Meteosat Third Generation (MTG-I1), LEOP preparation and challenging execution: expect the unexpected

Flammini A.(1), Calfapietra A.(1), Di Pietro F.(1), Pessina S.(2), Klinc M.(3), Perrella F.(4), Kaltenbach A.(4)

(1)Telespazio, Fucino, Italy, ambra.flammini@telespazio.com, antonio.calfapietra@telespazio.com, francesco.dipietro@telespazio.com

(2)EUMETSAT, Darmstadt, Germany, Stefano.Pessina@eumetsat.int

(3) WGS Workgroup Solutions GmbH at EUMETSAT, Darmstadt, Germany, Milan.Klinc@external.eumetsat.int

(4)Thales Alenia Space, Cannes, France, francesca.perrella@thalesaleniaspace.com, alexandre.kaltenbach@thalesaleniaspace.com

***Abstract* – The first Imaging satellite of the Meteosat Third Generation (MTG-I1) was launched on Ariane-5 from Kourou, French Guiana, in multiple payloads configuration, on the 13th of December 2022. After launch, Telespazio (TPZ) led the Launch and Early Orbit Phases (LEOP) from Fucino Space Centre in Italy, with EUMETSAT as customer and final responsible for operations at handover, at the end of LEOP; a joint team with ESA / Thales Alenia Space / OHB provided the project support (PST).**

The handover to EUMETSAT was on the 28th of December 2022, after the spacecraft successfully reached its position for in-orbit validation, at 3.4°W longitude in Fine Pointing Mode.

The LEOP faced multiple and concurrent in-flight anomalies, some of which mission critical.

This paper describes the LEOP sequence of events planning and execution for MTG-I1 from a mission analysis and flight dynamics perspective, with troubleshooting, lessons learnt and in-flight operational experience from a particularly challenging LEOP.

The concepts indicated are of general interest for geosynchronous mission with chemical propulsion transfer GTO-to-GEO, especially for those missions with a large Station-Keeping inclination dead-band.

I. INTRODUCTION

The Meteosat Third Generation (MTG) system will provide weather forecasters with new, more precise and more frequent data, to assist timely and accurate forecasts of rapidly developing, high impact weather events; the system is building on the decades-long legacy of Meteosat first and second-generation satellites (see [1]).

The first of the new satellites, MTG-I1 ("I" stands for Imager), was launched on 13th of December 2022. Two Instruments are present on MTG-I1: the Flexible Combiner Imager (FCI, with a two-axis Scan Mechanism and 16 channels between 0.3 and 13.3 microns, delivering full or partial images of Earth) and the Lightning Imager (LI, with four optical cameras that allow distinguishing lightning from the background signal). The FCI on-board MTG-I1 will provide the Full Disc Scanning Service, to scan the whole Earth disc every 10 minutes (see [2]).

The launch of a Sounding satellite (MTG-S1) will follow in 2025; this is based on the same platform of MTG-I1, but it is carrying on-board different instruments: the InfraRed Sounding (IRS) and the Ultraviolet-Visible-Near-Infrared (UVN) instrument, the latter being part of the Copernicus Sentinel-4 Service.

Both MTG-I1 and MTG-S1 are targeting 3.4°W longitude at the end of LEOP and 1 year commissioning, afterwards they are relocated and co-located in the same longitude slot at 0°. The launch and commissioning of a second Imaging satellite (MTG-I2) is then providing the full operational capability of the mission (see Fig.1), with this satellite located in a different longitude slot at 9.5°E and taking care of the Earth Rapid Scanning Service (2.5 min images of ¼ of the Earth full disc).

A second constellation of 2 imagers and 1 sounder will be deployed at a later stage, to ensure continuity of the mission. The attitude control concept changes from spin-stabilisation (which was the selected approach for the first and second generations of Meteosat), to a three-axes stabilisation, offering better pointing performances requested by the new generation of instruments.

Fig. 1. Meteosat Third Generation (MTG), full operational capability, artist's impression.

The design of the LEOP (Launch and Early Orbit Phases) nominal sequence was based on the in-flight experience from the previous Meteosat Second Generation (MSG) (see [3]), tailored to the specific platform characteristic of MTG.

The LEOP faced various in-flight anomalies, which extended its duration to 15 days: 4 days longer than originally planned, especially because of the re-design of the main manoeuvres' sequence, due to the abort of the first one in the nominal plan, after partial execution.

II. MISSION ANALYSIS

The GTO-to-GEO transfer was designed based on a sequence of 4 apogee firings, realized by a restartable bi-propellant chemical system. The GTO perigee raising phase was then followed by Station Acquisition phase, during which fine positioning manoeuvres were realized with 10N reaction control thrusters, to precisely acquire the initial conditions for the commissioning phase.

The sequence of apogee motor firings was optimized to allow a high robustness to the Liquid Apogee Engine (LAE) dispersions upon arrival to the final longitude for the fine station acquisition. Each manoeuvre was designed to cope with spacecraft constraints, such as maximum firing duration, robustness to injection and thrust uncertainties, and operational constraints, such as requirements on double Earth stations visibility and number of revolutions between firings.

The attitude during and around boosts was selected to achieve unperturbed TT&C link (thus without S-Band polarisation switch) while respecting Sun illumination constraints on the MTG platform and constraints on Star Tracker blinding; to this extent, two different values of the rotation around thrust axis were selected, depending on the launch season.

The selected LEOP Apogee Motor Firing (AMF) strategy was robust to a failure of any of the 4 main LAE burns, with a pre-identified tree of backup strategies (Nominal + Backup 1/2/3/4) compliant with all trajectory and launch window criteria, and including nodes' line rotation. Other contingency scenarios had been analysed in detail including the Main Apogee Engine failure and launcher anomalies.

