

Understanding Time-Drift for Different Aircraft Descent Guidance Strategies

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ABSTRACT

In this paper the effect of different aircraft automated descent guidance strategies on fuel burn and the temporal predictability of the executed trajectory is investigated. The paper aims to provide an understanding of how airborne automation can be permitted by Air Traffic Control to remain in control of the descent in the presence of disturbances while providing sufficient predictability. Simulations have been performed investigating different guidance strategies. While each strategy has its advantages and disadvantages, results indicate that improved temporal predictability comes at the cost of additional fuel burn and loss of predictability in other dimensions of the trajectory.

Categories and Subject Descriptors

J.2 [Physical Sciences and Engineering]: *Aerospace*.

General Terms

Performance, Reliability, Experimentation.

Keywords

Air Traffic Management, Aircraft Guidance Strategies, Continuous Descent Operations, Required Time of Arrival

BACKGROUND

In the past few decades technological development has delivered advanced airborne automation systems. An example is the Flight Management System (FMS). Traditionally, there has been a lag between technological advances of avionics on the flight deck and of Air Traffic Management (ATM) systems on the ground. Aircraft operators across the world are urging Air Navigations Service Providers to improve the interoperability of their respective systems and allow the advanced airborne automation to be used to its full extend. To improve on the current ATM paradigm, the International Civil Aviation Organisation (ICAO) has envisioned a shift from a current airspace-focused ATM to a trajectory-focused ATM [1]

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commonly referred to as Trajectory Based Operations (TBO). In present day operations, air traffic controllers hand-off aircraft to the next sector based on speed, altitude and spacing requirements which are not necessarily consistent with the efficient operation of an aircraft. In TBO, each flight will be executed as close as acceptably possible to the user's intentions which are reflected in SESAR¹ by the Reference Business Trajectory (RBT). Other operational concepts may use different terminology, but the principle of defining, sharing and facilitating a single, unambiguously defined trajectory is common.

The transition to TBO is a complex process and an appropriate first step is to improve on current arrival management procedures by allowing onboard automation to conduct a descent along an efficient profile that better reflects the user intentions and preferences. ICAO refers to such operations as Continuous Descent Operations (CDO) [2] as opposed to current operations in which often level segments are flown throughout the arrival generally due to ATC hand-off agreements and airspace design.

CONTINUOUS DESCENT OPERATIONS (CDO)

ICAO has defined Continuous Descent Operations (CDO) as “an aircraft operating technique aided by appropriate airspace and procedure design and appropriate Air Traffic Control (ATC) clearances enabling the execution of a flight profile optimised to the operating capability of the aircraft, with low engine thrust settings and, where possible, a low drag configuration, thereby reducing fuel burn and emissions during descent” [2]. For aircraft equipped with an FMS, the FMS determines the path that can be flown at the target Mach number and calibrated airspeed (CAS) that result from the flight-specific Cost Index (CI) yet taking into account operational constraints and limitations. In addition the FMS provides automated vertical guidance along the path. For aircraft not equipped with vertical guidance capability, simple rules of thumb can be applied manually by the crew to fly a near-idle thrust descent which is a less automated form of a continuous descent operation. Vietor described a method to fly a continuous descent profile using basic arithmetic [3].

¹ Single European Sky ATM Research (SESAR).

PROBLEM DEFINITION

From an ATM perspective, continuous descent operations provide the Flight Management function (either in the role of FMS or pilot) with more freedom to manage the descent compared to an ATC initiated step-down descent. This freedom brings with it an uncertainty for ATC regarding the aircraft's performance and profile. Secondly, for successful CDO, the entire lateral path to the runway threshold must be known by the Flight Management function prior to commencing descent, and this path should remain unchanged. Open-loop vectoring, a method commonly practised by ATC to establish a landing sequence, can therefore not be used. The uncertainty of aircraft performance combined with limited sequence resolution options makes ATC only allow a continuous descent operation in limited conditions. Increased predictability of the aircraft's performance during such operations is therefore essential to allow this procedure in dense traffic.

PREVIOUS RESEARCH WORK

Numerous studies have been performed throughout the world into the development of procedures to allow continuous descent operations in dense traffic conditions. Some of these studies focus on improved trajectory prediction by ATM systems to better anticipate aircraft behaviour [4-6]. Using data-link technologies existing today these authors successfully used a ground-based trajectory predictor to provide better temporal predictability by predicting the speed variations during a path managed descent [6].

Other studies focus on different guidance strategies for an aircraft to conduct a descent and consequently a different effect on predictability. In Ref [7] an aircraft guidance strategy, Continuous Descent Arrival (CDA) for Maximum Predictability (CDA-MP), is proposed that improves temporal predictability of an intermediate fix on descent while keeping the throttle at idle. Disturbance compensation is performed through use of the aircraft's potential energy to closer maintain the kinetic energy at the intended level therefore improving ground speed predictability and hence

time, however achieved at the cost of loss in vertical predictability.

Most modern FMSs possess the ability to provide active control to meet a time constraint on cruise. Some FMSs are even able to do so for a point on descent. This functionality is referred to as Required Time of Arrival (RTA) [8]. With use of the RTA function, the fix at which the time constraint is set will be crossed with high temporal predictability as demonstrated in flight trials [9; 10]. To do this the RTA algorithm changes the descent speed schedule, and therefore the descent profile, in the presence of disturbances. Again the increased temporal predictability comes at the cost of decreased vertical predictability.

In essence both the CDA-MP and RTA use potential energy (altitude) to account for disturbances during the execution of the descent. While this provides improved temporal predictability at a specific fix of interest, the resulting altitude variation needs to be solved prior to capturing the glide path for final approach. Any manoeuvres to affect this could lead to increased fuel burn and time drift effectively meaning that the problem of unpredictability has shifted from before the fix-of-interest to beyond.

CONTRIBUTIONS OF THIS PAPER

In this paper, time drift and additional fuel burn is investigated for different existing aircraft descent guidance strategies when after the fix-of-interest the aircraft is required to recapture the original path at some stage prior to landing. The aim is to provide an understanding of how the different guidance strategies performed by aircraft automation affect the predictability of the entire descent trajectory, and not just the trajectory into a specific fix-of-interest like a merging point, metering fix or any other intermediate fix on the descent trajectory.

