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Human-in-the-loop Performance Assessment of Optimized Descents with Time Constraints

Results from Full Motion Flight Simulation and a Flight Testing Campaign

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***Abstract*—TEMO (time and energy managed operations) is a new concept that aims to optimise continuous descent operations, while fulfilling with a very high accuracy controlled time of arrival (CTA) constraints at different metering fixes. This paper presents the results and main lessons learnt from two human-in-the-loop experiments that aimed to validate the TEMO trajectory planning and guidance algorithm: a full motion flight simulation experiment and a flight testing campaign. Positive results were obtained from the experiments, regarding the feasibility of the concept and acceptance from the pilots. TEMO descents typically showed lower fuel figures than conventional step-down descents. Moreover, RTA adherence at the initial approach fix (IAF) showed very good performance. Time accuracy at the runway threshold, however, did not fulfil the (very challenging) time target accuracies. Further work is needed to enhance the current algorithm once the aircraft is established on the instrument landing system glideslope.**

I. INTRODUCTION

Improving flight efficiency and reducing the environmental impact of aircraft operations is one of the main drivers in the aviation community. In terminal airspace, continuous descent operations (CDO) have been a subject of extensive research in the last decades, and have proven successful in reducing noise, fuel consumption and gaseous emissions [1]–[3].

Ideally, a CDO consists of an engine-idle descent, from the cruise altitude to the interception of the instrument landing system (ILS) glide slope. The main drawback of such operation is the loss of predictability of the trajectory from the air traffic control (ATC) point of view, in terms of altitude uncertainties and overfly-times at certain fixes. Thus, existing CDO implementations require ATC to introduce additional sequencing buffers to ensure sufficient separation among aircraft, thus reducing airport capacity. For these reasons, in some busy airports CDOs are often applied in off-peak hours only. Other airports, however, try to facilitate CDO as much as possible also with high traffic demand. In those cases, ATC often manage aircraft sequencing through speed control, path stretching (including tromboning or point merge strategies), or even fixing the vertical path of the CDO, as proposed in [4].

The International Civil Aviation Organization (ICAO) has published some CDO guidance material [5] to support air navigation service providers (ANSP) to design vertical corridors in which all descent trajectories must be contained, helping in this way to strategically separate them from other procedures in the vicinity. As reported in [6], however, these criteria have been established without explicitly considering the aircraft type, assuming international standard atmosphere (ISA) conditions and with coarse assumptions regarding the aircraft gross mass and performance data. This leads, in the majority of cases, to too restrictive corridors that limit the potential CDO adherence in real operations.

An alternative to allow for CDO in dense traffic scenarios, would be to assign controlled times of arrival (CTA) to flights at some strategic fixes for separation, sequencing and merging purposes. This requires ground-based [7]–[9] and/or on-board [10], [11] trajectory predictors, converting the received CTA into a required time of arrival (RTA) constraint for the on-board aircraft trajectory planning and/or guidance functions. Typically, this results into an active control loop, which continuously commands thrust aiming at nullifying trajectory time errors and/or remaining on path (using speed-brakes if needed). This continuous control on thrust or speed-brakes has a negative effect on noise emissions and fuel usage.

Time and Energy Managed Operations (TEMO) aim to overcome these issues. On one hand, the trajectory minimising a given objective (typically fuel) is planned, while fulfilling an RTA at one or more fixes. On the other hand, the concept uses energy modulation to couple altitude and speed allowing to efficiently meet these RTAs with a minimal usage of thrust and speed-brakes.

This paper presents some results and main lessons learnt from two human-in-the-loop experiments that aimed to validate the TEMO trajectory planning and guidance algorithm. The paper is focused on showing the time accuracy of the algorithm when fulfilling RTA constraints at the initial approach fix (IAF) and runway threshold. Moreover, fuel consumption is compared with fuel figures for conventional step-down descents and finally, the accuracy of the weather forecasts used in the trajectory planning is also discussed.

II. Time and Energy Managed Operations (TEMO)

TEMO is a new concept developed within the Management of Trajectory and Mission (MTM) work package of the area of Systems for Green Operations (SGO) of the Clean Sky European Joint Undertaking research initiative. TEMO is in line with SESAR step 2 capabilities, since it proposes 4D trajectory management and aims to provide significant environmental benefits in the arrival phase without negatively affecting throughput, even in high density and peak-hour operations. In particular, according to the SESAR air traffic management (ATM) master plan [12], TEMO addresses SESAR operational improvements *TS-0103* and *TS-0109* (CTA in medium density/complexity and high density/complexity environments, respectively).

From an ATC point of view, the TEMO concept assumes that the arrival management automation will use available trajectory information to determine the preferred landing route, landing sequence, inter-aircraft spacing, and arrival schedule based on the capabilities and constraints of the inbound aircraft, as well as the scheduled airport constraints (such as runway configuration, mixed-use runway use, dependent approaches, and weather conditions). The scheduling process will be coordinated with adjacent ATC centres and, when the schedule is frozen, a fixed RNAV arrival route (to the runway) with CTAs at some metering fixes will be provided.

When entering in the terminal airspace, ATC may either complement or substitute the CTA instruction with a CTA at the RWY or a Controlled Time Interval (CTI) instruction to facilitate relative spacing between the own aircraft and a designated aircraft ahead. The assigned control times will be entered as required time of arrival (RTA) by the on-board TEMO tool-set embedded into the FMS.

Along the descent the crew will monitor the operation and configure the aircraft as directed by the guidance application. Separation responsibility will remain with ATC as no transfer of responsibility will take place. TEMO operations will cease when the aircraft is on the correct lateral and vertical path, in the desired landing configuration, and thrust is stabilized and set to maintain the target Final Approach Speed (FAS). This stabilization point is assumed to be around 1000 ft above ground level (AGL).

A. The TEMO concept

The core principle of the TEMO concept is that the energy of the aircraft can be managed in order to control the aircraft to a given point in space and time. The total energy E_T of an aircraft is the sum of its kinetic and potential energy, which can be exchanged during a descent (energy modulation) in such a way that speed can be adjusted to meet an RTA, provided that altitude also changes in such a way that the total energy remains constant:

$$E_T = \frac{1}{2}mv^2 + mgh, \tag{1}$$

where m is the aircraft mass, v its velocity, g the gravitational acceleration and h the aircraft's altitude.

