ANALYSIS OF SEPARATION MINIMA USING A SURVEILLANCE STATE VECTOR APPROACH

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ABSTRACT

Many proposed strategies for increasing airspace capacity call for a reduction in separation minima. Before they can be implemented, methods of modeling these procedural or technical changes are essential to ensure that safety is maintained. A surveillance state vector approach based on a combination of traditional dynamic states (position, velocity and acceleration) with higher order intent and goal states is presented. The relevance and implications of uncertainty in each of the states is discussed. Due to its fundamental importance to separation assurance, the concept of intent is presented in detail, along with examples of its interpretation and use in today's ATC environment. Relationships between state uncertainty and current separation minima are presented to highlight the potential of this approach. By analyzing the effect of new technology or procedures on the surveillance state vector components, implications for the separation minima can be assessed.

1. INTRODUCTION

Challenges exist to increase both the safety and the capacity of airspace in the next few decades [1]. Separation standards are used by air traffic controllers to ensure safety by establishing the minimum allowable separation that should exist between multiple aircraft in the various phases of flight. However, airspace capacity is fundamentally constrained by these same separation minima, particularly at key points of the system such as at the runway, final approach and oceanic flight phases. Many of the proposed strategies to achieve capacity goals either implicitly or explicitly call for a reduction in the separation minima contained in the standards without compromising safety. Examples include the 'Free Flight' recommendations [2], more flexible independent parallel approach criteria [3], Reduced Vertical Separation Minima (RVSM) oceanic procedures [4] and reduced wake vortex spacing requirements [5]. However, the process of reducing separation standards is difficult due to the lack of a rigorous basis for analyzing aircraft separation. Therefore, a fundamental understanding of the issues surrounding separation standards and methods of modeling proposed changes to them are essential.

The primary separation minima currently used in the US are shown in Table 1.

Separation Category	Separation Minima	Remarks
VISUAL	**No limits**	Responsibility on pilot
OCEANIC NORTH ATLANTIC	**1000 ft vertical**	At or below FL290 (and RVSM)
	2000 ft vertical	Above FL290 (non RVSM)
	60 - 120 nm lateral	Depending on aircraft type and route
	10 - 30 mins longitudinal	Depending on leader/follower aircraft types
EN-ROUTE	**1000 ft vertical**	Below FL290
	2000 ft vertical	Above FL290
	3 nm lateral ('radar separation')	Below FL180 and both aircraft within 40 nm of radar
	5 nm lateral ('radar separation')	Below FL600 and either aircraft not within 40 nm of radar
LANDING WAKE VORTEX	**2.5 - 6 nm longitudinal**	Depending on leader/follower aircraft types (and airport for 2.5 nm)
LANDING PARALLEL APPROACH	Dependent: **1.5 nm**	Runways 2500-4300 ft apart
	Dependent: **2 nm**	Runways 4300-9000 ft apart
	Independent: **no parallel runway restrictions**	3400-4300 ft apart (with PRM) 4300-9000 ft apart (with FMA) 9000+ ft (without PRM, FMA)
LANDING RUNWAY OCCUPANCY	**No multiple occupancy of active runway**	Exception for Land And Hold Short Operations (LAHSO)
DEPARTURE	**3000 - 6000 ft or 2 - 3 mins**	Depending on leader/follower aircraft types, runway configurations, etc.

Table 1: Current US separation standards [6]

The en-route radar and vertical separation minima have not changed since the 1950s. There is little published documentation on the rationale behind the early radar separation criteria but they appear to have been based upon "radar accuracy, display target size and controller and pilot confidence" at the time [7]. Vertical separation standards were dictated by the accuracy of the barometric altimeters and static pressure calibration at cruise altitude. Wake vortex constraints have generally been reduced in the past three decades, although they are unlikely to be reduced further without advanced vortex-detection systems being installed at airports [5]. The apparent lack of formal analysis in the development of many of the standards, and the current low rate of mid-air collisions, has directly led to the difficulty in changing the standards today. The RVSM procedures, for example, have taken many years to implement for this reason. The absence of a known baseline safety level of the original system has made it extremely difficult to prove that incorporation of new technologies or procedures would allow reduced separation at an equivalent or increased level of safety.

Proposed factors to be included in a 'separation assurance budget' are illustrated in Figure 1. The budget could be in time or space and the relative sizes and shapes of the components are not meant to indicate the actual dimensions. The surveillance system budget component contains the accuracy and timeliness of aircraft state information coming from the surveillance system (primarily the position state but higher order states may also be output). Human performance aspects such as detection, comprehension, communication and action on the part of the controller and/or pilot are included. Once an action is initiated on the part of the pilot, the aircraft dynamics dictate the response behavior. On top of each of these budget components can be superimposed procedural and personal safety buffers. The former represents the safety factor required for uncertainties present in the other components. The personal safety buffer is over and above the minimum separation requirement, representing the risk aversion on the part of the controller to avoid violating the separation procedures [e.g. 8].

