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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 required time of arrival (RTA) 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 IAF showed very good performance. Time accuracy at the runway threshold, however, did not fulfil the (very challenging) time target accuracies. Further work is required to enhance the current algorithm when managing time deviations once the aircraft is established in the instrumental 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], [2], [3].

Ideally, a CDO consists of a full engine-idle descent, from the cruise altitude to the interception of the instrumental 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 waypoints. Thus, existing CDO implementations require ATC to introduce additional sequencing buffers to ensure sufficient separation among aircraft, reducing in this way 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 during periods of high traffic demand. In those cases, air traffic controllers 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 has 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 assume that separation plus sequencing and merging instructions are given by ATC with multiple controlled times of arrival (CTA) at some strategic waypoints, or even at the runway threshold. These concepts generally use ground-based [7], [8], [9] and/or aircraft-based[10], [11] trajectory predictors that convert the received CTA in to a required time of arrival (RTA) constraint into the flight management system (FMS) planning and/or guidance functions. Typically, this results to actively control altitude and/or speed to fulfil the RTA, continuously adapting thrust (and speed-brakes usage) to command speed changes required to maintain spacing or to remain on path. These thrust variations have a negative effect on noise nuisance and fuel usage.

The Time and Energy Managed Operations (TEMO) is a new CDO concept that aims to overcome these issues. TEMO uses energy modulation to couple altitude and speed, allowing to exchange kinetic and potential energy to plan a trajectory to a given point in space and time. The TEMO algorithm finds the best trajectory that minimises a given objective function (fuel, time, noise, CO2, or a compound function), while fulfilling an RTA at one or more waypoints. 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).

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 carried out with the Generic Research Aircraft Cockpit Environment (GRACE) simulator from NLR (Netherlands Aerospace Center); and a flight testing campaign with a Cessna Citation II, an experimental aircraft jointly operated by NLR and Delft University of Technology.

The paper analyses the time accuracy of the TEMO algorithm when fulfilling RTA constraints at the initial approach fix (IAF), final approach point (FAP) and runway threshold (RWY). Moreover, fuel consumption for TEMO descents is compared with fuel figures for conventional step-down descents. Finally, the importance of having good weather forecasts in the trajectory planning algorithm is also discussed.

II. Time and Energy Managed Operations (TEMO)

Time and energy managed operations (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. Section II-A describes the principles of the TEMO concept. Then, the TEMO development and testing history is summarized in Section II-B.

A. The TEMO concept

The core principle of the TEMO concept is that the energy of the aircraft (speed and altitude) can be managed in such a way that the RTA (or other ATC altitude/speed constraints) are fulfilled: speed on elevator is used to convert potential energy into kinetic energy and vice-versa as appropriate to gain or loose time. An optimization process determines the best energy trajectory, which minimizes the use of throttle and speed-brakes. TEMO implies that the speed and the vertical profiles are dynamically adjusted along the descent in case time and/or energy deviations exceed some predefined thresholds.

Different from other CDO concepts, TEMO optimizes the descent by using energy management to achieve a continuous engine-idle descent, while satisfying RTAs at one or several fixes and incorporating applicable standard operational procedures and limitations. Since fuel-optimal vertical paths are very sensitive to different aircraft types, aircraft weights, flap/slat settings and meteorological conditions, this optimization is performed on-board by the flight management system (FMS). On the one hand, the FMS plans the best trajectory that fulfils all ATC constraints; on the other hand, it guides the aircraft along this trajectory, coping with deviations resulting from model inveteracies or external perturbations.

This optimal descent trajectory is computed by the FMS while the aircraft is in cruise, well before the top of descent (TOD). The optimal outcome is not a fixed vertical trajectory from TOD to the ILS glideslope intercept, as generated in current FMS implementations, but a speed plan as a function of the distance to prescribed points along a fixed arrival route. The FMS will be triggered to re-plan the trajectory when the following occurs:

- The ATC may request to fulfil a RTA at a certain waypoint
- Due to model inaccuracies, weather uncertainties or flight guidance errors, the aircraft may deviate from the planned trajectory. TEMO algorithms continuously monitor time and/or energy errors (in terms of potential and kinetic energy) at the current position. When the errors exceed some allowable error margin, a re-plan is triggered.

In both cases, the trajectory re-planning consists on launching an optimization algorithm that generates a new speed plan from the current aircraft state to the RWY, aiming to minimize fuel and speed-brake usage at the same time RTAs (if applicable) are fulfilled [13].

