ANALYSIS OF STATION-KEEPING MANOUVRES STRATEGIES FOR METEOSAT THIRD GENERATION

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Abstract: *Meteosat Third Generation (MTG) is the next series of the meteorological satellites of EUMETSAT in geostationary orbit. Six satellites will carry imaging and sounding payloads; the first of them will be launched in 2019. Due to the in-orbit deployment plan of the satellites, there could be up to 4 MTG spacecraft flying together. Therefore, the mission analysis from the space segment procurement has been based on the most constraining scenario that is to operate up to 4 satellites in the same longitude slot.*
The proposed station-keeping strategy , typically intended for telecommunication satellites, is based on maintenance of a proper separation of the relative eccentricity/inclination of the satellites in the slot of ±0.1º longitude, ±0.15º latitude, and typical manoeuvres' cycles of 28 days (for both in-plane and out-of plane control).
The current geostationary slots registered to EUMETSAT and the operational baseline allows deploying 4 satellites in 3 different slots, with only 2 of them in the same slot, with a wider longitude and inclination dead-bands. Different analyses have been performed to optimise the station-keeping strategy not only for propellant consumption, but also for typical operational aspects, such as the load on the control centre and the service outages

Keywords: *MTG, mission analysis, orbit control, geostationary, station-keeping.*

1. MTG: Meteosat Third Generation programme of EUMETSAT

EUMETSAT is an intergovernmental organisation, founded in 1986, whose purpose is to supply weather and climate-related satellite data, images and products to the National Meteorological Services of its Member and Cooperating States, and to users worldwide (see RD.1).

The Meteosat Third Generation (MTG) System of EUMETSAT is the next series of the European operational meteorological satellites in geostationary orbit (see RD.2); it will provide observations with higher spatial, spectral and temporal resolution with respect to previous generations. The MTG Imager (MTG-I) will be a 3.6-tonne satellite with 16 spectral channels. Not present in previous generations, there will be also a Sounder (MTG-S), based on the same platform but carrying different instruments (see artistic impression in Figure 1).

Figure 1: MTG-I and MTG-S (credits ESA)

Unlike the predecessors spin-stabilised satellites (MSG, standing for Meteosat Second Generation), MTG will be based on a three-axes stabilized platform, to achieve compliance with more demanding requirements and to conduct soundings. In routine operations phase, the attitude will be controlled by reaction wheels, driven by measurements coming from star-trackers. The programme is currently in Phase-C, the first launch is scheduled at the end of 2019. The mission will comprise 6 satellites: 4 imagers and 2 sounders.

2. MTG deployment scenario and orbit control constraints

The MTG Full Operational Capability (see RD.3) foresees 4 satellites in-flight at the same time. Due to service constraints and to the geostationary ring's slots registered to EUMETSAT, the baseline deployment plan is:

- one Imager operating the Full-Disk-Scan Service (instrument repeat cycle of 10 minutes, imaging the whole Earth) and one Sounder, co-located in the same longitude slot at 0°
- another Imager in charge of the Rapid-Scan Service (instrument repeat cycle of 2.5 minutes imaging Europe only) from 9.5°E longitude
- a fourth satellite may be simultaneously launched/deployed at 3.4°W longitude, for the commissioning phase.

The first MTG Imager (MTG-I1) will take over the services of the last satellite of the Second Generation (MSG-4, that will be relocated); it is to be noted that the 2 co-located Imager and Sounder will be nominally positioned in a slot at 0°, whose actual width is relatively wide, ±0.5°; the latitude oscillation could also be wide: during its operational service, the inclination is to be kept below 1°. The MTG deployment scenario is qualitatively represented in Figure 2: the various longitude slots are on the x-axis, as a function of time, on y-axis.

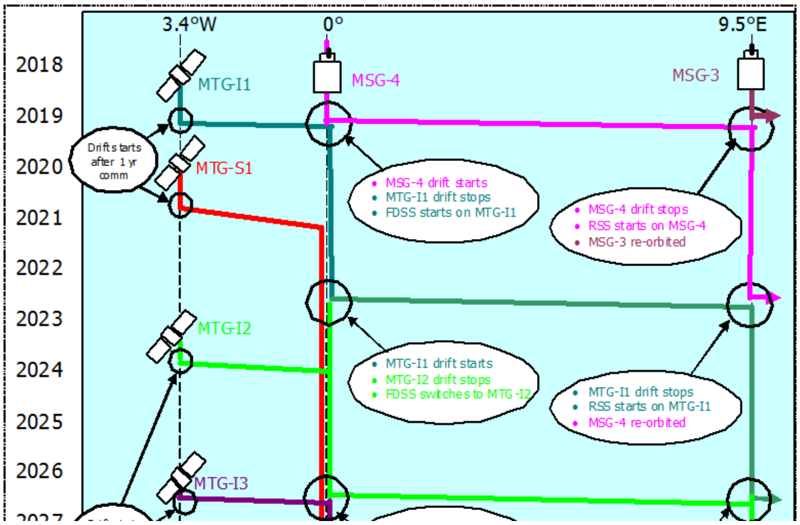

Figure 2: MTG deployment in the longitude slots

Due to the propulsion system design and accommodation, the maximum ΔV that can be delivered is 3.8 m/s; furthermore, when executing an out-of-plane ΔV, there is stochastic in-plane cross-coupling, in addition to a deterministic coupling in radial direction, for MTG is up to ~4%. The platform has 2 sets of thrusters for inclination control on 2 opposite satellite faces, allowing the execution of both North and South burns. The co-located satellites have to be kept at 1.15° angular separation, as seen from Earth, to receive telemetry from a single ground-station (as described in RD.7). Conjunctions in geostationary orbit are potentially harmful with a miss-distance of 5km; a minimum inter-satellite distance of 10km is a safe approach for constellation control.

