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End of Life Re-orbiting – The Meteosat-5 Experience

Milan Klinc
EUMETSAT, Darmstadt, Germany

This article illustrates the orbit maneuver sequence performed during Meteosat-5 End of Life (EOL) re-orbiting operations and the maneuver strategy concept followed to abandon the geostationary ring, depleting all the remaining fuel that was still left in the tanks, after more than 16 years in orbit. The targeted minimum height for the 'graveyard' orbit is calculated, according to the recommendations of the Inter-Agency Space Debris Coordination Committee (IADC), determining the mass of fuel to be allocated for the final re-orbiting maneuvers. A detailed strategy is elaborated to implement a sequence of burns and achieve the required disposal orbit, aiming also to a significant reduction of the satellite spin rate, as part of the satellite passivation and space debris mitigation measures.

Nomenclature

C_r	= Solar radiation pressure coefficient
ΔH	= Height above the geostationary altitude required for re-orbiting
Δv	= Velocity increment (delta-V)
e	= Orbit eccentricity
$GM_{\oplus}$	= Gravity potential of Earth (398600.440 km^3/s^2)
m	= Satellite dry-mass
M	= Initially estimated mass of fuel considered available at start of re-orbiting
m_c	= Consumed mass of fuel in re-orbiting maneuvers
r_{GEO}	= Geostationary orbit radius (42164.5 km)
S	= Satellite cross section area
v_{GEO}	= Geostationary orbital velocity (3.075 km/s)

I. Introduction

METEOSAT-5 was re-orbited from the geostationary orbit during April 2007. This was the first re-orbiting of a Meteosat satellite carried out from the EUMETSAT control centre in Darmstadt. The previous two Meteosat re-orbiting operations (Meteosat-3 and Meteosat-4) took place in November 1995, and were carried out by the European Space Operations Centre (ESOC), immediately prior to the handover of Meteosat operations to EUMETSAT.

The paragraphs below illustrate the details of the implemented maneuver sequence strategy for the Meteosat-5 re-orbiting at its End of Life (EOL). The aim of the re-orbiting operations was to ensure a safe transition into a disposal "graveyard" orbit, in compliance with the latest recommendations contained in the Space Debris Mitigation Guidelines (IADC-02-01) of the Inter-Agency Space Debris Coordination Committee (IADC).

II. Satellite Description

Meteosat-5 is a cylindrically-shaped spin stabilized satellite built by Aerospatiale (now Thales Alenia Space) in Cannes. Launched from Kourou, Franch Guyana, by an Ariane 4 launcher in March 1991, Meteosat-5 is the fifth of the first generation of European geostationary weather satellites and the second of the EUMETSAT's Meteosat Operational Programme (MOP) series of satellites.

The 282 kg dry-mass satellite is equipped with a hydrazine mono-propellant propulsion system and is initially loaded with 40 kg of fuel for a design lifetime of 5 years. Six thrusters provide the necessary forces and torques for orbit and attitude control maneuvers (see *Figure 1*). A pair of 10 N axial thrusters (A1 and A2) is located on the top surface of the main spacecraft body. They are directed parallel with the satellite spin axis and are used to change the spacecraft's attitude when used in pulsed mode, and to perform inclination maneuvers when used in continuous thrust mode. A second pair of 10 N thrusters (R1 and R2) is located at the side of the main body and is directed in the spacecraft spinplane at a slight offset from the spin axis. These thrusters are called radial thrusters. Fired simultaneously in pulsed mode, they are used principally for longitude control and relocation maneuvers. Two smaller 2 N vernier thrusters (V1 and V2), located near the pair of radial thrusters, provide satellite spin-rate control.