The aircraft longitudinal equation of motion (for a three degree of freedom model) is given by:

$$\frac{\mathrm{d}v}{\mathrm{d}t} = \frac{T-D}{m} - \frac{g}{v}\frac{\mathrm{d}h}{\mathrm{d}t}, \tag{2}$$

where t is the time and T and D are, respectively, the thrust and aerodynamic drag forces. Then, the total energy rate can be obtained by differentiating (1) and combining it with (2), yielding to:

$$\frac{\mathrm{d}E_T}{\mathrm{d}t} = v\,(T-D)\,. \tag{3}$$

Therefore, the total energy of an aircraft can be increased by applying thrust and decreased by increasing drag (and minimising thrust). Energy cannot be destroyed and can only be dissipated through work done by the Drag force.

Ideally a CDO should be flown at idle thrust (minimising fuel, emissions and noise). In this situation the aircraft can only adjust its airspeed profile by modulating energy. Thus, if speed should be increased (to meet a RTA for instance), the aircraft will have to loose altitude, and vice-versa. If energy modulation is not enough and total energy needs to be added, additional thrust will be required. Conversely, if the total energy needs to be further decreased, speed-brakes can provide with significant extra aerodynamic Drag.

Different from other CDO concepts, TEMO optimizes the planned trajectory, on one hand, in order to minimise fuel consumption and speed-brake usage, while satisfying RTAs at one or several fixes and incorporating applicable standard operational procedures and limitations. On the other hand, TEMO guides the aircraft along this planned trajectory (guidance command), coping with deviations resulting from model inveteracies or external perturbations, and benefiting from active energy modulation control. The reader is referred to [13] for a preliminary comparison between TEMO and typical FMS trajectories, showing improvements regarding RTA adherence performance and environmental impact mitigation.

Since fuel-optimal vertical paths are very sensitive to different aircraft types, weights, flap/slat settings and meteorological conditions; this optimization is performed on-board. In this paper, the TEMO planning and guidance modules are assumed to be part of the flight management system (FMS). Specific human machine interfaces have been designed for TEMO operations, including specific visual cues in the primary flight display (PFD) and navigation display (ND) [14], [15]. Other implementations, however, are also possible, such as embedding the TEMO planning algorithm into an electronic flight bag (EFB) and closing the control loop by pilot manual inputs into the auto-flight system [16]. Nevertheless, this is out of the scope of this paper and all experiments shown were conducted by using a research FMS integrating the TEMO planning and guidance functionalities.

1) Trajectory planning: Ideally, an energy-neutral trajectory (i.e. a complete descent down to the stabilisation point, at idle thrust and with no speed-brake usage) that minimises the fuel consumption will be obtained from this planning process.

Yet, some constraints along the trajectory (including eventual RTA) might require to add or remove energy. In this case, an optimization process determines the best trajectory such that the usage of fuel and speed-brakes is minimised, while fulfilling all constraints.

This optimal descent trajectory is computed by the FMS while the aircraft is still in cruise, well before the top of descent (TOD). The optimal outcome is not a fixed vertical trajectory from the TOD to the ILS glideslope intercept, as generated in current FMS implementations, but a speed plan as a function of the remaining distance to the runway threshold.

The guidance module will be in charge of following this speed plan but, due to model inaccuracies or weather uncertainties, or flight guidance errors, for instance, the aircraft may deviate from the planned altitude. TEMO algorithms continuously monitor time and/or total energy errors at the current position and the FMS will trigger a trajectory re-plan when one of the following occurs:

- time or energy errors exceed some pre-defined limits; or
- the ATC sends (or updates) a CTA at a certain fix.

A trajectory re-plan will optimise again the trajectory, but from the current aircraft state, generating a new speed plan aiming at minimising fuel and speed-brake usage while fulfilling all constraints [17].

The TEMO tool-set may also compute the so-called *Earliest* and *Latest* trajectories at the metering fixes, downlinked to ATC along with the Estimated Time of Arrival (ETA). These have an important operational value, allowing the ATC to know the feasible time window at these fixes and help to derive the CTA, which will become the RTA once entered into the FMS. In [18] the feasible time window sensitivity to aircraft position (altitude and remaining distance) when receiving a CTA was assessed by numerical simulation in a hypothetical scenario where only energy-neutral trajectories were allowed.

2) Trajectory guidance: The speed plan generated by TEMO can be executed by using different guidance concepts in the Energy or Time channels. With strategic guidance, *speed on elevator* control provides an effective way to modulate the total energy and accurately follow the speed plan. Time and/or energy deviations from the plan (due to modelling uncertainty) can grow as long as they remain below the allowable margins. Otherwise, a trajectory re-plan is triggered.

With tactical guidance, immediate action is taken to nullify any sustained error in time and/or energy. This is done by commanding, respectively, airspeed and/or thrust changes by an active control loop. More details on the different guidance modes can be found in [14] and the references therein.

B. TEMO developments and testing

Initial batch studies of the TEMO concept were done to test its feasibility, reaching technology readiness level (TRL) 3 and proving lower fuel consumption and noise levels on ground, if compared with conventional step-down descents [19]. A human in the loop study was performed to look at human factors aspects, reaching TRL-4 and showing acceptable RTA adherence performance and operational acceptability by qualified pilots [14]. Yet, the model contained several important approximations and limitations.

