Combined Orbit Raising and Spin Rate Reduction during Meteosat-8 End of Life Re-orbiting

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***Abstract* – This paper illustrates the orbit manoeuvre sequence performed during Meteosat-8 End of Life (EOL) re-orbiting operations and the manoeuvre strategy concept followed to abandon the geostationary ring, depleting all the remaining propellant still available in the tanks, after more than 20 years in orbit. While the implemented sequence of Meteosat-8 EOL re-orbiting burns aimed essentially at increasing as much as possible the orbit height, part of the manoeuvres were performed using asymmetrical thrusts, which achieved also a simultaneous reduction of the satellite spin rate, as additional passivation measure, to mitigate the risks of the satellite break up and fragmentation in the disposal orbit. The execution of the re-orbiting operations allowed to observe for the first time the actual behaviour of the Meteosat Second Generation (MSG) satellite platform during some of the critical phases, such as the run out of propellant and the venting of the residues and the pressurant gas. Lessons learned during the re-orbiting operations of Meteosat-8 are going to be applied to the planning of the disposal operations for the remaining three MSG satellites still in orbit, as they are going to be progressively replaced by the Meteosat Third Generation (MTG) satellites.**

I. Introduction

Launched in August 2002, Meteosat-8 was the first in the Meteosat Second Generation (MSG) series of geostationary weather satellites, operated by the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT). Meteosat-8 provided initially weather monitoring coverage over the European/African region and later, after moving to a position at 41.5°E longitude in 2016, took over the Indian Ocean Data Coverage (IODC) service. During 2022 it was replaced in that role by Meteosat-9 and then finally decommissioned in October 2022. The paragraphs below illustrate the details of the planning and execution of the End of Life (EOL) re-orbiting manoeuvre sequence, which was aimed at ensuring a safe transition into a disposal "graveyard" orbit, in compliance with [1]. Furthermore, a satellite spin rate decrease was to be achieved, to reduce the risk of a satellite break up, once in the disposal orbit.

II. Satellite Description

The spin-stabilised MSG satellites have a launch mass of 2,036 kg [2] and, after completing their transfer from the initial Geosynchronous Transfer Orbit (GTO) to the Geostationary Earth Orbit (GEO), they have a nominal design lifetime of 7 years [3]. A system of six 10 N Reaction Control Thrusters (RCTs) is available for orbit and attitude adjustments in GEO. A schematic representation of the layout of the thrusters, mounted on the 3.2 m diameter cylinder of the satellite main body, is provided in Fig. 1.

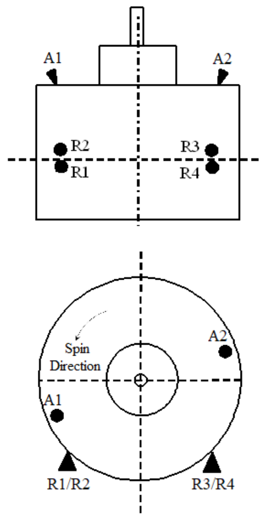

Fig. 1. *Position and orientation of the 10 N thrusters.*

During routine operations, the satellite is spinning at a spin rate of 100 rpm around the main body cylinder axis (or z-axis), which is kept perpendicular to the orbit plane. In-plane orbit corrections are therefore possible, using spin-synchronised pulsed burns of the R (or radial) thrusters, while continuous firing of the A (or axial) thrusters allows for out-of-plane orbit corrections.
The bipropellant propulsion system of the MSG satellites uses Mono-Methyl-Hydrazine (MMH), as fuel, and Nitrogen-Tetroxide with 1% Nitrogen-Monoxide (MON-1), as oxidiser [3].
Fig. 2 illustrates the utilisation of the Meteosat-8 onboard propellant during its routine phase in GEO. A considerable extension of the satellite lifetime was achieved by opportunely ceasing active orbit inclination control in 2010 and continuing operating the satellite at higher orbit inclinations. At that point, the decision was made to target reaching EOL, after achieving an orbit inclination of 8 degrees and having spent around 20 years in orbit.

