Eleventh USA/Europe Air Traffic Management Research and Development Seminar (ATM2015)

Real-Time Trajectory Predictor Calibration through Extended Projected Profile Down-Link

Jesper Bronsvoort, Ph.D.* & Greg McDonald#
*Operational Analysis / #ATM Planning
Airservices Australia
Melbourne, Australia

Mike Paglione & Christina M. Young, Ph.D.
William J. Hughes Technical Center
Federal Aviation Administration
Atlantic City, NJ, United States

Jean Boucquey
Directorate SESAR and Research
EUROCONTROL
Brussels, Belgium

Joachim K. Hochwarth, Ph.D.
Navigation & Guidance
GE Aviation Systems
Grand Rapids, MI, United States

Eduardo Gallo
Flight Efficiency Group
Boeing Research & Technology Europe
Madrid, Spain

Abstract— **This paper investigates the capability of the Extended Projected Profile (EPP) trajectory down-link definition to facilitate air-ground trajectory synchronisation. It will be demonstrated that the EPP allows for practically unambiguous description of aircraft intent, but that unknown aircraft performance characteristics such as climb thrust derate, anti-ice and tail-specific drag adjustments can still lead to significant errors. These errors especially impact the 'what-if' functionality of ground-based trajectory predictors essential to effective trajectory negotiation and management. A method is proposed that uses the EPP down-link trajectory to determine an aircraft performance calibration function accounting for any variables not specifically recorded in the EPP, thereby ensuring high accuracy for 'what-if' trajectories. Where EPP on its own synchronises the *current trajectory*, in combination with the calibration proposed in this paper, it can synchronise the ground *trajectory prediction process* with that of the FMS. EPP therefore enables the ground to properly synchronise with the aircraft and creates value based on airborne and ground-based trajectory prediction capabilities.**

Keywords; TBO; data-link, EPP; 4D-TRAD; trajectory synchronisation; AIDL.

I. INTRODUCTION

Trajectory Based Operations (TBO) is globally regarded as the future of Air Traffic Management (ATM) and is fundamental to increasing the efficiency of air transport operations. In the concept of TBO, the human role moves from that of continuous intervention towards supervision, as decision making is improved based on increased confidence on the optimum solutions provided by advanced automation and decision support tools as part of the trajectory management process. Trajectory management is the process by which the trajectory of an aircraft is planned, agreed, updated and revised. The resulting trajectory is defined as the business trajectory, and is the representation of an airspace user's intention with respect to a given flight, guaranteeing the best outcome for this flight (as seen from the airspace user's perspective), respecting monetary and permanent constraints [1].

The key enhancement for the transition to TBO is the application of the various trajectory prediction systems within the ATM environment and understanding of the key variables affecting those systems. The ICAO Global Air Traffic Management (ATM) Operation Concept (GATMOC) [2] envisions the future ATM system will rely on explicit, unambiguous and shared information regarding to the future trajectory of an aircraft, such that the ground system can accurately predict the trajectory an aircraft intends to fly, and base any negotiation of constraints and other automated decision support on that prediction model. To achieve this goal, the ICAO planning framework includes 4D Trajectory Data-Link (4D-TRAD). 4D-TRAD is based on the principle that the 4D trajectory is down-linked from the aircraft's Flight Management System (FMS), negotiated if necessary, agreed through the up-link of a clearance, and subsequently flown by the aircraft [3]. Therefore the recently released (DO-350/ED-228) standard by RTCA and EUROCAE [4] includes a new trajectory down-link definition called Extended Projected Profile (EPP).

This paper demonstrates how EPP can be used by a ground-based trajectory predictor to achieve air-ground trajectory synchronisation. It will be shown that the EPP has the ability for the ground to synchronise its trajectory with the *current* active trajectory held by the FMS, and how the EPP can act as a means to calibrate the ground trajectory prediction *process* with that of the FMS.

This paper is organised as follows. Section II provides background information on different trajectory down-link standards. In Section III, the trajectory synchronisation problem is discussed, after which in Section IV the ability of EPP to facilitate this synchronisation is demonstrated. Section V will propose a method to use the EPP to calibrate for unknown aircraft performance characteristics. An example based on operational data is presented in Section VI after which the conclusions are presented in Section VII.

II. TRAJECTORY DOWN-LINK STANDARDS

A. *Intermediate Projected Intent*

The first air-ground data-link network implemented was Aircraft Communication And Reporting System (ACARS) which uses a range of systems from very high frequency (VHF) data-link (VDL-A) and high frequency (HF) data-link (HFDL) to satellite communication when beyond VHF/HF range. While originally designed for airline use, ACARS' ready availability made it acceptable as the network for the Future Air Navigation System (FANS) concept. The FANS concept was introduced in the early 1990s to realise improved utilisation of non-radar airspace required by increasing air traffic. Boeing launched its FANS-1 product based on controller pilot data-link communication (CPDLC) and Automatic Dependent Surveillance Contract (ADS-C) for the 747-400 targeted at operations in the South Pacific. Airbus later developed its similar FANS-A product. The two products are collectively known as FANS-1/A. ADS-C is a form of surveillance for an aircraft such that the aircraft will automatically report information obtained from its on-board equipment according to agreed or contracted conditions. A less known aspect of FANS-1/A ADS-C is that in addition to position reporting it also has the ability to provide basic trajectory down-link referred to as intermediate projected intent (IPI). As a clear concept of use for IPI never existed, its content is limited and its format has many limitations.

B. ARINC 702

Since the initial introduction of FANS, Aeronautical Radio Inc. (ARINC) recognised the need for a suitable trajectory down-link standard that overcomes the limitations of IPI. In 2006 ARINC released the ARINC Characteristics 702A as “a best guess at the [future] CNS/ATM related functions to be supported by the advanced FMS” [5]. The 702A Characteristic includes an extensive trajectory down-link definition available through ACARS. Currently, a version of this definition has been implemented on General Electric (GE) Aviation Systems FMS, and then only available to ATC after retransmission of the information from the airline operational centre that receives the downlink from the aircraft via ACARS.

C. Extended Projected Profile

The Aeronautical Telecommunication Network (ATN) was designed to overcome the weaknesses of ACARS in terms of integrity, message addressing and response time and is currently based on digital VHF Data-Link (VDL-2). ATN forms the backbone for ATM modernization in especially Europe with programs such as Link2000+ of EUROCONTROL (CPDLC via ATN; ATN Baseline 1) and equipment mandates. In conjunction with CPDLC over ATN, the RTCA DO-350/EUROCAE ED-228 standard for Baseline 2 ATS Data [4] includes ADS over ATN and specifies the Extended Projected Profile (EPP) trajectory down-link.

In terms of content, the main difference between EPP and 702A is that EPP has been simplified in terms of lateral path description and removal of forecast wind information. Regarding lateral path, EPP does not explicitly support all ARINC 424 legs; legacy path terminators associated with aircraft performance (e.g. heading to altitude) are not supported, as EPP focusses on full transition to Performance Based Navigation (PBN) in the future. In contrast to 702A-3, EPP does however include the aircraft current gross mass, i.e. the mass at time of trajectory down-link.

While the concept of air-ground trajectory synchronisation is very general, the EPP was specified with two near-term applications in mind: air-ground trajectory synchronisation to support medium term conflict detection in enroute airspace (mainly 2D), and 4D-TRAD or initial 4D (i4D) in Europe to support time-based metering into the terminal area.

