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Design Considerations of Vertically-Constrained PBN Procedures for Trajectory Management

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***Abstract*—This paper investigates the interdependencies between the design of PBN procedures, FMS operating logic, and the concept of 4D-TRAD. Constraints that are added to PBN procedures impact on the delay absorption potential of airborne time-of-arrival-control capabilities in a concept like 4D-TRAD. Speed constraints are detrimental to the delay absorption potential, but the appropriate use of altitude constraints can actually lead to increased delay absorption potential. Forcing the aircraft down earlier than optimal top of descent increases the flight time window at the expense of additional fuel burnt. A concept is proposed whereby an altitude requirement can be dynamically set by ATC to increase the delay absorption potential, when required, while providing a closed-loop clearance that can be entered in the FMS. Typical delay absorption potential by airborne time-of-arrival-control capabilities is compared to actual flight data. It is concluded that typical delay is generally in excess of what can be absorbed. Therefore, even if allowances are made into the design of PBN procedures, like discussed in this paper, there will be a strong reliance on improved air traffic flow management procedures, to enable full 4D trajectory management, runway to runway.**

Keywords-component; OPD; PBN; 4D-TRAD

I. Introduction

The concept of 4 Dimensional Trajectory Downlink (4D-TRAD) [1] relies on negotiation between the ground and air of an appropriate trajectory free from conflicts with other aircraft. In terms of arrival management, this could entail the negotiation of a time constraint to facilitate metering into the terminal area. The spatial dimensions of the arrival trajectory are generally prescribed through published Performance Based Navigation (PBN) procedures, which ideally prescribe the complete lateral path from the enroute environment to the runway threshold. Such procedures are sometimes referred to as Optimised Profile Descents (OPDs) as they allow an aircraft's Flight Management System (FMS) to optimise the arrival trajectory with the knowledge of all applicable constraints. The ability of an FMS to accept a time constraint and optimise the descent path, is dependent on the flexibility within these OPD procedures to adjust altitude and speed profile. However, to provide predictability of the trajectory to Air Traffic Control (ATC), often many constraints are added, significantly limiting the ability of the FMS to accept a time constraint in a manner consistent with the efficient operation of the aircraft. In such situations, 4DTRAD and OPDs do not work together, and ATC must revert to conventional techniques such as radar vectoring.

This paper will demonstrate that aircraft flying on significantly constrained OPDs have limited ability to negotiate time constraints. This limited flexibility means that upstream sectors would need to pre-sequence the flight with much higher accuracy than occurs today, to prevent delay being inefficiently absorbed at low altitude closer to the destination airport. The paper will make some recommendations on how the concepts of 4DTRAD and OPD can be better integrated.

II. Background

A. Performance Based Navigation

Around the world significant investment is made in planning and implementing PBN procedures, like Standard Terminal Arrival Routes (STARs). PBN STARs, potentially combined with speed and altitude constraints, are sometimes referred to as Optimised Profile Descents (OPDs), as they, in principle, allow the aircraft's automation to optimise the arrival phase of flight (not necessarily fully continuous).

As part of the transition to PBN, Australia has introduced runway-linked STARs at most of its major airports. A runway-linked STAR overcomes a basic problem of Air Traffic Management (ATM) on how to define and publish a structured and separated design of air routes for a terminal area to cater for changing wind defining the duty runway and circuit direction. Published flight tracks remove the lateral variation generated by individuals – ATC or pilot – and demonstrated to deliver consistent and predictable flight paths. In the example in Figure 1, arriving aircraft into Melbourne, Australia through the metering fix ARBEY are assigned standard tracks to any utilised runways, well before descent is commenced. This methodology, assuming conflict free, enables the FMS to optimise and manage the full descent to the threshold. These arrival paths are separated from departure paths using published Standard Instrument Departures (SIDs), and when combined with an appropriate Required Navigation Performance (RNP) value, allow for independent aircraft operation with minimal dynamic ATC intervention. With such a design, the biggest challenge has been to sequence subsequent aircraft onto this structure, and allow these aircraft to continue without any intervention while maintaining separation and adequate airport throughput. Tactically, ATC often cancel the PBN procedure and vector the aircraft for arrival sequencing (Figure 2). Conceptually, an efficient descent is thus only achieved if the OPD planned by the aircraft's automation, is tactically facilitated by ATC and flown by the aircraft.

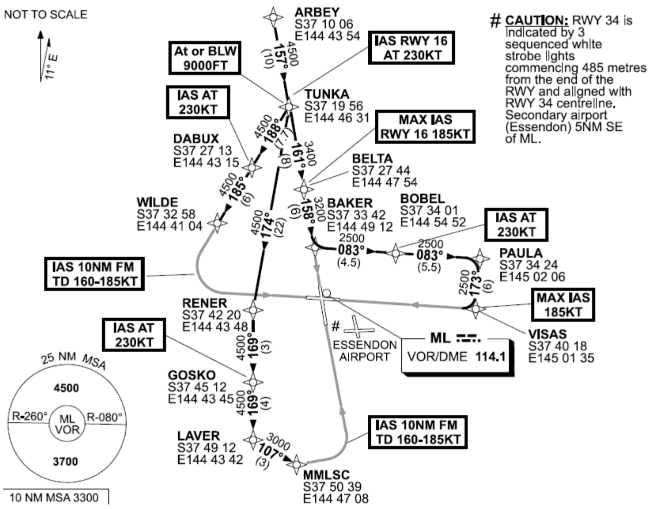

Figure 1. Runway-linked STAR at Melbourne, Australia.

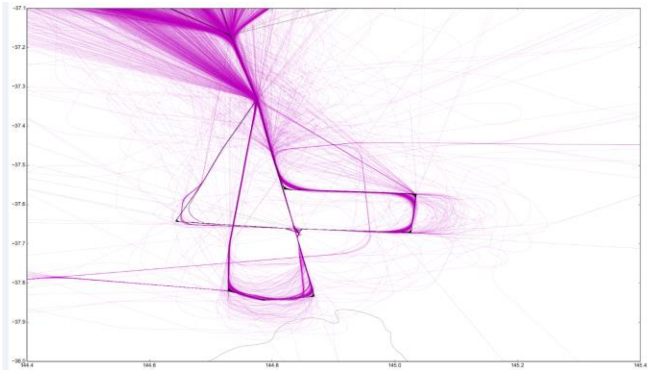

Figure 2. A sample of actual flight tracks into Melbourne, Australia, for the procedures of Figure 1.