DESCENT PLANNING

A typical aircraft optimised and managed descent is visualised in Figure 1 and would be performed as follows. Throttle is set to idle and descent is initiated at the cruise Mach number (cruise speed forward propagation). At

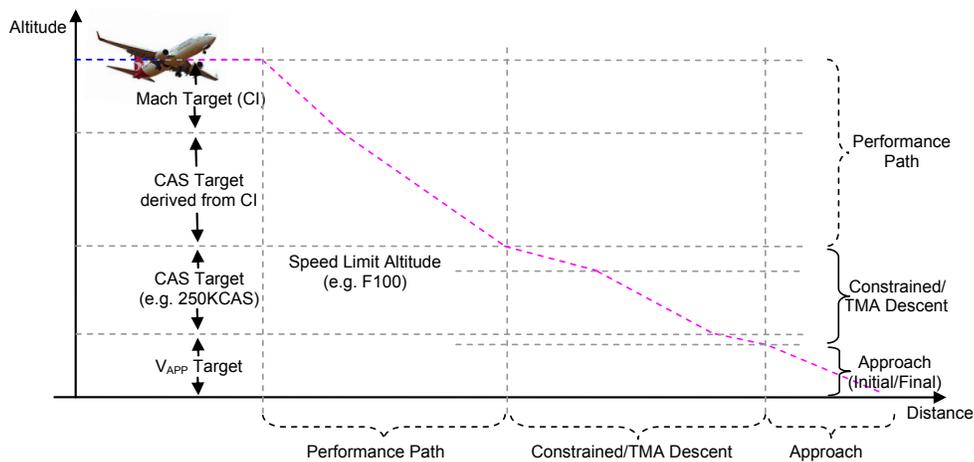


Figure 1: Optimised Procedural Descent.

crossover altitude, the descent is continued at the target descent CAS until the first constraint. Generally there exists some speed constraint at a point or at least below 10,000ft, airspeed is constrained to 250KIAS². Deceleration is achieved by a (near) level segment at idle thrust. The descent continues at 250KCAS until at some stage, depending on operator procedures, further deceleration to minimum clean speed is initiated. From this point on the aircraft decelerates on profile to final approach speed and the high lift devices are configured accordingly in steps. At final approach, thrust is required to maintain airspeed and stabilise the aircraft for landing.

This is a description only of the aircraft's longitudinal behaviour. Laterally, it is assumed that the aircraft flies a pre-defined lateral path with lateral ambiguity constrained by the performance based navigation value the aircraft is capable of.

The objective of the planning phase of the optimised descent is to build the descent profile for which the required deceleration and altitude loss from cruise conditions are achieved by the work done by drag forces and gravity, i.e. the engine throttle is set to idle and kept there until the Final Approach Fix (FAF). It is evident that accurate estimation of the energy dissipation on descent is essential, which is performed implicitly by the FMS. Equation (1) provides a simplified expression for the energy balance between Top of Descent (TOD) and the FAF,

$$\frac{1}{2}mV_{TOD}^2 + mgh_{TOD} + \int_{TOD}^{FAF} \hat{T} ds - \int_{TOD}^{FAF} \hat{D} ds = \frac{1}{2}mV_{FAF}^2 + mgh_{FAF}, \quad (1)$$

where V is groundspeed, h is altitude, T is thrust, D is drag and mg is aircraft weight. The first two left hand terms indicate the total energy possessed by the aircraft at TOD. This total energy is to be reduced such that the final approach speed and altitude are reached at the FAF. Therefore, the total energy dissipated on descent is implicitly determined in the descent planning process and given by

$$\hat{E}_{DES} = \int_{TOD}^{FAF} \hat{T} ds - \int_{TOD}^{FAF} \hat{D} ds. \quad (2)$$

In addition to accurate prediction of the aerodynamic, propulsive and gravity forces involved, also accurate prediction of the expected wind and temperature profile on descent is required. The forecast model used by the FMS is rather basic and hence influences the accuracy of the (implicitly) determined total energy to be dissipated on the computed descent path [11; 12]. Any difference between

the predicted total energy, \hat{E}_{DES} , and actual total energy, $(E_{DES})_{ACT}$,

$$E_{EXC} = \hat{E}_{DES} - (E_{DES})_{ACT}, \quad (3)$$

must be accounted for during the execution of the descent and leads to deviations from the reference trajectory depending on the active guidance strategy (this value could of course be negative to indicate a shortage).

AUTOMATED DESCENT GUIDANCE STRATEGIES

Next, three different existing guidance strategies will be discussed as means to achieve (components of) the planned reference trajectory discussed in the previous section.

Speed Managed Descent

For Boeing aircraft this mode is referred to as VNAV-SPEED (or speed descent even air-mass descent) and for Airbus aircraft as Open Descent. Other manufacturers may use different terminology but in essence they are very similar; elevator control is applied to maintain the target Mach or CAS while maintaining idle thrust [13; 14].

An error in predicted total energy or a disturbance will be balanced by altitude, i.e. potential energy. This means that in order to maintain the target speed, the aircraft deviates from the planned path. If for example the aircraft encounters more headwind than what was predicted by the forecast used in the descent planning phase, the planned descent path is too shallow to be flown at the target speed while maintaining idle thrust. Elevator control is applied and the aircraft is pitched down to maintain the target speed. Because of the pitch down the geometric path angle is increased and hence the aircraft enters a 'below path' situation. The prediction error will therefore be mainly in the altitude component of the trajectory. Prior to reaching the FAF a (near) level segment may be required to bring the aircraft back on the planned vertical profile.

During this mode of operation, the aircraft is executing the performance descent; the CI determined target speeds are attempted to be held at idle thrust setting.

Path Managed Descent

For Boeing aircraft this mode is referred to as VNAV-PATH (or Path Descent) and for Airbus aircraft as Managed Descent, however again in essence they are very similar; elevator control is applied to maintain the planned geometric descent path at idle thrust [13; 14].

An error in predicted total energy will be compensated by speed variations, i.e. kinetic energy. If for example again the aircraft encounters more headwind than forecasted, the planned descent path cannot be held at the target speed while maintaining idle thrust. Elevator control is applied and the aircraft is pitched up to maintain the path causing the airspeed to decrease. If required, thrust may be added through throttle control when the airspeed deviates too far below target (auto-throttle or manual). Or similarly, speed brakes deflection might be required when the speed

² Indicated airspeed (AIS) is not corrected for instrument and position error while calibrated airspeed (CAS) is. In the remainder of this paper the difference between IAS and CAS is neglected and reference is made to CAS only.

deviates too far above target (manual). With reasonably accurate wind predictions, only in a limited number of situations thrust will be higher than idle resulting in an efficient flight profile. The prediction error will therefore be mainly in the time component of the trajectory as the difference in total energy is balanced by kinetic energy.