In high surveillance airspace with high traffic density, aircraft often are tactically re-directed from their originally filed flight plan route. In addition, weather diversions also cause deviations from what was originally filed. For a variety of reasons, traditionally the ground system is poorly or not (manually) updated by the responsible controller after providing such clearances, resulting in discrepancies between the lateral trajectory flown by the aircraft and the trajectory the ground system expects the aircraft to fly. Paglione et al. (2010) [6] showed that lateral errors of 20 to 30 NM are common in the continental US and Europe. The research by Paglione et al. also linked the poor performance of conflict detection tools to the large lateral errors in the ground system. The lateral path as down-linked by the aircraft can therefore update the one held by the ground system leading to improved performance of (medium term) conflict detection tools.

Initial 4D is a concept proposed under SESAR in which the airborne time-of-arrival-control functionality is used to manage time constraints anywhere on the aircraft’s trajectory - climb, cruise and descent - although the current focus is on the specification of a single time constraint on the descent trajectory [3]. Using the EPP down-link, the reference trajectory computed by the FMS for the current cleared flight intent is down linked to the ground system. Using this EPP trajectory as start condition, the ground system will determine a conflict-free route including altitude constraints (if required). A route clearance is issued and uplinked to the FMS. If able, the newly computed trajectory based on the updated flight intent is down linked to the ground system including estimated min/max times at specific points along the agreed route. If unable, it is envisioned that different flight intent will be negotiated though it is not yet part of the current concept of operations. The ground system then determines an appropriate time constraint for one of the waypoints along the agreed trajectory within the provided min/max window and uplinks it to the aircraft. If able, the time-of-arrival-control functionality within the FMS is enabled to meet the time constraint. If unable, another time constraint will be negotiated.

It is evident that accurate air-ground trajectory synchronisation is key to successful implementation of the above applications, as the uncertainty that results from inaccurate air-ground trajectory synchronisation can lead to non-optimal tactical intervention.

III. AIR-GROUND TRAJECTORY SYNCHRONISATION

The most trivial approach to the trajectory synchronisation problem is for the ground to directly use the aircraft down-link trajectory obtained through EPP. However, the direct overwrite of ground computed trajectory with airborne predicted trajectory can lead to instabilities and inconsistencies due to differences in the trajectory computation processes [7]. In addition, the ground system needs to be able to compute ‘what-if’ scenarios to provide conflict and sequencing resolutions [8], i.e. generate trajectories for different objectives than those embodied within the original down-link trajectory. Direct overwrite can lead to inconsistencies between airborne trajectory and these ‘what-if’ trajectories computed on the ground (e.g. due to differences in support models such as meteorological forecast and aircraft performance). Klooster et al. (2010) [9] provide numerous other arguments against direct use of the airborne predicted trajectory by ATC automation systems.

Therefore, the goal of air-ground trajectory synchronisation is to produce trajectories in disparate systems whose discrepancies are operationally insignificant, increasing the likelihood of flying the planned conflict-free and business preferred trajectories [9]. The pre-SESAR ADAPT (1 & 2) studies investigated the use of airborne (recorded) data to improve ground trajectory prediction [7; 10]. These studies concluded "*In particular significant benefits from using FMS 4D trajectory information and aircraft mass have been observed on TP average prediction quality.*" Torres et al. (2011)[8] provided a first demonstration of how EPP can assist to achieve trajectory synchronisation. A FMS simulator was used to generate the EPP data broadly based on the then draft DO-350/ED-228 standard. The study emphasised the actual synchronisation process where the ground system built a trajectory based on a combination of a down-linked flight plan (via CPDLC) and the EPP. The study concluded that final lateral errors are effectively the result of different earth models as turn radius is provided in the EPP (fly-by only). Longitudinally, the EPP was used to derive the average vertical rate between trajectory change points to overwrite the standard values used by the ground-based trajectory predictor (kinematic calibration). The study recognised the limited validity of the average vertical rate and proposed that the EPP would contain sufficient points to control the error between trajectory change points [8].

The approach of Torres et al. allowed the ground system to build a trajectory consistent with the EPP; however this approach is limited by the fact that the EPP trajectory is a prediction for current conditions and constraints only. For example, in the context of 4D-TRAD and initial 4D, if the nominal EPP with estimated min/max time windows is used by the ground system to determine a time constraint, the trajectory resulting from adopting that time constraint will be different from the nominal trajectory (unless the time constraint is equal to the nominal time). That is because the FMS will change the speed targets to meet the time constraint, which on climb and descent will mean a change in vertical profile (see Figure 1). If it needs to be guaranteed that the trajectory resultant from a time constraint is free from conflicts with other aircraft, the ground system will need to be able to predict accurate 'what-if' trajectories. The approach of Torres et al. will no longer be valid and degradation in the synchronisation will occur.

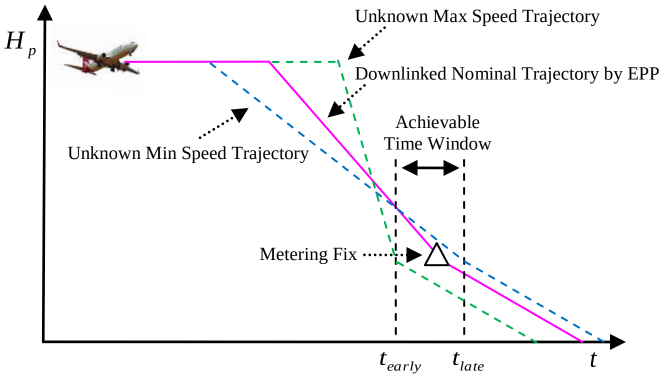

Figure 1. Changing vertical profiles with time at waypoint on descent.

Bronsvoort et al. (2014) [11] proposed that the down-link trajectory data in the form of EPP is used to re-construct the basic commands, guidance modes and control strategies available to the FMS to plan and execute the trajectory to be followed. These basic commands, guidance modes and control strategies are collectively referred to as aircraft intent. To model aircraft intent, the Aircraft Intent Description Language (AIDL)[12] was used, which is a formal language developed by Boeing Research & Technology Europe to express aircraft intent in a rigorous and standardised manner. By re-constructing the aircraft's trajectory in terms of intent, a ground-based trajectory predictor is capable of computing a trajectory consistent with its own support models, and by changing specific parts of the intent, capable of performing 'what-if' scenarios consistent with the original trajectory. In addition, re-computing the trajectory on the ground provides trajectory information between the EPP Trajectory Change Points (TCPs) rather than performing a basic interpolation. A brief overview of the intent generation process is provided in Appendix A of this paper. The approach was applied to a simulated example flight to demonstrate how EPP facilitates the nearly unambiguous synchronisation of trajectory data between a ground-based system and the FMS: the EPP unambiguously defined speed intent data (including speed changes), and allowed for accurate reconstruction of the lateral path, except for fly-over waypoints as the current EPP standard does not include turn radii for these manoeuvres [11].

The accuracy of the above intent based approach is related to the accuracy of the support models used by the ground based system, i.e. weather forecast and aircraft performance models. The weather forecast on the ground is likely of higher detail than that of the FMS which can lead to synchronisation issues. While the ARINC 702A-3 standard includes forecast winds at the trajectory change points, the proposal to include it in the EPP was rejected to reduce complexity and limit bandwidth requirements. Bronsvoort (2014) [13] showed that impact of different weather forecasts in the FMS and on the ground is mostly with respect to the temporal component of the trajectory rather than the vertical profile (provided the FMS holds a sufficient up to date forecast). With respect to the aircraft performance model, the EUROCONTROL Base of Aircraft DAta (BADA) 4 family [14] not only improves the accuracy over the existing BADA3 model, but it also greatly expands its applicability as BADA4 covers the complete aircraft operational envelope [15; 16]. An additional benefit of BADA4 is that it contains separate models for different airframe-engine combinations. While different airframe-engine combinations are not supported by the current ICAO flightplan and aircraft identifiers, this tail number-specific information can be stored in a database accessible by the ground system.

