MISSION ANALYSIS FOR MSG-3&4 CONSIDERING COMBINED LEOP/STATION-KEEPING COSTS AND IN-ORBIT STORAGE

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Abstract: *The mission analysis for the four EUMETSAT satellites of the Meteosat Second Generation (MSG) programme has a core activity in the optimisation of the mission lifetime, according to different launch dates and times. For the various MSG launches (all based on Ariane-5 dual spacecraft configuration) these techniques have been progressively improved.*
For the first two satellites in the programme (MSG-1 and -2), the optimisation was mainly based on the LEOP cost and the role of the rotation of the orbital node, from the launcher separation orbit to the target geosynchronous orbit, that is very relevant due to the relatively wide 1º station-keeping nominal deadband , used for inclination control by MSG.
For MSG-3 onwards, the perigee of the separation orbit has been significantly lowered, to cope with space debris mitigation; to counteract this, and thanks to the operational experience acquired by EUMETSAT in routine operations, the cost of the station-keeping cost was considered in combination with the LEOP cost, for the lifetime optimisation.
MSG-4 additionally foresees an initial period of in-orbit storage that was not required for the other satellites, that has also been considered for the pre-launch mission analysis.
This paper will illustrate the principle adopted with particular focus on the mission analysis results for MSG-4, whose launch is currently scheduled for mid 2015, combining all the aspects of the mission analysis of the MSG programme.

Keywords: *Mission Analysis, Geosynchronous, LEOP, Station-Keeping, In-orbit storage*

1. Acronym list

MFG=Meteosat First Generation
MSG=Meteosat Second Generation
MTG=Meteosat Third Generation
LEOP=Launch and Early Orbit Phase
GTO= Geosynchronous Transfer Orbit
NSO=Near-Synchronous Orbit
GEO=Geosynchronous
RAAN=Right Ascension of Ascending Node
EPS=EUMETSAT Polar System
FD=Flight Dynamics
MA=Mission Analysis
FDS=Full-Disk Service
RSS=Rapid-Scan Service
IOS=In-Orbit Storage
AEF=Apogee Engine Firing
H/O=Handover (ESOC to EUMETSAT)

1. Introduction

EUMETSAT is the "EUropean organisation for the exploitation of METeorological SATellites". It is an independent intergovernmental organisation created in 1986 to establish, maintain and exploit European systems of operational meteorological satellites. It currently operates a system of meteorological satellites, monitoring the atmosphere and ocean and land surfaces which deliver weather and climate-related satellite data, images and products – 24 hours a day, 365 days a year (see [1]). EUMETSAT currently has seven operational weather satellites. Meteosat-7,-8, 9 and 10, Metop-A, -B and Jason-2. Meteosat are the satellites of the geosynchronous (GEO) fleet. There are two generations of active Meteosat satellites, Meteosat First Generation (MFG) and Meteosat Second Generation (MSG). Metop are low-Earth polar orbiting meteorological satellites which form the space segment component of the overall EUMETSAT Polar System (EPS). Jason-2 reliably delivers detailed oceanographic data vital to our understanding of weather forecasting and climate change monitoring.

Meteosat-7 (launched in 1997) is the last of the first generation of EUMETSAT Meteosat satellites; it currently operates over the Indian Ocean, filling a data gap over the region.
The current generation of satellites is the Meteosat Second Generation (MSG, see [2]), providing real time imagery with Earth Full-Disk Service (FDS, images every 15 minutes) and Rapid-Scan Service (RSS, every 5 minutes) from GEO orbit (see Figure 1).

Figure 1. MSG satellites, Earth Full-Disk (left) and Rapid-Scan (right) services

The programme foresees 4 satellites of this kind, spin-stabilised. Three of them are operational: MSG-1 launched in 2002, MSG-2 in 2005 and MSG-3 in 2012. MSG-4 will be launched in 2015, completing the programme, before the third generation (MTG) will take over the service.
The current configuration of the Meteosat satellites is shown in Tab.1; this will be re-arranged after successful launch and commissioning of MSG-4.

Table 1. Current Meteosat satellites

Satellite	Launch date, Lifetime	Longitude	Services
MSG-4	Launch mid 2015 Lifetime dependant on launch date	-	-
Meteosat-10 (MSG-3)	Launch 05/07/2012 Lifetime (nominal) until 2022	0°	Full-Disk Service Real-time Imagery
Meteosat-9 (MSG-2)	Launch 22/12/2005 Lifetime extended until 2021	9.5° E	Rapid Scan Service(9/Apr/2013) Real-time Imagery
Meteosat-8 (MSG-1)	Launch 28/08/2002 Lifetime extended until 2019	3.5° E	Backup service for 0° RSS gap-filling (9/Apr/2013)
Meteosat-7	*Launch 02/09/1997(IODC from 1/11/2006)* *Lifetime extended 2016*	*57° E*	*Indian Ocean Coverage.* *Real-time Imagery*

It is to be noted that the EUMETSAT GEO satellites are re-named after in-orbit commissioning, with a progressive Meteosat number: MSG-1 as Meteosat-8, MSG-2 as Meteosat-9, etc... In this paper only to the second generation will be addressed, therefore the naming before entry in routine operations (MSG-x) will be mainly used for simplicity. MSG-4, as a difference from the other spacecrafts, will be initially stored in orbit.

For all of them, the insertion to GEO is done starting from a standard Geosynchronous Transfer Orbit (GTO) achieved with an Ariane-5 dual-spacecraft launch. The LEOP service provider is ESA/ESOC in all cases; after LEOP, once the spacecraft reaches the agreed Near-Synchronous Orbit (NSO) conditions, a formal handover to EUMETSAT is performed. The EUMETSAT control centre becomes then responsible for the satellite commissioning, routine operations, relocations and decommissioning.

Differently than for the first Meteosat generation, which used a dedicated solid apogee kick motor in LEOP, the MSG series of satellites uses a Unified Propulsion System (UPS) supporting both, the LEOP and the routine orbit phase for all orbit and attitude control needs, from the separation from the launcher to the end of life disposal operations. This fundamental difference created the need to develop LEOP strategies focusing with particular emphasis on the optimal propellant consumption, considering also the impact on the allocations needed for the Station-Keeping during the routine phase in orbit.

2. Mission analysis tasks for the MSG satellites

The Mission Analysis for these missions is based on different sequential tasks:

a) design of the LEOP sequence for in-plane manoeuvres (re-startable propulsion system) for GTO circularisation, according to various constraints (e.g. double ground station coverage, time to reach the target longitude slot) ; this includes the analysis of backup strategies in case of missed major manoeuvres
b) selection for optimal propellant consumption of the orbital node rotation and orbital inclination change (from the transfer GTO orbit after separation with the launcher, to the near-geosynchronous NSO orbit)
c) launch windows definition to respect the MSG spacecraft limits (Sun-Aspect-Angle, eclipses, attitude determination accuracy)
d) accurate definition of the LEOP manoeuvres and of the timeline of Flight Dynamics (FD) operations, including spin maintenance, attitude manoeuvres and special operations (instrument covers ejection), also considering specific constraints from the co-passenger launch window

The task a), b), c) are performed in a phase of the mission preparation when the launch period (3-months) and launch date (first day of the period) are not defined yet, as well as the selection of the co-passenger on the Ariane-5 flight. Therefore, they involve the analysis of all potential launch dates and time over one calendar year. This is internally called Generic Mission Analysis.

Task d) is instead part of the so called Specific Mission Analysis, after assignment of both launch date and co-passenger.

The main focus of this paper is the pre-launch Generic Mission Analysis for optimization of the mission lifetime: this is driven by task a) and b).

The task a) for the design of the LEOP sequence for in-plane manoeuvres will be briefly introduced: among all different analyses performed here, the main input to the life-time estimation is the ΔV budget.
Related to task b), novel concepts have been studied for MSG-3 and further developed for MSG-4 to take into account the in-orbit storage period, and they will be the focal point of this paper.
Some mentions will be made related to task c), due to the impact of the strategy selection on the launch window assessment that is currently on-going. Task e) is outside the scope of this paper.

After the preliminary mission analysis, run by the spacecraft manufacturer (Thales Alenia Space, former Alcatel), the Generic/Specific Mission Analysis is run by the LEOP service provider (ESA/ESOC) with guidance and supervision from EUMETSAT, that has also actively participated in the activities for MSG-3/4, for the Station-Keeping cost analysis and combined propellant optimisation.

3. Apogee Engine Firing (AEF) strategy

The design of the engine firing strategy is a central task in the planning of LEOP operations. The separation GTO orbit has an apogee at NSO height and the perigee in low-earth orbit. The main purpose of the AEF manoeuvres in-plane strategy design is to increase the orbital energy (semi-major axis) in order to raise the perigee from the GTO to the final NSO orbit, with proper adjustment to reach the orbit/attitude conditions for handover from ESOC to EUMETSAT.
The essential and desiderable constraints driving the manoeuvres strategy design include:

- earliest first burn (to allow adequate preparation, not earlier than 4^{th} apogee passage after separation)
- double ground-stations coverage (required for critical operations such as major manoeuvres)
- separations among apogee firings (a minimum of two revolutions)
- maximum burn duration (1750 s)
- [desiderable] balanced burn duration (for progressive calibration of the propulsion system on similar manoeuvres)
- [desiderable] shortest LEOP duration (due to constraints on the launch window driven by the solar aspect angle, as well as to the solar array degradation in the Van Hallen belts, to the overall mission safety and to the financial cost of the LEOP)
- size of the final trim burn (bigger than 50 m/s for predictable manoeuvre performances)
- NSO orbit conditions (for safe drift to final longitude, adequate time for EUMETSAT ground segment preparation and spacecraft acquisition , planned orbital inclination drift)
- Safe release of the instrument and cooler covers outside the GEO ring

The three-burns strategy originally planned by the spacecraft manufacturer for MSG-1 included a long second burn and a third burn that is so short to be considered as a trim manoeuvre. The second long burn, when more carefully analysed in the LEOP preparation phase, showed operational difficulties, because it could result in over cooling of the helium in the pressure regulator. The LEOP service provider (ESA/ESOC) investigated a strategy based on three major balanced burns, with similar duration, followed by a final orbit trim (for full details, see [3]); as an example, the MSG-3 LEOP trajectory is shown in Figure 2.

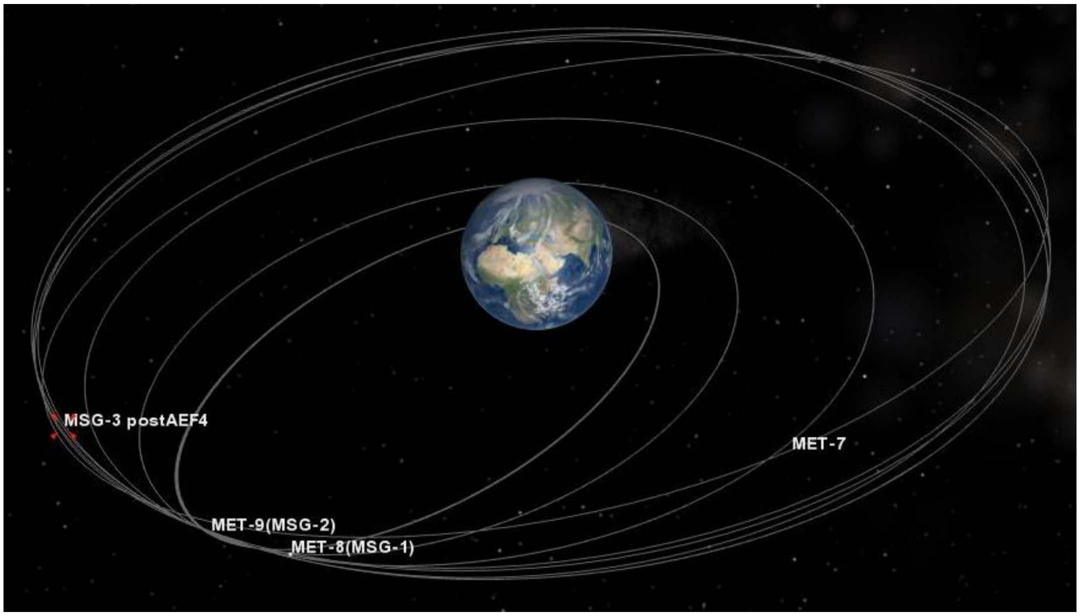

Figure 2. MSG-3 actual LEOP trajectory, after execution of the planned AEF strategy

The design of the AEF strategy involves the choice of the firing apogees and the semi-major axes of the intermediate orbits, to fulfil all the essential and desiderable constraints above mentioned.
The full strategy is made up of a nominal strategy and backup cases. The number of backup cases is equal to the number of firings in the nominal strategy as each backup case addresses the postponement of one of the burns. Each strategy case uses the same semi-major axes for the intermediate orbits whatever the launch date and time. This ensures that the same ground stations coverage pattern is achieved during the LEOP, which allows a single event sequence to be planned for all launch dates and times. The selection of the intermediate orbit semi-major axes is essentially the same as specifying the division of the total ΔV between the firing apogees.

