A NOVEL CONTROL APPROACH TO IMPROVE SPEED COMMANDS AND PILOT WORKLOAD FOR FLIGHT-DECK BASED INTERVAL MANAGEMENT

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Abstract

Flight-deck Interval Management is an aircraft spacing solution designed to increase air traffic efficiency and runway throughput. Tests and simulations of a current solution have shown good performance while operational concerns remain. In this research a different approach is proposed, targeting these concerns, in the aim to provide a solution with a strong focus on operational feasibility and acceptance.

1 Introduction

Growing air travel demand and aircraft increase as predicted by market outlooks [1] call for sophisticated systems to improve air traffic efficiency and runway utilization. Airborne Spacing Interval Management (ASPA-IM) and the flight-deck based variant FIM are two concepts, endorsed by the ICAO Global Navigation Plan [2], to achieve this target. By the use of FIM, a promising increase in aircraft throughput of up to 10% is possible [3].

In February 2017 NASA conducted a flight test session, evaluating the performance of a FIM solution with favorable results, but also highlighted remaining issues for operational aspects like workload, ecology or acceptance. [4-6]

Numerical simulations backed the time performance of this solution, but also seconded some of the feedback from the tests, indicating the need for further research. [7-9]

In the approach presented in this paper findings from the flight test and simulations are addressed and factored in the command generation process.

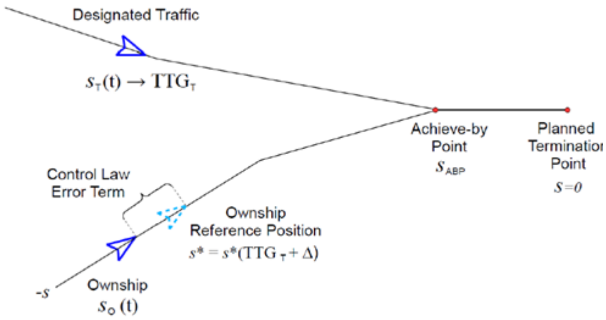

Fig. 1. Example of the time based spacing goal TBO logic [14]

The remainder of this paper first describes the general FIM concept and areas requiring improvement found during the flight test and simulations. Following a novel approach for speed profile generation is introduced and potential decision parameters explained. Examples for profiles generated by this code are provided and advantages and disadvantages of this approach discussed before an outlook into the author's future works concludes this paper.

2 Flight-deck Interval Management

2.1 General Concept

FIM is an airborne IM concept, giving the flight-crew the authority to manage the spacing distance between the own aircraft ("Ownship") and a pre-selected leading target aircraft ("Traffic-To-Follow", TTF) on their own.

The spacing is managed by comparing the Ownship's and TTF's trajectories to estimate each aircraft's time of arrival (ETA) for a common waypoint. Data is either obtained via the Flight Management System (FMS) or via

Automated Depended Surveillance Broadcast Communication (ADS-B) In.

Based on each aircraft's ETA and the spacing goal time (Δ) the spacing error e(t) can be calculated as follows:

$$e(t) = ETA_{ownship}(t) - (ETA_{TTF}(t) + \Delta) \qquad (1)$$

The objective of FIM is to reduce this error to zero upon reaching the pre-defined Achieve-by-Point (ABP) as seen in Fig. 1.

2.2 Airborne Spacing for Terminal Arrival

Developed by NASA's Langley Research Center and first published in 2002, Airborne Spacing for Terminal Arrival (ASTAR) has been the leading solution for FIM. Originally planned as a fully automated system, connected to the Auto-Pilot/Auto-Throttle system, ASTAR has been re-developed as an easy to add on "federated" solution by consumer demand. In this variation, FIM runs as an application on an Electronic Flight Bag (EFB) and commands must be manually inputted by the pilots. [10-13]

ASTAR offers two modes, a trajectory base operation (TBO) mode, used for two aircraft on different route heading towards a common waypoint, and constant time delay (CTD) after merging on the same route. [10] The mode evaluated in the flight tests and concerned in this research is the TBO mode. ASTARs TBO mode logic uses a direct feed forward control as seen in Fig. 2.