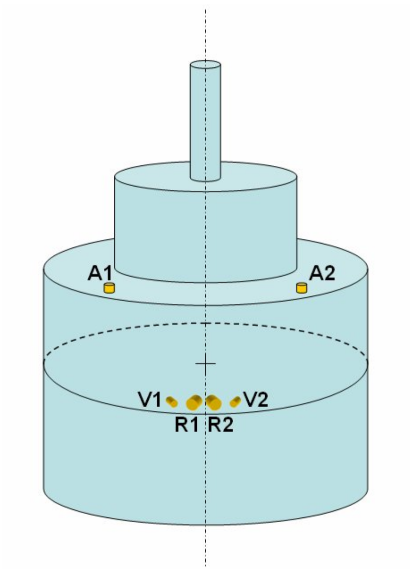

Figure 1. Meteosat Thruster Layout

The charts in *Figures 2A*, *2B* and *2C* summarize the history of Meteosat-5 maneuvers and fuel consumption. A significant extension to the originally foreseen 5-year lifetime was obtained by stopping the inclination control and continuing operations at higher orbit inclination. In April 2007 the orbit inclination of Meteosat-5 reached 9.1 degrees.

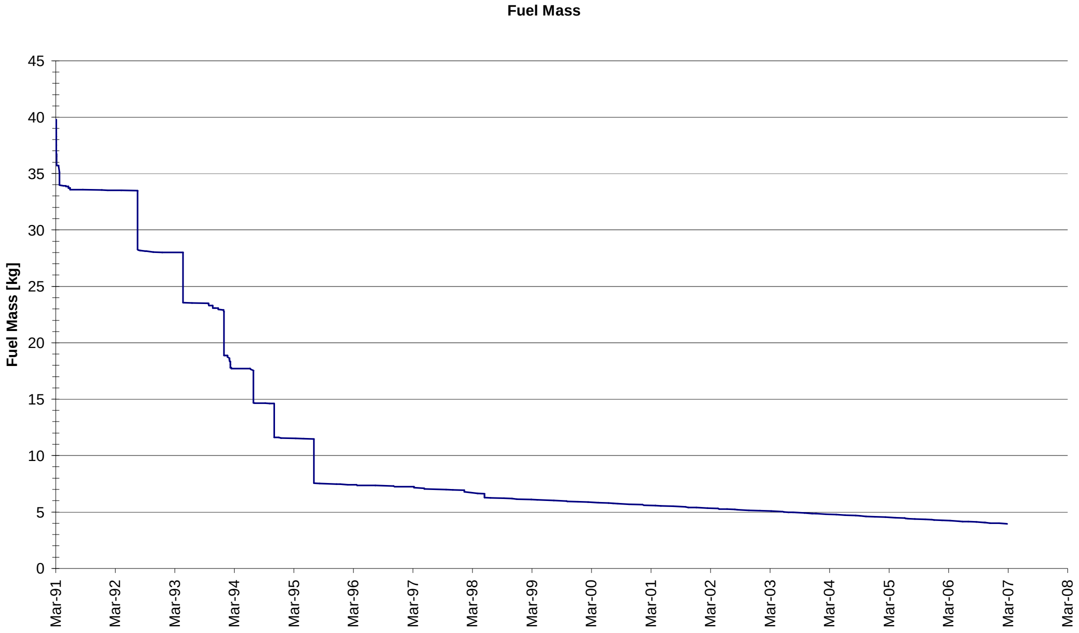

Figure 2A. Meteosat-5 History of Fuel Consumption before Re-orbiting

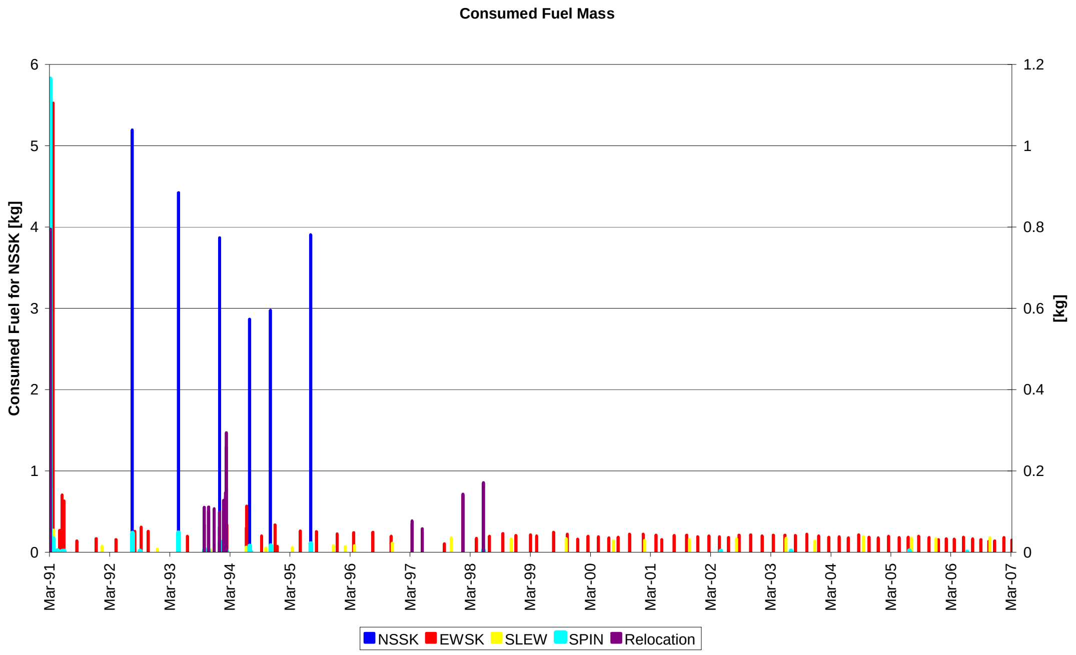

Figure 2B. Meteosat-5 History of Maneuvers before Re-orbiting