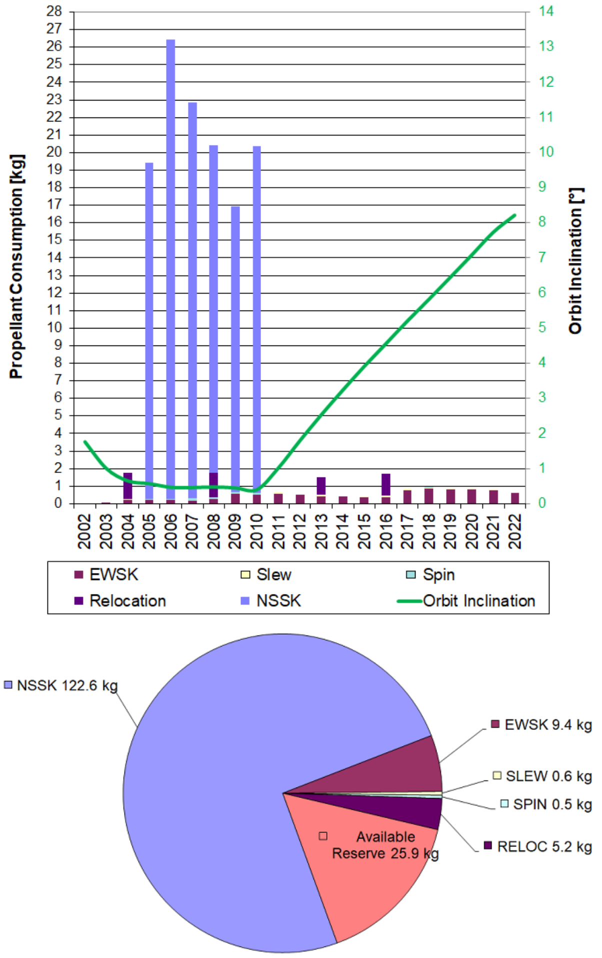

Fig. 2. *Meteosat-8 propellant consumption during routine operations in GEO for North/South Sation-Keeping (NSSK), East/West Station-Keeping (EWSK), attitude slew (SLEW) and spin rate (SPIN) adjustments and station relocation manoeuvres (RELOC).*

III. Required Minimum Altitude of the "Graveyard" Orbit

According to [1], the orbit state after disposal manoeuvres shall satisfy one of the following conditions:

a) the orbit has an initial eccentricity less than 0.003 and a minimum perigee altitude *ΔH* (in km) above the geostationary altitude, in accordance with:

$$\Delta H = 235 + \left(1000 \cdot C_R \cdot \frac{A}{m}\right) \qquad (1)$$

where C_R is the solar radiation pressure coefficient and *A/m* is the aspect area to dry mass ratio (in m^2/kg).

b) the orbit has a perigee altitude sufficiently above the geostationary altitude that long-term perturbation forces do not cause the spacecraft to enter the GEO protected region within 100 years after its end of life.

The GEO protected region extends +/-200 km from the geostationary altitude, in the latitude range between 15° south and 15° north.

For MSG satellites the cross-section area measures 8.475 m^2, while the determined average value over one year of C_R is 1.2. The satellite mass with empty propellant tanks is 1054 kg. The resulting average effective cross-section to mass ratio is then:

$$C_R \cdot \frac{A}{m} = 1.2 \cdot \frac{8.475}{1054} = 0.009649 \text{ [m}^2\text{/kg]}$$