The speed plan generated by TEMO can be executed by using different guidance concepts in the Time or Energy chanel. With strategic guidance, time and/or energy deviations can grow as long as they remain below the allowable margins. 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[14].

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 CTA 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 time requirements by the on-board TEMO toolset embedded in the FMS.

The TEMO toolset may also compute the so-called Earliest and Latest trajectories at the metering fixes. They have an important operational value, since they will allow the aircraft crew (and ATC) to know the feasible time window at these fixes. Thus, knowing these lower and upper time bounds the aircraft crew will be able to accept or reject the requested CTA/CTI. In [15] the feasible time window sensitivity to aircraft position (altitude and remaining distance) when receiving a CTA was assessed in a hypothetical scenario where only energy-neutral trajectories (requiring neither additional thrust nor speed-brakes use all along the descent) are allowed.

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

(a) NLR's GRACE full motion flight simulator

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

Fig. 1. Experimental platforms

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).

B. TEMO developments and testing

Initial batch studies of TEMO concept were carried out to test the feasibility of the concept, reaching technology readiness level (TRL) 3 [16]. Moreover fuel consumption and noise levels on the ground were proved lower than conventional step-down descents [17]. A human in the loop study was performed to look at human factors aspects, reaching TRL-4 [18], [14] and showing acceptable RTA adherence performance and operational acceptability by qualified pilots. Yet, the model contained several important approximations and limitations. 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 [19], [20]. In [21], [22], a preliminary comparison between TEMO and typical A320 FMS trajectories was done, showing improvements regarding RTA adherence performance and environmental impact mitigation.

In 2014 a second Human in the Loop study was performed in the NLR full motion flight simulator GRACE 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 [23], while a more detailed description of the optimisation algorithm used and the quantitative results obtained is found in [13]. Aiming at TRL-6, in October 2015 the Netherlands Aerospace Centre (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, including conventional step-down descents for benchmarking purposes, were tested. Details on the definition and preparation of this flight testing campaign are given in [24].

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

III. Experiments Setup

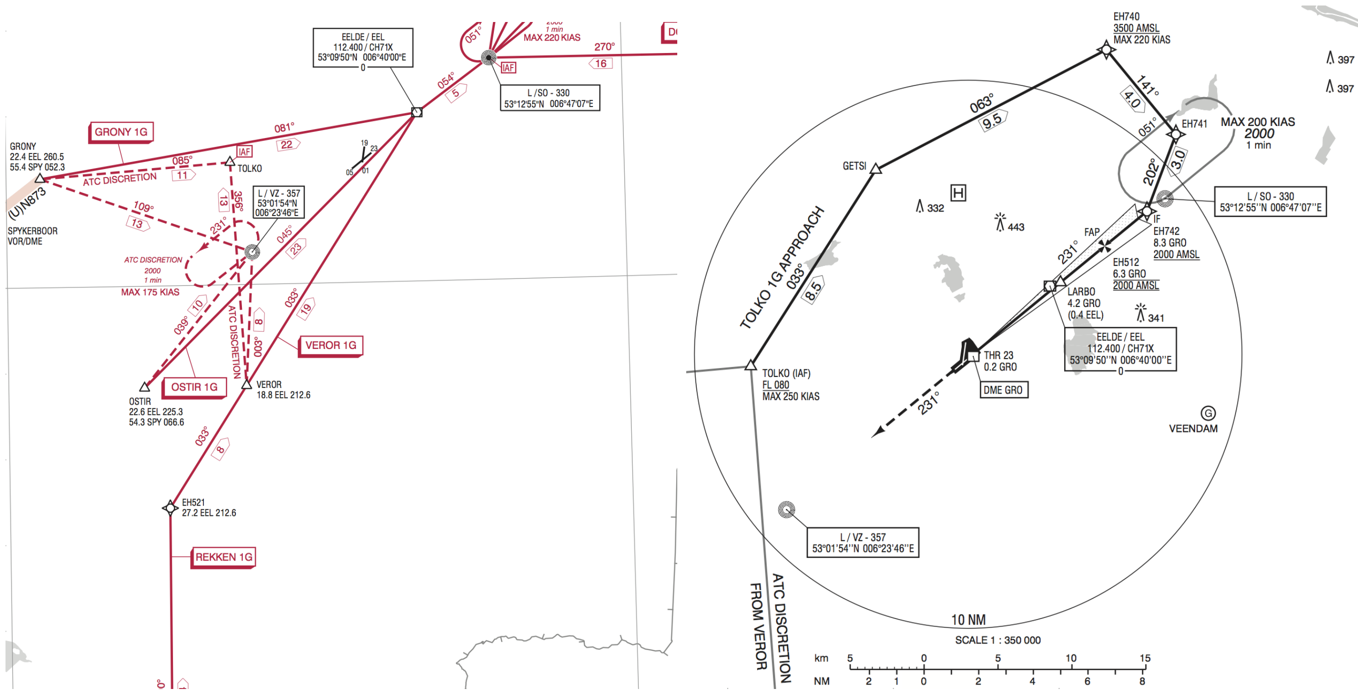
This section describes the setup of both experiments (GRACE full motion simulator and flight testing). The test aircraft was a Cessna Citation II aircraft For the GRACE simulations, the aircraft dynamics model used represented this same aircraft. Nevertheless, some specific functionalities were added, such as an auto-throttle system (not available in the experimental aircraft) and an auto-speed-brake feature that was able to deploy, without pilots 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 (FL300) 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, which is a P-RNAV ILS CAT-I approach for runway 23 at Eelde (see Fig. 2(b)). As seen in the chart, TOLKO is the IAF of the procedure, while EH512 is the FAP, where the aircraft shall intercept the glide slope of the instrument landing system (ILS) at 2,000ft AGL.