In Europe, the use of P-RNAV (~ RNP1) procedures in more complex terminal areas, has been validated in the Madrid terminal area and is now available as a SESAR Solution [2]. To allow the systematic use of P-RNAV in high density traffic areas, the Point Merge [3] concept has been developed. It primarily aims at improving final approaches, by securing the ILS interception and reducing noise nuisances even under high traffic conditions, as well as optimising descents, reducing workload and communications. Point Merge consists of sequencing the aircraft on a merge point typically located 5 to 10 NM from ILS intercept, and then letting it fly a direct segment between this point and the ILS. Point Merge is now operational in major international airports such as Oslo and other Norwegian Airports, Dublin, Seoul, Paris, Kuala Lumpur, Lagos, London. Point Merge essentially provides a 'hybrid' solution as a balance between sequence flexibility for ATC and automation managed descents for the airspace users, but often requires large airspace reservations. This limits the full potential of PBN, as low RNP values allow for compact and efficient terminal area structures. Nevertheless, Point Merge provides a means to bring flexibility to ATC while giving a closed-loop clearance that can be entered in the FMS.

In the United States, PBN has been implemented in all aspects of the National Airspace System (NAS). It has been implemented in small and regional airports to large metroplexes, located in major metropolitan areas with several airports near each other. The FAA has reported that PBN implementation is ahead of schedule and is one of four high-priority operational capabilities identified by the NextGen Advisory Committee (NAC). As an example, the Houston metroplex re-design incorporated over 49 new PBN procedures, modified 11 existing procedures, and retired 20 procedures. The PBN procedures often contain many altitude constraints, and essentially provide an envelope within which the aircraft is allowed to operate. While these procedures consolidate multiple step-down clearances issued by ATC into a single procedure clearance, often the numbers of constraints make it difficult for the FMS to optimise the profile [4]. In addition to altitude constraints, speed constraints are often added to ensure consistent aircraft behaviour and thereby providing predictability to ATC. Finally, the PBN procedure is often not connected to the duty runway threshold, allowing for flexibility by ATC to perform final arrival sequencing through conventional techniques such as 'tromboning' and other forms track stretching or shortening (similar to the example of Figure 2).

In summary, implementation of PBN around the world to date has resulted in more predictable and repeatable flight paths (2D) by reducing lateral variation caused by traditional navigation inaccuracy and the human component [5]. Combined with the addition of terminal area altitude requirements, departure and arrival streams can be systemically segregated (3D). However, as illustrated by the examples listed before, a significant challenge remains to manage the remaining dimension of the aircraft trajectories – time.

B. *4D-TRAD*

The ICAO concept of 4D Trajectory Down-link (4D-TRAD), or initial 4D (i4D) in Europe, is regarded as the future solution to tactical flow management [1], by utilising time-of-arrival-control capabilities of advanced FMSs to control the flow of aircraft over PBN (arrival) procedures. The concept of 4D-TRAD is based on the principle that the nominal 4D trajectory – defined over a PBN airspace structure – is down-linked from the aircraft's FMS, negotiated if necessary, agreed through the up-link of a clearance (that incorporate ATC and flow constraints), and subsequently flown by the aircraft.

De Smedt et al. [6; 7] used an actual arrival scenario at Melbourne, Australia to model the concept of 4D-TRAD in an arrival management context. The aim was to examine how current capacity could be maintained by assigning time constraints, while maintaining the integrity of the structured PBN terminal area (i.e. no cancellation of PBN procedures). The study concluded that in high-density traffic situations, the ability to absorb delay through only the use of airborne time-of-arrival-control capabilities is not sufficient. The PBN arrival procedures assumed for this study contained few restrictions, essentially giving the FMS full ability in applying speed control to absorb delay into the arrival trajectory. A study conducted by Herndon et al. [4] found when several different FMSs were faced with challenging PBN arrival procedures containing a large number of constraints, the resulting behaviour can vary widely as they attempt to meet all restrictions which is not always possible. The study also found of note that such challenging PBN procedures, while in theory designed as an OPD, can deviate significantly from the true optimal profile. While not investigated by the study of Herndon et al., it is likely that in the context of 4D-TRAD, constraints on a PBN procedure will impact the ability of an aircraft to meet a time constraint.

III. Problem Statement

Previous research work suggests that the interdependencies between the design of PBN procedures, FMS operating logic, and the concept of 4D-TRAD, are little understood. With use of an FMS testbed environment, this paper will investigate the impact of constraints on a PBN procedure to the range of delay that can be absorbed into the arrival trajectory using speed control. This range of delay will be compared to a sample of actual delay data from a representative operational scenario.

IV. Simulation of Delay Absorption

A. *Setup*

The simulation environment consisted of the GE Aviation (Systems) (GEAS) Flight Management Workstation (FMW) environment. The flights were set up to depart Gerald R. Ford International Airport in Grand Rapids, MI (KGRR), cruising at FL350 to Reagan National Airport in Washington D.C. (KDCA), and arriving using the FRDMM STAR with the RNV 01 Approach to Runway 01 (via IRONS Transition). The configuration was a Boeing 737-500W, and Internal Standard Atmosphere (ISA) conditions with zero wind conditions were assumed.