The minimum perigee altitude above GEO required for the re-orbiting of an MSG satellite, according to (1), becomes therefore:

$$\Delta H = 235 + 1000 \cdot 0.009649 = 244.6 \text{ [km]}$$

IV. Spin Rate Reduction

Due to the 100 rpm nominal spin rate, the satellite structure is constantly subject to high loads, in particular on the periphery of the 3.2 m diameter cylinder of the main body. To mitigate the risks of a satellite break up and fragmentation in the disposal orbit, it was therefore decided to target a substantial reduction of the satellite spin rate, as part of the passivation at EOL. As already successfully demonstrated during the re-orbiting of the last three satellites of the Meteosat first generation series (Meteosat-5 in 2007 [5], Meteosat-6 in 2011 and Meteosat-7 in 2017), the spin rate reduction can be efficiently obtained, performing the pulsed orbit raising burns with an unbalanced radial thruster selection. For an MSG satellite, firing thruster R2 alone would for example provide the desired spin-down effect (see also Fig. 3). The spin-down effect during the firing of the R2 thruster, for a total time t_{ON} can be calculated as:

$$\Delta\omega_{[\text{rpm}]} = t_{ON[s]} \frac{T_{R2[\text{Nm}]}}{I_{zz[\text{kgm}^2]}} \cdot \frac{30}{\pi}$$

where, for a thrust F_{R2} provided by the R2 thruster, the torque around the satellite z-axis is:

$$T_{R2[\text{Nm}]} = -1.202_{[\text{m}]} F_{R2[\text{N}]}$$

and, for a number of pulses n:

$$t_{ON[s]} = n \cdot \delta t_{Pulse[s]}$$

For pulsed burns, the pulse duration, δt_{Pulse}, is normally set to 0.1 seconds, but can be also adjusted for example to higher values, when the satellite spin rate is significantly lower than nominal. In this way, the required number of pulses to achieve a certain delta-v can be reduced.

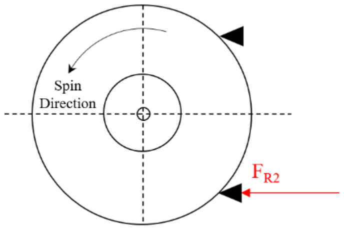

Fig. 3. *Force generated by thruster R2, providing a spin-down effect.*

A short rehearsal burn was executed in flight on 31 August 2022, to validate the approach end-to-end. The test burn consisted in firing the R2 thruster for 9 pulses (with nominal pulse duration of 0.1 seconds), achieving a delta-v of 0.0075 m/s in the desired direction and a spin rate reduction of 0.075 rpm.

V. Basic Principles and Objectives

A number of tangential orbital burns, separated by half of the orbit period, can be performed in order to increase the orbit height.

The strategy for the EOL re-orbiting manoeuvre sequence for Meteosat-8 followed the basic principles listed below:

- Achieve final circular or low eccentricity (e<0.003) orbit with maximum possible height above GEO (minimum perigee height: 244.6 km above GEO);
- Reduce satellite spin rate (to around 20 rpm);
- Deplete all the propellant left in the tanks;
- Minimize the time required to complete the re-orbiting manoeuvre sequence and allow sufficient time (about 7 days) to complete subsequently the rest of the de-commissioning operations, while still in visibility of one of the available ground stations.

Additionally, the following practical assumptions are considered for the implementation of the manoeuvre sequence:

- To achieve the minimum required perigee height using the normal thruster configuration: this is the best characterised configuration and therefore allows achieving accurately the targeted minimum disposal state;
- To limit the spin-down effect (i.e. manoeuvre size) of each single-thruster burn to -12 rpm: this is to ensure the good efficiency of the orbit raising thrust and, at the same time, to allow to bring the spin rate to a non-nominal range in a gradual way, providing sufficient time to monitor the achieved state;
- To gradually adjust the pulse duration to the average spin rate foreseen during the burn: this allows to minimise the duration of the individual manoeuvres;
- To avoid going below 20 rpm: this minimum spin rate is assumed to be required for a sufficiently stable state.

VI. Manoeuvre Sequence Planning

Considering the basic principles listed above, a reference sequence of burns was elaborated and simulated on the Flight Dynamics System (FDS).
Table 1 summarises the computed details for 12 manoeuvres, distributed over a period of about 5 days. A schematic overview of the sequence of orbit raising thrusts is shown in Fig. 4.