The traditional co-location schemes by eccentricity/inclination (e/i) separation and longitude separation have been considered and analysed for MTG.

3. Co-location by e/i separation

This scheme is typically intended for multiple satellites in the same slot. It is based on the consideration that uncertainty in predicting the along-track separation of two spacecrafts (S/C) is generally much higher than the radial and cross-track. Due to the coupling between semi-major axis and orbital period, small uncertainties in the initial position and velocity result in a corresponding drift error, thus a growing along-track error. The predictions of the relative motion over extended time are therefore particularly sensitive to both orbit determination errors and manoeuvre execution errors. To avoid a collision risks in the presence of along-track position uncertainties, proper separation of two spacecrafts is desirable in radial and cross-track direction. For each S/C, we define the equinoctial eccentricity and inclination vectors from the standard formulation of non-singular geostationary orbital elements:

$$\begin{aligned} E_x = e_x = e \cdot \cos(\Omega + \omega); \quad I_x = \sin(i) \cdot \cos(\Omega); \quad i_x = +2\sin(i/2) \cdot \sin(\Omega); \\ E_y = e_y = e \cdot \sin(\Omega + \omega); \quad I_y = \sin(i) \cdot \sin(\Omega); \quad i_y = -2\sin(i/2) \cdot \cos(\Omega); \end{aligned} \tag{1}$$

e is the orbit mean eccentricity, *Ω* is the right ascension of the ascending node, *ω* is the argument of perigee and *i* is the orbit inclination (the other two remaining elements are the longitude and longitude drift rate). Different notations for the inclination vector exist in literature: they are both indicated here in Eq.1 for clarity, as they have been also both used in different phases of the MTG project. It is noted that, due to the geopotential and Sun/Moon effects on a near geosynchronous orbit, the inclination vector $I_{x,y}$ has a natural drift towards the +y, while $i_{x,y}$ towards the +x direction (that is in both cases the direction towards the vernal equinox). We indicate with *Δe* and *Δi* (or *ΔI*) the difference in eccentricity and inclination vectors of 2 co-located spacecrafts.

The e/i separation strategy (see RD.4) consists in modifying the eccentricity control circles of the collocated satellites, so that the vector difference *Δe* is large enough. The relative motion of one satellite with respect to the other is an ellipse in the equatorial plane, whose semi-major and semi-minor axes are respectively $2a_r*\Delta e$ and $a_r*\Delta e$ (a_r being the semi-major axis of the reference orbit of the satellites). An additional separation is obtained by separating the inclination vectors (difference *Δi*), which produces a sinusoidal relative motion in the normal to the orbit plane direction. The collision risk is defined by the minimum separation perpendicular to the flight direction, therefore the orientation of the relative eccentricity/inclination vectors is selected in such a way that the formation is always separated in the cross-track/radial plane, thus with *Δe* co-linear (parallel or anti-parallel) to *ΔI* (or perpendicular *Δi*, using the alternative notation). In contrast, perpendicular *Δe* and *ΔI* means that radial and cross-track separation vanish at the same time.

For the design of e/i separation scheme:

- Separation in eccentricity is achieved placing each eccentricity vector as far as possible from each other (i.e. placing the eccentricity vector of each S/C at the vertex of a regular polygon
- Separation in inclination is achieved in the same way. However, in order to achieve safe e/i separation, there is need for co-linearity between *Δe* and *ΔI* vector
- Control in eccentricity is done with standard sun-perigee pointing strategy, but the centre of the eccentricity circles is not at the origin. The relative configuration of *Δe* and *ΔI* is naturally kept, each eccentricity-vector describes a circle in 12 months; for each S/C, the eccentricity (longitude libration) changes in the year, larger in some seasons than in others.
- For the control in inclination: the configuration is naturally kept during free-drift periods (all inclination vectors move uniformly under the effects of Sun/Moon and Earth geopotential), but the inclination control manoeuvres distort the relative configuration; so, they need to be executed favourably from the inter-satellite distance standpoint: S/C lagging behind the inclination drift, need to be manoeuvred first.

Although very simple and robust, this strategy requires a high de-coupling between north-south (NS) and east-west (EW) station-keeping (SK): if a S/C is not especially designed with low cross-coupling effects, EW eccentricity correction manoeuvre needed right after NS manoeuvres.

Another implication of this scheme is that inclination needs to typically be controlled at all times and for S/C; This means that "inclined orbit" operations may not always be possible within the co-located fleet: as soon as one S/C stops its inclination control (as a natural way to extend its operational lifetime), it needs to be moved out of the e/i co-located slot (or the co-location has to be performed by longitude separation). The same applies for the beginning of life operations: limited lifetime extension is possible by placing the S/C at an initially high inclination against its natural drift, in case the S/C is to be co-located under an e/i scheme from the start.
In addition to Radio-Frequency, there are 2 interference events for e/i co-located satellites:

- Instrument interferences: one S/C gets in the FOV of the sensing instrument, e.g. in between Earth and interfered S/C, with possible degradation of the image of the interfered satellite
- AOCS sensor interference: one S/C gets in the FOV of an optical sensor, i.e. star tracker.

With e/i separation, the satellites can be in conjunction no more than two times per day, once a day in inferior conjunction (interfering) and once a day in superior conjunction (interfered). With more than 2 satellites co-located, the same apply to each individual pair.