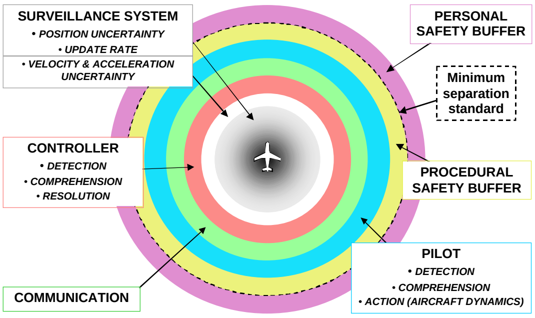

Figure 1: Separation assurance budget components

These aspects are important in defining space/time budgets required for recovery once a hazardous situation has initiated. However, the controller's principal role of maintaining tactical separation between aircraft for both present and short-term future times primarily requires surveilled aircraft state information (and particularly position, heading and velocity).

There is already an implied dependence between separation minima and the accuracy of state information available to the controller in some instances. For example, compare the highly conservative minima in oceanic airspace (where there is poor state information in terms of both accuracy and frequency) to the much smaller separations allowed for independent parallel approaches to airports (where state information is of much higher accuracy and frequency). The inference is that the level of state knowledge available to the controller plays a key role in determining safe separation.

This paper presents a surveillance state vector modeling framework to investigate the issues arising from this inference. A key aspect for the controller in maintaining separation is his/her knowledge of the aircrafts' future behavior (or ‘intent’). The philosophy of intent and how it integrates with the more traditionally-surveilled dynamic states to impact separation is presented.

2. SURVEILLANCE STATE VECTOR MODELING APPROACH

2.1 General state vector approach

The accuracy and timeliness of information provided to the controller via surveillance and other systems plays a key role in determining safe separation requirements. In order to provide a structure to evaluate surveillance effects, a surveillance state vector ***X(t)*** is defined by Eqn. 1 which represents the potential surveilled aircraft or hazard (e.g. wake vortex) states. The state vector contains traditional dynamic states as well as ‘higher order’ states representing the intent and goal structure of the pilot (discussed in more detail in Section 3).

$$X(t) = \left\{ \begin{array}{c} \text{Position, } R(t) \\ \text{Velocity, } V(t) \\ \text{Acceleration, } A(t) \\ \text{Intent, } I(t) \\ \text{Goals, } G(t) \\ \vdots \end{array} \right\} \qquad \text{(Eqn. 1)}$$

R(t) is the position vector; ***V(t)*** is the velocity vector; ***A(t)*** is the acceleration vector; ***I(t)*** is an abstract representation of the intent and ***G(t)*** represents high level ‘goal’ structures. In general, the states can be considered as being increasingly higher order, interacting in a manner illustrated in Figure 2.

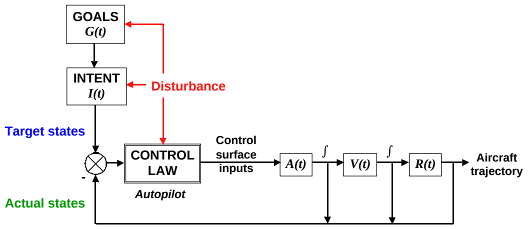

Figure 2: Integration of state vector elements

Other state information may also be important and hence it is not implied that the list of states is exhaustive. In many cases, only a subset of the states in the surveillance state vector ***X(t)*** will be directly measured and the controller must either synthesize those state estimates not directly surveilled or control without consideration of those state components.

Uncertainties and/or errors in the surveilled state variables relative to their 'true' values are modeled by δ***X(t)***, which are defined by:

$$\delta X(t) = \begin{Bmatrix} \delta R(t) \\ \delta V(t) \\ \delta A(t) \\ \delta I(t) \\ \delta G(t) \\ \vdots \end{Bmatrix} \qquad \text{(Eqn. 2)}$$

Each of the traditional dynamic state components of position, velocity and acceleration will be examined in the subsequent sub-sections. The intent and goal states are fundamental to the aircraft separation issue and will be discussed in detail in Section 3. The implications of the uncertainty and errors in the states contained in the δ***X(t)*** vector for separation assurance are discussed in Section 4.

2.2 Position vector, *R(t)*

The position state vector of the aircraft, ***R(t)*** is the three-dimensional position of the aircraft in a given reference frame as it is output from the surveillance system, e.g. $\boldsymbol{R(t)} = [R_{latitude}(t), R_{longitude}(t), R_{altitude}(t)]^T$. The elements that make up the position vector are typically provided to the controller from different systems (e.g. radars providing lateral states, aircraft transponder providing vertical state).