2.3. Studies on ASTARS

2.3.1 NASA Joint Flight Test

NASA, Boeing, Honeywell and United Airlines accomplished a nineteen-day flight test session in February 2017. Among the data taken to evaluate the algorithms spacing performance, the flight crew was surveyed in quantitative and qualitative manner. Repeatedly occurred comments are listed in the upcoming section. [4-6]

2.3.2 Simulations on the K Supercomputer

Leading up to this research we have conducted large scale Monte Carlo simulations, to get a quantitative representation of the behaviors identified in the Flight Test comments

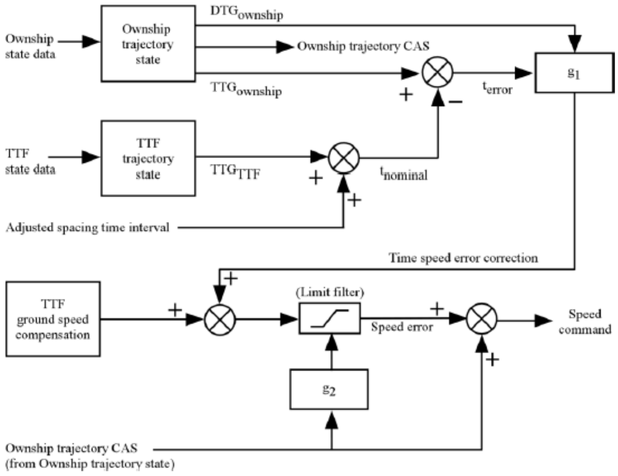

Fig. 2. ASTAR13 TBO logic controller chart [9]

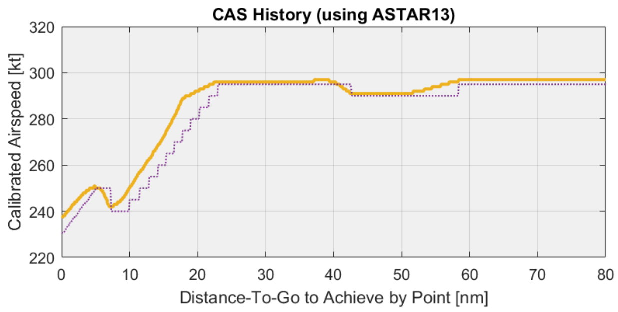

Fig. 3. CAS History for a flight using ASTAR13 based IM

that affect operational usability. Output examples are the total number of speed changes, changes within less than a minute, single step speed change magnitude. [8,9]

2.3.3 Identified Issues

Issues, mentioned in pilot comments and reproduceable by simulation, can be put into three categories: workload, acceptance and ecology.

An example for a workload related item is "Too many IM speed changes or the rate of speed changes is too high" (sometimes with intervals of less than 30s between commands).

The acceptance category included "large decelerations", often well above 40kts and up to 70kts, and high energy on final, causing handling difficulty for pilots and Air Traffic Controllers.

And ecology items include avertable accelerations, esp. "Reversals" (see Fig. 3), i.e. commands that negate the effect of a previous command, thus increasing fuel consumption and engine wear.

Another aspect given by the instantaneous nature of ASTARS is that the crew has no knowledge where or when the next speed command will occur. This can interfere with the crew's planning of configuration changes or resource management. [5,6]

3 Alternative Speed Planning Algorithm Design

In this approach, the speed schedule is changed as a whole instead of a feed forward logic. This approach has been evaluated in the past but suffered from long calculations times [14,15]. In the solution presented in this paper a pre-calculated map is used to encounter this problem, further the issues found during the ATD-1 flight test are factored in the profile selection process.

3.1 Map Concept

The central element of the system is the time required map, containing the information for any given achievable speed at any given Distance-To-Go (DTG).

The map's length, i.e. number of columns, is given by the distance from initiation to ABP in the interval of DTG_{STEP} (here: 0.02NM), its height, i.e. number of rows, by the speed envelope's absolute minimum and maximum achievable speed in the interval of CAS_{STEP} (here:1kt).

The speed envelope is derived from the aircraft type performance specific speed envelope, route specific and legal restrictions, before it is finally corrected for acceleration performance.

For each column the position and altitude are known from the aircraft's route and DTG. Further information, e.g. wind data, is also stored for each column to allow faster processing.

Based on the above information the time required for each DTG_{STEP} at any achievable CAS is calculated and stored in the respective cell.

An example for the generated map can be found in Fig 4. The map shows a Boeing 787-8 on the KAIHO arrival to Tokyo International Airport's (HND/RJTT) Runway 34L. Background colors indicate the time required for each distance step (here: from 0.1385s to 0.4896s). The solid black line indicates the BADA references speed, the dotted purple line CAS_{SET}, as it would be set on the Autopilot Control Panel or FMS.

