IMPACT OF MISSING LONGITUDINAL AIRCRAFT INTENT ON DESCENT TRAJECTORY PREDICTION

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Abstract

Accurate trajectory prediction is the cornerstone for future Air Traffic Management (ATM) concepts worldwide. To this purpose, researchers from Airservices Australia, the Federal Aviation Administration (FAA), and EUROCONTROL have collaborated on research into trajectory prediction.

A trajectory may be decomposed into lateral and longitudinal components. Laterally, the trajectory is mostly defined by the flight plan and if the plan is kept up-dated, lateral uncertainty should be minimal. Longitudinally however, the problem is more complicated as not all required longitudinal aircraft intent is known to the ground-based Trajectory Predictor (TP). An example is an unknown descent speed schedule, requiring ground-based TPs to make often incorrect assumptions which would not be the case using aircraft longitudinal intent information.

Performance of operational TPs from the FAA, EUROCONTROL, and Airservices Australia were compared, finding that with inaccurate longitudinal aircraft intent, excessive prediction errors are evident in all three TPs. The performance of the ground-based TPs was subsequently compared to data extracted from the aircraft's Flight Management System (FMS) through Future Air Navigation Systems (FANS) technology. FANS is standard fitment on wide-body aircraft and some domestic fleets yet its potential is widely overlooked.

In conclusion, significant improvements to prediction accuracy can be obtained if the ground-TP is enhanced with aircraft data. This paper demonstrates significant improvements in ground-based trajectory prediction are possible through the use of data-link technologies operational today.

Introduction

Accurate trajectory prediction is central to the effective use of many Air Traffic Management (ATM) Decision Support Tools (DSTs) and forms the cornerstone of ATM concepts for the future like Trajectory Based Operations (TBO). Ground-based Trajectory Predictors (TPs) often do not have access to accurate and unambiguous aircraft intent. A previous collaborative research effort of these authors investigated the impact of lateral aircraft intent error on the performance of a conflict probe [1]. It was concluded that the use of Aircraft Derived Data (ADD) in the form of lateral intent received through Automatic Dependent Surveillance Contract (ADS-C) significantly improved the conflict probe's performance as in many cases the flight plan held by the system did not reflect all tactical changes made by Air Traffic Control (ATC) in contrast to the aircraft's Flight Management System (FMS). Although the lateral path held by the ground system can be improved using aircraft derived lateral aircraft intent, large errors in the ground-based predictions can remain due to unambiguous longitudinal aircraft intent. An example thereof is the intended climb/descent speed schedule which is often unknown to the ground-based TP and must be guessed.

Continuing the previous research effort, this paper investigates the impact of the longitudinal aircraft intent error on TP performance for the descent phase of flight. To demonstrate that the problem of missing longitudinal intent is consistent throughout the world, operational TPs from EUROCONTROL, the Federal Aviation Administration (FAA), and Airservices Australia are compared in this paper. This performance is subsequently contrasted against the accuracy of trajectory predictions performed by the aircraft's FMS available to the ground through Future Air Navigation Systems (FANS) technology (ADS-C).

As it is widely accepted that a primary source for accurate aircraft intent is the aircraft's FMS[1] [2], much effort is given to define new data link capabilities to make this information available to ground-based TPs illustrated by the work on 4DTRAD [3]. However, this paper intends to develop a capability making use of an attribute of FANS technology, which has been available since the early 1990's and yet is widely overlooked for use in operational ATM systems.

The paper starts with a general description of Trajectory Prediction in an ATM context. The problem of missing longitudinal aircraft intent within the ground-based trajectory prediction process is introduced, and it is discussed how the operational TPs employed by EUROCONTROL, the FAA, and Airservices Australia make assumptions on aircraft performance and airline procedures to quantify these missing parameters. Throughout the paper the data sets from EUROCONTROL, the FAA, and Airservices Australia are simply referred to as the European, US, and Australian data, respectively. The performances of the different TPs will be presented using common accuracy metrics. Subsequently the airborne predictive capability is assessed and it is illustrated how this data can be of use.

Trajectory Prediction Process

Trajectory Prediction is defined by the EUROCONTROL/FAA Action Plan 16 (AP16) on Common Trajectory Prediction Capability as [4]

"The process that estimates a future trajectory of an aircraft through computation".

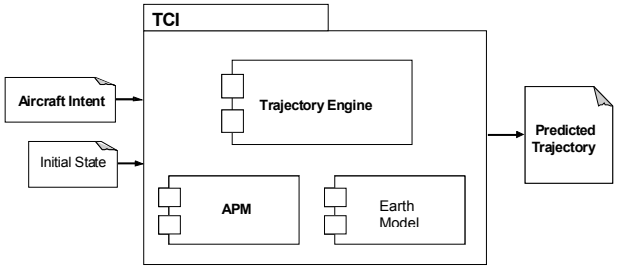

Figure 1: Components of the trajectory prediction process

[1] The best source for aircraft intent is the actor that controls it. If in a future TBO environment the aircraft is contracted to fly agreed aircraft intent, the most accurate source of aircraft intent would be the entity holding this intent (Flight Object).

Figure 1 provides a schematic overview of the major components involved in the trajectory prediction process as proposed by Boeing Research & Technology Europe [5].

The main component is formed by the Trajectory Computation Infrastructure (TCI) and consists of

Trajectory Engine (TE)- The TE is responsible for executing the trajectory computation process by performing all pre-integration calculations and integrating the equations of motion.

Aircraft Model (AM)- EUROCONTROL's Base of Aircraft Data (BADA) proposes an AM that consists of two main components: the Aircraft Performance Model (APM) and Airline Procedure Model (ARPM) [6] [7]. The APM provides characteristics of aircraft performance, aerodynamics, and aircraft specific constraints. The ARPM focuses on how the aircraft is to be operated. Examples of such operational procedures are nominal speeds for all flight phases. The ARPM is airline specific and can also be dependent on specific airspace procedures. Throughout the literature the AM is often referred to as simply the APM [4].