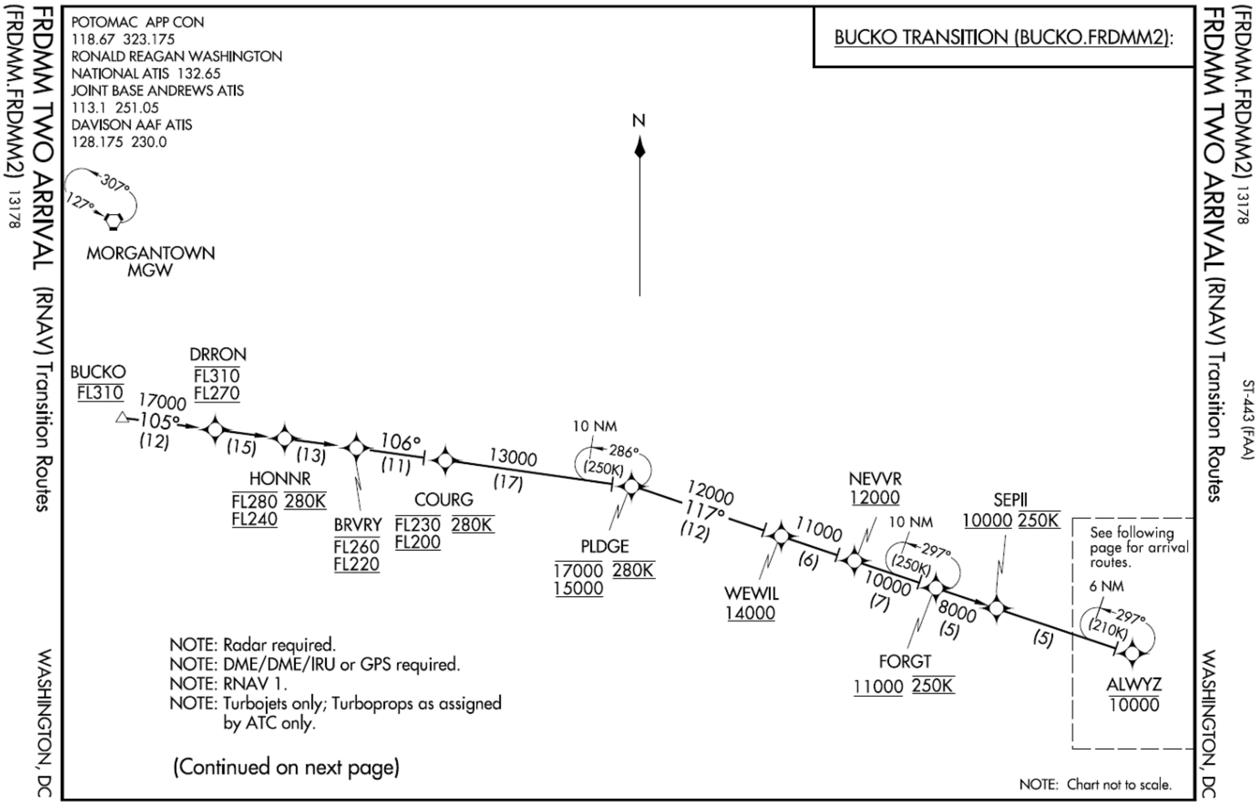

Figure 3. FDRMM Arrival, Washington Reagon National (KDCA)

The flights were simulated up until approximately 200 NM before KDCA (waypoint BUC01, approximately 20 NM prior to BUCKO). From this point, the FMS in the simulation determined the earliest/latest time-of-arrival windows for the procedure termination point ALWYZ. The min/max spread of the input cost index input properly reflected the possible time window for that flight. The 200 NM horizon is also identified as part of the i4D concept by SESAR [8], and corresponds to a nominal freeze horizon distance used in metering operations in the US [9]. GEAS used a tool to translate the FMS' Reference Trajectory to an Extended Projected Profile (EPP)[1] [10], which was exported for analysis.

B. Scenarios

The Cost Index was varied from a slowest 0 (Long-Range Cruise (LRC)) to a fastest 200 that is allowed for the B737 Classic (-300/-400/-500) Configuration.

The tested scenario included the Original (O) FRDMM STAR and an Unconstrained (U) version, where for the latter all altitude and speed constraints up to the Terminal Radar Approach Control (TRACON) at ALWYZ (@10,000 ft) were removed. Note that in the original STAR simulations (O), the FMS had problems to honour both altitude and speed constraints for certain configurations and sacrificed the latter to honour altitude constraints. Similar issues of an FMS not capable of honouring all constraints, were observed in the study by Herndon et al. [4]. Recognising that speed constraints are generally added to facilitate a predictable flow of traffic, it is likely that such speed constraints will be removed in a 4D-TRAD scenario, where separation between succeeding aircraft is envisioned through appropriately set time constraints. Therefore, in additional simulation runs (A), the impact of just the altitude constraints was assessed, by removing the speed constraints from the original FDRMM procedure.

The tested scenarios included a spread of gross weights from a light 81.3 klbs and medium 101.6 klbs to a heavy 122.0 klbs.

C. Results

Figure 4 shows the vertical profiles from the O and U simulations. The vertical profiles in the figure are aligned to a common altitude constraint at ALWYZ (10,000 ft). Note that there is a range of 67 NM between the earliest and latest TOD in the profiles shown. The FRDMM3 OPD procedure and altitude windows are included (black trace).

Figure 4 provides a bar plot indicating the range in flight time from the simulation start position at 20NM prior to BUCKO to ALWYZ, between cost index 0 and 200. This range is an indication of the amount of delay that can be absorbed – related to the impact of the cost index on the speed of the aircraft. Several observations can be made:

- In the case of the original procedure (scenarios O), there is limited ability to speed up due to the direct result of the speed constraints on the procedure. These speed constraints consequently limit the range of achievable delay. FRDMM has a 280KIAS restriction at HONNR, COURG, PLDGE and a 250KIAS at FORGT. As mentioned, in some cases the FMS could not honour these restrictions in combination with vertical constraints.

- In the case of the unconstrained procedure (scenarios U), the descent to ALWYZ is flown at idle thrust. The range of achievable delays is increased because of no speed constraints, but the maximum achievable flight time has reduced.

- In the case of the original procedure with speed constraints removed (scenarios A), the range of achievable flight time and delay is largest, and also the least sensitive to aircraft mass.