The target orbit for MTG-I1 LEOP was a geosynchronous orbit with 1° of inclination. For every launch date, the nodes' line rotation was optimized to minimize the combined ΔV of the LEOP phase (see Fig.2) and the North-South Station-Keeping (NSSK) over lifetime on-station, using concepts established from previous Meteosat generation (see [3]), with a refined cost model. The NSSK consumption was based on the variable natural drift of the inclination, due to perturbations. For a GEO satellite (~0° inclination), the orbital plane natural evolution results in a slow precession, where the normal to the plan initially drifts towards the vernal equinox, due to the combined effect of the Earth Geopotential (J_2 harmonic) and of the gravity of the Sun and the Moon. In the longer term, however, the natural precession of the orbit plane results essentially in a clockwise rotation of the equinoctial inclination vector $[i_x=+i*sin(RAAN),\ i_y=-i*cos(RAAN)]$ ($RAAN$= right ascension of ascending node , i=inclination), around the natural equilibrium point (i_x=0°, i_y=-7.4°, known as Laplace plane), which is completed in 54 years. Therefore, the use of the lower half of the inclination control-circle (half plane $i_y<0$) for NSSK allows for propellant saving, especially when the inclination deadband is relatively wide, as in the MTG case (1°). The NSSK cost for MTG was based on various simulations for the whole routine mission lifetime (10.7 years) with variable RAAN and inclination at LEOP end that is the routine phase Beginning of Life (BOL) (see Fig.3 top plot), and a fixed NSSK inclination control sub-circle, driven by the future co-location needs of MTG-I1/S1 via relative eccentricity/inclination separation (see Fig.3 bottom plot). The optimization of the combined propellant-cost models of LEOP and NSSK resulted in a different optimal value for the rotation of the line of nodes to be realised during the LEOP, depending on the launch date/time.

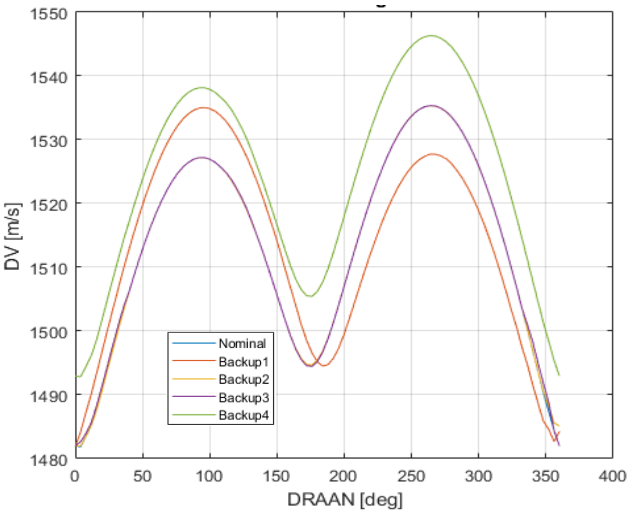

Fig. 2. MTG-I1 LEOP ΔV cost model for 1°inclination target at LEOP end, for the various AMF strategies, function of nodes' line rotation (BOL-GTO RAAN)

The MTG-I1 launch window was then computed considering for each launch date/hour the specific trajectory and manoeuvres corresponding to the optimal value of node rotation as described, together with all the constraints related to Sun/Moon direction during LEOP: eclipses position and duration, Sun aspect angle on the MTG platform during apogee manoeuvres, Star Tracker blinding constraints. The resulting window was fully compliant with Ariane 5 standard dual-launch window.

The total duration foreseen from launch to the end of the GTO circularization phase, excluding the near synchronous operations, was 8.5 days for the nominal apogee manoeuvres sequence, and up to 12.5 days for the longest of the back-up sequences corresponding to missed AMF cases.

For the effective launch date of 13th of December at 20:30 UTC, the targeted optimal node rotation was close to 81°, corresponding to a BOL RAAN of 300°.

The ΔV repartition among the four Apogee Motor Firings was optimized to allow for a small 4th burn, around 50 m/s or less, to correct the dispersions from previous big firings and start the station acquisition phase with a very precise initial condition on the longitude drift rate.

The pre-launch plan for the STation's ACQuisition (STACQ) phase was based on 3 East manoeuvres with nearly the same ΔV, realised within 36 hours to stop the longitude drift at the centre of the 3.4°W.station keeping box.

However, during MTG-I1 actual LEOP operations, an anomaly occurred during the first AMF (that will be detailed in section V.C) implied a redesign of the overall circularization strategy that led to a last Apogee Manoeuvre with a much higher ΔV with respect to what was initially targeted: 557 m/s instead of 30 m/s foreseen before the anomaly.

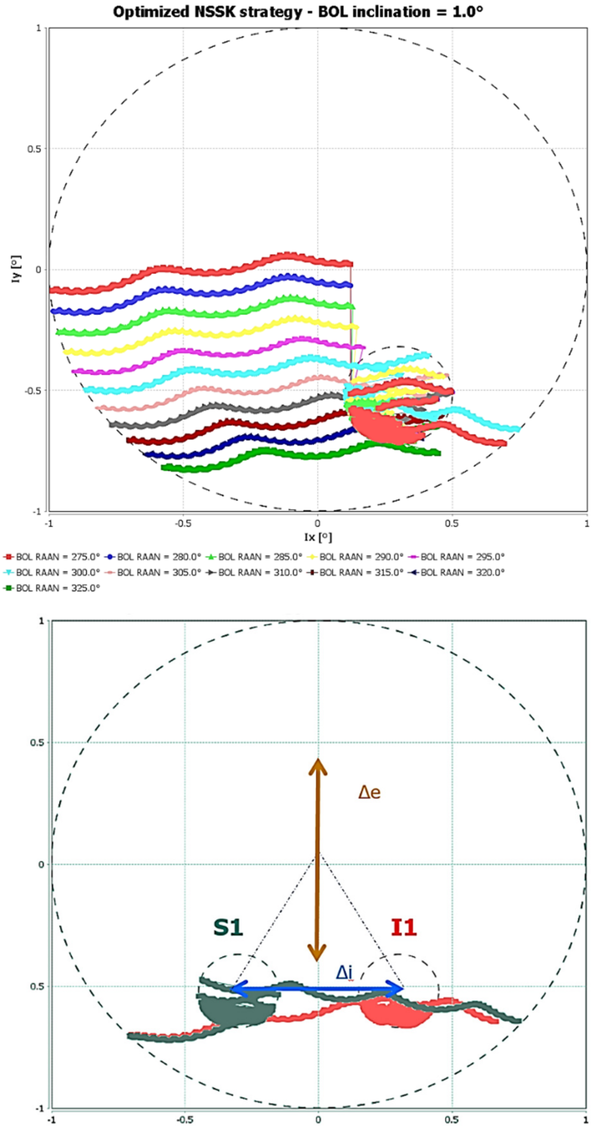

Fig. 3. (Top) MTG-I1 optimised NSSK strategy for BOL for i=1°, RAAN variable. (Bottom) MTG-I1/S1 Co-location target geometry for optimised NSSK strategy, BOL RAAN=315°, i=1°.

