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Time-based Spacing for 4D Approaches using Speed-Profiles

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Two of the major projects in ATM development, SESAR and NextGen, both forecast the use of 4D trajectories as an intermediate phase in the development of full Performance Based Trajectories. Using 4D trajectories, the full positional and time coordinates of the aircraft are known throughout the planned trajectory. During approach, when reduced separation minimums are applied, the accuracy of this profile is most important to ensure a safe approach to the runway. One implementation of 4D approaches is by using Required-Time of Arrival (RTA) to separate aircraft during approach. The latest Flight Management Computers are capable of calculating a flight-path w.r.t. to a RTA. This paper describes the amount of time error that can occur during approaches where an RTA is set at the runway threshold that could still be resolved by increasing or decreasing the speed-profile. The minimum and maximum bounds are referred to as control space. Using simulations, the recoverable time error is calculated. Lateral trajectories from Amsterdam Airport Schiphol, different wind conditions and two different aircraft types were included to investigate different factors influencing the time error, such as aircraft type, speed restrictions and wind. Finally, the paper discusses a new method to control time-based spacing using a closed-loop speed controller.

Nomenclature

α_T	Thrust angle of attack
γ_a	Aerodynamic flight-path angle
γ_k	Kinematic flight-path angle
$\Delta\gamma$	Difference between γ_k and γ_a
μ_a	Aerodynamic roll angle
D	Drag
g	Gravitational constant
L	Lift
T	Thrust
V_a	Aerodynamic speed (TAS)
V_w	Wind speed
V_{FE}	Maximum speed for a flap setting
$V_{stall_{flap}}$	Stall speed for a flap setting
χ_a	Aerodynamic track angle
χ_k	Kinematic track angle
χ_w	Wind track angle
X_g	X-coordinate in geodetic reference frame
Y_g	Y-coordinate in geodetic reference frame
Z_g	Z-coordinate in geodetic reference frame

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ASAS IM	Airborne Surveillance Applications Interval Management
ATC	Air Traffic Control
ATCo	Air Traffic Controller
BT	Business Trajectory
CBS	Dutch Central Bureau of Statistics
CDO	Continuous Descent Operations
CTA	Controlled-Time of Arrival
FICAN	Federal Interagency Committee on Aviation Noise
DBN	Distance-based Navigation
ERD	Energy Rate Demand
ETA	Estimated-Time of Arrival
FDE	Flight Dynamics Engine
FMC	Flight Management Computer
FSX	Microsoft Flight Simulator X
IAF	Initial Approach Fix
ILS	Instrument Landing System
P-RNAV	Precision Area Navigation
PBN	Performance-based Navigation
RTA	Required-Time of Arrival
SEL	Sound Exposure Level
TBN	Time-based Navigation
TBO	Trajectory-based Operations
TTG	Time-to-Go

I. Introduction

Both in the United States (NextGen) and in Europe (SESAR), the aviation industry and governmental organizations are collaborating in projects to increase the flexibility of their respective airspaces whilst increasing capacity, reducing the impact on the environment and increasing aviation safety.[1,2] To allow more flexibility, SESAR, aims at implementing Trajectory-based Operations (TBO)[3] where each aircraft is assigned a Business Trajectory (BT) which defines the mission intentions of the aircraft whilst adhering to all ATM constraints. The trajectory is constructed collaboratively between the involved ANSP's and the airline. The BT fully describes the trajectory the aircraft will fly in 4 dimensions (position [x,y], altitude and time). Since all stakeholders are involved in constructing a BT, the most 'efficient' trajectory complying with all demands from all users could be constructed. These routes are made possible by new navigation technologies, such as Performance-based Navigation (PBN),[4] which identifies the navigation requirements for a particular airspace which airspace users need to adhere to.

PBN applied during TBO has a number of advantages compared to the current ATM system applying Distance-based Navigation (DBN) and navaid based routings. PBN allows a more efficient use of airspace and does no longer require the use of expensive and maintenance-prone ground navaids. Depending on the aircraft equipment, a more efficient trajectory is possible based on the performance of onboard equipment.

As an intermediate stage between DBN and PBN, SESAR anticipates on the use of Time-based Navigation (TBN) as a method for aircraft separation spacing while the industry is developing technologies for full implementation of PBN. During TBN, aircraft are given a Controlled-Time of Arrival (CTA) at particular waypoints along their trajectory and the aircraft crew is tasked with meeting this CTA using the latest Flight Management Computers (FMC) with CTA capabilities[5,6] or by manually flying the aircraft. By setting a CTA or Required-Time of Arrival (RTA) at the threshold, aircraft separation can be assured during final approach to the runway and airport capacity can be maintained.[7,8] During this approach, constraints on airspeed and altitude can be given such that the FMC can construct a vertical- and speed-profile to reach the threshold in time. With this profile, the 4D position of the aircraft is known throughout the entire approach.

Another foreseen feature of TBN is Airborne Surveillance Applications Interval Management (ASAs IM).[9] ASAs IM is conceptually different from using CTA's or RTA's, as aircraft receive a *relative* time spacing from a preceding aircraft, where RTA's and CTA's are absolute time constraints. Aircraft broadcast their state-vector through ADS-B containing the Estimated Time of Arrival (ETA) at a predefined point along the trajectory such that trailing aircraft can use the ETA and instructed time interval to construct a variable, *absolute* 'CTA' at that specific point. The use of Interval Management is foreseen in a Dutch research initiative, which develops technologies for short-term improvements in noise and gaseous emissions.[10] This initiative uses ASAS IM at Schiphol to increase runway capacity during CDO operations.