3.2 Action Point Concept

Significant points along the speed schedule, i.e. beginning and end of a speed change, the Mach/CAS transition and the initialization point are called "Action Points" (AP). They are uniquely identified by their DTG, CAS and CAS_{SET} values. A list of all APs for the reference profile can be found in Table 1. Further they are marked in Fig. 4, with active interactions, i.e. system initiation (INIT) and speed changes (DEC) marked in black, others, i.e the Mach transition and end of speed changes / beginning of constant speed segments (CAS) are marked in grey.

In this concept the values of these APs will be changed to find a speed profile that compensates the spacing error *e(t)*. Change types are explained in chapter 3.5. To identify a specific AP, the letters AP are followed by the AP number in superscript and the change type in subscript, for example if the target speed of AP No. 8 is reduced by 10kts it would be denoted as:

$$AP^{8}_{CAS\text{-}10} \qquad (2)$$

3.3 Model and Trajectory Base

The models and conversion formulas used in this research are based on EUROCONTROL's Base of Aircraft Data (BADA) Version 3.12 [16] and RTCA DO-361 MOPS for FIM [17].

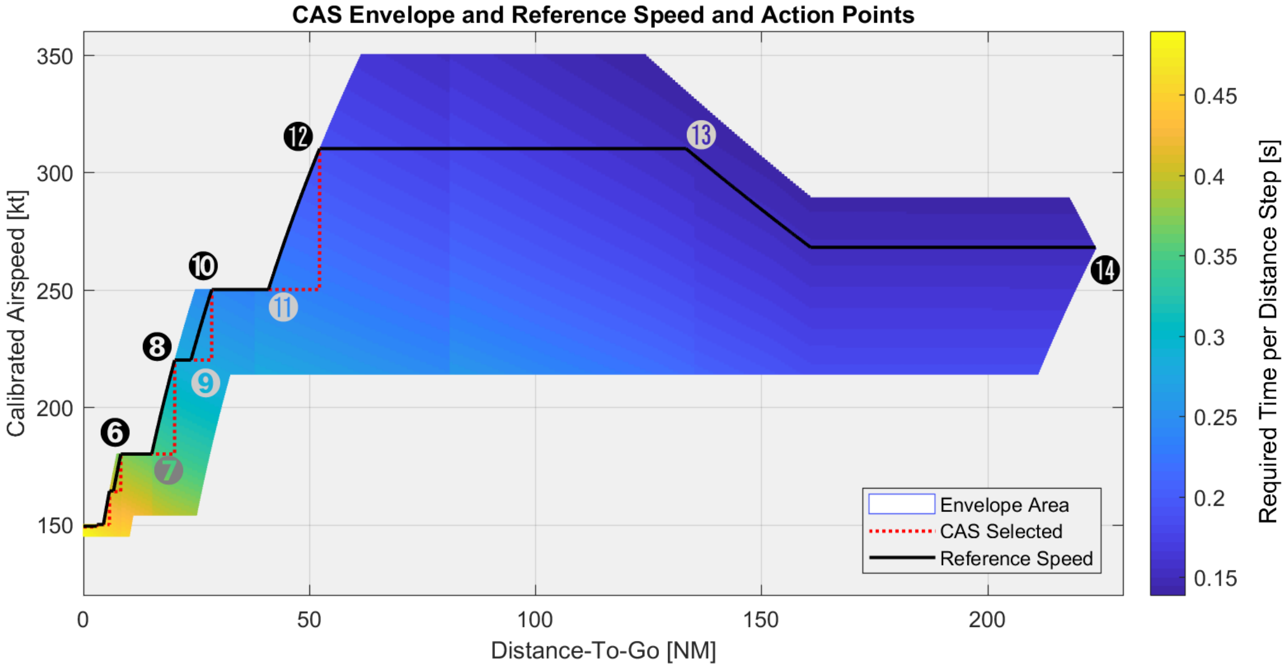

Fig. 4. CAS envelop for a Boeing 787-8 on the RJTT KAIHO approach (using BADA 3.12)

3.4 Adjustment Capabilities

The map in Fig. 4 highlights the range in which the speed can be changed to adjust the arrival time. Table 2. shows the Time-To-Go (TTG) for characteristic profiles, i.e. the reference profile, the fastest profile (proceeding continuously at CAS_{MAX}), slowest profile (continuous CAS_{MIN}) and the fastest profile prohibiting accelerations. The latter assumes reference speed until the first deceleration is initiated, from which on it will continue at CAS_{MAX}. In this example the first deviation occurs at approx. 30NM DTG. The TTG difference of just -8.28s highlights the severe restrictions and limited robustness to changes of e(t) implied by the no-acceleration requisition.