[1] The Extended Projected Profile (EPP) is trajectory down-link definition developed by RTCA (DO-350/ED-228) in support of 4D-TRAD [10].

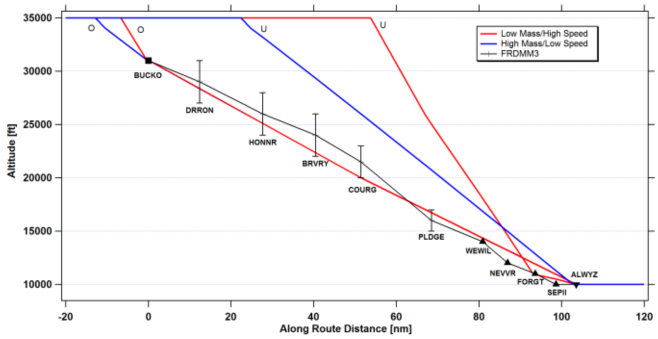

Figure 4. Verical profiles of original FDRMM procedure ("O"), and hypothetical procedure with most constraints removed ("U"). The Low Mass/High Speed (red) and High Mass/Low Speed (blue) combinations define the largest envelope of idle-thrust profile variability.

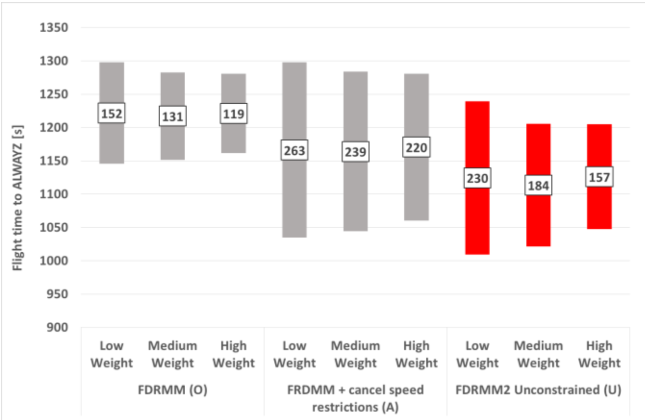

Figure 5. Flight time range for different scenarios.

The above results are somewhat counter-intuitive at first hand. One might expect that with many altitude constraints (scenarios O and A), leading to difficulties for the FMS to optimise the profile, its ability to accept a time constraint - should one be imposed - would reduce. However, the contrary is true. In case of the FRDMM arrival, the constrained solution through the altitude restrictions is much shallower than the optimal profile. The observed top of descent could be up to 60 NM earlier than the unconstrained descent. For the same cost index (and therefore target

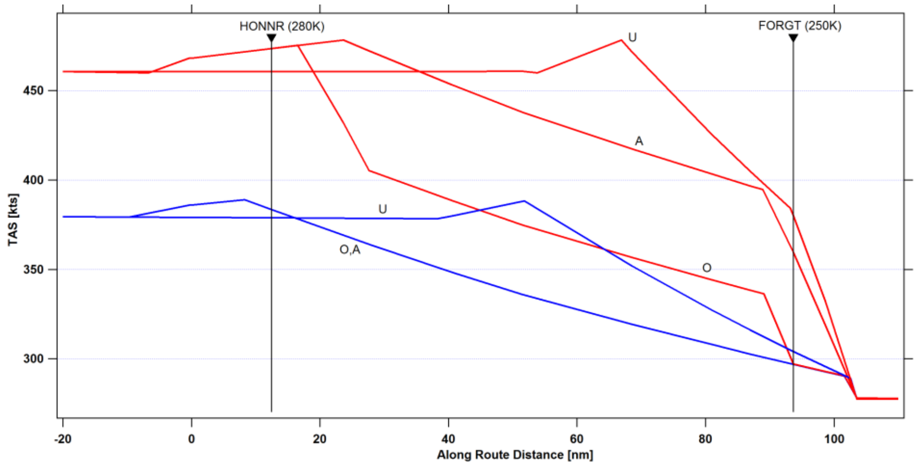

Figure 6. TAS profiles. A 280 KCAS restriction is in effect between HONNR and FORGT (80 NM).

speeds), the original (constrained) profile descends earlier. Therefore, below cross-over altitude, for the same calibrated airspeed, the true airspeed is reduced earlier, and hence more delay can be absorbed than in case of an unconstrained idle descent. This extra delay does come however at the cost of additional fuel burn, as the shallower descent is flown at higher-than-idle thrust. On the other hand, the at-or-below altitude constraints causing the shallow profile, limit the extension of the cruise phase possible in case of a high cost index to speed-up. An unconstrained descent can therefore achieve somewhat faster flight times, as cruise can be extended followed by a high speed idle descent.

To explain this further, refer to Figure 5 where the true airspeed (TAS) profiles for the different scenarios are shown. Note that for scenarios O (the original FRDMM) there is a hard speed restriction (280K) applicable between HONNR and FORGT. This forces a slowdown at HONNR, which is removed in scenarios A and U. The A simulations still contain the altitude restrictions, and the associated shallower-than-idle descents result in the TAS to be reduced earlier than for the scenarios U. This explains why the A scenarios result in the widest range of achievable flight times, and also the longest achievable flight times.

Aircraft weight impacts the flight path angle corresponding to idle descents. Therefore in case of the unconstrained procedure, the range of achievable delay changes with aircraft weight. Given the constrained procedure contains mostly geometric segments (forced by the altitude constraints), the weight has less impact on the delay that can be achieved.

D. Generic Simulations of Idle-thrust and Geometric Descents

The results of the simulations with the FMS testbed are specific to the FDRMM2 procedure. In this section additional simulations will be performed to generalise the findings of Section IV.C. For these simulations, the Dali trajectory modeller was used [11; 12].