Different guidance principles were tested in the experiments combining strategic and tactical guidance in both the Time or Energy channel:

1) Strategic Time and Energy (E_s/T_s)
2) Tactical Time and Energy (E_t/T_t)
3) Strategic Time / Tactical Energy (E_t/T_s)
4) Tactical Time / Strategic Energy (E_s/T_t)

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 without any time requirement was computed. Few seconds later a RTA was issued for TOLKO (the IAF), triggering a new TEMO



(a) REKKEN 1G STAR

(b) TOLKO 1G approach

Fig. 2. Instrumental charts depicting the lateral route flown in all experiments (Source: Dutch AIP)

plan to satisfy this RTA. Then, they received the clearance to descent and, on pilots discretion, they initiated the descent by changing the Flight Control Unit (FCU) altitude. At about 5NM prior to passing TOLKO, another time constraint was imposed at the landing runway threshold (RWY), triggering another TEMO re-plan.

Different RTAs were tested, asking the aircraft to arrive earlier or later than the initially predicted time of arrival at the metering fixes (IAF or runway threshold). It should be noted that during the experiments the ATC did not ask the aircraft crew to execute holds, issue radar vectors or direct-to instructions and was always cleared to descent before arriving the top of descent.

Finally, it should be noted that for safety and operational reasons, in all the experiments the flight crew was instructed to engage the autopilot approach mode once well established on the ILS localiser, and just before intercepting the ILS glide slope. The activation of the this mode automatically disabled the TEMO algorithm and consequently, time and energy deviations were no longer monitored and no actions were taken to nullify them.

A. GRACE simulations setup

GRACE is a six degree of freedom moving-base flight simulator that can be configured for the most popular Airbus and Boeing aircraft, Fokker 70/100, or experimental configurations using, for instance, synthetic vision displays. GRACE 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).

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

TABLE II
GRACE EXPERIMENTS SIMULATION RUNS

ID	Run configuration
xx1	no wind forecast errors
xx2	Wind error of 3 kt/2°
xx3	Wind error of 6 kt/4°
xx4	Wind error of 9 kt/6°
xx5	Wind error of 3 kt/2° (+ replanning malfunction simulation)
xx6	Wind error of 3 kt/2° (+ manual flight following flight director)

Table I shows the family of runs (scenarios) that were performed in the GRACE simulations. For each scenario four different runs were actually performed, introducing intentionally different weather forecast errors to test the robustness of the TEMO algorithm. Two additional runs were also performed simulating unusual situations that could provide extra workload to the pilots (runs xx5 and xx6). All runs characteristics are summarised in Table II.

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 send the different RTA via data-link to the aircraft crew, who had to enter it manually to the on-board FMS triggering in this way a new TEMO re-plan. 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 according to 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 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, implemented as time offsets added to the calculated Estimated Time of Arrival (ETA) at the two metering fixes: $RTA_{IAF} = ETA_{IAF} + \Delta T_{IAF}$ and $RTA_{RWY} = ETA_{RWY} + \Delta T_{RWY}$. Table III lists the values for these offsets.