Other profiles, e.g. the reference profile for the RJTT ARLON Arrival, have no ETA advancement capability without accelerations.

3.5 Speed Changes

The following paragraph introduces the four main speed schedule changes types. Each change is illustrated in Fig. 5, also showing the involved Action Points. The AP which is evaluated for a change is marked in yellow, APs affected by a change are marked in grey, added APs are marked in red and fixed (unchanged) APs in black.

Table 1. Action Point List for the BADA Reference Profile

AP No.	DTG	CAS	CAS Sel.	TYPE	TTG
14	223.96	0.84	0.84	INIT	2145.63
13	133.30	0.84	310	TRANS	1459.97
12	52.26	310	250	DEC	768.60
11	40.94	250	250	CAS	648.51
10	28.40	250	220	DEC	498.08
9	23.80	220	220	CAS	438.06
8	20.20	220	180	DEC	387.26
7	15.12	180	180	CAS	307.07
6	8.28	180	164	DEC	181.79
5	6.66	164	164	CAS	150.35
4	5.78	164	150	DEC	132.30
3	4.44	150	150	CAS	103.33
2	3.00	150	149	DEC	70.46
1	2.92	149	149	CAS	68.61

Table 2. TTG comparison for characteristic profiles

Profile Name	TTG [s]	Difference to Reference [s]
Reference Profile (BADA)	2145.63	-
Slowest (Minimum Speed)	2780.29	+ 634.66
Fastest (Maximum Speed)	2023.83	- 121.80
Fastest (No Accelerations)	2137.35	- 8.28

3.5.1 CAS Change

A CAS change alters the target value of a planned speed step. Candidates are calculated within +\- 10% of CAS_{REF} in the CAS_{STEP} interval. Only continuous profiles that do not conflict with the map borders are considered. The upper illustration in Fig 5. shows an example of a CAS change.

CAS changes imply a change to the considered AP, AP^N and the subsequently following two APs, AP^{N-1} and AP^{N-2}.

3.5.2 DTG Change

DTG changes alter the location, and subsequently the timing, where a speed change is initiated. A delayed deceleration advances the arrival time and an early deceleration will work conversely. Candidates are calculated within a pre-defined range (here +\- 5NM) and only considered if the change can be fully executed within the envelope's border. An example can be seen in the second illustration in Fig 5.

DTG changes effect the evaluated AP^N and the following AP^{N-1}.

3.5.3 Immediate Acceleration

If the arrival time can't be reasonably advanced by one of the above-mentioned methods an acceleration segment, extending until the next planned changed, is added to the current constant speed profile. Candidates are considered for a speed increase of up to 10%, and only if the CAS_{SET} can be kept for at least 5NM. If after initial acceleration to CAS_{SET} a deceleration becomes inevitable, CAS_{MAX} is kept until continuing into the next scheduled speed change.

The third illustration in Fig. 5 shows an example of the profile. In the above-mentioned case, that the accelerated speed has to be reduced to CAS_{MAX}, 4 APs are added to the entire profile, two for the acceleration (here: AP^6 and AP^5), and two for the return to CAS_{MAX} (AP^4, AP^3). Additionally, AP^2 is extended to join with the acceleration segment speed.

3.5.4 Immediate Deceleration

If necessary, e.g. due to ATCo intervention, or advisable a deceleration segment can also be inserted to the current constant speed segment.