A generalised scenario was investigated for an aircraft at cruise conditions, 200NM from landing, conducting an idle-thrust descent and a geometric descent. The flight path angle for the geometric descent was varied between -3.5 and -1.5 degrees. A shallow flight path angle essentially replicates a situation where a number of constraints 'push down' a descent profile, resulting in a (partly) geometric descent, like it is the case of the FDRMM arrival. The cruising altitude was varied between 31,000ft and 39,000ft. A Boeing 737-500 at a start mass of 101.6 klbs was used to replicate as close as possible the GE FMW environment. For aircraft performance computations, EUROCONTROL's Base of Aircraft Data (BADA) 4 was used.

The idle-thrust and geometric descents were simulated at low and high speed to replicate the cost index 0 and 200 cases. The cruise Mach number was determined by the Dali trajectory modeller based a simplified cost index algorithm using BADA4, while the descent speed was fixed at 240KCAS and 330KCAS for the cost index 0 and 200 cases respectively. Like with the GE FMW simulations, the achievable time window was captured, as well as the range in fuel burn. The -1.5 degree geometric descent could only be simulated for the 33,000 ft scenarios, as in the other cases 200 NM was insufficient distance to complete the descent. The results of the simulations are shown in Figure 6. Several observations can be made:

- For the geometric descents, the results show a clear trend of increasing minimum, maximum and range of achievable flight times, when the flight path angle becomes shallower. This increase comes at the cost of increased fuel burn, though the *range* of fuel burn appears less sensitive to flight path angle than range of achievable flight times.
- The -3 degrees geometric descent corresponds closest to the idle descent in terms of fuel burn and achievable flight time range. This was also concluded in a study by Wu et al. [13], though in that study it was also claimed that the geometric descent can be (slightly) more fuel efficient than the idle-thrust descent (for same cruise start conditions and flight time). The results of this paper do not support that finding, and continue to support that the idle-thrust descent is more fuel efficient than a comparable geometric descent[2]. This paper is however consistent with the finding of [13], in that the fuel burn difference between idle and geometric descent can be small enough for some path angles, to make the geometric descent a viable option, given the increased predictability of the vertical profile to ATC.

[2] Comparing the results, it appears that in the work of [13], the airspeed rate of change was not taken into account, as that study the idle descent had the same path angle for the constant Mach and constant CAS portions of the descent. These path angles are distinctively different as true airspeed increases for a constant Mach descent, and decreases for a constant CAS descent, as is clear from Figure 4 and Figure 7.

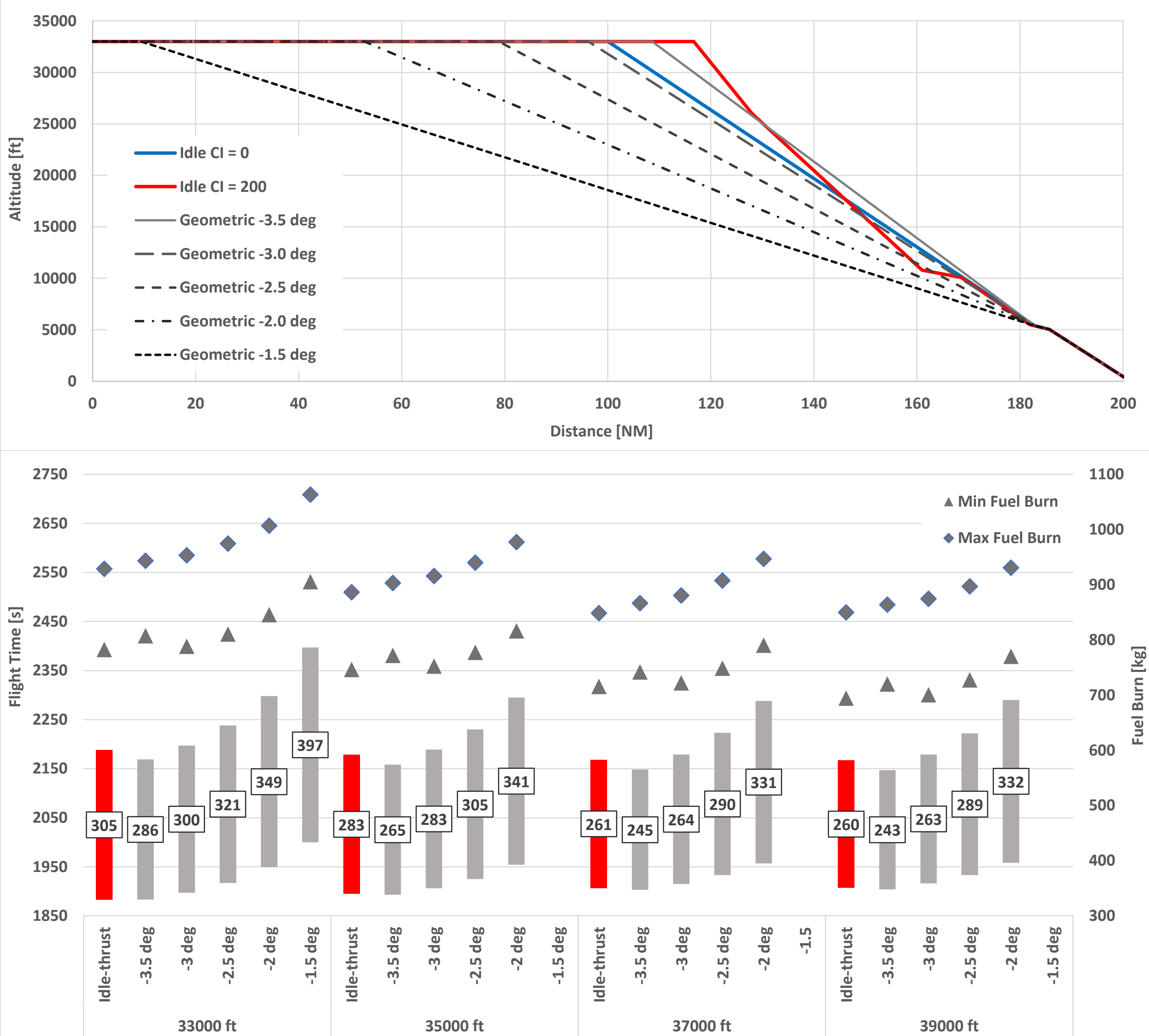

Figure 7. Idle-thrust and geometric descent simulations.