To make more robust, the fine station acquisition sequence with respect to the new apogee motor firing strategy, the longitude target at the beginning of the drift phase (i.e. at the end of last apogee manoeuvre) was shifted westwards by 2° with a higher drift rate.

After the realization of the last two Apogee Manoeuvres, a slight ΔV over-performance was observed, leading to an initial condition for the Station Acquisition phase, with an even farther longitude with respect to the target and a slower longitude drift rate.

The Station Acquisition strategy was then redesigned with one West manoeuvre, to increase the longitude drift rate during 36 hours, then two East stop manoeuvres to target the centre of the station keeping box.

This solution was retained considering its flexibility, robustness to dispersions, and overall duration. In particular, there was 1.5 day between first and second STACQ. Therefore, in case of trouble with first STACQ, it was possible to re-prepare a strategy. The strategy was robust to dispersion of ΔV, since it was possible to calibrate the first manoeuvre and then re-target and apply this calibration. In addition, the choice to include a West manoeuvre allowed reducing the overall station acquisition phase duration, with an almost negligible impact on propellant budget for the mission.

III. LEOP PHASE

The MTG-I1 LEOP starts with the Ariane 5 launcher ignition and is composed by the following main nominal mission phases:

- the separation of the satellite from the launcher;
- the autonomous activation of Sun Acquisition Mode (SAM) with the satellite spinning and pointing the LAE towards Sun;
- the transition to Guided Attitude Mode (GAM) by Ground, with activation of GTO transfer phase;
- the transition to Nominal (NOM) mode, to start commissioning operations.

The "Separation Sequence" is a procedure run autonomously by the SpaceCraft (S/C) Software (SW) upon detection of the satellite separation from the launcher: its objective is to bring the satellite into a safe and stable configuration, with the Solar Arrays (SAs) deployed, and pointing to the Sun without any need for Ground intervention. The activities performed during the Separation Sequence comprise:

- Health check of the satellite;
- Venting, Priming and Pressurization of the Unified Propulsion Subsystem (UPS);

- Rate damping and Sun attitude acquisition by means of thrusters;
- Attitude control for acquisition of sun pointing attitude using the thrusters;
- Deployment of the Solar Arrays to provide energy during the GTO configuration;
- SAM acquisition with SAs deployed.

The automatic sequence can be overridden by ground control, if necessary.

After limited spacecraft checks, the GTO transfer phase will be activated thanks to guidance parameters sent by Ground Control with the following activities execution:

- Post Separation Sequence System Activities;
- Data Handling Subsystem (DHS) reconfiguration after Separation Sequence;
- Reaction Wheels Activation and run-in (5 units);
- Star Trackers Activation (3 sensors).

After that, the transfer strategy sequence is executed to raise the perigee and decrease the inclination towards an orbit close to the targeted geostationary orbit.

As explained in the previous section, the nominal orbit raising strategy was thought to bring the MTG-I1 satellite in the target geostationary orbit with the use of four Apogee Motor Firings (AMFs), constituted by three main burns followed by one minor trim, executed with the Liquid Apogee Engine (LAE); then, three Station Acquisition manoeuvres, performed with four reaction control thrusters (see Fig.4), allow the S/C to reach the GEO commissioning longitude slot at 3.4°± 0.3°W.

To accomplish this task, the following activities are performed for each AMF manoeuvre (see Fig.5):

- Initial rate dumping and slew from SAM pointing to the Orbit Transfer Mode (OTM) inertial pointing attitude for manoeuvre, using intermediate ground commanded guidance in GAM;
- Rotation of Solar Arrays to a lock-position for the various attitude control modes and phases;
- Cooling Phase for LAE propellant piping;
- Attitude Thruster Check-out before AMFs;
- Apogee Motor Firing manoeuvre execution and return to SAM.

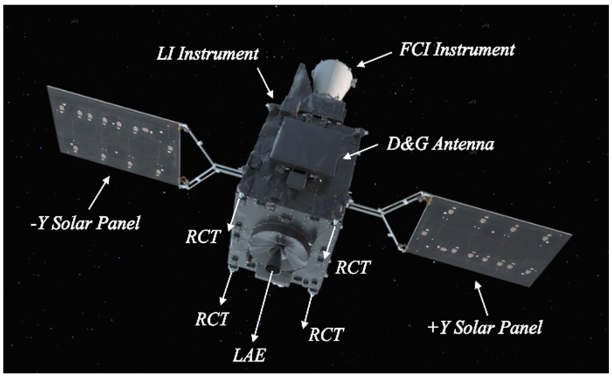

Fig. 4. MTG-I1 platform layout with the solar arrays deployed and the antennas stowed.

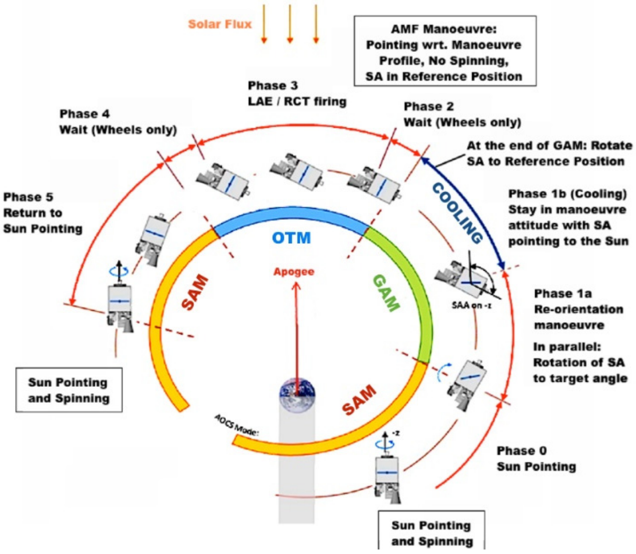

Fig. 5. Manoeuvre Phases of the MTG satellite in LEOP

At the end of the whole AMF burns sequence, the LAE isolation and the Helium tanks passivation are performed, followed by the deployment of the Data Collection & GEOSAR (D&G) and Ka-band Antennae. Then, activities similar to AMF are performed for each STACQ, to reach the MTG-I1 target longitude slot (see Fig.5 taking into account that the orbit manoeuvres are performed with the set C of RCTs, instead of LAE, there is no cooling phase and the firing attitude is parallel to velocity/anti-velocity):

- Initial rate dumping and slew from SAM pointing to the tangential manoeuvre attitude in OTM;
- Rotation of Solar Arrays to a lock-position for the various attitude control modes;
- Thruster Check-out before STACQs;
- GEO Slot Acquisition manoeuvres execution and return to SAM.