Although the profile and position are known throughout the entire 4D approach, wind prediction errors can accumulate such that the RTA is not reached at the agreed time. In cases where the pilot executes the profile manually, supported by display support tools,[11] pilot control errors can also contribute to time errors. The term time error at the threshold used in this paper is defined as,

$$\epsilon_T(s) = ETA(s) - RTA \tag{1}$$

A negative time error means the aircraft is early while a positive error means that the aircraft arrives late w.r.t. the RTA. Before starting the approach, an aircraft receives an RTA, which is fixed throughout the entire approach but the ETA and time error are variable. The research described in this paper investigated the time error that can be compensated for during approach while fulfilling constraints, such as speed or altitude restrictions. The results can be used for error prediction during automated flight but also serve as an error bound for pilot-errors introduced when manually flying an approach using a speed-profile.

Moreover, aircraft dynamics play an important role in the implementation of 4D approach trajectories. At the start of descent, the aircraft is in a high and fast state; hence, it has a high total-energy state, while at the end of the approach the aircraft is close to the ground at a speed close to the minimum reference speed and thus has a low total-energy state. An aircrafts approach can thus be described as a controlled loss of energy determined by the altitude and speed-profile as demanded by the trajectory from the Air Traffic Controller (ATCo). Traditional autopilot systems and avionics show velocity and altitude information separately, although in aircraft, these two types of energy are strongly coupled through total energy.[12] Using the elevator, the aircraft height can be lost in exchange for speed hence, exchanging potential energy for kinetic energy while maintaining the total energy level. Moreover, exchange of energy occurs relatively fast compared to increasing or decreasing total energy, by applying thrust or drag devices, due to the characteristics of engine and aircraft dynamics.[13]

In Section II, the operational scenario consisting of different aircraft and a real-world airspace scenario used in this paper is described. Section III describes the procedure to construct and update the speed-profile and RTA's. Different aircraft and different wind conditions require the development of different profiles. The simulation results are presented and discussed in Section V. Section VI covers a proposed design of a Time-to-Go controller which alters the speed profile to adjust for time errors. Finally, conclusions and recommendations are found in Section VII.

II. 4D Trajectories using Time Spacing

During night hours, Amsterdam Airport Schiphol operates using Continuous Descent Operations (CDO) to reduce the noise and gaseous emissions during night hours. Compared to conventional step-down approaches, CDO's require a low engine thrust to maintain airborne due to the removal of level flight segments from the approach path. Moreover, because of CDO's monotonically descending vertical path, the approaching aircraft maintains a higher flight path increasing the distance between the noise generating engines and residents living below approach routes; hence, less residents suffer from noise nuisance during the night.

Owing to the low engine thrust setting, CDO's can effectively reduce fuel burn and gaseous emissions compared to current conventional (step-down) approaches. Noise nuisance is also greatly reduced as less noise is produced by engines, while on ground the noise footprint is also reduced in size.

The CDO's at Schiphol are fixed lateral (P-RNAV) trajectories[14] from one of the three Initial Approach Fixes (IAF) to the active runway. At some locations, the vertical path is constrained by altitude or speed limits and the procedure requests pilots to construct a continuous descent to the runway. Besides these constraints, aircraft type, weight, equipage, pilot behavior and environmental factors determine the actual vertical trajectory to be flown.

Predicting aircraft trajectories of aircraft performing a CDO is a difficult task for ATCo's as a result of the many factors influencing aircraft behavior during these procedures.[15] Therefore, ATCo's use additional spacing buffers to increase aircraft separation but reducing the runway throughput and airport capacity. To allow the use of CDO's during hours of increased capacity, aircraft spacing should be minimal and the additional buffer should be removed. Using a tool as ASAS IM[10] should allow this since during ASAS IM, the aircraft, the flight crew executes and monitors IM commands to maintain properly spaced with the preceding aircraft, while the controller remains responsible for separation monitor.

Assume that an aircraft received clearance to execute the 4D engine-idle approach to the threshold and is halfway down to the runway and decelerating. Due to an underestimated head wind during the already flown segment, the aircraft will arrive later than the given RTA. By modifying the speed-profile, f.i, by keeping the current airspeed constant until a point where the aircraft must decelerate to reach the final approach speed, the obtained timing error could be resolved. An early arrival could be resolved using an opposite solution by rapidly decelerating final approach speed and maintaining the minimum speed for a longer period to increase the actual flight time. One remark has to be made here, in case the original profile was constructed with and engine-idle throttle setting, the new (error-free) profile is most likely not flown fully engine-idle. This research, assumes that an aircraft is capable of controlling its arrival time at the runway threshold, and to do so, the FMS generates a nominal speed- and vertical-profile flown by the autopilot (but could be flown manually using pilot support tools[11]).

Fig. 1 shows a nominal speed-profile and the maximum delaying and maximum accelerating profiles for an Airbus A321 at 17 NM from the runway. Clearly shown is a constant speed from 3 NM (or 1,000 ft) which corresponds to a stable ILS approach from 1,000 ft to the runway. It is assumed that the aircraft has the correct airspeed at the time the pilot decides to follow the maximum- or minimum-profile. In case of the maximum-profile, the IAS is kept constant until the maximum airspeed-profile is reached from which the aircraft will use its maximum deceleration capacity until the final approach speed is reached. In case of the minimum airspeed-profile, the aircraft immediately decelerates until the final approach speed is reached, and continues to the runway with a constant speed at the cost of increasing the thrust setting to compensate for additional drag generated by flaps. By following the maximum-profile, the aircraft can gain time w.r.t. to the current ETA while the dotted profile will delay the aircraft w.r.t. to the current ETA.

