MTG-I1 Flight Dynamics Commissioning Operational Experience

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***Abstract* – MTG-I1 is the first in-orbit spacecraft from the Meteosat Third Generation (MTG) Programme. The MTG System ensures continuation and introduces a vast enhancement of the weather services provided by the Meteosat Second Generation (MSG) Missions. MTG-I1 was launched by an Ariane 5C launcher into a Geostationary Transfer Orbit (GTO) on December the 13th 2022 at 20:30:00 UTC from the Europe's Spaceport in French Guiana. Following the separation into a GTO, the LEOP operations were conducted by Telespazio from their Main Control Centre located in Fucino (Italy). At the end of the LEOP the spacecraft had reached the geostationary orbit at a longitude of 3.4 degrees West and an orbital plane inclination below 1 degree. The hand-over of operations to EUMETSAT (Darmstadt) took place on December the 28th 2022, marking the start of the Commissioning Phase. More than a year later, in January 2024, MTG-I1 was relocated to 0 deg longitude, in collocation with MSG3 (Meteosat-10), to perform its nominal Mission. This paper provides a summary of the main activities carried out by the EUMETSAT Flight Dynamics Team during the one year Commissioning Phase in 2023.**

I. INTRODUCTION

MTG-I1 is the first in-orbit spacecraft (S/C) from the Meteosat Third Generation (MTG) Mission, a cooperation between the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) and the European Space Agency (ESA), with EUMETSAT being responsible of operating the satellites in Commissioning and Routine Phases. The MTG System provides a significant enhancement to the imagery mission of the MSG satellites and introduces completely new observation missions. The MTG satellites, are divided into two families according to the contribution of their payloads: four MTG-I (imagers) and two MTG-S (sounders). The Space Segment of the MTG Mission consists of a constellation of at least three in-orbit satellites, two imagers and one sounder, to support all observation missions. The main instruments onboard MTG-I1 are a Flexible Combined Imager (FCI) and a Lightning Imagery (LI). The FCI allows to scan either the full Earth disc in 16 channels every 10 minutes with a spatial sampling distance in the range 1 to 2 km or a quarter of the Earth disc in 4 channels every 2.5 minutes with a resolution twice as good. The LI detects continuously the lighting discharges taking place in clouds or between clouds and ground over almost the full disc with a spatial sampling distance around 10 km.

MTG-I1 was launched by an Ariane 5C launcher into a GTO on December the 13th 2022 at 20:30:00 UTC from the Europe's Spaceport in French Guiana. LEOP operations were conducted by Telespazio from their Main Control Centre located in Fucino (Italy). More details about the MTG-I1 LEOP operations can be found in [1]. At the end of the LEOP the hand-over of operations to EUMETSAT took place on December the 28th 2022. The satellite orbital parameters at hand-over (shown in Table 1) were compliant with the pre-agreed hand-over criteria. In particular, the criteria on orientation of the orbital plane (inclination and RAAN) were aiming at optimizing the overall fuel consumption during the complete Mission lifetime and the criteria on longitude and its drift were ensuring no need to execute any longitude maintenance manoeuvre in the week following the hand-over of operations to EUMETSAT.

Table 1. TOD averaged orbital elements after LEOP.

Longitude	3.4 deg West
Longitude drift	0.003 deg/day
Inclination	0.975 deg
RAAN	299.5 deg
Eccentricity vector	(-6.305, 0.290)10e-05

A. MTG-I1 Spacecraft Description

The MTG-I1 S/C, as the other MTG satellites, is a three-axis stabilized platform. The MTG Attitude and

Orbit Control System (AOCS) consists of the following sensors and actuators: two redundant branches of Coarse Sun Sensors, a Very High Performance Gyro Unit (GYR), two Coarse Rate Sensors, a Sun Avoidance Sensor to control that the Sun is not coming from a directions dangerous for the payload, a Reaction Wheel (RW) Assembly with a total of 5 wheels, as the main actuators of the AOCS; an internally redundant set of 16 Reaction Control Thrusters (RCT) and a Liquid Apogee Engine (LAE), operated during LEOP to acquire the Geosynchronous orbit.

When flying either in its nominal operational mode for imaging, called Fine Pointing Mode (FPM), or in the orbit maintenance manoeuvring mode, called Station Keeping Mode (SKM), the S/C target attitude is accurately controlled by RW torques, acting in close loop with the combined information from the STRs and the GYR.

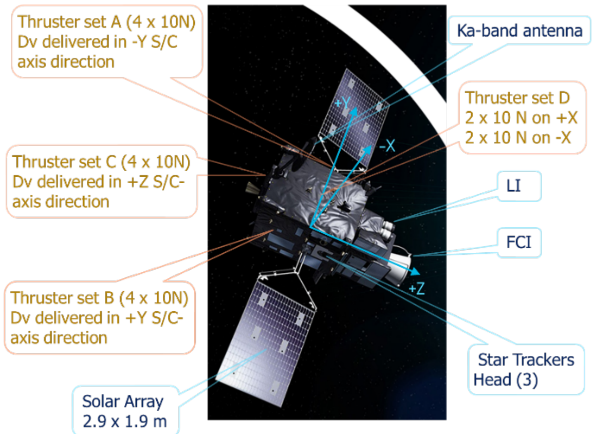

Fig. 1. MTG-I1 artistic impression depicting the S/C in FPM Summer season, together with a representation of the S/C reference frame.

In FPM the S/C +Z-axis, along the field of view of the main instrument (FCI), points towards a point on the Earth Equator called Earth Point Target (EPT). This point is close in longitude (between 0.5 deg and 0.25 deg depending on the Mission Phase) to the actual subsatellite point. The S/C Y-axis, along the Solar Arrays (SA), is kept nearly perpendicular to the orbital plane. The SA are always pointed towards the Sun by an autonomous rotation mechanism. The S/C X-axis is close to the orbital velocity direction. This Earth pointing attitude in FPM includes an additional peculiarity. In order to keep the S/C -Y-axis, which hosts the STR head and the payload radiator, protected from direct Sun illumination, the S/C performs twice a year near the equinoxes a rotation of 180 degrees around the S/C Z-axis. This rotation is commanded from ground and it is called Yaw Flip manoeuvre, performed using the RWs. This way the S/C +Y-axis points towards the South in Winter and towards the North in Summer.