Earth Model (EM)- The EM provides predicted characteristics of the atmosphere like pressure, density, temperature, and wind. It also provides the model for the Earth's shape, magnetic declination, and gravity/gravitation.

Inputs to the TCI are the aircraft's initial state and aircraft intent. The initial state provides the initial conditions of the prediction process. Aircraft intent describes *how* the aircraft is to be operated within the time interval of prediction. From the aircraft intent the TP generates a script defining how the degrees of freedom within the equations of motion should be closed. Ideally, aircraft intent should be an unambiguous description of aircraft operation [8]; however in case of the ground-based TP generally not all aircraft intent is known, subsequently assumptions and/or simplifications are required to close all degrees of freedom.

The Effect of Missing Longitudinal Intent

The lack of unambiguous aircraft intent is a common problem for ground-based trajectory

predictors. Generally, the only available source to derive aircraft intent is the flight plan which contains basic information about the lateral track to be flown, cruise levels, and cruise speeds. In AP16 terminology this is known as flight intent. Although this information might be sufficient for cruise where trajectory prediction is relatively straight forward, it leaves a lot of unknowns for climb and descent predictions requiring assumptions and simplifications to be made by the ground-based TP (e.g. climb and descent speed schedules are not part of the ICAO flight plan). The assumptions and simplifications result in an inaccurate geometric descent path build by the TP, leading to errors in the predicted Top of Descent (TOD) position, metering fix crossing level, and metering fix time.

The next three paragraphs discuss the TPs employed by EUROCONTROL, FAA and Airservices Australia and their respective assumptions regarding longitudinal aircraft intent.

European longitudinal intent assumptions

The data for this research has been extracted from a TP used within the Flight Data Processing System (FDPS) based on the Total Energy Model using the BADA APM

The lateral path is computed as a sequence of straight segments joined by fixed radius turns whereas the vertical path is computed as a sequence of segments during which only one parameter, e.g. speed or altitude, is varying. For specific combined changes a fixed energy share factor is used and gives a trade off between altitude and speed change.

In terms of aircraft intent it uses the cruise altitude from the flight plan and the ARPM data from BADA for the descent speed schedule. This speed schedule is differentiated only by aircraft type. Altitude and speed constraints for ATC operations are taken into account in the prediction process.

These two last elements are the major source of inaccuracies as aircraft operations differs per airline and even per flight but also because some ATC procedural altitude constraints considered at prediction time may be removed tactically during the descent.

US longitudinal intent assumptions

The US TP for en route airspace builds an aircraft trajectory prediction by first converting the cleared flight plan into its lateral path. The process begins by extraction of the specified route in the flight plan to a series of coordinates adjusted for site airspace adaptation and by applicable preferred departure and arrival route procedures. The vertical profile is then calculated based on requested and assigned altitudes, altitude restrictions, climb and descent gradients (provided by look-up table by mappings of particular aircraft types), and temperature and wind aloft data. Nominal climb and descent rates are provided in 3000 foot increments. Later processing will automatically adjust the vertical gradients applied by weighted averages of the nominal look-up rates and those measured from mode-C reported altitude.

The lateral and vertical processing are then integrated using kinematic equations of motion and applied to a data structure into a series of segments. Vertical gradients and accelerations are assumed constant along the segment. Turns are modeled simply as instantaneous turns at a fix.

Australian longitudinal intent assumptions

The system operated by Airservices Australia uses performance tables to compute the climb and descent trajectories similar to the US TP. These performance tables provide airspeed and climb/descent rate against altitude and reduce the physical model for trajectory prediction to a kinematic model. The horizontal part of the trajectory is calculated from integrating the airspeed (instantaneous speed changes assumed), and the vertical part is calculated from integrating the climb/descent rate; the horizontal and vertical motion are treated as independent. The complexity of the trajectory prediction process is much reduced at the cost of severe accuracy losses [9]. Furthermore, the TP does not consider any procedural vertical or additional speed constraints in the Terminal Maneuvering Area (TMA), leading to a further decrease in accuracy.

Comparison

Comparing the three systems to the TCI presented in figure 1, it is clear that the different

components are not well separated in the US and Australian TCI as the performance tables unifies aircraft intent (descent speed), APM (horizontal and vertical motion are uncoupled), and EM (descent rate is static and hence independent of atmospheric conditions). From the three TPs considered only the European TP, which is based on the Total Energy Model, has the different components of the TCI well separated.

Hypothesis

The numerous assumptions and simplifications made by ground-based TPs with respect to longitudinal aircraft intent lead to prediction errors associated with TOD and the metering fix. On the other hand, the aircraft's FMS is aware of the objectives of the flight and determines how the aircraft is to be operated. With respect to the descent phase of flight, the FMS builds the geometric path for descent from the selected descent speed schedule (derived from Cost Index) taking into account any speed and altitude constraints imposed. During execution of the descent, the FMS provides the guidance modes to ensure the descent is flown as intended. It is logical to assume that the primary source of unambiguous aircraft intent is the FMS [2].

In previous collaborative research of these authors [1], it was shown that the effectiveness of a ground-based conflict probe can be significantly increased when making use of Aircraft Derived Data (ADD) and more specifically, the lateral aircraft intent received from the FMS. Similar to this previous research effort, it is now hypothesized that the use of ADD can also significantly improve accuracy of longitudinal aircraft intent and hence result in improved predictions for TOD and metering fix. In contrast to other research efforts [10; 11], only sources of ADD which are operationally available today: FANS, are investigated.

Methodology

This paper mainly focuses on errors in the prediction of the longitudinal descent trajectory due to inaccurate longitudinal aircraft intent. These errors are quantified by the TOD longitudinal error and the errors in predicted crossing level and crossing time at the metering fix. These indicators have been chosen as they are particularly relevant for conflict detection and arrivals management.

With the use of a common set of metrics, the above mentioned errors associated with operational TPs from EUROCONTROL, FAA, and Airservices Australia are compared and baseline accuracy is established. The same metrics are also applied to assess the accuracy of the ADD trajectory information available through FANS thus providing direct comparison.