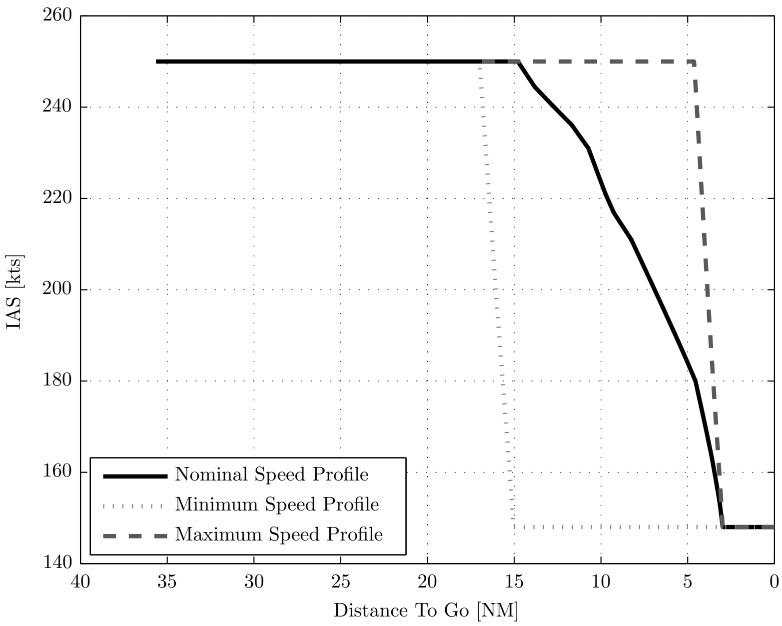

Figure 1. Example of nominal-profile for an Airbus A321 with minimum (dotted) and maximum (dashed) boundaries.

III. Constructing a Speed-Profile

When the vertical trajectory is fixed, the only alternative to control the arrival time of aircraft is by adjusting the (air)speed-profile. This section explains that for any given altitude-profile there exists a maximum airspeed-profile and a minimum airspeed-profile. Within this control space a new speed-profile can be found that resolves any occurring time error.

The airspeed-profile cannot be altered without constraints. Two constraints should be considered,

- The aircraft is limited in its deceleration capability by aircraft dynamics.
- The aircraft is not allowed to increase the Indicated Air Speed (IAS) during descending approach.

The first constraint, the maximum deceleration, is a physical constraint while the second constraint is imposed as it would be very unnatural for the pilot to accelerate during an approach. The maximum deceleration of the aircraft is determined by the equation of motion and corresponding aircraft state, such as flap setting, throttle setting, speed brakes, and altitude. The equations of motion for a point-mass are derived using the balance of forces in Fig. 2.

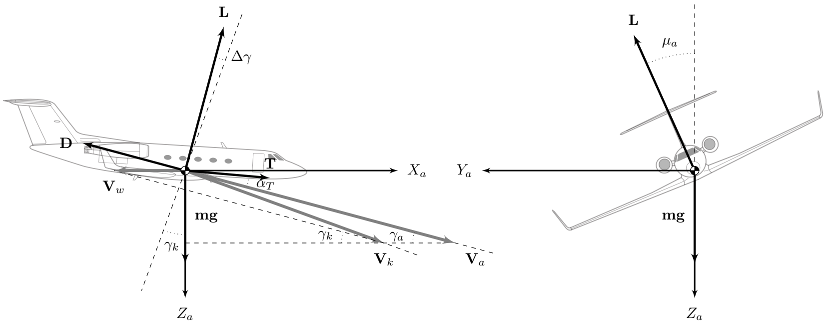

Figure 2. Equilibrium of forces acting on a modeled point-mass aircraft.

Assuming a small angle of attack and the thrust vector being in-line with the aerodynamic speed (true airspeed, V_a) ($\cos\alpha_T \approx 1$), the equations of motion in the aerodynamic reference frame, $\mathcal{F}_a$, are;

$$\begin{aligned} m\frac{dV_a}{dt} &= T - D - mg\sin\gamma_a \\ mV_a\dot{\chi}_a &= L\sin\mu_a \\ mV_a\dot{\gamma}_a &= -L\cos\mu_a + mg\cos\gamma_a \end{aligned} \tag{2}$$

When the vertical trajectory is known, the kinematic flight-path angle, γ_k is known as well. When no wind is present the aerodynamic and kinematic flight-path angles are equal and hence the aerodynamic flight-path angle, γ_a is known. However, in wind conditions, γ_a and γ_k are no longer equal. An aircraft experiencing a tailwind will have an increased the aerodynamic flight-path angle.[15] The opposite holds for a headwind which decreases the experienced aerodynamic flight-path angle. These changes in flight-path angle affect the deceleration of the aircraft and hence the possible speed-profiles.

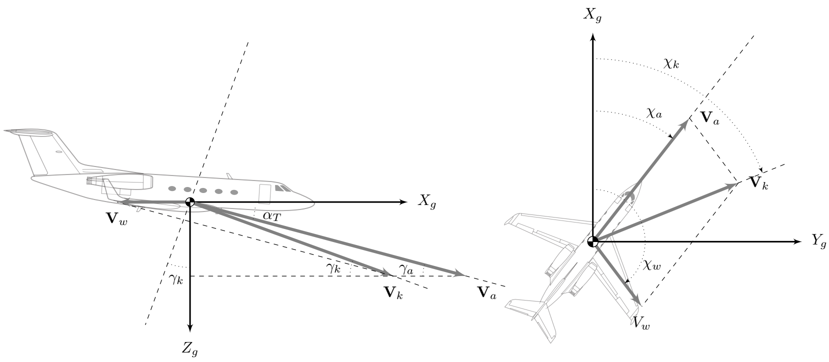

Figure 3. Side and top view of the kinematics of a point-mass model.

