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Trajectory Prediction Concepts for Next Generation Air Traffic Management

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"Understanding complex systems begins with an appreciation of uncertainty." – B. Russell

Abstract: Current flight path predictions for climb and descent phases of flight have much larger path uncertainty than during cruise segments. The uncertainty errors in path prediction are a major concern for development of decision support tools such as arrival and departure managers for hub airport traffic flow planning and for medium term (10 - 30 min) conflict detection in congested terminal and transition airspace. This paper outlines a trajectory synthesis methodology with emphasis on accuracy and integrity of trajectory predictions for decision support tools. The paper examines the specification of top level user requirements such as prediction accuracy, integrity, and availability, and the means by which such specifications could be realized by suitable technology development and integration of redundant source data. This paper extends the Required System Performance (RSP) concepts to trajectory synthesis, and uses Required Navigation Performance (RNP) as a direct analogy for development of trajectory prediction systems.

1. Introduction

An examination of recent and evolving ATC Decision Support Tools such as the URET conflict probe, CTAS arrival and departure managers, and PHARE3 en route / terminal area tools show the importance of trajectory synthesis as an enabling technology for development and evolution of such tools. If such tools are to achieve operational acceptance in supporting critical ATC functions such as flow management and separation assurance, then the underlying trajectory synthesis methods must be reliable and sufficiently accurate for intended applications. It is not required that all trajectory predictions be of the highest reliability and accuracy. Rather, it is more important that when a trajectory prediction is of lower quality or requires assumptions on flight intent, that appropriate monitoring / integrity be provided, or that ATC applications and decision support tools reflect the increased uncertainty in using such predictions for flight planning and decision support.

Current trajectory synthesis systems for climb and descent path predictions are inherently limited by sensing and modeling errors, and path uncertainty in five broad categories:

- Path routing & intent errors,
- Weather forecasting errors,
- Surveillance errors of current aircraft position and velocity states,
- Aircraft performance and profile modeling errors,
- Flight Technical Error (FTE) in trajectory path control.

Previous studies of trajectory prediction errors for conflict probe during cruise flight [1, 2] have shown that the first three error sources tend to dominate during cruise, and aircraft performance and FTE errors tend to be lesser error sources (at least for FMS or auto-pilot equipped aircraft). These studies have indicated the need for enhanced surveillance, rapidly updated wind forecasting, and a reliable means for updating flight path intent as the means for achieving substantially improved trajectory predictions in cruise segments.

Trajectory synthesis for climb and descent phases is considerably more difficult due to additional uncertainties such as airplane performance and reliability of a-priori climb and descent profiles. The performance of the CTAS system for arrival scheduling (CTAS-TMA, [3]) has been the subject of various studies and field testing which has established benchmarks for prediction uncertainty and error allocations using existing technology. For example, [4] shows that for descent predictions, the ability of non-FMS aircraft to maintain a reference speed may be on the order of 20 knots one sigma, and aircraft track ground speed error and wind forecast error for the CTAS system may be of comparable magnitude. These errors are substantially higher than is desirable for decision support tools such as medium term conflict probe and meter fix scheduling. A primary issue for next generation ATM is that of specifying overall requirements for decision support systems to achieve desired levels of performance, and allocating subsystem performance to navigation, surveillance, weather forecasting and other infrastructure elements to achieve the desired ATM performance.

It should be noted that simplified methods for trajectory prediction in climb and descent segments often use lookup tables of airspeed and vertical rate for specific aircraft types. These prediction methods typically yield errors on the order of one-three minutes in predicting time-of-arrival at a specific flight level or at a critical waypoint fix [5], and are probably not adequate for scheduling and sequencing aircraft or enabling medium term conflict planning during congested traffic periods. The heart of more recent methods is to tightly control velocity uncertainty due to sources such as aircraft surveillance, FMS speed scheduling, and wind forecasting. Although desired error levels for implementing more efficient traffic flow may be beyond that achievable with current trajectory prediction methods and with current radar trackers and wind forecasting systems, they are potentially feasible for next generation ATC system architectures.

