAV SPD at maximum descent speed may still not capture the path, resulting in a message to the flight crew to "add drag". This situation introduces intent that is not known. The added drag will likely continue until the original path is captured, if possible.

Aircraft – The aircraft systems are aware of the current aircraft mode of operation and configuration. When operating in certain modes, the plan for switching guidance mode is encoded as algorithms in the aircraft systems. However, the pilot intent may override this plan if the pilot switches modes. Certain company procedures can be encoded in the aircraft systems to address nominal operations (e.g., speed as a function of weight and wind when flying at a specified cost index).

In order to execute a maneuver, the aircraft systems always operate at the lowest possible level. For example, when executing a turn, the aircraft systems ensure the power is set properly, the turn is coordinated, roll-rates are specified, bank angle limits are met, and the next leg is properly intercepted.

4.2.4.2 Looking to the Future

Knowledge of intent will likely remain a challenge for trajectory prediction. The specifics of the information that is to be exchanged to provide the needed TP accuracy will also depend on the concept being considered.

It is a challenge to predict with certainty what future operations will look like. Concepts range from autonomous flight to highly managed trajectories. In all cases, some combination of air and ground will define a set of initial plans that manage anticipated traffic complexity. Controllers and/or pilots are provided advice on how to modify intent in order to resolve tactical concerns while meeting evolving strategic objectives. In such an environment, there is a need to seek consistency among the various automation systems to avoid conflicting decisions. The role of the human contribution to intent may also diminish if greater reliance on decision aids is anticipated.

4.2.4.2.1 Lateral intent

In the medium term, the application of alternative RNP/RNAV routes (as previously discussed) will allow the introduction of a discrete set of lateral intent that can be planned to. As soon as the intent is known, the selection of the route can be communicated, via voice, to the flight deck. The simplicity of pre-coded paths allows the ground automation and aircraft systems to be updated; thereby synchronizing intent. However, the application of these pre-coded routes stems from a decision at the *operational concept* level. The decision to move in such a direction requires consideration of the overall system performance of such an approach – and is beyond the scope of this document.

With the introduction of ADS-B, improved knowledge of the current state allows improved knowledge of short-term intent, as described in the section on lateral path initialization.

Synchronization of navigation databases using a common language between ground-based tools and airborne tools will remove inaccuracies resulting from such information discrepancies.

In the longer term, data communications and integration of data communications with ground decision support tools and aircraft automation <u>may</u> allow the dynamic development, communication and execution of complete trajectory solutions. This would ensure a synchronized lateral path between ground and air automation, once the solution has been computed. Ultimately, this represents an extension of the RNP/RNAV approach, with the routes being dynamically defined on a flight-by-flight basis.

Regardless of the operational changes being considered, lateral intent errors can be improved by ensuring consistency between the actors as soon as the lateral intent is known to the actor responsible for imposing it. This argues in favor of a consistent lateral path in the flight script that can be updated by the actor responsible for changes to the route.

4.2.4.2.2 Speed intent

For the most part, current speed intent is precisely known to aircraft systems. The future speed intent may also be anticipated by the aircraft systems (depending on the pilot's chosen mode of operations), assuming no mode switches on the part of the pilot. Data communication may be used as a means in the far-term to obtain the anticipated speed intent for the nominal profile as known by the aircraft systems. However, while the nominal speed intent may be expressed for all legs of the flight, this may not be useful for ANSP automation seeking to conduct the "what-if" analysis necessary to provide services for separation assurance, traffic-flow-restriction conformance, or user-preferred-trajectory requests. This is clear if one considers that the speed intent can be coupled to events and conditions, not just the route of flight.

As an example, we consider a hypothetical situation of the speed intent for a flight about to transition to a descent. The nominal profile is shown in Figure 4-8. The flight may have a cruise speed (M 0.82) followed by a constant mach (M = 0.82) idle-power descent

segment. Upon reaching a CAS of 300 knots, a target of 300 knots is followed on descent until a deceleration segment is required to reach a 250 knot target at a specified altitude. Even with explicit instructions on speed intent for the nominal case, a ground decision support tool looking at a proposed altitude constraint would be unable to predict the trajectory without knowledge of the speed intent for the new descent profile. The new speed profile may be driven by the need, *inter alia*, to meet an arrival time, to ensure separation assurance, to optimize an overall cost function, or to apply company preferences on descent targets.