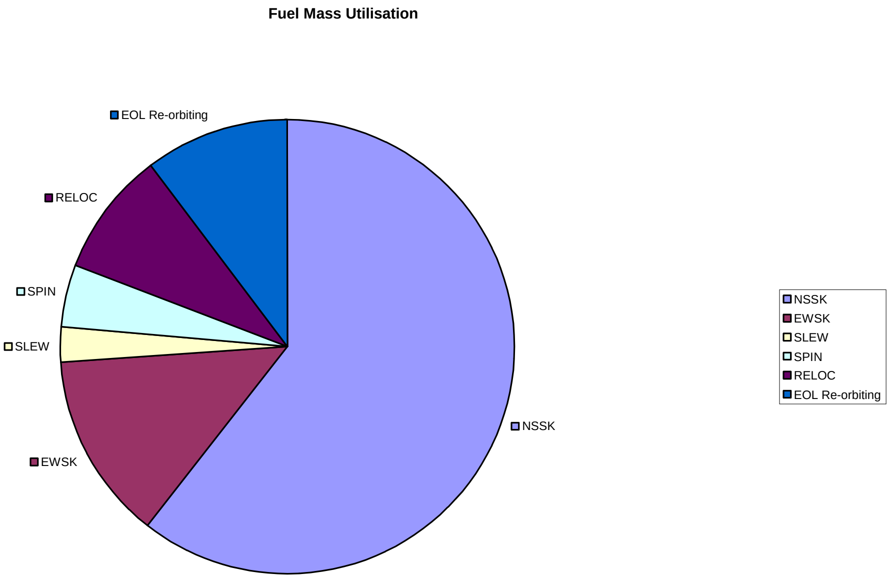

Figure 2C. Meteosat-5 Fuel Utilization

III. Required Minimum Altitude of the “Graveyard” Orbit

The recommendation from the IADC Space Debris Mitigation Guidelines for re-orbiting of Geosynchronous Earth Orbit (GEO) satellites is to reach a minimum perigee altitude above the geostationary altitude according to the following formula:

$$\Delta H_{[\mathrm{km}]} = 235 + 1000 \times C_r \times {}^{S}\!/_{m} \qquad [1]$$

where C_r is the radiation pressure coefficient of the satellite and *S/m* is the cross-section to dry mass ratio (in m^2/kg).