The Ka-band antenna (visible in Fig. 1) is a parabolic antenna mounted on the S/C -X-axis with its field of view along the S/C +Z-axis (Earth pointing). This antenna has steering capabilities around the S/C X-axis (-9.1 to +23.9 deg) and the S/C Y-axis (-23.2 to 9.1 deg). This steering range allows to point the Ka-band antenna towards the reception Ka-band ground stations (located in Lario, Italy and Leuk, Switzerland) not only when keeping the nominal Earth pointing attitude but also when the attitude is biased to point the main instrument away from the Earth disc for calibration purposes. After every Yaw Flip manoeuvre and during special attitude manoeuvres for instrument calibration, the Ka-band pointing parameters are computed by the Flight Dynamics (FD) System (FDS) for up-linking to the S/C. Regarding the S-band link, omni-directional coverage is ensured by having two S-band antennas (SBA-1 and SBA-2) pointing on the S/C X-axis with different polarizations to avoid interfering with each other. SBA-1 with Right Hand Circularization Polarization (RHCP) is accommodated in S/C -X direction and points towards Nadir in nominal Earth pointing attitude. SBA-2 is accommodated in S/C +X direction and points towards Zenith in nominal attitude.

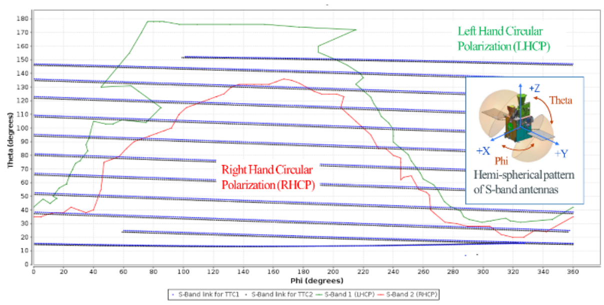

Fig. 2. On-board S-band antenna regions in Spacecraft Reference Frame together with the evolution (12 h) of the direction towards S-band ground stations in SAM.

The S/C safe attitude is a Sun pointing attitude corresponding to the AOCS mode called Sun Acquisition Mode (SAM). In this attitude, the S/C -Z-axis is constantly pointed towards the Sun with the SA surface perpendicular to the S/C Z-axis to enable maximum power generation. A slow rotation (0.1 deg/s) around the S/C Z-axis increases the gyroscopic stiffness of this attitude. SAM is the target attitude during the following Mission phases: LEOP, longitude relocation campaigns (described in section V) and after Failure, Detection, Isolation and Recovery (FDIR) transition. The AOCS is able to keep this attitude with an accuracy of +/- 20 deg in the Sun direction, in two sub-modes depending on whether the main actuators are the RCTs (sub-mode called SAM/TSA) or the RWs (sub-mode called SAM/RWSA). The transition from SAM/TSA to SAM/RWSA is commanded from ground. The Sun-pointing attitude is finer when in SAM/RWSA. In this attitude, due to the rotation around the S/C Z-axis, the on-board S-band antennas visibility from ground changes along the orbit. This means that the only way to keep commanding capability and ranging measurements in SAM is to perform polarization switches on the ground stations uplink. The FD Team supports the prediction of the times of these polarization changes by modelling the S-band antennas direction towards ground based on the best knowledge of the S/C attitude when in SAM. This FDS functionality is shown in Fig. 2.

II. FIRST OPERATIONS AFTER HAND-OVER

A. *On-ground Orbit Determination Initialization*

MTG-I1 has stringent orbit determination accuracy requirements, dictated by the FCI requirements for an accurate and stable Earth pointing attitude. The resulting operational approach to the orbit determination for MTG-I1 is based on combining the orbit determination solution obtained by the FDS using S-band radiometric tracking data and optical tracking data with the solution obtained by the Image Data Processing Facility (IDPF-I) by matching landmarks, making use of the FCI data and the STR attitude information.

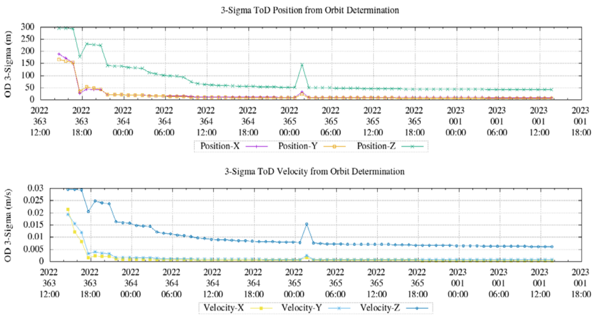

Fig. 3. Evolution of the determined position and velocity 3-sigma values during the 3 days alternate ranging campaign after Hand-over.

In absence of the image navigation solution (when the data from the FCI is not available, in particular at the start of the Commissioning Phase) the orbit determination function of the FDS is initialized based on S-band ranging measurements received from two ground stations called TTC1 (located in Fucino, Italy) and TTC2 (located in Cheia, Romania). The required accuracy of the FD orbit solution to initialize the image navigation is 1500m/500m/50m in along-track/cross-track/radial components of the Local Orbital Reference Frame (LORF) at 3-sigma confidence level. In order to achieve this accuracy using ranging measurements from the two S-band stations, a special ranging campaign is required with a measurements frequency of 20 minutes and uplink swaps between the two TTC stations every 3 hours. This ranging measurements pattern is called at EUMETSAT alternate ranging. It was demonstrated in [2] that when collecting ranging measurements (assuming a stability of those in the order of 5 ns at 1-sigma level) in alternate ranging pattern for a total of 3 days, the orbit determination accuracy fulfils the expected requirements. Fig. 3 shows the evolution of the orbit determination accuracy during the initial three days alternate ranging campaign, as new measurements were incorporated to the least square fit.

At the end of the three days, the extended parameters of the state vector (ground stations ranging biases, transponder delay and Solar Radiation Pressure (SRP) coefficient) were characterized in flight for the first time. In addition to the S-band radiometric data from TTC1 and TTC2, an Optical Tracking Service Provider (OTSP) delivers on a regular and on-demand bases optical measurements with an accuracy better than 1 mdeg in azimuth and elevation. The telescopes network of the provider (GMV/6ROADS) consists of seven sites located in South Africa (Springbok), Chile (Polonia), Spain (Nerpio), Italy (Rantiga), Poland (Solaris and Oborniki), USA (Beata) and Japan (Anjin-San). During the alternate ranging campaign the first set of optical data was received and incorporated to the orbital solution. The residual plot is shown in Fig. 4. Even though the mean and RMS of the fit were good, a clear signature was observed in the residuals.