2.0 Specification of High Level Trajectory Prediction Requirements

A recent development in the design of Communications / Navigation / Surveillance (CNS) systems for air traffic management is the specification of required performance standards for airborne and ground based systems to achieve overall goals in air traffic management. This development has led to the specification of Required Navigation Performance (RNP) standards for use of area navigation systems to support advanced airspace concepts and procedures. The heart of RNP is the specification of allowable navigation performance metrics for position accuracy, integrity, availability, and continuity of function. The success of this methodology in harmonizing different navigation technologies to achieve common performance targets has led to current efforts to specify similar metrics for Required Surveillance Performance and Required Communication Performance. This evolving methodology for specifying operational requirements independent of the implementing technologies appears to be valid also for specifying high level requirements on trajectory prediction systems. This section briefly defines such metrics for trajectory prediction and discusses why explicit specification of these metrics is needed to assure that trajectory prediction systems achieve the reliability needed for existing and future decision support tools.

<u>Trajectory Prediction Accuracy</u> – Trajectory prediction accuracy is typically measured as the prediction uncertainty in lateral, longitudinal, and vertical axes as a function of prediction lookahead time. Prediction uncertainty is commonly measured in terms of either a one sigma error uncertainty per axis, or as a 95% containment bound, e.g. as an error ellipse or error volume with 95% probability that the true position falls within the containment region. In this paper we distinguish between horizontal plane prediction errors and vertical errors and treat them separately. The main emphasis in this paper is on reliable and accurate prediction of horizontal plane positions, since the accurate

prediction of vertical profiles in climbs and descents is considerably more difficult. (Typically, trajectory uncertainty in vertical profiles is managed procedurally, e.g. by use of level-off clearances and altitude restrictions.)

Figure 1 illustrates the growth of trajectory uncertainty as a function of lookahead time. Trajectory uncertainty can be estimated in real time using covariance analysis methodologies to estimate prediction uncertainty [1], or can be bounded by methods such as conformance monitoring [2]. Typically, trajectory prediction systems for conflict detection today use some means of maintaining accuracy such as limiting the lookahead time to some fixed bound, e.g. four minutes max lookahead for the radar based en-route Conflict Alert system in the U.S.

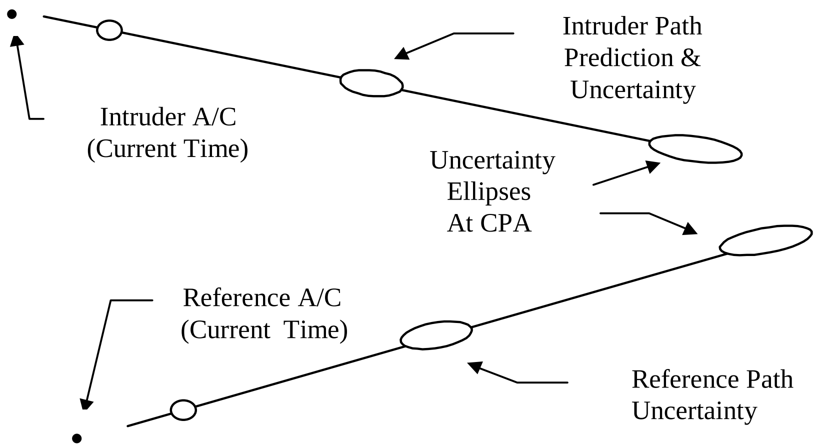

Figure 1: Aircraft Horizontal Prediction Uncertainty (Crossing Path Geometry)

<u>Trajectory Prediction Integrity</u> – Integrity refers to the probability that a predicted aircraft position provides misleading information to an application without suitable alerting. Integrity is typically measured in terms of a position containment bound and an acceptable probability level that the predicted position will fall outside the containment bound without alerting. An integrity failure in this context does not imply a system failure, simply the presence of an unacceptably large prediction error. The acceptable probability level depends on the safety consequences of an undetected error resulting in use of misleading information. At least two levels of integrity need to be considered for decision support tool applications:

- Nonessential – applications of trajectory prediction such as traffic load management, where minimal integrity is required since a poor prediction on a single aircraft has only minor operational and safety consequences, and
- Essential – applications such as arrival management advisories, where a basic level of integrity is required to avoid major safety consequences resulting in increased workload for pilots and controllers. Essential level integrity means that integrity failures are improbable [6], i.e. a probability level of 1x10^-5/ hr, or less.