In order to attribute the error in trajectory prediction solely to inaccurate modeling of longitudinal intent, it is essential that all sampled flights are free from ATC tactical intervention and the crew permit the FMS to execute the flight in lateral and vertical guidance modes (LNAV/VNAV). There should be no deviation from the lateral track as known to the ground system to avoid lateral intent errors (which have previously been assessed in [1]) contributing to longitudinal inaccuracy.

Ideally the wind and temperature error should be excluded as well however using operational data this is, however, practically impossible. It is therefore assumed that the characteristics of forecast wind and temperature error are similar for all data sources as the meteorological forecasts used by the three TPs are in principle based on the World Area Forecast System [12].

Section VII explains the performed filtering process for the different data sources in detail.

Metrics

In order to compare accuracy between the different operational TPs a set of rigid and common metrics is required. Consider Figure 2, the main indicators for TP accuracy in this paper are the prediction error of TOD position and the Estimated Time of Arrival (ETA) and Estimated Crossing Level (ECL) of the metering fix. The predictions are compared to the actual TOD position (dATOD), actual time of arrival (ATA), and actual crossing level (ACL), respectively. Due to data source limitations, which will be detailed later, it was not always possible to retrieve an actual time at the metering fix. In those cases the geographic location where the actual trajectory crossed FL200 was chosen as reference point. In either case, both the

vertical and temporal prediction errors are always determined as spatially-coincident [13].

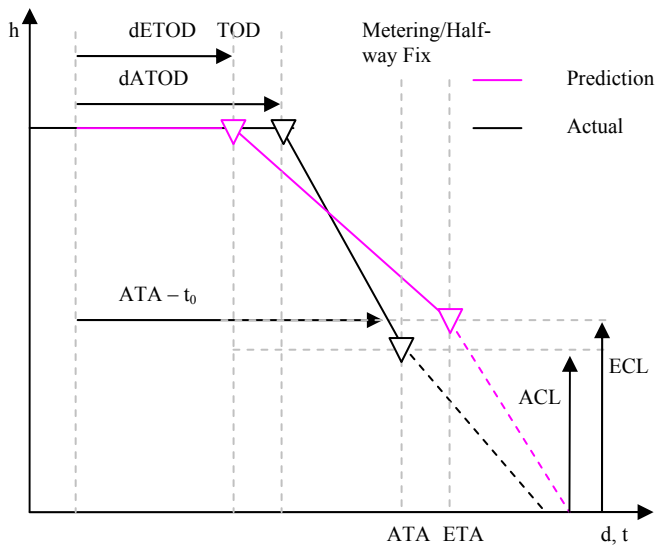

Figure 2: TP error metrics

As the main focus of this paper is to report on the effect of inaccurate longitudinal intent on trajectory prediction accuracy for descent, the cruise element of the prediction should be minimized as to exclude errors associated to the cruise (e.g. airspeed different to flight plan). It was therefore chosen to use predicted trajectories calculated when the aircraft in question was between 2 to 4 minutes prior to TOD.

The time to run to the metering fix (or half-way fix) can be different for each flight. Consider the situation in which the ETA error for two flights is 30 seconds; Flight A with 10 minutes to run and flight B with 15 minutes to run. In absolute terms the errors are equal; however flight B has a longer prediction horizon. Longitudinal intent errors as errors in the descent speed cause the ETA error to grow with prediction horizon. The ETA for flight B is therefore better in relative terms (30/15 vs. 30/10). Hence in case of the ETA error a relative metric is used:

$$(\varepsilon_{MF})_{ETA} = \frac{ETA - ATA}{ATA - t_0}, \tag{1}$$

The error in ECL and TOD position are related to the geometric descent path. Provided the TP does not make any aircraft intent changes – which it does not as the only information it has access to are the static aircraft performance tables – and does not update its meteorological model, this predicted path is static in time. The only variable is the ETA for points on that path, as these are affected by errors in the predicted groundspeed. Therefore for both the error in ECL and in the TOD position, the normal absolute metric is used:

$$(\varepsilon_{MF})_{ECL} = ECL - ACL \quad \text{[ft]}, \tag{2}$$

$$\varepsilon_{TOD} = dETOD - dATOD \quad \text{[nm]}. \tag{3}$$

Data Source Description

This section provides a description of the three main sources of trajectory data used in this study from Europe, the United States, and Australia, demonstrating the filtering approach.

European data description

The European data set is a collection of trajectories, flight plans, and track data from an en route center that covers a significant part of the core European area. This guarantees that there are enough cruise descent profiles, as the center is serving a set of near by airports.

As the data has been collected for a complete day without any specific set of requirements, it is important to describe its contents and characteristics and to explain the filtering required in order to provide a data set comparable with the data from Australia and the US.

Airspace coverage

The data set has no upper bound altitude limit and extends in the descent phase down to FL200 and below for some of the trajectories. However, as the area of responsibility of the center is bounded on its low altitude, the consequence is the absence of data for turboprops.

Aircraft fleet

Except for the lack of turboprop aircraft types, the data set covers all types of jet aircraft, including commercial and business jets. No military aircraft exists within the data set.

Aircraft operators

The data consists of information collected from multiple operators, including cargo operators and business jets. This could possibly lead to a wide

variation of aircraft intent between the different operators.

Filtering process prior to analysis

It was not possible to identify if a flight has been adjusted by ATC and as such the results not only show the error in the trajectory prediction process but also errors due to controller intervention.

To ensure that the data set used in the error analysis was as consistent as possible with the data provided by Australia and the US, some filtering has been done to remove flights with obvious deviations.

The first filtering was done on lateral error deviations (this error was already analyzed in [1]) to ensure that the route used by the predictor matches the lateral path flown. Any flight with one surveillance position report with a lateral deviation greater than five nautical miles was removed from the sample. This was a simple and efficient method of removing flights given direct to waypoint clearances not entered into the FDPS.