RTA Managed Descent

Some modern FMSs have been equipped with the Required Time of Arrival (RTA) functionality. If a time constraint is specified at a waypoint on the active flight plan, the FMS will attempt to eliminate the difference between the RTA time and the current Estimated Time of Arrival (ETA). On cruise this can be done by either speeding up or slowing down. On descent, a profile change could achieve the same result and maintaining the throttles at idle position.

The RTA descent can be flown as either speed or path managed. In a RTA speed descent the target speed schedule is respected and updated if the current Estimated Time of Arrival (ETA) exceeds the RTA with some threshold value. In a RTA path descent the path is respected where again the speed schedule is updated if the current ETA exceeds the RTA with some threshold value. The speed schedule is based on the CI, so effectively the RTA algorithm varies the CI such that ETA equals RTA.

SIMULATION OF TYPICAL DESCENT SCENARIO

To understand the effect of the different guidance strategies a generic descent scenario has been simulated with the use of MATLAB in the presence of a 10kt headwind error constant with altitude. It is investigated not only how the different guidance strategies affect the predictability of the arrival time at a metering fix, but also how it impacts the predictability of the remainder of trajectory beyond the metering fix. The scenario involves a Boeing 737-800 aircraft (B738) with a mass of 63000kg at a cruise altitude of 41,000ft. For all other aerodynamic and propulsive calculations the EUROCONTROL's Base of Aircraft Data (BADA) 3.8 is assumed. Further International Standard Atmospheric (ISA) conditions are assumed with nominal null wind conditions.

Reference Trajectory

A generic reference trajectory is computed according to the process discussed in the descent planning section (Figure 1), and similar to the way an FMS computes the reference trajectory. The assumed descent speed schedule is Mach 0.78 into 280KCAS. At 10,000ft a deceleration is modelled to 250KCAS. Descent is continued at 250KCAS until 5000ft where another deceleration segment slows the aircraft further down to minimum clean configuration speed after which flap deployment is commenced according to Table 1. While in reality these decelerations can be achieved through shallower-than-idle segments (as indicated in Figure 1, for simplicity of calculations level segments have been assumed. Upon reaching flap-5 speed, descent is continued along a -3 degree geometric segment to the FAF and subsequently to the runway. While

descending along this segment the aircraft is further decelerated and flaps and landing gear are configured accordingly. Assuming Visual Meteorological Conditions (VMC), the final approach speed (140KCAS) is reached well above the 1000ft minimum altitude for a stabilised approach. Appropriate thrust is added to stabilise the final approach.

In the simulations an altitude constraint (at-or-below 3000ft) is imposed at the FAF. This constraint can be compared to capturing the ILS glide path (from below) at the FAF.

A metering fix is assumed at 75 miles after TOD, the trajectory into this metering fix is not affected by any imposed constraints.

In Figure 2 the reference trajectory is indicated by the colour magenta. The top left plot shows altitude versus distance, and the top right plot shows CAS versus distance. The other lines represent the resulting trajectories of the different guidance strategies respectively which will be discussed in the following sections. The different strategies have been combined in a single figure to allow for quick comparison.

As previously mentioned, the nominal wind profile for calculating the reference trajectory assumes null wind, however the wind error at cruise altitude has been linearly blended with the nominal wind profile to 5000ft below the cruise altitude. This is believed to be consistent with the method an FMS blends observations with forecast to null the forecast error at the current position and altitude. The wind rate term in the equations of motion resulting from this linear blending has been ignored³.

This reference trajectory is subsequently executed using the three automated descent guidance strategies.

Table 1: Configuration Deployment.

	Flaps-1	Flaps-5	Flaps-15	Flaps-30 + L. Gear
CAS	210 kts	190 kts	170 kts	160 kts

Simulation of Path Descent

The path descent has been simulated by following the altitude profile of the reference trajectory at idle thrust. The middle row of plots in Figure 2 shows the deviation from the reference trajectory in altitude and airspeed (CAS). The presence of the constant headwind error effectively makes the path of the reference trajectory too shallow to be flown at idle thrust and at 0.78/280. As the path is actively controlled, consequently airspeed varies and the aircraft starts to slow down.

³ This term depends largely on the assumed wind error and blending characteristics. As these factors are uncertain and assumed, the term is chosen to be ignored.

Because of the lower airspeed, time drifts significantly from the reference trajectory as indicated by the lower right plot in Figure 2 where a positive error indicates a later arrival. Time drift and additional fuel burn for the metering fix and the FAF with respect to the reference trajectory are given in Table 2. There is an increase in fuel burn compared to the reference trajectory because of the increased flight time (due to lower groundspeed) and the final approach speed being reached earlier (thrust for stabilisation required earlier).

In terms of energy, the true energy dissipation occurs at a higher rate than anticipated by the idle-path of the reference trajectory⁴. As the path is held, the additional dissipation is achieved by bleeding off airspeed until equilibrium airspeed has been reached, i.e. kinetic energy is the source (or sink) to achieve the anticipated energy dissipation rate. This new equilibrium airspeed is effectively the speed at which the energy is dissipated as anticipated by the reference trajectory (but at a different airspeed). The energy deviation from the reference trajectory as a function of path distance is given in Figure 3; only the part of the descent into the metering fix has been displayed as the subsequent deceleration segments would make the graph complex to read. As the path is held, there is no deviation in potential energy, only in kinetic energy.

Simulation of Speed Descent

During the speed descent the target speed schedule 0.78/280 is held in the presence of the constant headwind disturbance. From Figure 2 it is clear that the speed schedule is respected, but at the cost of altitude. Note that the slight deviation in CAS visible in the constant Mach portion of the descent is due the path being steeper so as to maintain the target Mach number and distance being the plotting variable (cross-over altitude is reached after a shorter distance compared to reference trajectory). This is also the cause of the change in the altitude error plot around the cross-over point.