(a) NLR's GRACE full motion flight simulator

(b) NLR/TUD's Cessna Citation II experimental aircraft

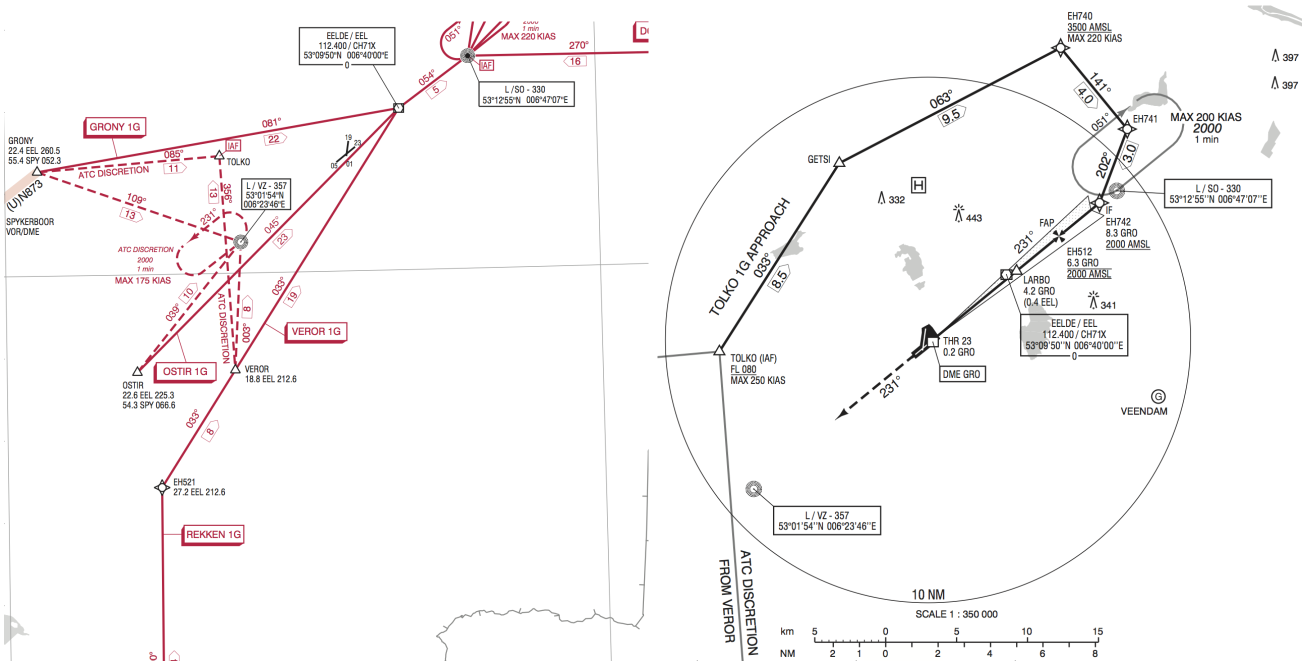
Fig. 1. Experimental platforms

The FASTOP (Fast Optimizer for Continuous Descent Approaches) project, funded by the CleanSky Joint Undertaking initiative, enhanced that version of the TEMO algorithm in order to test it in more realistic environments, aiming at the TRL-5 gate. The main improvements of the model were the consideration of realistic wind fields, non-standard atmospheres or curved routes; while the TEMO software was redesigned from scratch allowing to use it in real-time on-board applications [20], [21].

In 2014, a second human in the loop study was performed in the NLR (Netherlands Aerospace Center) full motion flight simulator GRACE (Generic Research Aircraft Cockpit Environment) to test TEMO in a more realistic simulated environment, achieving in this way TRL-5 (see Fig. 1(a)). The experiment setup and the qualitative assessments gathered from pilots are reported in [22], while a more detailed description of the trajectory optimisation algorithm and the quantitative results obtained is found in [17].

In 2015, and aiming at TRL-6, NLR in cooperation with Delft University of Technology (TUD) and with the support of the Concorde consortium, executed some flight trials with a Cessna Citation II research aircraft (see Fig. 1(b)). Several TEMO variants were tested, including conventional step-down descents for benchmarking purposes. Details on the preparation of this flight testing campaign are given in [15].

This paper wraps-up the main lessons learnt from these two human-in-the-loop experiments.



(a) REKKEN 1G STAR (b) TOLKO 1G approach

Fig. 2. Instrument flight rules (IFR) charts depicting the lateral route flown in all experiments (Source: Dutch AIP)

III. Setup of the Experiments

The test aircraft was a Cessna Citation II. For the GRACE simulations, the aircraft dynamics model represented this same aircraft. Nevertheless, some specific functionalities were added, such as an auto-throttle system (not available in the experimental aircraft) and an auto-speed-brake feature that was able to deploy, without pilot intervention, the continuous speed-brake plan as commanded by the TEMO algorithm.

The Eelde Groningen airport (EHGG), in The Netherlands, was selected for both experiments and all flights started with the aircraft stabilized in cruise and at some point within the first leg of the REKKEN 1G standard terminal arrival route (STAR) (see Fig. 2(a)). After the STAR the TOLKO 1G approach procedure was followed, a P-RNAV ILS CAT-I approach for runway 23 (see Fig. 2(b)). As seen in the chart, TOLKO is the IAF (initial approach fix) of the procedure, while EH512 is the FAP (final approach point), where the aircraft shall intercept the ILS glide slope at 2,000 ft AGL.

On the leg towards EH521 (see Fig. 2(a)), the TEMO software was activated and an optimal descent trajectory minimizing fuel consumption and speed-brakes usage (and without any time requirement) was computed. Few seconds later a RTA was issued for TOLKO, triggering a new TEMO plan to satisfy this RTA. Then, the crew was cleared to start the descent on their own discretion (i.e. following the TEMO plan). At about 5 NM before TOLKO, another RTA was issued at the landing runway threshold (THR), triggering another TEMO re-plan. Different RTAs were given in the experiments, asking the crew to arrive earlier or later than the ETA at the metering fixes (IAF or THR).

Moreover, different guidance principles were tested in the experiments combining strategic and tactical guidance in both time or energy channels. For the strategic guidance modes, specific energy (defined in this paper as the total energy divided by the weight of the aircraft) bounds were set to 500 ft in the cruise phase until the TOD, 200 ft at the IAF and 100 ft at the THR; while time bounds were set to 15 s, 10 s and 5 s respectively. Between these three points, specific energy and time bounds were linearly interpolated.