Using Fig. 3, the aerodynamic angles are derived. The derivation assumes that γ_a remains small using a small-angle approximation.

$$\begin{aligned} \chi_a &= \chi_k + \arcsin\left[\frac{V_w}{V_a}\sin(\chi_k - \chi_w)\right] \\ \gamma_a &= \arcsin\left(\frac{\tan\gamma_k}{\cos\chi_k}\left[\frac{V_w}{V_a}\cos\chi_w + \cos\chi_a\right]\right) \end{aligned} \tag{3}$$

To obtain maximum deceleration, drag, D, should be maximum while the engine thrust, T, should be minimal. In other words, maximum deceleration is achieved when the aircraft flies with engines set to idle and in full configuration with additional drag devices deployed. Drag can be controlled by applying flaps or speed brakes but flap deployment is limited by the maximum flap speed V_{FE} and aircraft stall speed V_{stall} for the different flap settings. Using these numbers, a flap schedule[15] can be constructed which contains the speed at which the pilot has to select the next flap setting. Thrust is controlled by the engine throttle setting which is minimal when set to engine-idle. The aforementioned parameters now determine the maximum obtainable decelerating for a particular aircraft.

An interesting metric which shows how close the aircraft is flying to its operational limits is the Energy Rate Demand (ERD), defined as,

$$\hat{E} = \frac{W\left(\gamma_c + \frac{\dot{V}_c}{g}\right)}{T_{idle} - D} \tag{4}$$

The numerator in Eq. (4) describes the *commanded* approach trajectory in the aerodynamic reference frame while the denominator describes the maximum obtainable energy dissipation by the aircraft. The ERD can, at maximum, be equal to 1, representing a situation where the aircraft is exactly flying the commanded vertical- and speed-profile. An ERD lower than 1, means that the aircraft has to increase thrust to be able to fly the prescribed profiles. An ERD greater than 1 is not possible during a decelerating descent. A full engine-idle approach would have an ERD of 1 during the entire approach, lower ERD values thus require an increased throttle setting. Energy Rate Demand is thus also a measure of how well the aircraft is performing an engine-idle procedure.

When an aircraft approaches a runway along a fixed (w.r.t. Earth) descent angle with a headwind component as prescribed by the altitude-profile, the aircraft will have to adjust its aerodynamic flight-path angle such that the aircraft follows the Earth-fixed descent trajectory. The longitudinal equation of motion (Eq. (2)) shows that this effects the deceleration performance of the aircraft and hence the speed-profile and finally the allowable time error. This effect occurs because the kinematic glide-path angle, γ_k, is fixed w.r.t. the ground and, therefore, the aerodynamic glide-path angle, γ_a, is reduced, resulting in a stronger deceleration.[15] The opposite is valid for a tailwind scenario; the aircraft will decelerate more slower. Due to the changing flight-path angle and deceleration, the values of V_c and γ_c in Eq. (4) change accordingly, influencing the value of the ERD.

The next section describes the set-up of vertical- and speed-profiles for the scenario used in this paper.

IV. Simulation Scenario

To investigate the effect of aircraft dynamics on the maximum allowable time error, expressed as either time profit (time able to gain) or time loss (time able to lose). If not specified otherwise, simulations were run using a point-mass model of an Airbus A321, based on reduced models of the actual flight models used by the Flight Dynamics Engine (FDE) of Microsoft Flight Simulator X (FSX).[15,16] Moreover, it is assumed that the flight-path angle, γ_a, is constant throughout the entire simulation because the vertical path is fixed. Any changes in flight-path angle due to wind and or path changes are modeled instantaneous; hence, the third equation of Eq. (2) results to $\dot{\gamma}_a = 0$.

The flap schedules applied in during simulations are based upon operational reference data, and shown in Table 1. For all scenarios, gear was extended while descending through 1,500 ft.

Table 1. Flap Schedule for the Airbus A321[17] and Boeing 747-400[18]

Airbus A321		Boeing 747-400	
KIAS	Settings	KIAS	Settings
250..231	clean	250..220	flaps 1°
231..211	CONF-1 (10°)	220..180	flaps 5°
211..163	CONF-2 (15°)	180..165	flaps 20°
163..153	CONF-3 (20°)	165..150	flaps 30°
153..148	CONF-Full (40°)		

The routing scenario used is an approach which is based on the P-RNAV routes to runway 18R at Amsterdam Airport Schiphol.[14] These fixed routes are used during the night hours during Continuous Descent Operations. The lateral path of the routes are situated as such that densely populated areas are not overflown. The ground track of the southerly approach route to runway 18R is shown in Fig. 4. Also shown in Fig. 4 are the wind directions covered in this paper. Wind, when present, is constant in both velocity and direction for all simulations and defined as shown in Fig. 4.

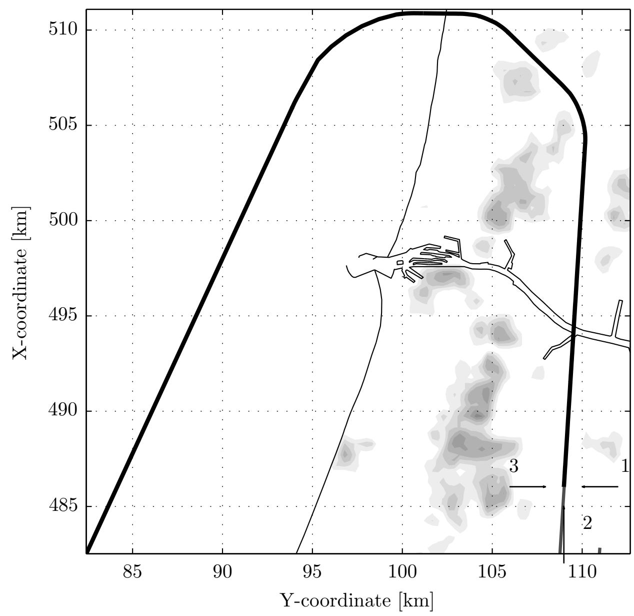

Figure 4. Approach ground track and simulated wind directions (threshold located at (109,486)).

V. Simulation Results

In this section the simulation results are presented. The following cases are investigated,

- Different aircraft types.
- Speed restrictions.
- Different wind conditions.

