4D Continuous Descent Operations Supported by an Electronic Flight Bag*

A Human-in-the-loop Study

Xavier Prats, Bianca Bendris and Ramon Dalmau
Department of Physics - Aeronautics division
Technical University of Catalonia (UPC)
Barcelona, Spain

Josep Montolio and Brent Day
Pildo Labs
Barcelona, Spain

Helge Lenz and Ralf Kohrs
Institute of Flight Guidance
German Aerospace Center (DLR)
Braunschweig, Germany

***Abstract*—This paper describes a set of flight simulation experiments carried out with the DLR's Generic Cockpit Simulator (GECO). A new concept named time and energy managed operations (TEMO), which aims to enable advanced four dimensional (4D) continuous descent operations (CDO), was evaluated after three full days of experiments with qualified pilots. The experiment focused to investigate the possibility of using a 4D-controller on a modern aircraft with unmodified or only slightly modified avionic systems. This was achieved by executing the controller in an Electronic Flight Bag (EFB) and using the pilot to "close the loop" by entering speed and other advisories into the autopilot Flight Control Unit (FCU). The outcome of the experiments include subjective (questionnaires answered by pilots) and objective (trajectory logs) data. Data analysis showed a very good acceptance (both in terms of safety and operability of the procedure) from the participating crews, only with minor suggestions to be improved in future versions of the controller and the speed advisories update rates. Good time accuracy all along the descent trajectory was also observed.**

Keywords— Continuous Descent Operations (CDO); required time of arrival (RTA); Electronic Flight Bag (EFB)

I. INTRODUCTION

Current flight management systems (FMS) are able to plan and fly efficient descent trajectories. Yet, it is rare that aircraft are allowed to fly them when arriving in dense terminal areas due to traditional air traffic control (ATC) procedures to separate traffic, such as path stretching (radar vectoring) or level-offs at intermediate altitudes. Allowing unconstrained optimal descents would compromise airspace throughput, since ATC would need to apply larger separation values.

Extensive research in the last decade has been devoted to address the environmental issues during descent and approach, whilst maintaining runway capacity. New concepts for continuous descent operations (CDO) that implement novel four dimensional (4D) trajectory planning and guidance strategies have been proposed in the literature and tested in simulation or even in real flight trials [1-5]. These concepts assume the ATC will deliver one (or multiple) required time(s) of arrival (RTA) at some waypoint(s), or even at the runway threshold. With these RTA, ATC could efficiently handle separation tasks without needing to increase separation intervals, use path stretching or level-off altitudes.

Nevertheless, FMS must be able to guide the aircraft efficiently through these RTA and with sufficient accuracy. These concepts generally use ground-based or aircraft-based trajectory predictors. In addition, most CDO concepts actively control altitude and/or speed, which often results in additional thrust variations (and/or speedbrake usage) to command speed changes required to maintain spacing or to remain on path. These have a negative effect on noise nuisance and fuel usage.

Aiming at overcoming these issues, a new concept, named Time and Energy Managed Operations (TEMO), has been developed co-sponsored by the Clean Sky Joint Undertaking [6-8]. Different from other CDO concepts, TEMO optimizes the descent by using energy management principles to achieve a continuous engine-idle descent, while satisfying time adherence along the descent trajectory.

TEMO is in line with SESAR step 2 capabilities, since it proposes 4D trajectory management and it is aimed at allowing CDOs in dense terminal areas without compromising the capacity. It is expected to bring operational improvements facilitating flow management and arrival spacing, increasing in this way, the arrival throughput while reducing the environmental fingerprint, even in high density and peak-hour operations. In particular, TEMO addresses SESAR operational improvement (OI) TS-103: Controlled Time of Arrival (CTA) through use of datalink [9].

In this paper the definition, preparation, performance and analysis of a flight simulator experiment is described. The objective is to test and validate the TEMO concept of operations using a 4D trajectory generator and a 4D controller (trajectory guidance) embedded into an Electronic Flight Bag (EFB) and developed by the German Aerospace Centre (*Deutsches Zentrum für Luft- und Raumfahrt*, DLR). The idea behind the usage of an EFB is to investigate the possibilities of integrating the TEMO concept into current cockpit infrastructure with almost no modification on the avionic systems. This would permit to implement the concept in a rather short period of time and reducing considerably development and certification costs.

Even modern avionics in the most recent aircraft do not have the computing power to run advanced 4D trajectory

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management (including optimisation) algorithms. EFB devices found in most cockpits today, however, might have this potential, but are not allowed to connect directly to the aircraft control systems. In this paper it will be investigated if this gap can be closed by the pilot operating directly the autopilot, through the Flight Control Unit (FCU), according to guidance advisories given by the 4D-controller running in the EFB.

II. Time and Energy Managed Operations (TEMO)

The TEMO concept aims to fly fuel and noise efficient approaches without airport capacity drawbacks by meeting time constraints along the descent trajectory. An idle descent profile is computed from the top of descent (TOD) down to the glide slope intercept, such that these time constraints are met at the same time it optimizes for minimum fuel and speedbrake usage. Then, the trajectory is followed by a TEMO guidance system, which can be configured to use different strategies [7].