Much research around the world has focussed on the benefit of aircraft mass knowledge to ground-based trajectory predictors [7; 10; 17-19], especially related to climb trajectories, arguing this information must be disclosed for the ground system to improve its performance. Aircraft gross mass, like the cost index, is often regarded by airlines as information that may reveal competitive aspects of their operations, and hence traditionally there has been reluctance to include it in the down-link. Because of its importance, the *current* aircraft gross mass has been included in the current EPP standard.

With aircraft intent generated from EPP, accurate aircraft performance models provided by BADA4, and the inclusion of the aircraft mass in the EPP, the air-ground trajectory synchronisation would appear to be solved. The next section of this paper will demonstrate this is however not the case.

IV. SIMULATION EXAMPLE

In this section, the intent generation procedure of Appendix A will be applied to a simulated flight with EPP down-links. Focus will be on the synchronisation of the climb and descent profile, to indicate that even with EPP, BADA4, and knowledge of aircraft mass, large errors in the trajectory synchronisation can still remain. The lateral dimension was extensively studied in [11], and concluded that the only major source of ambiguity remaining after synchronisation with use of EEP is related to fly-over waypoints as mentioned earlier.

A. *Scenario Description - Air*

This simulation and study was conducted with a real world operational scenario for realism however in nil wind and ISA temperature conditions for practicality. Environmental conditions were excluded as the intent of the work is to demonstrate trajectory synchronisation between the aircraft and the ground using EPP without added complexity of weather.

A standard Instrument Flight Rules (IFR) flight plan was generated for a flight departing Brisbane, Australia (YBBN) for Melbourne, Australia (YMML). The flight plan was amended with appropriate Standard Instrument Departure (SID) and Standard Terminal Arrival Route (STAR) procedures. GE used an FMS simulator to create sample EPP reports for this simulation flight in Extensible Mark-up Language (XML) format matching the terminology of the DO-350/ED-228 Annex B (PROVISION OF EXTENDED PROJECTED PROFILE DATA) Operational Requirements (ORs)[4]. The FMS simulator uses the actual FMS implementation but exposes internal FMS data that is needed to generate the EPP (which is not yet deployed in any FMS used in revenue flight). The FMS simulator used for this analysis was that of a Boeing 737-500 (B735) configured with CFM56-3B-1 18.5K engines, winglets, and a Zero Fuel Weight (ZFW) of 100klbs. A Cost Index (CI) of 60 was set for the FMS to apply an economy speed for all flight phases. The FMS was also configured to perform a geometric descent on approach only (which is a commonly chosen option by airlines), thus computing an idle descent prior to final approach.

B. *Scenario Description - Ground*

The simulated EPP down-link reports were used to generate aircraft intent in the AIDL format as described in Appendix A. This aircraft intent was subsequently fed to the Dalí trajectory modeller developed by Airservices Australia. For this study Dalí used BADA4 as aircraft performance model [14]. An overview of the process is given in Figure 2.

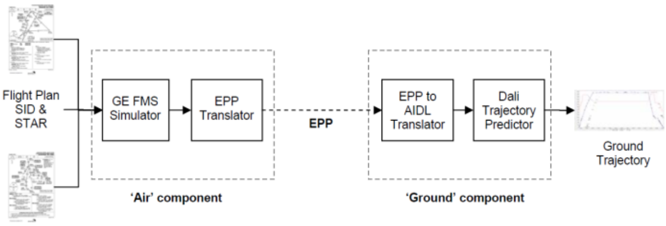

Figure 2. Simulation process overview.

C. *Results*

Figure 3 shows the climb trajectory (blue) as computed by the Dalí trajectory predictor based on the EPP data. The longitudinal aircraft intent has been added as a reference. As explained in Appendix A, Dalí takes the speed targets from the EPP (red line) and assumes the BADA4 maximum climb (MCMB) thrust regime when computing the trajectory. The solid grey line indicates the original EPP trajectory. Note that the EPP trajectory consists of straight lines connecting the different TCPs and hence deviations occur from the continuous trajectory computed by Dalí. This was indicated previously as one of the benefits of re-computing the trajectory on the ground based on the EPP information. In general, the Dalí trajectory matches the EPP data well due to synchronised speed intent and aircraft mass as provided by the EPP. Some larger deviations occur at higher altitude in the constant Mach part of the climb. As the simulation was performed in ISA conditions, deviations at the EPP TCPs are due to differences in the aircraft performance models and integration schemes/logic.

The simulation was run a second time with the highest derate setting for this engine selected in the FMS. Take-off and climb thrust derate settings are often applied by airlines in situation that do not require maximum thrust (e.g. sufficient runway length and mass well below maximum take-off). While derated climb thrust results in higher fuel burn for a given sector, it pays off against the reduction in engine wear and therefore maintenance [20; 21]. The dotted grey line in Figure 3 indicates the EPP trajectory with derate climb thrust. Dalí relies on the thrust models as provided by BADA4, and as only the full rated climb thrust model is provided, a significant error in the predicted vertical profile results even though speed intent and aircraft mass are synchronised.

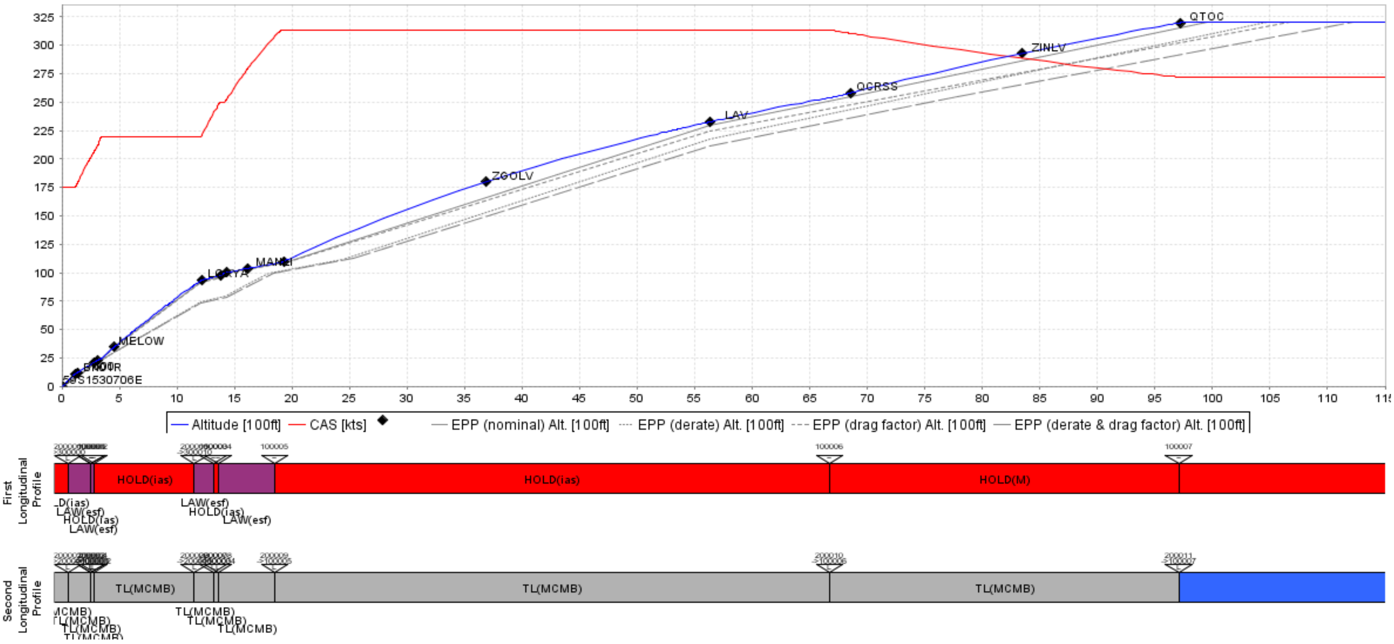

Figure 3. Climb trajectories. Aircraft intent represented in AIDL below graph. EPP trajectories for nominal (grey), derate (grey dotted), drag factor (grey small dashed), and derate and drag factor (grey large dashed). Ground trajectory is insensitive to these changes as aircraft intent generated from EPP remains equal.