4. Co-location by longitude separation

In this case, the co-located S/Cs are kept within non-overlapping adjacent longitude windows. Safety guard-bands (i.e. no-entry longitude regions) are specified in order to ensure minimum safety margins (minimum separation between S/C) in the following contingency cases:

- degraded orbit knowledge due to insufficient or temporary unavailability of tracking resources, or unexpected large biases in range measurements
- S/C anomaly, leading to either temporal lack of manoeuvrability capabilities on-board, or even to unintended ΔV (as in case of safe mode)

This co-location scheme is a-priori the simplest: each S/C can be controlled independently from the others. This scheme has anyway few important disadvantages:
- Relatively small number of S/C can be co-located within a ±0.1° longitude window
- Orbit determination errors are largest along-track, especially for single-station tracking-based systems, requiring large margins (safety guard-bands) and/or station cross-calibration
- In case of "missed-manoeuvre", the prescribed longitude windows are rapidly exceeded

The control by longitude separation can also be performed in overlapping longitude bands. The main advantage, when compared to the standard longitude separation, is that a higher number of S/C can now be controlled in the same longitude window. However, synchronized control cycles are now a must, complicating considerably the operations. Contingency scenarios are even more complex to cope with.
Related to interferences, if the satellites are separated in longitude, conjunctions should never occur (only during satellite relocations) since they are mainly separated in the EW direction.

5. Analytical longitude budget for co-location

The longitude budget is the total longitude window to be allocated to a given S/C in the co-location scheme; this section presents all the elements contributing to this: deterministic (A, B, C) and non-deterministic (from D to H); the analysis is a snapshot of what done in RD.5

<u>A. Amplitude of parabola due to Earth tesseral terms:</u> being $\ddot{\lambda}$ the longitude drift in °/day^2 and T the length of the station-keeping cycle in days, this contribution to the longitude budget is:

$$A = \frac{1}{2} \cdot \ddot{\lambda} \cdot \left(\frac{T}{2} \right)^2 \tag{2}$$

B. Longitude libration due to non-zero eccentricity: the solar radiation pressure is mainly affecting the equinoctial eccentricity vector. The perturbation creates a non-zero eccentricity, changing in direction throughout the year. Approximating, the eccentricity vector moves in a circle of fixed radius (natural eccentricity circle), with a period of a year, whose radius is:

$$e_{natural} = 0.011 \cdot (1 + \varepsilon) \cdot \frac{S}{M} \tag{3}$$

ε is the S/C reflectivity coefficient, S is the cross-section exposed to Sun and M is the S/C mass. In longitude-based co-location, the centres of the eccentricity circles are at the origin, to minimize the longitude libration. For e/i co-location, the centres are placed away from the origin, to reach separation in eccentricity. The maximum eccentricity reached throughout the year is:

$$B = 4 \cdot (e_{centre} + e_{control}) \cdot \frac{180}{\pi} \tag{4}$$

e_{centre} is the distance to the origin of the eccentricity circle centre (0 in the case of longitude-based co-location schemes), $e_{control}$ is the selected circle radius for orbit control.

C. Manoeuvre NS cross-couplings: the equations below give the changes in non-singular orbital elements by impulsive manoeuvre with radial, tangential, normal component Δv_R, Δv_T, Δv_N :

$$\Delta L = \frac{1}{v_{geo}} \cdot (-2 \cdot \Delta v_R - 3 \cdot \tau \cdot n \cdot \Delta v_T) \qquad \Delta n = -\frac{3 \cdot n}{v_{geo}} \cdot \Delta v_T$$

$$\Delta e_x = \frac{1}{v_{geo}} \cdot (\Delta v_R \cdot \sin\alpha + 2 \cdot \Delta v_T \cdot \cos\alpha) \qquad \Delta i_x = \frac{1}{v_{geo}} \cdot \Delta v_N \cdot \cos\alpha \tag{5}$$

$$\Delta e_y = \frac{1}{v_{geo}} \cdot (-\Delta v_R \cdot \cos\alpha + 2 \cdot \Delta v_T \cdot \sin\alpha) \qquad \Delta i_y = \frac{1}{v_{geo}} \cdot \Delta v_N \cdot \sin\alpha$$

α is the right ascension of the manoeuvre, τ is the time between the manoeuvre and the end of the cycle, L is the longitude, n is the mean motion and v_{geo} is the velocity on a near geosynchronous orbit (=3075 m/s). Using Eq.5, the NS manoeuvres contribution to the longitude budget in ° is:

$$C = 3 \cdot \tau \cdot \frac{X\%}{100} \cdot \Delta v_N \cdot \frac{\omega_s}{v_{geo}} + 2 \cdot \frac{R\%}{100} \cdot \Delta v_N \cdot \frac{1}{v_{geo}} \cdot (360/\pi) \tag{6}$$

X%, R% are respectively the normal and radial deterministic component of the cross-coupling, expressed as % of the NS manoeuvre size, ω_s is the Earth sidereal angular rate (360.98565 °/day)

D. Manoeuvre EW performance predictability: The contribution derived again Eq. 5 is:

$$D = 3 \cdot T^2 \cdot \frac{P\%}{100} \cdot \frac{\Delta v_{T\_YEARLY}}{N_{day}} \cdot \frac{\omega_s}{v_{geo}} \tag{7}$$

P% is the manoeuvre predictability, as a % of the manoeuvre size, T is the station-keeping cycle length in days and Δv_{T_YEARLY} is the total ΔV required to control the longitude over a complete year (e.g. 0.66 m/s at 0° longitude) and N_{day} is the number of solar day in one year (365.25 days)

E. Manoeuvre NS cross-coupling predictability: the previous contribution "C" is the deterministic part of the NS cross-couplings; the non-predictable part is:

$$E = 3 \cdot \tau \cdot \frac{XP\%}{100} \cdot \Delta v_N \cdot \frac{\omega_s}{v_{geo}} + 2 \cdot \frac{RP\%}{100} \cdot \Delta v_N \cdot \frac{1}{v_{geo}} \cdot (360/\pi) \quad (8)$$

XP% is now the NS cross-coupling predictability in along-track direction, RP% the same in radial, assumed to be a percent with respect to the total size of NS manoeuvre.