For the long-term implementation of the overall TEMO concept, it is foreseen that the system has full access to all flight control axes controlled by the autopilot as well to the auto-thrust and a hypothetical auto-speed-brake system. As this would require a lengthy implementation and certification process such a system will not be installed in modern aircraft in the near future. To be able to let nowadays aircraft already benefit from these highly optimized procedures, an alternative is to implement a human machine interface on an auxiliary display available in the cockpit (e.g. an Electronic Flight Bag) that gives the pilot the necessary guidance information to fly the calculated trajectory with the help of the auto flight and auto thrust systems available on board the aircraft.

A. TEMO Implementation

For the experiment presented in this paper, an initial 4D trajectory is planned in cruise, well before reaching TOD. It should be noted that besides an optimal 4D trajectory, the planning algorithm also computes the right locations where flaps/slats and landing gear shall be deployed. The objective of TEMO is to achieve high accurate and predictable 4D trajectories and therefore it is important to ask the pilot to use these hyper-lift devices and landing gear at the right moment (since they have a considerable impact in aircraft Drag affecting time and/or vertical trajectory adherence).

Once the TOD is reached, the descent is executed in “open descent” mode, meaning that thrust is set to idle and speed on elevator (SoE) is used by the autopilot to follow the commanded speed. If unexpected head -or tailwind conditions are met during the descent, the speed profile has to be adapted to be able to meet the time profile of the initially planned trajectory. This would also happen due to any other source of uncertainty, such as errors in the aircraft performance models.

During the execution of the descent the 4D-controller embedded in the EFB computes these different speed advisories in such a way that time deviations are nullified. Speed deviations from the nominal plan, however, may result in altitude deviations, which in turn shall be compensated by vertical speed (V/S) or speed-brake advisories, only in the case they exceed some predefined boundaries. In this way, a trajectory regeneration during the descent is not required and the pilot can keep the descent as initially planned by following the different advisories.

For paths crossing the lower altitude bound, a constant V/S advisory (in ft/min) will be immediately displayed in the EFB. The pilot should then interrupt the open descent by pulling the appropriate knobs at the FCU and selecting the proposed rate of descent. The open descent will be resumed by the pilot when the V/S advisory is not displayed any more on the EFB. These V/S advisories would recover altitude deviations below the nominal path, but may eventually result in automatic thrust application by the auto-thrust system. Conversely, speedbrake usage would be displayed in case the flown trajectory is above the nominal path. The pilot should in this case deflect the speedbrakes manually (full deflection) until the message on the EFB disappears. This does not imply more fuel consumption, but has a negative impact regarding noise emissions.

All these advisories are displayed on the EFB, together with the current time error. See Fig. 1 for an example of the implemented human machine interface, showing a speed advisory (194 kt) and an indication to deploy Flaps 1. The time error, for this example figure, is 1.5 seconds earlier (with respect to the initial computed trajectory in cruise) and the altitude error is represented with a dynamic orange bar on the right side of the screen.

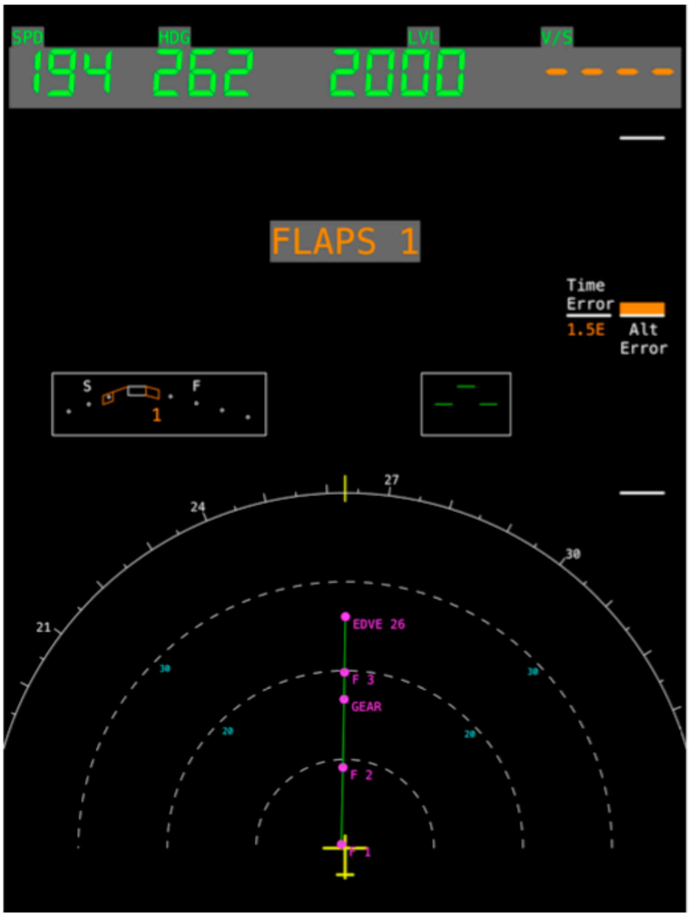


Fig. 1. EFB human machine interface example

It is expected that the pilot will manually introduce the speed or V/S advisories through the FCU. Speed-brake control will also be done manually by acting on the proper speed-brake lever of the airplane. When the pilot reacts to EFB advisories is completely up to him. It is not mandatory to do it immediately and this delay will be also subject of study in this experiment (by changing the update frequency of the speed advisories coming from the 4D controller, for instance).

Finally, it should be noted that for the experiment explained in this paper, pressing the approach mode button will stop the 4D-controller (e.g. speed, V/S and speed-brakes advisories will no longer be available). Time error and flaps/slats and landing gear setting points will still be displayed according to the planned trajectory.