Applications of trajectory prediction requiring even higher levels of integrity are probably not feasible in the near term and are not considered in this paper. It should be noted that the integrity level for a given application is an operational choice. Final approach monitoring, for example, may allow go-around rates in peak traffic on the order of 1x10^-3 per approach. An appropriate allocation of prediction integrity could be on the order of 1x10^-4 per approach, to support this function, even though integrity failures can result in extra workload due to missed approaches.

Most trajectory prediction methods in use today do not have a suitable means to assure integrity of aircraft predictions. As an example, a large wind forecasting error can produce aircraft predictions resulting in a poor planned arrival sequence, with consequent increases in workload for controllers and pilots. One objective of this paper is to show that it is feasible to build enhanced integrity into trajectory predictions by developing and integrating redundant sources of trajectory data for integrity monitoring and correction of unreliable source data such as outdated winds.

Trajectory Prediction Availability – Prediction availability here refers to the percentage of time that the prediction function is available and giving suitable predictions for decision support tools. There are multiple possible reasons for non-availability of acceptable quality predictions, i.e.

- Non-availability of basic trajectory information for predictions,
- Rapidly changing or hazardous weather conditions,
- Non-availability of updated wind forecasts,
- Non-availability of automation source data or functionality.

The first two causes are especially prevalent and deserve some elaboration. There can be literally hundreds of aircraft types operating in en-route airspace or a major hub airport today. It is probably not feasible to maintain accurate trajectory data on all possible types. Moreover, special performance options exist even within a single aircraft type, e.g. there are often high weight / high thrust versions of popular aircraft types which have somewhat different performance characteristics compared to standard aircraft models [7]. As a result, the developers of trajectory synthesis codes are challenged to maintain accurate data bases on even the most frequently flown models, particularly as the data base evolves slowly over time. A reasonable goal is to maintain accurate trajectory data on the most frequently observed aircraft at a hub or over the center airspace of interest. There will probably be some percentage of aircraft, say 5 to 10%, for which accurate trajectory data are not available and simpler, less accurate prediction methods must be used.

The other common reason for non-availability of accurate predictions is due to changing environmental conditions, which is difficult for current weather forecasting systems. When the wind and weather conditions along the flight path are stable and changing slowly, 1 to 3 hour meso-scale forecasts are probably reasonably reliable. However, the percentage of time when these conditions do not prevail may be sufficient to significantly reduce availability of accurate trajectory predictions.

3.0 Technical Approach for Enhanced Trajectory Prediction

The heart of the technical approach advocated here is an expansion of existing trajectory synthesis methods to enable dynamic estimation of prediction uncertainty, and monitoring of trajectory parameters for detection and correction of large prediction errors. Previous studies such as [1] have shown the feasibility of modeling many of the trajectory error sources internally, using a covariance analysis to estimate prediction uncertainty in parallel with nominal state predictions. We here show how the earlier studies can be generalized to include most error sources except for path intent. High quality predictions are then associated with small error uncertainty volumes for a fixed prediction time, and low quality predictions are those with large uncertainty errors.

Trajectory integrity encompasses various quality assurance methods to validate that anticipated prediction accuracy is in fact achievable. The emphasis in this paper is on using redundant sensed information to validate trajectory path and modeling assumptions. This includes path routing and speed intent conformance monitoring, wind forecast monitoring, and climb/descent energy-rate monitoring. In many cases, use of redundant data allows for correction of large parameter errors, e.g. updating poor wind forecasts. In other cases, it will be necessary to increase the modeled uncertainty of trajectory predictions, or to indicate prediction unavailability.