Besides constraints imposed by aircraft dynamics and pilot consideration, see Section III, constraints can be imposed by ATC for flow management reasons. Any imposed restriction will affect the amount of time error that can be resolved. The *time profit*, the time which can gained by maintaining the current airspeed, is calculated by determining the Time-to-Go (TTG) for the nominal-profile and the maximum-profile from a specific point during the approach. The time profit is equal to the the time error that at a particular point along the trajectory can maximally be resolved. The opposite holds for the *time loss* which is calculated by subtracting the TTG of the minimum-profile of the TTG of the nominal-profile.

In the case without speed restrictions it is assumed that the maximum indicated airspeed throughout the approach is 250 KIAS[a]. The vertical path is constructed such that all imposed altitude constraints are respected and all aircraft are capable of performing a decelerating descent without accelerating. Initially, the descent angle is 2° and at 3,000 ft, the descent angle increases to 3° to line-up with the geometry of a standard ILS glide slope.

V.A. Aircraft Type

All aircraft can assume any airspeed at any point along the approach provided that it can decelerate to the final approach speed before it reaches the stabilization/reference point (at an altitude of 1,000 ft). Fig. 1 shows the maximum and minimum airspeed-profiles. If the TTG of the altered airspeed-profile is subtracted from the TTG of the original airspeed-profile the result is the time profit obtained with the new airspeed-profile. The altitude and airspeed-profiles, ERD and thrust settings are shown in Fig. 5 and Fig. 6. The ERD-plots show that it is much harder for a 747 to lose total energy than for the smaller Airbus aircraft. The time profits for both aircraft types are shown in Fig. 7.

From Fig. 7 it is clear that a considerable amount of time can be gained by maintaining the current airspeed until the aircraft decelerates to the final approach speed. Doing this before the initial deceleration point has no effect as the speed is already at its maximum. The time delay which can be obtained by flying the minimum airspeed profile is even larger as the overall speed difference compared with the

[a]This is the maximum speed allowed below 10,000 ft.

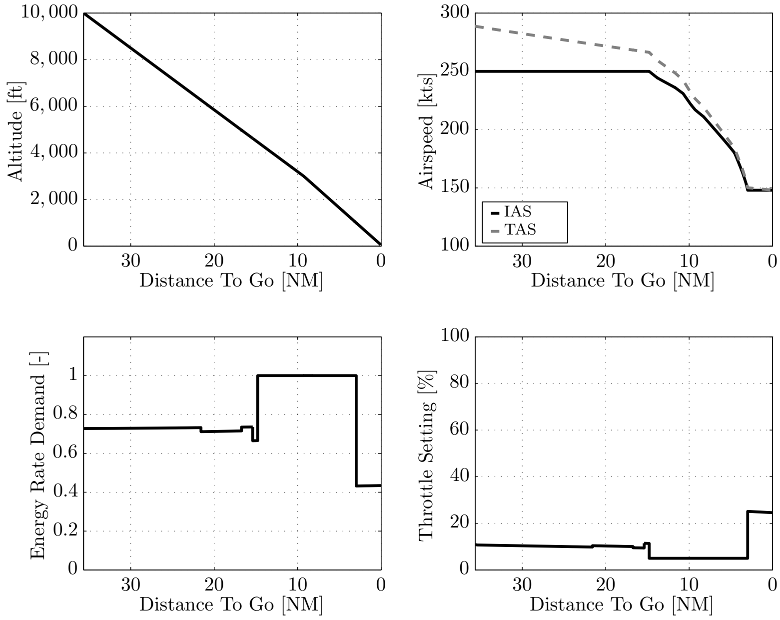

Figure 5. Approach profiles for the Airbus A321.

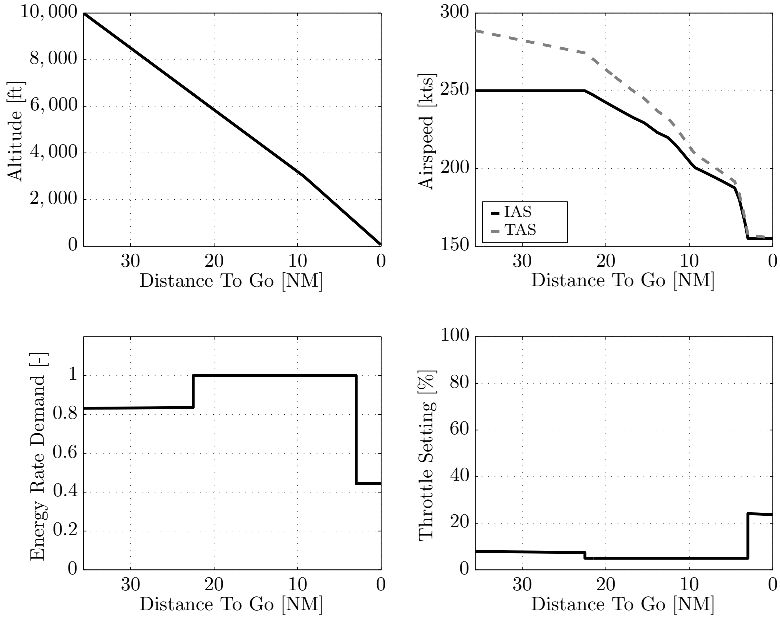

Figure 6. Approach profiles for the Boeing 747-400.