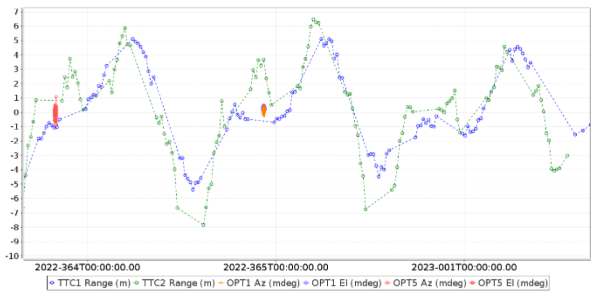

Fig. 4. S-band ranging and Optical measurements residuals after a 3-day alternate ranging campaign.

At a later point in time during the Commissioning this issue was addressed. The signature is introduced by the simplified modelling of the SRP perturbation with a single coefficient and area during the 7-day determination arc. The modelling of the evolution of the SRP area depending on the season, the Yaw Flip status and the solar local time of the S/C is planned to be incorporated to the FD orbit determination software in the near future.

B. *On-board Orbit Propagator (OOP) first updates*

The OOP is a function of the on-board software which primarily computes the pointing attitude (as a quaternion in the inertial EME2000 frame) required by the AOCS modes FPM and SKM. The application provides this result in real time based on an ideal geostationary trajectory. The deviation of the actual orbit with respect to this ideal trajectory is computed as a set of harmonic coefficients defining the time-series of the perturbation via Clohessy-Wiltshire linearisation. This set of coefficients is computed on-ground by the FDS and sent daily to the S/C in a telecommand. The telecommand also includes the rest of parameters defining the attitude in FPM and SKM, namely the quaternion representing the rotation from EME2000 to the true Equator of the day, the EPT longitude and the parameters to control and smooth the transition slew to achieve and follow the target between consecutive OOP updates.

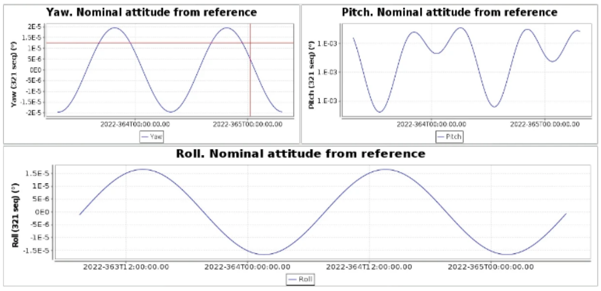

Fig. 5. Comparisons between consecutive FDS ground-computed attitude profiles to prevent wrong OOP parameters updates.

The OOP was initialized on the last day of LEOP operations. After the Hand-over of operations, the FD Team at EUMETSAT produced the first update of OOP parameters while the orbit determination and propagation on-ground was being initialized at the required accuracy. These first updates were conducted in a three-step approach:

- Step1: generation of OOP parameters based on a propagation of the latest determined orbit during LEOP. This step was aiming at generating for the first time the OOP parameters with the EUMETSAT FDS but still based on the same orbital information used to initialize the OOP function during LEOP. This update was performed in the so called “degraded” mode, which stablishes wide parameters for the smoothing of the slew to follow the target attitude.
- Step2: one day later, a new OOP update in “degraded” mode was prepared based on the latest determined and propagated orbit by the EUMETSAT FDS. This step was aiming at performing for the first time the OOP parameters update using an updated underlying orbit information.
- Step3: after conducting daily OOP parameters updates in “degraded” mode for several days to gain confidence on the update process, the first OOP parameters update in “precise” mode was commanded.

The execution of Step1 and Step2 was successful. Before every OOP update, checks were performed on ground by the FD Team to assess the maximum change in pointing target considering the orbit uncertainties, as well as possible errors in the On-board/UTC time correction at the EUMETSAT Mission Control System (MCS) up to 0.2 s. The typical result of these checks in shown in Fig. 5.

Step3 was attempted on 2023/01/12 with the first update of the OOP parameters in “precise” mode. After sending the command at 11:40 UTC, the attitude monitoring performed by the FD Team started showing increasing differences between the STRs joined solution received in Telemetry (TM) and the target attitude computed on ground by the FDS. The same deviation was observed when comparing the FDS generated attitude and the attitude target produced by the OOP function on-board (quaternion also received in TM). An investigation was immediately started involving the ESA and Industry partners, with the conclusion to command the OOP parameters in “degraded” mode to recover the Earth Pointing attitude. This was commanded at 19:40 UTC. As shown in Fig. 6, the pointing was recovered by this action and the maximum pointing deviation reached was 1.6 deg.

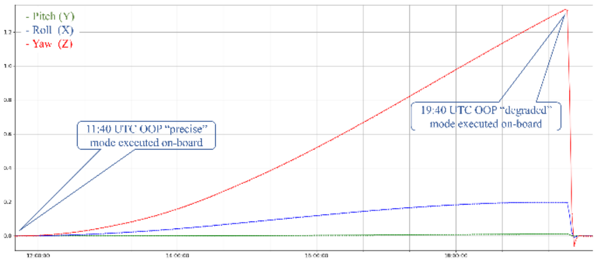

Fig. 6. Comparison of attitude quaternion produced by OOP function on-board and on-ground modelled attitude after the first OOP “precise” update.

Further investigations concluded that the root cause of this unexpected behaviour was the change of one of the OOP parameters in subsequent commanded updates. This parameter is the longitude of the ideal geostationary orbit used to project the actual ground determined orbit to generate the coefficients representing the offset between the two trajectories. This value was originally thought to be fixed to the centre of the control box, assuming the size of the box was +/-0.1 deg. However, the orbit control concept for the MTG satellites foresees larger longitude control boxes, in the range of +/-0.5 to +/-0.25 deg, depending on the Mission Phase. Consequently, to keep the maximum longitude difference between the ideal and the actual orbit below 0.1 deg, the longitude of the ideal geostationary orbit in the OOP model cannot be fixed in every OOP update. This is however possible when the OOP update parameters to control the transition slew are wider, as it is the case in the "degraded" mode. For this reason, the current approach to the OOP daily updates is to stay in "degraded" mode, since it has been demonstrated that this mode provides smooth enough pointing transition compatible with the main instruments pointing stability requirements.