The second filtering process has been applied to the vertical profile of the flights. Any flight that had a level segment longer than one minute after TOD has been removed.

Specificities of the data set and potential implications

As previously mentioned, large errors can be anticipated, since there is no guarantee, even with the extensive filtering applied, that the flights were untouched by ATC.

A second issue is related to different aircraft types. This TP uses BADA ARPM data for the cruise and descent speed schedule. These are approximations and since the sample consists of a spread of aircraft types and operators, it is expected that the intent error between the speed flown and the one assumed by the TP will be significantly greater than if there were only a few aircraft types; this might have a significant impact on the time error at the metering position.

Finally, as flights inbound to several airports were used, there was no clear method to define specific metering fixes for measuring time error. For consistency with all flights, it was decided to evaluate the time error not at a given fix, but when crossing FL200, the resulting position error was subsequently converted in time error using observed ground speed.

To conclude, the data set was filtered for obvious lateral and vertical deviations, but it cannot be guaranteed that the flights were untouched by ATC. This potential error source should be noted later when interpreting the results.

US data description

The US data set is a collection of actual and predicted trajectories from two en route center facilities- Atlanta and Chicago. Although their geographic location and air traffic patterns are quite different, both these facilities contain major airports, resulting in a significant number of arrival traffic. Two days of actual traffic were recorded from January 26th and 27th 2010. Like the European data, a filtering process was employed to select near continuous descents. These are atypical events within controlled airspace. As a result, only approximately one percent met the criteria after evaluating over 25,000 flights over the full 96 hours of air traffic recordings. The following sub-sections will further describe the source data and the filtering process utilized.

Airspace coverage

Like the European data, the US data set has no upper bound altitude limit and extends into the descent phase but ends before entry into the terminal airspace. Thus, the lower bound varies depending on location. To be consistent with the other data sets, the analysis was truncated at the crossing of FL200. In about ten percent of the data sample, flights are terminated before crossing FL200 due to various reasons (e.g. flight transferred air traffic control to the adjacent facility, recording terminated).

Aircraft fleet

The data sample contains 237 civilian flights ranging from wide-body jets to much smaller regional jets. There are 48 aircraft types that make up the sample, but only 13 types make up more than 75% of the sample. The top three make up 38% of the sample and include three Boeing aircraft types: 737, 757, and 717. Another common aircraft in the sample are regional jets from Bombardier (CRJs), making up about 15% of the sample.

Aircraft operators

With the exception of military aircraft, there was no filtering based on aircraft operator types, so, much

like the European data set, all carriers were included (e.g. civilian airliners, cargo, business jets).

Filtering process

There was an extensive filtering process employed on the original traffic recorded. This filtering is required to select flights that have near continuous descents in the selected en route airspace during the sample days chosen. Besides the obvious requirement that the flight must be an arrival into the en route facility, it must also have a clear top of descent point. This TOD altitude must be greater than or equal to FL300 and during the descent the flight cannot have any level segments greater than one minute of duration. This ensures that the flight has a measurable arrival profile of sufficient altitude and descent is near continuous. Typically, procedures require flights to perform step descents because of traffic constraints and safety. However, occasionally if the conditions warrant it, a flight may be cleared to descend without these steps. These are the flights selected for this analysis.

Furthermore, like the European analysis previously described, flights deviating laterally from their flight planned route by more than five nautical miles were removed from the analysis.

The sample resulted in 93 flights from the Chicago and 144 flights from Atlanta en route centers. A representative US TP, designed for en route airspace, was then executed on these flights approximately four minutes before the actual TOD point. Depending on the aircraft speed, this translates to approximately 9 to 39 nautical miles before the TOD point. It represents a minimum time horizon before the descent begins that air traffic would require an accurate descent prediction for strategic adjustments to the flight.

Australian data description

While the US and European data consists of a variety of flights through their respective airspaces, the Australian data contains only flights with a single destination for one aircraft type. The data was provided from the Tailored Arrivals trial at Melbourne airport where there is assurance the data is free of interventions. All arrivals into Melbourne fly runway linked Standard Terminal Arrival Routes (STARs) issued by ATC and loaded by the crew to the FMS about 45 minutes prior to TOD.

On the ground, the flight data record is updated with the lateral tracking of the STAR to the runway. In the air, the crew enters the STAR into the FMS, enabling it to calculate an idle thrust descent and hence determining the optimal descent point. The aircraft is subsequently cleared to "descend at pilot discretion," allowing the aircraft to descend at the FMS determined descent point. The airspace around Melbourne is designed such that although the aircraft is cleared in steps down to the runway, the new level clearance can mostly be given prior to aircraft reaching the previous one, resulting in no level segments.

Airspace coverage

There are no upper or lower limits to the data with respect to airspace coverage.

Aircraft fleet

The data consists of only B738 aircraft which is a predominant type operating at Melbourne.

Aircraft operators

All flights in the Australian sample were performed by Qantas Airways.

Filtering process prior to analysis

All flights in the Australian data participated in the Tailored Arrivals trial. Pilot and controller procedures were established to ensure that onboard automation was allowed to perform in lateral and vertical guidance. Only flights that had no open-loop vectoring or other tactical interventions were considered. As controllers were asked to log whenever an intervention was required, it can be stated quite confidently that the sample is clean. Flights could have been instructed with a higher or lower descent speed than preferred [2] (strategic intervention); however for this analysis only that part of the flight after the strategic intervention is considered, when the intent is consistent. In total the sample consists of 324 flights.

The Australian sample is not as diverse as the European and US samples. However, it can be stated with certainty that there was no ATC tactical intervention, which becomes its major advantage.

[2]The 'preferred' descent speed is the descent speed resulting from the flight specific Cost-Index (CI).

Results Baseline data

Using the methodology and metrics described previously, this section now presents an illustrative example using one flight in Australian airspace with statistical comparisons of many flights from the global data set.

