DESCENT PROFILE OPTIONS FOR CONTINUOUS DESCENT ARRIVAL PROCEDURES WITHIN 3D PATH CONCEPT

Kwok-On Tong, Ewald G Schoemig, Danial A Boyle, Julien Scharl, Aslaug Haraldsdottir
The Boeing Company, Seattle, Washington 98124

Abstract

Continuous Descent Approach/Arrival (CDA) procedures with idle thrust descent have demonstrated significant reduction in community noise, fuel burn, emissions and flight time when compared with conventional step-down procedures. However, to date such CDA procedures have only been implemented in low traffic conditions. This is partly due to the fact that Air Traffic Control (ATC) lacks the required ground automation to provide separation assurance services during CDA operations. Additionally, the deployment of CDA procedures in medium to high traffic conditions is hindered by the lack of capability on the ground to reliably predict the trajectory as executed by the airplane when descending under idle thrust. Insufficient or inaccurate knowledge on the ground regarding aircraft type, weight, aircraft specific operations and wind profiles in the Flight Management System (FMS), etc. can lead to large deviations between the ground computed profile and the actual profile flown.

Partially powered, low thrust CDA along a geometric vertical path provides a possible alternative to idle descents. Geometric paths explicitly specify the vertical profile that the aircraft will fly and hence provide increased predictability on the ground and significantly improved common situational awareness in the air and on the ground. These benefits come at the expense of increased noise, fuel burn, emissions, and flight time for individual flight in comparison to idle thrust descents. With proper design, however, it can be shown that the increases can be quite reasonable. The higher predictability will make this descent concept feasible in high traffic conditions. The overall benefits in noise, fuel burn, and flight time for the entire arrival stream can still be much higher than the level achievable with current step-down procedures.

When combined with the 3D Path Arrival Management (3D PAM) concept using lateral path options [1], the resultant operational concept provides a highly predictable 3D descent trajectory and, with supporting ground automation, enables the implementation of CDA procedures in high traffic conditions. In this paper, we will report relevant design considerations for geometric path CDAs and trade-offs between this low thrust descent scheme and idle thrust descents. The implementation of this descent scheme within the 3D PAM concept will also be discussed.

Introduction

CDA procedures were first developed for noise abatement. The associated reduction in fuel burn, emissions and flight time over conventional step-down procedures were soon recognized. Under the current high fuel price condition and increasing pressure in noise and emissions reduction, the environmental benefits provided by CDA operations become very attractive.

In the US, FMS based CDA procedures have been demonstrated in the 2002 and 2004 Flight Tests at Louisville International Airport, KY (SDF) with support from United Parcel Services (UPS). The 2002 Test demonstrated significant reductions in both noise and fuel burn by CDA procedures [2]. The subsequent 2004 Flight Test demonstrated the feasibility of CDA procedure under normal operating conditions and further demonstrated the noise and fuel burn benefits for idle thrust descent [3]. With the success of these two Flight Tests, UPS applied for and has obtained permission to perform CDA procedure with idle thrust descent during the nightly arrivals at SDF. Implementation of this type of CDA procedure has also started at Southern California airports and is being considered for Atlanta and other US airports.

However, the majority of these CDA procedures are limited to low to medium traffic conditions. Analysis of the Louisville type CDA procedures shows that the primary reasons for this limitation are two-fold. First, most procedures are based on a single arrival track. With a single arrival track and a fixed initial separation before Top-of-Descent (TOD), ATC is provided with only speed changes to regulate spacing between aircraft during CDA operations. As traffic increases, it becomes more difficult for ATC to rely only on speed changes to maintain the required aircraft separation. It is expected that lateral path stretches with various delay capability during cruise and descent will provide ATC additional ability to accomplish the required aircraft separation and spacing while allowing efficient descents. This capability is provided for in the 3D PAM concept [1, 4 and 5].

The second identified issue relates to the overall ground-based predictability of the idle descent flight path. Laterally this profile is well defined by waypoints along the ground track, and is known in the air and on the ground. Vertically, the issue on predictability is complicated. Ground based planning tools perform predictions based on available and assumed information. This includes aircraft type, nominally assumed weight and operating conditions, ground based wind predictions, etc. On the other hand, the airborne FMS computes and executes a vertical profile based on airline specific operational procedures, selected cost index, actual weight, FMS-specific vertical profile construction methods, and winds as input by the flight crew in the FMS. With engine thrust set at idle, both the vertical descent profile projected on the ground and the profile constructed by FMS are sensitive to these input parameters. Differences in air/ground data sources and flight path construction methods can lead to large discrepancies between air and ground predicted vertical and speed profiles. In the future, data link and intent download will solve some of these issues. In the current voice based environment, these issues are hard to overcome. Examples of large variations in the descent profile for different aircraft types and operating conditions will be shown later in this paper.

Given these uncertainties, ATC tend to reserve large airspace buffers (laterally and vertically) around each idle descent aircraft to ensure the required separation. This effectively prohibits the application of such CDA procedures in high traffic conditions. Implementing modern navigational technologies such as RNAV and RNP in CDA procedures can further improve the lateral flight path predictability on the ground and reduce the size of the lateral buffer. Ground predictability of the vertical flight path can be greatly increased if the arriving aircraft descend along a fixed path that is known to both ATC and flight crew. This leads to the development of a low thrust descent along a fixed geometric path as a CDA procedure design option. This descent concept is the main subject of this paper.