At the end, after the S/C thermal setup for GEO phase, the Earth Acquisition is performed with the achievement of the nominal Earth fine pointing attitude.

The previous description illustrates the nominal sequence of events foreseen for the MTG-I1, however some anomalies occurred during the Early Launch and Orbit Phase, making the LEOP of this new platform even more challenging.

IV. POST SEPARATION PHASE

A. Separation Sequence Anomaly

The MTG-I1 satellite was nominally launched on the 13th of December 2022 at 20:30:07 UTC from Kourou, in French Guiana, by the Ariane 5 launcher (VA259). The separation was performed at 21:04:38 UTC after 2075.817 s and the resulting injection orbit, provided by Arianespace just after the separation, was in line with the predicted one, resulting only in a difference of 8 km on the semi-major axis between the planned orbital element and the measured one (so, well inside the Ariane 5 launcher 3-sigma dispersion). The Ground-Tracks of MTG-I1, just before the separation and after the first Apogee, are reported in Fig.6 and in Fig.7 respectively, together with the Launch Service and LEOP Ground Station Networks (GSN).

After the nominal release of the satellite by Ariane 5, the separation from the launcher was correctly detected by the on-board Spacecraft SW (SCSW) and the automatic separation sequence started nominally at 21:04:44 UTC. Shortly after, the first anomaly occurred: during the priming phase of the Unified Propulsion System initialization, a UPS under-pressure was detected by the SCSW, triggering Survival Mode (SRM) entry on redundant processor module and the automatic reboot of the separation sequence from the first phase.
After the priming re-execution, the same alarm of the first run was received again, but the separation sequence continued (as expected) with the achievement of UPS Pressurization. The reboot finished at 21:13:29 UTC, with the satellite configuration on redundant equipment, completing with success the SCSW initialisation.
From the investigation on the occurred anomaly, the PST stated that threshold on the pressure was over-zealous for the priming phase. As a lesson learnt, the manufacturer will implement a new propellant tank pressure limit for the Fault Detection, Isolation and Recovery (FDIR) for the next MTG satellites, since this drawback generated a significant impact on the LEOP timeline, particularly due to the time needed to restore the nominal units.

Fig. 6. MTG-I1 Ground-Track just before the separation.

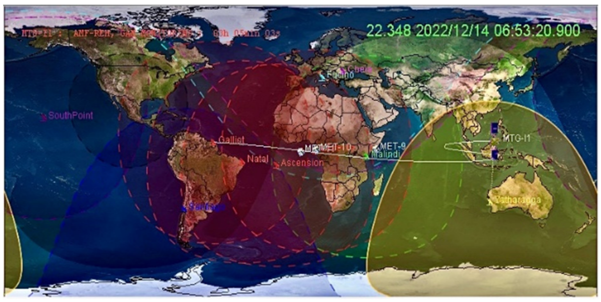

Fig. 7. MTG-I1 Ground-Track after Apogee 1 crossing.

After that, the nominal post-separation activities were postponed to recover from the Survival Mode on the redundant processor module. The resulting delay was about 9-10 h (including SRM recovery); consequently, the AMF1 Rehearsal, which was planned to be executed at Apogee 2, was moved to Apogee 3.

V. AMFs SEQUENCE

A. AMF Rehearsal Execution

The manoeuvre parameters for the AMF Rehearsal (AMFR), in terms of manoeuvre direction or duration, were taken from the AMF1 characteristics of the nominal strategy computed by the Flight Dynamics Subsystem (FDS) team, whereas the execution epoch was anticipated to perform the AMFR in proximity of the Apogee 3, taking into account also the delay in the activities caused by the extended Separation Sequence. The resulting "fictitious" LAE ignition epoch was the 14th of December 2022, at 21:54:37 UTC (preceded by 100 seconds of settling with the RCT of set C); starting from this, the relevant guided guidance profile were generated with the Mission Dependent Flight Dynamics SW, to reduce the S/C spin rate and to bring the S/C in the correct manoeuvre attitude, after having cooled down the propellants pipeline in the vicinity of the LAE nozzle. The LAE cooling concept for the MTG-I1 LEOP is based on an advanced elongation of the inertial pointing needed for each of the AMF manoeuvre, such that the sun incidence on the pipeline is reduced and maintained for an appropriate time (3 hours). The commanded ΔV of the AMFR was then set to 0 in the telecommand (TC) prepared by the S/C control centre.
Since the execution of the AMF1 was foreseen at the Apogee 4 and the schedule was tight, it was decided to employ the TM downloaded during the cooling phase (after the execution of the inertial profile and the slew to bring the satellite from the Sun Pointing Attitude to the Manoeuvre one) for the computation of the fuel consumption and for obtaining the propellants pressures values to be used for the AMF1 planning, without waiting the entering in the OTM mode.
In addition, the original schedule of AMF Rehearsal in terms of guidance profiles start/end times was shifted of about half an hour due to the unexpected satellite recovery after Separation sequence and the longer duration of post separation sequence activities and Reaction Wheels run-in (whose target speeds to be reached at the end of the run-in phase were computed and provided by the FDS team).
Then, the execution of the AMF Rehearsal at Apogee 3 was nominal: the change of attitude was in line with the calculation from FDS team; the Solar Arrays moved properly to the commanded angle and then went back to the reference position; the estimated three hours duration of LAE cooling was in line with the value provided by the manufacturer; so the AMFR execution allowed to efficiently test the S/C behaviour during a

critical scenario like the apogee manoeuvre.

The only anomaly occurred at the end of the manoeuvre: during the Sun Acquisition phase, the Star Tracker 3 Baffle Temperature started to increase due to the Sun exposure (~8° above thresholds), triggering a high temperature FDIR.

Since the STR3 baffle temperature was sensitive to the sun exposure, for AMF3 and AMF4 it was decided to use the thrusters, instead of the reaction wheels, to perform the Sun Acquisition after the burn, to reduce the Sun exposure time (that depends on the attitude and doesn't happen in all the manoeuvres).