Mostly relevant for this paper, from the point of view of the propellant optimisation, this allow considering the major contribution of the orbital energy change (in-plane component of the AEF manoeuvres) as a constant over one year. (There are small variations in the ΔV percentage allocated to the different burns as a function of the node rotation to be achieved for a particular launch date and time). The principal effects of the launch date/time selection are on the optimisation of the orbital plane change (inclination) and rotation (node shift) that will be analysed in the next sections.

An important point to address is the change of the GTO orbital parameters for the various MSG launches. Arianespace changed the standard GTO, to cope with space debris mitigation measures, to allow faster re-entry of launcher components. For MSG-3/4, the perigee height is significantly lower at 250 km rather than 580 km and 620 km respectively for the MSG-1/2 launches. The lower perigee height increases the amount of perigee rising to be achieved by the apogee engine firings, which it turn increases the LEOP propellant consumption.

Characteristic values of the propulsion system for all MSG spacecrafts are a nominal thrust (from both apogee engines together) 828.517 N, with a specific impulse of 3039.571 Ns/kg.

This can be used with the well-known Tsiolkovsky rocket equation below, to convert ΔV into propellant costs

$$m_p = m_0 *(1 - e^{-\Delta V/Cperf/g/Isp}) \tag{1}$$

where m_p is the spacecraft mass after a manoeuvre, m_0 the mass before, C_{perf} is the thrusters performance factor, g the gravity acceleration and I_{sp} the engine specific impulse.

Assuming the MSG-3/4 LEOP in-plane ΔV split strategy of the nominal AEF sequence (30.4%, 37.5%, 28.7%, 3.4% for AEF-1/2/3/4 respectively) and H/O drift orbit 150 km below the geostationary altitude (longitude drift ~2°/day eastwards at handover), the ΔV required for the orbital energy change only (GTO to NSO, no inclination or node change) is 1477.5 m/s, that translates into 802 kg propellant consumption for MSG.
The additional propellant required in the MSG-3/4 case with respect to MSG-2 higher GTO perigee is 15.0 kg which is approximately 0.8 years of spacecraft lifetime.

This triggered the need for an improved propellant optimisation, as it will be explained in the following sections. The main driver in the lifetime optimisation for MSG-1/2 was the minimisation of the LEOP cost only. To counteract the propellant penalties due to the lower GTO perigee, for MSG-3 the station-keeping consumption was also considered for selecting the NSO node, for a given NSO inclination. This has been further developed for MSG-4 due to the additional requirement of in-orbit storage, considering both NSO node and inclination as optimisation parameters.

4. Equinoctial inclination definition and drift

For GEO missions, it is convenient to express the orbital plane parameters using the equinoctial inclination vector that will be used in this paper in the True-Of-Date Earth Centred pseudo-inertial frame, with x-axis towards the vernal equinox (see Figure 3, left plot)

$$\mathbf{i}\,(i_x, i_y) = (i \sin \Omega, -i \cos \Omega) \tag{2}$$

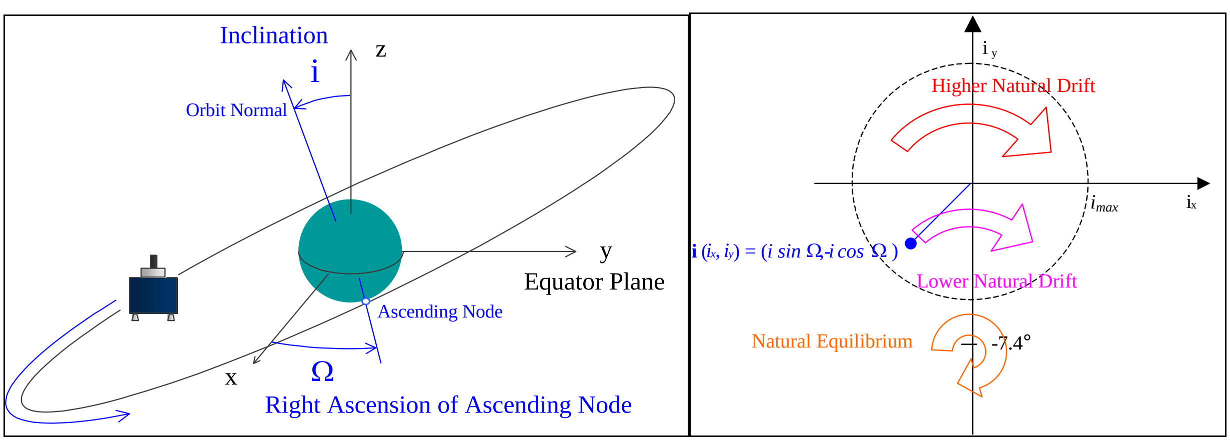

Figure 3. Definition of equinoctial inclination vector, and schematic explanation of its drift

For a GEO satellite, the orbital plane natural evolution results in a slow precession where the inclination vector initially drifts towards the vernal equinox, due to the combined effect of the Earth Geopotential (J2 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 around the natural equilibrium point (i_x=0, i_y=-7.4º), which is completed in 54 years. The natural drift rate of the equinoctial vector inclination is therefore affected by the location within the i_x i_y plane, and is faster when the distance from the equilibrium point is bigger, as it is schematically represented in the right plot of Figure 3. This is particularly relevant for the computation of the North/South Station-keeping cost, as it will be illustrated in the next section.

The inclination of MSG during routine operations has to be controlled within a 1º deadband, for a proper use of the payload within all design limits. This is represented with equinoctial inclination coordinates as a control circle of 1º radius, centred in the origin (see i_{max} circle in Figure 3, right plot). For MSG-1/2 the routine operation followed this control limit for the planning of the North/South SK manoeuvres.
However, the inclination limit is not mandatory for performing commissioning activities. This is way, the target inclination at the end of the LEOP is selected to be greater than the control limit, typically 1.8º, allowing the commissioning operations to take place and starting the routine phase when entering the control circle.
The selection of the NSO orbit node and inclination is also determining the initial point of the equinoctial inclination vector for the routine phase (that affects the station-keeping strategy, as mentioned before) but also the necessary orbital node rotation and inclination change (from GTO to NSO) and the subsequent LEOP manoeuvre direction design and cost, as it will be explained in the next section.

5. Preliminary analysis of IOS effect on NSO node and SK control

For MSG-4, the mission analysis purpose was the same as in previous launches (propellant minimisation) with specific target to minimise the losses coming from the additional requirement of 1.5 years of In-orbit Storage (IOS); for this, two ideas have been proposed, as a difference with respect to all previous MSGs:

- selection of a higher NSO inclination, to allow a longer natural drift (without inclination control) while the spacecraft is in the storage configuration
- the use of an increased inclination control circle during Station-Keeping of 2° instead of 1°, thanks to the experience with the payload operations at high inclination in lifetime extension of MSG-1 (after the execution of the very last North-South manoeuvre)

For the introduction of the IOS period, a set of values for the NSO inclination was found with different orbit propagations, to identify the envelope of the NSO conditions (RAAN=NSO node, and NSO inclination) that allows exactly 1.5 years drift before reaching an increased control cycle of 2°.
An NSO inclination of 3.1° was found to be the maximum of this envelope, while 2.2° was the minimum, as it can be seen in the thick blue line in Figure 4.

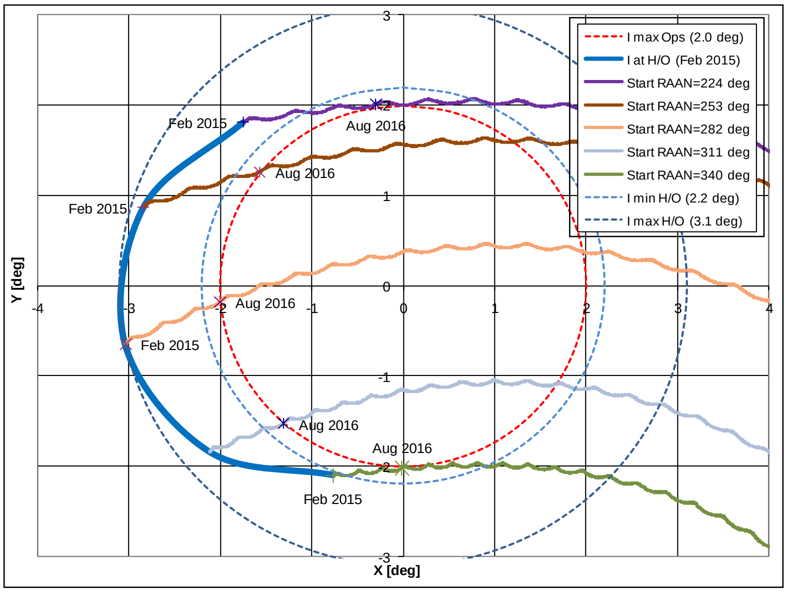

Figure 4. Natural inclination drift for IOS period of 1.5 years

With a fixed H/O inclination of 3.11º, the range of H/O RAAN values that allow to arrive to the control inclination circle of 2.0º by natural evolution, is restricted to RAAN values between 243º and 326º. The time until i < 2.0° ranges between 1.50 years and 3.53 years (for H/O RAAN values respectively of 282º and 326º).

Assuming a fixed value of the H/O inclination, it is to be noted that the natural drift time to the 2.0° inclination is depending on the RAAN at H/O, therefore on the launch date and time

6. Station-Keeping cost analysis with IOS

For the routine phase station keeping cost analysis, the following main objective is considered for the long-term inclination control strategy:

- Targeting 10.5 years until i > 2.0°(reduced inclination control): the advantages in selecting a larger inclination control circle, instead of the nominal one of 1°, was demonstrated. The 10.5 years are chosen to take into account 1.5 years of initial payload in-orbit storage, in order to have a total of 9 years of effective payload use.

Four inclination cases at H/O are considered for a direct comparison of the results:

- $i_{H/O}$ = 3.11°: this is the upper limit for having a minimum in-orbit storage period of 1.5 years before reaching the control circle.
- $i_{H/O}$ = 1.8°: this is the value used for MSG-3, therefore deeply studied already in the frame of MSG-3 generic mission analysis (see [3]). It is known from Figure 4 that 2.24° would be the lower limit, eventual penalties for using a lower value will be quantified hereafter.
- $i_{H/O}$ = 0.5° and $i_{H/O}$ = 0 °: these have been added to investigate the eventual advantages of further reducing the LEOP node rotation cost

Seven different starting values for the NSO node(RAAN) are used for the comparisons in an interval between 204° and 360°. For the cases where the natural inclination drift doesn't reach the 2° control cycle, North-South manoeuvres are executed, not before 1.5 years after H/O. This is applicable to $i_{H/O} = 3.11°$ only (for the others the routine phase after handover starts directly in the control circle) and only at the extreme values of the analysed RAAN interval .