TABLE III
TIME OFFSETS USED TO DEFINE THE RTAS

RTA update	ΔT_{IAF}	ΔT_{RWY}
Zero	0	0
Late	+20s	+10s
Early	-20s	-10s
Very late	+30s	+15s

Regarding the weather model, two types of models were considered. Firstly, weather forecasts from the KNMI in form of standard GRIB files, dowloaded few hours before starting the runs for a given day. These GRIB files were processed by the TEMO toolset in order to provide temperature, pressure and wind estimates to the TEMO trajectory planning function[20]. 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 [25], [26].

Table IV shows all runs performed in 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.

TABLE IV
RUNS OF THE FLIGHT TESTING CAMPAIGN

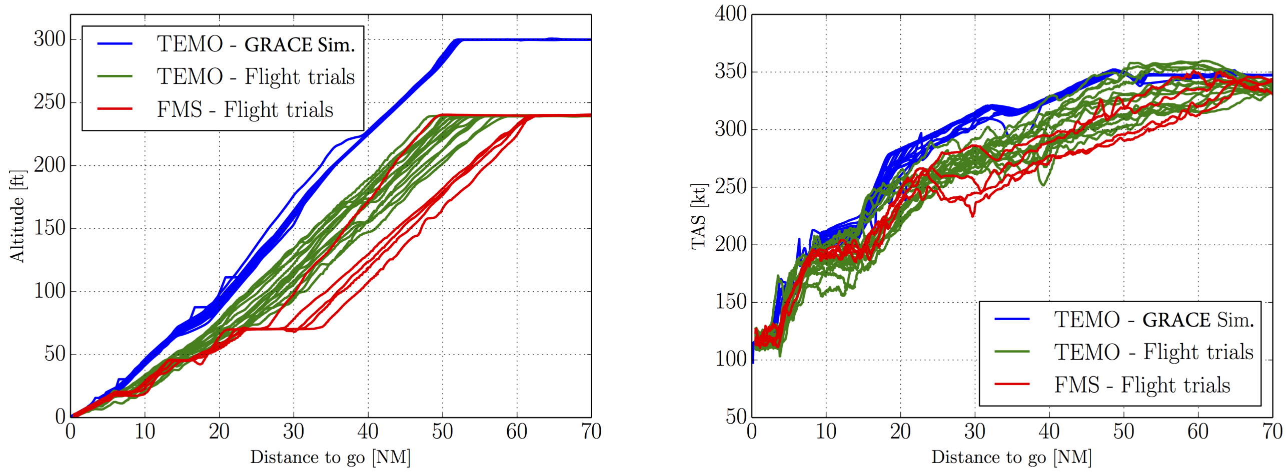
ID	Planning & guidance	RTA update	Date	Weather data source
909	TEMO E_s/T_s	Zero	19-10-2015 17:09	Recorded
901	FMS step down	Zero	19-10-2015 17:43	Recorded
901.1	FMS step down	Zero	22-10-2015 16:18	GRIB
905	TEMO E_t/T_t	Zero	22-10-2015 16:40	Recorded
909.1	TEMO E_s/T_s	Zero	22-10-2015 17:22	Recorded
913	TEMO E_s/T_t	Zero	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	Zero	26-10-2015 21:15	Recorded

All runs started with the aircraft in cruise at FL240 and Mach 0.60. For all flights, the experiment leader, who sat in the cabin with a control console controlling the TEMO toolset, was in charge to entering the RTAs into the FMS at the right moments, triggering in this way a new TEMO re-plan. 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 TEMO human machine interface [24]. When overflying the RWY threshold, the aircraft executed a missed approach procedure returning to EH522 to start a new run.

While conceptually required, during these flight trials the auto-throttle and auto speed-brake systems were not available as these systems are not implemented on the Cessna Citation II experimental aircraft. Therefore, it was required to provide additional TEMO Human Machine Interface (HMI) support to help pilots set proper throttle or speed-brake settings manually at the appropriate moments.

IV. RESULTS

Fig. 3 shows the altitude and true airspeed (TAS) profiles for all runs. As explained before the GRACE simulated runs started at FL300, while for operational limitations in the Amsterdam TMA, the flight trials had to be contained into the lower airspace, commencing at FL240. This figure also shows the profiles of the conventional FMS step-down runs, where a level-off at FL70 was enforced to emulate current operations. As seen in the figure, there is much more dispersion in the flight trials trajectories. This is due to the fact that the flight testing campaign spanned more than one week (see Table IV) and quite different meteorological conditions (namely wind fields) were encountered.