Anyway, PST assessed that this exposure doesn't provide any risk for STR3 (only the undesired effect of the FDIR with heater group swap).

B. *Space-Track communication issue*

A communication issue occurred with an external interface, to the 18th SPace Control Squadron (18 SPCS): from the 14th of December, the 18 SPCS was not able to receive the MTG-I1 Orbit Ephemeris file produced by Telespazio and loaded on the Space-Track portal for conjunction screening purposes.

In coordination with 18 SPCS analyst and EUMETSAT customer representatives, checks were performed on the verification of the file path on the portal and on the correctness of the temporal satellite ID assigned to MTG-I1. In the meanwhile, the support for Collision Avoidance screening was guaranteed thanks to the auxiliary service provided directly by EUSST to EUMETSAT, acting as middle man for sending them the ephemeris file generated by TPZ.

After some days of investigation, it was found that the MTG-I1 ID provided by the 18 SPCS was not correct and from that moment the issue was solved.

As a lesson learnt, this interface would be tested just before the launch of the next MTG satellite, to avoid unexpected situations.

C. *AMF1 Partial Execution*

Despite the numerous anomalies occurred just after the satellite separation and the consequent race against time (there was the concrete risk to not be able to perform the AMF1 at Apogee 4 and go to the Back-Up 1 strategy for the AMFs sequence execution), the FDS team was able to generate all the products for the burn execution and the satellite engineers managed to generate in time the relevant TCs: so it was possible to execute the AMF1 at the nominal selected apogee, with LAE which started to ignite, as planned, at the 08:24:367 UTC of the 15th of December, after 100 s of settling performed by the four reaction control thrusters.

During the AMF1 execution, however, an unexpected anomaly happened: the burn was interrupted after 6 minutes and 48 seconds from the start of boost, at 08:31:24 UTC, due to an attitude violation error.

During the initial 400 s of firing, the threshold on attitude de-pointing is relaxed to 20°, to allow the expected initial overshoot; after this, during the OTM steady-state phase, the attitude transient error around the Y axis exceeded the allowed FDIR threshold value of 2°, causing the abort of the manoeuvre and the transition to Sun-pointing in SAM. The trend of the attitude errors when the AOCS mode was in OTM is shown in Fig.8.

Specifically, the achieved ΔV coming from the TM was 50.061 m/s (instead the planned one was 466.663 m/s) and an observed firing duration of 507 s, rather than 3810.905 s, as originally foreseen.

To assess the effect of the AMF1 partial execution on the orbit and to allow the generation of the new pointing data for the Ground Stations, a preliminary investigation was performed by the FDS team with the MI-FDS SW, from which resulted that the perigee altitude was increased of about 690 km.

A more precise estimation could be performed later, when the collection of a sufficient number of ranging measurements collected from the ground stations network allowed to execute the full Orbit Determination.

Due to the AMF1 partial execution, the nominal AMFs strategy was no more applicable; it was decided to skip the use of the Back-Up 1 strategy (with next manoeuvre at Apogee 8), since Telespazio recommended to avoid hasty actions, until exhaustive investigations and complete analysis on the occurred anomaly were performed by the Project Support Team. In fact, with a perigee altitude of 690 km the Van Allen belts are crossed (with possible degradation of the Solar Arrays), there is an effect of the drag, so the thrusters are activated at the perigee passage for attitude control (with the consequent propellant consumption), but this prudential approach was preferred to have a clear understanding of the high attitude error cause, to avoid its repetition on the next AMF manoeuvre.

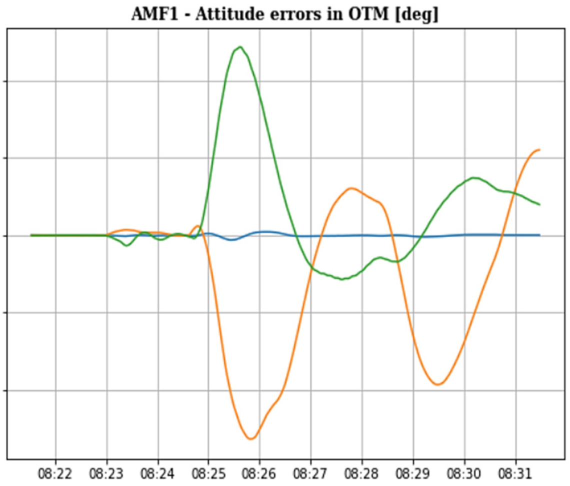

Fig. 8. Attitude Error during AMF1 OTM phase: X-component is green, Y-component is orange, Z-component is blue.

Therefore, while PST was performing its investigations on the attitude issue, the FDS and Mission Analysis team was working on the best GTO transfer strategy to be applied, taking into account the conditions reached after the interruption of the AMF1.

The Flight Dynamics analyses showed an interesting element: the specific manoeuvre size achieved by the burn partial execution (~10% of the nominal AMF1) led to have exactly the same sequence from apogee 13 onwards (2 days later).

Therefore, the new AMFs strategy was recomputed considering that the same longitude before the AMF1 burn (or the Back-Up 1 profile) occurred every 2 days starting from the Apogee 13, with an increasing propellants consumption over time to bring back the natural nodes' regression. In this way, the constraints for the AMFs execution were automatically respected, without the need to perform a new strategy re-computation at Mission Analysis level.

Consequently, the first opportunity to perform the AMF was the 19th of December, at the apogee 13.

In addition, it was recommended by TPZ to implement a 3-burns strategy, instead of 4, since the last burn (the fourth) would be eventually so short that only a transient phase would occur, with no knowledge of the direction along which the Liquid Apogee Engine would be firing. Eventual corrections after the last AMF could be performed with the execution of the following STACQs manoeuvres, during the Station Acquisition phase.

Based on these considerations, a 3 burns strategy was computed with MI-FDS SW GTO optimizer, with the three AMFs of similar duration to be performed at the Apogees 13, 15 and 18 respectively.

It has to be noted that the longitude reached with the computed strategy after the AMF4 was of 351° (instead of the nominal 352°), but in this way it could be possible to act on the drift depending on the conditions obtained after the real execution of the AMF2 (the final strategy in fact could be obtained after the AMF2 execution and evaluation, once it was possible to assess the attitude disturbance behaviour).