F. Initial longitude offset due to previous cycle: due to the non-deterministic effects on the previous cycle, independent from the current one, any cycle can start with a random offset value, given by the Root of the Sum of Squares of the contribution D and E.

G. Orbit propagation error, along-track: it depends on the tracking system; the along-track orbit determination error contribution (the part not propagating further along the cycle) is:

$$G = \frac{180}{\pi} \cdot \tan^{-1}\left(\frac{\delta_{AT}}{a_{GEO}}\right) \quad (9)$$

a_{geo} is the geosynchronous-orbit radius (42164.125 km) and δ_{AT} is the longitudinal uncertainty in km (measured along the S/C velocity direction at a_{geo} altitude)

H. Orbit propagation error, semi-major axis: an error in estimating the semi-major axis translates in a change in the longitude drift rate. The contribution to the longitude budget is:

$$H = -\frac{3}{2} \cdot \frac{\omega_s}{a_{GEO}} \cdot T \cdot \Delta a \quad (10)$$

Total longitude error is the sum of deterministic with the Root of the Sum of Squares of the non-deterministic components: $\mathrm{A} + \mathrm{B} + \mathrm{C} + \sqrt{D^2 + E^2 + F^2 + G^2 + H^2}$ (11)

6. Longitude budget for MTG

The following are the assumptions and results for the MTG longitude budget.

Maximum inclination drift per year	0.95	°/y
Mass in-orbit	1337	kg
Cross section	20.285	m^2
Reflectivity coefficient	0.22589	[-]
ΔV for inclination control	50.985	m/s
Days between NS and WE manoeuvres	2.5	days

NS Cross-coupling Along-Track	0	%
NS Cross-coupling Radial	9.2	%
EW performance predictability	2	%
Cross-coupling predictability	1	%
Orbit determination error (along-track)	2000	m
Orbit determination error (semi-major axis)	26.4	m

			Longitude separation (Adjacent)			Longitude separation (Overlap)			e/i separat.
	Cycle specifications	Unit	2 S/C	3 S/C	4 S/C	2 S/C	3 S/C	4 S/C	2 to 4 SCs
	Eccentricity control radius	-	0.000138	0.000138	0.000138	0.000138	0.000138	0.000138	0.000138
	Eccentricity centre offset	-	0	0	0	0	0	0	0.000125
	Longitude of the slot centre	°	0	0	0	0	0	0	0
	Longit. Window width per S/C	°	0.1	0.0667	0.05	0.108	0.075	0.052	0.2
	Cycle duration	day	16	9	5	17	11	6	27
	Max N/S manoeuvre size	m/s	2.235	1.257	0.698	2.375	1.537	0.838	3.771
	Deterministic Contributions								
A	Amplitude of parabola	°	0.021	0.007	0.002	0.023	0.01	0.003	0.059
B	Longitude libration due to e	°	0.032	0.032	0.032	0.032	0.032	0.032	0.06
C	Cross-coupling	°	0.015	0.009	0.005	0.016	0.011	0.006	0.026
	Stochastic Contributions								
D	E/W predictability	°	0.003	0.001	0	0.004	0.002	0	0.009
E	Cross-coupling predictability	°	0.021	0.012	0.007	0.023	0.015	0.008	0.036
F	Initial longitude offset	°	0.022	0.012	0.007	0.023	0.015	0.008	0.037
G	Orbit det. error (along-track)	°	0.003	0.003	0.003	0.003	0.003	0.003	0.003
H	Orbit det. error (semi-major a)	°	0.005	0.003	0.002	0.006	0.004	0.002	0.009
	Longitude budget								
	$A+B+C+\sqrt{(D^2+E^2+F^2+G^2+H^2)}$	°	0.099	0.064	0.048	0.105	0.073	0.052	0.199
	Margin to longitude window	°	0.001	0.002	0.002	0.003	0.001	0	0.001

The final margins are due to the fact that integers are used (not decimals) for the days in the cycle duration: this is done to easily compare co-location scheme and operational load on the basis of station keeping control cycles in days. From the practical point of view, it is operationally convenient to schedule station keeping cycles as multiple integers of calendar weeks, i.e. for regular pattern and to avoid operations over week-end.

The yearly ΔV needed for eccentricity due to a control radius different from the natural radius is:

$$\Delta V = \pi \cdot \mathrm{v}_{\mathrm{geo}} \cdot \left(e_{control} - e_{natural}\right) \qquad (12)$$

The eccentricity circle radius and offset are designed according to the natural eccentricity, for a cost neutral eccentricity control (performed with single-burn, with semi-major axis corrections).

The budgets above are computed for 0° longitude slot; the same analysis has been performed also at ±10° longitude slot (limits for the nominal MTG operations). The case related to e/i separation is valid for a number of spacecraft from 2 to 4, while for the longitude separation scheme, the allocation of the longitude window is dependent on the number of S/Cs.