It is worth noting that during the experiments the ATC did not request any holding or path stretching manoeuvre, neither direct-to instructions. Moreover, the aircraft crew was always cleared to descent before arriving the TOD. For safety and operational reasons, the crew was instructed to always engage the autopilot approach mode once well established on the ILS localiser, and just before intercepting the ILS glide slope. The activation of this mode automatically disabled the TEMO algorithm and consequently, no actions were taken to nullify time and/or energy deviations.

A. GRACE simulations setup

GRACE is a six degree of freedom moving-base flight simulator that incorporates a weather simulation tool generating a 4D weather grid, which feeds the flight mechanics model of the simulator. For the experiments presented in this paper, realistic weather conditions were simulated using data coming from standard Gridded Binary (GRIB) files corresponding to January 13th 2008 and provided by the Royal Netherlands Meteorological Institute (KNMI).

This experiment was mainly focused to test strategic guidance on both energy and time channels, which is one of the main differences between TEMO and other state-of-the-art CDO concepts. A hybrid mode was also tested (see Table I). For each day of simulations four different runs were executed, intentionally introducing different wind forecast errors to test the robustness of the TEMO algorithms. Two additional runs were also performed simulating unusual situations that could provide extra workload to the pilots (see Table II for details).

TABLE I
GRACE EXPERIMENTS SIMULATION SCENARIOS

ID	Planning & guidance	Date
60x	TEMO E_s/T_s	07-07-2014
70x	TEMO E_s/T_s	08-07-2014
80x	TEMO E_s/T_t	09-07-2014

E_s: Energy strategic - E_t: Energy tactical
T_s: Time strategic - T_t: Time tactical

TABLE II
GRACE EXPERIMENTS SIMULATION RUNS

ID	Run configuration
xx1	no wind forecast errors
xx2	3 kt/2° constant wind error
xx3	6 kt/4° constant wind error
xx4	9 kt/6° constant wind error
xx5	3 kt/2° constant wind error + replanning malfunction
xx6	3 kt/2° constant wind error + manual flight with flight director

All simulation runs started with the aircraft in cruise at FL300 and Mach 0.60. The experiment leader, from the GRACE simulator control room, was in charge to simulate ATC and to send the different CTA via data-link. Upon reception, the aircraft crew had to knowledge the CTA instruction and to enter it manually into the FMS, triggering in this way a new TEMO re-plan. CTA at the IAF were set to 10 seconds earlier than the ETA, while CTA at the THR were set to 5 seconds earlier. A nominal run for most of the scenarios took approximately 25 minutes to complete.

It should be noted that all operations were flown in full automatic flight (except for runs xx6) following the standard operating procedures of the aircraft. Subject pilots monitored the progress of the flight and anticipated trajectory changes. They also had to select high-lift devices and gear right at the planned locations (computed by the TEMO algorithm). A timer and specific visual cues in the PFD assisted the pilots in executing these manual actions in due time.

B. Flight testing setup

For the flight trials, four families of RTA were tested as shown in Table III. Regarding the weather data, two types of models were considered. Firstly, weather forecasts from the KNMI in form of standard GRIB files, downloaded few hours before starting the runs for a given day. These GRIB files were processed by the TEMO tool-set in order to provide temperature, pressure and wind estimates to the TEMO trajectory planning function [21].

Alternatively, some runs used weather estimates coming from in-flight measured data collected by the same aircraft during a previous run. Since some runs were executed sequentially (after a go-around and the time required to reach again the initial position at cruise altitude), it was expected to have better weather estimates in those cases rather than in the GRIB forecast (few hours old). The idea behind this strategy was in line with some research proposals, where aircraft share meteorological data with surrounding aircraft in order to enhance the quality of on-board weather information [23].

TABLE III
TIME OFFSETS USED TO DEFINE THE RTAS (RTA = ETA + ΔT)

Metering fix	ETA	Late	Early	Very Late
IAF	ΔT=0	ΔT=20s	ΔT=-20s	ΔT=+30s
THR	ΔT=0	ΔT=10s	ΔT=-10s	ΔT=+15s

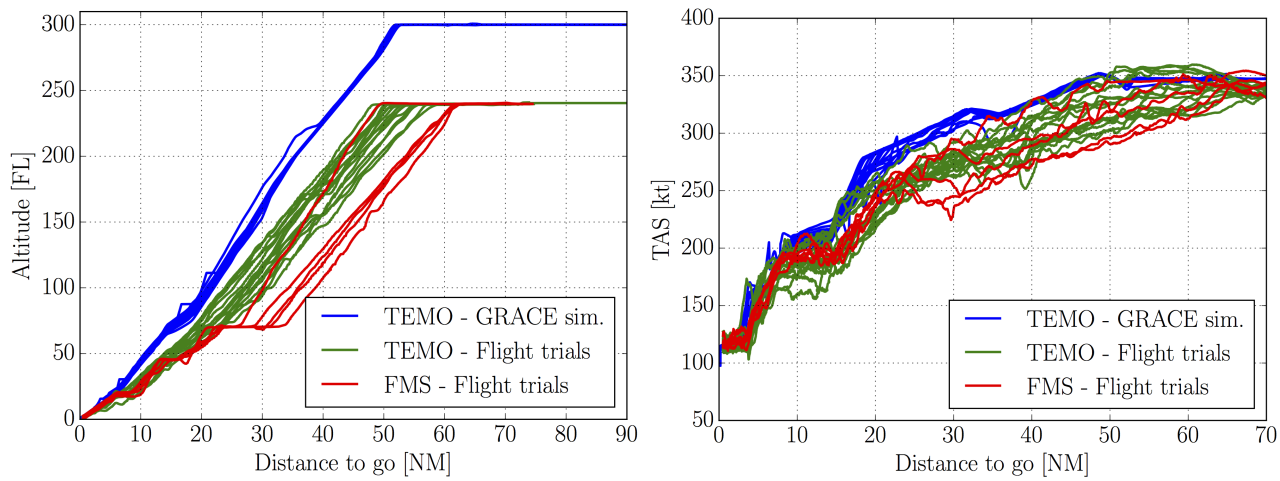
TABLE IV
RUNS OF THE FLIGHT TESTING CAMPAIGN