- The achievable flight time range decreases with increasing altitude. This is the result of the aircraft performance envelope in terms of true airspeed, becomes narrower with altitude, as lower density results in higher stall/buffer true airspeeds.

While exact figures and impact on fuel burn depend on the aircraft type investigated (only Boeing 737-500 in this analysis), the physics behind the simulations of Figure 6 – discussed in Section IV.C – support the finding that shallow geometric descents increase the minimum, maximum and range of achievable flight times in comparison to an idle descent, however at the cost of increased fuel burn.

In the study by De Smedt et al. [6; 7], any delay in excess of what could be absorbed through airborne time-of-arrival-control, was simulated to be absorbed by lowering the cruise altitude. Essentially, this is based on the same principle as a shallower-than-idle geometric descent discussed in this paper, whereby the true airspeed is reduced early in comparison to an idle descent from the original cruising altitude. While FMSs do not currently consider lowering the cruise altitude as an option to absorb more delay as part of the time-of-arrival-control capability (or the use of shallow geometric descents), this could be triggered by setting an appropriate altitude constraint or ATC instruction.

Suppose that 25NM after the 200NM metering horizon (i4D), thus 175 NM from landing, a waypoint is introduced at which an altitude requirement can be set by ATC. Rather than an 'at-or-below' constraint, like in the FDRMM arrival, here it is chosen to have an 'at-X-descent-to-X' constraint/instruction to ensure that there is sufficient time from the 200NM horizon, to enter the constraint/instruction

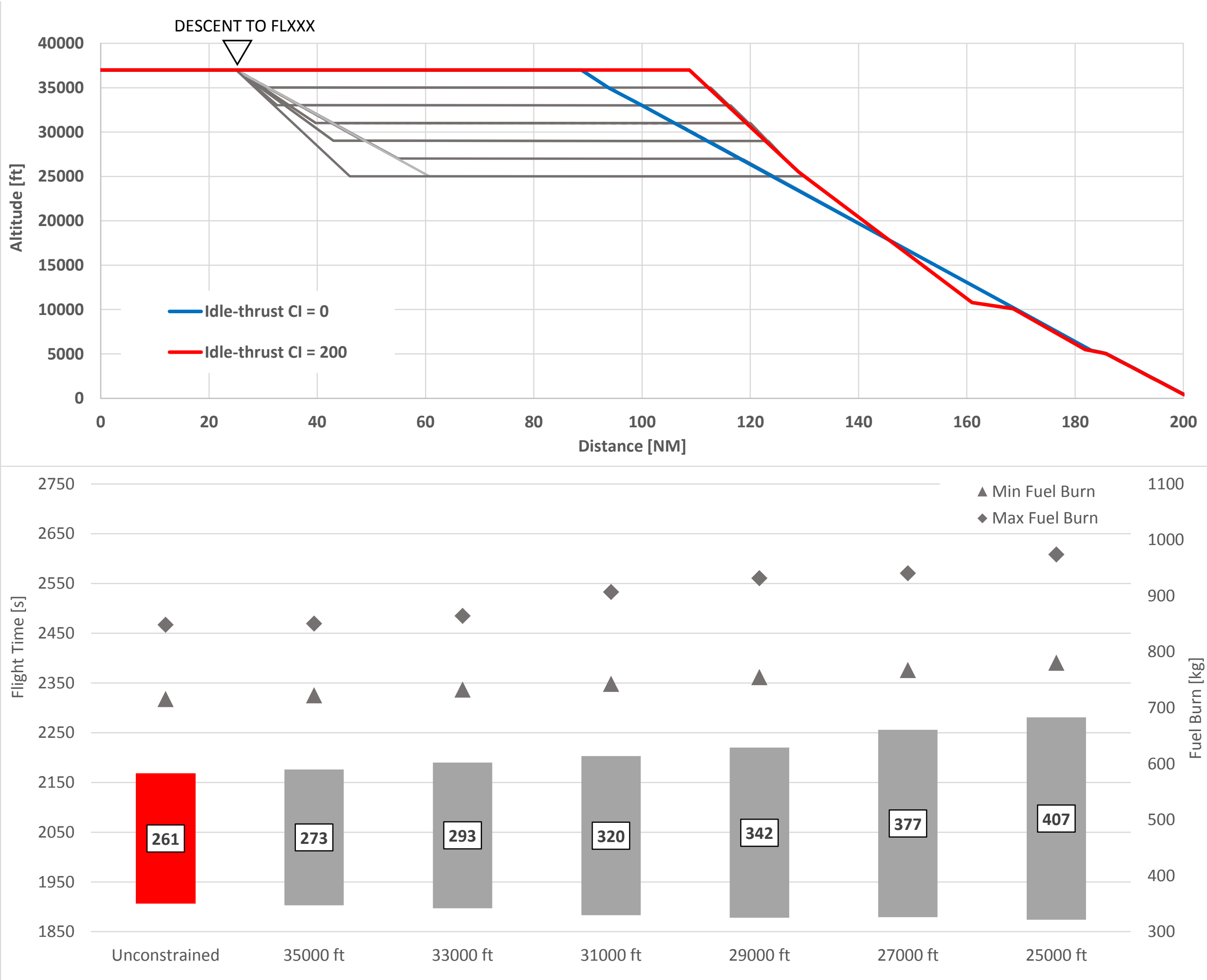

Figure 8. Early descent simulations.

in the FMS, without risking overflying the associated descent point. Using the same conditions as in the simulations of Figure 7, another set of simulations was run with the application of a range of such constraints, for an initial cruising altitude of 37,000 ft. As a result of these constraints, at 175NM from landing, the aircraft in the simulations was forced onto an early descent, followed by a level segment, until an idle-thrust descent was intercepted. Like with the other simulations, these scenarios were run for both the cost index 0 and 200 cases. The results are shown in Figure 8.