III. Orbit Manoeuvres

The MTG satellites are equipped with a bi-propellant Unified Propulsion System (UPS) integrated into the satellite body. It consists of two identical propellant tanks (MON-3 and MMH), two He tanks, a Pressure Regulator, a 400 N Liquid Apogee Engine (LAE) and sixteen 10N Reaction Control Thrusters (RCT). The LAE is used during LEOP in pressure regulated configuration to reach the Geosynchronous orbit. At the end of LEOP the LAE and He passivation is carried out, leaving the UPS in blow-down configuration for the rest of the Mission's lifetime. The sixteen RCTs are distributed in four sets (each set with four thrusters):

- Set A and B, located on the S/C Y-panels are nominally used for the execution of North/South Station Keeping (NSSK) manoeuvres, Reaction Wheel Offloading (RWOL) manoeuvres and to achieve the attitude control during the execution of East/West Station Keeping (EWSK) manoeuvres. Additionally, they are the backup thruster sets for execution of orbital relocation and end of life manoeuvres.
- Set D, with two redundant thrusters located on the S/C +X-panel and two located on the -X-panel, are used for the execution of EWSK manoeuvres.
- Set C, located on the S/C -Z-panel, are used in Survival Mode (SRM) and for orbital relocation and end of life manoeuvres.

The distribution of the RCTs is depicted in Fig. 1.

The Commissioning activities and tests covered the three possible manoeuvre types in SKM, this is, NSSK, EWSK and RWOL manoeuvres.

A. RWOL manoeuvres

The offloading of the RWs is achieved by firing a combination of RCTs from sets A and B without imparting any change to the orbital velocity. The attitude during the burn in SKM is Earth pointing as in FPM. The offloading can be carried out during the execution of a NSSK manoeuvre or as a stand-alone RWOL manoeuvre. During the Commissioning phase there were no regular NSSK manoeuvres, since the inclination vector at Hand-over was selected precisely to avoid the need of inclination/RAAN corrections during the Commissioning phase of over a year, therefore the frequency of the stand-alone RWOL manoeuvres was higher during the first year of operations than it is expected to be once NSSK manoeuvre are executed regularly (every 56 days). Additionally, stand-alone RWOL manoeuvres are always required after a Yaw Flip manoeuvre. The parameters computed by the FDS for the generation of the manoeuvre command include the main inputs to the propulsion system model (RCTs forces, mass flows, mixture ratios and tanks mass properties) and the target for the RW speeds, which are season dependant (equinox or solstice). A total of 8 RWOL manoeuvres were executed in 2023. The calibration of the RWOL manoeuvres shows delta-v values near to zero, within the expected range provided by the S/C manufacturer as it can be seen in Fig. 7. The post Yaw Flip manoeuvres were expected to be the longest ones due to the large required offloading and therefore, the ones imparting the largest delta-vs.

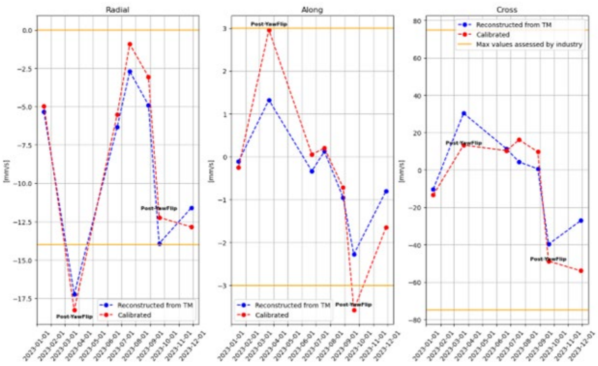

Fig. 7. Determined RWOL Delta-v in LORF components. Yellow lines show the maximum expected values.

B. EWSK manoeuvres

When entering SKM for the execution of EW or NS SK manoeuvres, the attitude controller aligns the S/C reference frame with the LORF. The selection of the thruster within the set D (see Fig. 1) depends on the manoeuvre direction (East or West), the Yaw Flip status (Winter or Summer) and the thruster health status (prime or backup). The attitude during the actual thruster firing is controlled by a combination of 4 thrusters from the sets A and B.

The first EWSK manoeuvre in East direction was executed on 2023/01/31-11:16:19 UTC. The planned manoeuvre delta-v was 0.09 m/s with a total estimated duration of 15 s. After the end of the firing, at 11:17:17 UTC, the S/C AOCS mode transitioned unexpectedly to SAM. The investigation with the ESA and Industry Teams concluded that the transition to SAM was triggered by a larger than expected disturbance torque which caused the attitude de-pointing to grow over a configured threshold of 2 deg and this triggered an FDIR. This de-pointing was observed in the FDS attitude monitoring in the minutes after the burn as it can be seen in Fig. 8. The autonomous Sun acquisition manoeuvre at the transition to SAM was performed by firing the RCTs sets A/B in SAM/TSA mode. This thrusters' actuation imparted a delta-v on the orbit. The main task for the FD team in the subsequent hours was to run orbit determinations to assess the longitude drift resulting from this delta-v. An alternate ranging campaign was scheduled, as well as an activation of the OTSP for the coming night. On the following day, with almost 24 hours of collected ranging and optical measurements, the result of the orbit determination confirmed that the thrusting during the Sun acquisition had imparted a delta-v of 0.03 m/s in the flight direction (or East). This delta-v, added to the executed EWSK before the SAM transition, resulted on a stronger than desired drift towards the Western limit of the longitude control band, which would require the execution of a manoeuvre against the flight direction (or West) within the next 17 days to revert the drift.

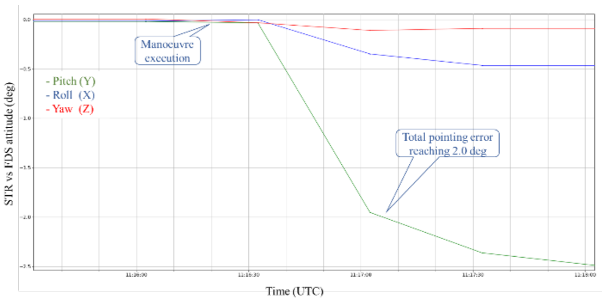

Fig. 8. Comparison of attitude quaternion produced by STR joined solution on-board and on-ground modelled attitude after EWSK manoeuvre on 2023/01/31.