For the longitude separation in overlapping band, with perfect station-cycle synchronization, the overlap can be increased by 0.016, i.e. 11.5 km (element A). Using a more realistic and conservative ±4 days synchronization, the gain overlap was set to 0.008 deg, i.e. 5.9 km. Each S/C could therefore occupy 0.108 degree longitude window. The overlap is done keeping the same total longitude band of 0.2° total width, while this could be actually increased (see next section). The case with 4 SCs shows to be clearly too demanding with the longitude separation schemes, with manoeuvres more frequent than weekly.

7. Station-keeping manoeuvres simulation and trade-off analysis

The MTG system is designed to operate in the most demanding scenario. As seen in section 2, there could be up to 4 MTGs in-flight at the same time; the MTG system is required to allow their operations in a slot of ±0.1º longitude (0.2° width). As from the previous section, due to the manoeuvre frequency, the most convenient co-location strategy for 4 S/Cs is the e/i separation. This scheme has been used as baseline for the space segment procurement and mission analysis: a 28-day control cycle for each satellite, with a single NS inclination control manoeuvres (with magnitude up the maximum of 3.8 m/s), followed by a EW as a single burn for both longitude and eccentricity control, also to correct eventual non-deterministic cross-coupling after NS.

Indeed, this control scheme requires monthly execution of inclination manoeuvres; these are treated in EUMETSAT as special operations: it may easily end up in high workloads, in intense manned support and also in frequent service outages associated with each NS ΔVs.

As said, driver for selecting this scheme was mainly the possibility of controlling 4 S/Cs in the same slot, but this scenario is actually never present in the MTG deployment: only 2 S/Cs are co-located (see section 2). In addition, the dead-band for longitude control of ±0.1º is stricter than what is actually available to EUMETSAT from the ITU frequency registration point of view, for the slot at 0º longitude (that is ±0.5º).

The actual deployment scenario and available margins triggered further analyses of alternative station-keeping schemes. These have been performed with EUMETSAT Station-Keeping Analysis Tool (SKAT, see RD.6); the tool allows automated manoeuvre planning and end-to-end simulations with high-fidelity models, for both space environment and satellite performances.

All the simulations consider the current baseline of the MTG Full-Operation-Capability that is 2 spacecrafts in co-location. Instead of e/i vector separation scheme, the co-location by longitude separation is deeply investigated, because of its advantages for NS execution and interferences.

The simulation scenarios foresee the execution of NS manoeuvre (single or in sequence) 1 day inside the start of a specific manoeuvre cycle, followed by an EW manoeuvre at the end of the NS manoeuvre or sequence (at least 1 day after).
To better compare the effects of the various strategies on the in-plane station-keeping control only, all the NS have been assumed to have magnitude of 3.8 m/s, according to sponge refill limitations of the MTG thrusters' PMD (Propellant Management Device). In order words, the optimisation of NS consumption (that is the major contributor to the propellant and lifetime optimisation) is analysed separately: as demonstrated with the previous generation of Meteosats, the lifetime can be optimised when considering together the target orbit for the LEOP and the resulting station keeping costs, function of the transfer orbit node, inclination and launch date (as detailed in RD.8).
Common simulations setting have been chosen to represent as closely as possible the MTG-I/S spacecrafts performance, such as different masses for the S/Cs according to their lifetime while in co-location (1892kg for MTG-S and 2067kg for MTG-I) and different thrusters performances (thrust level, specific impulse) for each plate on each spacecraft. All the simulations are based on numerical integration of the dynamics equations, considering the effects of Earth geopotential (36x36), solar radiation pressure, third-bodies (Sun and Moon); in addition, the effect of manoeuvres are propagated as continuous burns, according to the specific control logic of each of the scenarios. The simulations start on 2026-Dec-01 (maximum inclination natural drift). The longitude slot assumed is at 0°. The MTG mission also foresees a seasonal flip in yaw at the equinoxes for thermal reasons: these are also simulated, with execution of yaw-flip manoeuvres on the 20/March and 20/September; this is affecting the selection of the thrusters' plate to be used, according to the selected ascending/descending node for the NS manoeuvres.

Specific settings have been assumed for the station-keeping control and/or thrusters handling during manoeuvres. These have been be grouped in 3 main cases, according to the duration of the manoeuvres cycles. In all, the inclination is controlled with a 0.5° absolute deadband, with dedicated control settings for the 3 cases. The control dead-band for longitude and eccentricity are selected accordingly to the various manoeuvres cycles, as follows.

- Case 1: manoeuvres cycle of 28 days; the inclination control has 2 sub-circles of 0.07° radius, placed internally and tangent to the absolute circle, in the intersection of this with x-axis of the True-of-Date frame. The longitude is controlled in adjacent bands of 0.1° around 0°. It is to be noted that the inclination dead-band is selected this way, to force the execution of 1 NS manoeuvre per cycle, in magnitude equal to the maximum allowed of 3.8 m/s.
- Case 2: manoeuvres cycle of 56 days; the longitude dead-band is enlarged accordingly, but keeping the 0.1° East limit (so shifting the control band centre westwards), just for simplicity in simulation setup. The inclination control has 2 sub-circles of 0.1° radius. With double duration of the manoeuvre cycle and twice the inclination dead-band, in this case it will be necessary to execute 2 NS per cycle per spacecraft.
- Case 3: manoeuvres cycle of 112 days; the longitude control is further enlarged accordingly, again keeping the 0.1° East limit (so shifting the control band centre westwards), just for simplicity in simulation setup. The inclination control has 2 sub-circles of 0.2° radius. In analogy with the previous Case 2, the manoeuvre cycle is 4 times the one of Case 1, so it will be necessary to execute 4 NS per cycle per spacecraft.