An additional allocation of 10 m/s for other station keeping needs is also included in all considered cases and a simplified conversion from ΔV to mass of propellant is then derived from the rocket equation Eq.1, using average mid-life conditions (satellite mass of 1160 kg, I_{sp}=285 s, performance factor of 0.98).

All the assumptions for this analysis are summarised hereafter:

- H/O date: Feb 2015, H/O inclination: 0° , 0.5°, 1.80° or 3.11°
- Extended H/O RAAN interval: between 204° and 360°
- 1st inclination manoeuvre: not before Aug 2016
- Inclination control target: 10.5 years until i>2.0° at EOL
- Remaining manoeuvres (not North/South) ΔV: 10 m/s

It is to be noted that the launch date changed from February 2015 to the current baseline of July 2015 after running this analysis, but this has negligible effects on the analysis outcome.
The obtained results are shown in the following figures. Figure 5 and Figure 6 show the planned strategies in the equinoctial inclination for North-South station keeping, obtained with long term optimization strategy.

Nodes around 310° have a low station-keeping cost as the natural change in the initial NSO inclination is a reduction towards zero followed by an increase to the two degree station-keeping limit. In other words, there is a long period (of several years) before the first North/South station-keeping manoeuvre is required and this helps produce a low Station-Keeping cost over the full 10.5 years considered. For nodes on this region, the higher the initial NSO inclination, the longer the drift period to the first North/South station-keeping manoeuvre and the cheaper the 10.5 years of station-keeping.
This does not mean that with these nodes the overall cost (LEOP+SK) is always minimised by a high NSO inclination: the LEOP cost to achieve the high inclination can be large if a considerable node rotation is required, as it will be detailed in the following sections.

It is noted that the analysis includes NSO inclinations below 2° for which payload operations would be possible immediately after handover. Even for these cases, the first 1.5 years are still referred to as in-orbit storage and the station-keeping cost is assessed over 10.5 years. As the MSG-4 interval of acceptable NSO nodes is much wider than for MSG-3, there is a considerable difference in the nature of the station-keeping cost of the two missions. This in turn creates differences in the total cost and the optimal NSO inclination and node functions.

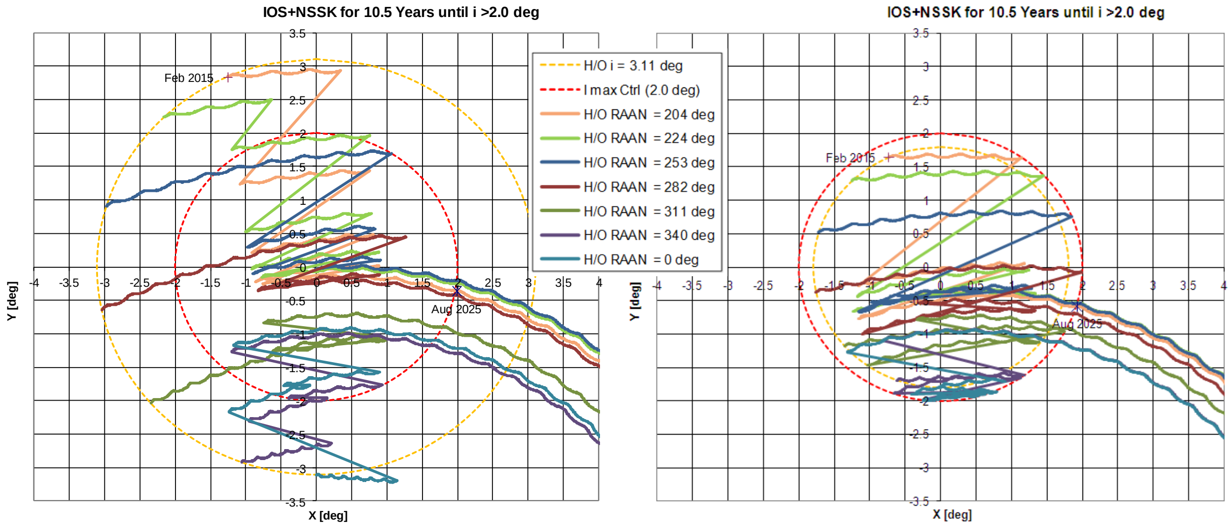

Figure 5. Equinoctial inclination, SK control for NSO inclination 3.1°(left) and 1.8°(right)

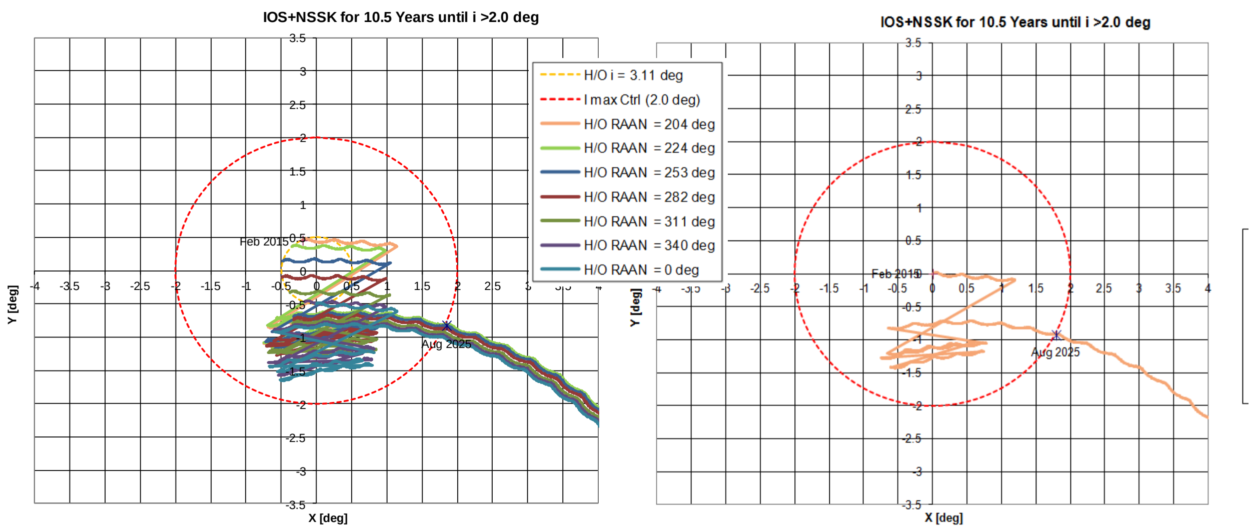

Figure 6: Equinoctial inclination, SK control for NSO inclination 0.5°(left) and 0°(right)

Table 2

$RAAN_{H/O}$ [°]	**SK Cost for $i_{H/O}$ = 0.0° [kg]**	**SK Cost for $i_{H/O}$ = 0.5° [kg]**	**SK Cost for $i_{H/O}$ = 1.80° [kg]**	**SK Cost for $i_{H/O}$ = 3.11° [kg]**
204	140.4	143.8	154.7	168.2
224	140.4	140.4	143.0	149.2
253	140.4	135.7	124.9	118.1
282	140.4	132.0	110.2	89.6
311	140.4	130.6	104.0	76.5
340	140.4	131.7	109.4	90.5 (104.5)
360 (=0)	140.4	134.0	119.7	114.1 (125.6)

For nodes towards the ends of the [204°, 360°] interval, the free drift period can be such that the natural evolution of a high NSO inclination will produce an initial reduction but fail to achieve a value below 2°. It is also possible, for example for the 360° node, that the inclination actually increases during the free drift period. All these cases are allowed, as an appropriate inclination below 2° can be achieved after 1.5 years with station-keeping manoeuvres. The station-keeping over 10.5 years is then correspondingly expensive and for some cases it's cheaper when starting from a lower NSO inclination. For 0° NSO inclination, the NSO node is undefined and all nodes are allocated the same station-keeping cost. This is the cost of starting the free drift from the centre of the station-keeping circle.

For the station keeping cost analysis of the scenario with 3.1° orbit inclination at H/O, the cases for RAAN at H/O of 340° and 0° were calculated, using a staged strategy to achieve an inclination vector inside the 2.0 degrees circle for nominal routine phase operations. The first inclination manoeuvre, executed 3 years after launch, targets an inclination of 2.5° (rather than 2.0°), following which the 2.0° inclination constraint is achieved by natural evolution within about 1.5 years of further free drift. This was done to avoid large propellant penalties (about 10-15 kg), that would result from forcing the inclination to fall within the 2.0° constraint with the first inclination control manoeuvre (see values in brackets in Table 2). A smoother and more natural shape of the cost functions was also obtained in this way, which is then furthermore beneficial for the final determination of the optimal target solutions for the NSO parameters, to be achieved with the LEOP manoeuvres.
As additional information, the inclination reached after 1.5 years of free drift for the cases with iH/O=3.1° is listed in the following table:

Table 3

$RAAN_{H/O}$ [°]	i after 1.5 yrs of free drift [°]
204	3.0
224	2.6
253	2.1
282	2.0
311	2.3
340	2.8
360 (=0)	3.2

It is highlighted that for the cases where the inclination at NSO is 1.8° or lower, after the handover the mission will start and stay always below the control value of 2°.
For the case where the inclination at NSO is 3.1° the initial inclination drift toward the control circle of 2° is variable in duration according to the NSO node, and it can be up to 4.5 years. This could be changed advancing the North/South manoeuvre to enter the control circle earlier for high NSO node, at the price of higher total SK cost (see brackets value in Table 2).

The SK cost are then interpolated using Bicubic Spline values for the station keeping costs plotted in Figure 7 (with correspondent contour plot), as function of NSO inclination and NSO node. This model will be then used for the LEOP+SK combined propellant optimization. The covered NSO RAAN range is 204° to 360° and the station keeping costs are given for inclination values at handover between 0° and 3.1°.