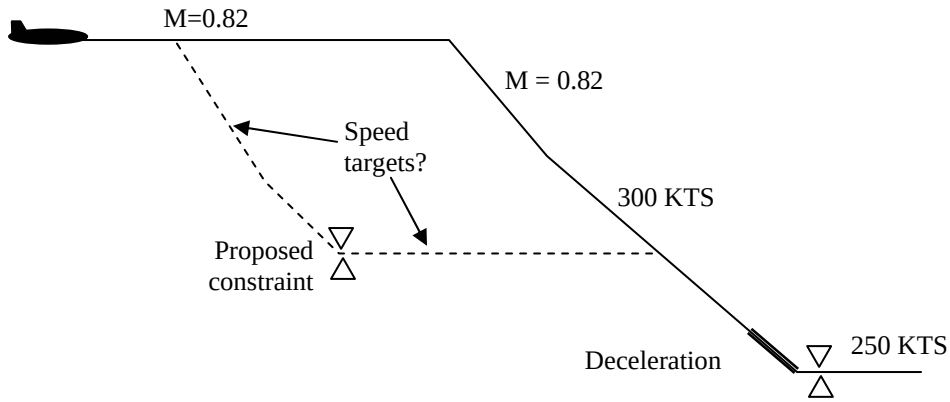

Figure 4-8 Example speed intent on descent

What the above example illustrates is that speed intent is more complex than simply expressing the speed target for a given leg. Algorithms and procedures known to the FMS or pilot are used to determine the speed intent in certain flight segments and these can vary by FMS model and between operators. These algorithms and procedures are not necessarily known to a ground TP or flight object. In order to determine what information is required within the flight object to support trajectory prediction for active decision support tools, *research into how to express this information is required*.

Initial areas of research have identified methods [8] of expressing the intent for a nominal trajectory. These methods allow the expression of coupled conditions such as "capturing" the CAS target after the constant Mach descent, or determining the start of the second deceleration segment based upon meeting the 250 knot target at a specified constraint. However, the methods do not yet express the logic in setting the overall descent schedule strategy as required to conduct the what-if analysis described above.

When explicit speed control is provided to the flight deck by the controller, these instructions should form part of the flight script, together with conditions for start and end of control. Concept development needs to consider how these explicit instructions can be communicated and entered into the automation in a timely manner. However, even for speed control, knowledge of reasonable limits on speed control in various flight segments should be specified to limit the search space for DSTs to feasible solutions.

4.2.4.2.3 Altitude

A description of the information requirements to support an accurate altitude profile is highly coupled with those related to: speed intent, constraint specification and aircraft control modes. As for speed and lateral path changes, in the mid- to far-term, as soon as changes become known to altitude constraints, the automation should be updated to reflect these. The issue of how to know when an interim altitude allows a climb (or descent) to resume must be resolved at the concept level. This may be specified in a closed-form manner, or tied to conditions/events. The former case favors predictability against robustness to disturbances. However, if the latter case is selected, techniques for the description of these events must be developed.

Desired altitude step climbs (or cruise climb, if applicable) should be included in the flight script, as a measure of altitude intent (pilot). As for other aspects, the concept will determine when a flight is actually cleared for these flight levels. Trajectory predictors will likely need to maintain both the cleared and the requested flight levels, as the probing of requested flight levels can assist in the issuance of clearances.

The altitude *profile* is dependent on the mode of control, targets and mode-switching/setting logic during climb or descent transition. These, together with constraints and speed profile will lead to the prediction of such locations as top-of-descent and top-of-climb points. The altitude degree-of-freedom re-iterates the need for knowledge of control, targets and mode-setting logic. These may vary with the specific model of avionics systems on-board the aircraft. Furthermore, limits on aircraft performance must be reasonably well known by DSTs using TPs to allow altitude constraints to be properly assigned. These limits may be dependent on various other parameters.

4.2.4.2.4 Control Inputs

The aircraft systems may be aware (depending on mode) of the anticipated control inputs along the nominal path. This includes control-law, targets, expected mode switches and configuration changes. In the long-run, this information may be incorporated into the flight script to allow improved prediction of the nominal trajectory. Note that we are discussing a level of control input required to predict trajectories for ATM applications. For example, this includes instructions required for turn computation, but not necessarily gains in control loops to improve aircraft dynamic characteristics.