In those cases where it is not possible to achieve suitably reliable and accurate predictions, trajectory path control may be used as a means of compensating for trajectory prediction uncertainty. For example, if it is not feasible to estimate the vertical profile accurately during climbs or descents, it may be sufficient to impose altitude restrictions on the path routings at critical waypoints, so that separation assurance and flow management can be achieved by procedurally separating arrival, overflight, and departure traffic. Other means of trajectory path control include the use of Required Time of Arrival (RTA) clearances at specified metering fixes, and the use of vertical path guidance profiles, e.g. synthetic glideslope clearances on descent.

An example of accuracy requirements for trajectory predictions and source error modeling is found in our conflict probe work. In our previous Monte-Carlo studies on medium term (10 – 30 minute) conflict probe [1], we found that good probe performance could be directly related to along-track prediction error performance. Typically, good conflict detection performance is obtained when one sigma prediction error is less than 2.0 nm. For a typical 20 minute lookahead period, this means that the along track velocity error should be no bigger than 2 nm / 1/3 hr = 6 knots (one sigma). Similarly, the maximum sustained acceleration error that can be tolerated in a vertical transition can be estimated. Such velocity and acceleration error requirements can be used as a starting point for trajectory synthesis, i.e. error sources or modeling errors substantially less than desired error levels can be ignored. Error sources potentially exceeding these levels are to be mitigated with technology or procedures to reduce the overall prediction error to desired levels. If necessary, the lookahead time for trajectory planning may need to be reduced when path intent, path synthesis assumptions, or input sources are not of sufficient quality for operational use.

Table 1 summarizes the overall technical approach and the analogy with RNP navigation requirements.

Table 1: Trajectory Quality Assurance Methodology

Trajectory Requirement	Implementation Method	Navigation Analogue
•**Prediction Accuracy**	Covariance Analysis of Normal Error Sources	Estimated Position Uncertainty e.g. GPS HFOM, VFOM
•**Prediction Integrity**	Redundancy Monitoring: Wind Forecast, Airspeed, Path Routing, Energy-Rate	RNP Integrity Monitoring e.g. GPS HIL, VIL
•**Prediction Availability**	Trajectory Synthesis and Covariance Analysis, or Trajectory Path Control	RNP Availability

4. Source Uncertainty Modeling and Trajectory Quality Assurance

Table 2 shows the major data sources used today or proposed for future CNS implementation which potentially could be used to perform aircraft trajectory predictions.

The data sources are shown in three categories: (1) flight plan and user preferred routing and intent data, (2) dynamic weather and aircraft surveillance data, and (3) aircraft specific performance data. In this section we analyze how these data sources are used for trajectory predictions, and examine potential future system options and uses of data sources to achieve operational accuracy and integrity requirements for trajectory predictions.

Table 2: Typical and Proposed Trajectory Synthesis Data Sources

Trajectory Data Sources	Status
• **Trajectory Routing and Intent**	
- Flight Plan as Sequence of Waypoints	Today
- Airspeed Intent / User Preferences	*Future*
- FMS Climb/Descent Profiles / User Preferences	*Future*
• **Weather and Aircraft Surveillance Data**	
- Along Track Temperature Forecasts (Tk(x,h))	Today
- Along Track and Cross Track Wind Forecasts	Today
- Radar / ADS-B Surveillance Data	
- Horizontal Position and Mode-C / S Altitude	Today
- Velocity Vector (Ground Speed, Ground Track)	Today
- Next Waypoint Intent	*Future*
• **Aircraft Performance Data-Base**	
- Thrust, Drag Profiles / BADA Coefficients	Today
- Nominal Flight Parameters, e.g. CAS / Mach Transitions	Today
- Flight Plan Weight Estimation	*Future*

The major error sources of interest for trajectory synthesis are:

- Path routing & intent errors,
- Weather forecasting errors,
- Surveillance errors of current aircraft state estimates,
- Aircraft performance and profile modeling errors,
- Flight Technical Error (FTE) in trajectory path control.