To some procedure designers, CDA procedures are reserved for those arrival procedures with idle thrust descent only. This narrow definition of CDA procedures should be expanded to include descents with non-idle thrust. Under this extended viewpoint, a CDA procedure is re-defined here as any descent procedure that minimizes or even eliminates high thrust level flight segments during descent and still supports the required traffic flow. As expected, analysis shows that the low thrust descent concept along fixed geometric path comes with reduced benefits in noise, flight time, fuel burn and emissions for individual flight when compared with the levels achievable with idle thrust descents. With proper design, analysis also shows that such reductions in benefits are quite reasonable. Thus, with the increased descent profile predictability, under high traffic conditions, this descent concept has the potential to improve the overall efficiency of the arrival stream far better than the level achievable with conventional step-down procedures. This descent along fixed geometric path is considered as another design alternative to idle descents. In this paper, we will use descent path along constant Flight Path Angle (FPA) as an example for fixed geometric path.

In the following sections, examples of high variability in the vertical profile for idle descent will be shown first, followed by discussions on predicted fuel burn and flight time for descents along various fixed FPA and different aircraft types. Design considerations for this fixed FPA descent scheme will be included. Implementation of this fixed FPA descent within the 3D PAM concept will be discussed together with the fixed FPA implementation options in FMS.

Idle Thrust Descent Profile and its Variability

Given a defined lateral path, airborne FMS computes and executes an ideal descent with fuel optimal vertical profile providing maximum efficiency in the descent. However, the vertical profile is difficult to predict on the ground due to its dependency on a range of airside parameters that may or may not be available to the ground automation systems as previously discussed.

Examples of idle descent profile variability resulted from different aircraft types and deicing system settings are shown in Figure 1. Two different aircraft types (B737-700 and B777-200) are used to illustrate the effect of different aircraft on the descent profile. The effect of deicing system settings may be more difficult to anticipate by the ground automation systems, because the settings depend on the temperature forecast provided by individual airline to their fleet and the operational practice of each airline.

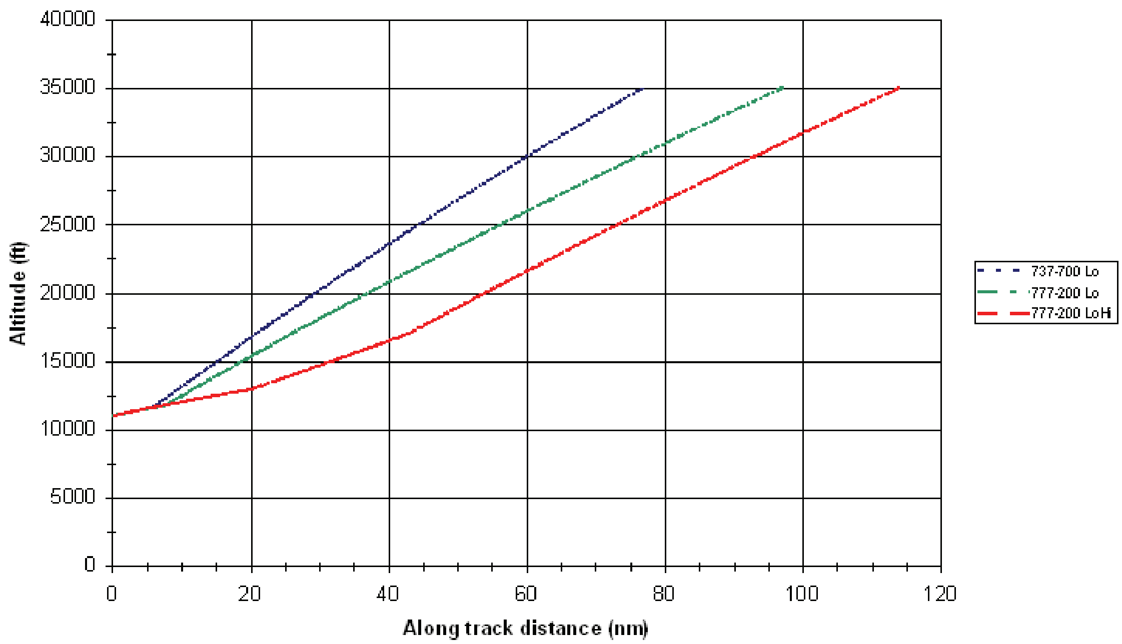

Figure 1. Idle Descent Profiles

In Figure 1, the altitude profile (in ft) versus along track distance (in nautical mile (nm)) is shown. The blue and green profiles represent a B737-700 (~128,000 lb) and a B777-200 (~445,000 lb), respectively, and with their respective deicing system set at low level for the entire descent. The red profile is also for B777-200, but with deicing system set at low above 17,000 ft and at high level below 17,000 ft representing a potential icing environment at lower altitudes. The three profiles shown are the predictions by the Boeing Climbout Program (BCOP) for idle thrust descent and with no ambient wind. All three aircraft start at 35,000 ft and 290 kts Calibrate Air Speed (CAS), and remain at constant 290 kts during majority of the idle descent to the same end location at 11,000 ft with no speedbrake and flaps deployed. A 240 kts speed constraint is also applied at the end location in addition to the 11,000 ft altitude constraint. For all three cases shown, the deceleration to 240 kts just before reaching 11,000 ft is achieved with a constant 500 ft/min descent rate. This descent rate is commonly used by different FMS models for deceleration under idle thrust descent. With this 500 ft/min descent rate, all three descent profiles show that aircraft descend along a shallower angle than the segment under constant CAS.