As described in the section on speed intent (Section 4.2.4.2.2), research into languages to describe these inputs has yielded some candidates for description of the detailed control inputs. However, certain issues remain:

- It is a challenge to fully capture pilot intent in the aircraft systems. This includes company-specific procedures both en route and within the terminal area.
- If this approach is to be implemented in the terminal area, concepts should ensure that actors are synchronized on the expected control targets, mode switches, configuration changes, etc that are critical to achieving the required TP performance. This may be straightforward for a nominal case, but poses a

challenge when time-critical instructions are provided to and executed by the flight deck.

- As this information becomes available to trajectory predictors, the TP engines and aircraft performance models must be able to use the information appropriately. For example, if configuration information is known, aircraft performance models must have data for these configurations. If descents are to be computed at non-idle thrust settings, this data must be available. If roll-rates are specified, the turn modeling should incorporate these effects.
- Decision support tools seeking to develop alternative trajectory-based solutions must be aware of how provisional instructions will alter the series of control targets, mode switches, configuration changes, and even selected modes. Research is required to determine methods for specifying this information. Note that much of this information could be specified as static data and need not necessarily be exchanged.
- TPs should be capable of determining the validity of a provisional instruction in order to minimize negotiation upon issuance of an instruction. For example, constraints should be reachable, particularly multiple constraints (e.g. RTA with altitude). One approach could require the TP to possess knowledge of ranges of control inputs (under the myriad of conditions possible).

The synchronization of intent between the ground and air remains an area requiring some research to fully resolve. While it is possible to synchronize nominal trajectories, the ability to anticipate the result of proposed instructions is necessary to move forward with *active* decision support automation that depends on TP engines to generate trajectory-based solutions to ANSP problems.

4.3 Trajectory Script

Figure 3-1 illustrates the role of the trajectory script in the trajectory prediction process. The trajectory script provides an unambiguous set of trajectory prediction instructions uniquely associated with a specific trajectory prediction. However, this relationship lacks ambiguity, not because specific rules have been defined for inference of intent, but because the instructions, along with the laws of physics, allow no room for ambiguity. Any person or system reading a trajectory script should be capable of deriving what the aircraft will do assuming consistent aircraft performance and meteorological data. Users of trajectory script data do not have latitude in the aircraft behavior. As a simple example, the trajectory script may specify an altitude constraint at a waypoint together with the control law that is required (e.g. constant power, constant CAS). The lack of a control law would leave multiple options for meeting the constraint.

Under current operations, a significant amount of “guesswork” (i.e., intent modeling) is required to develop a trajectory script from a flight script. As we move forward with the provision of required information into the flight script, the flight script will begin to lose some ambiguity. Eventually all ambiguity should be removed except for those situations associated with future actions that are currently unknown because a decision has not yet been made by an actor. Thus the need to support multiple trajectory scripts per flight script will likely remain. For example, since not all future actions are known, there will

likely remain a need to evaluate candidate solutions assuming multiple scenarios for these future actions (i.e., the service performed by active DSTs). The choice among the options will likely be made by the system requesting the trajectory. One may envisage multiple important candidate trajectory scripts, including:

- **No button-push** – This describes a trajectory assuming no further action is taken by any human actor.
- **Most likely** – This describes the ensuing trajectory assuming the most likely actions to be taken by the human actors.

One can also conceive of a concept in which the above two have been harmonized to a single case. There are various reasons one may wish to investigate multiple levels of intent. For example, a DST looking at nominal performance would wish to use the most likely intent, assuming this can be defined. However, systems protecting against errors and providing early detection of conformance violation would wish to look at multiple possible intent scenarios to prevent unacceptable situations due to blunders or misunderstandings of intent.

For active decision support tools, trajectory predictors should be able to generate trajectory scripts for provisional plans with a minimum of guesswork. This implies a need for information described in 4.2.4.2.4 to specify how to obtain control targets, control laws, mode-switching, etc, that are critical to achieve the required TP performance.

5 Trajectory Description

It is expected that the flight object will contain at least one trajectory that was the output of a trajectory predictor. Prior to discussing the details of the description of a trajectory, at least one concept-level question must be addressed – whose trajectories? The prior sections described a one-to-many relationship between the flight script and the trajectory script. Since the trajectory script represents an unambiguous description of the aircraft intent, each trajectory script should produce a unique trajectory. Trajectories can be produced on airborne or ground systems, with a variety of differing assumptions on intent, and for a nominal plan or a trial / tentative plan.

For each trajectory script, this section discusses a proposed description of the trajectory itself. One approach is to describe the trajectory script, the unique input to trajectory engine. The other involves the use of actual trajectories as output from a trajectory engine.