Candidates are considered to a speed decrease of down to -10% or if manually

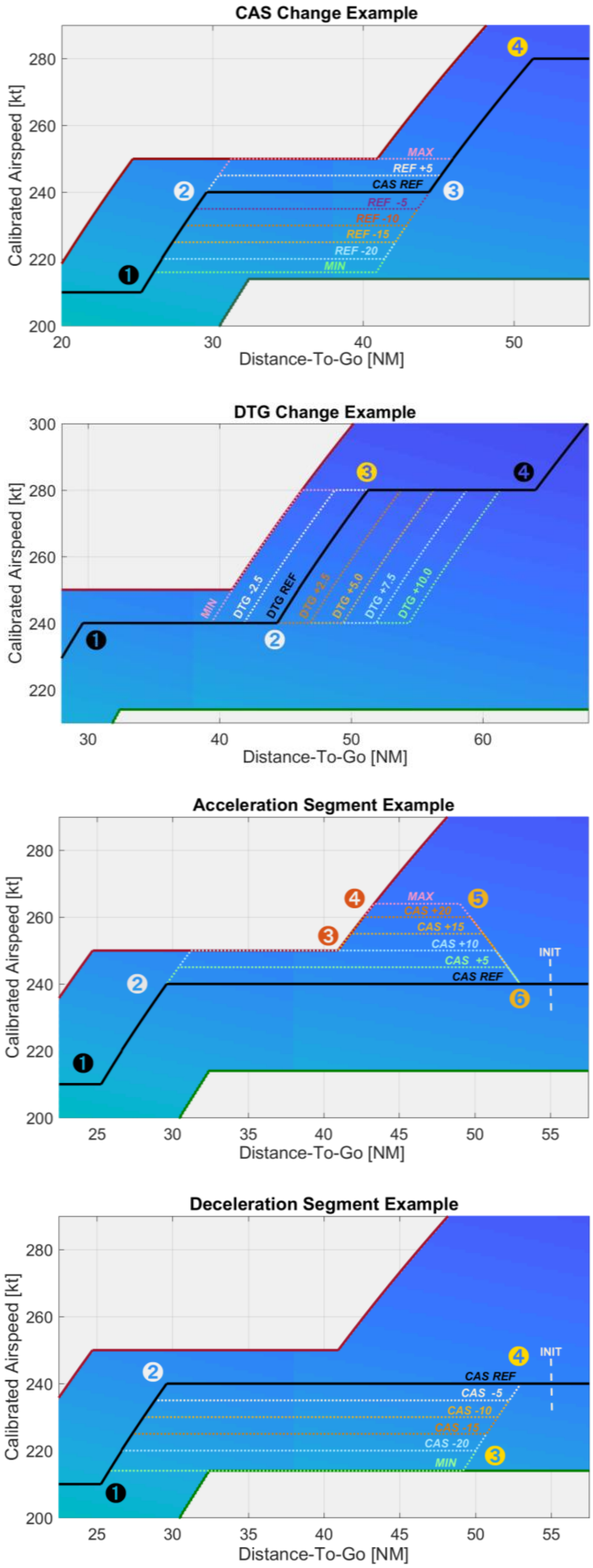

Fig. 5. Illustration of speed schedule changes considered by the algorithm

overwritten the set speed. CAS_{SET} will be kept until it reunites with the next scheduled change.

The lower illustration in Fig. 5 shows an example of an immediate deceleration.

3.6 Candidate Selection

From all suitable profile changes, a primary selection is made from the candidates with the best spacing error compensation capability, i.e. minimizing the remaining spacing error. This candidate set is then evaluated for a set of secondary characteristics (described in the next chapter), individually weighted by a cost function and the candidate with the best score is finally selected. If a single adjustment cannot compensate the error within a predefined threshold, the selection cycle is repeated based on a temporary profile implementing the changes from all previous cycles.

3.7 Cost Function

The following sections gives an introduction about the elements and factors considered for the cost function. The full details, like specific weights and formulas to calculate the individual cost, will be presented in the author's future papers.

3.7.1 Time (remaining error)

The primary selection factor is the remaining error after profile update $e(t)^*$ given by the original spacing error and the profile compensation time t_{comp} as per:

$$e(t)^* = e(t) - t_{comp}(AP^{N}_{Change}) \qquad (3)$$

Candidates are pre-selected upon this value within a given threshold.

3.7.2 Secondary Selection

Factors for the secondary selection were mostly derived from the identified issues in chapter 2.3.3. They are grouped in operational, acceptance, robustness and ecology factors.

Operational factors include waypoint and action point proximity, to avoid areas of high workload, conflicts with other tasks and limit the speed commands. (A desired value as per [5] has been not more than one per minute). Specified