A third simulation was run with a 5% drag factor configured in the FMS. The drag factor can be used by operators to calibrate an airframe-specific additional profile drag due to repairs, antennas (e.g. wireless internet for passengers), etc. The dashed grey line in Figure 3 indicates the EPP trajectory with the 5% drag factor applied. The high altitude part of the climb is significantly impacted when compared to the nominal EPP trajectory. The ground-based trajectory predictor relies on the BADA drag polar and it is not aware of this additional drag. It is not unrealistic to assume that certain flights would use both a climb thrust derate and drag factor, vertical profile errors then become even larger as shown in Figure 3 (line with large dashes). The error in Top Of Climb (TOC) position is about 15NM and the maximum vertical error about 2500ft, that with synchronised intent and mass!

Figure 4 shows the descent trajectories for the simulated flight. This particular STAR contained an altitude constraint that impacted the profile and resulted in a level segment. This level segment is contained in the EPP and subsequently appropriate aircraft intent was generated. The Dalí trajectory again matches very well the nominal EPP (solid grey) trajectory facilitated through the EPP by synchronised speed intent, aircraft mass, and constraints. Note that the mass at Top Of Descent (TOD) is not part of the EPP, but can be requested from the aircraft through a ADS-C Speed Report using the same message set as with which EPP can be requested.

The simulation was run a second time for the descent, now with the anticipation of anti-ice selected between FL280 and 10,000ft in the FMS. As bleed air from the engines is used for anti-ice, the engines run at a higher than idle rating whenever anti-ice is turned on. In case of the GE FMS, pilots can specify the anticipated use of anti-ice between altitude bands, such that the FMS can adjust the vertical profile to be slightly shallower between those altitude bands as to prevent acceleration due to higher than idle thrust. The dotted grey line in Figure 4 shows the corresponding EPP trajectory. Again, the ground trajectory predictor relies on the Low Idle (LIDL) model provided by BADA and is not aware of anti-ice selection (see Appendix A). This results in an error in the predicted trajectory, though for this particular example not as significant as in the case of climb derate. Mondoloni (2013) [22] and Ferrante et al. (2012) [23] argued as well that significant errors in predicted TOD can result if the effect of anti-ice is ignored. These studies found an even larger shift in TOD as the 737 New Generation (NG) was used while the study of this paper used the 737 Classic due to licence restrictions. Some aircraft/FMS have the option for a ‘high-idle’ setting. When enabled, the descent profile is constructed for a higher than idle thrust allowing the pilots to tactically select anti-ice without the need for pre-entering the correct altitude bands in the FMS. This is another example of a performance characteristic unknown to the ground, but that impacts the aircraft’s planned trajectory.

D. Discussion

As demonstrated by the simulation examples, and in Reference [11], EPP provides the ability to synchronise lateral, speed and altitude intent, however ‘thrust intent’, like climb rating and use of anti-ice, remains uncertain. In addition, the FMS could be configured for additional profile drag which also impacts the accuracy of the ground system which relies on a nominal drag model. While BADA4 allows for significant accuracy gains, this would only apply to new aircraft with no drag calibration, and no use of derate and anti-ice. Even if BADA4 possessed derated climb models, how would the ground system know that derate was activated and at what setting? While information such as airframe-engine combination can be stored in a static database ensuring the ground system selects the right aircraft performance model, elements as derate, anti-ice, and to some lesser extent drag factor, are of a dynamic nature and can change flight to flight. Including this information in the EPP downlink would significantly increase its complexity and impact on data-link bandwidth requirements. In addition, some of this information can be considered proprietary by the aircraft and/or FMS manufacturer. The kinematic synchronisation method of Torres et al. [8] provides a solution, but only results in synchronisation with the current active trajectory in the FMS, but does not synchronise the trajectory prediction process as required for successful trajectory negotiation. As the EPP allows for practically unambiguous description of the aircraft intent, the next section will propose how it can be used to perform a *kinetic* calibration to account for unknown elements of the aircraft performance model, thereby aiming to synchronise the *process* rather than a single *trajectory*.

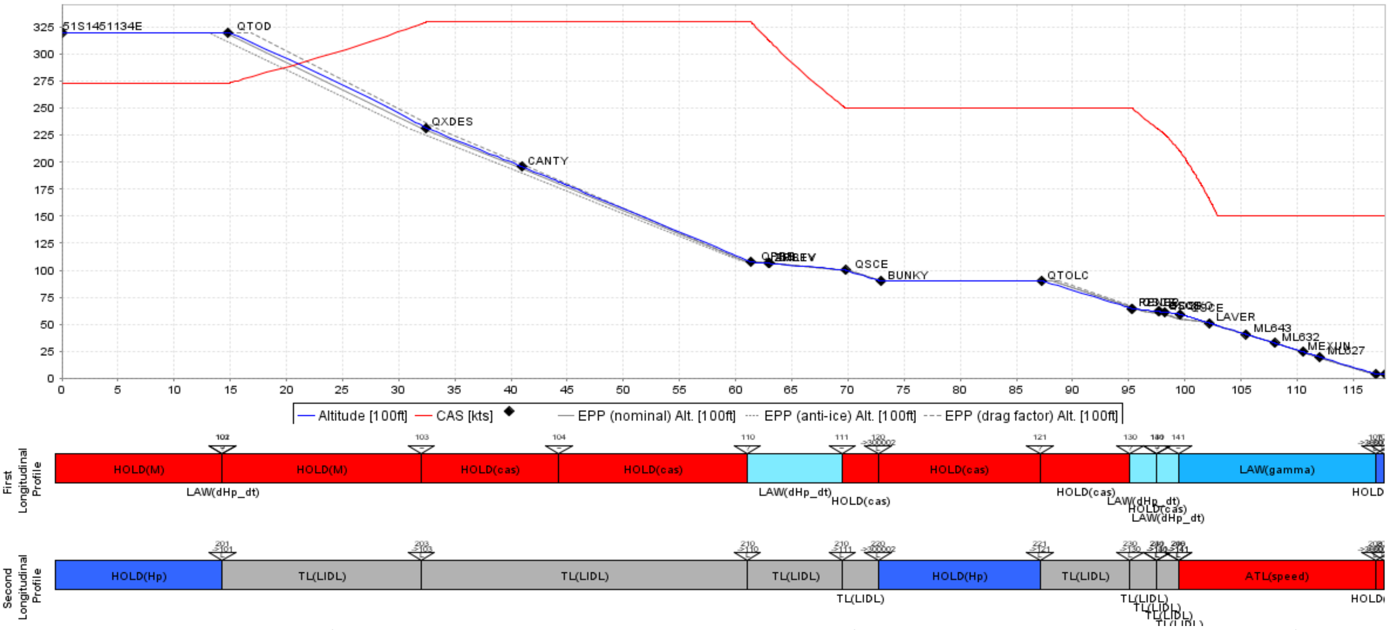

Figure 4. Descent trajectories. Aircraft intent represented in AIDL below graph. EPP trajectories for nominal (grey), anti-ice (grey dotted) and drag factor (grey small dashed). Like for climb, ground trajectory is insensitive to these changes as aircraft intent generated from EPP remains equal.

