HIGH FIDELITY END-TO-END ORBIT CONTROL SIMULATIONS AT EUMETSAT

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Abstract: *End-to-end orbit maintenance operations for Low Earth and Geostationary missions are simulated in a realistic and high fidelity manner, taking into account all processes and logic of real operations. This includes variability of space environment, orbit determination uncertainties, maneuver predictability issues, time constraints between the different on-ground processes, other operational constraints (such as eclipse related) and well defined contingency scenarios implemented over simulated time in a stochastic manner. This simulation concept is implemented on the basis of currently available technologies, and its use demonstrated with current and future EUMETSAT satellite systems. The operations to date of Metop-A Sun-Synchronous Orbit (SSO) satellite (launched in 2006) are mimicked and then projected to a possible end-of-life. The future Sentinel-3 SSO operations are then analyzed and orbit maintenance strategy fine-tuned accounting for all known uncertainties. Finally, long term constellation simulations are performed for the Meteosat Third Generation geostationary program. These include standard longitude separation as well as alternative eccentricity/inclination co-location. The evolution of key performance parameters, like minimum inter-satellite distance or maximum angular separation as seen from a given on-ground antenna (necessary for keeping the antenna sharing operational concept), is shown under realistic and operational conditions.*

Keywords: *Low Earth Orbit, Geostationary Orbit, Maneuver design, Simulation, Real operations.*

1. Introduction

EUMETSAT is the European Organisation for the Exploitation of Meteorological Satellites. Its main purpose is to deliver weather and climate-related satellite data, images and products 24 hours a day, 365 days a year. For fulfilling its mission, EUMETSAT operates a fleet of meteorological satellites. Our present system includes two generations of geostationary Meteosat satellites. Their global overview is complemented by the detailed observations provided by the polar orbiting Metop satellite(s) and the marine observer Jason-2, a joint project of space agencies in Europe and the United States. In parallel, EUMETSAT prepares next European operational meteorological satellite systems, notably Meteosat Third Generation (MTG) and EUMETSAT Polar System (EPS) Second Generation (EPS-SG). Other future satellites in preparation include Jason-3 under a program led by EUMETSAT and NOAA, and GMES Sentinel-3 satellites, a Low Earth orbiting mission to support services relating to the marine and global land environment and for which EUMETSAT will become operator.

According to the EUMETSAT policy principles, their activities shall be implemented in a manner which is affordable for its Member States and achieves best value for money and cost-effectiveness.
In the frame of system engineering support activities to current and future programmes, and in view of currently available technologies, the need was identified for realistically modelling with sufficient fidelity Orbit Maintenance Strategies for LEO (Low-Earth-Orbit) & GEO (Geostationary) orbits of interest to EUMETSAT. In particular, it was required to propagate orbits over long time spans (up to full satellite lifetimes), allowing for the implementation of maneuver planning and implementation concepts in the propagation process (including major propagation and maneuver uncertainties as well as “missed maneuver” scenarios) and analyzing a number of resulting performance parameters applicable to single spacecraft (number of maneuvers, delta-V and their temporal distribution, effective control achieved and box violations, if any) or spacecraft pairs (inter-satellite distance or angular separations as seen from ground antennas).

2. The Station Keeping Analysis Tool

Classical Mission Analyses are typically based on perturbation analysis and individual considerations derived mainly from experience. These are very useful for providing key insight into orbit maintenance activities and related operations. When it comes however to real operations, these preliminary analyses need further optimization, for incorporating certain operational aspects: robustness to anomalies or certain degraded scenarios (including sufficient control margins, maneuver re-planning for a day later...) or other operational constraints such as the necessity of maneuver execution during working hours, for cost saving purposes. In some cases marginal violations of the station keeping windows can even be allowed, but a quantification of these is difficult until real operations take place.
Thanks to the exploitation of currently available technologies, high-level programming languages and associated packages in the area of space flight dynamics, it was felt possible, as well as convenient from the precise operations analysis standpoint, the implementation of end-to-end orbit maintenance operations simulations in a realistic and high-fidelity manner, accounting for all processes and logic of real operations. This includes variability of space environment disturbance with respect to predictions (i.e. air-drag and solar radiation pressure), orbit determination uncertainties, maneuver predictability issues, maneuver cross-coupling effects, maneuver implementation issues (quantization, long burn effects), time constraints between the different on-ground processes, other operational constraints (i.e. eclipse related, working hours) and even well-defined contingency scenarios (implemented over simulated time in a stochastic manner).
A prototype station-keeping simulator, named SKAT (Station Keeping Analysis Tool), was developed in Java and fulfilling all previously described requirements (see [1]). SKAT was built upon two external components:

- The Orekit space flight dynamics library [2], providing all flight dynamics features like orbit propagation, time, frames as well as useful mechanisms like event detection and step handlers that can be used to monitor propagation
- The Apache Commons Math mathematical library [3], providing all mathematical algorithms such as random generator or curve fitting

The implementation was meant to be flexible enough to allow the simulation of different types of station keeping control strategies and to take various mission profiles or constraints. The design, highly modular, is depicted in Fig. 1. New types of controls or constraints can be added as necessary. The main loop is shown in Fig. 2. The propulsion system is modelled separately per maneuver type and including blow down effects over lifetime, thrusters force vectors and performance curves, cross-couplings (deterministic as well as uncertainties) and performance uncertainties. Maneuver planning can be performed with a number of predefined orbit controls, either on the basis of fixed-length cycles or just boundary violations:

- for GEO, classical longitude, eccentricity (sun perigee pointing) and inclination controls, including compatibility with e/i co-location control schemes
- for LEO, inclination, Mean Local Solar Time (MLST) and grid (Ground Track) controls

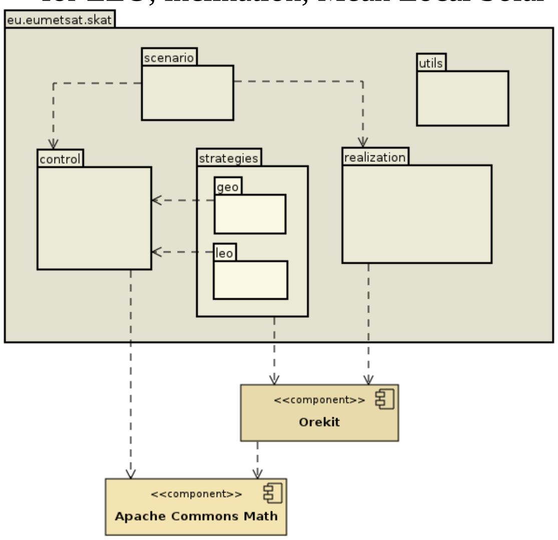

Figure 1. SKAT packages and two external dependencies

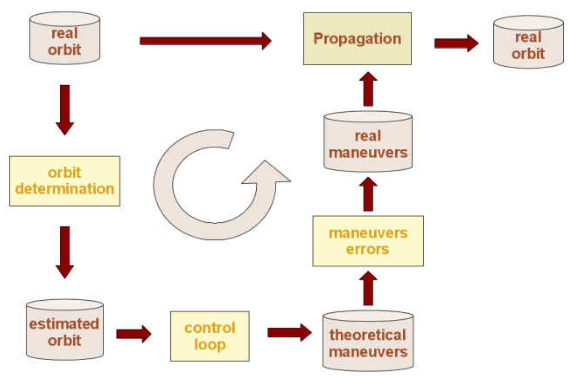

Figure 2. SKAT main internal loop

Other features include orbit determination and propagation (perturbation) uncertainties, and time constraints or delays between processes (such as orbit determination and first maneuver time opportunity, or between maneuver types belonging to same cycle). Montecarlo analyses are also possible, by which each run is performed varying given user-defined configuration parameter(s). The full implementation, object oriented, resulted in just about 6000 lines of code (comments and blank lines removed). In terms of CPU time performances, Tab. 1 shows these for a typical dual core 3-year-old PC (Pentium Dual-Core CPU E5400@2.70GHz, 3.2 Gb RAM)[1].

Table 1. CPU Typical time performances achieved

Case, main characteristics:	CPU time
10 year simulation of 2 GEO s/c, numerical propagation with 6x6 gravity field, Sun & Moon attraction and Solar Radiation Pressure, 4-week maneuver cycle with controls on longitude, eccentricity and inclination with just north/south and east/west maneuvers, 5% missed maneuvers, usual realistic uncertainties.	20 minutes
10 year simulation of 1 LEO SSO s/c, numerical propagation with 8x8 gravity field, Sun & Moon attraction, Solar Radiation Pressure and air drag (NRLMSISE-00, solar activity based on MSFC MSAFE), 4-week horizon time control with controls of +/-2 min in MLST and +/-5Km in Ground Track (grid-based, along-track), 5% missed maneuvers, usual realistic uncertainties	40 minutes

[1] Orekit is currently not thread-safe yet. Performance is expected to improve in the future.

Noting the CPU time performances of single end-to-end simulations from Tab. 1, one can see that multiple Monte Carlo simulations would still be affordable in days to weeks of CPU time, depending mainly on time spans to be simulated, number of simulations and level of fidelity.
The main aim of this paper is however to present the results obtained by such implementation in the frame of a number of real application cases, and the usefulness and potential of these results as opposed to more basic classical mission analyses studies. This is what will be shown in the next sections, and in particular in the frame of Metop-A/B, Sentinel-3 and MTG satellites/programmes.