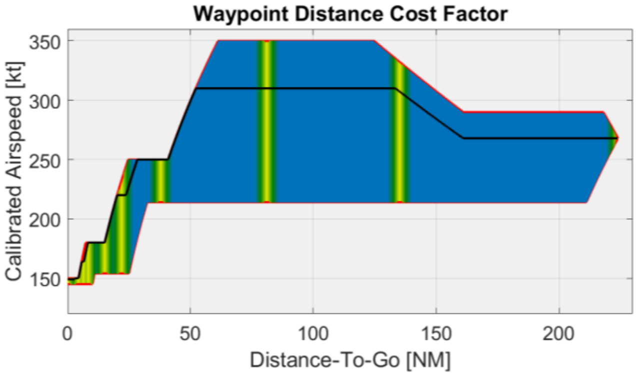

Fig. 6. Waypoint proximity penalty area

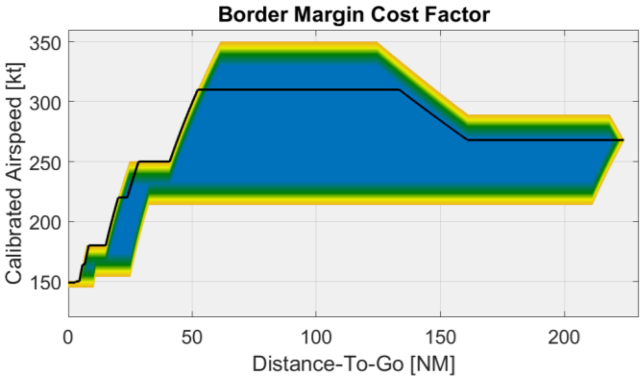

Fig. 7. Envelope border proximity penalty area

areas, shown in yellow and green in Fig. 6 will therefore be penalized. Blue areas have no cost.

Acceptance factors cover the single speed step size (magnitude) of a speed command and penalize operation close to or at the envelope border (as marked in yellow and orange in Fig. 7).

The latter is also relevant to the robustness requirement, as profiles that move along the envelope border, like the reference profile, only leave small room for further compensation should the error increase and thus risk successful FIM execution. Hence, a lower manageable error in relation to the DTG is penalized.

Last, ecology factors benefitting profiles with less acceleration and reversal actions in clean configuration to reduce fuel consumption and engine wear are also considered.

3.8 Exemplary Results

Fig. 11, shows two exemplary profiles generated by the algorithm, using a time based only selection. Profile P+ with an initial positive spacing error i.e. requiring an earlier arrival, and P- with an initial negative spacing error, conversely requiring a later arrival.

For both profiles the system is initiated at 135NM before the ABP (allowing for the earliest system advisory at 130NM) with an initial spacing error of + or – 10s. From thereon the spacing error increases by 1 second per 20NM in the direction of the initial error, starting at 120NM and ending at 20NM (as seen in Fig. 8), triggering a total of six profile re-calculations. The solid yellow line represents the profile of P+ and the solid green line P-. For comparison the reference profile is indicated by the dotted black line. The resulting APs for both profiles are listed in Table 4 and 5, with values differing from the reference profile marked by bold letters.

As discussed in chapter 3.4 an initial error of +10s cannot be compensated under the no-acceleration constraint, hence Profile P+ starts with an initial acceleration segment (adding AP^{13} and AP^{14}) from 310kts to 315kts. All following errors were then compensated with the margin left, by prolonging higher speed segments or decelerating to higher target speeds, e.g. AP^{10} has been shifted by -2NM and +10kts.

As AP^{11} was raised to meet with the inserted acceleration segment, only two APs (one actively changing speed) have been added to the original profile. Finally, profile P+ will make the aircraft arrive at the ABP after 2130.86s, 14.77s earlier than the reference profile, leaving a remaining error of +0.23s

Profile P- was achieved solely by advancing decelerations (e.g. $AP^{12}_{DTG+0.5}$) or lowering the target speeds (e.g. AP^{10}_{CAS-4}), thus not requiring any additional steps at all. P- causes arrival at the ABP after 2160.77s, 15.14s later than the reference profile, creating a minor overcompensation with an error of +0.14s left.

Fig. 9 and 10 show the progression of the spacing error in time and distance for both profiles. In both cases the spacing error is eliminated two minutes (here: approx. 5NM) before the ABP. The example shows that for the TBO portion of FIM, speed profiles with sufficient spacing performance can be generated by adjusting the execution timing and target speed of planned speed changes. However, the profiles shown above still contain violations of the single speed step ideal. As multiple solutions can exist for a given compensation problem, it is crucial to distinct these solutions based on other characteristics (as presented in section 3.7) than just time.

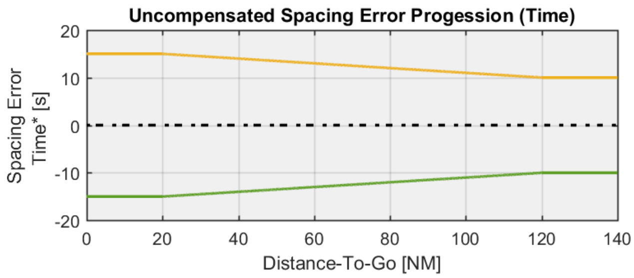

Fig. 8. Chosen (uncompensated) spacing error progression from FIM initiation to ABP