V. CALIBRATION THROUGH DATA-LINK

A. *Theory*

Prior to the EPP standard, aircraft mass has been unavailable to ground-based trajectory predictors, and several attempts have been made to infer the aircraft mass from operational data, and thereby performing indirect calibration. Thippavong et al. (2013) [18] used preceding radar track data to estimate the aircraft mass from the observed energy rate. This estimated mass was subsequently used in a kinetic three-degree-of-freedom model to predict the remainder of the climb trajectory. A similar study was performed by Alligier et al. (2013) [19]. The approach of Thippavong et al. and Alligier et al. are both related to real-time adaptive trajectory prediction and can only be applied if the aircraft is performing an unimpeded steady climb as sufficient preceding track data needs to be available. Bronsvoort (2014) [13] proposed a method to calibrate a ground-based trajectory predictor through a 'pseudo mass' inferred from FANS IPI trajectory data. As IPI data provides information on the aircraft's future trajectory rather than solely state information, the method can be performed prior to the aircraft commencing climb or descent. The algorithm of is based on an optimisation scheme that employs a trajectory predictor to find the mass and target descent speed schedule that result in a computed trajectory with minimum deviation from the FANS-1/A IPI trajectory. Note that in case of IPI, speed targets are unknown and hence also need to be inferred. In essence, the algorithm uses the longitudinal equations of motion to match the vertical profile of a trial-trajectory (trajectory for a certain descent CAS and mass) with the down-linked intermediate projected intent.

Fundamentally, the methods discussed above used the longitudinal equation of motion that relates the rate of change of the airspeed $\dot{V}_{TAS}$ to the difference between thrust T and drag D and the component of the gravity g along the direction of the airspeed as specified by the path angle γ_{TAS}. The rate of change of the airspeed and the path angle are either observed or derived (OBS), and the thrust, drag are obtained from an aircraft performance model (APM),

$$\left[\dot{V}_{TAS} + g\,\sin\gamma_{TAS}\right]_{OBS} = \frac{\left[T - D\right]_{APM}}{m_{INF}}. \tag{1}$$

The inferred mass m_{INF} is effectively a combination of the true unknown mass and a calibration due to differences between the aircraft performance models [13]. Using the EPP as the 'observation' data and noting that the EPP includes the FMS estimated mass of the aircraft, (1) can be amended to

$$\left[\dot{V}_{TAS} + g\,\sin\gamma_{TAS}\right]_{EPP} = c\,\frac{\left[T - D\right]_{APM}}{m_{EPP}}. \tag{2}$$

where c is the aircraft performance model calibration factor. The algorithm of Reference [13] was expanded upon to find the calibration factor c such that the ground-computed trajectory, based on aircraft intent generated from the EPP in combination with the BADA aircraft performance model and EPP mass, leads to minimal deviation from the original EPP trajectory. Individual calibration factors should be derived for climb and descent as the impact of the unknown aircraft performance characteristics is inherently different, e.g. climb thrust derate versus anti-ice. In addition, a single calibration factor for the entire climb or descent will likely not suffice either; anti-ice might only affect certain altitude bands and the effect of the climb derated thrust did not appear constant with altitude either (see Figure 3). The algorithm was therefore designed to determine calibration factors for each of the EPP segments, thereby establishing a calibration function with altitude.

B. *Results*

Table I shows the calibration factor for the different EPP segments as determined by the algorithm for the nominal EPP trajectory, the EPP trajectory with climb thrust derate and the EPP trajectory with both derate and a 5% drag factor. Note that the altitude bands where each calibration factor applies can differ between the EPPs. This is due to varying aircraft performance that causes trajectory-defining points like speed constraints to impact the trajectory differently. The segments at low altitude related to take-off have been omitted from calibration due to aircraft configuration complexity (c=1). The resulting ground-based trajectories are presented in Figures 5 to 7 for the nominal, derate and derate & drag factor cases respectively. In all cases, the calibration resulted in accurate climb profiles reproduced by the ground-based trajectory predictor. Even in the nominal case, the calibration resulted in a reduction of the error at high altitude pointed out before.

TABLE I. CALIBRATION WITH ALTITUDE.

Nominal EPP Trajectory			**EPP Trajectory with Derate**			**EPP Trajectory with Derate & Drag Factor**		
Altitude Band [ft]		***c***	**Altitude Band [ft]**		***c***	**Altitude Band [ft]**		***c***
0	2127	1	0	2113	1	0	2116	1
2127	3466	1.00	2113	3044	0.72	2116	3017	0.74
3466	9292	0.97	3044	7480	0.72	3017	7327	0.70
9292	9661	1.03	7480	7958	0.78	7327	7827	0.77
9661	10000	1.04	7958	8991	0.82	7827	8781	0.76
10000	10355	1.00	8991	10000	0.83	8781	10000	0.82
10355	10896	1.01	10000	11156	0.84	10000	11228	0.82
10896	23013	0.99	11156	21768	0.96	11228	21174	0.91
23013	25452	0.98	21768	25452	0.97	21174	25452	0.90
25452	32000	0.99	25452	32000	0.99	25452	32000	0.88

The results of Table I demonstrate that a single calibration factor over the entire climb profile will indeed not suffice. In the case of the derated climb thrust, the calibration only appears to affect the climb profile at lower altitudes. This is consistent with information sourced from public papers of GE and Rolls Royce [20; 21]. According to these papers there are typically two basic climb derate selections: CLB1 and CLB2 corresponding to two fixed derates, respectively 3% reduction in N1 (~10% thrust reduction) and 6% reduction in N1 (~20% thrust reduction). The nominal thrust reduction is effective up to a certain altitude (e.g. 10,000ft), after which it washes out to full climb thrust at a particular altitude.

C. *Application*

Suppose that the aircraft of the simulation is climbing at cost index 60 and derated thrust (like in the simulation before) to a level above a crossing aircraft. To ensure separation, but aiming to facilitate a continuous climb, suppose that a controller considers a 280KCAS climb speed restriction and he/she is interested what will be the resulting vertical profile prior to issuing the constraint. To perform the 'what-if' computation, the aircraft intent generated from the original EPP (based on current clearances and cost index 60) can be amended by simply changing the climb speed target. If subsequently this amended aircraft intent is integrated without any calibration, the 'what-if' trajectory of Figure 8 will result. For comparison the EPP has been added when the FMS simulator is configured for a 280KCAS climb (manual overwrite of cost index climb speed), though this EPP has not been used to generate the 'what-if' trajectory. As can be seen, a too optimistic climb profile results as the derated climb thrust has not been accounted for. However, if the original EPP is

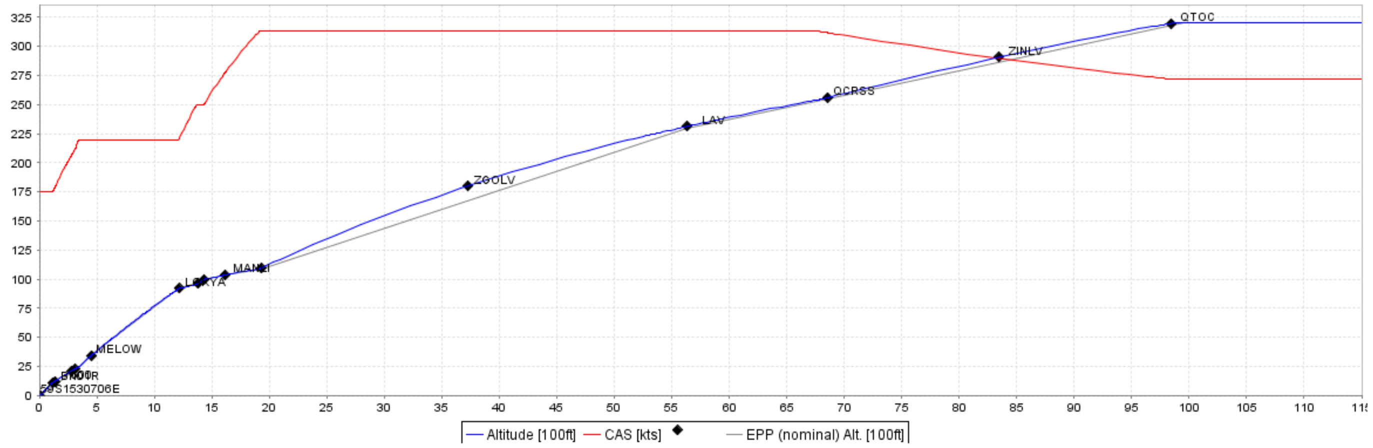

Figure 5. Calibrated nominal climb trajectory.