Before the execution of this manoeuvre, the S/C manufacturer completed the analysis of the observed problem and provided a list of recommendations for the execution of future EWSK manoeuvres: On the S/C side, the integral gain of the SKM controller was modified and the de-pointing threshold to trigger the subject FDIR was increased from 2 to 15 deg. On the FDS side, the generation of the manoeuvre command parameters was changed to reduce the manoeuvre duty cycle from 1.0 to 0.3 and the parameters providing the mass properties of the tanks under the manoeuvre acceleration were substituted by the unaccelerated ones, since the short duration of EWSK burns (in the order of tens of seconds) does not allow for the Centre of Gravity (CoG) of the tanks to get to the settled values.

Seven more EWSK manoeuvres were executed in 2023 which allowed the characterization of the prime (D1 and D2) and redundant (D3 and D4) thrusters. Fig. 10 shows the difference in percentage between the calibrated manoeuvre along-track component and the planned one. The evolution of the MTG-I1 longitude in 2023 before its relocation is shown in Fig. 9.

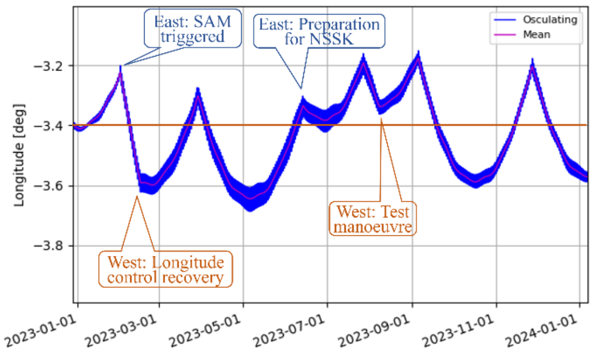

Fig. 9. MTG-I1 longitude evolution in 2023.

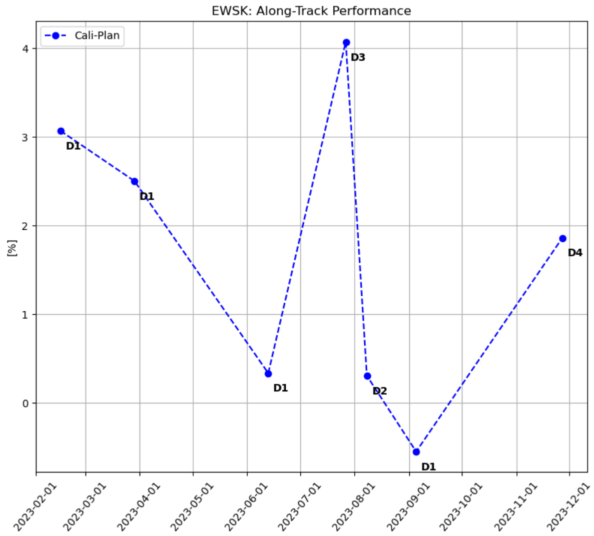

Fig. 10. Evolution of EWSK manoeuvre performance factors (LORF along-track component) for thrusters D.

C. NSSK manoeuvres

The evolution of the inclination vector at Hand-over was selected to avoid the need of NSSK manoeuvres during the first year of Commissioning operations. Therefore, there was large flexibility in allocating the slots for the execution of NSSK tests manoeuvres in 2023. The selection of the manoeuvre days was driven by the position of the S/C within its longitude control box: the date was selected so that the initial longitude and longitude drift rate were favourable in case there occurred a SAM or SRM entry when attempting the test manoeuvre (with the subsequent RCTs actuation to acquire the Sun pointing attitude described in Section I.A).

When entering SKM for the execution of NSSK manoeuvres, the attitude controller aligns the S/C reference frame with the LORF. The selection of the thruster set A or B (see Fig. 1) depends on the manoeuvre direction (North or South), the Yaw Flip status (Winter or Summer) and the thruster health status (prime or backup). In order to test both RCT sets, since all test manoeuvres were conducted in Summer configuration (S/C +Y-axis always pointing North), at least one North manoeuvre (set B) and one South manoeuvre (set A) were required.

Due to the thrusters' alignment and the S/C mass properties, the delta-v obtained when activating the selected combination of thrusters is not perfectly aligned with the S/C Y-axis, therefore a residual delta-v mostly in the radial component is expected. It is however possible to command a bias to the target attitude in SKM, to align the delta-v direction with the desired manoeuvre direction in LORF. Both NSSK manoeuvre options, with and without commanding this bias for the AOCS target attitude in SKM, were tested.
Another parameter subject to testing was the computation by the FDS and commanding of the plume impingement corrections. As it can be seen in Fig. 1, the exhaustion plume of thrusters sets A and B goes along the direction of the Solar Arrays. As a result, the following manoeuvres test cases were executed:

- NSSK-1: executed on the 2023/06/01 in North direction, delta-v 2.444 m/s with thruster Set-B, de-activation of plume-impingement correction, de-activation of attitude bias in SKM.
- NSSK-2: executed on the 2023/07/03 in South direction, delta-v 2.445 m/s with thruster Set-A, de-activation of plume-impingement correction, de-activation of attitude bias in SKM.
- NSSK-3: executed on the 2023/07/04 in South direction, delta-v 2.445 m/s with thruster Set-A, activation of plume-impingement correction, activation of attitude bias in SKM.

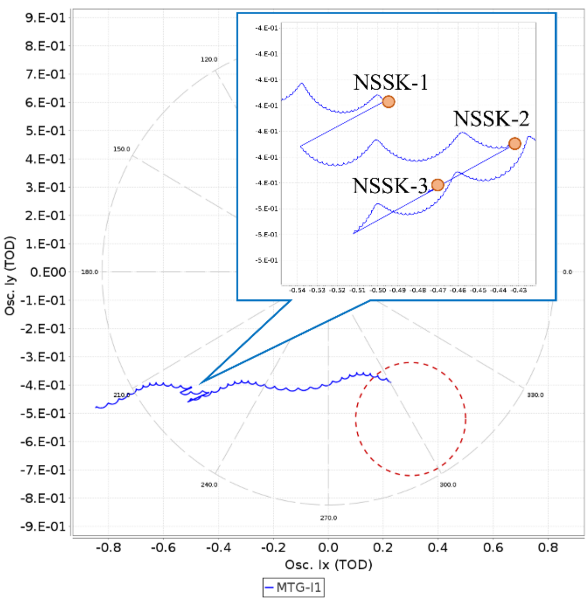

Fig. 11. TOD Inclination vector evolution from Hand-over, showing the effect of the NSSK test manoeuvres. The red circle is the control region for Routine Phase.