B. *TEMO Operation*

In cruise flight the altitude is constant and speed is controlled with the auto-thrust system; while during the descent, different methods are used to control the system total energy:

- Neutral: Idle descent with the speed totally controlled via the flight path vector (speed on elevator).
- Negative Energy Error: Powered descent with a specific thrust command and speed on elevator.
- Positive Energy Error: Thrust idle and additionally specific amount of speedbrakes and speed on elevator.

However, in modern aircraft, the combined descent modes are not available. Currently, speedbrakes are only operated manually by the pilot without an exact indication of the actual deflection angle. In this paper, the vertical control channel of the autopilot and the auto-thrust system work together to control the three parameters: target speed (SPD); vertical speed (V/S) or altitude (ALT); and thrust (THR); with the elevator and auto-thrust. Hence, depending on the simulation, the following operation modes should be used by flight crew to follow TEMO optimum trajectory:

- Constant Speed Level flight (V/S = 0, ALT = fixed, SPD = fixed, THR = variable): Thrust is set to fly the target SPD. If thrust is increased or reduced the aircraft accelerates or decelerates.
- Open Climb (V/S = variable, ALT = target, SPD = fixed, THR = fixed): Depending on the target SPD, the aircraft climbs with a certain V/S. If the target SPD is too high, this V/S could be zero.
- Open Descent (V/S = variable, ALT = target, SPD = fixed, THR = fixed to idle): Depending on the target SPD, the aircraft descends with a certain V/S, which will be always negative due to idle thrust.
- V/S climb mode (V/S = fixed, Alt = target, SPD = fixed, THR = variable): Depending on the target V/S, the thrust is adjusted to climb with the given V/S at the given speed. If the V/S is increased, the thrust will be increased up to climb power. If increased even further, the aircraft has to decelerate to meet the V/S target violating the SPD target.
- V/S descent mode (V/S = fixed, ALT = target, SPD = fixed, THR = variable): Depending on the target V/S, the thrust is adjusted above idle to meet the V/S and SPD target. If the V/S is increased beyond the vertical speed of the idle descent, speedbrakes can be used to meet both V/S and SPD targets.
- Accelerated/Decelerated Climb/Descent modes: If the speed target changes in an open descent or open climb phase, the V/S is changed up to zero to reach the new SPD target before continuing the climb or descent.

III. Experimental Evaluation

The following section outlines the design of the experiment in terms of equipment, experiment design, subject pilots and schedule.

A. *Validation Platform*

The validation was conducted using the Generic Experimental Cockpit (GECO), a modular cockpit simulator placed at the Institute of Flight Guidance at the German Aerospace Center (DLR), in Braunschweig. The GECO consists of several hardware and software modules that form together a feature rich fix-base experimental flight simulator. The layout of the simulator cockpit is derived from the coming Airbus A350 XWB aircraft and incorporates a state-of-the-art glass-cockpit with wide-screen LCD, as well as modern input devices like the KCCU (keyboard cursor control unit), introduced by Airbus on the A380 flight deck. The underlying flight dynamics of the simulator are based on the new DLR Airbus A320 test aircraft ATRA (Advanced Technical and Research Aircraft).

For this experiment, the simulation was driven by the commercial flight simulation software X-Plane 10, by Laminar Research, running a high sophisticated Airbus A320 flight model simulating, not only the flight dynamics and primary control elements very realistically, but also many auxiliary systems needed to simulate complex failure scenarios. In the flight model particular interfaces were added to connect to the simulation environment e.g. visualization system, simulator hardware and other software modules like the DLR AFMS (Advanced Flight Management System).

As seen in Fig. 2, the GECO cockpit hardware available during the experiments included the interior with displays, controls and seats for two pilots as well as the racks, computers and controller console behind the simulator itself. All software programs needed for the simulation were developed at DLR allowing easy adaptation to different projects.

Besides the GECO permanent software, which exchanges different information between all the simulation systems involved while recording all the data with a rate of 20Hz, two additional modules were included for this experiment:

- TEMO Predictor/Optimizer: The TEMO V2 trajectory predictor/optimizer was integrated into the software environment. The predictor calculated the initial vertical profile based on the standard approach procedure. Close to the TOD the initial plan for the continuous descent was updated and optimized. TEMO V2 was restricted to straight-in arrivals and international standard atmosphere (ISA) models with no winds.

- 4D-Guidance: a 4D-Guidance module adjusted the speed of the aircraft and thus minimized the time error.

The simulations were setup and supervised from the GECO controller station, located behind the simulator (see Fig. 3).

Finally, the subject pilot was seated in the right side of the cockpit and the experimental EFB was located in the right side of the pilot position, approximately in line with his/her shoulder.

Fig. 2. GECO cockpit layout

Fig. 3. GECO simulation control position

B. Experiment Design

1) Operational Context

The operational scenario to test the basic features of the TEMO implementation in the simulation environment was based on an arrival and approach to Braunschweig airport (EDVE), runway 26, starting before the top of descent at cruise flight level (FL350) and down to the runway threshold. The lateral route was based on a straight flight from the east, starting around 150NM from the airport, in the area of Berlin.