With airspeed (Mach or CAS) actively controlled, time drift at the metering fix is less than during the path descent (17sec; Table 2) but still present because of the headwind error (airspeed but not groundspeed is controlled). This reduced time drift, and thus increased temporal predictability comes at the cost of reduced predictability of altitude; the aircraft is 540ft below the reference trajectory when crossing the metering fix. The increased fuel burn into the metering fix is the combined result of increased flight time due to lower groundspeed and idle thrust at slightly lower altitudes (as the aircraft is below profile).

A path deviation at the metering fix has consequences for the predictability of the remainder of the trajectory. As the

aircraft is low on profile, the speed constraints of 250KCAS below 10,000ft and 185KCAS at 5,000ft are reached earlier along the track. Therefore a longer segment of the track is flown at lower speeds compared to the reference trajectory leading to additional time drift on top of the 'nominal' time drift due to the head wind error. This increased rate of time drift is clearly visible in the lower right plot of Figure 2. Note that the increased time drift rate only occurs when there is a speed deviation compared to the reference trajectory, in this case because the speed constraint is being reached earlier (middle right plot of Figure 2). Secondly, the 3000ft altitude constraint at the FAF is also reached earlier requiring a level segment to be flown (intercepting the glide-slope of the precision approach leading) to additional fuel burn (Table 2). Therefore the increased temporal predictability at the metering fix comes at the cost of loss in altitude predictability and additional fuel burn to compensate for this. The time drift at the FAF is the same as in the case of the path descent. This could be very much dependent on the scenario, definition of the wind profile error, mass of the aircraft, configuration deployment, etc; but it indicates that additional time drift after the metering fix can occur because of a below profile situation. In the next section a large number of simulations are investigated.

In terms of energy, the energy required to maintain the speed schedule is sourced from (or sunk to) the aircraft's potential energy. Figure 3 shows that at the metering fix there is a large deviation in potential energy but a smaller deviation in kinetic energy than in case of the path descent. The reason why there is still a deviation in kinetic energy is that only the Mach/CAS portion of the groundspeed is actively controlled (wind error still present). The deviation in potential energy is particularly interesting. With a fixed lateral path and a trajectory endpoint fixed in space (like the runway threshold), this deviation has to be corrected as altitude at the trajectory endpoint is not free. Assuming no time constraint at the runway threshold (this scenario will be discussed later), the potential energy deviation needs to be compensated for by a deviation in kinetic energy and/or energy needs to be added (setting higher than idle thrust: headwind) or dissipated (deployment of speed brakes: tailwind). In the simulation it has been assumed that the deviation in potential energy is solved by a level segment into the FAF where additional energy is added by the application of higher-than-idle thrust.

Simulation of RTA Descent

As previously discussed the RTA descent can be either executed as a path or speed descent where the target speed schedule is updated whenever the current ETA exceeds the time constraint with some threshold value. Difference between the RTA path and speed descent is very much dependent on this threshold value plus the difference of the forecast winds and the actual winds. Secondly, how the FMS constructs the RTA descent is dependent on if the altitude of the fix associated with the time constraint is below a certain threshold altitude, if there is a speed

⁴ The total energy decreases particularly fast in the first 15 nautical miles; this is a direct effect of the wind error blending discussed in the reference trajectory section.

constraint associated with the fix as well, and whether this speed constraint requires flap extension. Unfortunately, the RTA algorithms are proprietary information and therefore the behaviour can only be estimated. It is therefore why the time constraint in these simulations has been purposely chosen in the part of the descent free of constraints and where the aircraft is in clean configuration (performance path). In absence of specific knowledge on a particular RTA algorithm, a continuous re-computation of the target

speed schedule is assumed as to eliminate the difference between the ETA and the time constraint. This target speed schedule is subsequently executed at idle thrust. Note that in this particular case the RTA path and RTA speed descent are identical.