2.3 Velocity vector, *V(t)*

The velocity state vector, ***V(t)*** contains surveilled information on horizontal and vertical velocities of the aircraft at a given time. In conventional radar systems, the horizontal velocity components can be obtained from a tracker system in the radar which filters previous target returns to estimate aircraft velocity. The vertical velocity component can be obtained in a similar fashion based on previous transponder altitude returns.

2.4 Acceleration vector, *A(t)*

Although not directly surveilled with radar systems, acceleration data from on-board sensors (e.g. accelerometers) may be available in future ADS-B environments. Under visual separation operations, pilots appear to use aircraft attitude components as surrogates for acceleration states. The enhanced (feed forward) ability to predict the dynamics of proximate aircraft by observing the attitude is thought to be a key factor in pilot acceptance of close parallel approaches in visual conditions.

3. INTENT AND GOAL STATES

3.1 Intent state vector, *I(t)*

The intent state vector, ***I(t)*** is a conceptual method for handling higher order states to indicate the aircraft trajectory in state space after time *t*, to the extent it is known or assumed. It can be viewed in terms of future position ***R(t)***, velocity ***V(t)*** or acceleration ***A(t)***, depending on which is most convenient for the analysis at that stage. Indeed, an intent matrix containing all three components could be defined. Examples of sources of intent are the aircraft's Flight Plan, the currently active ATC instructions or standard sets of procedures that are followed at a given location and/or time.

Dictionaries define intent in a number of different ways: “an aim or purpose”; “the state of one's mind at the time one carries out an action”; “an anticipated outcome that is intended or guides your planned actions”; “the intended meaning of a communication” [9]. Interpretations of intent in the technical literature include estimates of future action based on a continuance of past actions, specific actions with short term returns and higher level goals with returns over longer timeframes [10].

Although there is no formal definition of intent in the aviation environment, it is typically understood to be a representation of planned future behavior of the aircraft. This intent is articulated via a command structure between controllers and pilots (i.e. the Flight Plan) and between the pilot and the flight automation system. These control loops and command structures are observed within the air traffic management environment in use today as shown in Figure 3.

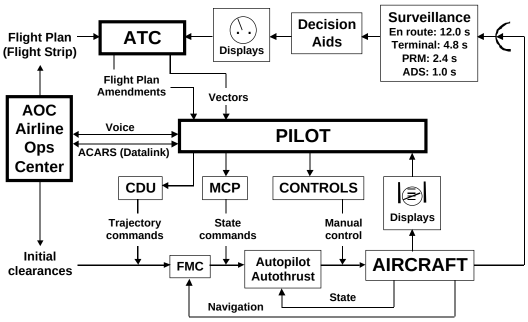

Figure 3: ATM control loops

The aircraft intent as it is understood by the ATM system is represented by the Flight Plan which defines the trajectory in terms of a series of 'target states' as represented abstractly in Figure 4.

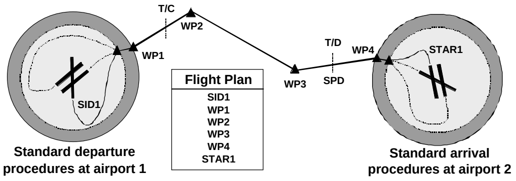

Figure 4: Abstraction of Flight Plan

The Flight Plan is initially filed by the Airline Operations Center (AOC) and is presented to the controllers in the Flight Progress Strip (Figure 5).

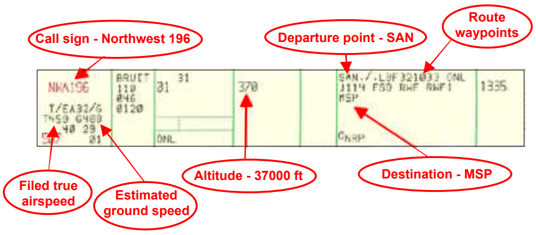

Figure 5: Example Flight Progress Strip

The trajectory level definition of intent is executed by the pilot or the flight automation system in a manner consistent with the two components of the intent vector shown in Eqn. 3.

$$I(t) = \left\{ \begin{array}{c} \textit{Current target states} \\ \textit{Subsequent planned trajectory} \end{array} \right\} \qquad \text{(Eqn. 3)}$$

At any point in time, the aircraft is controlled to a specific set of target states defined by *Current target states*. Examples include airspeeds, altitudes, headings, or attitudes. Once the current target states have been satisfied (e.g. after achieving the current waypoint target) the aircraft follows the next target state contained in the target state evolution of the *Subsequent planned trajectory*.

The controller compares tracking behavior of the aircraft based on data received from the surveillance system (Figure 3) to the presumed target states (Figure 2) based on the Flight Plan or clearance amendments to determine if the plan is being followed. This 'conformance monitoring' process is a key separation assurance task of the controller and will be discussed in more detail in Section 5.