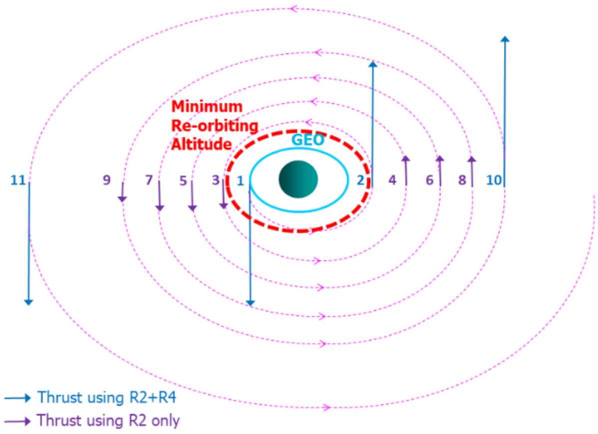

Fig. 4. *Schematic overview of the sequence of planned orbit raising thrusts (figure not drawn to scale).*

The last manoeuvre listed in Table 1 does not contribute to the orbit raising and is needed only to deplete the propellant tanks as quickly as possible. Depending on the actual remaining propellant mass, the last burn was expected to terminate prematurely at tank depletion of one of the two propellants. If tank depletion would not have occurred before the planned burn end time, the last manoeuvre was to be repeated a second time, until eventually reaching tank depletion. Further activations of the thruster valves were planned after that, to vent the residues of propellant and the pressurant gas (Helium), completing the passivation of the propulsion system.

Table 1. Meteosat-8 Reference Re-orbiting Sequence.

Burn	Midpoint (elapsed time from Burn-1 Centroid) hh:mm:ss	ΔV [m/s]	Used RCT(s)	N. of Pulses	Pulse Duration [s]	Prop. Cons. [kg]	Final Spin rate [rpm]	Final Height above GEO [km]
1	00:00:00	4.500	R2+R4	2731	0.100	1.997	99.8	0x253
2	12:01:11	4.500	R2+R4	2734	0.100	1.994	99.7	247x254
3	24:05:32	1.112	R2	1360	0.100	0.492	88.0	248x314
4	36:10:39	1.112	R2	1379	0.100	0.496	76.2	309x315
5	48:16:34	1.112	R2	1352	0.100	0.483	64.6	310x376
6	60:23:15	1.112	R2	1397	0.100	0.497	52.7	371x377
7	72:30:43	1.112	R2	660	0.200	0.474	41.4	371x438
8	84:38:58	1.112	R2	725	0.200	0.519	28.9	433x438
9	96:48:00	0.729	R2	423	0.200	0.302	21.7	433x479
10	108:57:32	5.400	R2+R4	876	0.350	2.829	21.6	477x737
11	121:10:53	4.375	R2+R4	711	0.350	1.761	21.5	725x735
12	126:15:00	32.526	A1+A2	1	1800	12.370	20.7	721x731

VII. EOL AND RE-ORBITING DECISION

Following the termination of all services provided by Meteosat-8 and completing a last series of EOL technology tests, aimed at trying out special satellite functionalities, that could be relevant to improve the operations of the remaining MSG satellites, it was decided to proceed with the final disposal and passivation operations. At the end of September 2022 Meteosat-8 lifetime in orbit exceeded 20.1 years and the orbit inclination reached 8.2°. The estimated remaining propellant onboard was 25.9 kg (equivalent to 2.7% of the initial mass loaded at launch). For a successful disposal, at least 4.0 kg of propellant would be required, to achieve the minimum separation from the GEO arc. The propellant gauging uncertainty error for the MSG satellites, using the bookkeeping method, was analysed in [6] and estimated in up to +/-14.3 kg at EOL. Even considering additional vapour losses and hold-ups in propellant lines (estimated in a total of 4.3 kg), it was concluded that the mass error tolerance margin was relatively comfortable, but also appropriate for the first re-orbiting to be attempted in a satellite family. The disposal operations would involve for example observing for the first time the MSG satellite behaviour during the run out of propellant and the subsequent venting of the residues and the pressurant gas. Furthermore, the general ageing of the satellite onboard equipment and a series of issues, some also related to the displacement of parts of the thermal insulation material, in one case, blocking the R1 thruster, and in another, partially obstructing the onboard sun sensors, contributed to the decision to retire the satellite. Sufficient reserves were ultimately also needed to be able to cope with contingency situations, potentially arising during the disposal operations. The EOL re-orbiting manoeuvre sequence was then finally set to start on 06 October 2022, following the end of the autumn eclipse season for Meteosat-8. The disposal operations were expected to last for about 8 days in total, 5 days for the re-orbiting manoeuvres and 3 days for the passivation operations and final switch off.