Flight Example

One flight from the Australian sample has been selected to illustrate the effect of missing longitudinal aircraft intent on TP performance. It also provides some understanding of the metrics used before the global results are presented.

In Figure 3 the profile computed by the Australian TP (red) and the actual profile flown by the aircraft (dotted blue) are presented for a typical B738 arrival into Melbourne. The green line indicates the ATC assigned altitude, demonstrating how continuous descents as described in the Australian data description section are facilitated; descend-to clearances are generally received by the crew well in advance such that no level segments are flown.

At 20:14:47, the time the ground-based prediction was made, the aircraft was about 35nm prior to TOD. Ten nautical miles later a "descend when ready" clearance for FL250 was given, and the aircraft commenced descent when it reached its planned optimal descent point 25nm later, still 45nm in front of the ground-based predicted descent point! The aircraft crossed the metering fix ARBEY at FL117, about 6000ft below the ground-based predicted profile. The predicted crossing time for ARBEY was 20:30:34 but the aircraft overflew the fix at 20:32:03, 89 seconds later. The prediction horizon to the metering fix is 1036 seconds, hence a relative time error of 89/1036 = 0.086 = 8.6%.

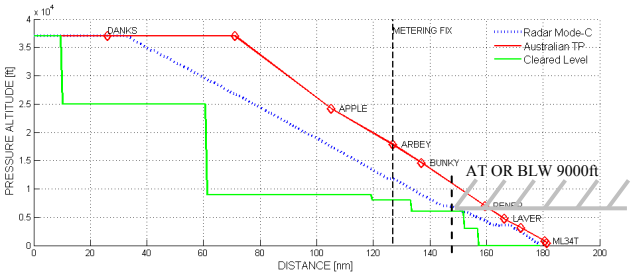

Figure 3: Example flight profile

The reason for the excessive errors can be traced back to the errors in the longitudinal intent used by the Australian TP. Firstly the performance table for the B738 reflects a Mach 0.78 into 300 knots Calibrated Airspeed (300KCAS) descent [9] while the majority of B738 actually descend at 280KCAS. Secondly, there is a procedural altitude constraint at point BUNKY that requires all passing aircraft to be at or below 9000ft at that point (to ensure procedural separation between arriving and departing traffic). Figure 3 shows the aircraft meets the constraint perfectly, while the ground-based predicted profile does not. Predicted altitude crossing at BUNKY is at about FL150, breaching the constraint by 6000ft! Using these profiles for conflict detection is pointless, as many false alerts will be given for conflicts with departing traffic overtop the 9000ft at BUNKY.

Both the steeper profile due to the expected higher descent speed and not taking the altitude constraint into account cause the cruise phase to be stretched significantly, adding to the time error.

Distribution Graphs

This section presents a graphical analysis in which error values from three sources are plotted for comparison. The Airservices Australia, EUROCONTROL, and FAA data sources are identified in the following graphs as AUS, EUR, and USA respectively. In the Metrics section three types of errors were defined which are investigated in Figures 4-6. In all cases, error is the difference between a predicted value from a trajectory and the actual path flown.

Figure 4 presents the data for metric (1), relative ETA error at metering fix. Each data point represents an error value from the corresponding source listed on the horizontal axis. The black lines overlaid provide "box plot" information for each group. The center horizontal line through the box indicates the median or 50th percentile value, while the bottom and top of the box indicate the 25th and 75th quartiles, respectively. The "whiskers" at each end extend one and half times the interquartile range, or to the outermost data point if that is closer. The shaded gray areas illustrate four different density levels of data points, representing the density of the data sets. These densities are formed by equal probability contours illustrating four spatial regions with

increasing density proportional to the darkness of the shading. The inner darkest shading represents the densest region and the lightest the broadest and least.

From Figure 4 it is clear that the European data has a larger spread in the distribution of relative ETA error compared to US or Australian data, which are both relatively compact. Possibly, this can be caused by the limited filtering described in European data description section. The spread in aircraft types and the associated intent error in the descent speed profile may also play a role.

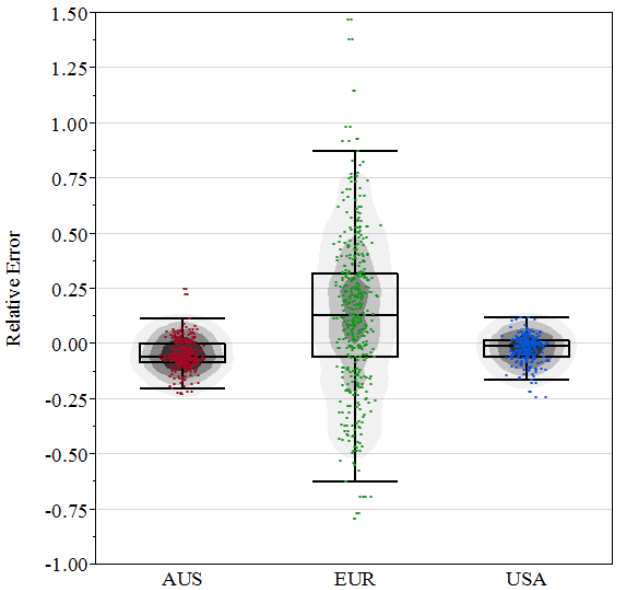

Figure 4: Relative ETA Error at Metering Fix

Figure 5 presents the data for metric (2), altitude error at metering fix. The graphical elements are identical to those in Figure 4. The large negative errors in Figure 5 for the European sample can be explained as follows. In some occasions the reference point at FL200 fell outside the area of interest for the en route center and as such the trajectories had not been updated unless manually forced by the controller. The vertical error in the Australian data is almost completely positive for reasons explained in the Australian data description section.

The height of the inner of the box plot forms a robust measure of the spread of the data and is called the interquartile range[3]. The interquartile range for the European data is 6832 ft which is more than double that of the US data (3083 ft). The interquartile range for the Australian data is 1921 ft.