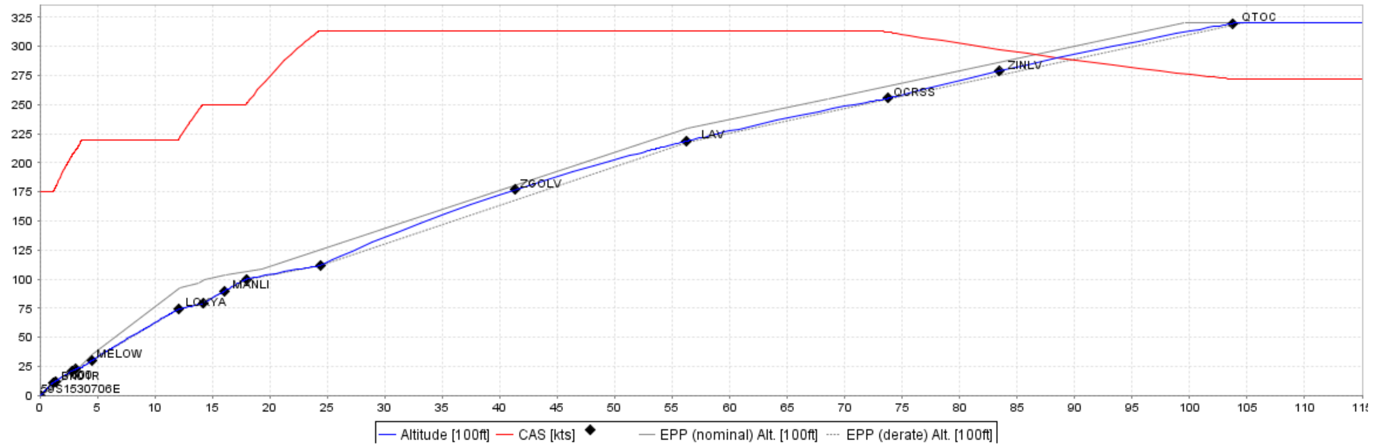

Figure 6. Calibrated derated climb thrust trajectory.

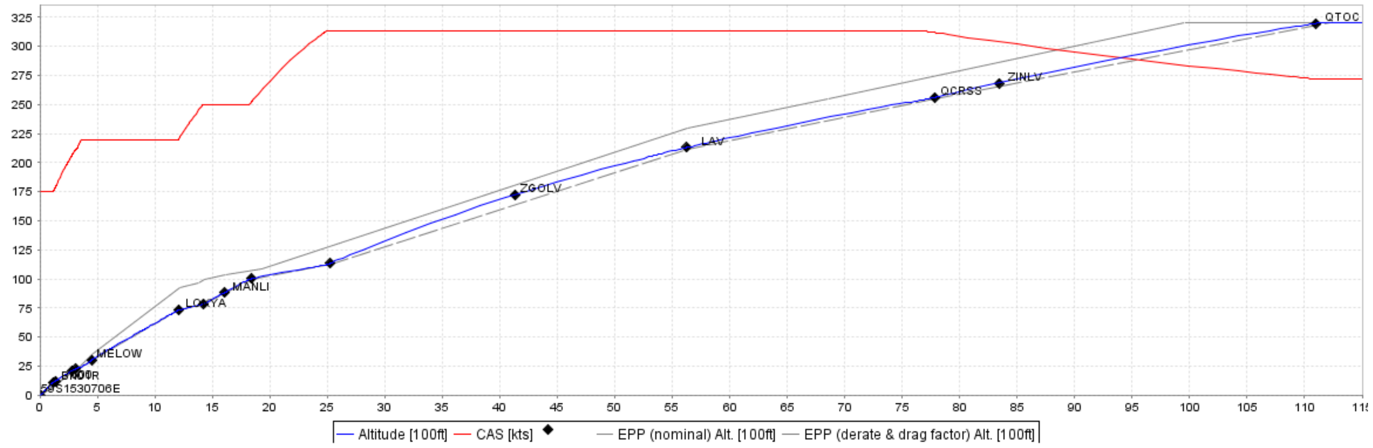

Figure 7. Calibrated derated climb thrust and drag factor trajectory.

used to derive a calibration function, the trajectory of Figure 9 will result. This latter 'what-if' computation matches very well the yet unknown EPP response of the FMS when adopting the constraint. Therefore based on the original EPP report, the ground-system would be capable of synchronising not only the trajectory, but the trajectory computation *process* by correcting for any unknown aircraft performance characteristics like climb thrust derate. This subsequently enables a ground-based trajectory predictor to perform high accuracy 'what-if' computations essential for successful trajectory negotiation.

VI. OPERATIONAL DATA EXAMPLE

The concept of real-time aircraft performance calibration based on trajectory down-link information is further illustrated with operational data. As part of previous research work by these authors [24], FANS IPI trajectory data was collected from in-service Qantas Airbus A380 (A388) aircraft to Los Angeles (LAX). Through an agreement with Qantas, all A388 flights arriving to LAX during April, May, and June 2012 participated in the data collection trial. A temporary pilot instruction was released by Qantas for their crews to log on to the data collection system via FANS/ADS-C manually 2 hours prior to their arrival at LAX. No special treatment from ATC was provided to the participating flights. In total 119 flights participated in the trial. While the IPI data is not as extensive as EPP, in this particular scenario the IPI limitations posed no significant problem to reconstruct the trajectory on the ground. As no aircraft mass is available in the IPI, the calibration focused on inferring the mass which is a combination of the unknown true mass and aircraft performance calibration.

For 27 of the 119 flights, Qantas provided detailed aircraft state data from the aircraft's Quick Access Recorder (QAR).