The manoeuvre performance error for the three manoeuvres was below 1% and did not trigger any further investigation. Also, the attitude was nominally controlled in SKM during the burns. The effect of the NSSK manoeuvres on the evolution of the TOD inclination vector is shown in Fig. 11.

The major outcome of the three test manoeuvres was the impact of the attitude bias commanded with the NSSK-3. At the beginning of life, this bias (originating from the evolution of the S/C CoG as the fuel in the tanks diminishes) is close to 1 deg in the roll direction. When the bias command was executed on-board, the Ka-band link to ground was lost for approximately one minute, due to the fact that the on-board Ka-band antenna pointing is not modified during the stay in SKM. This was not foreseen in the MTG-I1 operational concept, since this AOCS functionality for commanding a bias to the target attitude was incorporated to the operational baseline at a late stage (after Critical Design Review). The outcome of this test triggered a System level discussion at EUMETSAT which has resulted in the acceptance of this short outage, in favour of the advantages of applying the attitude bias. The main advantage in the commanding of the bias is the removal of a constraint to execute NSSK manoeuvres as two-burn manoeuvres at opposite orbital locations (12 hours approximately apart), that would be needed to cancel out the parasitic delta-v component in the radial direction.

IV. ATTITUDE MANOEUVRES IN SUPPORT OF INSTRUMENT CALIBRATION

The characterization of the coefficients involved in the Sun Straylight correction model for the main instrument, the FCI, required in-flight dedicated Commissioning tests. This testing involved taking measurements on the visible and near-infrared channels in a certain Sun, Earth and FCI Field of View (FoV) geometry: the Earth had to be out of the FCI FoV with an additional margin to avoid Earth straylight; the Sun has to pass close to the outer swath of the FCI full disc scan pattern. The angular distance of the Sun from the centre of the FCI FoV had to remain above 9.45 deg during the whole Sun pass. This geometry is depicted in Fig. 12 for Yaw-flip Summer configuration.

This geometry is achieved by executing an attitude manoeuvre with the RWs to bias the S/C attitude with respect to its nominal FPM attitude two hours before the Sun pass and staying in that biased attitude until the measurements are completed. The range of possible de-pointing attitudes is determined by the steering capabilities of the on-board Ka-band antenna described in section I.A and the Yaw Flip status, since these steering ranges are not symmetric. This determines the time intervals throughout the year when this calibration is possible. The test was conducted in July 2023, this is, in the Summer Yaw Flip configuration, meaning that the Ka-band steering limitation was allowing de-pointing attitudes to achieve the require geometry only in the North/West direction as shown in Fig. 12.

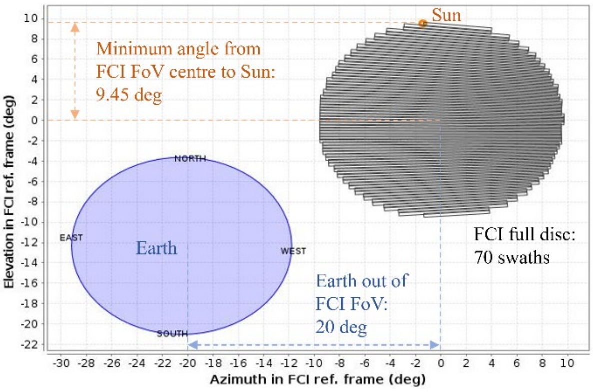

Fig. 12. FCI Sun straylight characterization test geometry in Yaw Flip Summer configuration, represented in FCI reference frame. Note the East/West direction inversion.

The attitude guidance function on-board is able to apply linear and harmonic biases at the frequency of the orbital period to the computed target nominal attitude in FPM. Three harmonic biases were superimposed to achieve a three-step rotation in yaw (Z-axis), pitch (Y-axis) and roll (X-axis) from the nominal attitude to the target attitude. The tasks of the FD Team for these operations were to derive the required attitude offset in pitch (East/West direction) and roll (North/South direction) to achieve the desired Sun/Earth/FCI geometry, provide the offsets as input to the attitude manoeuvre flight operations procedure and to generate the Ka-band antenna pointing elements to re-direct it towards the ground receiving stations during the de-pointed period and afterwards, when returning to the nominal FPM attitude.

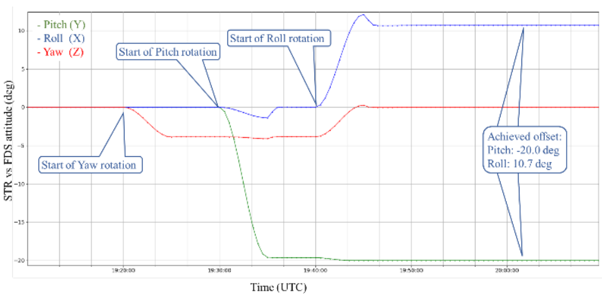

Fig. 13. FD monitoring of the attitude offset between the STR joined solution received in TM and the ground modelled unbiased FPM attitude during the attitude manoeuvre on 2023/07/20.

The test was conducted twice. The first time, on the night of 2023/07/06, the test was not successful due to an error in the reference frame input definition for the attitude offset in the flight procedure. As a consequence, the de-pointing was not performed in North/West direction but in South/East direction. In this attitude the Ka-band antenna could not be steered towards the ground stations. The test was aborted, nonetheless, it was a successful end-to-end test of the platform de-pointing operations. After confirming together with the S/C manufacturer and the Control Team at EUMETSAT that the problem was a reference frame issue, the attitude was commanded back to nominal FPM. The second attempt, after a thorough validation of the flight procedure, took place on the night of 2023/07/21, starting at 19:20:00 UTC. During the de-pointing attitude manoeuvre the FD Team monitored the evolution of the S/C rates derived from the GYR and the comparison between the attitude received in TM from the STR joined quaternion solution. The three-step on-board execution of the harmonic biases took place as nominally expected, shown in Fig. 13. The attitude manoeuvre to return to the nominal FPM attitude took place on 2023/07/21-13:15:00 UTC, by commanding the harmonic biases that led to the rotation toward the FPM attitude in reverse order, this is, roll (X-axis), pitch (Y-axis) and yaw (Z-axis).