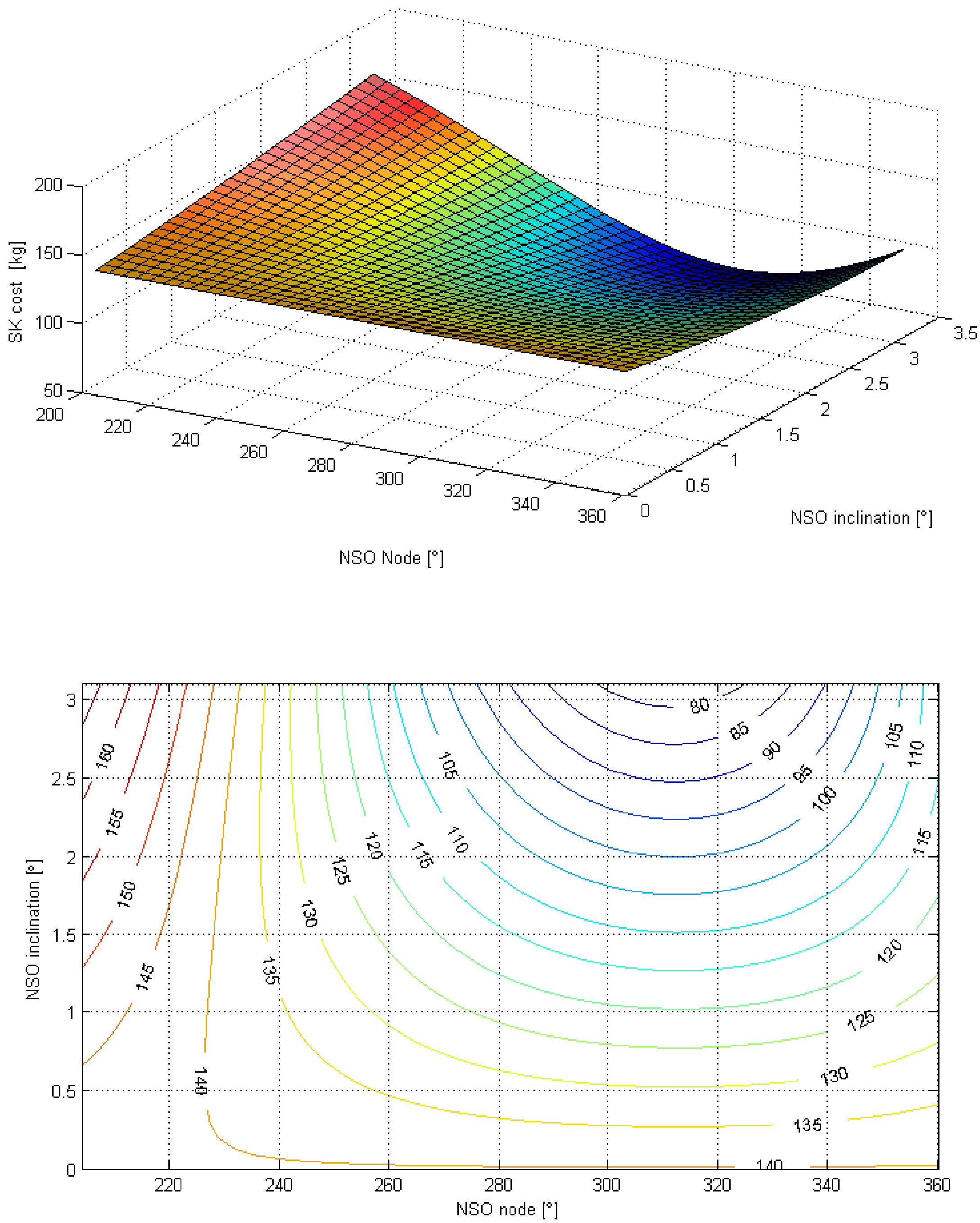

Figure 7. MSG-4 SK cost, function of Node rotation & NSO inclination (Bicubic Spline)

7. LEOP cost analysis

The change from the transfer orbit node to the synchronous orbit node is referred to as node rotation. If the inclination of the target synchronous orbit is small (less than 0.1º), the cost of even the worst case node rotation is guaranteed to be small. However, as the synchronous orbit inclination increases, the cost difference between favourable and unfavourable node rotation cases also increases. The relatively high synchronous orbit inclination of 1.8º assumed for MSG-1/2/3 ensures that node rotation has a considerable influence on the optimal AEF solution and the associated propellant budget. This is even more relevant when NSO inclination of up to 3.1º are considered for MSG-4

The ESOC manoeuvre optimisation software for LEOP has been run for a reduced set of node rotations, starting from a Ariane-5 standard GTO orbit inclined of 6º.
It is expected that the cost of reaching the final NSO orbit increases with the size of the required node rotation. Therefore, the global minimum in the 0º node rotation period is predictable for the LEOP consumption alone.
However, rather than having a maximum for the largest node rotation of 180º, the cost functional takes a local minimum close to this point. This is because a node rotation of 180º can be achieved by over-correcting the inclination. If the AEFs reduce the orbital inclination beyond the target of NSO inclination to zero degrees, then any additional ΔV in the same direction will cause the descending node of the orbit to become the ascending node with the result that the node is shifted 180º. As a 180º node shift is essentially only an additional inclination correction, it can be achieved with a firing centred round apogee and is relatively inexpensive.
The most difficult node rotations to achieve are the rotations furthest from the 0º and 180º cases, namely around the -90º and 90º node rotations. That is why node rotation cases around the -90º and 90º values are usually referred to as high rotation cases. The results are shown in Table 4. These results indicate a considerable increase in consumption for the cases with node rotation away from the 0° or 180° cases, when targeting an NSO inclination of 3.1°. The LEOP costs for NSO inclination of 1.8° were obtained from the MSG-3 mission analysis. The case with a target NSO inclination of 0° is not dependant of the node rotation (NSO node is not defined).

Table 4. MSG-4 LEOP cost for different NSO inclination and Node rotations

LEOP cost [kg]		**Node rotation**				
		-180°	-91.6°	0°	+90.6°	+180°
$\mathbf{i_{NSO}}$	**0°**	809.55	809.55	809.55	809.55	809.55
	1.8°	814.7	844.8	805.7	841.5	814.7
	3.1°	819.1	871.2	803.7	867.5	819.1

To provide a refined model for the successive LEOP+SK propellant analysis, the tabulated numbers are interpolated using Bicubic Spline, as shown in Figure 8 (with correspondent contour plot), as function of NSO inclination and Node rotation.
For MSG-3, a fixed NSO inclination of 1.8º was used, only the NSO node had to be selected from the interval of acceptable values (see [3]); the selected NSO node function was a simplified version of the optimal NSO node function. The optimality is obtained in the sense of combined LEOP and SK cost analysis. The simplification is made to reduce the number of discontinuities in the NSO node function which translate to discontinuities in the launch window.

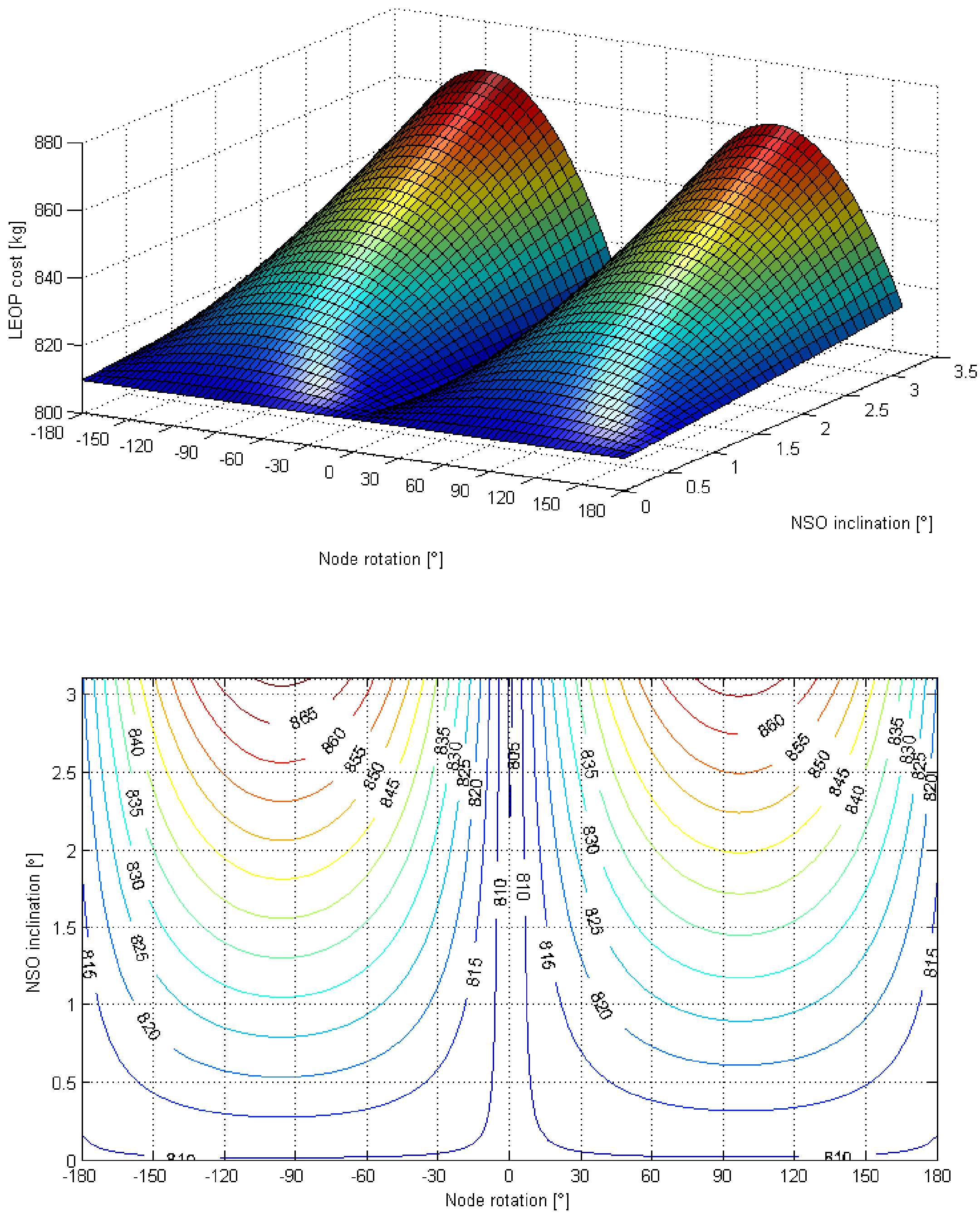

Figure 8. MSG-4 LEOP cost, function of NSO inclination & Node rotation (Bicubic Spline)

MSG-4 has the additional flexibility of being able to select the NSO inclination on an interval: this is a possible further source of launch window discontinuities. In addition, every effort is to be made to ensure the MSG-3 AEF strategy and timeline can be re-used. For MSG-3, this proved to be feasible every day of the year, with very tight margins around -90º and 90º node rotations, where the AEF have different directions and have to be performed away from the apogee. This means that the cases with the higher LEOP cost, the optimal NSO node/inclination selection should be driven by the mission analyst to have at maximum 1.8º NSO inclination. This process is illustrated in the next two sections.

8. Combined LEOP+SK cost analysis, preliminary runs

This phase of the study uses LEOP costs from the interpolated model in Figure 8 (function of NSO inclination and Node Rotation) and the SK model in Figure 7 (function of NSO inclination and NSO node). An optimisation software then searches these models to find the NSO inclinations and NSO nodes minimising the sum of the LEOP and SK cost under various conditions. In the different optimisations, the NSO node is always optimised whereas the NSO inclination is either optimised or given a fixed profile.

The results of the different cases are presented as a series of plots including first the optimised or pre-defined NSO inclination function; then a summary plot is presented, divided in 6 sub-plots, showing (top, left to right) 1) the GTO node, 2) the LEOP node rotation, 3) the optimal NSO node function, then (bottom, left to right) 4) the station-keeping cost, 5) the LEOP cost, and 6) the total cost, all of them over a calendar year (see Figure 9). As the NSO inclination and node are target elements for the manoeuvre optimisation software, their selection has a major influence on the optimised firing directions and therefore on the launch window.

8.1 MSG-3 optimised NSO node for a fixed NSO inclination of 1.8º

As initial test case for successive comparisons, the MSG-3 optimisation results are shown in Figure 9. It is reminded that for MSG-3 the NSO inclination was fixed to 1.8º, and only the NSO was optimized. This is only mentioned here as a reference, the results take into account only the NSO node optimisation, without manipulations to take into account launch window discontinuities.