Path routing and intent errors are a major issue since the main source of information to ground based systems today is the IFR flight plan, which is often out of date and is incomplete for the purpose of predicting climb and descent profiles. The next source errors of interest are those caused by weather forecasting, since these errors often dominate the ability to predict fix timing for arrival and departure management. Surveillance errors are also an issue, since current generation tracking systems do not accurately estimate aircraft velocity components, and typically exhibit excessive lag and slow convergence following a turn or vertical maneuver. Aircraft climb and descent dynamics are an additional source of uncertainty since aircraft thrust, drag and weight parameters can exhibit substantial variations from typical values per flight. Finally, FTE errors are important since they limit the potential accuracy achievable in trajectory predictions.

4.1 Trajectory Routing and Intent Uncertainty

The trajectory synthesis process typically begins by specifying horizontal waypoints beginning with the next waypoint to be traversed out to some horizontal distance from the intended departure or arrival point [8].

This process is probably sufficiently reliable for departure planning, based on flight plan data available at the scheduled departure time. However, additional methods may be required for achieving desired integrity in en-route and arrival path routings, since the airplane may be following a different routing than that in the flight plan. Three potential options for achieving enhanced routing integrity are:

- Dynamic Flight Plan Updating – One observed problem for deployment of conflict probes in NAS airspace is that routing and speed deviations en-route are infrequently entered into the ATC automation system in the U.S. [2]. One option to solve this problem is to redesign the controller interface to make altitude, routing and speed clearances more easily available for dynamic flight plan updating.

- Aircraft Broadcast of Routing Intent (ADS) – A second method to obtain updated routing data is to have aircraft routinely (ADS-B), or upon request (ADS-A), broadcast currently available navigation waypoints for integrity checking and flight plan updating.

- Path Conformance Monitoring – The most basic method of updating path routings is to automatically check the consistency of flight plan and surveillance data. Correcting the flight plan for future waypoints is problematic, however. If the aircraft is not on the flight plan, then it may be possible to use an "educated guess" to determine nominal waypoints for arrival route planning. For example, if the aircraft is currently traversing one of the major ATC preferred routings to a destination airport, then it is reasonable to use those waypoints for route planning. However, some metric for trajectory quality may then be needed to reflect intent uncertainty.

In the future, flight plan information may be expanded to include user preferences such as intended climb/descent airspeeds, e.g. CAS / Mach transitions, and preferred climb/descent gradients. Such information could be used to replace nominal aircraft performance parameters used in trajectory synthesis today.

Another aspect of path intent uncertainty is navigation and guidance error in controlling the aircraft to follow the intended path. The author has developed fairly simple second order dynamics models driven by white noise disturbances to model lateral path and vertical path / energy FTE errors during approach [9]. Figure 2 illustrates example sample paths for the lateral model. It is fairly straightforward to generalize such models to climb/descent flight regimes and to include such models in a covariance analysis for dynamic modeling of lateral and vertical FTE uncertainty.