In the meantime, PST performed its analyses on the unexpected attitude control behaviour: since the force level of the thrusters responsible for the attitude control was in line with the requested torques during the burn, the propellant sloshing not nominally dumped was the probable cause of the problem (to be confirmed by future post-LEOP more extensive/exhaustive analyses).

After a Mission Review Board held on the 17th of December, the manufacturer recommended to increase the attitude surveillance threshold for OTM steady-state from 2° to 15° for AMF2 and all the following AMFs, to avoid the triggering of the FDIR. The PST would monitor the manoeuvre execution and the trend of the attitude error, to manually stop the burn if a not stable behaviour is observed.

It was underlined that if this workaround didn't work well and the AMFs could not be executed with the LAE, the RCTs would be used, making the LEOP duration of about one month.

D. AMF2 Re-Planning and Execution

According to the new strategy, which was recomputed by the FDS team (taking into account that the distance between the Geostationary Ring and each Apogee radius after an AMF must be greater than 40 km for space traffic management), the AMF2 was planned on the 19th of December, at the apogee 13.

During the Calibration phase of the interrupted AMF1, performed with the MI-FDS SW, an issue arose: it was noted that the observed force level was of about 8.25 N smaller than the predicted one of 437.854 N, which also during the planning phase seemed greater than the expected nominal value.

Also PST agreed that the force level corresponding to the observed propellants pressures was in line with the one computed by Mission Independent FDS (MI-FDS) SW in the calibration process. So, an investigation was performed to detect the reason of the discrepancy.

At the end of the analysis, it was found by the FDS team that the LAE coefficients (used for the computation of the force, mass flow and mixture ratio), present in the FDS Database (DB) and provided by PST pre-launch, were relevant to a different LAE engine than the one employed by the MTG-I1 satellite (same manufacturer but different serial number) and undifferentiated for the various RCT: for this reason the performances computed by the Mission Dependent FDS (MD-FDS) during the planning phase of the AMF1 were over-estimated with respect to the propellants pressures level given as input.

To solve the problem, the FDS DB was manually updated inserting the proper LAE and RCTs coefficients used for the computation of their performances, provided by PST.

Moreover, PST recommended to use the results obtained with the MD-FDS SW on the reconstruction of the LAE direction (coming from the estimation of the on-board LAE disturbance torque) for the directional calibration of the subsequent AMF, to improve the on-board application of the LAE feed-forward torque and the consequent compensation, with an enhancement of the controller performance during the propellant sloshing transient phase.

So, the on-board LAE direction was updated with the FDS output for the AMF2 planning; the same approach was applied also for the subsequent AMFs, to reduce the amplitude of the initial transient oscillation.

After the AMF2 execution, the FDS performed all the activities related to the estimation and calibration of the manoeuvre, together with the fuel consumption.

Then, the AMF2 execution was nominal, but with no "clean" steady state during the OTM phase (2°-3° of max de-pointing, as shown in Fig.9, but without major effect on the orbit): the threshold value for attitude transient error had been brought to 15°, therefore no attitude violation and FDIR occurred this time.

E. AMF3 and AMF4 Execution

The planning of AMF3 and AMF4 were conducted following the same principles of previous AMFs, included the check on the distance of the resulting apogee height from the GEO ring (which shall be greater than 40 km) and the verification that no S-Band antenna polarization switchover happened during the OTM phase (for occurrence in GAM, instead, the suitable antenna polarization switchover could be commanded at the proper epoch from ground). This last constraint is applicable also for relocation manoeuvres, performed during the routine phase (for details see [4]).

The execution of these two manoeuvres was nominal too (as shown in Table 1), allowing to acquire the nominal condition for the drift orbit start, after the AMF4 burn.

Table 1. Observed AMFs Manoeuvre, including the interrupted first burn.

Burn	**LAE Ignition Epoch**	**ΔV**	**Perf.**
AMF1	2022/12/15@08:24:37	49.9 m/s	N.A.
AMF2	2022/12/19@08:25:01	440.922 m/s	+0.1%
AMF3	2022/12/20@08:56:07	509.244 m/s	+0.5%
AMF4	2022/12/22@09:42:22	558.783 m/s	+0.6%

The executed AMFs strategy and the originally planned one are displayed in Fig.10 and compared.

In addition, the estimation of the LAE Disturbance Torque showed that the effective LAE direction during the burns was in line with the commanded one and the attitude error had the same behaviour as the previous AMFs, during the two burns realization.

Fig. 9. Attitude Error during AMF2 OTM phase: X-component is green, Y-component is orange, Z-component is blue.

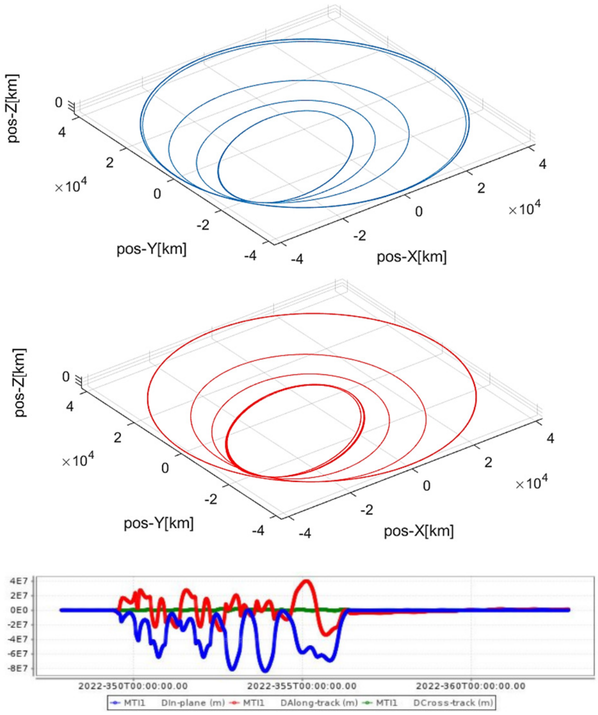

Fig. 10. MTG-I1 planned (top plot), executed (middle plot) trajectory in EME2000 frame, position differences (bottom plot) in local orbital frame.

VI. STATION ACQUISITION PHASE

The planning of the Station Acquisition Manoeuvres Strategy was done with the support of the PST Mission Analyst. Starting from the orbital conditions reached at the end of AMF4, two possible options were considered:

1) execution of two East STACQs on the 27th of December, at 4:20 UTC and 18:00 UTC respectively, with magnitude 1.7 m/s and 2.4 m/s;
2) execution of a first West STACQ of 1.3 m/s on the 24th of December at 9:00 UTC, followed by two East STACQs, both of 2.6 m/s, on the 26th at 12:00 UTC and 24:00 UTC respectively.