In comparison with the simulation of geometric descents of Figure 7 (37,000ft case), the minimum flight time slightly decreases when forcing the descent profile down. This is the result of the optimisation of the airspeed on the level segment, based on the simulated cost index. Between the unconstrained arrival and early descent to 25,000 ft, the achievable flight time window is increased from 261 seconds to 407 seconds, an increase of nearly 2.5 minutes (55%).

In comparison to the geometric descents of Figure 7, the range of achievable flight times is larger for the same fuel penalty. For the geometric descents from 37,000 ft, the largest fight time range is 331 seconds, but comes at the estimated fuel burn range of 790-950 kg over 200NM (see Figure 7). In case of the early-descent simulations, a similar range is achieved through level flight between 29,000 ft and 31,000 ft at the estimated fuel burn range of 750-920 kg.

If the airspace is available, this technique could provide a practical means to increase the amount of delay that can be absorbed by airborne time-of-arrival-control capabilities in the 4D-TRAD concept. At the 200 NM horizon, an aircraft would downlink its original achievable flight time window, based on the published PBN procedure including any applicable constraints. If this window fails to provide sufficient delay absorption capability, an altitude constraint, could be negotiated to increase the achievable flight time window. In case the original window is sufficient, no altitude constraint needs to be applied. One could refer to this technique as a ‘vertical point merge’ as all trajectories eventually merge back onto their respective idle-thrust profiles. In more complex airspace, where the airspace is not available, the use of permanent vertical constraints could ensure increased ability to absorb delay as was shown for the FRDMM arrival. The downfall of such an approach is that all arrivals incur the associated fuel penalty over an unconstrained idle-thrust descent, even if little delay needs to be absorbed. As part of an overall traffic management solution, these individual aircraft fuel penalties need to be compared to the cost of additional fuel burnt as part of conventional delaying techniques like low-level holding and radar-vectoring. In addition, if the shallower-than-idle geometric descent is implemented at low altitudes, there can be a negative impact on aircraft noise footprint.

Provided the vertical airspace is available, in some situations this vertical-delay-absorption technique could provide benefits over the lateral-delay-absorption technique Point Merge, given the latter requires in general large lateral airspace reservations, and often leads to suboptimal airspace designs for low traffic scenarios (due to additional track miles to facilitate flow onto the Point Merge arcs). The authors do not claim one solution is better than the other; the right option to supplement a PBN airspace design with any of the above opportunities to support arrival management, is dependent on the operational conditions of the airspace targeted.

V. Actual Delay Analysis

So far, the analysis presented in this paper has been concerned with the achievable range of flight times – i.e. ability to absorb delay – between different descent techniques, along a PBN procedure. This achievable range of delay needs to be put into perspective with the typical delay that aircraft typically incur during the arrival phase of flight. As discussed in Section II of this paper, PBN procedures are implemented around the world, but often air traffic controllers cancel the procedure, and tactically direct aircraft to manually absorb the delay required to fit them into the arrival sequence. To gain insight into the extent of these inefficiencies, specifically associated with the FRDMM arrival procedure, a sample of recorded traffic into KDCA has been analysed.

An 18-hr block traffic sample was collected on October 14, 2016. Flights, whose surveillance track data showed that they flew the FRDMM arrival, were selected for analysis. A total of 118 flights were analysed. The lateral paths of these flights are shown in Figure 7. From these lateral paths it is clear that the procedure is often cancelled prior to reaching ALWYZ, but also, for those aircraft that complete the procedure, significant delay is also absorbed through 'tromboning' in the circuit area (Figure 8). The PBN procedures therefore essentially provide a predictable transition (to ATC) from the enroute environment, through a complex airspace separated from other traffic streams where there is less flexibility (or need) for sequencing actions, to the circuit area, where final sequencing is performed through conventional techniques.

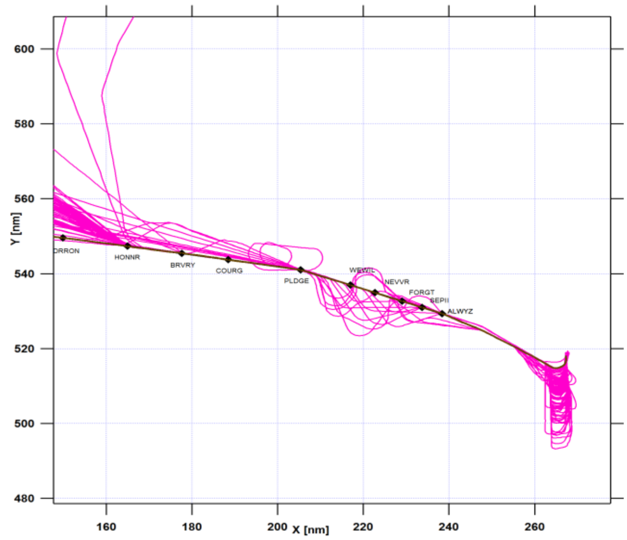

Figure 9. Arrival tracks on FRDMM 3 demonstrating ATC sequencing actions.

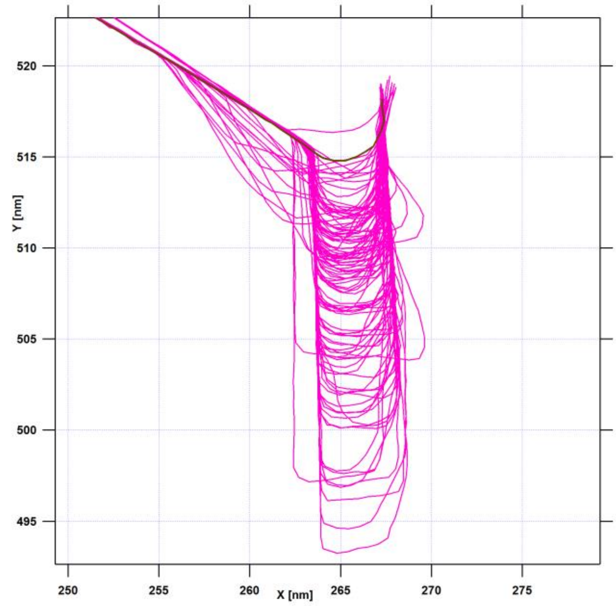

Figure 10. Tracks (2016 sample) showing downwind-base-final leg detail.