The vertical profile of the flight plan was calculated by the TEMO V2 software and the resulting 4D-trajectory was transferred into the EFB. It contained a Metering Fix positioned at 50 NM from the runway with an altitude constraint of FL100. The profile intercepted the glideslope of the ILS (instrumental landing system) at runway 26 via the initial fix VE028 and the final approach point (FAP) LIDMO at an altitude of 2000ft. As the aircraft approached the TOD, the TEMO software updated the vertical profile, and the calculated time of arrival at the threshold was fixed as required time of arrival (RTA) at this point.

The flights were simulated without additional traffic, and under standard atmospheric conditions. Wind in the simulation was modelled as steady state error and therefore, implemented as constant head or tailwind component by setting the wind inside the simulation directly into the flight direction.

2) Simulated Scenarios

To demonstrate and assess the TEMO trajectory predictor in a modern airliner cockpit, several scenarios were prepared and tested including a standard step down approach. This conventional baseline was flown fully automatically to assess fuel consumption benefits of the later TEMO approaches. Beside this conventional baseline, a TEMO baseline scenario was prepared in which the initial plan was flown fully automatically without external constraints or events and thus with as little re-calculation of the TEMO profile as possible.

Scenarios with variations of the head and tailwind component were also prepared to assess whether the algorithms could cope with these situations and if the workload of the pilot increased in manual control mode. See Section IV.B for the detailed list of validation scenarios simulated in the experiment.

C. Subject Pilots and Daily Schedule

In order to achieve a more realistic simulation environment, 3 different qualified pilots were involved in the experiment. The average age of the subject pilots was 51. Their total flying hours ranged between 11,400 and 26,000 hours. All pilots had experience flying CDOs, but only 2 of them had experience with RTA operations.

The experiment was performed along 3 days and a different pilot was involved each day. Each day started with a welcome by DLR, followed by a briefing on the TEMO concept. After this introduction, the subject pilots filled out a pre-experiment questionnaire to gather information about their background. Then, subject pilots familiarized themselves with the GECO simulator environment by performing a training run.

After this training session, experiment scenarios were conducted, each lasting around 30 min. After each run, a run-questionnaire was filled out by pilots. Additionally, at the end of the day, a group discussion was held to gather general remarks and feedback.

IV. Validation Methodology

The following section details the validation methodology followed in the experiment by listing the validation objectives and success criteria, the validation scenarios and the validation assessment.

A. Validation Objectives and Success Criteria

The validation objectives (VO) and associated success criteria (SC) for the experiment were formulated as follows:

- VO1: To assess the feasibility of flying an optimized trajectory by means of speed, heading and altitude/altitude rate commands.
- SC1: It is feasible to guide the aircraft along a calculated trajectory by means of speed, heading and altitude/altitude rate commands in the given environment from the TOD to approach and landing.
- VO2: To assess whether the provided guidance information is sufficient to guide the aircraft along the calculated trajectory.
- SC2: The provided guidance information is sufficient to guide the aircraft along a calculated trajectory and no additional guidance information is required/requested.
- VO3: To assess whether the additional task to guide the aircraft along the calculated trajectory is acceptable to the pilot during this phase of flight.
- SC3: The additional task of guiding the aircraft along a calculated trajectory is acceptable to the flight crew in the given environment.
- VO4: To assess the additional workload caused by the task to guide the aircraft along the calculated trajectory.
- SC4: The workload does not exceed a predefined level on a tailored NASA TLX scale.
- VO5: To assess the flight technical error
- SC5: The flight technical error along the route does not exceed a predefined threshold.

Details on the metrics used to assess the different success criteria are given in section IV.C.

B. Validation Scenarios

The following validation scenarios (VS), or runs, were carried out each day by a different subject pilot:

- VS1: Manual approach with unexpected 10 knots headwind and 10 seconds update frequency for speed advisories.
- VS2: Manual approach without wind and 1 second update frequency for speed advisories.
- VS3: Manual approach with 10 knots unexpected tailwind and 10 seconds update frequency for speed advisories.
- VS4: Manual approach with 10 knots unexpected headwind and 1 second update frequency for speed advisories.
- VS5: Manual approach without wind and 10 seconds update frequency for speed advisories.
- VS6: Manual approach with 10 knots unexpected tailwind and 1 second update frequency for speed advisories.

It should be noted that by "manual approach" we refer to automatic flight with the auto-throttle system on and the autopilot system engaged in "selected mode". This means that that the pilot *manually* introduces the heading, speed, altitude or V/S commands to the autopilot through the FCU.

C. Validation Assesment

All validation objectives were assessed by means of either questionnaires or data logging from the simulator. Two different types of questionnaires were used: an initial Run Questionnaire (RQ) that pilots had to fill up after each validation scenario, and a Post-experiment Questionnaire (PQ) that pilots had to answer at the end of each simulation day. Table I shows the different questions (or logs) that were used to asses each validation objectives.

The first question of the run questionnaire (RQ1) was a tailored task load assessment questionnaire based on the NASA TLX (task load index), in which the pilots expressed the amount of additional task load that following the EFB indications supposed for them. Several task load parameters were assessed and the corresponding acceptance criterion was that all rates should be superior to 72 points (out of 100).

The second question of the run questionnaire (RQ2) and the first one of the post experiment questionnaire (PQ1) were based on the controller acceptance rating scale (CARS), leading to 10 possible acceptability marks [10]. The acceptance criterion for these questions was a mark of 8 or more.