We first consider the description of the trajectory script itself. Since the trajectory script represents an unambiguous description of the instructions required to predict a trajectory, systems *should* be able to uniquely reconstruct predicted trajectories based upon these. While such an approach *may* reduce the bandwidth requirements for trajectory exchange, several considerations remain:

- Systems requiring a trajectory must take the time to construct a trajectory by executing the trajectory script within its supporting trajectory engine.

- Differing trajectory engines can introduce discrepancies in the output through modeling differences or differences in the aircraft performance models. For example, one model may not model the same level of fidelity in turns or acceleration. Additionally, during climb, a model with lower drag for the same speed and weight would have a higher climb rate.
- Trajectory scripts may have to incorporate the impact of model logic, since mode switching often needs to be predicted. This may require understanding proprietary information.

A more conventional approach involves the specification of the predicted trajectory itself. One possible approach for the medium-term involves an extension of ARINC Characteristic 702A – *Advanced Flight Management Computer System* – (Section 5.2.1.12, and Attachment 8) for trajectory intent. Briefly, this specification includes the following data elements:

- **Geometry** – Supported geometries are: start point, line to point and (circular) arc to point.
- **Characteristics** – This describes the type of point and includes the following:
    - **Start of climb** – Point to begin a climb following a level segment.
    - **Top of climb** – The point at which a cruise level is reached. Multiple TOC may exist for a step climb.
    - **Top of descent** – The point at which the flight descends from cruise.
    - **End of descent** – The point at which the descent procedure ends and the approach procedure begins.
    - **Level-off** – The point in a climb or descent at which a level-off segment begins.
    - **Crossover altitude** – The point at which the aircraft transitions between Mach and IAS control during a climb or descent.
    - **Transition altitude/level** – The transition altitude (in climb) or flight level (in descent). This identifies the transition from using a standard versus corrected altimeter pressure setting.
    - **Speed change** – A point at which an acceleration/deceleration segment begins or ends to reach a speed constraint.
    - **Named fix** – A named fix on the trajectory.
    - **Named fix with a constraint** – A named fix on the trajectory for the purposes of identifying an altitude constraint.
    - **Unnamed fix** – A point inserted between trajectory points to provide a more thorough trajectory description. In particular, vertical points may be inserted.
    - **Aircraft projection --** The projection of the current aircraft position onto the current flight plan leg.
    - **Non-flyable** – The trajectory from the prior point to this point is not flyable.
    - **Discontinuity –** The trajectory from the prior point to this point is not defined.
    - **Runway –** The point corresponds to a runway.

    - **Start of descent** – The point at which a descent is initiated from an intermediate level segment.
- **Point location –** The latitude, longitude and altitude of the point.
- **ETA –** The estimated time of arrival at the point.
- **RNP level –** The RNP level for the segment.
- **Point name –** For named waypoints, the name of the waypoint.
- **Altitude constraint (lower bound)** – The lower bound altitude constraint on the named waypoint.
- **Altitude constraint (upper bound)** – The upper bound altitude constraint on the named waypoint.
- **Turn radius** – The turn radius (in NMI) for an arc to point segment.
- **Turn center location** – The latitude and longitude of the center of the turn for an arc to point segment.

While the above provides a starting point for consideration of the aircraft trajectory description, several items are absent and worthy of additional consideration:

- Speeds – Trajectory points should include speed-at-point indication. This may include a full description of the wind as well as air and ground velocity vectors (including the specification of which speed is independently specified).
- Speed constraints – Speed constraints should be described in the trajectory in the same manner as altitude constraints.
- Required Time of Arrival – Time constraints should also be described in the trajectory in the same manner as altitude constraints.
- Uncertainty – Many applications will require uncertainty in trajectory prediction. Specification of precision of prediction (lateral, longitudinal and vertical) would be beneficial to these applications. However, the precision is likely to also vary based upon the interpolation scheme used between points.
- Mode and target – The along-track position and altitude between points are typically not linear functions. For example, a long cruise segment flown at a fixed cost index will have a variable speed throughout the segment. A constant IAS segment on climb or descent will experience a variable true airspeed throughout the segment. A constant vertical-speed segment with acceleration to a target will not experience constant acceleration. Inclusion of the mode and target in the *trajectory* defeats the purpose, as trajectory engine-type calculations would be required to reconstruct the segments. Several solutions may be considered. The specification of a required accuracy level would require the introduction of interim points to ensure accuracy using the simple segments proposed. An alternative is to develop basis functions that approximate known modes of control and express trajectories parametrically. This alternative approach would not only ensure an adequate representation of the trajectory, it would also facilitate the generation of what-if trajectories that active DST automation needs to solve ANSP problems.
- Path recapture – The path from current aircraft state to the planned trajectory should be defined in a manner that allows consistency between applications.