Profiles in Figure 1 show that even with the same low deicing settings, B737 and B777 have drastically different descent profiles, with the TOD for the B777 at ~20 nm before that of the B737. In the descent, at a location ~30 nm before reaching 11,000 ft, the B777 is about 2,500 ft lower than the B737. The profiles also show that for the B777, changing the deicing setting from low to high level during the descent at lower altitudes results in yet another shift of the TOD location (~17 nm earlier) and an even lower descent profile (~3,000 ft lower at ~30 nm before reaching the 11,000 ft point). Other parameters such as ambient wind profile, speed profiles, and aircraft weight, etc will result in further variations in both the TOD location and vertical descent profiles.

These variations of TOD location and vertical profiles for idle CDA descents are solely caused by airborne operational parameters, and some of these parameters are unknown to the ground. With inaccurate aircraft operational parameters, it is expected that the ground projected vertical profiles will have a level of uncertainty similar to the magnitude of variations between profiles shown in Figure 1. For ATC to be able to provide separation despite these uncertainties, large buffers are required laterally and vertically. Without further ground-based information on the actual aircraft trajectory this will prevent high-density application of CDA arrivals with idle thrust.

To support operation under high traffic condition, the trajectory of the descending aircraft must be predictable on the ground so that the size of the buffer assigned by ATC can be reduced. With modern navigational technologies such as RNAV and RNP, the lateral buffer assigned by ATC can be reduced to a level equal to or smaller than the variations among descent profiles shown in Figure 1. In that case, the buffer assigned by ATC may become dominated by the lateral buffer. The vertical buffer can be reduced if the descent is along a fixed geometric vertical path known to both air and ground. In the following sections, CDA procedures with such descent profile will be discussed.

Descents Along Constant Path Angle

As discussed earlier, descent along a fixed vertical geometric path provides the required trajectory predictability in support of high traffic operations. In general, thrust is required to maintain the fixed vertical path, and the benefits in noise, fuel burn, emissions and flight time will be lower than the levels achievable with idle thrust descent. However, with proper design, the projected reductions in benefits are reasonable. A vertical path with fixed FPA is a simple form of fixed geometric path and will be discussed in this paper. Performance and design consideration for fixed FPA descents will be discussed first. Implementation of this type of descents in the FMS will be discussed in the 3D PAM section since it depends on how the path options are implemented.

CDA procedures with low thrust descent along fixed FPAs were studied for the 2002 Test at SDF [6], and have also been suggested for independent parallel runway operations where highly predictable descent profiles are essential to ensure vertical separation [4]. In both cases, the constant FPA descent starts at 11,000 ft or lower. In this paper, this continuous descent concept is extended to the descent from cruise altitude. The overall objective is to provide an efficient descent with ground predictable vertical profile that enables the CDA implementation in high traffic condition.

Following the energy considerations reported in [6], the sum of losses in potential energy (due to descent) and kinetic energy (due to deceleration) equals the difference between drag and thrust when there is no ambient wind. For descents along a constant FPA, thrust required during constant CAS increases as FPA decreases, and maximum thrust occurs at level flight with 0° FPA. Analysis shows that when the FPA is ~2° or larger, the required thrust level is only a small fraction of that required for level flight. This leads to the potential of efficient operations with smaller fuel flow, emissions and fuel burn. When descending along fixed FPA, deceleration can be achieved by reducing engine thrust without changing the descent path, and maximum deceleration occurs when engine thrust is reduced to idle. This is different from the case of idle descent in which deceleration can only be achieved by reducing the path angle. In the presence of ambient wind, both the required engine thrust for constant CAS descents and the maximum deceleration achievable with idle thrust depend on ambient wind in addition to FPA and other aircraft specific parameters. From an operational view point, the ability to decelerate during descent is an important performance parameter to be considered during procedure design.

BCOP analysis has been used to predict the fuel burn and flight time characteristics and the maximum deceleration capacity for both fixed FPA and idle descents. In this particular analysis, a representative lateral path along the current DAS Six Arrival Alexandria Transition into George Bush Intercontinental Airport at Houston, TX (IAH) is assumed. It is also assumed that the descent is under zero ambient wind condition. All the descents start from a fixed point located at ~20 nm before the Alexandria (AEX) waypoint with a 33,000 ft cruise altitude and 290 kts CAS, and end at another fixed point located at ~7 nm prior to the Daisetta (DAS) metering fix. A 240 kts speed and 11,000 ft altitude constraint is applied at the end point. Most of the descent is under constant 290 kts CAS except for the deceleration to 240 kts just prior to reaching 11,000 ft. Figure 2 shows the vertical profiles used in the analysis for a B737-700.