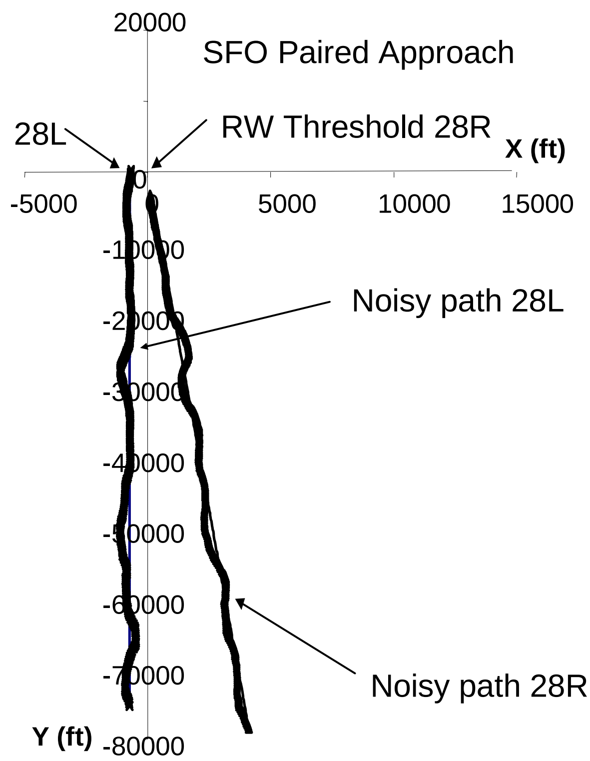

Figure 2: Sample Paths with Lateral FTE

4.2 Wind and Airspeed Vector Uncertainty

Once the intended path routing is established, equations of motion for aircraft velocity can be integrated forward from the current position to the desired lookahead time for predictions. Typically aircraft ground velocity Vg is synthesized using the wind triangle for airspeed vector Va and the predicted wind vector Vw shown in Figure 3 The problem experienced with this process is that neither the wind forecast Vw nor the airspeed Va is known very precisely. In theory, we could use the aircraft ground velocity vector to perform conformance monitoring on the synthesized ground vector. However, radar based ground speed and track are also very imprecise today, and thus all three legs of the wind triangle are subject to large uncertainty errors.

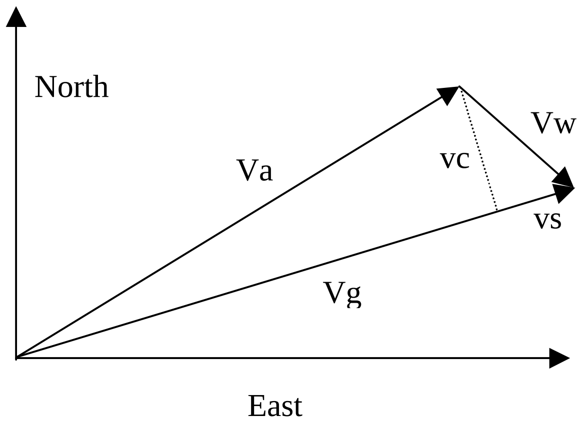

Figure 3: Wind Triangle for Airspeed Vector

Integrity of intended airspeed can be achieved by accurate monitoring of ground velocity and wind vector, or by directly monitoring airspeed. Potential enhancement options for next generation implementation include:

<u>Wind Forecast Integrity Monitoring</u> – Current large scale wind forecast systems with update periods on the order of several hours can occasionally generate forecasts errors on the order of 30 knots or more. Forecast integrity could be enhanced by systematic downlink and monitoring of aircraft based MDCARS weather data. The basic idea is to flag airspace regions where the forecast wind vector is significantly different than aircraft observed values. Either such forecasts could be corrected with MDCARS data, or trajectory uncertainty using such data could be increased to reflect poor prediction regimes. The major advantage of MDCARS is that studies have shown that major gains in wind accuracy are achievable with fairly low aircraft equipage and downlink rates [10].

<u>Ground Speed Conformance Monitoring</u> - Plans are in place today for the NAS and elsewhere to enhance surveillance by networking radar sensors and performing multi-sensor data fusion to enhance surveillance performance. One major advantage of such systems is much greater accuracy of derived velocity vector. This should enable accurate monitoring of synthesized or flight plan based ground speed. If both ground vector and wind vector are known accurately, then errors in intended airspeed can be detected and trajectory synthesis processing changed to accommodate large intent errors.

<u>Direct Airspeed Intent Monitoring</u> - Another potential means of achieving airspeed integrity is direct downlink of airspeed or FMS selected airspeed intent via ADS-A or ADS-B avionics. However, this option only applies to ADS equipped aircraft. Consequently, the other methods are seen as more appropriate for near term trajectory synthesis applications.

Nominal error uncertainty in synthesizing the aircraft ground velocity can be modeled with fairly simple models of each of the nominal error sources, e.g.

- Wind forecast error
- Surveillance / Tracker error
- Airspeed Intent Error
- Airspeed FTE Control Error.