(a) Altitude

(b) True airspeed (TAS)

Fig. 3. Altitude and speed profiles for all runs

Energy bounds were set to 500 ft in the cruise phase (until the top of descent, TOD), 200 ft at the IAF and 100 ft at the RWY; while time bounds were set to 15s, 10s and 5s respectively. Between these three points, energy and time bounds were linearly interpolated. It is worth noting that ±5s of time accuracy at the runway threshold is a very demanding target, well below to RTA adherence of current state-of-the-art FMS.

A. *Example of TEMO descent*

As representative example of a TEMO descent is shown in Fig. 4, where the planned and executed trajectories are shown in Fig. 4(a) and Fig. 4(b). These figures plot, as a function of the remaining distance to the runway threshold, the pressure altitude (h_p), the calibrated airspeed (CAS), the TAS, the ground speed (GS) and the Mach number (M).

The vertical dotted lines of the plots are located at the distances where a trajectory re-plan was performed: the first two re-plans were due to RTA updates (first at TOLKO, then at the runway threshold). After the first RTA (received at about 70 NM from the runway threshold) an optimal trajectory was computed allowing for a complete continuous descent operation and placing the TOD at about 48NM from the runway threshold. The second RTA instruction was given slightly before reaching TOLKO with a RTA at the runway threshold. The third re-plan was triggered by an excessive energy deviation. In Fig. 4(d) time and energy deviations (with respect to the planned trajectory) are plotted together with the maximum bounds allowed for these deviations. As seen in this figure, at around 22 NM from the runway threshold the energy error exceeds the maximum bound, triggering a trajectory re-plan that becomes active in the FMS at about 19 NM from the runway threshold.

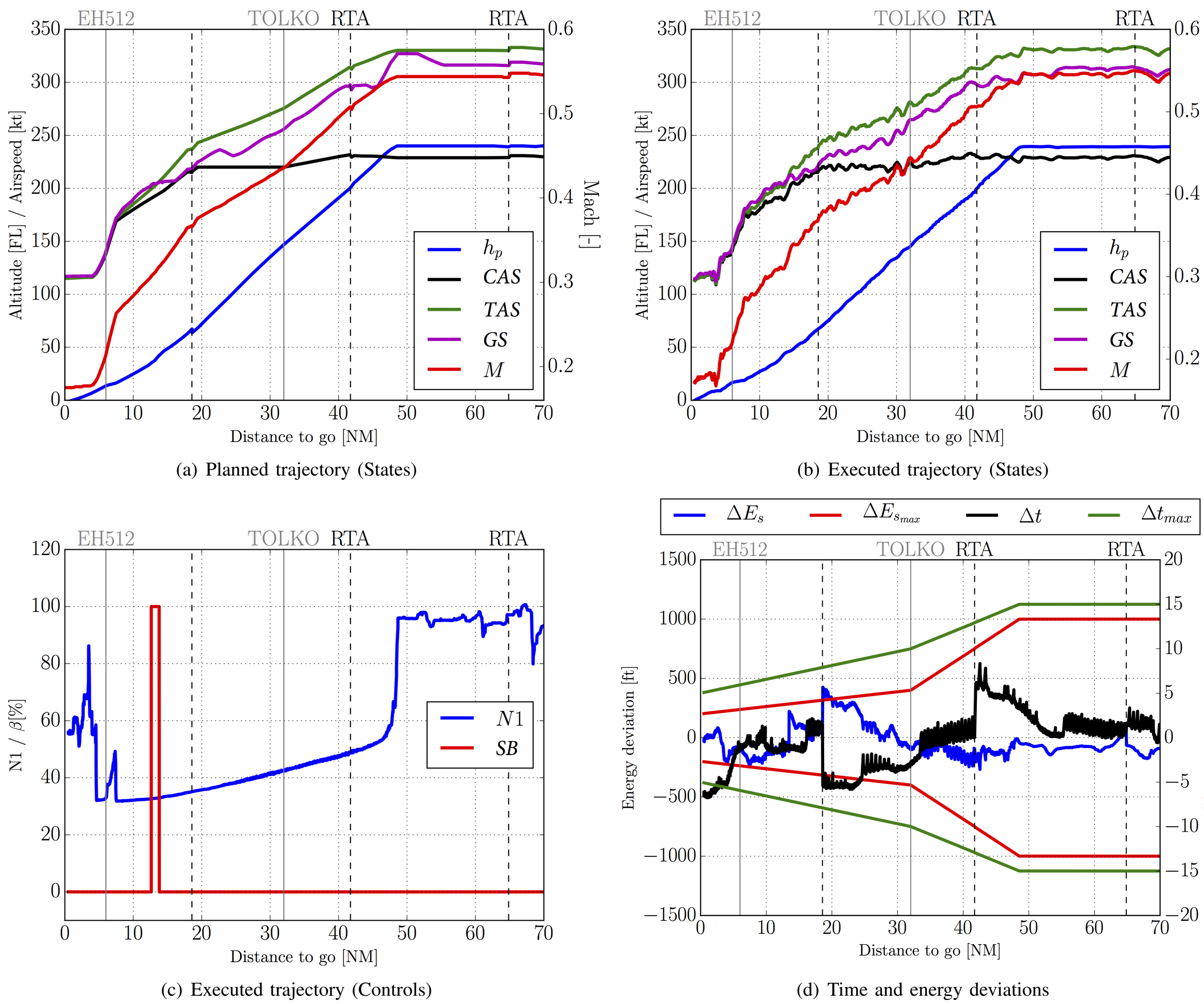
Fig. 4(c) shows low-pressure compressor speed ($N1$), which is directly proportional to aircraft throttle, and the speed-brake usage. As seen in the figure the aircraft follows a completely idle descent from the ToD down to EH512, where the ILS glideslope is intercepted and some thrust is required to maintain path and speed. Regarding the speed-brakes, the two initial trajectory computations planned for a zero speed-brake usage. However, due to energy deviations cumulated through the descent the TEMO algorithm allocates some speed-brake usage, at around 13 NM, when the third trajectory plan is triggered.