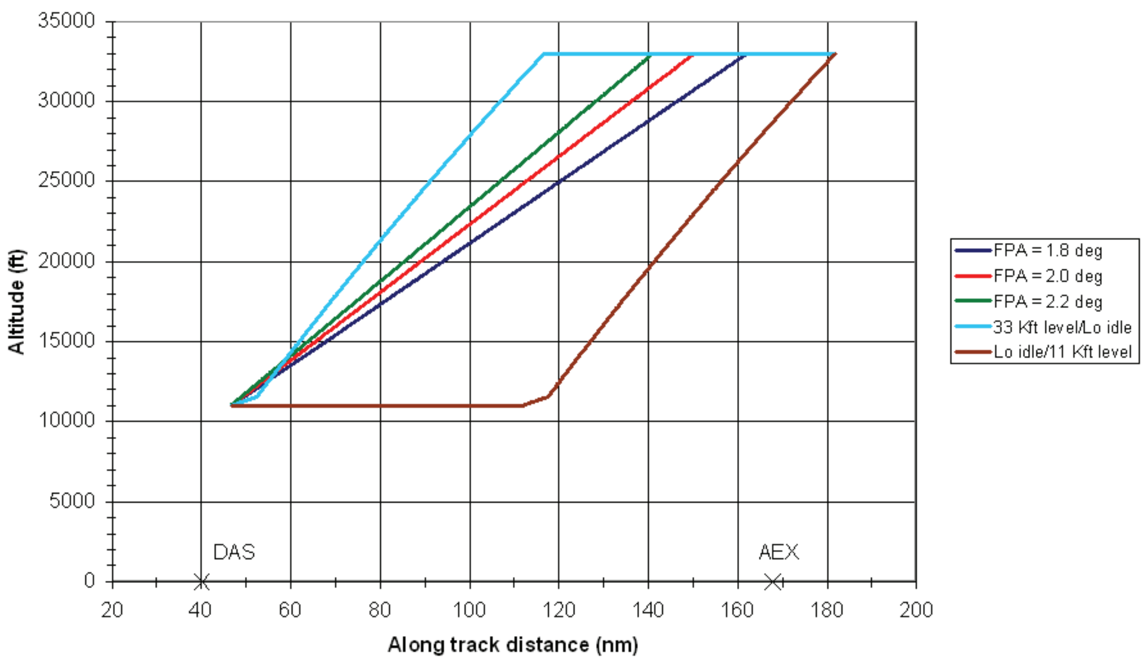

Figure 2. Descent Profiles for B737-700

In Figure 2, the dark blue, red and green lines represent descents along constant FPAs of 1.8°, 2.0° and 2.2°, respectively. Since the descents from the 33,000 ft cruise altitude starts at different locations for different FPAs, each descent path contains a level flight segment with varying length prior to TOD. Deceleration along these constant FPA descents is achieved by reducing thrust to low idle level without changing the path angle. Two idle descent profiles are also included in Figure 2. The first idle descent (light blue line) consists of a relatively long level segment at 33,000 ft followed by an idle descent at 290 kts and a deceleration phase to 240 kts just before reaching the end point at 11,000 ft. The second idle descent (brown line) shows a vertical idle descent profile from the 33,000 ft cruise altitude at the start point and followed by a long low altitude level segment at 11,000 ft. It should be noted that these two idle descent profiles shown are with zero winds; with ambient winds these profiles would be quite different. The three constant FPA descent profiles are not wind dependent, assuming that the wind is within the capability of aircraft control system. However, the required thrust during the constant CAS descent segment depends on the FPA, ambient wind, aircraft type, aircraft weight and aircraft specific operational parameters.

During the level flight segments, aircraft will burn more fuel and have longer flight time when flying at lower altitudes. Thus, the light blue profile represents the most efficient idle descent and will be the optimal profile constructed and executed by the FMS. On the other hand, the brown profile represents the least efficient idle descent and will be the profile if the "descend now" function is initiated at the start point. Fuel burn and flight time predicted by BCOP analysis are summarized in Table 1 for each of the five descent profiles shown in Figure 2.

Table 1. Predicted Fuel Burn and Flight Time for B737-700 Descent Profiles

	Relative Fuel Burn (%)	Relative Flight Time (%)	Deceleration (kts/sec)
33,000' Level /Lo Idle	0	0	0.8 averaged
2.2° FPA	~4.8	~3.5	~0.3
2.0° FPA	~8.0	~4.4	~0.4
1.8° FPA	~10.1	~5.9	~0.5
Lo Idle / 11,000' Level	~24.2	~19.7	0.8 averaged

In Table 1, the "33,000' Level/Lo Idle" and the "Lo Idle/11,000' Level" represent the light blue and brown profiles in Figure 2, respectively. When compared with the most efficient descent, BCOP projects that for descent along a 1.8° FPA or larger, the penalty in fuel burn is less than ~10% of the total fuel consumed during this segment between the start and end points shown in Figure 2. Similarly, the penalty in flight time is less than ~6% of the flight time required for the most efficient idle descent scheme. The magnitudes of these two penalties seem reasonable and may be acceptable from operational considerations. For the maximum achievable deceleration along these three constant FPA descents, it ranges from ~0.3 to ~0.5 kts/sec. A deceleration of ~0.5 kts/sec is considered reasonable as both descent and deceleration occur simultaneously. The 2.2° FPA descent may be too steep for the ~0.5 kts/sec deceleration consideration. It should be pointed out that the ~0.8 kts/sec deceleration for both idle descents is achieved by reducing the path angle, and if the deceleration is not from 290 to 240 kts/sec, then the descent profile will be changed.