ID	Planning & guidance	RTA update	Date and time	Weather data source
909	TEMO E_s/T_s	ETA	19-10-2015 17:09	Recorded
901	FMS step down	ETA	19-10-2015 17:43	Recorded
901.1	FMS step down	ETA	22-10-2015 16:18	GRIB
905	TEMO E_t/T_t	ETA	22-10-2015 16:40	Recorded
909.1	TEMO E_s/T_s	ETA	22-10-2015 17:22	Recorded
913	TEMO E_s/T_t	ETA	22-10-2015 20:10	GRIB
902	FMS step down	Very late	22-10-2015 20:43	Recorded
906	TEMO E_t/T_t	Very late	22-10-2015 21:07	Recorded
910	TEMO E_s/T_s	Very late	22-10-2015 21:43	Recorded
914	TEMO E_s/T_t	Very late	23-10-2015 15:45	GRIB
903	FMS step down	Early	23-10-2015 16:08	Recorded
911	TEMO E_s/T_s	Early	23-10-2015 16:44	Recorded
907	TEMO E_t/T_t	Early	23-10-2015 17:24	Recorded
915	TEMO E_s/T_t	Early	26-10-2015 15:37	GRIB
904	FMS step down	Late	26-10-2015 16:13	Recorded
908	TEMO E_t/T_t	Late	26-10-2015 16:35	Recorded
912	TEMO E_s/T_s	Late	26-10-2015 17:23	Recorded
916	TEMO E_s/T_t	Late	26-10-2015 19:47	GRIB
917	TEMO E_t/T_s	Late	26-10-2015 20:21	Recorded
919	TEMO E_s/T_s	ETA	26-10-2015 21:15	Recorded

Table IV shows all runs of this experiment, detailing the planning and guidance mode used in the descent, the type of RTA update, and the source of the weather forecast data. As seen in the table, besides the TEMO descents (with different guidance variants), some conventional FMS step down procedures were performed for benchmarking purposes (enforcing a level-off at FL70 to emulate current operations).

It should be noted that although all possible guidance modes were tested, the aim of the experiment was not to assess their performance and compare one against each other. Assessing the benefits and drawbacks of the different guidance options deserves further work and would require a comprehensive sensitivity batch study.

Due to operational limitations in the Amsterdam TMA, the flight trials had to be contained into the lower airspace. For this reason, all runs started with the aircraft in cruise at FL240 and Mach 0.60. The experiment leader, who sat



(a) Altitude

(b) True airspeed (TAS)

Fig. 3. Altitude and speed profiles for all runs

in the cabin with a control console controlling the TEMO tool-set, was in charge to enter the RTAs into the FMS at the right moments. The Captain acted as safety pilot and could, in any moment, override the experiment and take manual control of the aircraft. The other pilot was indeed the experimental pilot who flew the aircraft according to the TEMO concept and using the experimental displays with the specific TEMO visual cues [15]. When overflying the runway threshold, the aircraft executed the published missed approach procedure and waited for ATC clearance to directly proceed to EH522 to start (eventually) a new run.

While conceptually required by TEMO, during these flight trials the auto-throttle and auto speed-brake systems were not available, as these systems are not implemented on the experimental aircraft. Therefore, it was required to provide additional HMI support to help pilots to set proper throttle or speed-brake settings manually during the whole descent.

IV. Results

Fig. 3 shows the altitude and true airspeed (TAS) profiles for all runs. As seen in the figure, there is much more dispersion in the flight trials trajectories, due to the fact that the flight testing campaign spanned for more than one week (see Table IV) and quite different meteorological conditions were encountered (namely wind fields).

A. Example of TEMO descent

A representative example of a TEMO descent is shown in Fig. 4, plotting different variables as a function of the renaming distance to the THR. The vertical dotted lines are located at the distances where a trajectory re-plan was performed: the first two re-plans were because of RTA updates (first at TOLKO, then at the THR). After the first RTA (received at about 70 NM from the THR) an optimal trajectory was computed allowing for a complete continuous descent operation and placing the TOD at about 48NM from the THR. The second RTA instruction was given slightly before reaching TOLKO with a RTA at the THR. The third re-plan was triggered by an excessive energy deviation.