V. LONGITUDE RELOCATION CAMPAIGN

During the Commissioning Phase in 2023, MTG-I1 was controlled in a +/- 0.5 deg longitude box at 3.4 deg West. The MTG-I1 longitude control box for the Routine Phase is centred around 0.35 deg West, with an amplitude of +/- 0.25 deg, flying next to MSG-3 which is controlled at 0.15 deg East with the same longitude control box amplitude. In January 2024 a one-week relocation operations campaign was carried out, resulting on the acquisition of the target longitude for MTG-I1.

The manoeuvre sequence to achieve the longitude change is in principle simple: a two-burn drift-start manoeuvre (burns 12 hours apart approximately) to achieve a circular orbit with a semi-major axis lower than the Geosynchronous one, a drift period towards the target longitude and a two-burn drift-stop manoeuvre to return the geosynchronous semi-major axis and Sun-pointing perigee upon arrival on target. Additional operational complexity is however imposed by the safety of MTG-I1 and its neighbour S/C during the relocation, by the constraints imposed by the MTG-I1 platform and the need of backup scenarios accounting for manoeuvre performance errors and manoeuvre execution delays. These topics were analysed by the FD Team in a study during the preparation activities, shortly summarized hereafter.

The relocation manoeuvres are not performed in the

AOCS mode dedicated to routine manoeuvres (SKM) but in the same mode used in LEOP to perform the apogee firings, called Orbit Transfer Mode (OTM). In this mode, the S/C target attitude is generated on-ground by the FDS and sent to the S/C as a ground guidance telecommand. This attitude is computed as a quaternion profile representing the desired attitude as a function of time. A Chebyshev polynomial fit is then performed, splitting the profile in one or several segments to reduce the fit error below a given threshold. The resulting coefficients are the actual input parameters expected by the AOCS software. The target attitude is determined by the selection of thrusters for the manoeuvre. As described at the beginning of section III, the nominal thruster set for the execution of manoeuvres in OTM is set C, located on the S/C -Z face. Therefore, the nominal targe attitude in OTM for relocation manoeuvres aims at aligning the S/C Z-axis with the velocity direction for semi-major axis changes. In case one or more thrusters in set C are flagged as unhealthy, the thruster sets A and B are used as backup. The target OTM attitude should then align the S/C Y-axis with the velocity direction. In this case, the illumination constraints on the S/C Y-axis introduce a strong limitation on the selection of the manoeuvre execution times. As explained in section I.A, the angle between the Sun direction and the S/C -Y-axis must be always larger than 90 deg (S/C -Y face in shadow). Additionally, due to thermal reasons, the elevation of the Sun above the S/C +Y face has to be kept between 0 and 23.5 deg, as it is always the case in the nominal FPM attitude. To fulfil these constraints in OTM with backup thrusters, the range of S/C local solar times for manoeuvre execution was limited to a +/- 100 minutes orbit arc around the S/C local noon and midnight, as shown in Fig. 14.

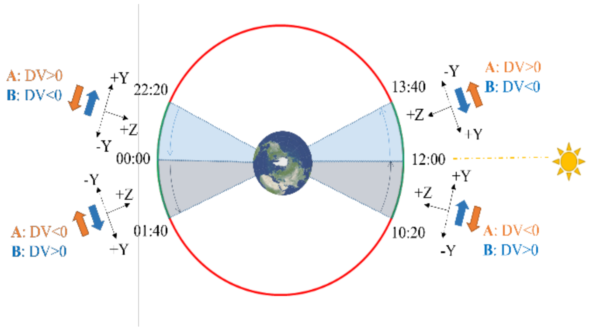

Fig. 14. Sun illumination constraints on S/C Y-axis for OTM using backup thrusters set (A/B). Manoeuvres can only be executed on the green orbit arcs.

A set of backup strategies to ensure the safety of MTG-I1 and the active geosynchronous satellites in its vicinity (found in the public TLE catalogue) was generated as part of the analysis, including pre-defined decisions in case of abortion or delay on the execution of any of the drift-start or drift-stop burns at any point within the manoeuvre sequence. The robustness of the strategy against the manoeuvre performance errors in OTM was assessed, with the conclusion that performance errors within +/- 2.5% in the execution of the drift-start manoeuvres were resulting on a drift-rate compatible with the drift-stop imposed execution times by the illumination constraints. Outside this performance range an additional drift-rate correction manoeuvre was required. The selected drift-rate for the relocation was 0.5 deg/day with an overall drift duration of 6.5 days. This drift rate is achieved by lowering the semi-major axis by 39 km. Based on this set of constraints an initial manoeuvre plan was generated (see Table 2). This plan was used as input to an extensive operational validation campaign at EUMETSAT before the actual start of the relocation operations.

Table 2. Planned relocation manoeuvre sequence.

Manoeuvre	Midpoint UTC time	Delta-v (m/s)
Drift-Start 1	2024/01/23 23:00	-0.6030
Drift-Start 2	2024/01/24 11:00	-0.7810
Drift-Stop 1	2024/01/30 11:02	0.7160
Drift-Stop 2	2024/01/30 23:00	0.7160

Operations during a relocation are conducted with the S/C in Sun pointing attitude, this is, in AOCS mode SAM instead of FPM. The transitions to the OTM attitude for manoeuvre execution had to be guided by ground, entering an AOCS mode called Guidance Attitude Mode (GAM). The attitude in GAM is managed by the RWs in close loop with the GYR and STR. In this mode, as in OTM, the S/C attitude profile is computed by the FDS on-ground and sent to the S/C. The generation of this attitude profile has to verify a number of constraints including, not only the S/C Y-axis illumination constraints mentioned before, but also constraints on the angular velocity and its derivative during the attitude slew, RW maximum and minimum speeds, on-board S-band antennas visibility from ground stations and exclusion angles of the Sun and Earth directions with respect to the STRs and the FCI FoV.