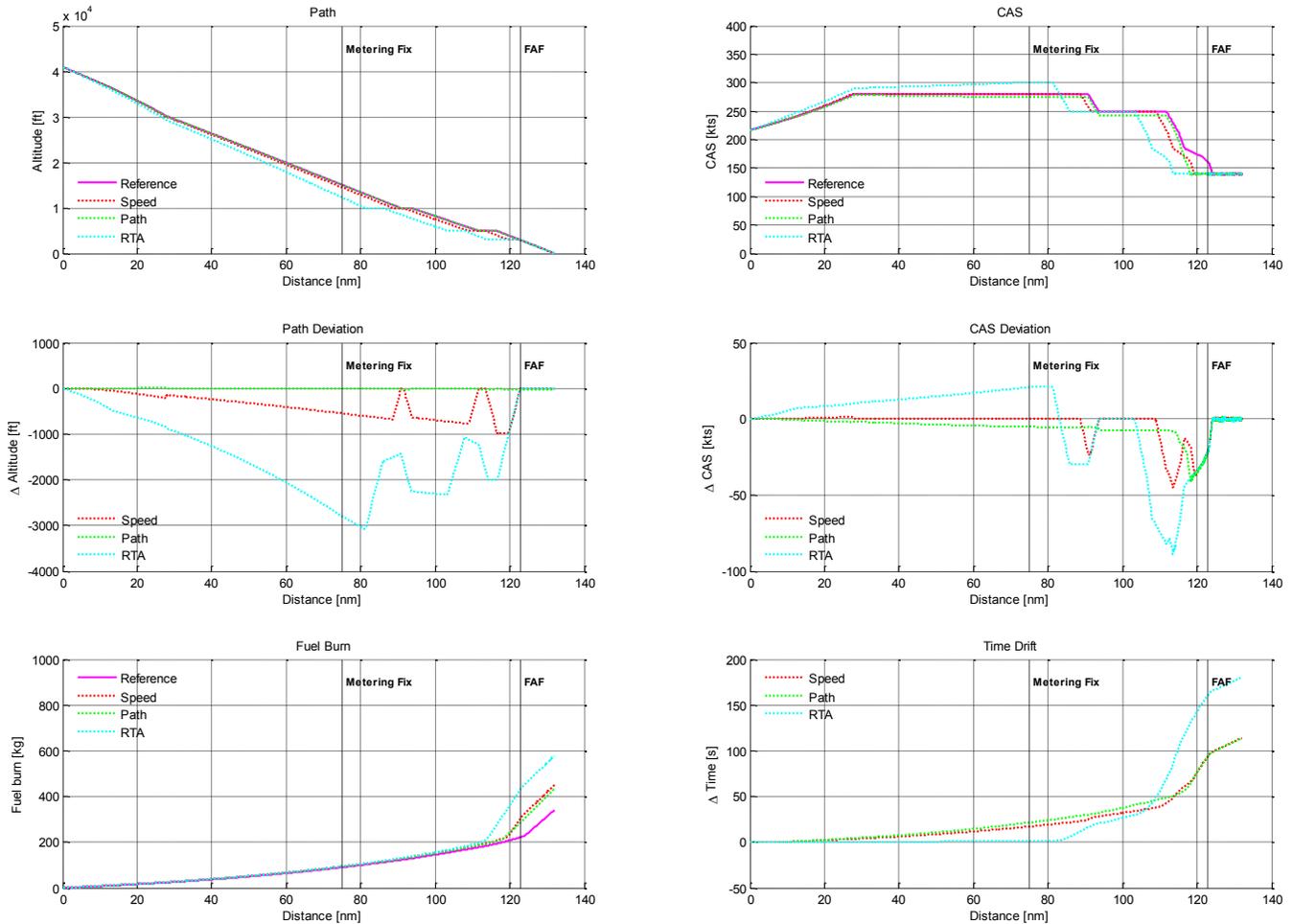


Figure 2: Simulation results.

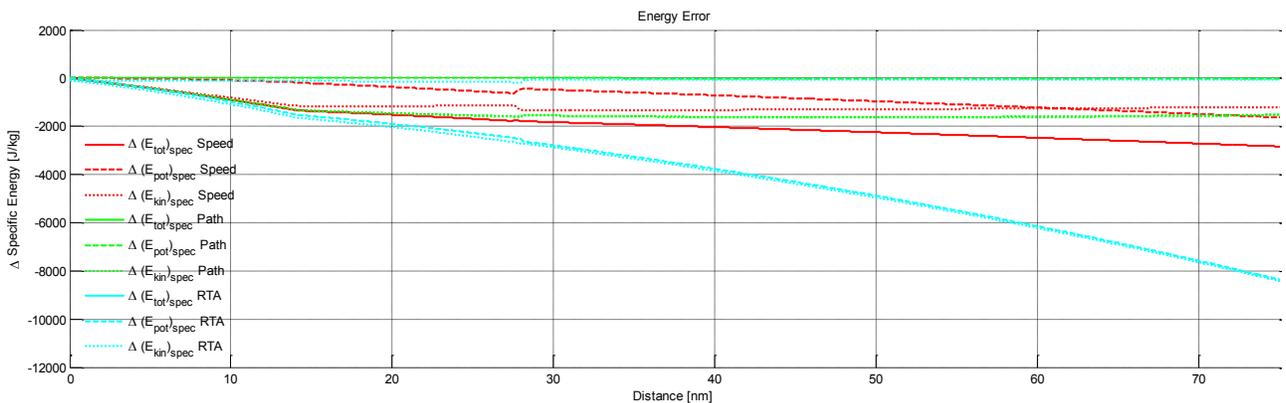


Figure 3: Energy Error (TOD to Metering Fix).

In this scenario it is assumed that the ETA at the metering fix of the reference trajectory is set as the time constraint. As the simulation starts at TOD, and there is no initial time-drift, no profile re-computation is triggered by the assumed RTA algorithm (also due to the vertical wind blending).

From Figure 2 it is clear that the aircraft continuously increases the airspeed (CAS) due to the headwind error, effectively attempting to maintain the groundspeed profile of the reference trajectory. With the throttle at idle, the energy required to do this is sourced from the aircraft's potential energy, i.e. descent rate is increased. Figure 2 clearly shows the large path deviation that result. After the metering fix, the speed schedule is no longer updated and the last determined speed schedule is held until reaching the speed constraint.

Similar to the speed descent, the additional energy required for the higher level of temporal predictability is sourced from the aircraft's potential energy and hence reduces the vertical predictability. The deviation at the metering fix in this case is nearly 2800ft. The reason why it is much larger is that more energy is required to not only maintain airspeed, but effectively to maintain the groundspeed of the reference trajectory. This path deviation at the metering fix needs to be managed prior to intercepting the final glide slope impacting the remainder of the trajectory. The path deviation is much larger than in the case of the speed descent, as is the additional time drift (speed constraints reached much earlier), and the additional fuel burn (altitude constraint reached much earlier). Another option would be to set the time constraint at the runway threshold; this option will be discussed later. Effectively, the uncertainty has shifted from before to after the metering fix. The additional fuel burn into the metering fix is small (idle thrust at slightly lower altitudes), but significant after. The high temporal predictability achieved with the RTA is therefore not free, with the cost coming after having passed the RTA point.

To limit the altitude deviation at the metering fix an altitude constraint could be specified. While this limits the vertical deviation, it would also limit the ability of the RTA algorithm to meet the time constraint with idle thrust. Higher-than-idle thrust or speed brake deployment might be required, or a larger tolerance to meet the time constraint must be accepted.

Figure 3 shows the large deviation in total energy at the metering fix. The additional kinetic energy is again sourced from the aircraft's potential energy. Similar to the previous discussion for the speed descent, this deviation in potential energy needs to be compensated for prior to touching down. Again it is assumed a level segment is flown as consequence of the altitude constraint at the FAF at higher-than-idle thrust to add the required additional energy to the system. Instead of a level segment the FMS could plan a shallower-than-idle segment. The consequence of this will be discussed later.

Table 2: Time drift and add. fuel burn (10kt headwind error).

	Δt_{MF}	ΔH_{PMF}	ΔFb_{MF}	Δt_{FAF}	ΔFb_{FAF}
Path	21 sec	10 ft	3 %	114 sec	27 %
Speed	17 sec	540 ft	3 %	114 sec	33 %
RTA	1 sec	2790 ft	4 %	180 sec	70 %

Tailwind Disturbance

In case of a tailwind error, the above discussion can be mostly reversed. In the path descent the aircraft is speeding up and in the speed and RTA descent the aircraft ends up being above path. In both cases this additional energy, either kinetic or potential, needs to be dissipated prior to intercepting the final glide slope which for safety reasons should never be intercepted from above [15]. This energy dissipation can either be achieved through manual speed brake deployment, or anticipation can be made in the reference trajectory by planning a short level segment into the FAF or intentionally 'adding' energy to the path. The latter effectively means that the path is intentionally build a little shallow to account for tailwind disturbances (balance the additional energy). This ensures to some degree that the automation can remain in control in the presence of (tailwind) disturbances and undesirable 'high and fast' situations (i.e. too much energy) are prevented. Additionally, speed brake deflection in flight results in some discomfort to passengers and additional wear on the airframe.