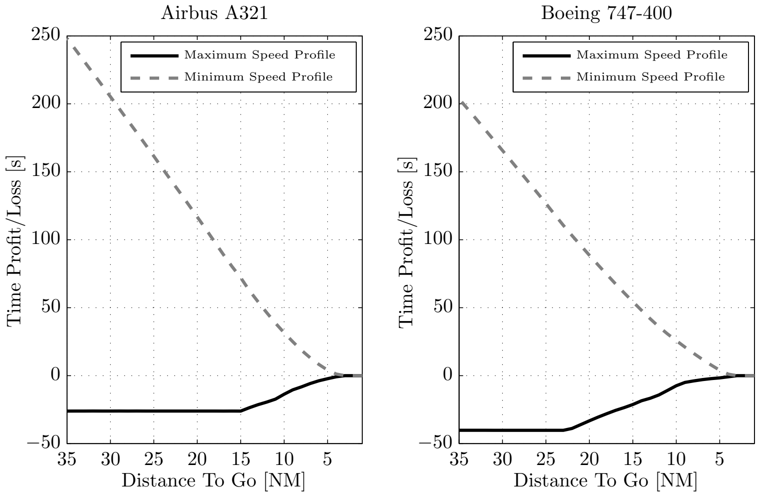

Figure 7. Time difference when using maximum or minimum airspeed profile.

nominal profile is larger. As the Boeing aircraft requires more altitude and time to decelerate, the maximum time profit is larger further away from the runway as it can maintain this maximum velocity for a longer duration. On the other hand, because the final approach speed is higher compared to that of the smaller Airbus aircraft, the minimum delaying time is slightly smaller.

V.B. Airspeed Restrictions

Airspeed restrictions limit the freedom of the aircraft to change its speed profile when required. In this scenario, aircraft are no longer allowed to decelerate during turns but must maintain a constant IAS. The result of these restrictions on the nominal profiles lead are shown in Fig. 8. A typical nominal, maximum and minimum airspeed profile for an Airbus A321 located 17 NM from the threshold is shown in Fig. 9. Moreover, the time profit and loss is shown in Fig. 10.

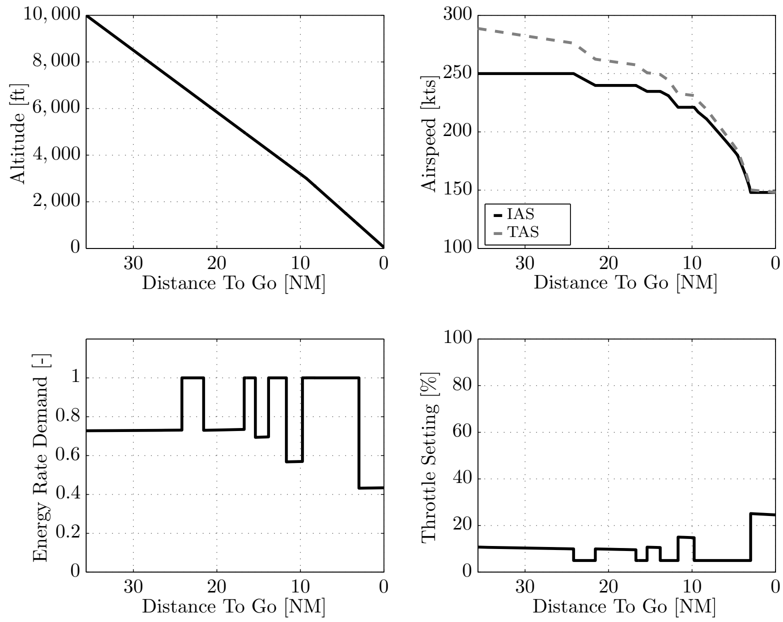

Figure 8. Approach profiles for the Airbus A321 with airspeed restrictions.

Comparing Fig. 10 with Fig. 7 shows that the restrictions cause a reduction in time profit during constant speed turn maneuvers. Both time profit and loss are constant during turns as no changes are allowed. Since the aircraft is not allowed to accelerate, there is actually already a speed restriction in

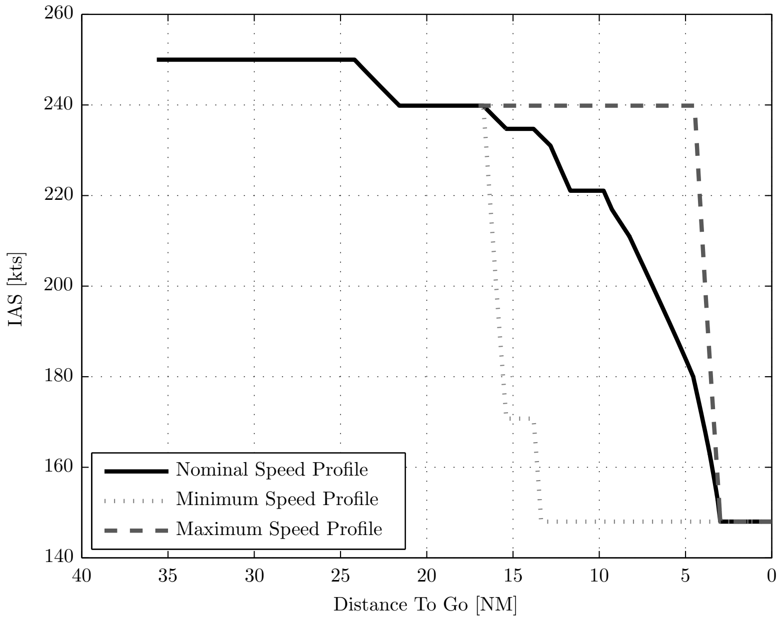

Figure 9. Maximum and minimum airspeed profiles with airspeed restrictions in turns included.

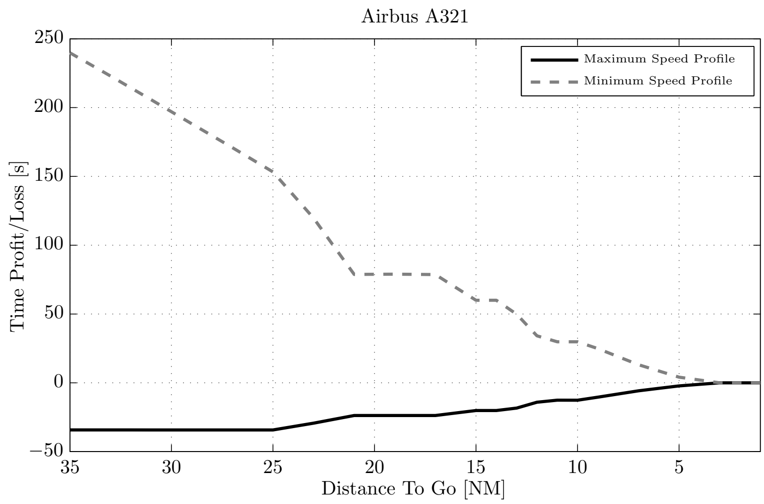

Figure 10. Time profits with airspeed restrictions included.

place. Lifting this restriction will lead to more time profit.