The remaining questions of both questionnaires could be answered using a 6-point Likert scale, except few of them, which were just open questions to gather textual remarks or opinions from the participants. Appendix A details all questions used in this experiment. The acceptance criterion for the Likert questions consisted of answering "Slightly agree", "Agree" or "Strongly agree" in all the simulation runs.

Finally, for the VO5, the simulator data logging was used. The maximum time deviation allowed was ±30 seconds, whereas the maximum altitude deviation allowed was ±2000ft.

V. Experiment Results

In this section, the fulfillment of the different validation objectives (VO) previously defined is presented. The strategy used to validate them is by assessing the corresponding run questionnaire and post questionnaire (RQ/PQ) answers given by the pilots as well as the data loggings registered during the simulation runs. Table I shows the correspondence between each VO and its corresponding dependent measures (RQ/PQ question or data *log*). Moreover, at the end of this section some discussion is given, summarizing the different remarks and feedback from the individuals participating in the experiment.

A. Fulfillment of Validation Objectives

Table I shows which dependent measures (questionnaire or log) where succesfully achieved in the experiment, which did not pass the acceptance criterion and which were not relevant for the validation objective. As seen in the table, each validation objective has been assessed separating the results from Day #1 and from Days #2 and #3. This is because some changes in the simulation set-up were introduced after Day #1 (as explained below).

TABLE I. FULFILLMENT OF VALIDATION OBJECTIVES

Validation Objective	Day	Dependent measure (questionnaire or log)	Valid measures
VO1	*#1*	RQ5, RQ6, RQ7[a], RQ8, PQ6	4/5
	#2 #3	RQ5[a], RQ6, RQ7,RQ8, PQ6	4/5
VO2	*#1*	RQ10[a], PQ5, PQ8[a], PQ10, PQ11, PQ12, PQ13, PQ14[b], PQ16, PQ17, PQ18, PQ19, PQ20[b], PQ22, PQ23, PQ24, PQ25, PQ26[b],PQ28, PQ29, PQ30, PQ31, PQ32[b], PQ34, PQ35, PQ36, PQ37, PQ38[b], PQ40, PQ41, PQ42, PQ43, PQ44[b]	25/27
	#2 #3	RQ10, PQ5, PQ8, PQ10, PQ11, PQ12, PQ13, PQ14[b], PQ16, PQ17, PQ18, PQ19, PQ20[b], PQ22, PQ23, PQ24, PQ25, PQ26[b],PQ28, PQ29, PQ30, PQ31, PQ32[b], PQ34, PQ35, PQ36, PQ37, PQ38[b], PQ40, PQ41, PQ42, PQ43, PQ44[b]	27/27
VO3	*#1*	RQ2[a],RQ3,RQ4,PQ1[a],PQ4	3/5
	#2 #3	RQ2[a],RQ3,RQ4,PQ1[a],PQ4	3/5
VO4	*#1*	RQ1[a],RQ9[a],PQ7[a]	0/3
	#2 #3	RQ1,RQ9,PQ7	3/3
VO5	*#1*	LOG time deviation, LOG altitude deviation	2/2
	#2 #3	LOG time deviation, LOG altitude deviation	2/2

a. Questions that did not fulfill the acceptance criterion

b. *Questions that are not relevant for the validation of the objective*

*1) **VO-1.** To assess the feasibility of flying an optimized trajectory by means of speed, heading and altitude/altitude rate commands.*

This first objective could not be fully validated as 2 out of 10 RQs/PQs associated with it were not positively fulfilled. During the first day of simulations, a single pilot answered "*slightly disagree*" when asked if the amount of speedbrake usage was acceptable (RQ7- Day #1- VS3) and during the 2nd and 3rd day of simulations, a single pilot answered "*disagree*" when asked whether the usage of the EFB was operationally acceptable (RQ5 – Day #3 – VS1). Nevertheless, the great majority of questions were successfully answered. The dependent measure that failed during the 1st day of simulation was related to the speed profile used during that day, that was find to be higher than recommended during a conventional approach. Moreover, in the particular run that the RQ7 failed the pilot encountered unexpected tail wind that added with the high speed profile caused an increased in the altitude error that lead to the appearance of too many speedbrake messages. Nonetheless, after the correction of the speed profile during the 2nd and 3rd day, this particular RQ did not fail again.

Regarding the failure of the RQ5, it must be noted that the disagreement mark was made at the very first simulation for the pilot performing in the Day #3. In all other runs we can see clear positive evolution of pilot's EFB acceptance while going through the different simulations. Then, it can be remarked that this bad grade to RQ5 could be due to lack of confidence with the new equipment that is gained after some practice.

*2) **VO-2.** To assess whether the provided guidance information is sufficient to guide the aircraft along the calculated trajectory.*

The objective was achieved during the 2nd and 3rd day of simulations as it had fulfilled all the 27 questions associated to it. Yet, it failed for Day#1, as 2 answers did not reach the acceptance criteria: one pilot answered "*slightly disagree*" or "*disagree*" when asked if the commanded FCU changes were manageable. (RQ9-Day #1- VS1, VS2 and VS3) as well as "*slightly disagree*" when asked if the configuration changes were manageable. (RQ7-Day #1- RQ).

It is worth noticing that the dependent measures that lead to this objective failure are related with the acceptability of the EFB indicators along the procedure. The issue that appeared during the 1st Day was corrected for Day#2 and #3 by better highlighting during the training session that the EFB indications were not supposed to be followed automatically by the pilot, they were just that: indications. We consider that this small correction made the same objective to pass during the last two days of simulations and would have the same effect in a future experiment.