Figure 6 presents the data for metric (3), position error at TOD. It illustrates that the US data for position error at TOD is more evenly distributed than data from the other sources and also more negative (aircraft descended later than predicted). European data has the tightest distribution for this metric, with an interquartile range less than half that of the US. Again a remarkable result for the European data when compared to the vertical and temporal error; as TOD is relatively accurate, one would not expect such a large distribution in the temporal and vertical error.

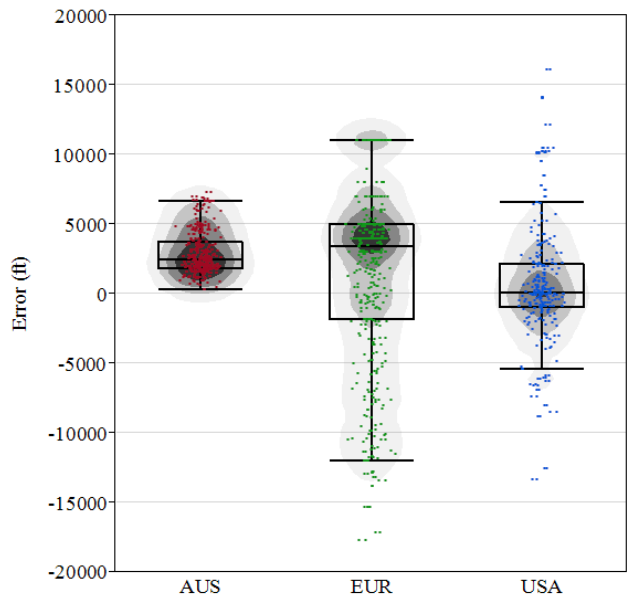

Figure 5: Altitude Error at Metering Fix

[3] The interquartile range is the distance calculated by taking the difference between the 75th to 25th percentiles.

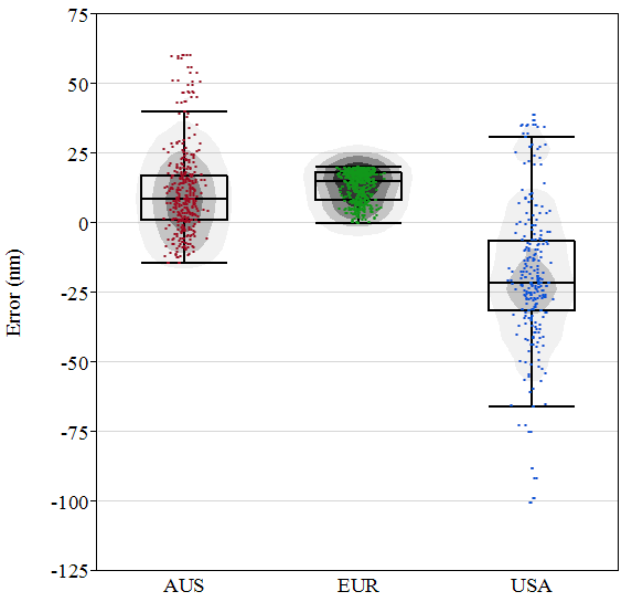

Figure 6: Position Error at TOD

The Australian TOD error is mainly positive which is consistent with the mainly positive vertical error, i.e. predicted geometric path is steeper than actual. The inconsistency observed for the European data might be explained by the fact that it cannot be stated that it is free of ATC intervention with the same confidence as for the US and mainly Australian data.

Although the samples presented are from fundamentally different sources and the filtering process might not have eliminated all invalid flights, they have one thing in common: the prediction errors are large. The results do not aim to show that the performance of one TP is better than another, but to illustrate the problem of inaccurate aircraft intent is common. In the following sections the performance of the ground-based TPs is compared to the performance of a FMS TP which does have accurate knowledge of aircraft intent, and it is assessed if the airborne side can assist.

Airborne Data Description

The sample considered in this analysis consists of Qantas' FANS equipped B738 flights into Melbourne. In fact, the flights in the sample are the same flights from the Australian sample for which there was also a ground-based prediction available. The flights in this sample all flew consistently, that is, the on-board automation controlled the aircraft according to consistent aircraft intent (LNAV/VNAV-PATH). Coupled with the published runway linked STAR at the destination, the trajectory of these aircraft as determined by the FMS can be stable well prior to TOD, due to consistent aircraft intent.

In addition to the surveillance for non-radar airspace and the benefit of Controller Pilot Data Link Communications (CPDLC), FANS provides a way for the ground to access airborne trajectory data through ADS-C. ADS-C should not be confused with ADS-Broadcast (ADS-B) as ADS-C is not a general broadcast function but a unique specific data-link contract between aircraft and ATC [14; 15]. Airservices Australia and research partners set up a duplicate ATC system to facilitate the collection of airborne trajectory data. Pilots of Qantas' FANS enabled B738s routinely log on to this system whenever they operate a leg to Melbourne. Once the logon is successful, the aircraft will report its predicted trajectory at a two-minute interval. This reporting occurs automatically and is transparent to the crew.

The trajectory data available through FANS is from the group called Intermediate Projected Intent (IPI) consisting of a sequence of up to ten Trajectory Change points (TCPs). A TCP can either be a profile change (e.g. Top of Climb (TOC) and TOD), a bearing change and/or a speed change. Note that an Air Traffic System waypoint will only appear in the IPI if a trajectory change occurs at that point. IPI intent is limited to TCPs within a maximum look-ahead time of 4 hours. Therefore the entire trajectory might not be visible to ATC with each report. Laterally, trajectory change points are given as a sequence of bearing and distance from the position at which the FMS generated the ADS-C report. Each trajectory change point also holds an estimate for the crossing altitude and time.