For the period covering the manoeuvre sequence execution, an intensified conjunction screening approach was agreed in advance with EU Space Surveillance and Tracking (EU SST), in order to coordinate dedicated daily ephemeris uploads for screenings, in parallel with the routine screenings provided by space-track.org. The prompt provision of updated screening results would allow to identify ahead of time the need of adjustments in the planned re-orbiting burns, to avoid potential hazardous close approaches.

VIII. EXECUTION OF THE RE-ORBITING MANOEUVRE SEQUENCE

The first two burns of the EOL re-orbiting manoeuvre sequence, using a balanced pair of radial thrusters (R2+R4), were executed successfully and according to the planning, respectively at 08:46 UTC and 20:47 UTC, on 06 October 2022. The orbit determination results of the manoeuvre performance assessments showed that both burns were very nominal (slight overshoot, within 0.5% of the planned magnitudes), achieving an essentially circular orbit, 248 km above the GEO height. On 07 October 2022 however, the execution of the third burn in the re-orbiting sequence, the first one planned to use a single radial thruster (R2), and scheduled to start at 08:58 UTC, had to be cancelled at the last moment, due to a problem at one of the two available ground stations. As a precautional measure, both stations were required to be available and fully functional during critical operations, such as the execution of the re-orbiting burns. Having achieved a satisfactory orbit, the decision was then taken to put the re-orbiting sequence temporarily on hold, until the meanwhile identified software issue at the ground station could be finally resolved. As soon as both stations were again operational, it was possible to resume the re-orbiting sequence on the same day, in time for the originally scheduled Burn-4. To save time, the magnitudes of Burn-4 and Burn-5, executed respectively on 07 October 2022 at 20:58 UTC and 08 October 2022 at 09:01 UTC, were both increased by about 50%, compared to the

original planning. This allowed then to essentially catch up again with the originally planned orbit raising sequence from Burn-6 onward. The orbit raising Burn-6 (on 08 October 2022 at 21:11 UTC), Burn-7 (on 09 October 2022 at 09:23 UTC) and Burn-8 (on 09 October 2022 at 21:28 UTC) were executed with the originally computed manoeuvre parameters, achieving the planned combined orbit raising and spin-down of the satellite.
An adjustment of the size of Burn-9 (on 10 October 2022 at 09:36 UTC) was however performed, to allow reaching more accurately the end spin rate (21 rpm), expected for the remaining larger final burns. Burn-10 (on 10 October 2022 at 18:38 UTC) and Burn-11 (on 11 October 2022 at 06:22 UTC), which used again a balanced pair of radial thrusters (R2+R4), could be then executed with the manoeuvre parameters of the original planning, including the calculated phasing for the pulse synchronisation, to achieve the correct tangential direction of the thrusts. Fig. 5 shows the evolutions observed in the satellite spin rate and Solar Aspect Angle (angle between the satellite spin vector and the vector pointing to the Sun) across the complete manoeuvre sequence of the Meteosat-8 EOL re-orbiting.