MULTIPLE SIMULATIONS

The previous simulation was mainly included for illustrative purposes. To gain a broader understanding of the time-drift for the different automated descent guidance strategies, multiple simulations have been performed by application of the Monte Carlo method. In addition to a (stochastic) wind profile error, a stochastic Aircraft Performance Model (APM) error has been added. All other variables remained unchanged. The simulation was repeated 2500 times.

Wind Profile Error

Again null wind conditions are assumed for the nominal case (reference trajectory) so as to provide an averaged case between forecast headwind and tailwind on descent. The constant component is assumed to be Gaussian with zero mean and 5kts standard deviation,

$$\varepsilon(W) \sim N(0, (5\text{kts})^2). \quad (4)$$

which is consistent with previous research performed into the accuracy of forecast meteorological products [12].

Aircraft Performance Model Error

Assuming a point mass model, the equation of motion in the direction parallel to the airspeed is

$$m\dot{V}_{TAS} = T - D - mg \sin \gamma_{TAS} + m\dot{W}, \quad (5)$$

where V_{TAS} is true airspeed, γ_{TAS} is aerodynamic path angle and W wind parallel to the airspeed. If it can be assumed that the wind rate of change parallel to the airspeed is small⁵, (5) can be written as

$$\frac{1}{g} \dot{V}_{TAS} = \frac{T-D}{mg} - \sin \gamma_{TAS}, \quad (6)$$

where the term $(T-D)/mg$ is associated with the APM.

When computing the reference trajectory, there will in general be some error in the definition of the APM term. For example the true idle thrust value is difficult to estimate due to its dependence on atmospheric conditions, but also the true mass of the aircraft is not known. In addition, as discussed before, the term could be intentionally in error to provide a buffer to account for non forecast tailwinds; the descent path is intentionally build shallow to absorb additional energy due to higher groundspeeds because of tailwind disturbances to prevent over-speed situations [11].

From previous research work by these authors the following distribution for the APM error is assumed [6],

$$c_{APM} \sim N(-0.02, 0.01), \quad (7)$$

which for the B738 effectively means an intentional lower mass of 1000kg giving the capability to balance energy for the path (with T and D accurate) and a 95% error of ± 1000 kg to the aircraft mass (with T and D accurate).

Note that this APM error is added to the definition of the reference trajectory, while the wind profile error is added to the execution of this reference trajectory, i.e. the APM used to simulate the execution is assumed to be correct.

Results

The results of the Monte Carlo simulations are given in Figure 4. From the top, the rows indicate path descent, speed descent and RTA descent respectively. From left to right, the columns provide the distributions for metering fix ETA error, path deviation at the metering fix, additional fuel burn into the metering fix, ETA error at the FAF, and additional fuel burn into the FAF respectively. The bias in the distributions is clear and is a direct result of the additional energy intentionally ‘added’ to the reference trajectory as to account for tailwind disturbances without requiring constant (manual) speed brake deflection. In Table 3 the 95% ranges are given as a performance measure.

The data in Figure 4 and Table 3 are only of those flights that met the before mentioned stability criteria at final approach (hence the bars do not add up to 1). In some cases the tailwind disturbance is too large and could not be absorbed by the extra energy capacity built into the path. In such cases, manual speed brake deployment by the crew would have been required. As this study focuses on fully automated descent guidance strategies these manual actions have not been modelled. In total 98% of the simulated path descents met the stability criteria, 93% of the speed descents, and 76% of the RTA descents. As the speed and RTA descents are above path when experiencing strong non forecasted tailwinds (too much energy; high and fast), the required energy dissipation could not be achieved prior to passing 1000ft on final approach.

The results presented in Figure 4 and Table 3 are consistent with the previous discussions. Speed descent and RTA

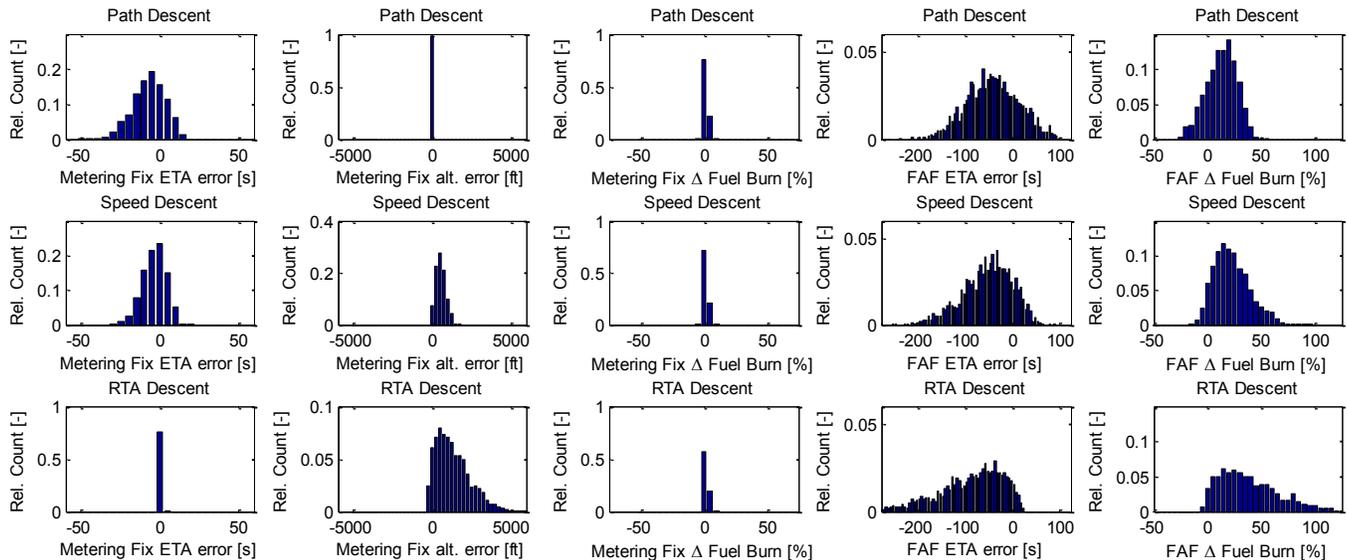


Figure 4: Monte Carlo simulations results.