For each of the 3 main cases, there are 6 sub-cases to investigate the effects of the thrusters' radial cross-coupling when executing a NS (that is a strong deterministic effect for MTG)

a) / b) 0% radial cross -coupling, 24 hours between NS, without/with eccentricity control

c) / d) ±4% radial cross-coupling, 24 hours between NS, without/with eccentricity control

e) / f) ±4% radial cross-coupling, 12 hours between NS, without/with eccentricity control

g) Yaw bias for NS with combined EW control, Roll bias for radial cross-coupling

The cases a),b) are ideal, with no radial coupling, to be used for comparison with the more realistic cases after. In these cases c), d), e), f), the magnitude of the radial cross-coupling is compatible both in sign and magnitude with the envelope of deterministic MTG thrusters' performance during the station-keeping lifetime. The idea of the subcases e) and f) is to try to self-compensate the radial coupling exploiting the 2 North and South thrusters plates, alternating their use within half-orbits. The eccentricity control is deactivated or activated, to highlight the difference of a controlled behaviour versus the cost-free natural eccentricity evolution: when it is activated, the longitude control is combined with a passive eccentricity control with single-burns if feasible (simply selecting appropriately the EW execution time for proper eccentricity steering, in sun-perigee pointing strategy), otherwise double burn are implemented (with subsequent propellant penalties). For the eccentricity control, the dead-band is set to $2.0*10^{-4}$ for the mean eccentricity (that is the actual control dead-band) and $3.5*10^{-4}$ for the osculating eccentricity (limit used just for monitoring) with an offset in y-direction of $\pm1.0*10^{-4}$ for the eccentricity circles centres (the offset is used to force a safer configuration of the constellation, with respect to the relative inclination; indeed, it is not strictly necessary for this kind of co-location scheme, as the separation is obtained with longitude; the centre offset could be also set to 0, to reduce the maximum longitude libration during the year).The subcase g is implemented to show the effect of executing combined NS and EW control: this is performed obtaining the desired in-plane component during NS manoeuvres, by means of implementing a Yaw bias of the platform, having full attitude bias control during manoeuvre (as from MTG attitude control system); in this subcase, it is assumed also to impart a Roll bias to cancel the deterministic radial cross-coupling. The NS have to be executed at the orbit nodes, therefore fixing the execution time: this cannot be freely selected anymore for eccentricity control, as it was for dedicated EW manoeuvres; in this case, it is therefore not possible by definition, the natural eccentricity drift is only to be monitored (eventually from time to time, with a single dedicated EW).

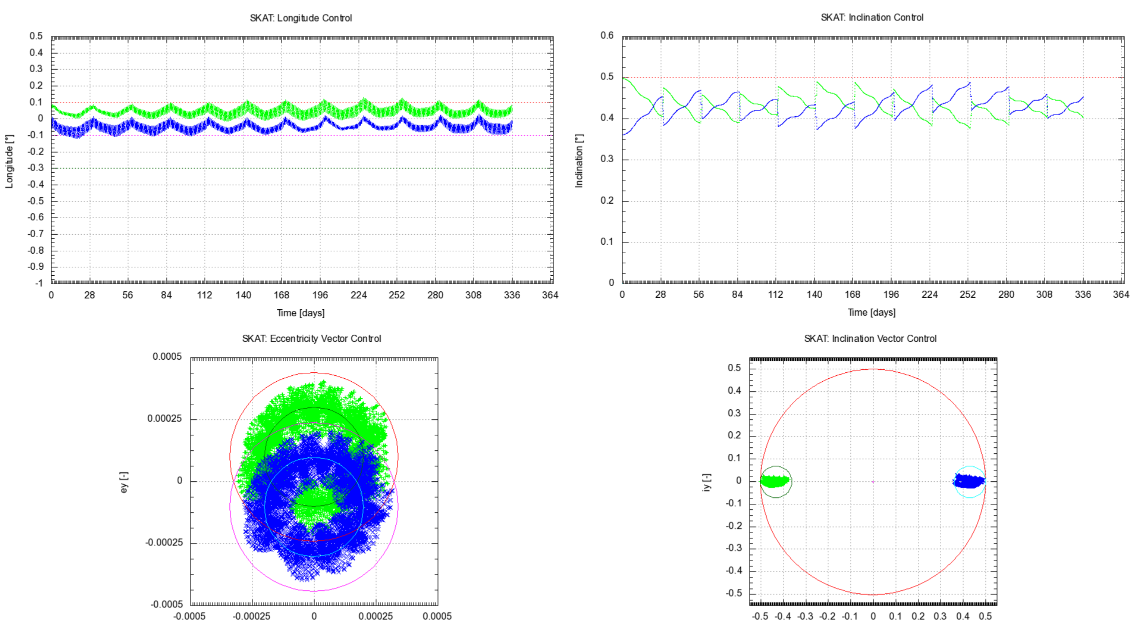

Figure 3: Case 1f, 28 days cycle, ±4% radial X-coupling, ecc.control, 12 hours between NS

The typical output of the simulations is the execution time and size of the planned manoeuvres, together with the orbital elements evolution, as shown in Figure 3, Figure 4, Figure 5: the 2 top plots give the evolution in time (elapsed days) of longitude and inclination, while the bottom plots give the equinoctial eccentricity $e_{x,y}$ and inclination $i_{x,y}$ (as defined introduced in Eq.1). Green lines are used for MTG-S, blue for MTG-I.