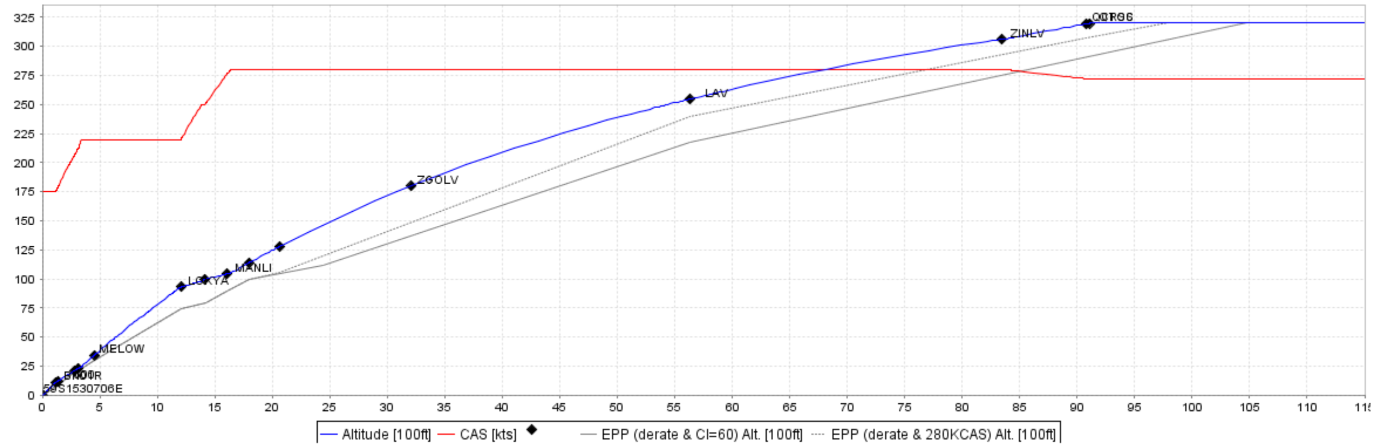

Figure 8. Non-calibrated ‘what-if’ trajectory for 280KCAS climb speed.

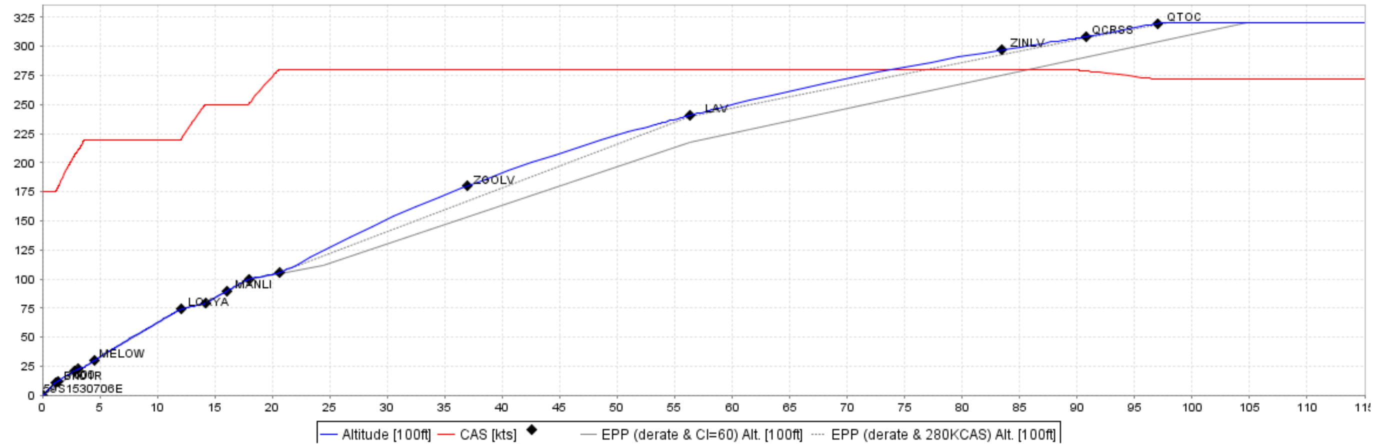

Figure 9. Calibrated ‘what-if’ trajectory for 280KCAS climb speed.

Of these flights, the actual mass at TOD had a mean value of 368100kg with a 5300kg standard deviation. Using the algorithm of Reference [13], the mass of the aircraft was inferred from the IPI data. Using BADA4 (Trent 900 engines), the inferred mass was on average 59000kg too heavy and a standard deviation of nearly seven times the true value. Clearly the inferred mass is not representative of the true operations. To investigate further, trajectories were predicted with both the true mass and the inferred mass. The distributions for the TOD error with respect to the IPI trajectory for the different masses are presented in Table II. Use of the inferred mass in the predictions resulted in no statistically significant bias in the TOD error despite the large bias in the inferred mass. However when using the actual mass from the QAR, a significant bias results with the minus sign indicating the descent path of the prediction with the actual mass is steeper than indicated by the intermediate projected intent downlink. In addition when referring to the standard deviation in the TOD error, the use of the actual mass results in a larger spread of the error than when using the inferred mass even though the variance in the inferred mass is several times larger than the variance in the true mass. This difference is not statistically significant at a 95% confidence level due to the relatively small sample, however as the shift in bias is statistically significant, it indicates that the inferred mass appears to correct for an unknown in the ground-based trajectory prediction process.

TABLE II. TOD POSITION ERROR.

		Inferred Mass A388/BADA4	Actual mass A388/BADA4
Sample Size	27		
MEAN		**0.9 NM**	**-3.4 NM**
MEAN 95% lower		*-0.7NM*	*-5.1 NM*
MEAN 95% upper		*2.4 NM*	*-1.6 NM*
STD		**4.0 NM**	**4.6 NM**
STD 95% lower		*3.1 NM*	*3.6 NM*
STD 95% upper		*5.5 NM*	*6.3 NM*

In terms of the A388 sample, the calibration effect seems to be most evident in a bias correction between the aircraft performance model in the FMS and that available to the ground-based trajectory predictor (e.g. BADA4), i.e. a static calibration effect. A first explanation could be that the aircraft in the sample are configured with a higher idle rating than assumed by the BADA4 model. Second, there could be inaccuracies in the BADA4 idle thrust models for the A388. Third, it is not uncommon for the FMS to apply an energy buffer to an idle thrust descent to account for non-forecast tailwind as noticed in previous research by these authors [25]. Fourth and final, a large portion of the flights in the sample could have had the FMS configured for the anticipated use of anti-ice leading to shallower than idle vertical profiles. However, irrespective of the cause and similar to the simulation example presented previously, the problem arises that with synchronised intent (facilitated here through IPI [13]), use of an accurate performance model as BADA4, and knowledge of the aircraft mass, a ground trajectory predictor might not be able to accurately reproduce either the nominal trajectory nor any ‘what-if’ trajectories due to unknown aircraft performance characteristics. Applying real-time calibration based on the down-link trajectory data provides a solution.

Results for the A388 sample were also compared to a test platform of the United States En Route Automation Modernization (ERAM) system [24]. ERAM supports surveillance and flight data processing including prediction of 4-dimensional aircraft trajectories and separation management functions (e.g. conflict probe). The currently deployed ERAM trajectory model utilises aircraft type look-up tables that provide vertical rates and true air speed (TAS) at various altitude and temperature bins. Thus, ERAM uses the same vertical rates and speeds for all flights with the same aircraft type, resulting in large TOD errors. A trajectory model enhancement is under development that has vertical rates computed using aircraft dynamics, atmospheric data, and flight specific aircraft intent data. Furthermore, these enhancements are a required capability to support future TBO concepts envisioned in the FAA's Next Generation Air Transportation system – NextGen. In Europe, the PEGASE (Providing Effective Ground and Air data Sharing via EPP) SESAR demonstration aims at showing the benefits of the use of EPP in ground systems by more than one hundred flights equipped with EPP. The methods presented in this paper are very timely and provide detailed guidance on how to further refine the implementation of trajectory down-links in operational systems in the US, Europe, and anywhere else across the globe.