*3) **VO-3.** To assess whether the additional task to guide the aircraft along the calculated trajectory is acceptable to the pilot during this phase of flight.*

The affirmation stated by this third objective was not completely validated as 2 out of 5 questions of Day #1, Day#2 and #3 were not achieved. Pilots considered in some runs that the system needs "much improvement-(5)", "*some improvements-(6)*" or "f*ew improvements-(7)"* when rating the system using the CARS template (RQ2).

After the debriefing sessions, it was concluded that the reason leading to this result was that there was a general disapproval regarding the physical position of the EFB in the cabin that led uncomfortable positions for the pilot. Moreover, as TEMO automatically was disconnected after arming the APPROACH autopilot mode, the time error increased in the final approach segment. This made the pilots to consider that the system was not working well enough especially in windy scenarios, where this time error kept growing significantly once TEMO was disconnected.

Nonetheless, the majority of objectives were successfully achieved and it is considered that with some minor improvements and better training explanations this objective could be validated in a future experiment.

4) VO-4. To assess the additional workload caused by the task to guide the aircraft along the calculated trajectory.

Pilot's feedback from the run and post questionnaires associated with this objective passed the acceptance criteria for the 2nd and 3rd days, as pilots encountered no difficulty and no increase in the workload when realizing the task demanded. Nonetheless, the same objective failed during the 1st day as one pilot answered *"slightly disagree"* when asked if the commanded FCU changes and configuration changes were manageable (RQ9 and RQ7– Day #1). This also lead to a too high workload rating by the pilot (RQ1).

Again, as mentioned for VO2, the high speed profile used during the 1st Day generated a high amount of speed changes and the wrong conception of the pilot that tried to follow exactly all the EFB indications in a timely manner. This situation was corrected during the 2nd and 3rd day and as a consequence, this objective has been completely validated by the pilots assisting the last two days of simulations.

*5) **VO-5.** To assess the flight technical error (altitude deviations from the calculated trajectory and time deviations from the RTA)*

This particular objective was assessed through logs registered during the simulations. Both altitude and time deviation along the trajectory have kept between the allowed margins (±30s of time deviation and ±2000ft of altitude deviation) for the entire group of simulation scenarios and for all three days. The Table II shows the time error at the final approach point (FAP), when the APPROACH mode was engaged, whereas the Figs. 4 and 5 show an example (Day #2, VS6) of time and altitude error along the simulated route.

These figures highlight the effect of the APPROACH Mode activation as the time error deviates from the almost steady 0 s line and reaches a value of -1.43s at the FAP as seen in the Table II. The wind error present in this run causes these altitude deviations. Nonetheless, this objective remains validated as both the time error and the altitude error did not reached the target boundaries for this pariticular objective.

B. Discussion and Remarks of Participants

In the following section, remarks and opinions from all pilots involved, the instructor pilot and DLR or CONCORDE engineers are grouped in different topics. The opinions were gathered from group debriefings and discussions, notes taken during the simulations and remarks that some pilots made textually in the questionnaires.

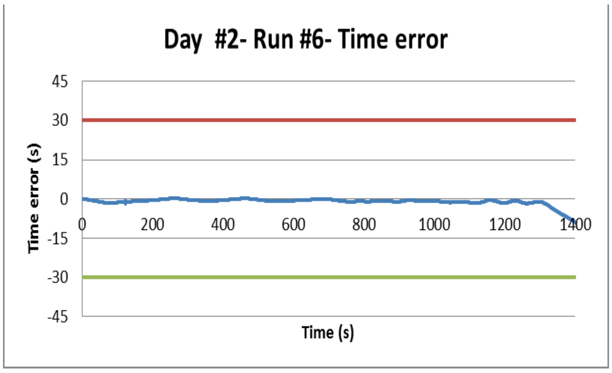
1) Conops and Economic Feasibility

All pilots involved in the simulations congratulated the TEMO team, acknowledging TEMO can be very useful and the system tested a promising functionality that could equip future aircraft. All agreed that the system could be attractive to airlines; yet, they did not see it being implemented until ATC promotes a change over the ATM system focused in 4D navigation. All agreed that, at present, even small savings in fuel (and noise in some airports) are significant enough to justify the certification and adoption costs for such a new technology. Again, all coincided that this new system is providing good RTA results as long as the time errors at FAP are usually below 5 seconds.

Over the simulations, all pilots agreed that they were gradually familiarised with the TEMO concept and felt comfortable flying the new procedures. This acceptability evolution could be also detected over the run questionnaires.