Similar BCOP analysis has also been performed for B777-200 aircraft for the two idle descent schemes and the descent along 2.0° and 1.8° FPA. The vertical profiles for both constant FPA descents are the same as those shown in Figure 2. However, the idle descent profiles are different from the B737-700 as shown in Figure 1. Predictions of fuel burn and flight time are summarized in Table 2.

Table 2. Predicted Fuel Burn and Flight Time for B777-200 Descent Profiles

	Relative Fuel Burn (%)	Relative Flight Time (%)	Deceleration (kts/sec)
33,000' Level /Lo Idle	0	0	0.6 averaged
2.0° FPA	~7.7	~3.6	~0.15
1.8° FPA	~10.8	~4.2	~0.2
Lo Idle / 11,000' Level	~19.4	~11.0	0.6 averaged

In Table 2, the predicted fuel burn penalty for both 1.8° and 2° FPA are less than ~11% of the total fuel consumed by the most efficient idle descent scheme. The penalty in flight time is ~4% of that required for the most efficient idle descent. Levels of these two penalties are similar to those predicted for the B737. However, the deceleration capability for the constant FPA descents and idle descents are much lower than that predicted for the B737-700. This means that the B777 will start deceleration earlier and at a higher altitude than the B737, especially for the case with a larger (e.g. 2°) FPA.

Such vast differences in deceleration capability mean that different aircraft types will start their deceleration at very different altitudes when descending along the same FPA. This complicates the implementation of a single fixed FPA for all aircraft types in the current fleet. There are two potential approaches to resolve this issue. The first approach is to start deceleration at the same altitude for all aircraft types, and for those aircraft types with lower deceleration capabilities, deceleration is increased through deployment of drag devices such as speedbrake, flaps and even landing gears at lower speeds. However, this approach can lead to adverse effects on ride quality for the passengers onboard and increase the noise level both inside and outside of the aircraft.

The second approach is to utilize multiple constant FPA descent segments with different FPA for each segment. A smaller FPA is used in the areas where deceleration is likely to occur so that all aircraft types can achieve the required speed change. BCOP analysis shows that along a 0.9° FPA descent, reasonable deceleration levels of 0.67 and 0.49 kts/sec can be achieved by B737-700 and B777-200, respectively with clean aircraft configuration. Several of the current RNAV Arrivals into the Sky Harbor International Airport at Phoenix, AZ consist of multiple FPA descent segments and with less than 1°FPA segments in the areas where deceleration is required. It is expected that the design for fixed FPA descent will be site and fleet composition specific. Further analyses and tradeoffs are needed to achieve a proper design.

There are two methods to implement a constant FPA descent in the FMS. The first method is by defining the descending path angle to a waypoint as part of the Navigational Data Base (NDB). The other is by applying altitude constraints at both the start and end points of each constant FPA descent segment. Since the selection of FPA implementation is affected by the particular way 3D lateral path options are implemented, the discussion of FPA implementation will be included in the following 3D Path Arrival Management section.

3D Path Arrival Management with Path Options

In [1, 4, and 5], the 3D PAM concept with different lateral path options is proposed for high traffic conditions. This concept is discussed in [1 and 4] using Houston airspace as an example. Under this concept, required sequencing and spacing between arriving aircraft at a waypoint such as the metering fix at the TRACON entry, or the FAF on the final approach course to a runway, can be achieved by selecting a particular lateral path option together with proper descent speed and initial separation before TOD. The descent from cruise altitude is further divided into two different segments, one in En-route airspace and the other in TRACON airspace, and with a short level or near-level segment in between. This gives ATC an additional opportunity to re-select path option for the descent inside the TRACON to accommodate changes in traffic conditions after the initial descent clearance is issued prior to the TOD. Analysis of several key parameters that influence this arrival management process has been reported in [5].

Figure 3 shows the same 3D path design as reported in [4]. Here, the arrival traffic follows the current DAS Six Arrival Alexandria Transition into IAH. The nominal path is from AEX direct to DAS, and then to MKAYE located along the ILS final approach for runway 26L. Four additional lateral path options with a ~3.5 nm path length increment are available between AEX and DAS, while two additional path options with a ~1.5 nm length increment are available after DAS. Lateral path options shown in Figure 3 occupy the same areas currently used by ATC for vectoring the arriving traffic [1]. This 3D PAM with path options concept emulates the current ground track vectoring technique used by ATC. Additional analysis and/or simulation are needed to fine tune this path design to ensure its ability to support the expected traffic level along this particular arrival.