3.2 Goal state, *G(t)*

Several different types of goals typically exist. *Mission goals* include such objectives as flying from the origin airport to the desired destination via an efficient and comfortable route to arrive on time. The controllers and pilots may have their own *personal goals* in terms of performance and job satisfaction. *Safety goals* will also exist, both in terms of survivability and hazard avoidance, but also risk aversion elements unique to each pilot and controller (e.g. the personal safety buffer shown in Figure 1).

Mission goals between the various agents may be different. For example, the pilot is a *maximizer*, concerned primarily with optimizing his/her own aircraft's operation. The controller, however, is a *satisficer*, with a much broader set of system requirements which need to be satisfied across all of the aircraft under control. The controllers and pilots may be aware of the differences in one another's mission goals, and the differences have to be negotiated on a case by case basis if necessary.

Tradeoffs are also likely to exist both within and between the different goals. Their relative importance will also be context-specific. For example, the mission goals which play important roles during a normal flight may be totally overridden in emergency situations, at which time the safety goals dominate all others. In an emergency situation, a common set of safety goals are likely to exist for both controller and pilot such that no negotiation is required.

For the purposes of this study, the goal vector contains the high level objectives which drive the intent as shown in Figure 2.

4. STATE UNCERTAINTY

4.1 General

The uncertainty states $\delta \boldsymbol{X(t)}$ contain the error or uncertainty present in the $\boldsymbol{X(t)}$ component states. As discussed in Section 2.1, not all states may be surveilled to the same degree of accuracy and some states may not be directly measured at all. In these instances, the delta states for those elements may be large with potentially important consequences for separation criteria. This section will discuss the implication of state uncertainty in each of the components of $\delta\boldsymbol{X}(t)$. The last part of the section compares separation examples using the uncertainty states to explain differences in separation minima.

4.2 Position uncertainty, $\delta\boldsymbol{R}(t)$

Due to inaccuracies inherent in the surveillance system, the measured position will contain uncertainty $\delta\boldsymbol{R}(t)$. In the current air traffic control system, radars are the primary surveillance technology. Most radars have much higher resolution in the range (ρ) measurement than in azimuth (θ). The resolution at a given range, AR is primarily determined by the antenna's 3dB beamwidth, θ_{3dB} such that:

$$\mathrm{AR} \approx \rho\theta_{3dB} \qquad \text{(Eqn. 4)}$$

Here, AR is the arc length subtended by the 3dB beamwidth of the radar at the target range ρ. Figure 6 shows a plot of the variation of AR with ρ and θ_{3dB}. Also marked on the plot are the operating points (in terms of 3dB beamwidth and maximum operational range) of common radar systems used in the US. The en-route lateral radar separation minima are also indicated for comparative purposes. The correspondence of the lateral separation minima variation with range and the radar azimuthal resolution indicate that radar accuracy was a primary factor in the establishment of the current separation standards. It should be noted, however, that in the current operational environment the observed resolution of modern radars is significantly better than that indicated by the θ_{3dB} criteria. Beam sharpening and tracking estimation techniques are used to significantly improve the effective radar resolution performance.

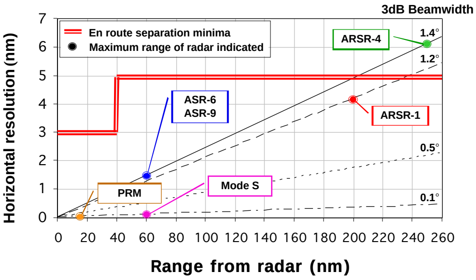

Figure 6: Variation of resolution with range and beamwidth plus US radar operating points

The position uncertainty $\delta\boldsymbol{R}(t)$ is also influenced by the update rate of the radar. The scan time for radars used within the US range from 1.0 s for the ASDE (used at airports for ground surveillance) to 12.0 s for the longest-range ARSR en-route radars. Between updates, the controller infers position based on the last position update, heading, velocity and intent. Since all contain their own uncertainties, the inferred position uncertainty grows beyond the basic resolution uncertainty discussed above, until position is updated with the next sweep of the radar.

The vertical uncertainty component of the position state vector $\delta\boldsymbol{R}(t)$ can be attributed to several factors which influence the altitude data received from the aircraft's transponder. These include the 100 ft discretization of the aircraft altitude, calibration errors of the altitude encoders and static system errors.

In an ADS-B environment with a differential GPS (e.g. WAAS) surveillance basis, the positional uncertainty would be significantly reduced due to the higher measurement accuracy (5 - 10 m) and the higher update rate of the ADS-B system (1 s).