Relocation operations started with the transition from FPM to SAM on 2024/01/19-12:25:00 UTC. This transition time was selected because at this time, close to the S/C local noon, the nominal FPM attitude (S/C +Z-axis towards a point on the Equator) is close to the SAM attitude (S/C -Z-axis towards the Sun). Shortly after the transition, at 2024/01/19-14:20:00 UTC a RWOL in SAM was commanded to bring the RW speeds evolution to values within the required range to perform the transition to the OTM attitude for the first drift-start manoeuvre. After stable acquisition of the Sun pointing attitude, the FD team had to determine the actual S/C rotation phase around the S/C Z-axis; this is needed to generate predictions of the on-board S-band antennas visibility from the ground stations TTC1 and

TTC2 (as explained in section I.A). These predictions were generated and provided to the Ground Stations Operations Team during the whole relocation period after every transition to SAM, as input to perform uplink polarization switches. Additionally, the frequency of ranging measurements was increased from 60 to 20 minutes during the relocation to increase the likelihood of receiving at least one ranging measurement every 60 minutes, despite having any issues when performing the polarization switches at the S-band stations. After calibrating the small orbital velocity change imparted by the RWOL in SAM, the FD Team re-optimized the complete relocation manoeuvre sequence, without any significant change with respect to the original sequence shown in Table 2.

The FD input parameters for the population of the telecommand sequence for the drift start burns, including the manoeuvre and the guided attitude profiles for the transition SAM-GAM-OTM, were generated and checked with a set of independent quality assurance tools 24 hours before the first drift-start burn. Even though preliminary orbit determinations after the execution of the drift-start burn-1 were planned, the approach to the manoeuvre execution did not contemplate the possibility to re-plan the drift-start burn-2 in the 12 hours between burns.

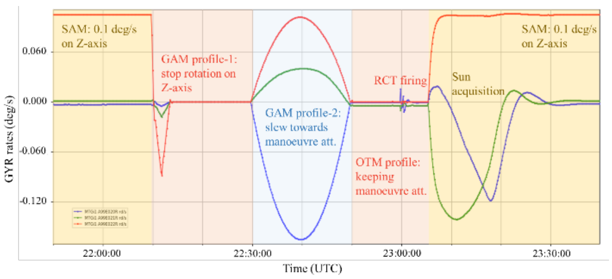

Fig. 15. GYR rates monitoring during drift-start burn-1 on 2024/01/23. Guidance attitude segments and SAM highlighted in different colours.

The relocation manoeuvres were performed with the primer thruster set C. The main activity of the FD Team during the relocation burns was to monitor the attitude transition by checking the S/C rates and comparing the attitude computed on-board by the STR with the ground modelled one. The GYR rates during the drift-start burn-1 are shown as example of this monitoring in Fig. 15. An alternate ranging campaign was commenced after the first drift-start burn for 36 hours. The OTSP was also requested to provide data around the two burns. This data made possible an accurate calibration of the drift-start manoeuvres. This calibration, as well and the manoeuvre reconstruction from the thruster activity received in TM, showed nominal performance results, as shown in Table 3.

Table 3. Calibration of relocation manoeuvre sequence.

Along-track dv (m/s)	Planned	Commanded	Determined	Difference with respect to Plan (%)
Drift-Start 1	-0.6030	-0.6108	-0.6045	+0.25%
Drift-Start 2	-0.7810	-0.7911	-0.7828	+0.23%
Drift-Stop 1	0.7160	0.7235	0.7161	+0.01%
Drift-Stop 2	0.7160	0.7235	0.7171	+0.15%

This good performance was achieved by applying scale factors for the delta-v during the preparation of the manoeuvre command inputs. For the drift-start burn the scale factor was extrapolated from the Station Acquisition manoeuvres performed at the end of the LEOP; for the preparation of the drift-stop burns the scale factor derived from the drift-start manoeuvres was applied. No additional manoeuvres to adjust the resulting drift-rate was required. The drift-stop burns were executed on 2024/01/30 after a 6.5-day drift period, following the same approach described for the drift-start manoeuvres. For these manoeuvres, the FD Team generated inputs for the manoeuvre commands for both prime and backup thruster sets, since in case of detecting any issue with the prime thrusters it was essential to keep the manoeuvre execution times to stop the longitude drift. The drift-stop manoeuvres were nominally performed with thruster set C. The final transition from SAM to FPM took place on 2024/02/02-13:23 UTC followed by the commanding of the pointing elements for the Ka-band antenna, marking the end of the relocation operations.

The first EWSK manoeuvre at its Routine Phase longitude was performed on 2024/03/13. The complete MTG-I1 longitude evolution starting before relocation is shown in Fig. 16. The full orbit control concept (including the control of the orbital plane orientation through the execution of NSSK manoeuvres) will start at the end of June 2024, based on the execution of manoeuvres at fixed dates, every 56 days.

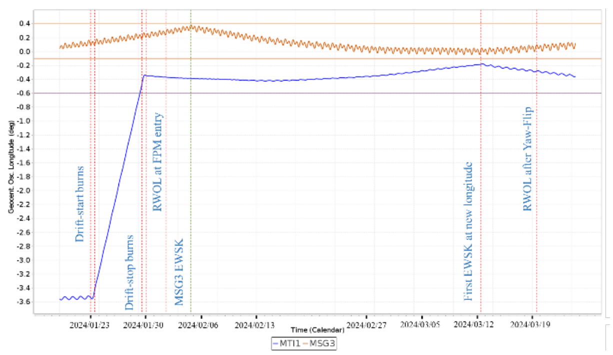

Fig. 16. Longitude evolution of MTG-I1 and MSG3 since the start of the MTG-I1 relocation campaign.

MTG-I1 will follow this orbit control until the end of the Commissioning Phase of the first sounder MTG-S1, currently planned to happen during the first half of 2026. At this time MTG-S1 will be relocated to join MTG-I1 at the longitude box close to zero degrees, flying in collocation driven by eccentricity - inclination separation.

VI. References

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[2] S. Pessina, J.M. De Juana, J. Fernandez, D. Lazaro, P. Righetti, "Operational concepts refinement for the orbit determination of MTG", Proceedings of the 23d International Symposium on Flight Dynamics (ISSFD).