⁵ In the simulations constant wind with altitude is assumed and hence this term is zero.

descent provide more predictability of the crossing time at the metering fix, but at the cost of vertical predictability at the metering fix and increased fuel burn after the metering fix. In reality, terrain surrounding a destination could limit the use of these guidance strategies but is not considered in this paper. In case of the RTA descent, there is also significant increased time-drift after the metering fix; 260 seconds compared to 173 and 171 seconds for the speed and path descent respectively. The difference in time-drift after the metering fix between the path and speed descent is interestingly not significant, however this is most likely dependent on the assumed speed constraints and the altitudes at which they are affected. This time drift after the metering fix means that additional sequencing actions will be required although the metering fix might have been passed 'on time' as clearly such large variations of FAF times is unacceptable to maintain runway throughput.

Table 3: 95% ranges.

	Δt_{MF}	ΔH_{PMF}	ΔFb_{MF}	Δt_{FAF}	ΔFb_{FAF}
Path	40 sec	50 ft	6 %	211 sec	53 %
Speed	29 sec	1200 ft	6 %	202 sec	63 %
RTA	1 sec	4030 ft	5 %	261 sec	105 %

DISCUSSION

The results of the simulations show the increased temporal predictability at the metering fix comes at the cost of additional fuel burn (speed/RTA) and decreased predictability (RTA) after the fix. The key is the deviation in potential energy at the metering fix. As explained previously, the endpoint of the trajectory is the runway threshold and hence is fixed in space (position and altitude). Therefore an energy error with respect to the reference trajectory cannot be compensated by potential energy as the end altitude of the trajectory is constrained and not free. If no time constraint at the runway threshold exists, kinetic energy can be used to compensate instead and forms the principle of the path descent. The path descent balances the total energy error over the entire descent with kinetic energy, leading to a consistent time drift. On the other hand, the speed and RTA guidance strategies are based on the principle of compensation by potential energy. As explained, at some point along the descent the obtained deviation in potential energy needs to be corrected either by adding energy or balancing it with kinetic energy. The problem of compensating for the error in energy is effectively pushed beyond the metering fix or any other fix at which high temporal predictability is desired, with resultant increased fuel burn and possibly additional time-drift as illustrated in Figure 5. Note that the total energy error at the metering fix in case of the RTA is purposely larger as previously illustrated in Figure 3. For these strategies the energy error is left to be solved after the

metering fix; this is why fewer simulations met the stability criteria.

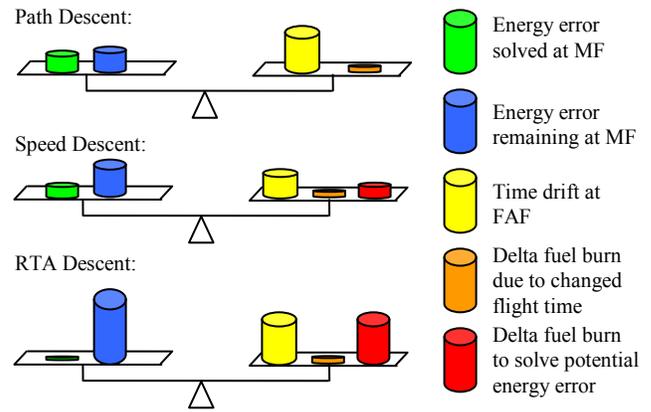


Figure 5: Energy error vs. time drift and extra fuel burn.

As briefly mentioned before, it is possible to set an RTA at the runway threshold. Flight trials have shown promising results in achieving the time constraint [9; 10]. With the trajectory endpoint now constrained in all four dimensions, the energy error with respect to the reference trajectory computed when still on cruise cannot be compensated with kinetic or potential energy. Instead this energy needs to come from additional fuel burn in the case of a headwind disturbance or dissipated through speed brake deployment in the case of a tailwind disturbance. While this appears a good solution, though at a cost of increased fuel burn (when path is intentionally shallow), a problem is the unknown behaviour of the aircraft to meet the RTA. The uncertainty at the runway threshold has now shifted to uncertainty of the aircraft's behaviour into this point. Different FMSs can have different RTA algorithms, and even with the same algorithm, depending on the forecast winds entered in the FMS and other specific settings, different speed schedules can be computed but also updated differently. As a result two initially separated aircraft both flying to respective appropriately set time-constraints over the same lateral track can infringe separation between them while attempting to achieve the constraint. As a solution time separation between following aircraft could be increased potentially leading to lost longitudinal capacity. This problem has not yet been solved and research is ongoing [16; 17].

A criticism of this study could be that instead of fuel-expensive level segments, shallower-than-idle segments are flown to correct the deviation in potential energy. If such segments are flown at idle thrust, the airspeed will drop and effectively kinetic energy is used to correct the potential energy deviation. If higher-than-idle thrust is commanded to keep the airspeed within close limits of the target, the required energy is again added by fuel burn. Level segments or shallow segments, either way the deviation in potential energy needs to be solved leading to some deviation from the reference trajectory, either in time,

altitude, fuel burn or combination of these. In addition, FMS strategies to rebuild the reference trajectory while on descent as to compensate for such errors are not fully understood or even proprietary (especially in the case of RTA algorithms). This lack of knowledge contributes to the uncertainty regarding the aircrafts behaviour when it is not controlling to a consistent reference trajectory as in the case of the path descent. Other criticism could be the simplistic RTA algorithm assumed (e.g. ETA drift threshold and allowed profile deviation), but again lack of knowledge of the true algorithms contribute to the uncertainty of aircraft behaviour to ATC while performing such descents.

While automated descent guidance strategies based on the principle of compensation by kinetic energy (e.g. path descent) do not provide the best temporal predictability at a single point of the trajectory, the discussions and simulations presented in this paper lead to believe that when considering the entire descent trajectory instead, such a strategy might be more appropriate than automated descent guidance strategies based on the principle of compensation by potential energy (speed/RTA descent). Firstly during the descent in normal conditions the FMS reference trajectory remains unchanged. This is not the case for guidance strategies based on the principle of compensation by potential energy as discussed. Secondly, the path descent is most fuel economical as shown by the simulations and as mentioned in Ref [18].