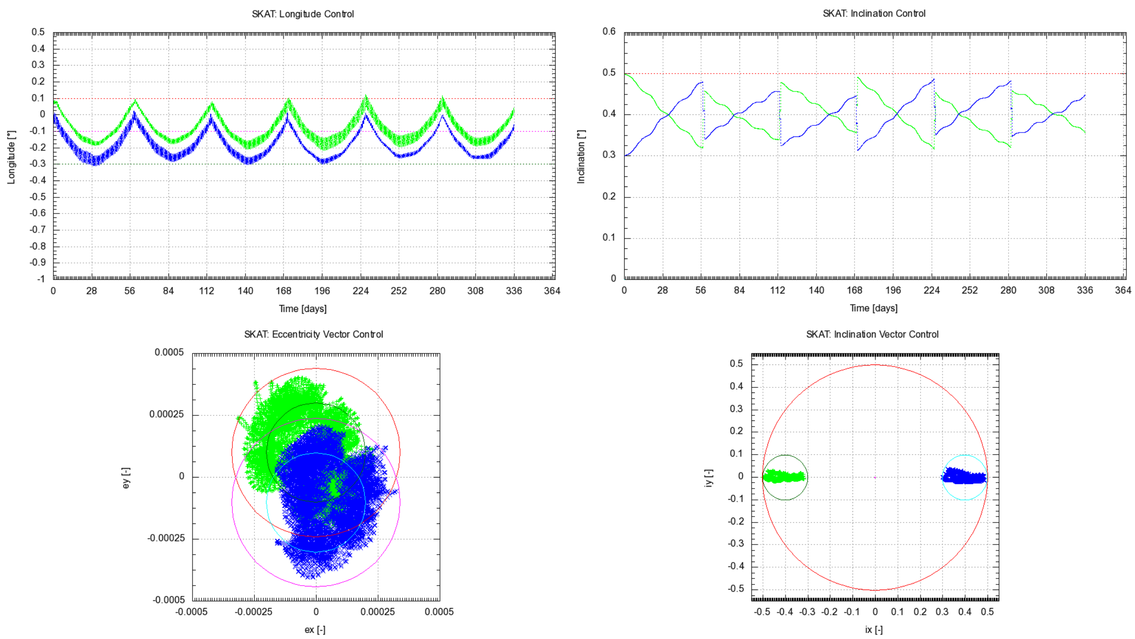

Figure 4: Case 2d, 56 days cycle, ±4% radial X-coupling, ecc.control, 24 hours between NS

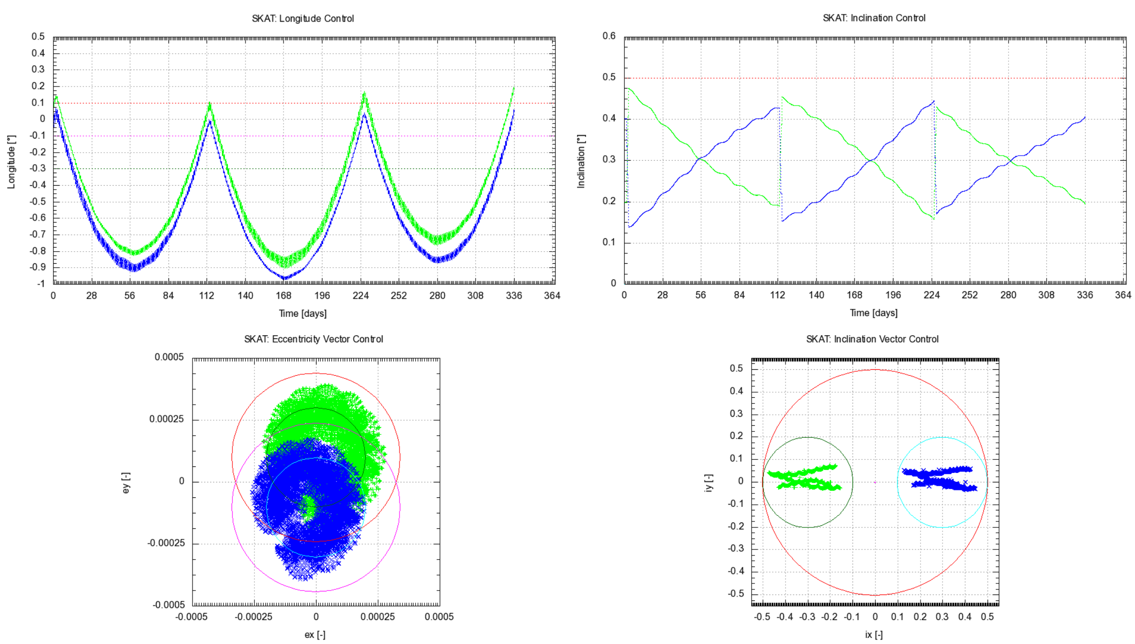

Figure 5: Case 3g, Yaw bias for combined NS+EW control, Roll bias for radial X-coupling

The following is the summary of the EW station-keeping cost in the various cases, after 336 days simulation. (the results of subcase g are omitted, simply because they matched his definition, giving 0 dedicated EW manoeuvres).