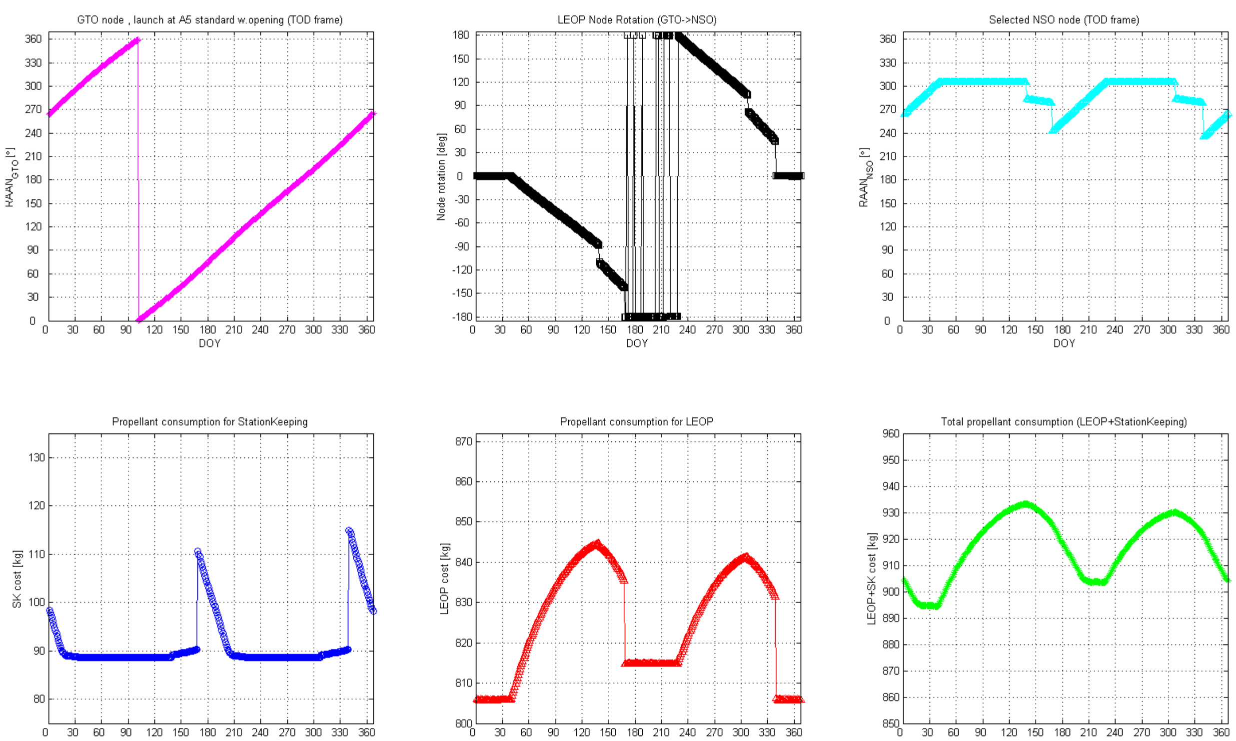

Figure 9. MSG-3 case, optimization results: Top (left to right) GTO node, Node rotation, NSO node; Bottom (left to right) SK cost, LEOP cost, SK+LEOP cost

8.2 MSG-4 Case-A: Optimised NSO Inclination and NSO node

In this run, the NSO node is optimised together with the NSO inclination. The selected NSO inclination is shown in Figure 10, while the summary plots in Figure 11.

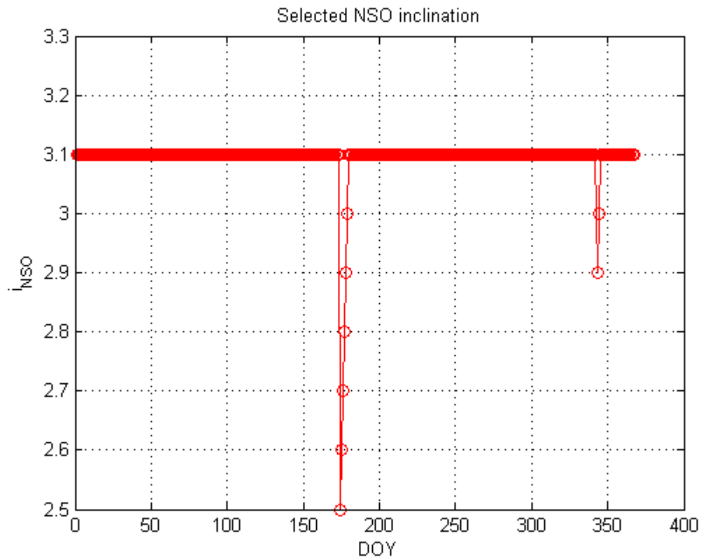

Figure 10. Case-A, optimised NSO inclination

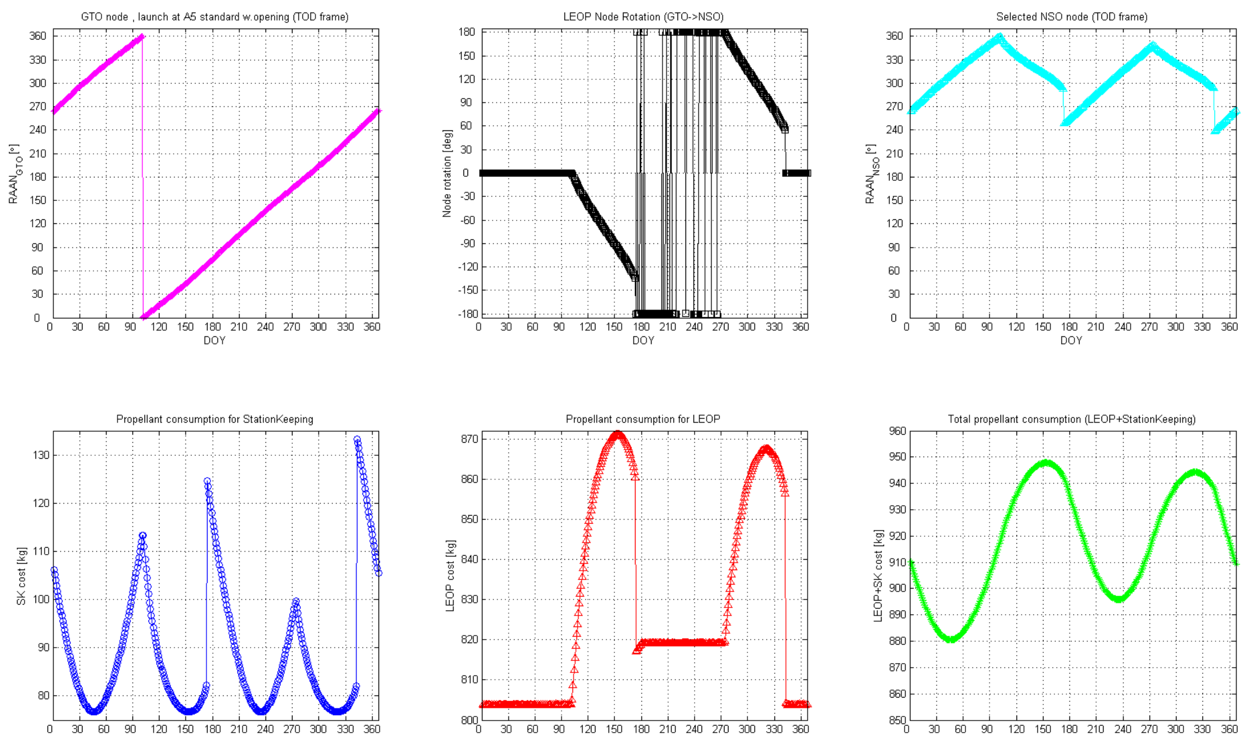

Figure 11. Case-A, optimization results: Top (left to right) GTO node, node rotation, NSO node; Bottom (left to right) SK cost, LEOP cost, SK+LEOP cost

A key result of the study is that when the NSO inclination is fully optimised, the selected value is essentially the maximum 3.1° for all launch dates and times. Therefore, the optimisation problem as regards the NSO inclination appears to have a simple solution.

However, there is a problem implementing this option because of the high LEOP cost during the spring and autumn node rotation periods. These LEOP costs are much higher than the equivalent values for MSG-3 (reported in Figure 9) when a 1.8º NSO inclination was used. The high LEOP cost will leave only a limited amount of propellant for station-keeping and reduce the options for routine operations.

A more serious problem is the associated large slew between the first two firing directions which is difficult to accurately achieve with the limited time available for precise attitude determination and control between apogees 4 and 6. The resulting inaccuracies in the second burn firing direction could easily lead to a significant propellant penalty. To avoid this, a mission re-design would be necessary involving a nominal second burn at apogee 8 and the selection of associated backup cases. This could make the LEOP longer and introduce a SAA margin problem which in turn influences the launch window. This risks can be mitigated re-using at a maximum extent the MSG-3 AEF strategy and timeline, that was already proved to be feasible for a NSO inclination of 1.8º: further solutions are investigated with fixed NSO inclination profiles as described in Sections 8.3 and 8.4. Before this, further conclusions can be drawn from the full optimisation results of Case-A.

The equivalent results for the MSG-3 mission are provided in Figure 9. A comparison of the total costs this with Case-A in Figure 11 shows there are dates where the MSG-4 mission, even with its storage orbit, can be less expensive than MSG-3. The MSG-4 cost is considerably cheaper during the winter and summer periods but more expensive for the spring and autumn node rotation periods. As there is no problem with the LEOP cost in winter and summer, the optimal high inclination NSO can be selected on these periods in the later examples and the corresponding saving achieved. It is recalled that for Case-A, a full optimisation is conducted and nothing better will be found for the MSG-4 mission cost. Therefore, during the spring and autumn periods, it is not possible to find a storage orbit where the storage period can be achieved without an extra cost. The favourable news is that for this full optimisation, the extra cost can be accommodated within the propellant budget (maximum loadable propellant, that is ~960 kg). Care must be taken to ensure this is still the case in future examples when sub-optimal inclination profiles are used.

The optimal NSO node is just as important as the optimal NSO inclination and its form in the full optimisation of Case-A is best described by considering the winter, spring, summer and autumn periods. For the winter zero node rotation period, the optimal NSO takes the expected simple form being linearly increasing and equal to the transfer orbit node. The range of NSO nodes used on this period is typically [240º, 360º] which produces a zero node rotation period of around 120 days. As the NSO node could be selected on the range [204º, 360º], the zero node rotation interval is less than its maximum possible size. Use is not made of the lower NSO nodes, because their high station-keeping cost makes the overall cost too expensive.

For the summer 180º node rotation period, the optimal NSO node again takes the expected form being linearly increasing and equal to 180º plus the transfer orbit node. The range of NSO nodes used on this period is typically [245º, 355º] producing a 180º node rotation period of around 110 days, slightly less than the zero node rotation period. Again, the lower NSO nodes are not used as their station-keeping cost makes their overall cost too expensive. For the spring and autumn node rotation periods the optimal NSO node function takes the same form. It is an approximately linearly decreasing function with a discontinuity at the end of the period. It is known that this NSO node function discontinuity translates directly into a launch window discontinuity. The optimal NSO node function is therefore essentially made up of four linear parts, alternately increasing and decreasing, and contains two discontinuities, one at the end of each of the linearly decreasing parts of the function. The NSO node function shows that favourable node rotation periods apply for typically 230 days of the year. This improvement over MSG-3 is because of the larger interval of allowed NSO nodes, which in turn is due to the increase in the station-keeping circle from 1º to 2º.

8.3 MSG-4 Case-B: Fixed NSO Inclination Profile

As discussed above, the high LEOP cost prevents the implementation of the optimal maximum NSO inclination during the spring and autumn node rotation periods. As a result, the next step of the study investigates the effect of using a fixed inclination profile.
This case uses the optimal 3.1º NSO inclination on the winter and summer periods but reduces the inclination for the spring and autumn node rotation periods. The reduction is on a parabolic curve with a minimum of 1.8º at the points of worst case node rotation.
Shortly after the minimum, the inclination profile contains a discontinuity as the inclination switches back to its maximum value of 3.1º.