4.3 Velocity uncertainty, $\delta\boldsymbol{V}(t)$

In the ATC radar systems, the horizontal velocity is normally inferred from previous positional state measurements, and is subject to the same error and uncertainty components discussed in Section 4.2. The velocity estimate output from the α-β tracker is also delayed by the filtering process itself, which results in a lag of several radar scan cycles. This significantly adds to the velocity uncertainty.

In the vertical domain, the altitude is normally discretized to the nearest 100 ft by the transponder. Hence, there is significant noise in the vertical velocity based on these measurements so typically only a climb/descend indicator is supplied on the surveillance display in the current system.

In ADS-B systems the expected horizontal velocity uncertainty will be much lower. If velocity is broadcast directly, the uncertainty will be at the level of the GPS velocity measurement precision with the 1 sec delay. If only position is broadcast, then the uncertainty will still be reduced due to the higher precision in the position measurement and the more rapid scan cycle.

4.4 Acceleration uncertainty, $\delta\boldsymbol{A}(t)$

In most radar environments, acceleration is not directly measured and can only be inferred by the rate of change of the velocity as measured by the tracking system. The uncertainty is significant and acceleration is not normally used as an ATC control variable. In the ADS-B environment, direct measurement of acceleration or attitude may be made and transmitted. In the visual surveillance environment, acceleration is estimated based on aircraft attitude. This is effective at indicating direction of acceleration but significant uncertainty in magnitude remains.

4.5 Intent uncertainty, $\delta \boldsymbol{I(t)}$

The uncertainty in the traditional dynamic states of $\boldsymbol{R(t)}$, $\boldsymbol{V(t)}$ and $\boldsymbol{A(t)}$ are defined relative to true dynamic states of the aircraft. In contrast, the *uncertainty* in the intent state is fundamentally different in character. Since intent is a prediction of future trajectory at a given time, there is *always* a certain amount of uncertainty due to unplanned and unexpected events. Intent *errors*, however, result from a totally different understanding of intent between two 'agents' in the ATC environment, e.g. pilot, controller or aircraft automation. The notation $\boldsymbol{I^N(t)}$ is used to define the intent of the aircraft from time *t* as assumed by agent ***N***. Hence, $\boldsymbol{I^P(t)_i}$ is the pilot's intent for his/her own aircraft (aircraft ***i***). $\boldsymbol{I^C(t)_i}$ is the intent of aircraft ***i*** to the extent it is known or assumed by the controller. $\boldsymbol{I^A(t)_i}$ is the intent from the perspective of aircraft ***i***'s on-board systems (e.g. flight management system).

Note that the complete set of intent states amongst the various users may be very different in both extent and form. For example, the aircraft intent may be a pure electronic abstraction of the Flight Plan as programmed into the Flight Management System while the complete pilot and controller intents will be influenced by higher level goals. However, the $\boldsymbol{I^N(t)}$ state vectors for the different agents are simply those components of the intent concerning aircraft ***i***'s future trajectory which can be formally represented. In the nominal operating environment, all of these intents across the various agents in the system should be compatible with each other, i.e. $\boldsymbol{I^A(t)_i} = \boldsymbol{I^P(t)_i} = \boldsymbol{I^C(t)_i}$. Aircraft ***i*** flies the trajectory that the pilot and controller expect and have planned for.

Uncertainty and errors in the controller's intent $\delta \boldsymbol{I^C(t)}$ are fundamentally important from a separation standpoint because it is the controller who is responsible for maintaining separation between aircraft. *Uncertainty* in the controller's intent for specific aircraft arise when the intent is defined stochastically such that a number of different intent interpretations can feasibly exist at the same time. *Errors* occur when incompatibilities exist amongst the various $\boldsymbol{I^N(t)}$: see Figure 7.

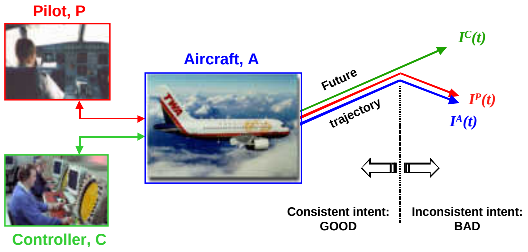

Figure 7: Compatibility of $\boldsymbol{I^N(t)}$ intents

Intent incompatibility can occur for a number of different reasons including:

- Controller error: Controller miscommunicates Flight Plan amendment or vector.
  Result: $\boldsymbol{I^C(t)_i} \neq \boldsymbol{I^P(t)_i}$
- Cognitive error: Pilot misunderstands Flight Plan amendment or vector.
  Result: $\boldsymbol{I^P(t)_i} \neq \boldsymbol{I^C(t)_i}$
- Omission or programming error: Incorrect input of Flight Plan into FMS by pilot.
  Result: $\boldsymbol{I^C(t)_i} = \boldsymbol{I^P(t)_i} \neq \boldsymbol{I^A(t)_i}$