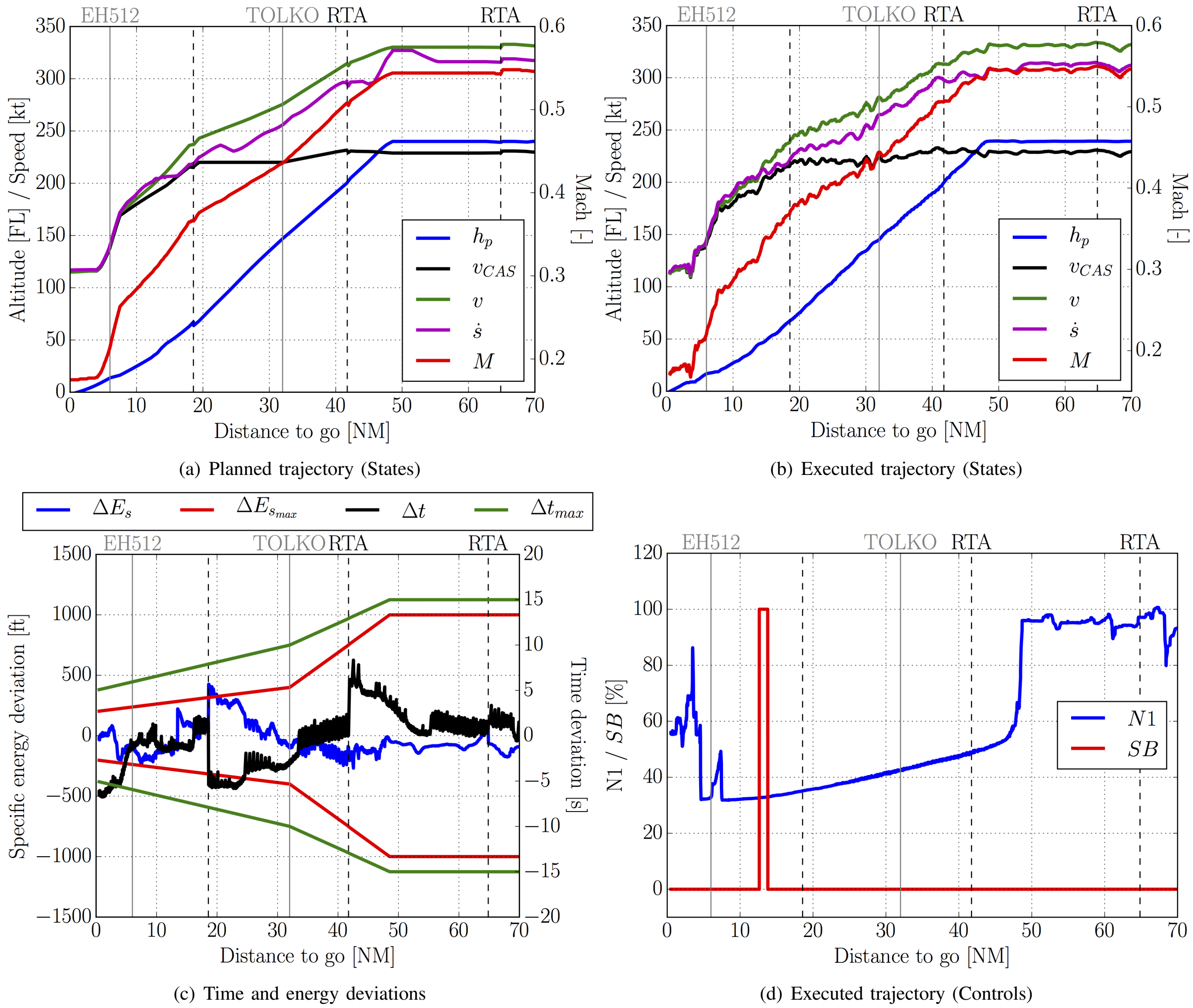
Figs. 4(a) and 4(b) show respectively, the state variables of the planned and executed trajectories: pressure altitude (h_p), calibrated airspeed (v_{CAS}), true airspeed (v), ground speed ($\dot{s}$) and Mach number (M).

In Fig. 4(c) deviations (with respect to the planned trajectory) on time and specific energy are plotted together with their maximum bounds. As seen in this figure, at around 22 NM from the THR the specific energy error exceeds its maximum bound, triggering a trajectory re-plan that becomes active in the FMS at about 19 NM from the THR.

Fig. 4(d) shows low-pressure compressor speed ($N1$), which is directly proportional to aircraft throttle, and the speed-brake (SB) usage. As seen in the figure, the aircraft follows a completely idle descent from the TOD down to EH512 (the FAP), where the ILS glideslope is intercepted and some thrust is required to maintain path and speed beyond this point. Regarding speed-brakes, the two initial trajectory computations planned for a zero speed-brake usage. Due to energy deviations cumulated through the descent, however, the third trajectory plan had to include some speed-brake usage at around 13 NM from the THR to fulfil all trajectory constraints.

It is worth noting that at around 15 NM from the THR, the energy deviation decreases suddenly, but no re-plan is triggered. This is due to the fact that the pilot just switched the altimeter setting from Standard pressure to QNH (local aerodrome pressure), reducing in this way errors in the pressure and temperature forecast used to plan the trajectory.

Finally, it is observed how at EH512 the time deviation starts to increase (negative values, meaning the aircraft is arriving too early at the THR), exceeds the maximum time error bound, but not action is taken to compensate. As explained before, this is due to the fact that in the glideslope interception the TEMO algorithm is disconnected and the trajectory is too constrained (flight path angle is fixed and there is little room



(a) Planned trajectory (States)

(b) Executed trajectory (States)

(c) Time and energy deviations

(d) Executed trajectory (Controls)

Fig. 4. Example of TEMO descent (Flight trials run 909)

for speed changes, since the aircraft must be stabilized at the final approach speed when reaching 1000 ft AGL).

B. RTA compliance

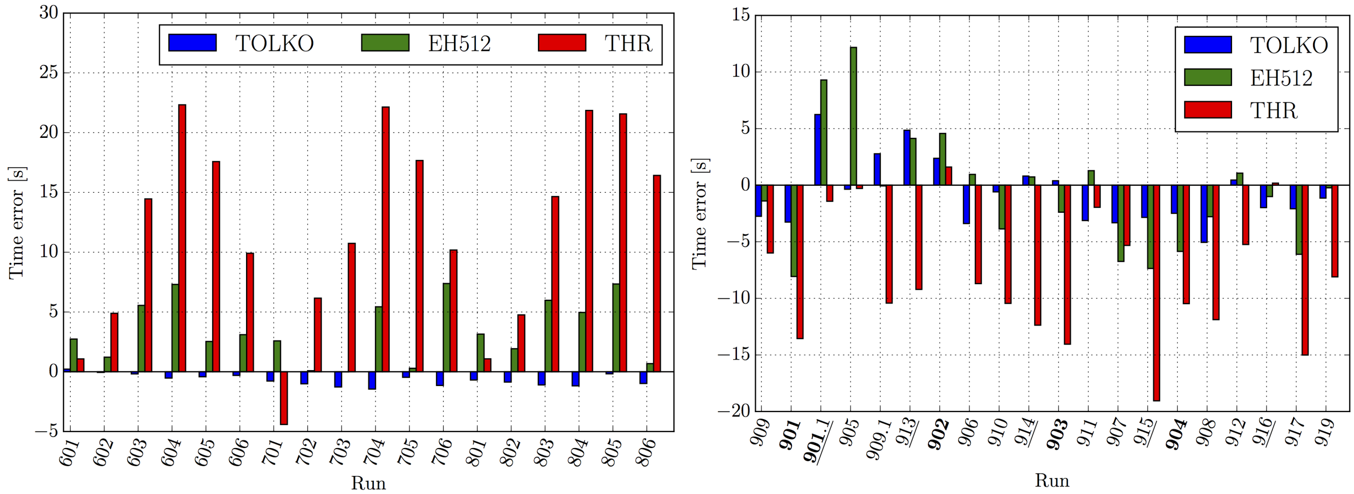
Fig. 5 shows the time deviations at TOLKO, EH512 and the THR for all runs. As seen in the figure, we observe that the time accuracy to meet the RTA at the IAF is very good, well below the ± 10 seconds of target accuracy. At the THR, however, the time deviations are much larger exceeding in the majority of runs the the target accuracy of ± 5 seconds.