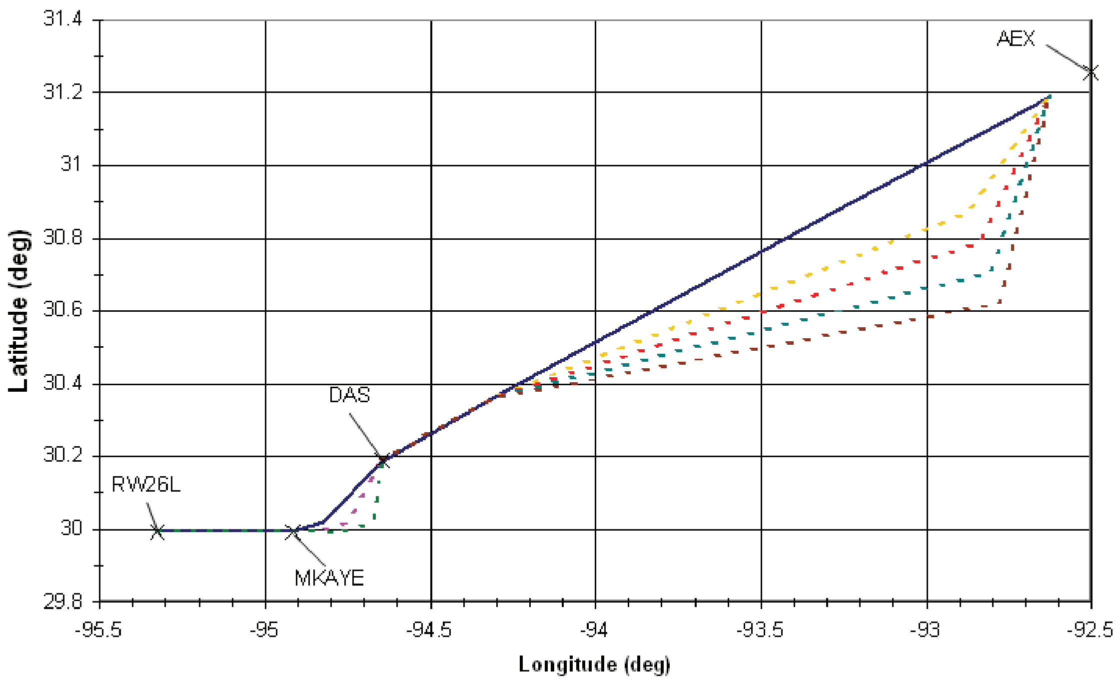

Figure 3. Ground Track with Path Options for Runway 26L

In order to fully utilize the combined capabilities of lateral path options and speed, ground based ATC automation tools are needed [1, 5]. These tools must be able to accurately project on the ground the descent trajectory constructed by all FMS models in the current fleet. With this capability, the automation tools can provide options of lateral path and speed profile for each arrival aircraft to ATC. Each of these options allows the aircraft to descend with a conflict free profile and to arrive at the metering fix or the FAF of a runway with proper sequencing and spacing. ATC can then select a particular path and speed option, transmits the information to the flight crew via voice or datalink in the future, and the flight crew executes the corresponding descent through the FMS.

These automation tools are being developed by several different groups in both the US and Europe. In the US, the En-route Descent Advisory (EDA) tool development is being led by NASA Ames Research Laboratory, and the LEADER tool is under developed by the MITRE Corporation. In Europe, the SARA tool is being developed by the Dutch air service provider LVNL; the AMAN-P tool which is the Arrival Manager under P-PNAV program is funded by the European Union as part of the TMA2010+ activity; the OPTAMOS tool is developed by AviBit Data Processing GmbN, Austria, and is being used in TRACON within Austrian airspace.

There are several methods to construct the lateral path in FMS. In Figure 3, each path is shown in a triangular shape with a common start and end point for all the options in the same set. The apex of each triangle or the turn back point can be located using Place-Bearing-Distance (PBD) function in the FMS. If the common start and end points in each path option set are waypoints specified in the Navigational Data Base (NDB), then either the start or end point can be used as the referenced place in the PBD function. All aircraft equipped with FMS have the PBD functionality regardless of whether the referenced place is in the en-route or TRACON airspace. The turn back point location can be transmitted in PBD format from ATC to the flight crew using voice communication.

Each path in the path option sets can also be defined as an offset to the left or right side of the nominal path with different offset values. With this path geometry, each path option deviates from the nominal path at the start point, followed by a segment parallel to the nominal path, and then turns back to the end point of the path option. If both the start and end points of the offset are waypoints defined in the NDB, then only the offset distance and the side (left or right) of the nominal path need to be transmitted to flight crew by ATC. This is very feasible with current voice communication. However, in some FMS models, if the nominal path is part of a STAR, or STAR transition, the offset function may be unable to support this path maneuver without intervention by the flight crew.