The last strategy, including a West manoeuvre to increase the longitude drift rate, was the selected one: as explained in the Mission Analysis section, it was more robust and flexible, allowing the possibility to re-plan the following manoeuvres in case of problems (thanks to 1.5 day between first and second STACQ); furthermore, it allowed using the calibration results of the West STACQ for the calibration of the next East burns, since the platform employs the same set of thrusters for both manoeuvre directions, simply performing a different attitude slew.

After the completion of the LAE isolation, Helium passivation and the Ka and D&G antennas deployment activities (whose effect on the orbit was estimated by

FDS team), the orbit determination was performed and the STACQs final strategy was refined.

In addition, since the propellants depleted masses were wrongly reset to 0 by the SCSW at the transition to STANDBY mode during the D&G antenna deployment, their value was restored using the results of the consumption computation performed by FDS before STACQ1 firing, using the related TC.

The execution of all the three STACQ manoeuvres was nominal, allowing to reach the MTG-I1 target longitude, inclination and a negligible eccentricity, as displayed in Fig.11 and in Fig.12.

Table 2. Observed STACQs Manoeuvre, employed to reach the MTG-I1 target longitude.

Burn	MidPoint	ΔV	Perf.
STACQ1	2022/12/24@09:00	1.187 m/s	-1%
STACQ2	2022/12/26@11:10	2.710 m/s	+0.5%
STACQ3	2022/12/27@00:10	2.713 m/s	+0.6%

As shown in Table 2, the execution of the STACQ2 was in line with the ΔV expected, so the applied increment of a proper calibration factor (+0.5%) in the commanded ΔV had compensated well the foreseen underperformance. This effect was taken into account also for the planning of the following STACQ3 manoeuvre, which also had a nominal execution.

The only remarkable event was the Star Tracker 1 switch off by the SCSW, due to an internal error during the slew profile of the STACQ2, because it was blinded by the Earth, as predicted by the FDS team but supposed to be tolerable. To avoid this problem, during the STACQ3 guidance profiles execution, the FDS team adjusted manually the yaw bias and spin phase values, to avoid any star tracker blinding by the Earth (even if, based on pre-flight constraints definition for guidance planning, the attitude profile could have been generated with only one Star Tracker out of three with a free field-of-view).

Despite all STACQs execution was in line with the planned strategy, during the manoeuvres preparation phase some issues happened, which required the support of the Thales Alenia Space MD-FDS SW Developer, on-call in case of unexpected anomalies.

Specifically, during the STACQ1 planning, a problem related to the convergence of guidance computation module was observed: the anomaly was worked around in LEOP by manual tuning of the pitch angle.

Then, during the STACQ2, another problem occurred: the slew guidance profile broke in two pieces, not for physical reasons, but due to a math artefact, because, at the split epoch, the Satellite-Earth line crossed the Vernal Axis, changing the attitude representation during the relevant guidance: before and after this point, the same quaternion was expressed in two different ways, risking to be considered a discontinuity by the on-board AOCS, which would have reject the relevant TC.

Manual changes of yaw bias and spin phase were implemented as workaround to solve this issue.

VII. EARTH ACQUISITION AND HANDOVER

After the completion of the Station Acquisition manoeuvres, the FDS team supported the Earth Acquisition phase, generating the relevant guidance profiles, providing the Wheels Offloading (WO) target speeds and generating the data to initialize the On-board Orbit Propagator (OOP): this is used by the SCSW to compute the target pointing in Fine Pointing Mode (FPM), which is the control mode to be used for most of the science mission in Routine phase.

All the activities were nominal and the automatic transition in FPM occurred on 27th of December 2022 at 16:31:02 UTC.

After a period of 8 hours of ranging activities performed by TPZ to take into account the (limited) effect of the

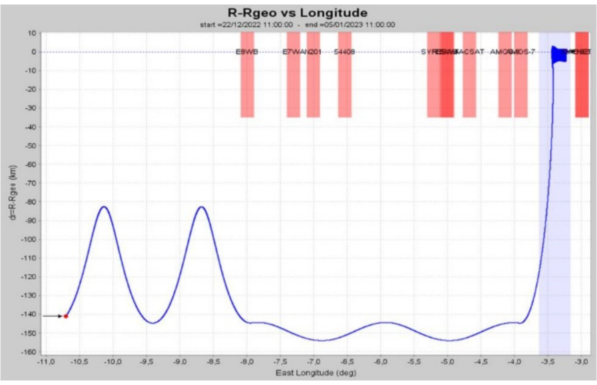

Fig. 11. Evolution of the Orbit Radius Difference wrt. the GEO Radius as function of the East Longitude.

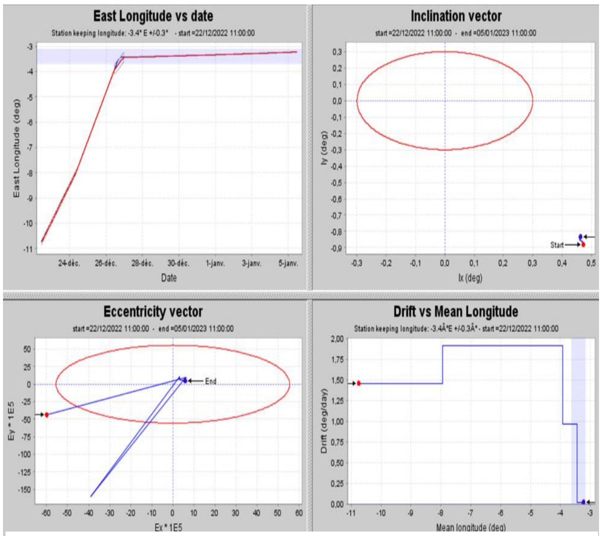

Fig. 12. Evolution of Longitude, Inclination vector, Eccentricity vector and Drift Rate, resulting from the STACQs Strategy.

Wheel Offloading on the orbit, the TPZ GSN brought down the carrier to allow EUMETSAT to execute a ranging session of 6 hours.

Then, the last LEOP orbit determination performed by TPZ showed that the handover to EUM occurred nominally with the MTG-I1 satellite located at 3.400°W, exactly the longitude dead-band midpoint.