The first three items in the preceding list are currently incorporated in a DRAFT ARINC Characteristic 702A-3. Uncertainty is currently incorporated to some degree through the RNP level. Extension of the RNP to incorporate along-track and altitude measures would provide the equivalent of uncertainty in all necessary dimensions (a sort of 3D/4D trajectory navigation performance).

6 Summary, Recommendations and Future Efforts

The preceding discussion has described many aspects of trajectory prediction that impact the content of the flight object. Furthermore, concept-level decisions will affect information requirements for trajectory prediction. Since not all future concept decisions are currently known, *it is critical for the flight object to maintain flexibility in its initial development effort*. One important flexibility-preserving approach is the idea that the flight object allow for a mapping between an individual flight script and many potential trajectories.

One goal of the flight script is to improve interoperability between the different actors (e.g. ground/ground, air/ground and air/air interactions). *A necessary condition for such interoperability is to provide information that is consistent enough to allow each system to perform its intended function without contradicting another system*. The flight object contributes to the consistency of information, but the information must be fit-for-purpose. Synchronization on trajectories alone is not adequate in a concept requiring ground-based generation of trajectory alternatives to resolve ANSP problems.

Table 2 summarizes the information issues that should be considered to develop the flight script for trajectory prediction purposes. These issues include the need to develop further understanding in certain areas in addition to specific information that must be included for trajectory prediction. It is recognized that additional information will be required from other communities of interest to support trajectory prediction activities. These include:

- Atmospheric forecasts such as winds, temperature and pressure. Reductions in the size, frequency, and correlation of significant errors will improve the trajectory.
- Aeronautical information including named fixes/waypoints, procedures, runway information, and airspace constraints such as SUA. These are merely examples of a larger set.
- Surveillance data to provide accurate information on the current aircraft position and velocity. Improvements should allow precision in the aircraft state information.
- Aircraft performance models that accurately reflect the aircraft behavior and define the operational flight envelope for speed and altitude.

Several categories have been defined, which are somewhat arbitrary and may need to be revisited to reflect actual schedules for system deployments. The first category describes the current situation and the immediate future. A second category, would allow for certain improvements based upon the following grouped capabilities:

- Improvements in ground automation to allow for additional information provided for trajectory prediction
- Improved accuracy of surveillance information
- Time-based metering implemented via controller instructions
- Wider implementation of RNP/RNAV routes on arrival and departure
- Expanded navigation database onboard aircraft to allow for pre-coded alternatives

Assumptions for the third category include:

- Further improvements in ground automation to allow for *real-time* evaluation of multiple alternative flight paths
- Development of aircraft performance models including: flight-envelope coverage, information for multiple configuration, control mode behavior
- Data communication between aircraft systems and ground information systems

It is clear that the combination of the second and third category represent the more advanced "far-term" situation. However, various service providers may envisage situations for which certain capabilities in the third category are implemented prior to capabilities in the second.

As we move towards the future, there are some concept-level decisions that can affect the requirements for information content within the flight object. Some of these we have listed as assumptions above. Additional concept-level decisions should be based upon the answer to certain research issues that remain to be investigated. Several of these research issues have been described in this document and are summarized in Table 2.

As an example course of action for the flight object, information content for the present must include information necessary to support existing TP capabilities. This information content includes the classical flight plan information coupled with: amendment information, and references to current surveillance data. Information adapted for the TP under such a situation includes: constraints based on LOA/SOP, control instructions that can be input via amendment to the flight plan, and generic information by aircraft model and operator (climb/descent speed schedule, configuration schedule, nominal estimates of aircraft weights on departure and arrival).

As we move forward, additional information can be incorporated into the flight script. *Note that this phase may also refer to the time-frame for the initial implementation of the flight object depending on circumstances*. Additional information, described in Table 2, includes the following:

- Flight-specific information such as, departure/arrival runways and weight.
- Some initial mode-of-control targets such as climb and descent speed schedules, cost index (if applicable)
- Flight-specific constraints (time, speed, altitude) and manner in which constraints are implemented. At a minimum, this includes coarse mechanisms to determine if descent/speed change is NOW, or constructed to reach a target by a point. Some engineering effort is required to establish how this information should be shared.