3. Metop-A/B operations

Metop-A is a 4 ton satellite launched in October 2006 with a planned lifetime of 7 years and flying on a repeating sun synchronous orbit with a 29 day repeat cycle (14+6/29). Its ground track is to be maintained within 5 km, constraint derived from the calibration needs of ASCAT instrument (given viewing geometry to be maintained from on-ground transponder over Turkey). This constrain can normally be relaxed in real operations and in liaison with users and experts.
The MLST is also to be maintained within 2 minutes from 9:30 at descending node and also for the sake of GOME instrument calibration (sun within a given field of view over the entire year). Operations could however be fulfilled with MLST within 30 minutes from nominal, where sun would definitely get out of the AOCS sun field of view. This opens the possibility for lifetime extensions with relaxed MLST control and only some degraded performance from some instruments. Moreover, no fuel was allocated for End of Life Disposal operations, although a large amount was allocated for AOCS contingencies and can definitely be used for EOL operations. A more detailed description of EOL Metop-A can be seen in [4].
Regarding orbit control and maneuvers, the reader should refer to papers [5], [6] and [7]. In particular, out of plane maneuvers are to occur within eclipse, pre- and post-maneuver slews are performed on thrusters and cost a non-negligible amount of fuel, and number of maneuvers is to be minimized for maximizing service. In turn, these maneuvers are performed around the autumnal equinox, where eclipse is larger and better centred around the node, and the total delta-V to be implemented is segmented in 2, 3 or 4 burns maximizing each burn the eclipse occupation (at least 80% of eclipse useful time for manoeuvring is typically occupied). As tanks deplete, pressure inside decays, and same delta-V required longer durations, which is also to be considered.

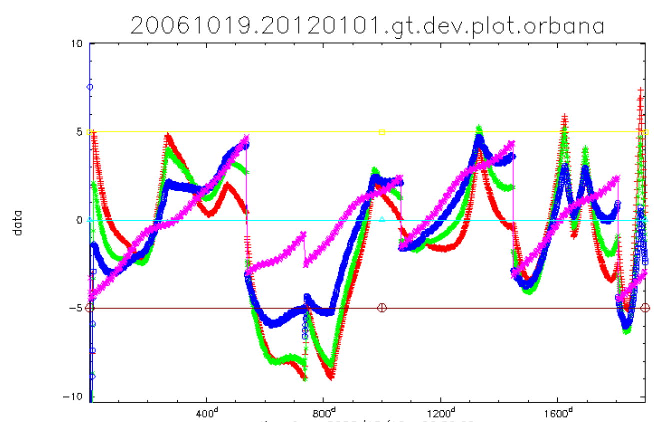

Figure 3: Metop-A Ground Track deviation [km] from launch (in October 2006). Over ascending passes at 0° (red), 30° (green), 60° (blue) and maximum (pink) latitudes

An end-to-end modelling of Metop-A past operations is performed. For this, an Orekit-provided high fidelity numerical propagator is used with perturbation forces including Earth gravity field (36x36), air drag model based on NRLMSISE-00 Earth atmospheric model with future solar activity estimates from MSFC (MSAFE average is used) and a 50% three sigma uncertainty on the ballistic coefficient at the time of in-plane maneuver control check and planning. The spacecraft (S/C) characterization includes propulsion system modelling. The Ground Track control is performed with in-plane corrections only, based on semi-major axis control (orbital period is adjusted to adapt the times the spacecraft crosses the reference latitudes). In this case, only true equator crossings are considered. This control was implemented with enough versatility and simplicity for allowing both automated in-the-loop control as well as reasonable CPU performance. For this, the control uses a parabolic ascending node mean evolution model, obtained by simple fitting and performs a maneuver maximizing staying in the GT dead-band if a violation is conservatively predicted to occur within a so-called configurable "horizon time" for in-plane control. The other control used is an MLST control, which drives the need of out-of-plane (or inclination) maneuvers. For this, the maneuvers are scheduled at a fixed day of the year around the autumnal equinox: the eclipse constraint is properly considered, the maneuvers are segmented in several delta-V each occupying at least 80% of the eclipse useful duration (for optimizing fuel consumption); additionally the maneuvers are only implemented if a violation at the lower dead-band is expected to occur before the next maneuver opportunity, and these are sized as much as possible to achieve the upper dead-band.