For the first generation Meteosat satellites the value of C_r is typically 1.1, while the cross-section area is 3.953 m^2. The dry mass of Meteosat-5 is 281.901 kg. The resulting effective cross-section to mass ratio is therefore:

$$C_r \times S/m = 1.1 \times \frac{3.953}{281.901} = 0.015 \qquad [2]$$

The minimum perigee altitude above GEO required for Meteosat-5 re-orbiting was then:

$$\Delta H = 235 + 1000 \times 0.015 = 250 \ \text{[km]} \qquad [3]$$

IV. Required Mass of Fuel for EOL Re-orbiting

The total velocity increment (delta-V) required to increase the orbit height by *ΔH* of an initially geostationary orbit can be formulated with the following expression, generally valid for small altitude raising maneuvers of circular orbits using the classical Hohmann transfer:

$$\Delta v = \frac{1}{2} v_{GEO} \frac{\Delta H}{r_{GEO}} \qquad [4]$$

where:

$$r_{GEO} = 42164.5 \ \text{[km]} \qquad [5]$$

and

$$v_{GEO} = \sqrt{\frac{GM_{\oplus}}{r_{GEO}}} = \sqrt{\frac{398600.440}{42164.5}} = 3074.648 \ \text{[m/s]} \qquad [6]$$

For the required altitude increase of 250 km, the relation gives then:

$$\Delta v = \frac{1}{2} 3074.648 \frac{250}{42164.5} = 9.115 \ \text{[m/s]} \qquad [7]$$

The velocity increment that can be generated by the propulsion system from a given amount of fuel can be derived from the thruster specific impulse measured during on ground testing. Furthermore, a performance factor calibration is determined after each orbital maneuver, measuring the actual velocity increment provided by the propulsion system. An extrapolated figure for the expected performance factor of the re-orbiting burns led to a specific impulse providing a delta-V of 4.809 m/s per kg of fuel. The required fuel to achieve the minimum target height of 250 km above GEO was then calculated as follows:

$$\frac{9.115_{[m/s]}}{4.809_{\left[\frac{\text{m/s}}{\text{kg}}\right]}} = 1.895_{\text{[kg]}} \qquad [8]$$

To take into account the uncertainty on the available mass of propellant in the tanks, one should consider also an additional reserve margin. Taking into account the outcomes of the past Meteosat re-orbiting operations (see Table 4), an uncertainty tolerance margin of +/-2.0 kg was assumed to satisfy appropriately any realistic expectation for the error in the determination of the propellant mass onboard. As a result, the latest possible time for re-orbiting Meteosat-5 was given when the estimated remaining propellant mass reached 1.9 kg + 2.0 kg = 3.9 kg.

V. Re-orbiting Maneuver Sequence

The strategy for the re-orbiting maneuver sequence followed the basic principles listed below:

- Deplete all the fuel left in the tanks;

- Achieve final circular orbit with minimum target height of 250 km above GEO for the worse case error of fuel reserve overestimation;
- Achieve final circular orbit with maximum possible height above GEO for the nominal case of estimated fuel reserve;
- Achieve final low eccentricity orbit (e<0.002) with maximum possible height above GEO for all intermediate cases or cases beyond the nominal fuel reserve estimation;
- Reduce satellite spin rate to mitigate the risks of a satellite break up and protect the GEO ring from particles generated by a hypothetical fragmentation in the disposal orbit;
- Minimize the time required to complete the re-orbiting sequence and allow sufficient time to complete de-commissioning operations, while still in visibility of the primary ground station.