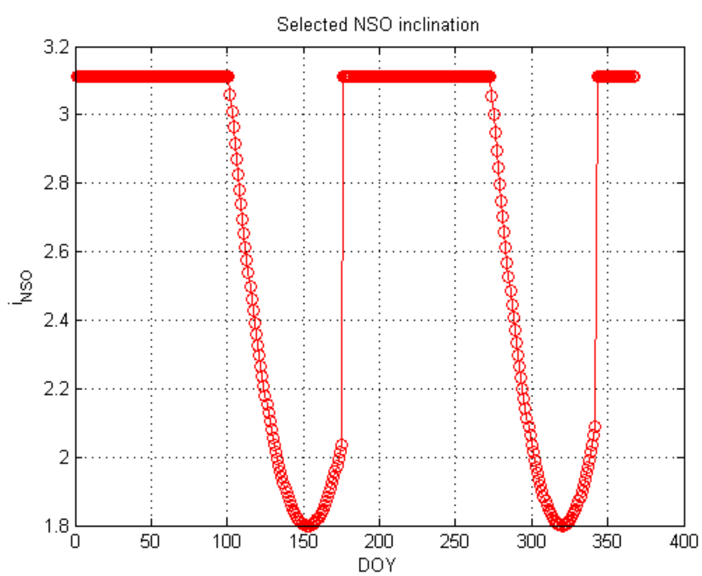

Figure 12. Case-B, fixed profile for NSO inclination

The summary results for Case-B (see Figure 13) show that using the fixed inclination profile has successfully reduced the worst case LEOP cost by typically 30 kg. What is particularly interesting is that the total cost and the optimal NSO node function are essentially unchanged from those of Case-B (Figure 11). This indicates that the use of the inclination profile on the spring and autumn node rotation periods hardly influences the optimality of the solution, but causes a transfer of the cost from the LEOP phase to the Station-Keeping phase. This opens up the possibility of using even simpler inclination profiles which can reasonably be expected to produce a similarly optimal solution.

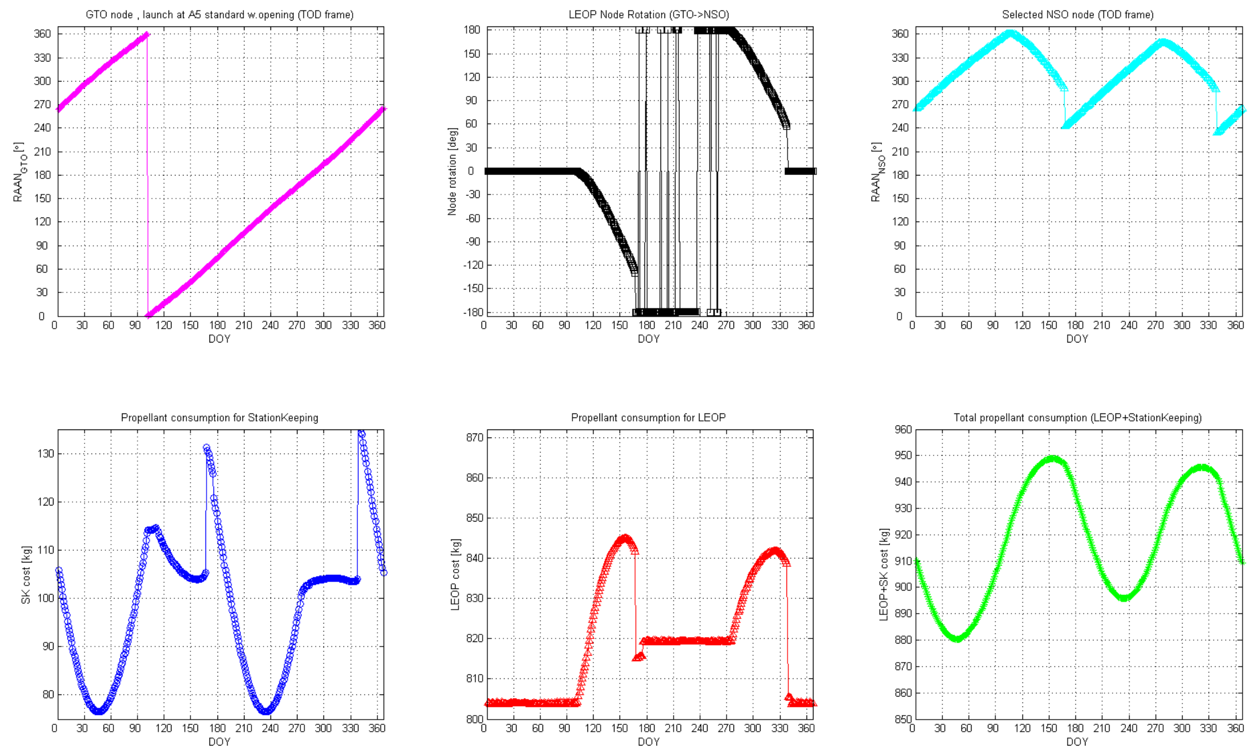

Figure 13. Case-B, optimization results: Top (left to right) GTO node, node rotation, NSO node; Bottom (left to right) SK cost, LEOP cost, SK+LEOP cost

8.4 MSG-4 Case-C: Fixed NSO Inclination Profile and Reduced Discontinuities

Discontinuities in the NSO inclination and node functions are a key issue as they produce corresponding discontinuities in the launch window which in turn cause operational difficulties. In this run, we use a fixed inclination profile, similar to the one in Case-B, but we change the optimisation function to include a cost for the presence of discontinuities. In this way, the cost function is minimising the sum of the LEOP and station-keeping cost and the size of the discontinuities in the NSO node function.

The results of the optimisation show that smaller discontinuities are achieved in the NSO node function by extending the approximately linear reduction before the discontinuity. In addition, the inclination profile is adjusted to place its two discontinuities on the same days as the smaller remaining discontinuities in the NSO node function. Although the number of discontinuities in the NSO inclination and node functions is unchanged, with two discontinuities in each function, as they occur on the same day the number transferred to the launch window is two rather than four. Reducing the size of the NSO node function discontinuities will also cause a corresponding reduction in the size of the launch window discontinuities. Comparing the total cost plots of

Case-B (Figure 13) and Case-C (Figure 14) show reducing the discontinuities has had little effect on the total cost, with Case-C being only marginally more expensive. Therefore, Case-C has successfully reduced the effect of the discontinuities and maintained the number of launch window discontinuities at the two present for MSG-3.

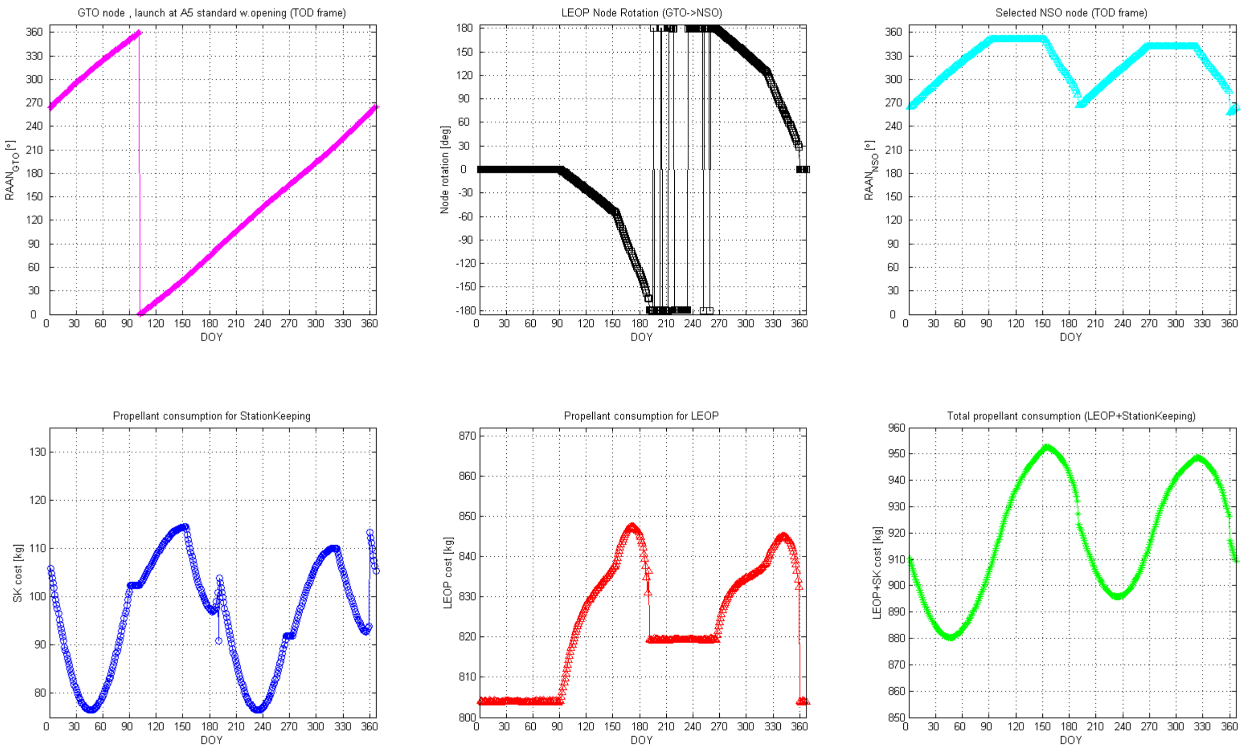

Figure 14. Case-C, optimization results: Top (left to right) GTO node, node rotation, NSO node; Bottom (left to right) SK cost, LEOP cost, SK+LEOP cost

9. Combined LEOP+SK cost analysis, final results

This section describes the final selection of the NSO inclination and node. An initial choice is made and updated as necessary following tests with the manoeuvre optimisation software. The choice of the NSO inclination profile is made first.

In Section 8.3, Case-B is investigated which uses a fixed inclination profile varying between 3.1º and 1.80º on the spring and autumn node rotation periods. The results show that the selected profile successfully limits the LEOP cost over these periods without any significant increase to the overall cost of the mission. However, a drawback of the inclination profile is that it contains a discontinuity which can create a discontinuity in the launch window. It is expected there are simpler NSO inclination functions which also produce favourable cost results and in particular it is preferred to have a continuous function.

The choice of the NSO inclination function is strongly influenced by the desire to re-use the MSG-3 AEF strategy and timeline. The NSO inclination is chosen to have the fixed value of 3.1º on the winter and summer periods. During the first ten days of the spring node rotation period it decreases linearly to the MSG-3 value of 1.8º. It is then maintained at this value until the last ten days of the period when it linearly increases back to 3.1º. The selected NSO inclination function has the same profile during the autumn node rotation period. By using a 1.8º NSO inclination for

the majority of the node rotation periods with higher LEOP cost, MSG-3 type conditions are achieved on these intervals. The LEOP cost and the slew between the first two firing directions will not be significantly larger than the corresponding MSG-3 values. Values that were acceptable for MSG-3 are acceptable for MSG-4, which means the MSG-3 AEF strategy and timeline can be reused.
Furthermore, a continuous function has been selected which is the first step towards producing a continuous launch window.

The choice of the NSO node function is made next. A particularly interesting result of the previous studies is the way smaller discontinuities are achieved by extending the linear reduction before the discontinuity. This suggests the discontinuity can be completely removed by continuing the linear reduction to the end of the relevant spring or autumn period. This idea is incorporated into the selection of the NSO node function which is a continuous function, linearly increasing on the winter and summer periods and linearly decreasing on the spring and autumn node rotation periods. As the NSO inclination and node functions are both continuous, the launch window will also be continuous.
Following the selection of the NSO inclination and node functions, a series of tests are conducted with the manoeuvre optimisation software. These tests identify the start and end dates of each of the winter, spring, summer and autumn periods and the corresponding NSO inclination and node values. The tests show an update to the NSO inclination function is not necessary but an enhancement of the node function is advantageous.
During the summer period, the 180º node rotation case is expected to be optimal from typically day 190 to day 290. This period has been studied in detail and the interval where the 180º node rotation is optimal ends on day 240. From day 240 to day 300, the optimal solution has a node rotation between 180º and 170º. For these days, using a node rotation slightly less than 180º allows the launch window to open earlier. This achieves a better station-keeping cost and an improved overall propellant consumption.