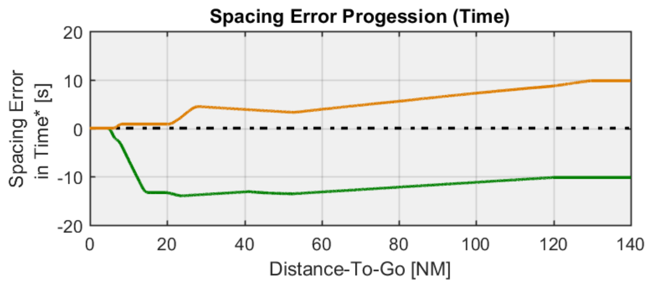

Fig. 9. Development of the spacing error in time, compared to the reference profile

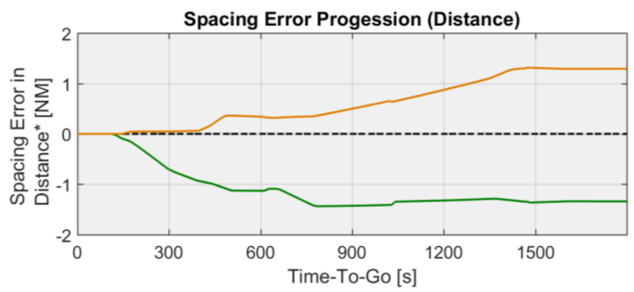

Fig. 10. Development of the spacing error in distance, compared to the reference profile (interpolated)

Table 3. TTG and spacing performance for all profiles

Profile	TTG [s]	Accum. Error [s]	TTG incl. Err.	Diff. to Ref. [s]
Reference	2145.63	0	2145.63	-
Profile P+	2130.86	+15	2145.86	+0.23
Profile P-	2160.77	-15	2145.77	+0.14

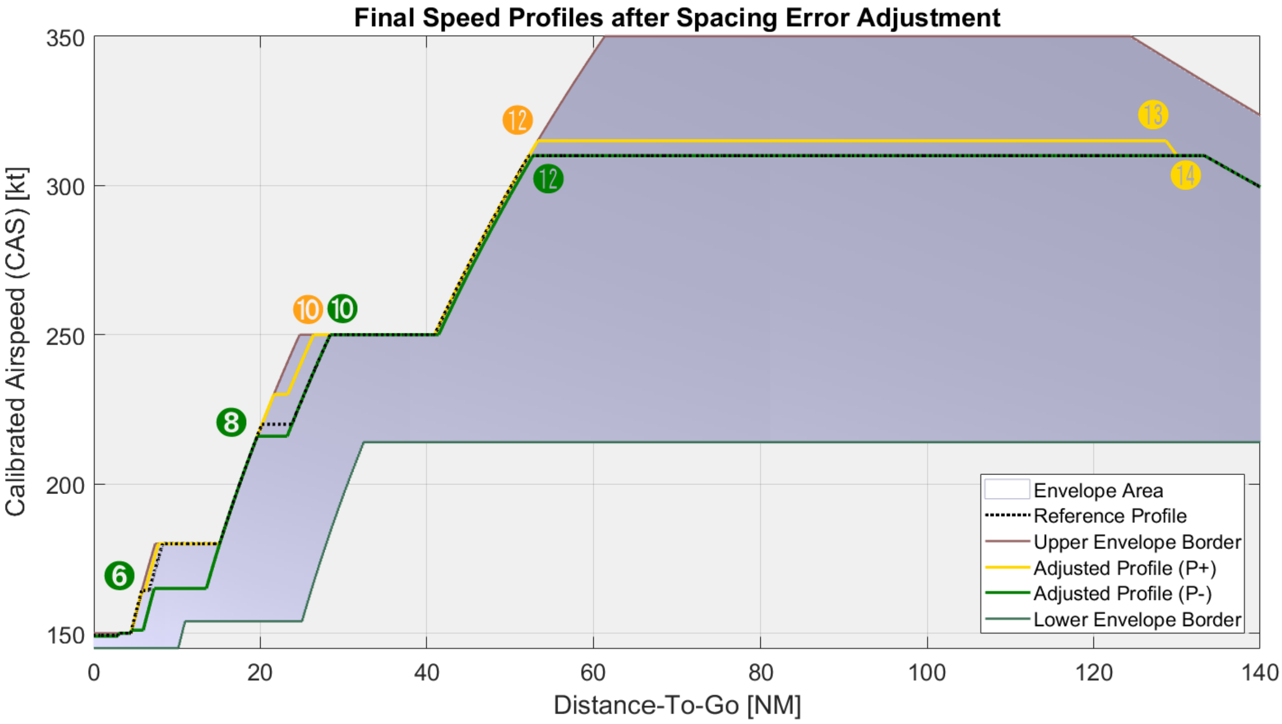

Fig. 11. CAS schedule after profiles have been added modified for error compensation
Significant APs have been marked in the color of the representative profile