For the GRACE simulations the aircraft was always arriving late (due to headwind conditions), while for the majority of the flight tests the aircraft was arriving earlier than planned due to the fact that most runs were flown in tailwind conditions. Moreover, in the GRACE simulations, larger deviations are observed, logically, for those runs with more wind forecast errors (see Table II).

High time errors at the THR could be explained by several reasons. First of all by the activation of the autopilot approach mode just before the FAP, which disables the TEMO algorithm. In fact, the speed on elevator controller is disengaged and path on elevator control is applied to follow the ILS glideslope. Then, since the path is fixed, any modelling or guidance error quickly increases the time error. Moreover, in the glideslope the aircraft is flying at lower speeds and wind forecast errors are relatively more important.

It was also identified that engine dynamics cannot be neglected in the glideslope, since throttle is used to maintain speed. In this context, the planned trajectory assumes instantaneous throttle changes (and thus instantaneous N1 changes), which is an acceptable assumption thorough all the descent, except for the glideslope phase.

Recall also that for the flight trials the final approach phase was always flown manually (no auto-throttle functionality was available) and the workload for the pilot was rather high (many cues to follow). Better results would be expected with an autopilot and/or an improved HMI. Finally, the commanded



(a) GRACE simulations

(b) Flight trials (in bold: FMS step down; underlined: KNMI forecasts)

Fig. 5. Time Deviations at the IAF, FAP and runway threshold (THR) for all runs

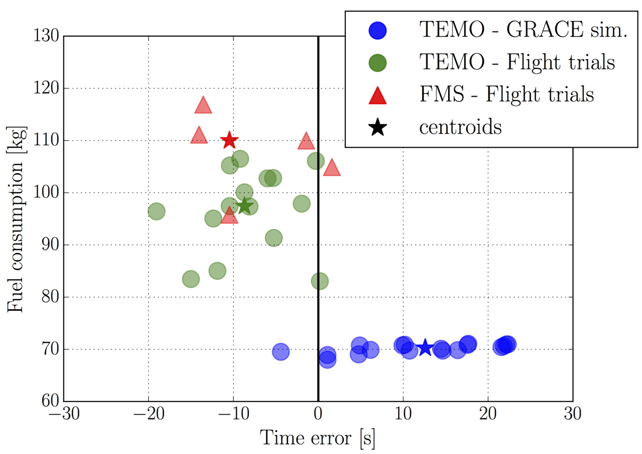


Fig. 6. Time errors at the THR and fuel consumption for all runs

speed, in case of using the tactical time controller, was not correctly calculated by TEMO in scenarios 905, 906 and 913.

TEMO time accuracy performance was assessed at the FAP too (waypoint EH512). Fig. 5 also plots the time deviations of the executed trajectory, with respect to the planned trajectory, at this point. As seen in the figure, almost all runs showed a very good time accuracy at the FAP, being most of them within ± 5 s target accuracy or only slightly exceeding it.

In light of these results, it is interesting to observe how quickly the time error grows (in absolute terms) only in the glideslope phase. Even if this error has been confined within its bounds (± 5 s) thorough all the descent down to the FAP (i.e. for more than 60 NM); more than 10 seconds of time deviation can be accumulated only in the glideslope phase, which is only about 6 NM long. In order to achieve the required time accuracies at the THR, it is expected to improve the TEMO planning and guidance algorithm in this particular phase in the near future.

C. *Fuel savings*

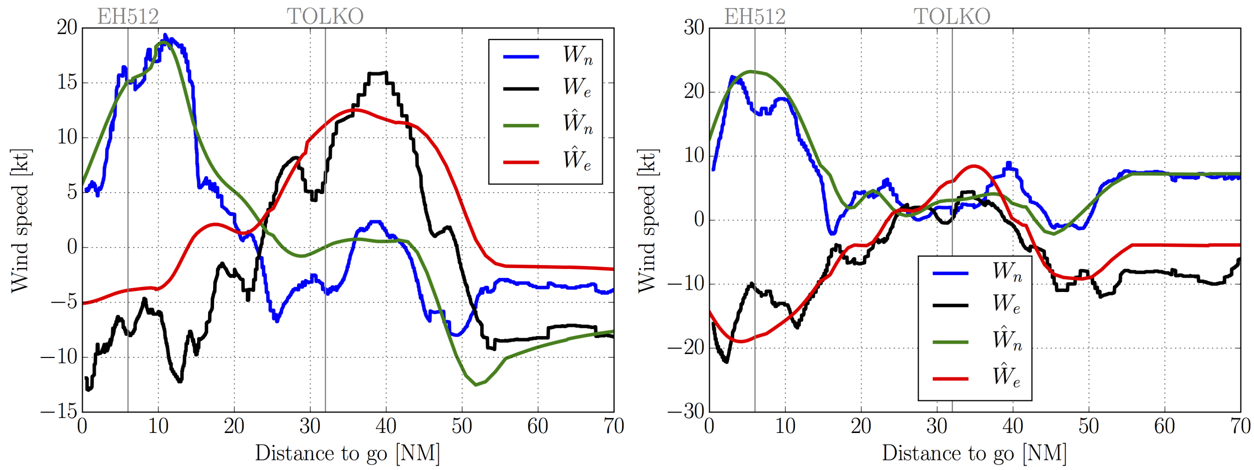
Fig. 6 shows the time deviation at the THR and the fuel consumption between EH521 and the THR. GRACE simulations show less fuel consumption than the flight trials because the cruise altitude was much higher in the simulations and, in general, the aircraft always flew higher (see Fig 3). Moreover, the dispersion in fuel figures is higher in the flight trials because, on one hand much diversity was encountered regarding weather conditions; and in the other hand, several TEMO variants were tested (see Table IV) mixing strategic and tactical guidance modes.