4.6 Goal uncertainty, $\delta \boldsymbol{G(t)}$

Because of the complexity and subtlety of individual goal structures, it is difficult to have a comprehensive understanding at the goal level. As a consequence there is a significant degree of uncertainty in the goal state $\delta \boldsymbol{G(t)}$. At one level the mission goals such as the destination are fairly well defined and can be determined from the Flight Plan. However, the goal space is very complex and it is difficult to predict the relative preference for ride comfort, fuel efficiency, risk avoidance, and other factors which may influence the pilot's decisions to modify the intended trajectory. This is particularly true for interrupted operations where the intended plan becomes inappropriate due to equipment failure, traffic, weather or some emergent condition. It should be noted that in many cases the goal state is influenced or defined by the airline, either through the dispatcher or through operational procedure. If the goal state is defined by a Standard Operational Procedure which is well understood by the controller, the goal uncertainty $\delta \boldsymbol{G(t)}$ is significantly reduced.

4.7 Relationships between state uncertainty and the current separation minima

Because the separation minima appear to be dependant on the collective state uncertainties $\delta \boldsymbol{X(t)}$, it is useful to visualize the relative uncertainty in the different state components in some representation such as a bar chart. The value of each of the uncertainty state components in $\delta \boldsymbol{X(t)}$ are depicted on an abstract scale. A value of 10 points indicates no knowledge of that state, while a value of 0 implies perfect knowledge (no uncertainty). Clearly the relative uncertainties presented in the following are not calibrated on an absolute scale but are rough estimates used purely to illustrate the impact of different levels of state knowledge.

Example: En-route Radar Control (Conforming)

Figure 8 presents an example of the relative state uncertainty in the en-route radar control environment. It is assumed that the aircraft is conforming to the Flight Plan, and is used as a baseline example. As previously discussed, the radar position has a relatively small uncertainty due to the limited angular resolution, 12 s scan rate and discretized altitude data. The velocity state is not directly surveilled, but is estimated from an α-β tracker in the radar. As such, it is known with less certainty than position because it is subject to both the position and filter performance/lag errors. The acceleration can only be deduced from the velocity data, so is subject to even more uncertainty than the velocity state. Because the aircraft is conforming to the plan, the current target intent can be inferred quite well from the position and heading states of the aircraft relative to the filed Flight Plan or current clearance. There is somewhat more uncertainty in the trajectory after the next target state due to unpredictable events, but nominal future behavior is also well established from the Flight Plan. As discussed in Section 4.6 only a subset of the goals are well understood so there is significant uncertainty in the goal state.

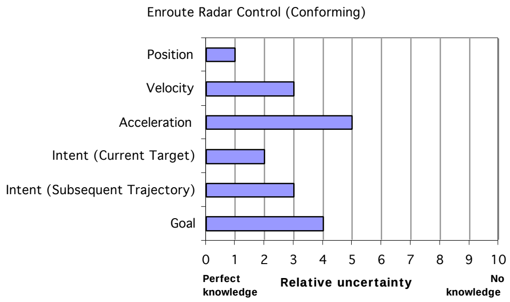

Figure 8: Assumed state uncertainty in the en-route environment (conforming aircraft)

Example: Oceanic Surveillance

The lateral separation minima in the oceanic environment are much more conservative than in the en-route (see Table 1). The reasons for this can be viewed in terms of the much larger state uncertainties shown in Figure 9. Because oceanic surveillance is limited to pilot's HF voice reports of position which occur at infrequent intervals (typically once every 10° of longitude or about once an hour), the position uncertainty between updates can be very high. Velocity and acceleration uncertainties are even higher as they can only be inferred from these position reports. Nominally, the goals and intent (both current target and future trajectory) are known to the same degree of certainty as in the en-route environment using filed Flight Plans.

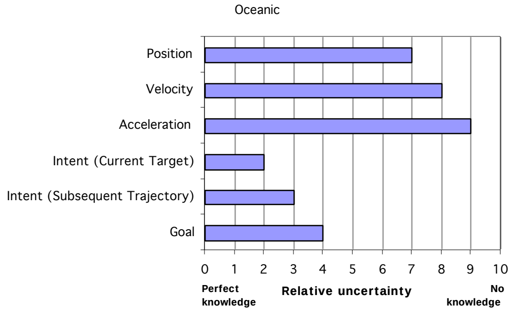

Figure 9: Assumed state uncertainty in the oceanic environment

Example: ILS Approach with PRM

An example where the separation minima are less conservative than in the en-route environment, is provided by an ILS approach procedure with the Precision Runway Monitor (PRM) radar. Here, the PRM radar has much higher azimuthal resolution (θ_{3dB} = 0.06°) than in the en-route ASR/ARSR radars (θ_{3dB} = 1.4°). Updates are also provided much more often by the PRM (2.4 s) than by the ASR (4.8 s) or ARSR (12.0 s) radars. As a result, the uncertainties in position (and hence estimated velocity and inferred acceleration) are lower in this environment compared to the en-route, as shown in Figure 10. Since the current target trajectory is well established (i.e. maintain trajectory along a defined localizer/glideslope path) and the future trajectory does not exist beyond touchdown, the intent components are also known with lower uncertainty. Goal state uncertainty exists for the same reasons discussed above.