	Case1				Case2				Case3			
	MTG-S		MTG-I		MTG-S		MTG-I		MTG-S		MTG-I	
	N man.	ΔV [m/s]	N man.	ΔV [m/s]	N man.	ΔV [m/s]	N man.	ΔV [m/s]	N man.	ΔV [m/s]	N man.	ΔV [m/s]
a	12	0.5936	12	0.5884	6	0.5630	6	0.5579	3	0.5957	3	0.5912
b	12	0.5934	12	0.5888	7	0.5636	6	0.5583	5	0.5955	3	0.5908
c	12	0.5930	12	0.5891	6	0.5621	6	0.5588	3	0.5948	3	0.5920
d	14	0.7556	14	0.7209	8	0.7201	7	0.7054	5	0.6778	4	0.7937
e	12	0.5951	12	0.5911	6	0.5624	6	0.5586	3	0.5951	3	0.5924
f	12	0.5951	12	0.5915	7	0.5631	6	0.5592	5	0.5966	3	0.5942

As expected from the analytical budget, Case 1 results show that the co-location scheme by longitude separation cannot be maintained with 4 weeks period for longitude control; violations of the longitude dead-band ±0.1° will occur regularly; a tighter 2 or 3 weeks cycle should be implemented, or the longitude band increased accordingly.
From the subcases a) and b), it can be seen in all Cases that the selected bandwidth for eccentricity control gives a total cost that is nearly the same of the case with control deactivated (that is: the control as designed can actually be accommodated with a single burn, just adjusting the time of the manoeuvre for eccentricity control; no EW double burns are necessary). As a difference, introducing a systematic radial cross-coupling and comparing c) and d) , the active eccentricity control has evident propellant cost; in addition, c) results shows also that an eccentricity control is actually needed, to avoid eccentricity divergence in case the evolution is left to the natural drift only. This is the same for all subcases c). In all Cases, from results of subcases e) and f), the effectiveness of the strategy is evident: when using alternate North and South burns with half-orbit separation, this allows keeping low stable eccentricity even without active eccentricity control, but also with active control at practically the same costs.
Case 2 and 3 show the feasibility and benefits of increasing the duration of manoeuvre cycles: less frequent manoeuvres organised in batches are possible when tolerating a wider East/West boundaries for longitude control; these are anyway within 1° longitude total band, that is the bandwidth already used operationally for the second generation of Meteosats, and foreseen by the current MTG ITU frequency registration.

In all simulations, the minimum and maximum inter-satellite distance is monitored: the maximum distance is always kept below the required 1.15° (for using a single station for the 2 satellites); its maximum are 1.04° for the Case 1, 0.91° for Case 2 and 0.77° for Case 3 (more or less similar in all subcases). In addition, the minimum distance is kept always above 35 km, excluding subcases c), that have eccentricity divergence (here, it goes down to 11 km).
In the dedicated Case 3g, it can be seen that, even if the manoeuvres are not planned in optimal time for eccentricity correction, their split and execution within half-orbit allows for proper automatic compensation of this the radial cross-coupling: the eccentricity drifts according to its natural evolution due to solar radiation pressure effects, without impact in the constellation control: if a platform roll bias is implemented, the deterministic effect of the radial cross-coupling can be cancelled a-priori (thus allowing manoeuvres every 24 hours without eccentricity perturbation due to NS). In this scenario, it is possible to skip at all the execution of dedicated EW manoeuvres; the implicit use of NS manoeuvres for EW control will of course impact in the long term the NS ΔV budget, but due to the relative size (about 1/100), this can be accommodated with slight modification of the NS control dead-bands. The advantages of this

approach are evident, due to the overall reduction of executed manoeuvres, related service outages, and overall operational load.

8. Conclusions

This paper introduced the possible co-location schemes for MTG, and it showed the feasibility of from the analytical point of view. Then, taking into account the actually foreseen deployment scenario for MTG and its wide control limit for both inclination and longitude, the co-location of 2 spacecraft by longitude separation was analysed in depth. The final recommended control solution for station keeping of the co-located MTG satellites is the execution of NS manoeuvres with combined EW control in manoeuvre cycles of ~112 days, arranged in manoeuvres batches with half-orbit separation. The NS and EW can be combined with yaw bias of the platform, while roll bias allows cancellation of radial deterministic cross-coupling.
The proposed strategy allows:

- Reducing the number of manoeuvres, combining EW to NS manoeuvres
- Longitude control with wider bandwidth (1°), anyway within slot registered for MTG
- Keeping the required maximum angular separation of 2 spacecrafts (for using the same antenna for both) and keeping a minimum safe distance, for mitigation of conjunctions risks
- Minimum perturbation on the eccentricity/collocation control due to radial cross-coupling, thanks to the auto-compensation by means of splitting manoeuvres every half orbit
- Diminution of the operational workload, with less frequent planning of manoeuvres, executed in campaigns
- Higher flexibility in planning manoeuvres (scheduling of manoeuvres campaign in adequate and/or convenient slot, from the spacecraft or ground segment standpoint)
- Reduction of the potential service outages (due to the overall reduction of executed manoeuvres)

Future analyses will cover the handling of different cycles duration for NS and EW to tune the control bandwidth (i.e. NS cycle duration integer multiple of EW cycle), also with the introduction of realistic manoeuvres errors (stochastic performances, missed manoeuvres, etc..)
In addition, the NS propellant optimisation will be investigated, as done for the previous generations of Meteosat: this involves the positioning of the routine phase inclination control circle in the $i_{x,y}$ plane, considering the LEOP and Station-Keeping costs combined.

9. Reference documents

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RD.8 Pessina S., Klinc M., “Mission Analysis For Msg-3&4 Considering Combined LEOP/Station-Keeping Costs and In-Orbit Storage” 24th ISSFD by APL, Laurel, Maryland, USA, May 2014