The final selection of the NSO inclination and node are shown in Figure 15 and Figure 16 respectively. The periods of 1.8º NSO inclination are colour coded blue, the intervals of 3.1º NSO inclination are colour coded green and the switches between them are colour coded purple.
The same colour coding is used in the subsequent Figure 17 and Figure 18, showing respectively the final selected MSG-4 LEOP cost and SK cost over one calendar year (for comparison, the MSG-3 equivalent are also reported with a dashed line).
Figure 19 shows the magnitude of the slew manoeuvre between AEF-1 and AEF-2, that is a direct measure of the operational difficulty of the LEOP: a 0º slew is typical for the favourable case of 0º and 180º node rotation, with all AEF manoeuvres in the same direction; from this plot it can be seen that the target of re-using the MSG-3 AEF strategy and LEOP timeline is successfully achieved, as the maximum slew size is equivalent between MSG-3 and MSG-4

The success of the overall strategy selection is demonstrated later in the propellant consumption plot in Figure 20. The advantages of considering the SK cost for combined optimisation (as done for MSG-3/4) is evident. In addition, MSG-4 strategy can cope with the 1.5 years in-orbit storage during the currently selected launch period (02/July/2015, DOY 183, for 90 days) resulting in reduced penalties at the beginning of the period, while being even more advantageous towards the end of the same.

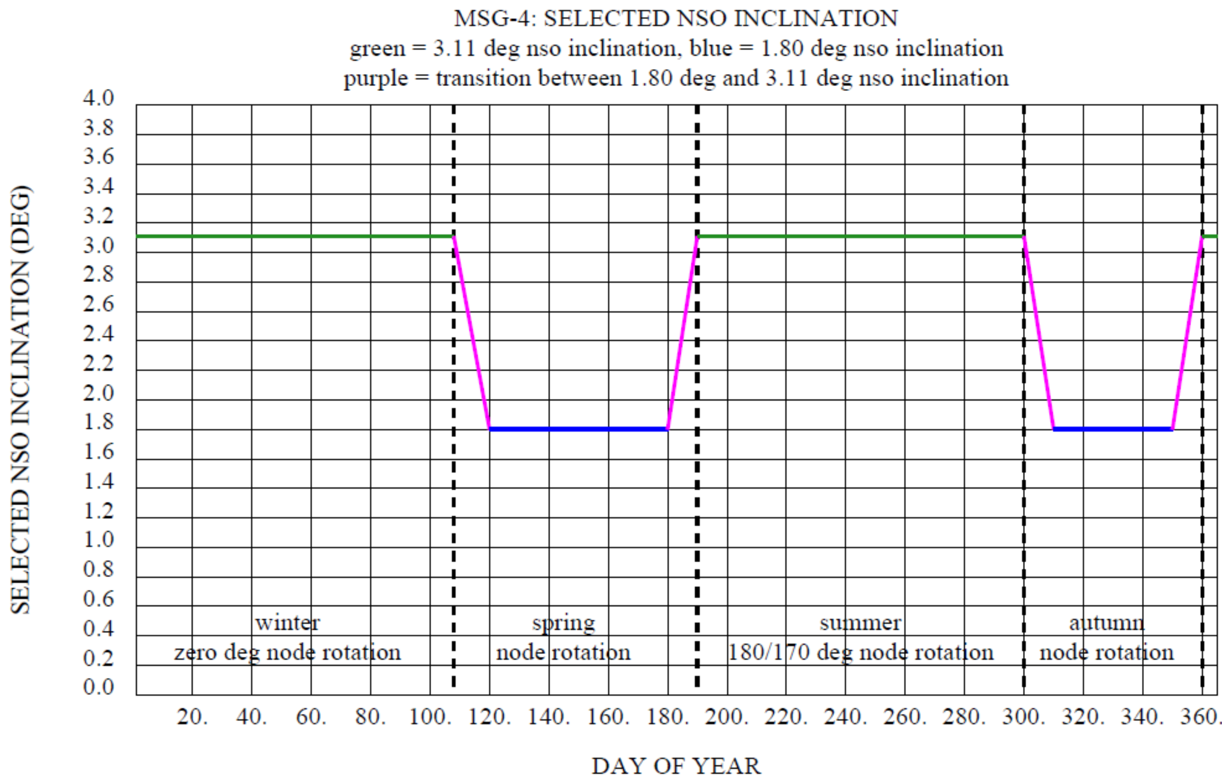

Figure 15. Final selected NSO inclination for MSG-4

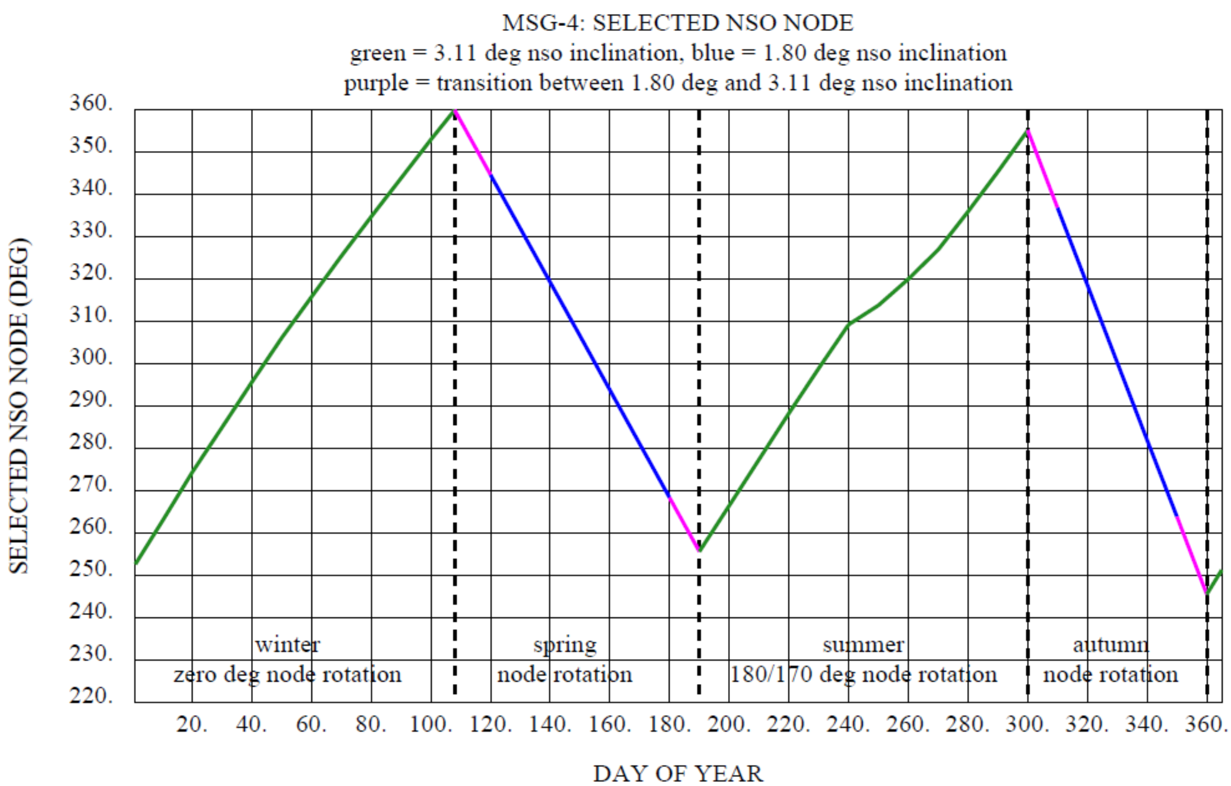

Figure 16. Final selected NSO node for MSG-4

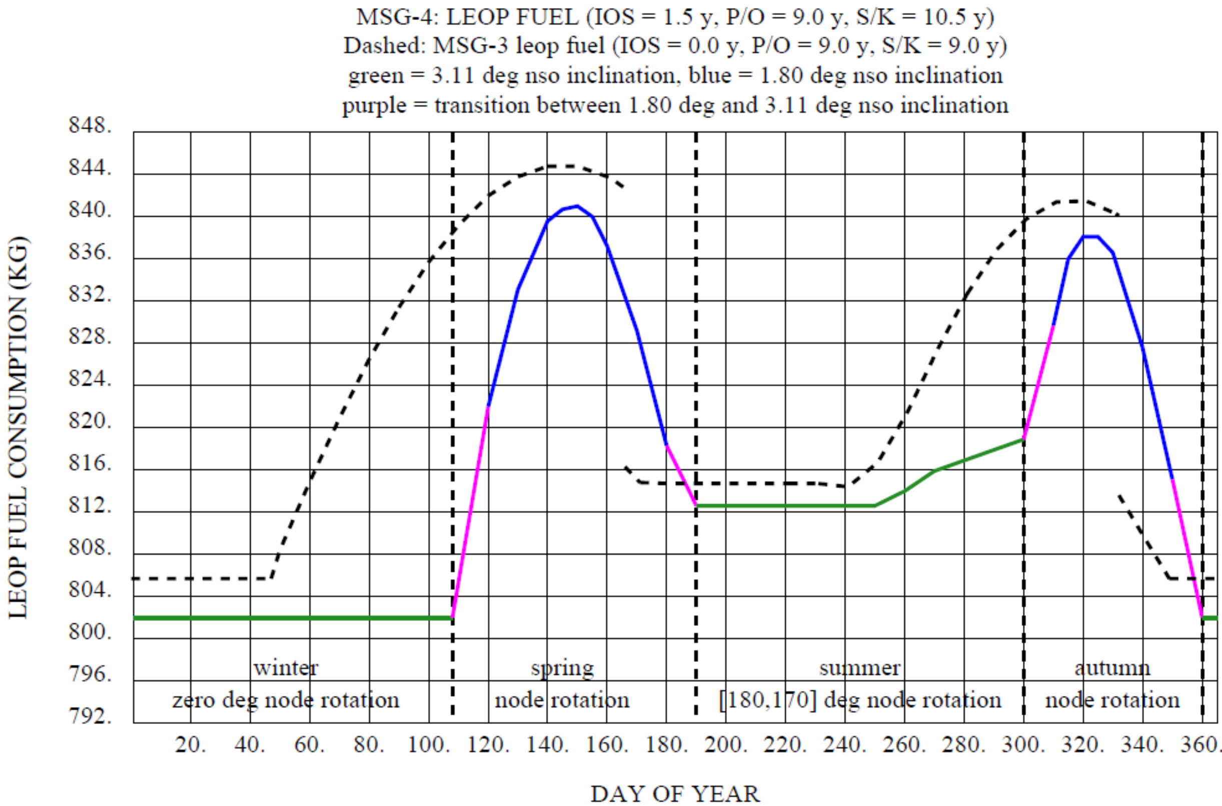

Figure 17. Final selected LEOP cost for MSG-4 (dashed line = MSG-3)