In addition, each path can also be pre-defined in the NDB with unique name, and with the start, end and all the turn points as waypoints. In this case, each path is not restricted to simple geometric shapes associated with PBD or offset. ATC need only deliver the name of a particular path via voice to the flight crew. However, this approach will greatly increase the size of NDB in the FMS, especially if the 3D PAM operation concept is being implemented across the entire National Air Space (NAS). The increase in NDB size may easily exceed the capability in certain FMS models. Further analysis is needed to establish the performances of each of the path construction methods, and to support the selection of a path construction method for NAS wide implementation.

Figure 4 shows an example of the vertical and speed profiles for a CDA descent with constant FPA segments for the nominal path in Figure 3.

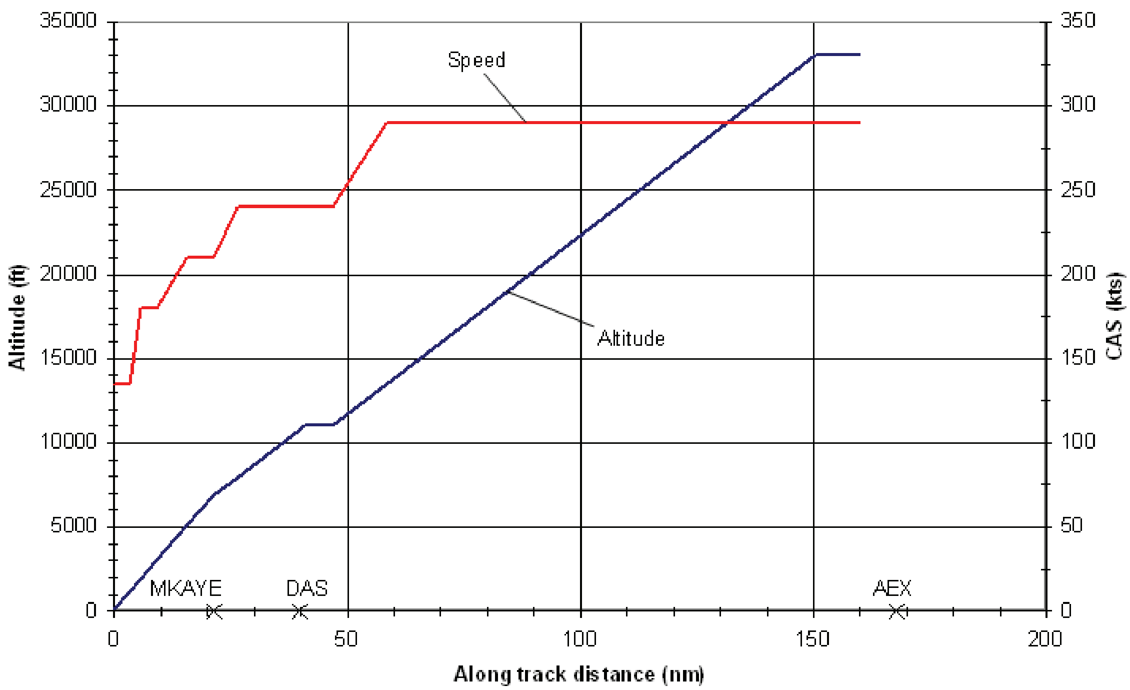

Figure 4. Vertical Descent Profile with constant FPA Segments

Here, both altitude and CAS are shown against the along track distance. The vertical profile (in blue) is similar to the one shown in Figure 5 of [4], except the idle descent from cruise to 11,000 ft in [4] is replaced with a representative low thrust 2° FPA descent. The descent from 11,000 ft near DAS until the intercept with the runway 26L ILS at ~6,000 ft altitude is also along a 2° FPA path in order to support independent operation of runways 26L and 27 at IAH [4]. As discussed earlier, the short (~6 nm) level flight segment between the two 2° FPA segments provides the flexibility to re-select descent path within TRACON. The speed profile (in red) is the same as shown in Figure 5 of [4]. Based on the discussion in the previous sections, it is expected that the entire descent profile in Figure 4 may still have a reasonable performance in terms of fuel burn and flight time. However, the predictability of this vertical profile makes it feasible in high traffic conditions.

As briefly mentioned earlier, there are two methods to construct fixed FPA descent segments in FMS. One is by defining the descent FPA to a waypoint as part of the NDB. The other is by defining an altitude constraint at the start and end points of each constant FPA descent segment. Selection of a particular implementing method is complicated by the fact that the TOD location is different among lateral path options with different lengths. The way by which lateral path options are implemented in FMS also affects the selection of FPA implementation.

The end points of each constant FPA segment are fixed waypoints and defined in the NDB for all three lateral path implementation methods, i.e. PBD, offset and pre-defined paths. If the FPA for the descent into these end points are also specified in the NDB, then FMS will calculate the appropriate TOD location for each lateral path. This method will introduce a slight increase in the size of NDB. However, the implementation of this method is complicated by the fact that the FPA descent functionality varies among different FMS models in the current fleet. In addition, some FMS models may have restrictions in implementing multiple segments with different FPAs.

The implementation method relying on altitude constraints at the two ends of each descent segment requires additional information in the NDB, and thus further increases the NDB size. When PBD or offset options are used for the path construction, the additional locations and altitude constraints at both ends of each flight segment will drastically complicate the delivery of clearances via voice. Further work is needed to resolve the issues on implementing fixed FPA descents under current voice environment. One of the possible outcomes may be a fleet wide common requirement on the functionality for descent with constant FPA in the FMS to support the descent from cruise altitude along multiple segments with different FPAs.