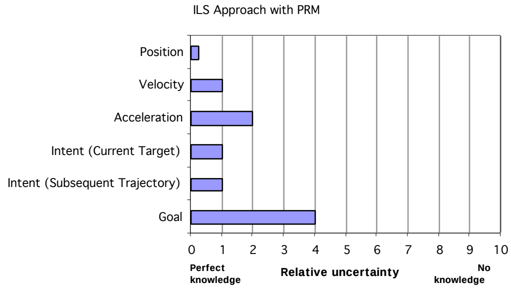

Figure 10: Assumed state uncertainty in an ILS approach environment with PRM

5. CONFORMANCE MONITORING

In normal tactical ATC operations, the controller forms a mental picture of the current states and the future dynamics of all aircraft under his/her control. This dynamic projection is based on the understanding of the intent of each aircraft. It is speculated that the controller operates at two levels of focus. At the sector level, the controller is monitoring the overall pattern of traffic flow within the sector. At this level of focus, the controller is principally concerned with the intent state level as the dynamics are projected forward to determine any potential conflicts or other problems. At this level, the uncertainty states are used to establish how much buffer needs to be built in to the plan and where monitoring resources may need to be concentrated.

At the individual aircraft level, the controller is monitoring the conformance of each aircraft to determine if they are behaving in a manner consistent with their presumed intent. In other words, the controller performs conformance monitoring to determine if the surveilled states of the aircraft are consistent (i.e. conforming) to the plan. Special monitoring attention is reserved for those aircraft where the controller has a larger intent uncertainty $\delta \boldsymbol{I}(t)$. Examples of such cases include:

- aircraft in transitioning flight (e.g. vertical or lateral maneuvering)
- aircraft having emergency status (e.g. with primary system failures)
- aircraft piloted by inexperienced or foreign crews with language difficulties where miscommunication may be likely
- aircraft not tracking within acceptable limits.

The conformance monitoring task tracks how well the pilot(s) adheres to the expected or cleared path (i.e. to the trajectory defined by the next target state) to maintain the planned separation with other aircraft. If threshold levels can be established in the n-dimensional state space of $\boldsymbol{X}(t)$ which define a 'hypertube' about the target trajectory as shown in Figure 11, then an aircraft conforming to the path should stay within the hypertube ($\boldsymbol{I}^C(t) = \boldsymbol{I}^P(t)$). If it is outside the conformance hypertube, then it is non-conforming ($\boldsymbol{I}^C(t) \neq \boldsymbol{I}^P(t)$) and this would be a basis for the controller to take corrective action.

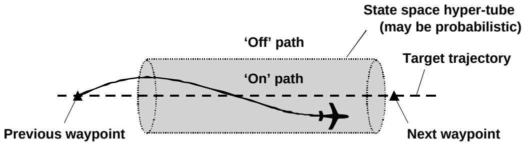

Figure 11: 'Hypertube' thresholds as a basis for conformance monitoring

Conformance monitoring processes include the lateral adherence of an aircraft to its Flight Plan or to the localizer on final approach. An example is shown in Figure 12 which presents cross-track deviations from the nominal Flight Plan segment. This was derived from radar track data and Host Computer System Flight Plan data for a general aviation aircraft operating in the Memphis ARTCC.

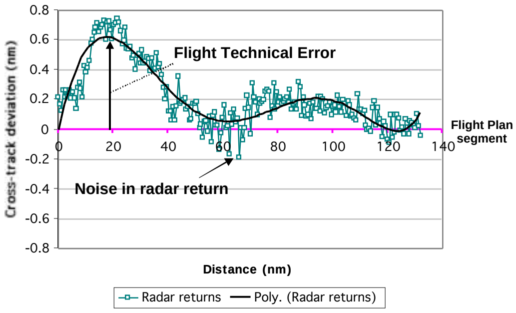

Figure 12: Conformance monitoring example (GA aircraft) [11]

This figure illustrates many of the issues which are formalized in the surveillance state vector approach presented in this paper. The noise and concomitant position/velocity uncertainty in the radar track is clearly visible. A sixth order polynomial fit to smooth the radar data is shown. The controller's intent is defined by the Flight Plan segment represented by the abscissa (*x* axis). The cross-track deviation is a combination of the ability of the pilot to maintain the path and the on-board navigation system errors (i.e. the flight technical error). In the first 20 nm, the radar track is diverging from the assumed intent path. While the position and velocity states indicate divergence from the Flight Plan, it is unclear at what point the controller would determine that this aircraft is not conforming to the assumed intent and take corrective action. The controller has higher order goal knowledge and a model of the tracking behavior of different aircraft (which was probably being hand flown in the case of the GA aircraft shown in Figure 12). The controller is therefore likely to give more track-conformance flexibility to the GA aircraft than to an autoflight-equipped aircraft capable of much better tracking performance such as that exhibited by the A320 in Figure 13.