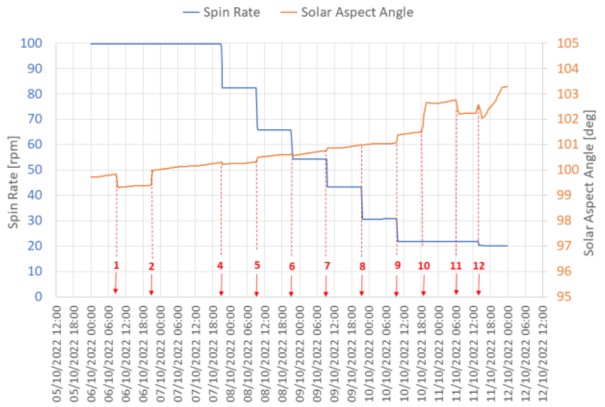

Fig. 5. *Satellite spin rate and Solar Aspect Angle variation during the EOL re-orbiting manoeuvre sequence.*

The determined manoeuvre performance factors and spin rate accelerations for the executed pulsed orbit raising burns, using the radial thrusters (R2+R4 or R2 alone) are shown in Fig. 6.
The orbit raising burns were followed by the final Burn-12 (on 11 October 2022 at 13:00 UTC), which was a continuous thrust, using both axial thrusters. The burn was commanded to last 30 minutes, but was expected to terminate prematurely at tank depletion of one of the two propellants. Propellant combustion stopped indeed about 19 minutes into the burn, when fuel (MMH) run out, while the FDS propellant bookkeeping was predicting still 3.0 kg of MMH and 4.2 kg of MON to be available. The propellant mass estimation errors found were in accordance with the expectations (+/-14.3 kg for the total of the combined masses of MMH and MON) and consistent with the accuracy assumptions, considered so far in the calculation of the projected propellant lifetimes for the remaining MSG satellites.

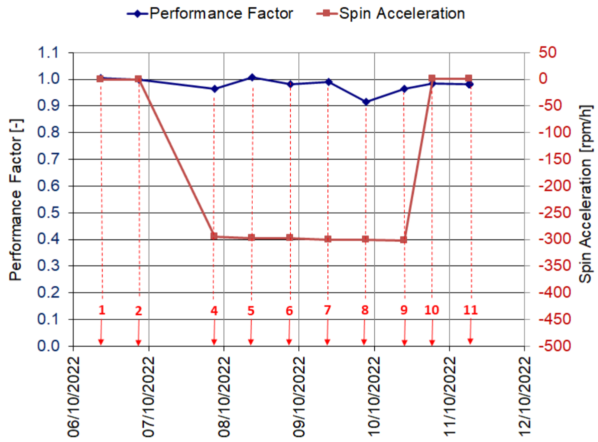

Fig. 6. *Determined manoeuvre performance factors and spin rate accelerations for the executed orbit raising pulsed burns.*

IX. Final Venting Operations and Achieved Disposal Orbit State

After reaching MMH tank depletion during Burn-12, the passivation operations continued almost immediately with the venting phase, which took about two days to complete. Operations during the venting phase were mostly driven by actual thermal conditions developing onboard, as the activation of the thruster flow control valves was associated with significant drops in temperatures, requiring immediate reaction, to avoid going below the allowed operating limits. A total of 481 thruster valve actuations were executed, of which 294 had to be manually stopped. Finally, the MMH and MON tank pressures dropped both below 2 bars, achieving their targeted passivation state.
The unpredictability of the disturbance forces during the 2-day venting phase meant that orbit determination could not be performed over that time interval and that the Burn-12 effect could not be properly assessed. However, based purely on the satellite attitude knowledge, determined using Earth and Sun sensor data, and the observed duration of the thruster firing, a simpler estimate could be made for the achieved orbit after Burn-12. For the final disposal orbit state, a quick assessment was then attempted, using measurements collected over a short undisturbed orbit arc, following the end of the venting phase. The measurement set included the last available ground station ranging data, before the switch off of the satellite transmitter, and the following night of optical directional observations, delivered by a telescope of the optical tracking network available to EUMETSAT (see also Fig. 7).
Table *2* summarises the main results obtained between the end of the sequence of orbit-raising burns and the final satellite disposal, revealing a significant

deterioration of the achieved orbit eccentricity (increase of 0.0015) and perigee height (reduction of more than 100 km), caused by the venting operations.