It is worth noting that at around 15 NM the energy deviation decreases suddenly, but no re-plan has been 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 runway threshold), 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 for speed changes, since the aircraft must stabilize at the final approach speed when reaching 1000 ft AGL).

B. *RTA compliance*

Figure 5 show the measured energy and time deviations at TOLKO (IAF), EH512 (FAP) and the runway threshold 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 runway threshold, however, the time deviations are much larger exceeding in the majority of runs the the target accuracy of ±5 seconds. In the GRACE simulations, these large deviations are observed, logically, for those runs with more wind forecast errors (see Table II). For the GRACE simulations the aircraft was always arriving late



(a) Planned trajectory (States)

(b) Executed trajectory (States)

(c) Executed trajectory (Controls)

(d) Time and energy deviations

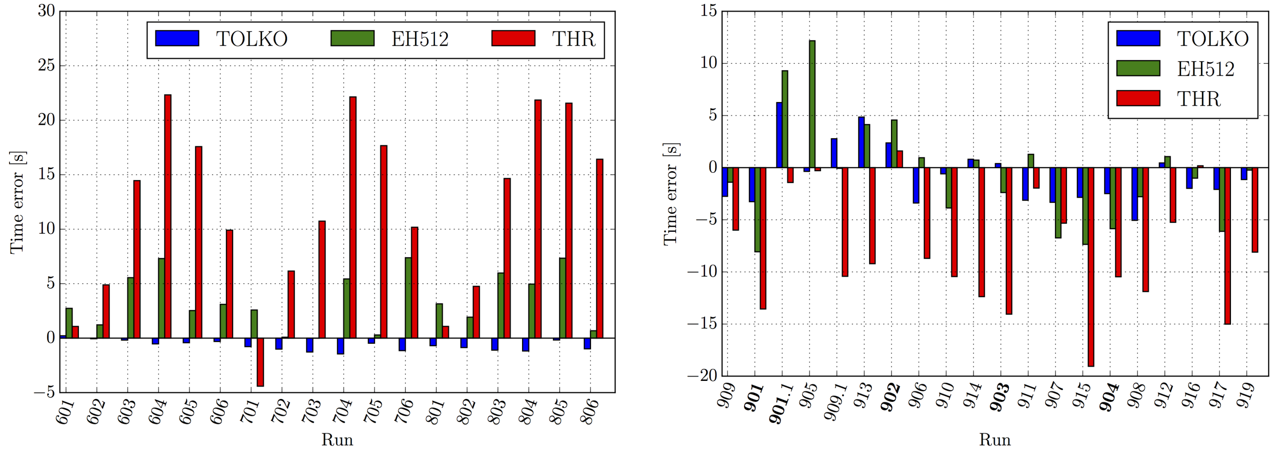
Fig. 4. Example of TEMO descent (Run 909)

(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.