In the future when datalink is available NAS wide, the entire path definition together with speed and altitude constraints at selected waypoints will be completely defined by the ground automation. ATC then could select a particular path and uplink to the flight crew via datalink. Once the flight crew agrees with a particular path, all the path information will be loaded into the FMS, and the entire descent path, both lateral and vertical, can be constructed by the FMS and the descent executed through the FMS.

Conclusions

Low thrust descent along a fixed FPA path is discussed in this paper as another descent option for CDA procedures. This descent concept provides a highly predictable vertical profile that is capable to support high traffic conditions. Deceleration can be achieved by reducing thrust from the level for maintaining constant CAS descent to idle thrust while staying on the descent path. This increase in trajectory predictability comes with a reduction in fuel burn and flight time benefits for individual flight in comparison with idle thrust descent. However, BCOP results show that with proper design, the reduced benefits in both fuel burn and flight time can be small and may be acceptable. Maximum deceleration capability while thrust is reduced to idle depends on the FPA value, aircraft type, ambient wind and other aircraft operation conditions. Differences in deceleration capability among various aircraft types need to be considered during procedure design. The deployment of drag device and multiple descent segments with at least one segment with a FPA of 1° or less for deceleration have been suggested as two possible methods to resolve the variations in deceleration capability issue.

When this low thrust fixed FPA descent concept is combined with the 3D PAM concept, the resultant trajectory is highly predictable both laterally and vertically. With the possibility of using lateral path stretches for aircraft separation and spacing, it is expected that the combined concept can be implemented at a traffic level significantly higher than that supportable with idle thrust descents. To fully utilize this combined concept, a ground based automation tool providing descent advisories to ATC is required. This ATC automation tool must be able to predict a descent trajectory on the ground that emulates the descent profile constructed by the airborne FMS with sufficient accuracy for all the aircraft models in the current fleet. Even though the descent profile along fixed FPA is wind independent, ambient wind information is still an important parameter in determining the arrival time at different waypoint locations. Thus, consistency between wind profile used on the ground and that input into FMS by flight crew is highly desired.

Under the current voice based clearance delivery environment, implementation of fixed FPA descent depends on the particular FMS model onboard of the aircraft, and the way that lateral path options are being implemented. Further analyses are required to resolve the implementation issues. One of the possible outcomes may be a common requirement on FPA descent functionality across all FMS models. In the future, when datalink is available NAS wide, the entire lateral path definition, altitude and speed constraints at selected waypoints can be transmitted from ground to air via datalink with improved accuracy and efficiency.

References

[1] Schoemig, Ewald, et al, September 2006, "Application of Required Navigation Performance in High-Traffic Conditions for Houston Airspace", AIAA Paper 2006-7775, 6th AIAA Aviation Technology, Integration, and Operation (ATIO) Conference, Wichita, KS.

[2] Clarke, J.-P., et al, September-October 2004, "Continuous Descent Approach: Design and Flight Test for Louisville International Airport", AIAA Journal of Aircraft, Vol. 41, No. 5, pp. 1054-1066.

[3] Clarke, J.-P., et al, January 2006, "Development, Design, and Flight Test Evaluation of a Continuous Descent Approach Procedure for Nighttime Operation at Louisville International Airport", Report No. PARTNER-COE-2006-002, PARTNER, Massachusetts Institute of Technology, Cambridge MA.

[4] Tong, Kwok-On, Daniel A. Boyle and Anthony W. Warren, September 2006, "Development of Continuous Descent Arrival (CDA) Procedures for Dual-Runway Operations at Houston Intercontinental", AIAA Paper 2006-7750, 6th AIAA Aviation Technology, Integration, and Operation (ATIO) Conference, Wichita, KS.

[5] Haraldsdottir, Aslaug, et al, July 2-5, 2007, "Arrival Management with Required Navigation Performance and 3D Path", presented at the 7th US/Europe ATM R&D Seminar, Barcelona, Spain.

[6] Tong, Kwok-On, Anthony W. Warren, and John A. Brown, September 2003, "Continuous Descent Approach Development for Noise Abatement Tests at Louisville International Airport, KY," AIAA Paper 2003-6772, AIAA 3rd Aviation Technology, Integration, and Operation (ATIO) Conference.

Acknowledgements

The authors would like to acknowledge the technical contributions and supports from their Boeing colleagues: Tony Warren, John Brown, Sam Miller and John Armbruster during the development of this fixed FPA descent concept. The authors also like to acknowledge Capt. Bill Vaughn of Continental Airlines for his suggestion of applying fixed geometric path descent from cruise altitude to the metering fix.

Email Addresses

Kwok-On Tong: kwok-on.tong@boeing.com

Ewald G Schoemig: ewald.g.schoemig@boeing.com

Danial A Boyle: daniel.a.boyle@boeing.com

Julien Scharl: julien.scharl@boeing.com

Aslaug Haraldsdottir: aslaug.haraldsdottir@boeing.com