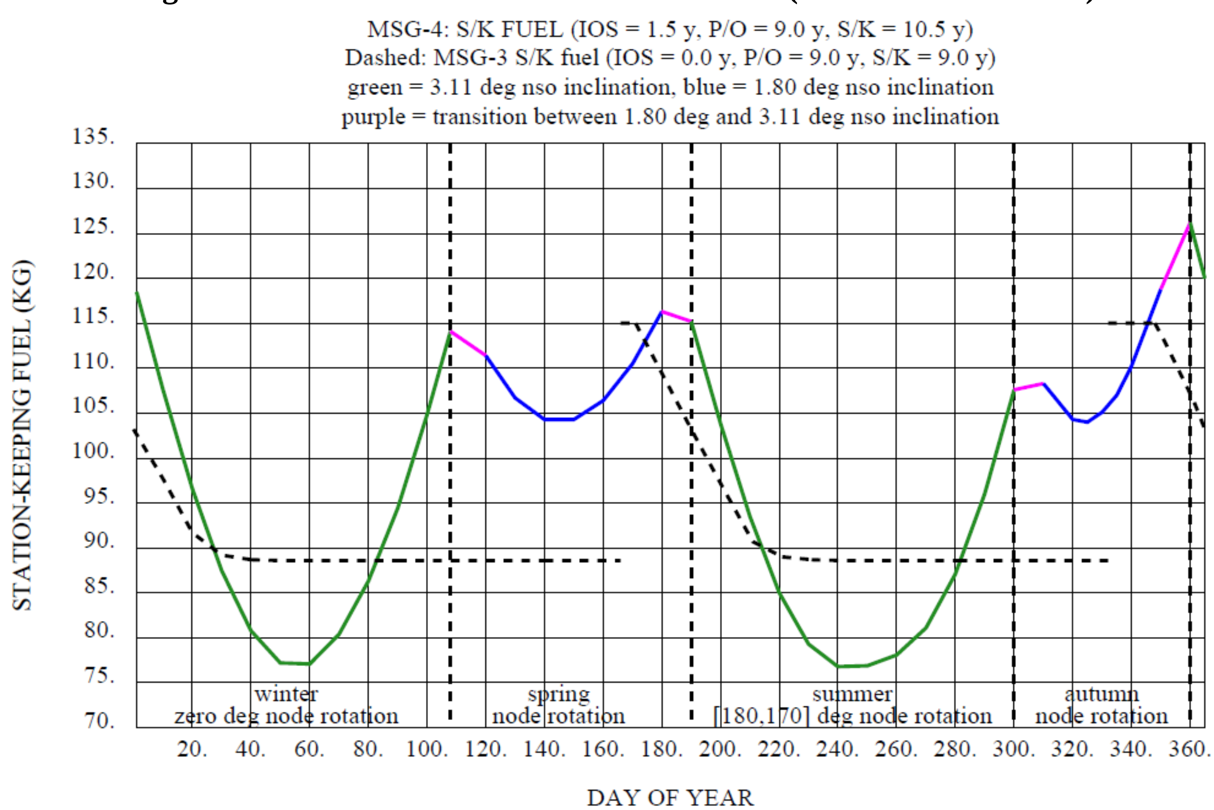

Figure 18. Final selected SK cost for MSG-4 (dashed line = MSG-3)

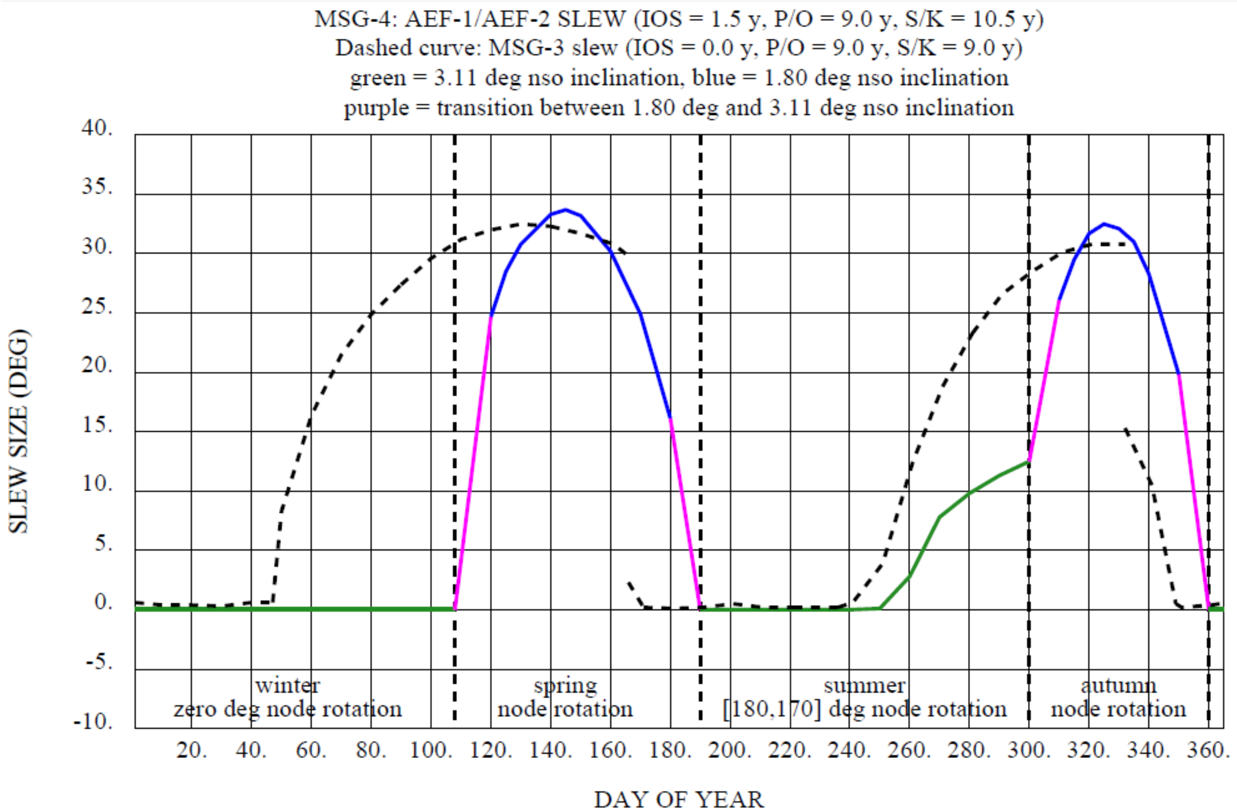

Figure 19. Final magnitude of MSG-4 slew between AEF-1 and -2 (dashed line = MSG-3)

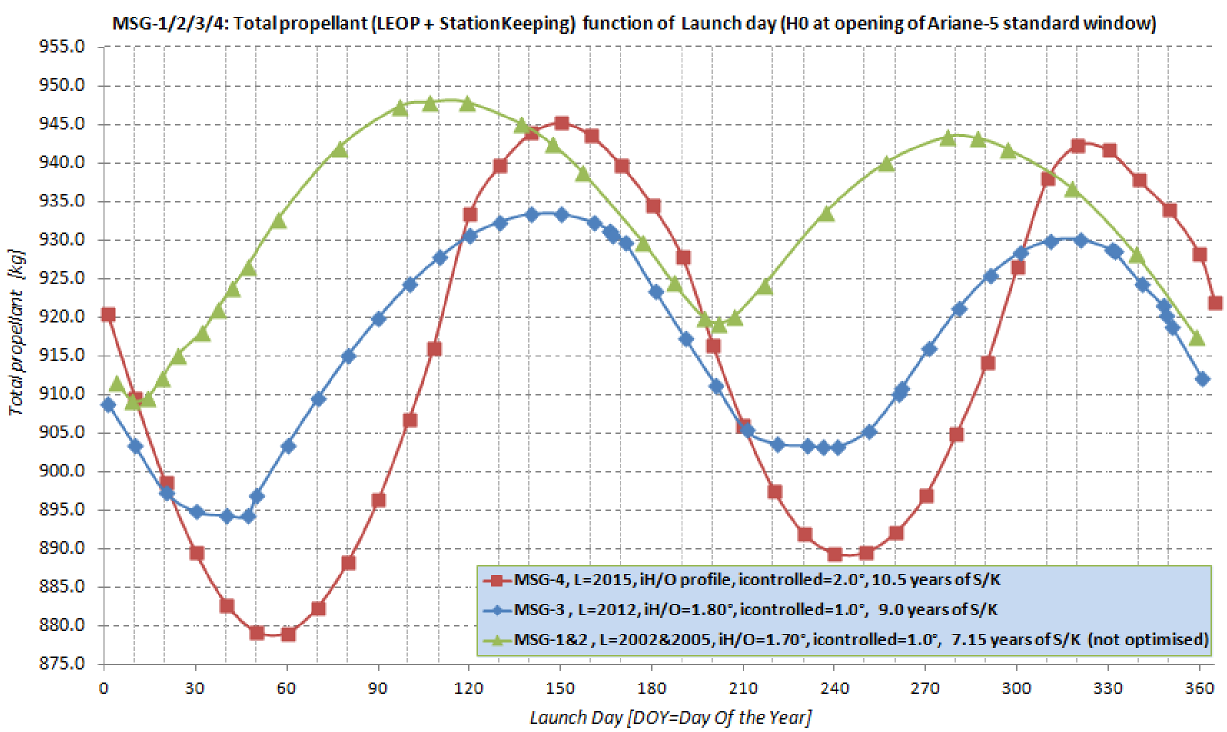

Figure 20. Summary propellant consumption for the various MSGs

10. Conclusions

The reason a generic mission analysis is required for MSG-4 is the introduction of a 1.5 year in-orbit storage phase at the start of the mission. The aims of this work are to identify the best storage orbits. Identifying the best storage orbits reduces to selecting the NSO inclination and NSO node as a function of the calendar date at the opening of the launch window.
The definition of the best storage orbit involves minimising the sum of the LEOP and SK cost but also considers the advantages of being able to re-use the MSG-3 AEF strategy and timeline.

As preliminarily analysed, the optimal NSO inclination is essentially the fixed maximum value of 3.1º for the whole calendar year. However, this solution cannot be implemented using the MSG-3 AEF strategy and timeline because of a large slew between the first two firing directions. It also has the drawback of an associated high LEOP cost which leaves only a limited amount of propellant for station-keeping and reduces the flexibility of routine operations.
A fixed NSO inclination functions can successfully limit the slew size and LEOP cost without making any significant change to the optimality of the solution.

Therefore, a fixed NSO inclination function is used here with a simple design. The NSO inclination is a continuous function which is a first step towards the ideal case of creating a continuous launch window.
The further selection a continuous NSO node function consolidate this: this function is essentially in four parts, alternately linearly increasing and decreasing intervals.
The LEOP cost and the slew size do not exceed the equivalent MSG-3 values. This is expected as a result of the NSO inclination choice and ensures the MSG-3 AEF strategy and timeline to be re-used for MSG-4.

For MSG-1/2, the mission analysis only considered the optimization of the LEOP cost. With MSG-3, the concept of combined LEOP+SK cost optimization has been considered. MSG-4 posed the additional requirement of a pre-fixed in-orbit storage period. The comparison of the results of the various mission analyses is shown in Figure 20.
As it can be seen, due to the relatively high SK inclination control deadband of MSG (1º), the advantages of considering the SK cost in the overall propellant optimizations are evident.
The adoption of ad-hoc measures, such as the increased NSO inclination (up to 3.1 º) and widened SK control circle (2º), ensure that MSG-4 has mission lifetime advantages for some periods of the year with respect to MSG-3, even if accommodating an extra 1.5 years of in-orbit storage. During the winter and summer periods, when a high inclination storage orbit is possible, the MSG-4 cost is significantly less than the MSG-3 value, despite the additional 1.5 years of station-keeping. However, for the spring and autumn node rotation periods, the 1.5 years in-orbit storage always has an extra cost. As studied, this can be anyway accommodated within the MSG-4 propellant budget.

The continuous launch window (and subsequent continuous deployment attitude), the optimality of the total cost and the re-use of the MSG-3 AEF strategy and timeline, all confirm the successful choice of the storage orbit. A basic fact of the MSG missions is that it is a considerable advantage to launch in either the winter or summer period. This is even truer following the introduction of the in-orbit storage for MSG-4.

11. Acknowledgments

The authors of this paper wishes to thank Xavier Marc, Flight Dynamics Manager for MSG at ESOC, for the in-depth expertise and the guidance provided in developing this mission analysis studies.

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