VII. CONCLUSION

This paper investigated the capability of the Extended Projected Profile (EPP) to facilitate air-ground trajectory synchronisation. Based on an example of a simulated flight with EPP down-links, it was demonstrated that the EPP allows for practically unambiguous description of the aircraft intent, but that unknown aircraft performance characteristics as climb thrust derate, anti-ice and tail-specific drag adjustment still can lead to significant errors, especially impacting 'what-if' functionality essential to successful trajectory negotiation. A method was proposed that uses an EPP down-link trajectory to determine an aircraft performance calibration function accounting for any variables not specifically recorded in the EPP. Therefore with a single EPP down-link, the trajectory prediction process can be synchronised through this calibration function, ensuring high accuracy 'what-if' trajectories and thereby anticipating the FMS behaviour upon changes in aircraft intent. As it is impractical to include all variables that impact the air-ground trajectory synchronisation process into a trajectory down-link definition, real-time calibration like proposed in this paper will be essential for effective trajectory negotiation and management.

APPENDIX A: AIRCRAFT INTENT GENERATION BASED ON EPP

In this appendix, a brief outline will be provided of the aircraft intent generation process based on EPP data. For a detailed explanation, the reader is referred to Reference [11].

Aircraft intent generation is an essential step in the prediction of every trajectory that captures how the aircraft is to be operated for the duration of the flight. The key characteristic of properly defined aircraft intent is that it is unambiguous, and hence the trajectory computation is a deterministic process resulting in a unique trajectory (for given initial conditions, aircraft performances, and weather info). The Aircraft Intent Description Language (AIDL)[12] is a language designed to express aircraft intent in a standardised manner.

TABLE III. LATERAL INTENT GENERATION.

Segment	AIDL	Description
Straight segment	TLP(GEOD)	Defined by two EPP succeeding trajectory change points.
Fly-by	TLP(CIRC)	Turn geometry computed based on turn radius in EPP.
Fly-over	Not supported	Ignored as no turn information is provided. Instantaneous turns.
Radius to Fix (RF)	TLP(CIRC)	Defined by EPP trajectory change point at end of RF leg with radius provided.

The lateral path can be constructed based on AIDL Track Lateral Path (TLP) instructions defined by either geodesic segments (e.g. great circles) or circular arcs depending on the lateral type of the trajectory change points. Fly-by and RF manoeuvres are fully defined by the turn radius provided in the EPP. A summary of the lateral intent is provided in Table III.

Most climbs are managed by the FMS in VNAV SPD (Boeing) or Managed Climb (Airbus) mode employing the power plants maximum climb (MCMB) regime, with potential derate, while adhering to some speed intent, which is in general the CAS/Mach profile employed to build the reference trajectory. Therefore, there is no direct control on the resulting geometry (altitude and path angle) of the trajectory. To model this behaviour, AIDL can be generated where the two longitudinal degrees of freedom are closed by speed instructions and power plant regime instructions. Segments of constant target speed are modelled by AIDL hold speed (HS) instructions, and target speed changes (on climb) are modelled by Energy Laws (EL). An energy law dictates how the available power is distributed between climb and acceleration in terms of an Energy Share Factor (ESF). While the energy share factor is not provided in the EPP it can be readily determined from the start and end of the acceleration segment.

In cruise the guidance targets are airspeed and altitude and well defined in the EPP.

Compared to climb and cruise, the modelling of the descent contains some complexities as the intent to describe the computation of the descent profile is often different to the intent to describe the execution [26; 27]. For most jet aircraft, the descent profile is computed based on idle thrust and speed intent derived from the cost index. To execute the descent multiple options are available. During a VNAV PATH descent (Boeing) or Managed Descent (Airbus), the aircraft will follow the reference trajectory path angle while allowing deviations in the speed profile up to a certain limit. During a VNAV SPD (Boeing) descent or Open Descent (Airbus), the speed target is adhered to, and the altitude acts as a benchmark. Therefore, the 'execution intent' can differ from the 'computation intent'. As the objective of this study is to synchronise a ground trajectory with the reference trajectory within the FMS, aim is to synchronise the computation intent. For more detail on 'execution intent' the reader is referred [26; 28]. To model the descent in AIDL, the speed intent from the EPP is applied in combination with the Low Idle (LIDL) regime (prior to final approach). Deceleration segments are modelled at constant Rate Of Descent (ROD) using AIDL Hold Vertical Speed

TABLE IV. LONGITUDINAL INTENT GENERATION.

Segment	AIDL	Description
Constant Speed on Climb	HS(CAS/M) TL(MCMB)	Speed targets provided in EPP. MCMB regime assumed.
Acceleration on Climb	EL(ESF) TL(MCMB)	ESF can be determined from acceleration defined by speed change start and end in EPP.
Cruise	HS(M) HA(PRE)	Altitude and speed provided by EPP trajectory change points. TOC and TOD trajectory change points identified for transition.
Idle at constant speed	HS(CAS/M) TL(LIDL)	Speed targets provided by EPP. LIDL regime assumed.
Deceleration on Descent	SL(CAS/M) HVS(ROD)	ROD can be determined from deceleration defined by speed change start and end in EPP.

(HVS) instructions. The rate of descent of the deceleration segment can be computed from the start and end of the deceleration segment. An overview of the longitudinal intent is provided in Table IV.

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AUTHOR BIOGRAPHIES

Jesper Bronsvoort is a Technical Research Specialist at Airservices Australia, Melbourne. He holds a B.Sc. (2006) and M.Sc. degree (2011) in Aerospace Engineering from Delft University of Technology, and a Ph.D. degree (2014) in Telecommunications Engineering from Universidad Politécnica de Madrid. Dr. Bronsvoort has performed extensive research into the use of aircraft derived data to improve ground-based trajectory prediction.

Greg McDonald is an Air Traffic Controller with in excess of 30 years experience in all facets of the craft. Since 1998 has been involved in the Australian ATM Strategic Plan and implementing efficiencies for airlines including AUSOTS flex tracks. His now works on several initiatives to efficiently manage the increasing air traffic in Australia.

Mike Paglione is the Branch Manager of the FAA's Concept Analysis Branch at the FAA W. J. Hughes Technical Center, Atlantic City, New Jersey. The Concept Analysis Branch (ANG-C41) conducts research to validate new aviation concepts' technologies, investigate system capacity issues, and evaluate the performance of both emerging and existing systems within the National Aviation System (NAS). Mr. Paglione holds B.S. and M.S. degrees in Industrial and Systems Engineering from Rutgers University.

Joachim K. Hochwarth graduated from the University of Stuttgart with a Diplom-Ingenieur in Aerospace Engineering and received his Ph.D. in Aerospace Engineering from the University of Minnesota. He worked at NASA Langley on the Autonomous Operations Planner (AOP) before joining Smiths Aerospace (now GE Aviation Systems) in 2003. Dr. Hochwarth is a Principal Engineer working on the system architecture for Flight Management Systems (FMS) and has been involved in many R&D projects related to ATM.

Jean Boucquey holds B.S. and M.S. degrees in Computer Science from Université Libre de Bruxelles, and a M.S. degree in Business Administration from Solvay Business School, Brussels. He currently works in EUROCONTROL's Directorate SESAR and Research and contributes to several SESAR projects in the fields of Trajectory Management, Trajectory Prediction and Complexity Assessment and Resolution. He also coordinates EUROCONTROL effort in the PEGASE SESAR Demonstration.

Christina M. Young received the B.S. degree in Industrial Engineering from Rutgers, The State University of New Jersey. She worked on FAA research projects under a fellowship grant while earning graduate degrees: M.S. in Statistics and Ph.D. in Industrial and Systems Engineering. Dr. Young now works on NextGen projects at the FAA William J. Hughes Technical Center.

Eduardo Gallo holds a Master's Degree in Aeronautical Engineering by the Polytechnic University of Madrid, Spain. His main achievements have been the development of the BADA4 aircraft performance model for EUROCONTROL, the creation of the Aircraft Intent Description Language (AIDL), and the implementation of an advanced trajectory computation infrastructure for ATM use. He currently works for Boeing Research & Technology Europe in Madrid, Spain.