In the framework of the flight trials, the lower fuel consumption mean value is achieved when using TEMO Energy Tactical / Time Strategic configuration; while the higher fuel consumption mean value is achieved when using TEMO Energy and Time Strategic. Nevertheless, it is hard to extract conclusions regarding the different guidance modes used in the flight trials, since the obtained data are not statistically relevant (in fact, some TEMO variants were flown only once, as seen in Table IV). The objective of the flight trials was to test and verify the different TEMO variants, which all worked well during the experiments. Further work is needed to accurately assess the performance of these variants.

In Fig. 6 the conventional FMS step-down approaches are also included, showing a greater fuel consumption (as expected) and similar performances when complying the RTA as in the TEMO cases.

D. *Weather prediction considerations*

As explained in Section III-B, two different sources of weather data were used in the flight trials: forecast data from the KNMI and recorded data from a previous run. Taking into account that the trajectory prediction (and RTA adherence) is much more sensitive to wind fields, rather than pressure or temperature, for instance, this section is focused in wind prediction errors.



(a) Run 915 (prediction using the KNMI forecast)

(b) Run 917 (prediction using recorded data in the previous run)

Fig. 7. Observed (real) north and east wind components (W_n, W_e) vs. prediction of north and east wind components ($\hat{W}_n$, $\hat{W}_e$)

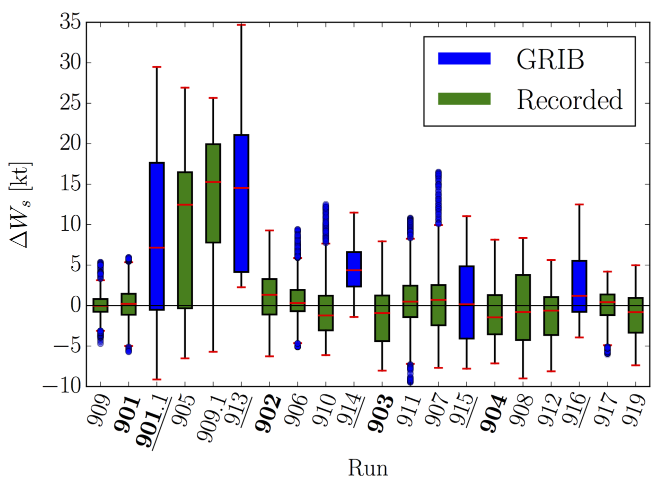


Fig. 8. Along track wind (ΔW_s) component errors (in bold: FMS step down)

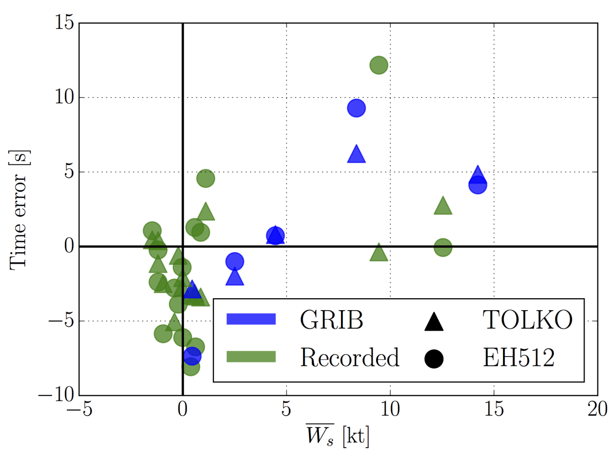


Fig. 9. Correlation between along track wind component and time errors

Fig. 7 shows a comparison between the forecast and observed (measured by aircraft sensors) wind components for two example runs. Fig. 7(a) corresponds to Run 915, where the KNMI forecast was used, showing how the forecast data overestimated the North wind component at the cruise altitude (50 NM to 70 NM from the THR) and improved at lower altitudes. A similar behavior is observed for the east wind component, where the forecast data this time underestimate it.

Fig. 7(b) shows the same comparison for Run 917, which used recorded data from the previous run executed around half an hour before (see Run 916 in Table IV). Since the descent trajectory was very similar between these two runs (same lateral route and slight deviations in the vertical path), wind forecast errors are much lower, as expected.

Fig. 8 shows the along track wind prediction errors for all flight trial runs, comparing each sample of wind data stored by the FMS (at a 5 Hz recording frequency) with the forecast data. The plots show the median; the 25 and 75 percentile; and the 1.5 IQR (inter-quartile range) of the errors; while outliers are shown as circles. As expected, recorded data show better accuracies (especially for the first runs). Yet, a very good performance of the GRIB files is observed for latter runs, showing almost the same accuracy as the recorded data.

Finally, Fig. 9 shows, for each run, the relationship between the time errors at the IAF and FAP and the average along track wind prediction error. A clear correlation cannot be found, since time accuracy not only depends on the weather forecast, but also if the trajectory replans were successful: a bad forecast could be mitigated by many replans and still achieve good time adherence at the metering fixes. Moreover with the few number of experiments performed we have not enough evidence to claim statistical significance in this topic.

V. Conclusions

The TEMO concept was successfully tested in a simulated and real-world environment with positive results and feedback of all participants. The experiments were a proof of concept and technology demonstrating that TEMO flight operations were safe and acceptable by pilots, and showing that accurate timing can be achieved while preserving fuel benefits in line with current day fuel consumption of continuous descent operations (CDO). Results obtained with the Cessna Citation II are representative enough to extrapolate them to larger commercial aircraft types, especially in the Calibrated Airspeed regime.

The experiments indicated that two aspects at conceptual level that require further attention: the instrument landing system (ILS) glideslope interception and new or enhanced strategies to manage time deviations once established on the glideslope. Further work is also needed to thoroughly assess the different guidance options for TEMO and their implications in fuel consumption and noise impact.

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