The delay that is absorbed through tromboning was estimated, by measuring the excess time and distance flown relative to a nominal minimum distance track (black track). In addition to the tromboning delay, it is observed that for some flights there is additional vectoring between PLDGE and ALWYZ, which was not taken into account in this analysis. The excess distance metric is defined as the path distance (meter fix to touchdown) flown by the flight minus the same distance for the reference minimum distance flight. A similar metric, the excess time, is defined in terms of the time flown between the meter fix and touchdown. The 118 arrivals landing on runway 1 have a median (50th percentile) excess distance of 13 NM and excess time of 3.5 minutes. The excess time and distance distributions are however highly skewed with long tails, as can be seen in Figure 11 and Figure 12. The flight with the largest delay along the trombone shows an excess distance of 43 NM and excess time of 15 minutes, with respect to the nominal track. In addition to arrival sequencing, there could be additional factors that are not apparent contributing to excess distance on final. Therefore, the measurement presented above provides only an estimate of the excess time statistics.

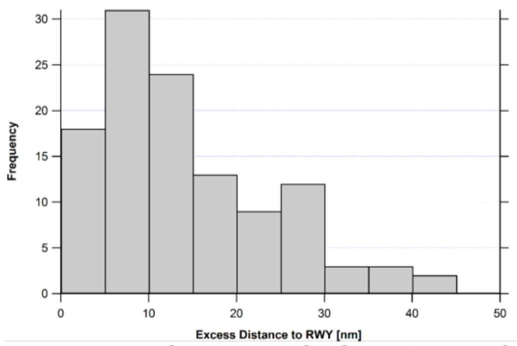

Figure 11. Excess distance metric distribution (2016 sample)

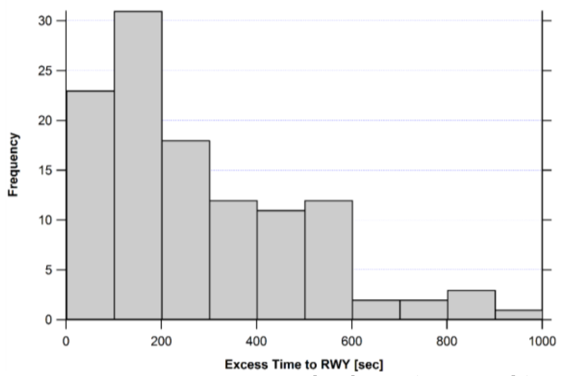

Figure 12. Excess time metric distribution (2016 sample)

Ideally, if all aircraft arrived to ALWYZ on time with respect to the allocated landing time, then the final approach controller would simply clear the aircraft to follow the shortest path to the runway (the shortest length of the trombone). In such case, the procedure could be re-designed to terminate at the runway threshold allowing the FMS to fly the entire arrival in managed mode (runway-linked STAR). All delay that is absorbed through tromboning would need to be absorbed upstream from ALWYZ along the PBN arrival procedure, for example through airborne time-of-arrival-control in a concept like 4D-TRAD. Referencing the delay distribution of Figure 12 to the estimated achievable delay range along the FDRMM procedure from 200NM in Figure 5, it can be concluded that the typical delay is generally in excess of what can be absorbed along the procedure through a concept like 4D-TRAD. In case of the original FDRMM procedure with all altitude and speed constraints (scenarios O), approximately only 25% of the traffic in the sample, the delay could have been absorbed along the procedure. For the unconstrained idle descents (scenarios U) this improves to about 40%. As was discussed, the largest range of delay is achieved by maintaining the vertical constraints and forcing an early descent (scenarios A), but even in this case, approximately only 55% of the traffic in the sample, the delay could have been absorbed along the procedure using airborne time-of-arrival-control. A sample for a second day (February 1, 2015) was analysed providing very similar results. While these are relatively small traffic samples, the delay observed for these two days are common for operations in continental US and Europe [14].

The study by De Smedt et al. based on a Melbourne traffic scenario [6; 7], also concluded that typical delay is generally in excess of what can be absorbed through a concept like 4D-TRAD. Therefore, even if allowances are made into the design of PBN procedures like Point Merge or the use of early descents discussed in this paper, there will be a strong reliance on improved air traffic flow management procedures in upstream sectors (or ground delay), to absorb the delay that is represented by the tails in the typical approach delay distributions as seen today.

VI. CONCLUSION

This paper investigated the interdependencies between the design of PBN procedures, FMS operating logic, and the concept of 4D-TRAD. An FMS optimizes an arrival trajectory taking into account the lateral path and any other constraints, such as altitude and speed, defined by a PBN procedure. Constraints that are added to provide ATC with predictability, can be problematic for the aircraft as in some cases it cannot fully comply with them. In addition, as demonstrated in this paper, these constraints can have an impact on the delay absorption potential of airborne time-of-arrival-control capabilities in a concept like 4D-TRAD. Speed constraints are detrimental to the delay absorption potential, but the appropriate use of altitude constraints can actually lead to increased delay absorption potential. The aerodynamic coupling between speed, mass and vertical profile (flight path angle) during an idle-thrust descent, is essentially a limiting factor on the amount of delay that can be absorbed. Forcing the aircraft down earlier than optimal top of descent (of an unconstrained idle-thrust descent) increases the flight time window at the expense of additional fuel burnt (which is offset against conventional delaying methods). A concept was proposed whereby an altitude requirement can be dynamically set by ATC to increase the delay absorption potential, when required, while providing a closed-loop clearance than can be entered in the FMS.

In addition, typical delay absorption potential by airborne time-of-arrival-control capabilities was referenced against actual flight data. It was concluded that typical delay is generally in excess of what can be absorbed. Therefore, even if allowances are made into the design of PBN procedures, like the use of early descents discussed in this paper, there will be a strong reliance on improved air traffic flow management procedures, to enable full 4D trajectory management, runway to runway.

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