Partially, this can be explained buy the activation of the autopilot approach (APPR) mode just before the FAP, disabling in this way, the TEMO algorithm. In fact the speed on elevator controller is disengaged in order to maintain the trajectory path (the ILS glideslope) and any modelling or guidance error quickly increases the time error. On the other hand, the aircraft is flying at lower speeds and wind forecast errors are relatively more important. Furthermore, 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 when in the glideslope. For the flight trials, recall that the final approach phase was 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 improved HMI. Finally, the commanded 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 also assessed at the FAP (waypoint EH512). Figure 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 very interesting to observe how quickly the time error can grow (in absolute terms) only in the glide slope phase. Even if the time error has been maintained within its bounds (± 5 s) thorough all the descent down to



(a) GRACE simulations

(b) Flight trials

Fig. 5. Time Deviations at the IAF, FAP and Runway Threshold

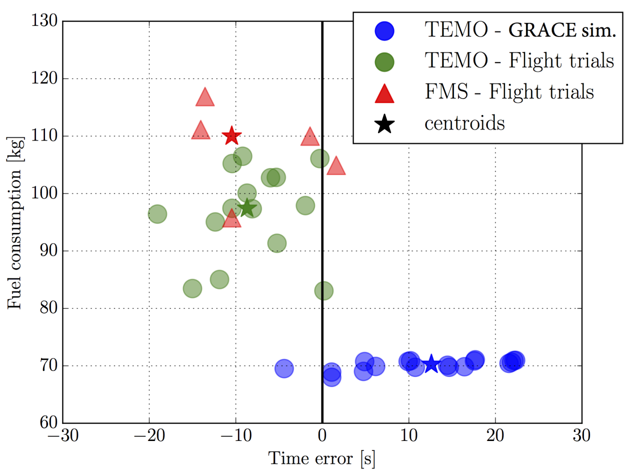


Fig. 6. Time errors at the RWY threshold and fuel consumption for all runs

the FAP (for more than 60 NM), more than 10 seconds of time deviation can be accumulated only in the glide slope phase (about 6 NM long). In order to achieve the required time accuracies at the runway threshold, it is expected to improve the TEMO planning and guidance algorithm in this particular phase in the near future.

C. Fuel savings

In Fig. III-B the time deviation at the runway threshold and the fuel consumption between EH521 and runway threshold are shown. 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.

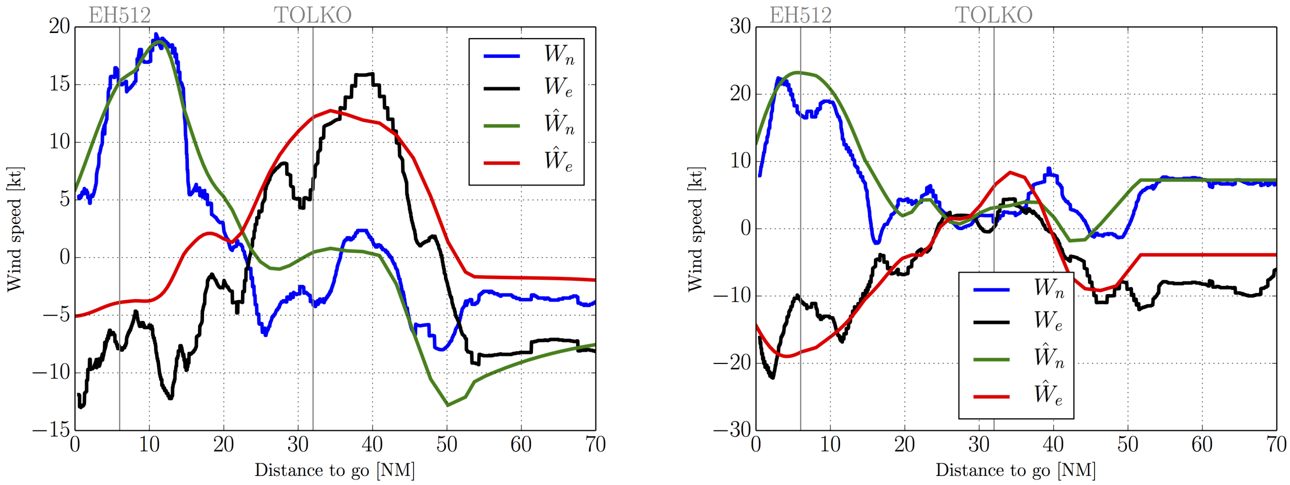
In the framework of the flight trials, the lower fuel consumption mean value is achieved when using TEMO Energy Tactical / Time Strategic configuration; while the higher fuel consumption mean value is achieved when using TEMO Energy and Time Strategic. Nevertheless, it is hard to extract conclusions 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. III-B 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, two different sources of weather data were used in the flight trials: forecast data in form of standard GRIB files, downloaded few hours before starting the run; and recorded data by the same aircraft gathered in 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.