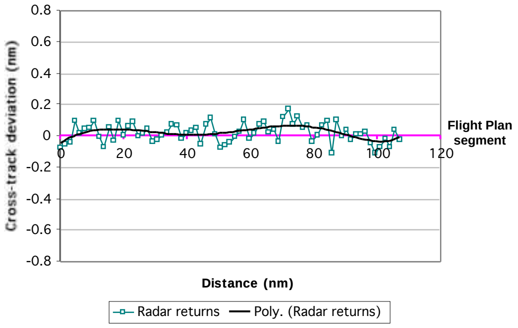

Figure 13: Conformance monitoring example (A320 aircraft) [11]

If the aircraft in Figure 12 was assumed to be non-conforming, then the uncertainty regarding the aircraft's intent would increase significantly as shown in Figure 14. Because of the intent uncertainty, the controller needs to significantly increase the separation buffer for the aircraft and route other aircraft out of its way until the intent can be established and the separation plan reinstated. A similar situation exists when aircraft lose radio contact and ATC must increase the separation buffer around it presuming it will either fly the original Flight Plan or divert to an alternate.

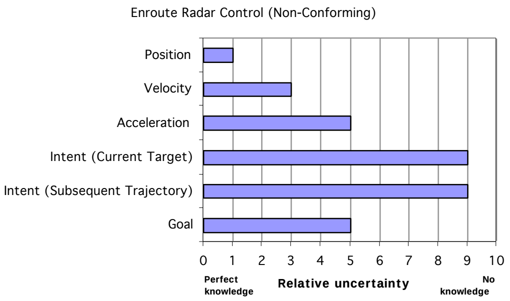

Figure 14: Assumed state uncertainty in the en-route environment (non-conforming aircraft)

6. CONCLUSIONS

A surveillance state vector framework has been developed to evaluate important issues regarding separation standards using dynamic, intent and goal states. The concepts contained within the intent state vector are fundamental to the projection of dynamic states into the future. This, coupled with the level of uncertainty that exists in the states drives the safety buffer and hence the separation requirements.

The conformance monitoring task of the controller has been shown to involve the combination of the states and uncertainties with the aircraft separation function. By examining the impact that new procedures and technologies have on the state uncertainties and conformance monitoring function can also indicate their impact on separation safety. Hence this approach provides a basis for evaluating new technologies and procedures. For example, the effect of enhanced surveillance (e.g. GPS coupled with ADS-B) on state knowledge and uncertainty and hence on intent and conformance monitoring, can be used to imply its effect on separation safety. However, further work is necessary to formally investigate these relationships between the surveillance states $\boldsymbol{X(t)}$, state uncertainties $\delta\boldsymbol{X(t)}$ and the separation standards.

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REFERENCES

1. NASA Global Civil Aviation Pillar Goals in safety and throughput, http://www.aero-space.nasa.gov/goals.
2. *Final Report of RTCA Task Force 3 Free Flight Implementation*, RTCA, Oct. 1995.
3. "Issues in Airborne Systems for Closely-Spaced Parallel Runway Operations", A. Pritchett et al., *Proceedings of 14th AIAA/IEEE Digital Avionics Systems Conference*, Cambridge, MA, Nov. 1995.
4. *An Authoritative Guide to Oceanic Operations*, FAA Advisory Circular, AC No. 91-70, Sep. 1994.
5. *NASA Wake Vortex Research for Aircraft Spacing*, R. B. Perry et al., AIAA 97-0057, Jan 1997.
6. *FAA Air Traffic Control*, FAAO 7110.65L, Jan. 1999.
7. "Terminal Area Separation Standards: Historical Development, Current Standards and Processes for Change", S. D. Thompson, MIT Lincoln Laboratory Report ATC-258, Jan. 1997, p.16.
8. "An Analysis of Landing Rates and Separations at the Dallas/Fort Worth International Airport", M. G. Ballin & H. Erzberger, NASA TM-110397, Jul. 1996.

9. *The American Heritage Dictionary*, Dell Publishing, 1994.
10. *Intention*, G. E. M. Anscombe, Blackwell, 1957.
11. Mike Paglione, FAA Technical Center, personal communication, Jan. 2000.

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