Table 4. Action Point List for Profile P+

AP No.	DTG	CAS	CAS Sel.	TYPE	TTG
16	223.96	0.84	0.84	INIT	2130.86
15	133.30	310	310	TRANS	1445.19
14	**130.00**	**310**	**315**	**ACC**	1420.16
13	**128.68**	**315**	**315**	**CAS**	1410.14
12	**53.34**	**315**	250	DEC	773.82
11	40.94	250	250	CAS	643.64
10	**26.40**	250	**230**	DEC	468.71
9	**23.28**	**230**	**230**	CAS	428.58
8	**21.64**	**230**	180	DEC	406.42
7	15.12	180	180	CAS	306.22
6	**7.78**	**180**	164	DEC	171.68
5	**6.12**	164	164	CAS	139.29
4	5.78	164	150	DEC	132.30
3	4.44	150	150	CAS	103.33
2	3.00	150	149	DEC	70.46
1	2.92	149	149	CAS	68.61

Table 5. Action Point List for Profile P-

AP No.	DTG	CAS	CAS Sel.	TYPE	TTG
14	223.96	0.84	0.84	INIT	2160.77
13	133.30	0.84	310	TRANS	1475.11
↓	↓	↓	↓	↓	↓
↓	↓	↓	↓	↓	↓
12	**52.76**	310	250	DEC	788.46
11	**41.42**	250	250	CAS	668.40
10	28.40	250	**216**	DEC	512.21
9	**23.22**	**216**	**216**	CAS	443.99
8	**19.64**	**216**	**165**	DEC	392.47
7	**13.52**	**165**	**165**	CAS	290.26
6	**7.26**	**165**	**151**	DEC	164.91
5	**5.92**	**151**	**151**	CAS	136.47
4	**4.52**	**151**	150	DEC	105.14
3	4.44	150	150	CAS	103.33
2	3.00	150	149	DEC	70.46
1	2.92	149	149	CAS	68.61

4 Discussion

4.1 Operational advantages

One advantage of this approach is the greater planning horizon, allowing to generate more efficient time compensating profiles and potentially benefit for spacing error reducing outside factors.

As the speed reduction profile is changed as a whole, the speed schedule can always be presented to the pilots to give them better awareness of the systems intentions and when to expect the next speed change.

Since the system is working with the pre-planned descent and speed schedule, the number of required interactions and consequently pilot workload, is not expected to increase significantly.

4.2 Flight-Path reliance

As the underlying map (as explained in 3.1) is calculated for a specific flight path, accuracy is highly dependent on the observation of such. A threshold to which a deviation can be tolerated and when a re-calculation, using a corrected flight path, becomes mandatory must be defined.

4.3 Model based error

Depended on the resolution of the map the system is prone to model-based error, e.g. speed that are not represented by the map. However, in the 1kt / 0.02NM setup the resolution error occurred to be around 0.05s for the entire profile. During actual operation the system would be able to perform a self-evaluation, by comparing the estimated and actual en-route arrival times. Based on this difference a correcting factor could be introduced.

4.4 Calculation time

The simulation that generated the results in chapter 3.8 was run in a single-threaded Java environment on a 2.6GHz Intel Core i7-6700HQ processor. Preparing the system for engagement, which includes reading out route information and wind forecast data, setting up the route and aircraft specific envelope, calculating the time required map and TTG values for the fastest, slowest and reference speed profile, takes about 0.9s for the step values of d_{step} = 0.02NM and CAS_{step} = 1kt and a route length of approx. 224NM.

Provided that the flight path is observed, and the forecast wind information is unchanged, the speed map will remain valid and does not have to be updated.

A full evaluation of the profile for a given error takes about 1s at a length of 224NM.

The system would also be capable to prepare solutions during idle time, making them readily available if needed.

5 Outlook and conclusion

In this paper a different approach for Flight-deck Interval Management, addressing issues found in the ATD-1 flight test, was introduced and exemplary results have been presented. The next step of this research will be to further develop and tweak the cost function for improved profile selection. The outputs of the developed systems will then be compared to ASTAR generated profiles. Once the system has been thoroughly tested it will be ported to an iPad version to simulate and EFB application. Finally, the EFB version will be evaluated in a Human-in-the-Loop experiment.

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