TABLE II. TIME ERROR LOGS

Day	VS	Time error at the FAP [s]	Time error when APP mode ON [s]	VS	Time error at the FAP [s]	Time error when APP mode ON [s]
#1	*1*	6.86	0.58	*4*	3.79	1.77
	2	-2.05	-1.18	*5*	-0.46	-0.6
	3	-2.1	-6.18	*6*	-1.6	-2.34
#2	*1*	3.8	1.45	*4*	3.95	2.27
	2	-1.28	-0.83	*5*	0.32	0.54
	3	-2.37	-3.1	*6*	-1.43	0.44
#3	*1*	5.32	0.86	*4*	4.86	0.39
	2	1.06	0.68	*5*	0.52	0.87
	3	-1.43	-1.35	*6*	3.86	5.63



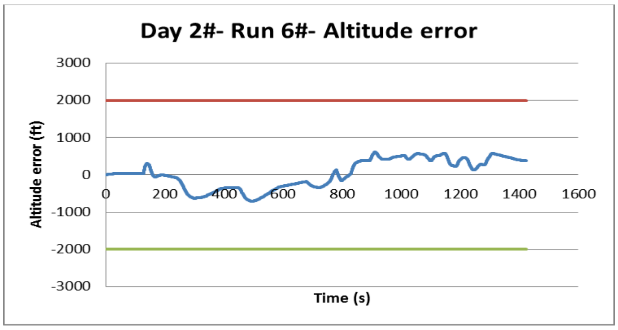


Fig 4. Time and altitude errors for Day #2, VS6 (wind forecast error: 90º/10kt)

One of the pilots was convinced that TEMO could reduce crew workload towards ATC communications, as long as the communications would be reduced to a RTA indication at a certain waypoint per part of ATC. Besides fuel and noise, the gains in capacity and in reducing ATC workload were also acknowledged. All agreed that TEMO can really help in maintain or even increase capacity in dense and complex terminal airspace.

Discussions related to the implication and responsibilities of the ATC were brought up in several occasions. Although it is well understood that ATM is out of the scope of CleanSky, the active participation of ATC was considered of vital importance in the future developments of the TEMO concept.

2) On-board Integration and HMI Acceptance

Pilots were comfortable with most of the TEMO visual indicators displayed and considered they were very useful and necessary. One pilot found not useful the Gear Down and Flaps information boxes displayed over the EFB, as long as both indicators are already displayed over the Engine Warning and System Displays (EWSD).

One pilot considered that the function and visual representation of the flap and gear cues were not clear enough, more specifically that they were too small. The same pilot considered that they were actually not necessary to ensure the TEMO operations. The other two pilots though just the opposite answering that these cues were actually necessary.

All pilots had the feeling that they were in the loop while introducing the EFB indications into the FCU as after several runs all of them tried to anticipate the next EFB indication. Moreover, they all intended to help the system once TEMO was disconnected at the FAP by decreasing the time error produced by the unexpected wind condition.

The integration of TEMO concept inside an EFB was seen by all the pilots as the most suitable way to integrate TEMO inside the aircraft in the short/mid-term. It would suppose a small inversion for the airlines, in terms of equipment, and the consumption benefits could be noticeable from the first flight.

All pilots complained about the position of the EFB inside the cockpit. Located in the right side of pilot position, it was too far from pilot's field of view prompting him to turn the head every too frequently to check the EFB display. In case of an A320, it was suggested to place the EFB on the retractable table in front of the pilot.

Related with the time indications on the EFB, one pilot considered the possibility of adding a time trend scale just next to the time indication. By adding this time trend, the pilot considered that the anticipated actions that one could realise would be even more accurate and efficient.

3) Operational Feasibility and Potential Safety Issues

All three pilots had a good impression on TEMO's operational feasibility and considered it to be a possible system from a future aircraft cockpit.

During the first simulations on each day, pilots were focused on following all the EFB indications strictly, a behaviour that was increasing its workload and hoarding most of their attention due to the numerous speed advisories. This situation even caused the pilots to set the QNH or the Missed Approach altitude later than they would normally do. Then, they started using the EFB indications as suggestions, not to be used exactly but as an indication that pilot is able to consider. This was proved to be the right way of using the system without adding extra workload over the pilot.

Pilots remarked that they always wanted to reduce the time error zero as soon as possible. However, the EFB indications were not producing big changes in short time (when the update frequency of the advisories was set to low values), and in some cases this was no understood by the pilots.

In some cases, it was observed that pilots relied too much in the EFB alerts, since they wanted to deploy flaps or gear earlier but waited for the system to raise the configuration alert. Time error and altitude error indicators were useful to help the pilots to anticipate configuration alerts.

Regarding the use of speed-brakes, the majority of pilots thought that their usage should be minimised. Several reasons were given, such for instance to avoid vibrations, uncomfortable flight for passengers, mitigate wear and tear and other maintenance issues.

Some pilots suggested that the EFB indicators updates should be triggered using bigger steps of changes in order to attenuate constantly small changes.

4) Realism of the Simulations.

All pilots acknowledged the level of realism of the simulation platform was high. Being a research experiment, all of them were somehow expecting a less accurate environment. Some pilots, however, complained about the lack of realism of the operations being simulated (straight-in approach procedure, no traffic, etc.) leading to too low workloads for them.

Without the need of going for extreme conditions (thunderstorms or wind-shear) or aircraft anomalies (engine failure...), they considered that some turbulence, instrument meteorological conditions and other traffic were missing in order to have a realistic baseline where to study the benefits of TEMO in terms of workload reduction. In this line, some pilots were expecting more demanding scenarios and could not find any differences between some runs.

VI. CONCLUSION

The goal of the experiment presented in this paper was to investigate the possibility of using the TEMO trajectory prediction on a modern aircraft with unmodified or only slightly modified avionic systems. For an implementation of the TEMO approach in future avionics, this will help to gather experience with existing aircraft and create acceptance in the community by demonstrating the benefits of the approach. It could also enable different implementation levels to retrofit existing aircraft with lower level TEMO capabilities while the full functionality will be only available to new aircraft.