During a path managed descent and with three of the four dimensions of the reference trajectory actively controlled, only time remains open. While the path of the reference trajectory remains constant in time (provided no crew or ATC intervention during the CDA), the time-drift can be quite large as shown in this paper and form the major drawback of this guidance strategy. Previous work by these authors has shown that if the reference trajectory is down-linked from the FMS, the speed variations as result of holding the path at idle thrust can be predicted by a ground based trajectory predictor. Use was made of existing data-link technologies as Future Air Navigation Systems (FANS) which allows (part of) the FMS reference trajectory to be transmitted to ATC. Therefore, when this reference trajectory is transmitted to ATC prior to TOD, the ground based predictor can predict what the speed variations will be prior to the aircraft actually commencing descent! The research found a significant improvement in temporal accuracy of the metering fix crossing time compared to the aircraft's FMS through integration of the speed variations [6]. In addition, when the reference trajectory can be transmitted prior to commencing descent it provides visibility of the planned profile to both ATC and the flight crew. Using this new prediction methodology the non-controlled dimension, time, becomes better predictable, and hence the path descent appears most predictable and fuel economical when considering the entire descent.

CONCLUSION

Modern FMSs have the ability to execute efficient idle-thrust descents. Uncertainty of aircraft behaviour while performing such descents is a prime reason why ATC cannot always facilitate without intervention. This paper investigated and compared the impact on predictability of the executed trajectory for different aircraft guidance strategies.

Automated descent guidance strategies based on the principle of disturbance compensation by potential energy (e.g. speed descent and RTA descent) support the most accurate temporal predictability for an intermediate fix on the descent trajectory. This increased predictability is not free but comes at reduced vertical predictability of the entire descent, increased fuel burn, and possible reduced temporal predictability after the fix of interest. These guidance strategies therefore effectively shift the problem of reduced temporal predictability beyond a fix of interest.

Automated descent guidance strategies based on the principle of disturbance compensation by kinetic energy (e.g. path descent) provide the least temporal predictability at a single point of the trajectory, but these strategies provide a more predictable descent due to a consistent descent profile. In addition, these descent guidance strategies are the most economical. Allowing an aircraft to control to a known path in the presence of disturbances leaves only the fourth dimension, time, as uncertain. However, previous research by these authors has demonstrated that this problem can be overcome through the use of existing data-link technologies and advanced ground-based trajectory prediction. With use of these technologies aircraft can be permitted to operate in an efficient, consistent, and predictable manner meeting ATC objectives.

REFERENCES

- [1] International Civil Aviation Organization. (2005). *Global Air Traffic Management Operational Concept*. ICAO.
- [2] International Civil Aviation Organisation. (2010). *Continuous Descent Operations (CDO) Manual (Doc 9931)*. Montreal, Quebec, Canada: International Civil Aviation Organization.
- [3] Vietor, C.W. (1990). *Precision Three-Dimensional Flying for Jet Transport Aircraft - The Profile Descent*.
- [4] Courdacher, T., & Mouillet, V. (2008). *ADAPT Aircraft Data Aiming at Predicting the Trajectory*: EUROCONTROL.
- [5] López, J., Vilaplana, M., Bayraktutar, I., Klooster, J.K., Asensio, J.M., McDonald, G.N., & Kappertz, P. (2009). *Towards an open test bed for the study of trajectory synchronization in the future ATM system: The ASIS Initiative*. Proceedings of the ICNS 2009 "The Integrated Trajectory" - Getting There, Arlington VA.

- [6] Bronsvooort, J. (2011). *Improved Ground-Based Trajectory Prediction for Air Traffic Management*. MSc Thesis. Submitted to Department of Air Transport Operations (ATO), Faculty of Aerospace Engineering, Delft University of Technology, Delft, The Netherlands.
- [7] Gomez Ledesma, R., Navarro, F.A., & Figlar, B. (2007). *Continuous Descent Approaches for Maximum Predictability*. Proceedings of the 26th Digital Avionics Systems Conference.
- [8] Jackson, M.R.C. (2008). *Role of Avionics in Trajectory Based Operations*. Proceedings of the 27th Digital Avionics Systems Conference.
- [9] Wichman, K.D., Carlsson, G., & Lindberg, L.G.V. (2002). *Flight Trials: "Runway-to-Runway" Required Time of Arrival Evaluations for Time-Based ATM Environment - Final Results*. Proceedings of the AIAA Guidance, Navigation, and Control Conference and Exhibit, 5-8 August 2002, Monterey, California.
- [10] Klooster, J.K., Wichman, K.D., & Bleeker, O.F. (2008). *4D Trajectory and Time-of-Arrival Control to Enable Continuous Descent Arrivals*. Proceedings of the AIAA Guidance, Navigation and Control Conference and Exhibit, Honolulu, Hawaii, USA.
- [11] Bronsvooort, J., McDonald, G.N., Potts, R.J., & Gutt, E. (2011). *Enhanced Descent Wind Forecast for Aircraft*. Proceedings of the Ninth USA/Europe Air Traffic Management Research and Development Seminar (ATM2011), Berlin, Germany.
- [12] Bronsvooort, J., & McDonald, G.N. (2009). *Tailored Descent Winds Evaluation*. Melbourne: Airservices Australia.
- [13] Honeywell. (2002). *Airbus A319/320/321 Pegasus Flight Management System Pilot's Guide*. Phoenix, Arizona, USA: Honeywell Aerospace Electronic Systems.
- [14] General Electric Aviation Systems. (2010). *FMCS Guide (FMC Update 10.8A)*.
- [15] CANSO. (2011). *Unstable Approaches ATC Considerations*. [Brochure]. <http://www.canso.org/safety>: CANSO – the Civil Air Navigation Services Organisation
- [16] Klooster, J.K., & de Smedt, D. (2011). *Controlled Time-of-Arrival Spacing Analysis*. Proceedings of the Ninth USA/Europe Air Traffic Management Research and Development Seminar (ATM2011), Berlin, Germany.
- [17] Jackson, M.R.C. (2009). *CDA with RTA in Mixed Environment*. Proceedings of the 2009 IEEE/AIAA 28th Digital Avionics Systems Conference (DASC) Orlando, Florida, USA.
- [18] Boeing. (2008). *737 - 600/700/800/900/900ER Flight Crew Training Manual*: The Boeing Company.