In practice, for an initially estimated propellant mass M (>= 3.9 kg) considered to be available at the start of the sequence, the general strategy concept for the re-orbiting sequence consisted of sizing the individual burns to satisfy the cases in the table below:

After Consuming m_c [kg]	**Achieved Orbit**
$m_c = 1.9$	Circular orbit at least 250 km above GEO
$1.9 < m_c < M$	Low eccentricity orbit at maximum possible height above GEO
$m_c = M$	Circular orbit at maximum possible height above GEO
$m_c > M$	Low eccentricity orbit at maximum possible height above GEO

Table 1. Re-Orbiting Sequence Objectives

As already mentioned in the list of basic principles, in addition to the objectives of the above table, a reduction of the spin rate was to be performed as additional space debris mitigation measure. The satellite structure is permanently subjected to the centrifugal forces, which are proportional to the square of the spin rate. The reduction of this load should mitigate the risk of fragmentation over the very long term period.

The nominal spin rate for a Meteosat satellite during routine operations is 100 rpm. As part of the satellite passivation at EOL, the options for a spin rate reduction were investigated. A possibility to achieve at the same time the necessary orbit raising and a significant spin rate reduction was given by using the radial thruster R2 alone during most of the planned pulsed orbital burns (see *Figure 3*). This was an unusual thruster configuration, as all previous in-plane orbital burns had been performed using a balanced pair of radial thrusters R1 and R2. This innovative solution provided the desired spin rate reduction at no additional cost of fuel, without affecting the performance of the orbit raising maneuvers.

The EUMETSAT control centre in Darmstadt was originally designed to support only the satellite routine phase in orbit and particular care had to be taken in preparing the satellite control and monitoring system for operations at lower satellite spin rates and to allow the commanding of thruster configurations originally not foreseen for use in maneuvers.

A time delay relative to a reference signal, such as the Sun sensor pulse, is used on board the satellite to define the direction of the firing during pulsed maneuvers. The satellite spin period is however required to stay within the maximum delay value that can be stored into the phase count register onboard the satellite. Considering this constraint, it was computed that the spin rate had to stay above 51.1 rpm in order to fire the pulsed burns in all desired directions.

A sequence of seven burns was planned and executed, between the 16th and 19th of April 2007 (see *Figure 4* and *Table 2*). A spin rate of 54 rpm was achieved after the fourth burn and the sequence continued using the standard paired R1+R2 thruster configuration. The last burn terminated 5 minutes into the planned 13 minute duration, showing that no fuel was left in the tanks. The achieved minimum separation from the GEO ring of the final orbit was 500 km.