Moreover, it was aimed to show how this system can guide the aircraft accurately all along the descent trajectory, but with special focus on the arrival time at the final approach point (FAP). The experiments showed also good time accuracies, which were within the very demanding tolerances proposed in SESAR or NextGen programs.

Nevertheless, since conclusions were based on data from only three pilots (and taking into account that 2nd and 3rd days were corrected due to training deficiencies identified in the 1st day), the results of this study considered as preliminary. Further assessment is needed, taking into account all improvements identified in previous section. In this context, some flight trials are planned with the ATRA (DLR's Airbus A320 flight test aircraft) in the first quarter of 2016.

APPENDIX A - EXPERIMENT QUESTIONNAIRES

A. Run Questionnaire (RQ)

The RQ1 was a task load assessment questionnaire based on the NASA TLX (task load index). RQ2 was a modified CARS (controller acceptance rating scale) that could lead to 10 different acceptability marks. The remaining questions could be answered using a 6-point Likert scale (*strongly disagree,*

disagree, slightly disagree, slightly agree, agree, strongly agree) and are depicted in Table III.

TABLE III. RUN QUESTIONNAIRE (QUESTIONS 3 TO 10).

RQ3	The descent was safe
RQ4	The descent was overall acceptable
RQ5	The usage of the Electronic Flight Bag was operationally acceptable
RQ6	I was "in the loop"
RQ7	The amount of speedbrake usage (if any) was acceptable
RQ8	The amount of thrust usage (if any) was acceptable
RQ9	The commanded FCU changes were manageable
RQ10	The guidance was sufficient and acceptable to guide the aircraft along the calculated trajectory

B. Post-experiment Questionnaire (PQ)

The post-experiment questionnaire was divided in three main parts to assess a) the overall acceptance of the experiment; b) TEMO procedures; and c) TEMO visual indicators.

To assess the overall acceptance PQ1 was a modified CARS (controller acceptance rating scale) that could lead to 10 different acceptability marks, as in RQ2. PQ2 and PQ3 were specific questions that could be answered with a 6-point Likert scale (see Table IV). To assess TEMO procedures 5 questions (PQ4-PQ8) with a 6-point Likert scale were created, plus one additional question (PQ9) asking for general remarks or suggestions (see Table V).

TABLE IV. QUESTIONS TO ASSESS OVERALL ACCEPTANCE

PQ2	The simulator provided a good level or realism and was appropriate for this experiment
PQ3	Enough information and training was provided to execute the tasks requested during the experiment

TABLE V. QUESTIONS TO ASSESS TEMO PROCEDURES

PQ4	The TEMO procedures were operationally acceptable
PQ5	The TEMO procedures are correctly designed; it was clear to me what I should do at any time.
PQ6	I was "in the loop".
PQ7	The configuration changes were manageable.
PQ8	The guidance was sufficient and acceptable to guide the aircraft along the calculated trajectory

Finally, to assess TEMO visual indicators, 5 questions with a 6-point Likert were designed to assess each of the following aspects: the speed, heading, altitude, and vertical speed indicators; the flap, gear, approach mode configuration messages; the flap, slats status box; the gear status box; the time and altitude error indicators; and the flap and gear cues on the navigation display (ND). That lead to a total of 30 questions, as displayed in Table VI. Additionally, for each of the previous aspects an additional question asking for general remarks or suggestions was also included (questions PQ15, PQ21, PQ27, PQ33, PQ39 and PQ45).

TABLE VI. QUESTIONS TO ASSESS TEMO VISUAL INDICATORS

PQ10	The function of the indicators was clear
PQ11	The visual representation of the indicators were clear
PQ12	The indicators are *necessary* to be "in the loop"
PQ13	The indicators are *necessary* for correct TEMO operations
PQ14	The indicators are *a nice extra feature,* but not necessary
PQ16	The function of the configuration messages were clear
PQ17	The visual representation of the configuration messages were clear
PQ18	The configuration messages are *necessary* to maintain "in the loop"
PQ19	The configuration messages are *necessary* for correct TEMO operations
PQ20	The configuration messages are *a nice extra feature,* but not necessary
PQ22	The function of the flap / slat status box was clear
PQ23	The visual representation of the flap / slat status box was clear
PQ24	The flap / slat status box is *necessary* to maintain "in the loop"
PQ25	The flap / slat status box is *necessary* for correct TEMO operations
PQ26	The flap / slat status box is *a nice extra feature,* but not necessary
PQ28	The function of the gear status box was clear
PQ29	The visual representation of the gear status box was clear
PQ30	The gear status box is *necessary* to maintain "in the loop"
PQ31	The gear status box is *necessary* for correct TEMO operations
PQ32	The gear status box is *a nice extra feature,* but not necessary
PQ34	The function of the time / altitude error indicators were clear
PQ35	The visual representation of the time / altitude error indicators were clear
PQ36	The time / altitude error indicators are *necessary* to maintain "in the loop"
PQ37	The time / altitude error indicators are *necessary* for correct TEMO operations
PQ38	The time / altitude error indicators are *a nice extra features,* but not necessary
PQ40	The function of the flap and gear cues on ND were clear
PQ41	The function of the flap and gear cues on ND were clear
PQ42	The flap and gear cues on ND are *necessary* to maintain "in the loop"
PQ43	The flap and gear cues on ND are *necessary* for correct TEMO operations
PQ44	The flap and gear cues on ND are *a nice extra features,* but not necessary

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