A remark needs to be made regarding the estimate for the crossing altitude at a TCP. The crossing altitude is either a planned or predicted value depending on the current guidance mode. Climb is generally performed at some fixed throttle setting and holding a target speed using elevator. Altitude or altitude-rate is then the free variable and results during the prediction from the evaluation of the equations of motion. Any altitude values given at

TCPs on climb are therefore a prediction, as the aircraft might or might not cross that TCP at that altitude. The altitude at TOC however is a planned altitude- the aircraft will stop climbing at that point. The position of TOC is predicted as it is dependent on the variable altitude-rate. Altitudes at TCPs on cruise are also planned and not predicted. If the aircraft flies a level different from the original flight plan, it represents a change in longitudinal intent and it cannot really be called a prediction error.

The same holds for TOD. The FMS builds the geometric descent path based on the selected target speed, altitude constraints and weather predictions. The resulting TOD is a planned point calculated by the FMS where the aircraft will descend. If while cruising into TOD the aircraft senses winds significantly different to those forecasted, the FMS will change the TOD accordingly, thereby changing its longitudinal intent or plan. However at some time prior to TOD, the FMS will freeze the geometric descent path and is then committed to fly this path irrespective of newly observed winds. The ground-based TP, on the other hand, makes a prediction of the TOD based on a forecast (not necessarily identical to the aircraft), then with an assumed descent speed or performance tables predicts the point where the aircraft will commence descent. Without detailed intent information from the aircraft, the point estimated by the TP will only be at best a guess. This makes the airborne derived TOD a very accurate parameter to be used in the ground-based TPs.

Comparison of Airborne and Ground-Based

This section presents data from both airborne and ground-based TPs by first presenting an illustrative example of a single flight and then through statistical analysis of a large sample of flights.

Flight Example

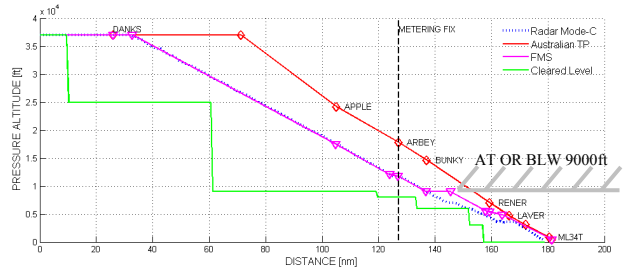

Figure 7: Example flight profile including aircraft derived data

Figure 7 is similar to Figure 3 however now also the Intermediate Projected Intent (magenta) is added that was received at about the same time as when the ground-based prediction was made. Contrasting the IPI to the radar track clearly shows that until BUNKY, the aircraft was operated as per plan; it commenced descent at the planned TOD and adhered to the planned path. The aircraft overflew ARBEY 88ft above target profile, compared to the 6000ft prediction error made by ground-based TP. The airborne ETA was only 7 seconds out or 0.7%, compared to 8.6% for the ground TP.

From Figure 7 it can also be seen that the FMS planned profile accounted for the at-or-below constraint at BUNKY. The FMS planned to level off at BUNKY until it would re-capture the idle thrust descent path. The radar profile shows that the crew deviated from the plan and continued descending to the cleared altitude. This deviation from the plan does not however impact the crossing time and level at the metering fix, as it has already been passed.

Analysis

This section presents graphical and statistical analysis to compare the performance of ground-based predictions and airborne trajectories using metrics (1) and (2). Metric (3), the TOD position error, is not relevant for the airborne data as the TOD is a planned point; provided the FMS is in control of the aircraft and the pilot does not force a ‘descent now’, the aircraft should descend at this point and hence the prediction error is not defined.

As mentioned in Section IX, the data set from Airservices Australia contains ground-based predictions and airborne trajectory data for the same

set of flights. Therefore a paired t-test comparison can be used to establish whether there is any statistical difference between the means of the two sources. The two error metrics being investigated are the relative ETA error and altitude error at metering fix. The magnitude of these errors was statistically compared in these tests by calculating the absolute value of all paired errors. From the paired t-test for relative ETA error, the mean difference from ground-based to airborne data is 0.0519 (approximately 5% difference). This difference is highly statistically significant; the t-ratio is 20.6. Figure 8 compares the error distributions graphically without taking the absolute value. The blue hashed bars illustrate the frequency of relative ETA error values from the ground-based predictions and the red solid bars illustrate the same for the airborne trajectory data.

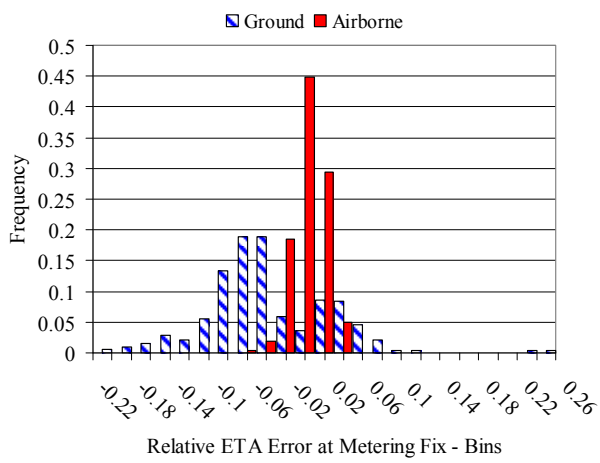

Figure 8: Distribution of Relative ETA Errors

From Figure 8 it is clear that the errors in the ground-based predictions are more widely spread than in the airborne data. Also, the airborne errors are centered near zero while those from the ground-based predictions are quite negatively skewed. This indicates the ground TP was often predicting an earlier arrival to the metering fix than actually occurred. In contrast, the airborne TP with its improved longitudinal intent has very little bias and much smaller variation.

The altitude error at metering fix was investigated as well. Similar to the previous analysis, the absolute values were paired and t-test calculated a mean difference of 2736 ft. This difference is again statistically significant with a t-ratio of 32.6. Figure 9 illustrates the error distributions for altitude error from the ground-based and airborne trajectory data.