V.C. Wind Conditions

For the wind conditions, three different wind directions are considered and the wind speed is set to 10 m/s. The wind directions considered are from the South (almost head-on during final approach), West and East. The wind directions are shown in Fig. 4. This resolvable time errors for wind conditions is shown in Fig. 11. In this case, no air speed restrictions are applied. The amount of time profit or loss is comparable to the values found when no wind is applied. However, wind direction shows an effect on time profit and loss. This happens due to a change in ground speed caused by different experienced wind components throughout the descent.[15]

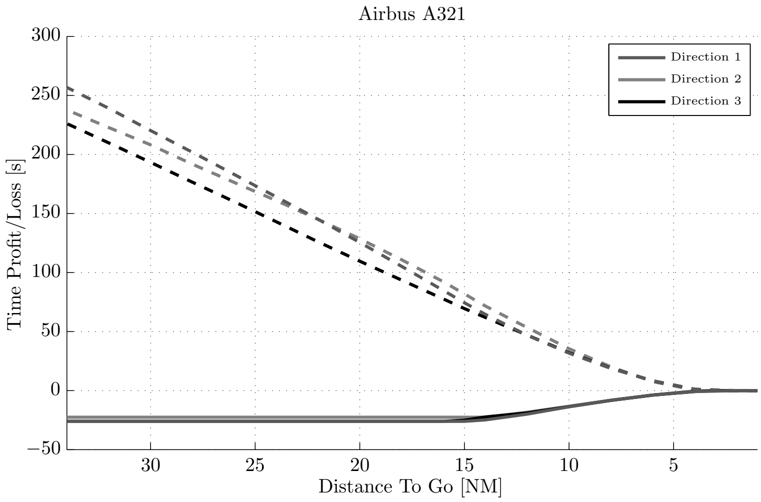

Figure 11. Time profit of nominal profile under wind conditions. Wind velocity 10 m/s.

VI. Solving for Time Errors within the Control Space

To solve for time errors that are within the minimum and maximum resolvable time error, a closed-loop speed controller (conceptually shown in Fig. 12), based on the NASA LaRC closed-loop speed controller[7] is proposed. The controller uses the FMCs current profile and current velocity and by subtracting these two profiles determines any time error and automatically tries to solve this by adjust the speed profile. The rate at which the controller is allowed to adjust the profile depends on the application of the controller.

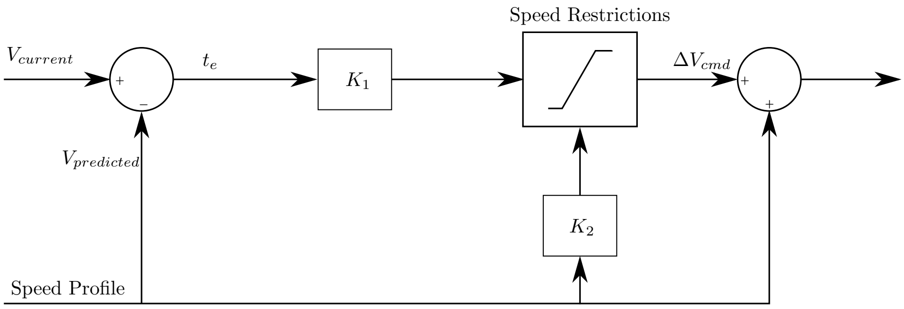

Figure 12. A closed-loop TTG speed controller used to solve time errors.

This paper assumes two different scenarios where the aircraft will have to correct for a time error. First, any deviation from the speed profile will result in a change in time of arrival. These deviations can be caused (amongst others) by FMC prediction errors or pilot errors. FMC prediction errors can be caused by different wind fields experienced during descent compared to the wind field anticipated. Pilot errors on the other hand are late flap selection, turn anticipation or speed-profile following. All these errors are highly dynamical and for this reason, an active, continuous speed-controller can be applied to resolve these errors. In other words, any time error is immediately closed by the controller by commanding a speed adjustment. This adjustment is fed to the auto-throttle which will adjust the speed according the instruction. The controller does not necessarily be active all the time but could be triggered once a preset time-error is reached. The application of a continuous controller is beyond the scope of this paper.

Second, during ASAs IM approaches, any errors in the execution of the descent by the preceding aircraft will affect the CTA of the ownship, requiring a change in speed profile to adjust its arrival time. The errors caused by this are assumed to be of a lower rate than in the previously discussed scenario. Therefore, the controller does not necessarily need to adjust the speed profile at the current location but could adjust the speed-profile somewhere further along the descent. Moreover, the controller is only active when an new ADS-B broadcast of the preceding aircraft is received. The advantage of this scenario is that the speed-commands will fluctuate less but on the other hand could prove to have sluggish behavior as lags behind the error due to its lower rate.