- Ability to include simple control instructions such as current assigned heading in the flight script.
- If the concept requires, pre-computed alternative paths.
- Improved surveillance data for better speed, heading and position information.
- Harmonized trajectory description

As we look to the future, we introduce more dependencies on concepts, as described previously, but the flight object expansion will likely include information such as:

- Surface information such as taxi-paths, pushback times and expected departure time.
- Complete aircraft state information including current control modes and targets.
- Solutions from ground-based decision support tools such as: time, altitude or speed constraints at waypoints, or alternative proposed paths.
- Planned control modes and targets as part of the flight.
- Trajectory description to incorporate uncertainty in forecast, including path probability.
- Nominal path recapture from present position.

Research is required to migrate from the present situation towards the far-term. The specific details of information elements need to be identified, as these depend on the concept, systems and mechanisms available for information exchange. Example research issues identified herein include:

- Disparate requirements on the part of tools using trajectory prediction require methods for harmonization of the output of these tools.
- Aircraft performance models must be developed to incorporate off-nominal conditions (e.g., non-idle descents).
- Predictors must be capable of handling a variety of control modes.
- Research into the information required to support ground-based "what-if" scenarios is required. This may include:
    - Development of methods for communication of intent and intent-switching logic
    - Determining how to describe aircraft algorithms for control, control mode selection and constraint application
- Methods for determination and specification of uncertainty in predicted trajectories.
- Research into approaches for improving accuracy between trajectory change points.

The need for increased TP precision and accuracy will grow with the increased need to achieve greater levels of productivity and capacity out of our airspace system. Trajectory-based and super-density operations will require the ability to precisely plan, define, share, and execute 4D trajectories. While the modeling of flight dynamics is well understood, TP performance depends on the ability to solve the challenges related to defining and communicating Trajectory Script information. If the Flight Object does not support and

facilitate the TP needs of our future automation systems, the risk and costs of early obsolescence will weigh heavily.

Table 2 Flight Script Information Issues

Area	Today	Phase II	Phase III
General	- Control instruction phraseology can impact TP accuracy	- Transition may have to accommodate multiple levels of fidelity and data elements - Weight of specific flight - Multiple trajectory scripts per flight script	- Disparate requirements versus need to harmonize output of TP clients - Improved aircraft performance models (e.g., including off-idle)
Constraints	-Adapted altitude/speed constraints based on LOA/SOP	- Time-of-arrival constraints used by controller - Altitude/speed constraints on individual flight	- Interim constraints from DSTs including RTA, altitude and speed
Path Initialization	- Current surveillance data	- Use of improved surveillance data including accurate speed.	- Complete aircraft state information including selected targets
Intent (including route)	-Current route information: -Departure/arrival airport -Route of flight w/ SID/STAR -Amendment information as entered -Adapted hold-stack locations - Adapted information on waypoints (fly-by, fly-over) - Generic company procedure information (on transition speeds, configuration changes by aircraft type) - Cruise altitude, some step climbs - Cruise speed - Simple control instructions (speed, altitude)	Aircraft intent will be decomposed into: - Lateral profile, including: - Departure / arrival runway - RNP/RNAV route to/from runway - Pre-coded alternative paths - Use of ARINC 424 leg types or similar for specification of individual segments - Altitude profile - Speed profile - Thrust profile - Configuration profile - Inclusion of options for holding - Communication of impact of company procedures - Manner in which constraints are implemented (e.g., some control targets climb/descent CAS/Mach schedules, location of TOD) - Additional control instruction (heading)	- Pushback time - Taxi-path - Development of dynamic alternative paths - Known/planned holding - Wheels-up time - Provisional/trial scenarios - Codification of algorithms - Reduction in number of TS per FS as intent becomes known. - Development of method for communicating selected mode/ mode switching - Anticipated control modes and targets - Configuration information - Control instructions with start/end, or - Possibly communicate closed-form solution - How to deal with time-critical instructions
Trajectory	- Current trajectory description varies by TP and applications using TP - Which trajectories are in FO?	- Use of proposed ARINC trajectory intent – type trajectory description	- Specification of uncertainty - Harmonization of trajectory script definition - Full path recapture path included from present position - Resolution of interpolation accuracy issue

7 References

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