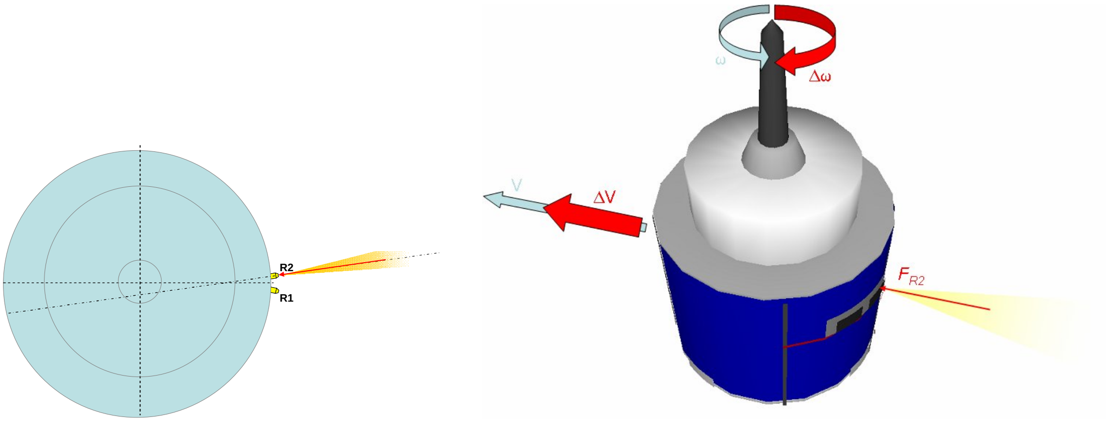

Figure 3. R2 Thruster Combined Effect on Orbit and Satellite Spin-Rate

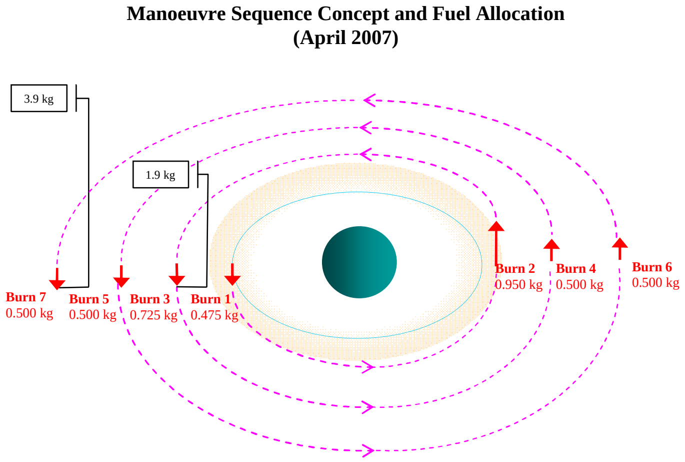

Figure 4. Meteosat-5 Re-orbiting Sequence Concept

Burn	Maneuver Start Time (UTC)	Thruster	Pulses	Final Spin Rate [rpm]	Determined Final Orbit Height [km above GEO]	Consumed Fuel Mass [kg]	Expected Fuel Reserve [kg]	Actual Fuel Reserve [kg]
1	16/04/07 05:50:05	R2	1922	91.03	-4x144	0.470	3.456	3.235
2	16/04/07 17:36:49	R2	3760	73.78	137x229	0.905	2.551	2.330
3	17/04/07 05:42:26	R2	2734	62.13	228x324	0.650	1.901	1.680
4	17/04/07 17:50:54	R2	1950	54.04	319x351	0.456	1.445	1.224
5	18/04/07 06:05:45	R1+R2	968	53.90	345x459	0.448	0.997	0.776
6	18/04/07 17:10:08	R1+R2	1425	54.02	456x541	0.651	0.346	0.125
7	19/04/07 05:27:01	R1+R2	275(*)	53.99	500x540	0.125	0.221	0.000

(*) Estimated pulses with hot firing. The planned number of pulses for Burn 7 was 721.

Table 2. Meteosat-5 Executed Re-orbiting Maneuver Sequence

An additional spin rate reduction was obtained after the re-orbiting sequence, during the pressurant venting operations, which were carried out mainly via the V1 thruster, generating the largest possible spin-down effect (see *Table 3* and *Figure 5*). This approach required however a longer time to complete the depletion of the gas and had to be carried out over several days. However, since the satellite was initially stationed over the Indian Ocean region, the visibility condition from the primary ground station in Fucino, Italy, for the west-drifting satellite remained favorable for several weeks. Thruster valves were opened in 10 separate venting operations and the last determined satellite spin rate was 45 rpm. Therefore, compared to the initial nominal spin rate, the centrifugal forces were reduced in total by 80%.

Tank Pressurant Venting	Thruster	Spin Rate Change [rpm]	Final Spin Rate [rpm]
1	V1	-3.82	50.17
2	V1	-0.63	49.54
3	A1+A2	-0.01	49.53
4	R1+R2+V1+V2	0.15	49.68
5	V1	-1.6	48.08
6	V1	-1.11	46.97
7	V1	-0.82	46.15
8	V1	-0.63	45.52
9	V1	-0.39	45.13
10	all	-0.01	45.12