The result of the controller at work is shown in Fig. 13. The aircraft is at 9 NM from the threshold and receives an instruction to arrive 5 seconds earlier. The controller is triggered and the aircraft maintains the current speed resulting from the TTG-controller output. As the gained time increases, the controller output fed into the auto-throttle increases because the deviation from the nominal profile increases as well. This results in the dashed profile shown in Fig. 13. Finally, the aircraft starts to decelerate back to the nominal, engine-idle profile. By allowing speed-brakes, the deceleration rate of the aircraft is increased such that it can reach the nominal profile sooner and continue the engine-idle descent, as shown in Fig. 13. If speed-brakes are not used the nominal path will be intercepted closer to the threshold. Another option for deceleration, not simulated in this paper, is by changing the flapschedule or by deploying the gear earlier.[15] Operational considerations will determine whether speed-brakes are used or earlier flap and gear selection. The amount of additional thrust applied to compensate the new assigned arrival time is limited as shown in Fig. 13.

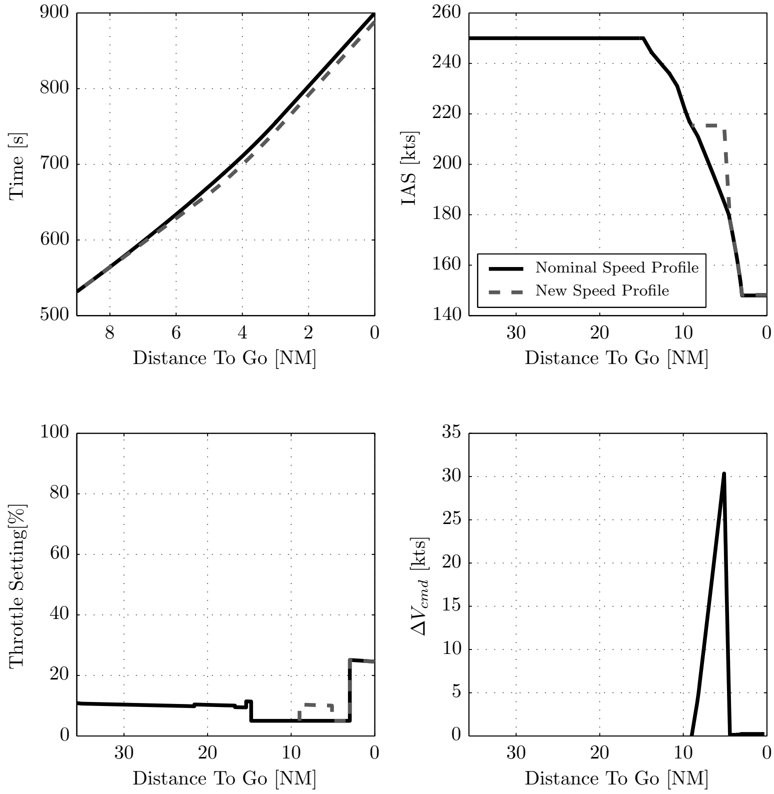

Figure 13. Early arrival of 5 seconds solved by closed-loop speed controller (no wind).

A qualitative noise assessment is done for both approaches by calculating the number of expected awakenings. The expected awakenings are calculated using a dose-response relationship between the Sound Exposure Level (SEL) and expected percentage of awakenings combined with population data provided by the Dutch Central Bureau of Statistics (CBS); the population data is shown in Fig. 4). This relationship is based on research done by the Federal Interagency Committee on Aviation Noise (FICAN) in 1997.[19] The Sound Exposure Level was determined using FAA's Integrated Noise Model (INM).[20] For the night approach flown, the nominal speed-profile resulted in 451 expected awakenings compared to 455 expected awakenings for the adjusted speed-profile. The slight increase in thrust thus results in only a few more people awoken.

VII. Conclusions and Recommendations

From the results a number of conclusions are made,

- It is possible to control the arrival time of an aircraft by altering the airspeed profile. With an unrestricted airspeed profile it is possible to compensate for wind speeds.
- Restrictions on the airspeed reduce these possibilities.

- It is relatively easy to delay an aircraft. It is possible to 'lose' time during an approach by flying at a lower airspeed at the cost of increased fuel burn. But once an aircraft slows down it should be kept in mind that acceleration is no longer allowed.

The advantage of a dynamic airspeed profile is that it helps the aircraft and pilot to correct for its own produced errors. Adjusting the speed-profile allows aircraft to arrive on time and hence airport capacity, based on the arrival schedule, is maintained. When a strong but constant wind is present, all aircraft will be affected and the change in aircraft separation introduced by the constant wind field will not be a large problem. With or without airspeed restrictions, the results show that in all cases it is possible to correct small deviations using a slightly adjusted airspeed profile. It is possible to gain more then 30 seconds in the case of an Airbus A321 and lose more than 200 seconds. Both gaining and losing time will results in an increased fuel burn as thrust has to be applied to maintain the constant speed. To increase the amount of time to be gained, the restriction of no acceleration could be lifted.

A new closed-loop controller which uses the velocity deviation from a predetermined speed profile is introduced. As long as the error to solve is within the possible time errors (control space), the controller is capable of guiding the aircraft to the threshold using a small amount of additional thrust. For late arrivals, speed brakes are required, but the deceleration performance could also be increased by early flap or gear deployment.

New research should investigate when the TTG controller should be activated. In theory, it could be active constantly, updating the profile continuously to solve for any (small) errors. The downside of this approach is that the speed-profile will change constantly leading to a loss of situation awareness and passenger comfort. Another method entails the use of a trigger on the time error. When the time error exceeds the value of the trigger, the controller is activated and the speed profile is adjusted to resolve the time error. This method reduces the amount of changes made to the speed profile but could prove insufficient in solving the time error completely.

By allowing slightly more thrust during the nominal profile, deceleration can be achieved by reducing thrust instead of using speed brakes. This might be more natural to pilots but will result in a slight increase in fuel use and noise. Moreover, the maximum deceleration will be larger when using speed brakes and as a result the current speed can be maintained for a longer period resulting in more time profit.

The TTG Controller could be used to update a dynamic airspeed (reference) profile as used in the display of Van den Hoven (2010).[11] A dynamic airspeed profile could compensate for small disturbances, such as turbulence or a mismatch in predicted mass or wind field.

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