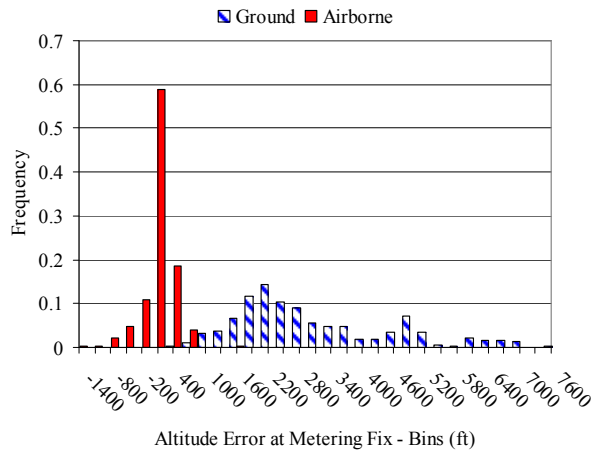

Figure 9: Distribution of Altitude Errors

Once again, the error distribution for ground-based predictions is much more widely spread than its airborne counterpart. The mean of the airborne errors is within 100 feet of the zero altitude, while the ground TP errors are positively skewed with a mean near 3000 feet. Thus, the ground-based TP tends to predict a higher altitude than actually occurs. This is consistent with the ETA error above, translating to a ground-based TP that tends to predict a steeper geometric descent path than actually occurs on average. This steeper path results in a later TOD for the ground and hence longer cruise segment. As cruise speed is held longer, the earlier the ETA becomes at the metering fix. Furthermore, the majority of the sampled flights are operated in a path managed mode, which is assumed the reason for the small bias and variance in the airborne vertical error. Clearly as the TP in the FMS has access to, and it this scenario ownership of unambiguous longitudinal intent, e.g. descent speed schedule, its predictions are several orders of magnitude more accurate than the predictions made for the same flight by the ground-based TP.

Conclusions

This paper evaluated operational ground-based Trajectory Predictors across the globe from the FAA, EUROCONTROL, and Airservices Australia by comparing actual and predicted trajectories in the arrival phase of flight - the indication of large errors are a common problem. A critical parameter missing

to the trajectory prediction process on the ground is the speed schedule the aircraft intends to fly on descent. The TPs use a static nominal descent speed or basic performance tables to calculate the vertical profile which leads to excessive errors. Vertical errors of several thousand feet and temporal errors of a few minutes are not uncommon, making estimates for TOD position and metering fix crossing unreliable.

This paper showed that a significant improvement is possible when trajectory data calculated by the FMS can be used. It was found that when the onboard automation is operating the aircraft, the flight will be executed as per the FMS plan making the FMS derived trajectory data a reliable source of data to enhance ground-based TP accuracy; vertical accuracy is within the order of a few 100ft and temporal accuracy is in the order of tens of seconds.

Recommendations

This paper demonstrated that significant improvements in ground-based trajectory prediction are possible through the use of data-link technologies that are operational today**.** It was shown there is real potential to make use of trajectory data received through Future Air Navigation System (FANS) technology. Although the data has limitations, it is worthwhile to further exploit the possibilities of FANS without specifying new equipment to be fitted to aircraft.

References

[1] Paglione, M., Bayraktutar, I., McDonald, G.N., & Bronsvoort, J. (2009). Lateral Intent Error's Impact on Aircraft Prediction. Proceedings of the Eighth USA/Europe Air Traffic Management Research and Development Seminar (ATM2009), Napa, CA, USA.

[2] Konyak, M.A., Doucett, S., Safa-Bakhsh, R., Gallo, E., & Parks, P.C. (2009). Improving Ground-Based Trajectory Prediction through Communication of Aircraft Intent. Proceedings of the AIAA Guidance, Navigation, and Control Conference, Chicago, IL.

[3] Muresean, S., (2008). Initial 4D - 4D Trajectory Data Link (4DTRAD) Concept of Operations. Brussels: EUROCONTROL.

[4] AP16. (2009). White Paper Common TP Structure and Terminology in support of SESAR & NextGen (White Paper): EUROCONTROL/FAA.

[5] López-Leones, J., Vilaplana, M., Bayraktutar, I., Klooster, J.K., Asensio, J.M., McDonald, G.N, & Kappertz, P. (2009). Towards an open test bed for the study of trajectory synchronization in the future ATM system: The ASIS Initiative. Proceedings of the ICNS 2009 "The Integrated Trajectory" - Getting There, Arlington VA.

[6] Gillet, G., Nuic, A., & Mouillet, V. . (2010). Enhancements in Realism of ATC Simulations by improving Aircraft Behaviour Models Proceedings of the 29th Digital Avionics Systems Conference, Salt Lake City, UT.

[7] Poles, D., Nuic, A., & Mouillet, V. (2010). Advanced Aircraft Performance Modeling for ATM: Analysis of BADA Model Capabilities. Proceedings of the 29th Digital Avionics Systems Conference, Salt Lake City, UT.

[8] Boeing Research & Technology Europe. (2008). Aircraft Intent Description Language (AIDL) Specification v1.3 Revision r1.

[9] Bronsvoort, J., & McDonald, G.N. (2010). TAAATS TP accuracy. Melbourne: Airservices Australia.

[10] Courdacher, T., & Mouillet, V. (2008). ADAPT Aircraft Data Aiming at Predicting the Trajectory: EUROCONTROL.

[11] R. Christien, & Marayat, A. (2009). ADAPT2 Aircraft Data Aiming at Predicting the Trajectory: EUROCONTROL

[12] U.S. National Weather Service. (2008). NWS Instruction 10-806: World Area Forecast System.

[13] Paglione, M.M., & Oaks R.D. (2007). Implementation and Metrics for a Trajectory Prediction Validation Methodology. Proceedings of the AIAA Guidance, Navigation and Control Conference and Exhibit, Hilton Head, SC, USA.

[14] Roberts, C.J. (2009). ATC Data Link News. Retrieved January 10, 2011, from

HTTP://WWW.MEMBERS.OPTUSNET.COM.AU/~CJR/INDEX.HTML.

[15] Galotti, V.P. Jr. (1997). The Future Air Navigation System (FANS). Aldershot, UK: Ashgate Publishing Ltd.

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