Covariance analysis was used to model trajectory uncertainty for wind forecast error and radar surveillance error in earlier studies such as [1]. These models can be extended to include uncertainty in the intended airspeed profile for climb / descent predictions, and to incorporate FTE models for airspeed control similar to those in [9].

4.3 Aircraft Climb / Descent Uncertainty

Aircraft vertical transitions are typically computed today using nominal or simplified thrust and drag calculations, some simplified parametric means of estimating weight, and nominal speed and guidance parameters typical for each airplane type. In more sophisticated systems, such as the CTAS trajectory synthesis process, default parameters based on aircraft type are used to estimate climb and descent speed profiles, and to provide vertical guidance dynamics for integrating nominal trajectory equations of motion [8]. Much of the intent information used in this process are "educated guesses", however and do not reflect actual knowledge of aircraft intent per individual flight. The extension of flight plan information to include user intent / preferences, as mentioned above, would improve the integrity of this process.

Perhaps the biggest source of uncertainty, at least for climb transitions, is uncertainty in estimating aircraft energy-rate, primarily due to variations in thrust, drag and weight during vertical transitions. Several options for reducing this uncertainty exist for near-term and future trajectory prediction applications:

Enhanced Weight Estimation – Probably the best weight estimates for flight planning are those computed by pilots and Airline Operational Centers prior to gate departure. Both accuracy and integrity of weight estimates could be significantly enhanced by including departure weight estimates in pre-departure clearance procedures, or by adding this information to the flight plan prior to departure. In the near term, the author has suggested [7] that a simplified flight planning process be used to estimate aircraft weight, based on average or anticipated load, destination distance, and aircraft type. This calculation process would use simplified lookup tables commonly found in pilot manuals for specific aircraft types, and is needed only once per flight segment.

Aircraft Energy-Rate Monitoring – In a previous paper [11], the author has suggested monitoring vertical-rate to validate the ability of trajectory codes to accurately predict climb / descent energy-rate profiles, and if needed to update nominal energy-rate profiles using an equivalent weight parameter. Recent field test evidence [12] shows that vertical-rate is unreliable for this purpose, since vertical-rate can exhibit large phugoid-like oscillations during climb segments. Although all the parameters for computing energy-rate, e.g. pressure altitude and true airspeed, are available from current air data systems, there is no commonly available means of transmitting true airspeed to ground systems today. Thus, energy-rate monitoring is probably an option for future system development, either through direct downlink of airspeed via ADS-A or ADS-B systems, or on the basis of higher quality radar / wind vector synthesized airspeed as discussed in section 4.2.

Whether or not the above refinements are implemented, it is feasible in the near term to estimate prediction uncertainty including internal models of energy-rate uncertainty, and possibly other variables such as wind gradient uncertainty. Covariance analysis including such errors is recommended to account for significant prediction uncertainty due to these error sources. It is anticipated however, that the accuracy and integrity of the vertical predictions will lag that of the longitudinal and lateral variables, due to the complexity of climb and descent dynamics and the effects of rapidly changing winds and temperatures often experienced in vertical transitions.

5. Conclusions

In this paper we have analyzed the trajectory prediction process from the viewpoint of Required ATM Performance, i.e. what are system level requirements and implementation methods to achieve prediction accuracy, integrity and availability metrics for near term and future ATM decision support tools. This methodology is seen as an important tool for exploring alternative means to enhance future system operations. We could, for example, compare the relative benefit of enhancing flight plan information versus that in enhancing surveillance or other CNS elements desirable for future system operations.

This paper specifically outlines potential options that could be used for trajectory quality assurance, i.e., obtaining trajectory predictions with assured accuracy and integrity for supporting critical flow management and separation assurance functions. Several specific areas suggested for future systems include: (1) developing a means for reliable updating of flight path intent, (2) developing a means for assuring airspeed intent accuracy, and (3) developing a means of accurately estimating aircraft departure weight for climb transitions.

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7. Biographical Note

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