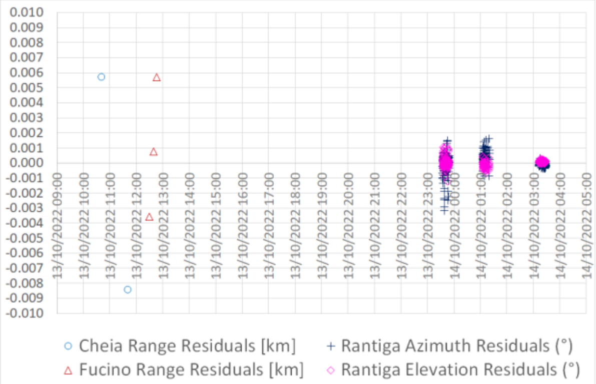

Fig. 7. *Meteosat-8 orbit determination measurement residuals.*

While larger than expected, the worsening of the final orbit state did not compromise the fulfilment of the requirement on the disposal orbit state. In any case, a more careful planning of the thruster valve activations during venting will be required in future re-orbiting operations of the remaining MSG satellites. A possibility, also under investigation, would be to try to use the thrust generated during the venting, to achieve part of the desired spin-down (the estimated potential spin rate reduction would be of about 22 rpm). This would in turn allow decreasing the number of manoeuvres to be performed, reducing the total duration of the re-orbiting sequence.

Table 2. Meteosat-8 estimated final orbit data and achieved disposal state.

	After Burn-11 (last orbit raising burn)	**After Burn-12** (South thrust to deplete tanks)	**Final Orbit State** (after passivation operations)
Epoch (UTC)	22.284.07.30.00	22.284.13.45.00	**22.290.00.00.00**
Semi-major Axis	42885.377	42887.109	**42842.379**
Eccentricity	0.0003929	0.0003013	**0.0017694**
Inclination	8.23°	8.63°	**8.61°**
Perigee Height above GEO	704 km	710 km	**602 km**
Spin Rate	21.9 rpm	22.0 rpm	**20.2 rpm**

Overall, the Meteosat-8 disposal operations went relatively smoothly. The planned duration to complete all the required activities, originally set to 8 days, proved to be however very demanding for the control centre team and, after achieving a satisfactory depressurisation of the tanks, the remainder of the passivation and switch off activities was moved forward, so that the disposal was essentially completed one day earlier than planned, about 7 days after the start of the re-orbiting sequence.

X. CONCLUSIONS

The Meteosat-8 EOL re-orbiting manoeuvre sequence was successfully completed over a 5-day interval, reaching the intended targets for the disposal orbit and final satellite spin rate. Single thruster pulsed firings were used to achieve a simultaneous orbit raising and spin rate reduction. The propellant mass estimation errors, found at tank depletion detection, were in accordance with the expectations and consistent with the bookkeeping method accuracy assumptions. A larger than expected disturbance was determined for the subsequent venting operations, which caused a reduction of the final perigee of more than 100 km. The determined final disposal orbit state remained in any case more than satisfactory, well exceeding the minimum perigee altitude requirement and with an eccentricity still perfectly within the allowed limit. To improve the results during future re-orbiting operations of the remaining MSG satellites, a better approach to cope with the venting disturbances is currently under study.

Overall, the Meteosat-8 disposal operations went relatively smoothly, but the duration required to complete all the activities proved to be demanding for the control centre team. The possibility, currently under study, of using the thrust generated during the venting, to achieve part of the desired spin-down, would allow for example to decrease the number of manoeuvres and therefore also the total duration of the re-orbiting sequence.

XI. ACKNOWLEDGMENTS

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