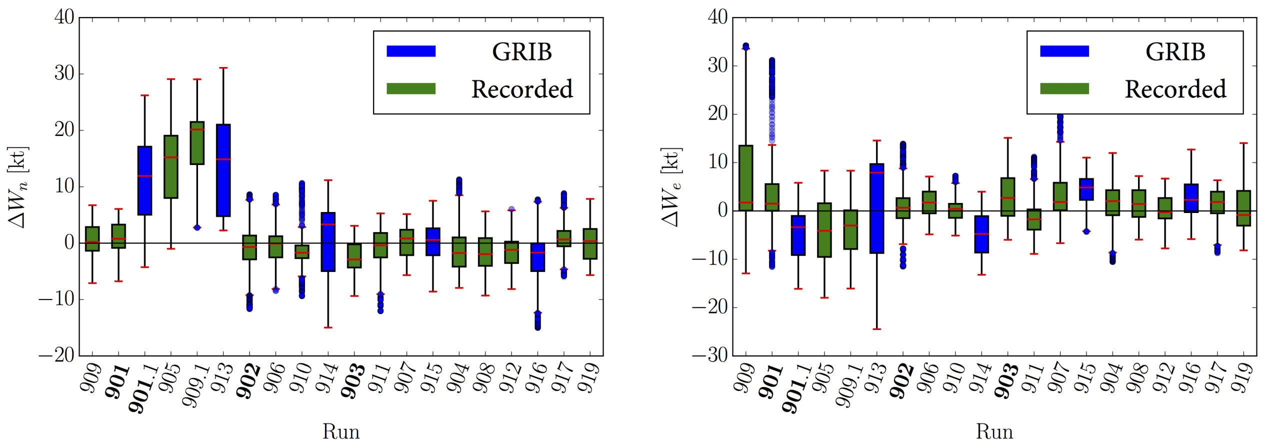
Fig. 7 shows a comparison between the forecast and observed (measured by aircraft sensors) wind components for two example runs. Fig. 7(a) shows this comparison for Run 915, where a standard GRIB file was used to feed the TEMO toolset. As seen in the figure, the forecast data overestimates the North wind component in the cruise altitude (50 NM to 70 NM from the runway threshold) and tends to better match the real wind encountered at lower altitudes. A similar behavior



(a) Run 915 (using the KNMI GRIB)

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

Fig. 7. Comparison on forecast and observed winds



(a) North wind component errors

(b) East wind component errors

Fig. 8. Wind prediction errors

is observed for the East wind component, where the forecast data this time underestimates it.

Fig. 7(b) shows the wind comparison for Run 917, which used recorded weather 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 two runs (same lateral route and slight deviations in the vertical path), wind forecast errors are much lower in this case.

Fig. 8 shows the wind prediction errors for all flight trial runs, comparing each sample of wind data stored by the FMS (at a 5Hz recording frequency) with the forecast data. These plots show the median; the 25 and 75 percentile; and the 1.5 IQR (inter-quartile range) of the wind prediction errors; outliers are shown as blue 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.

V. Conclusions

The primary objective of the Time and Energy Managed Operations (TEMO) research effort is to develop a flight planning and guidance system and associated concept that offers operationally acceptable solutions to capacity and environmental problems during the arrival phase. The system should be able to contribute to predictable and consistent, user-friendly, and "green" descents and approaches during high capacity demand with the ownship as a participant in an orderly flow of dissimilar aircraft.

The TEMO concept has been successfully tested in a simulated and real-world environment with positive results and feedback of all participants. The experiments have demonstrated that TEMO flight operations are safe and pilot acceptable. The experiments have indicated that two aspects at conceptual level of a TEMO flight operation require further attention: the instrumental landing system (ILS) glideslope interception and new or enhanced strategies to manage time deviations once established in the ILS glideslope. Both aspects are solvable and need to be addressed in a next step.

With these experiments, it has been demonstrated the accurate timing can be achieved while preserving fuel benefits in line with current day fuel consumption of continuous descent operations (CDO). A promising prospect that indicates that the capacity challenge can be addressed while greening aviation!

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