VIII. MTG-I LEOP FLIGHT DYNAMICS SW

The functions of the MTG-I1 FDS system are structured into two interacting components:

- the Mission Independent FDS SW;
- the Mission Dependent FDS SW.

The first component collects all of the modules whose application, from a physical point of view, considers the system as a material point and consequently, all of the environment forces acting on it are applied only to a single geometric point in which the Spacecraft mass is supposed to be concentrated. The MI-FDS SW solves classical flight dynamics tasks and for this reason, it is applicable to any other space mission.

The MD-FDS SW, on the other hand, includes all the modules whose input data are related to the satellite characteristics (the FD database provided by the manufacturer) and whose output supports the definition of S/C platform TCs; therefore, this component is strictly related to the specific MTG mission.

A. MTG Mission Independent Flight Dynamics SW

The MI-FDS SW, also called TFDS, is the generic Telespazio Flight Dynamics Software used for over three decades to support all the LEOP and GEO operations performed from the Fucino Space Centre.

It is loosely based on the ESOC legacy codes LEOPOLD, PEPSOC-2000 and PEPSOC+, dealing respectively with LEOP, GEO-chemical and GEO-electric mission phases (see [5]). These legacy codes have been improved and evolved over the years to reflect the gained operational experience and the needs of the several missions supported, with most of the SW modules entirely developed in-house.

The MI-FDS supports all flight dynamics activities during Transfer, Drift and Geosynchronous Phases, related to classical flight dynamics tasks (as tracking data pre-processing, orbit determination and propagation, orbit archiving and retrieval, orbit events generation and antennas pointing data provision).

It also supports the manoeuvre planning for each phase, with a dedicated module for East/West manoeuvres computation and a specific optimizer for the AMFs Strategy calculation.

In addition, the Sequence of Events and the manoeuvre strategy computed by the MI-FDS SW are employed as input by the automatic LEOP Sequence of Events (SOE) software, a tool which is used to display in real time the Ground Segment operations synchronised with the Spacecraft orbital parameters.

In fact, the operations listed in the SOE are time linked to Orbit Events, whose occurring time is included in the operational files sent from FDS after each new orbit determination and propagation. In this way all S/C operations are carried out with updated time constraints and aligned with the actual Spacecraft orbit evolution.

B. MTG Mission Dependent Flight Dynamics SW

The MD-FDS SW was developed specifically for the MTG mission by Thales Alenia Space and the LEOP of MTG-I1 was the first time that it was used operationally. It deals with flight dynamics computations that are specific to the design of the MTG common platform, to be performed during the MTG LEOP operations.

In particular, it provides the inputs to allow the instantiation of TCs which support the satellite AOCS functions (as the generation of the guidance profiles or the LAE disturbance torque calibration), the mass management functionality and the On-Board Orbit Propagator update, taking as input the received on-board TMs and the manoeuvre strategy parameters (and the relevant orbit file) generated by the MI-FDS to perform its calculations and generate the related products.

IX. FDS TEAM ORGANIZATION

The Flight Dynamics team that participated to the LEOP of MTG-I1, in the Fucino Space Centre, was composed by five Telespazio FD engineers, performing the operations, two EUMETSAT FD engineers as support and two Mission Analysts of Thales Alenia Space; in addition, one of the Telespazio Flight Operations Directors was a senior Flight Dynamics expert.

The MD-FDS software developer of the Thales Alenia Space was on-call in case of anomalies with the SW, ready to support the detection and resolution of the eventual MD-FDS problems.

The operations team was organized in two groups:

- Team A: dedicated to the most critical activities (as the orbit determination or the manoeuvre planning and TCs parameters generation); it was on-call during the other phases for potential contingencies.
- Team B: dedicated to monitoring activities (e.g. a manoeuvre execution), with the capability to handle an unexpected situation, till the arrival of team A.

The allocation of the people in the specific activities was done with the purpose of ensuring maximum coverage «people versus activity» with a suitable rotation considering different expertise. The selected shifts allowed to cover 24h/7d, as requested by the mission.

In addition, for the computations performed with the new MD-FDS software, it was arranged to have 2 members of the team A to run simultaneously and independently 2 separated SW instances, to be robust to human errors and to eventual unexpected issues coming from the first operational use of the new software.

X. CONCLUSIONS

The LEOP of MTG-I1 was very challenging, with the occurrence of simultaneous anomalies of several kinds, which had a great impact on the nominal sequence of events. The most critical issue was the AMF1 abort, which required extensive investigations during LEOP: this was solved with the complete re-planning of the LAE burns strategy, outside of the boundaries and foreseen backup scenarios, broadly analysed in the pre-flight mission analysis.

Despite these unexpected events, thanks to the LEOP and PST teams expertise and preparation for handling time/mission critical contingencies, the satellite was always in a safe condition; only a marginal and acceptable increment of LEOP duration and propellant consumption occurred, without noticeable lifetime impact.

In particular, by means of clever re-planning of both the AMFs and STACQs strategies, the satellite was released on target, exactly at the midpoint of allocated longitude dead-band, ready for the beginning of the commissioning activities (see details in [4]) that followed the handover of operations responsibility to EUMETSAT, on the 28th of December 2022.

XI. REFERENCES

[1] Meteosat series, EUMETSAT website https://www.eumetsat.int/our-satellites/meteosat-series

[2] L. Pirson, L. Ascani, S. Pessina, E. Cerone, G. Sechi, “Meteosat Third Generation: first AOCS in flight results from PFM-I1 LEOP and commissioning” , 12th International Conference on Guidance, Navigation & Control Systems (GNC) (Sopot, Poland) · Jun 12, 2023

[3] Pessina S., Klinc M., Hocken D. “Mission Analysis for MSG-3&4 Considering Combined LEOP/Station-Keeping Costs and In-Orbit Storage”, 24th International Symposium on Space Flight Dynamics (ISSFD at APL, Laurel, Maryland, USA) · May 1, 2014

[4] M.A. Martín Serrano, S. Pessina, M. Del Monte, M. Klinc, D. Lázaro, “MTG-I1 Flight Dynamics Commissioning Operational Experience”, Proceedings of the 29th International Symposium on Flight Dynamics (ISSFD).

[5] E.M. Soop, Handbook of Geostationary Orbits, ESA, Space Technology Library, volume 3.