Table 3. Spin Rate during Pressurant Venting Operations

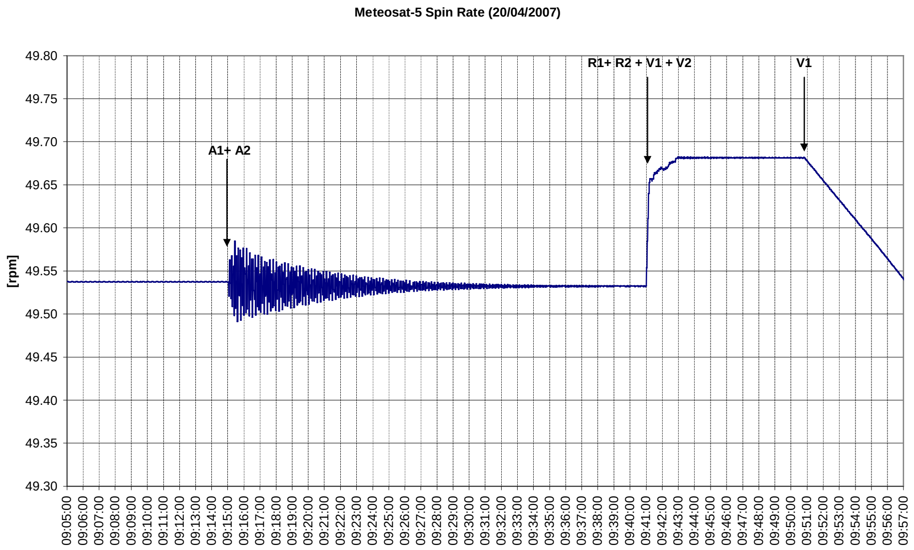

Figure 5. Spin Rate during Pressurant Venting Operations

Satellite	Re-orbiting from GEO Started on	Total Lifetime in GEO	Initial Fuel Mass (estim.)	Initial Fuel Mass (determ.)	Error in Fuel Mass (det.-est.)	Spin Rate after Re-orbiting sequence	Height from GEO at Perigee	Height from GEO at Apogee
Meteosat-2	02 Dec 1991	10.5 years	4.2 kg	2.3 kg	-1.9 kg	100 rpm	334 km	542 km
Meteosat-3	21 Nov 1995	7.4 years	7.0 kg	5.1 kg	-1.9 kg	100 rpm	940 km	977 km
Meteosat-4	09 Nov 1995	6.7 years	4.7 kg	6.1 kg	1.4 kg	100 rpm	852 km	973 km
Meteosat-5	16 April 2007	16.1 years	3.9 kg	3.7 kg	-0.2 kg	45 rpm	500 km	540 km

Figure 6. Re-orbiting Summary for Meteosat Satellites

The re-orbiting approaches illustrated above, implemented for the first time for the case of Meteosat-5, will be reused during future re-orbiting operations of the two remaining first generation Meteosat satellites, while most of the elaborated concepts and principles will remain valid also for the second generation Meteosat series.

VI. Conclusions

The Meteosat-5 EOL re-orbiting manoeuvre sequence, performed between the 16th and 19th of April 2007, placed the satellite into a safe disposal orbit, as planned. A combined effect of orbit rising and spin rate reduction was successfully achieved by using an unpaired single radial thruster for most of the executed orbital burns.

The achieved separation from the geostationary ring of 500 km, two times the required minimum set by the IADC, was mainly the result of the actual availability of almost all of the additional uncertainty margin fuel reserve, considered in the planning. The achieved orbit ensures therefore an even more effective protection of the geostationary ring, also against particles or fragments generated by a hypothetical break up of the re-orbited satellite. The risks associated with such scenarios were also minimized by the spin rate reduction, obtained performing part of the pulsed orbital burns with a single radial thruster (R2). Pressurant venting operations through the V1 thruster at the end of the maneuver sequence also contributed to reduce the spin rate to a final value of 45 rpm, decreasing the load of the centrifugal forces on the satellite structure by a total of 80%.

Considering the record total lifetime of the satellite, surpassing more than three times the 5-year design lifetime, and the sometimes completely new approaches followed to implement the sequence of re-orbiting operations, involving innovative spin rate reduction techniques and enhancements of the satellite monitoring and control system, the re-orbiting of Meteosat-5 served as an important experience for the planning of similar future operations for the two remaining Meteosat satellites of the first generation series. Moreover, most of the basic strategy concepts remain valid for the second generation series of satellites.