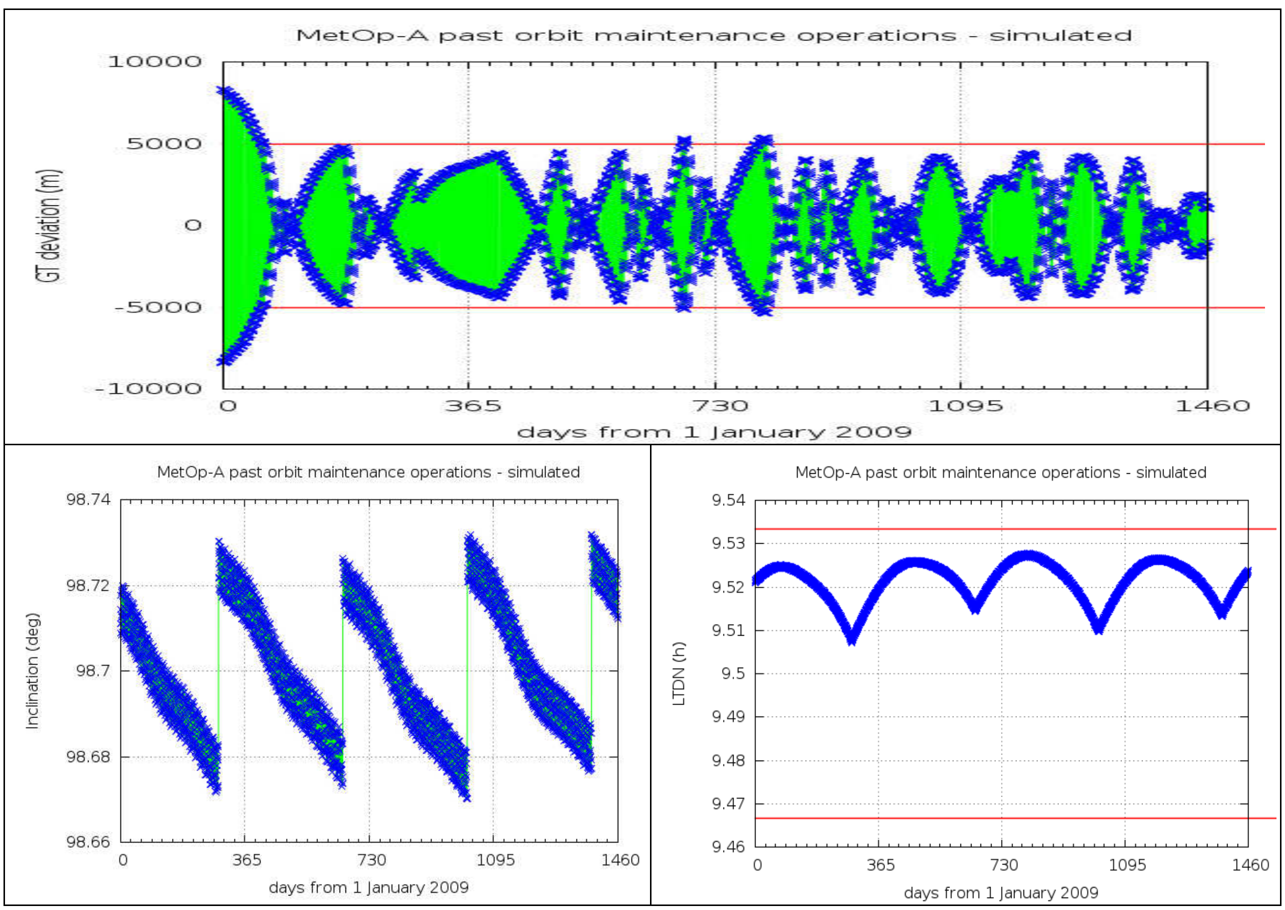

Figure 4: Simulated Metop-A GT deviation, Inclination (Mean of Date) and Local Time at descending node evolutions from 1 January 2009

The results for a simulation covering from 1 January 2009 until 1 January 2013 are shown in Fig. 4. The resemblance with out-of-plane real control is clear, since this is more deterministic and better predictable than the in-plane control performance, which is mainly driven by air drag uncertainty. The in-plane control is obviously different, but provides comparable results in terms of delta-V and number of maneuvers (real operations perform less maneuvers but also allow a larger number of GT violations).
Figure 5 shows another simulation taking actual Metop-A state and conditions in September 2012 (as of writing these lines) and projecting operations for a hypothetical scenario until EOL. A last out-of-plane maneuver is performed in 2012 allowing for other 1.5 years of nominal operations and thereafter a further 2 year extension with no inclination control and degraded performance (MLST constraint violated) could still be possible and before the S/C is de-orbited (in 2016). The Ground Track control is kept, although only at equator crossings.

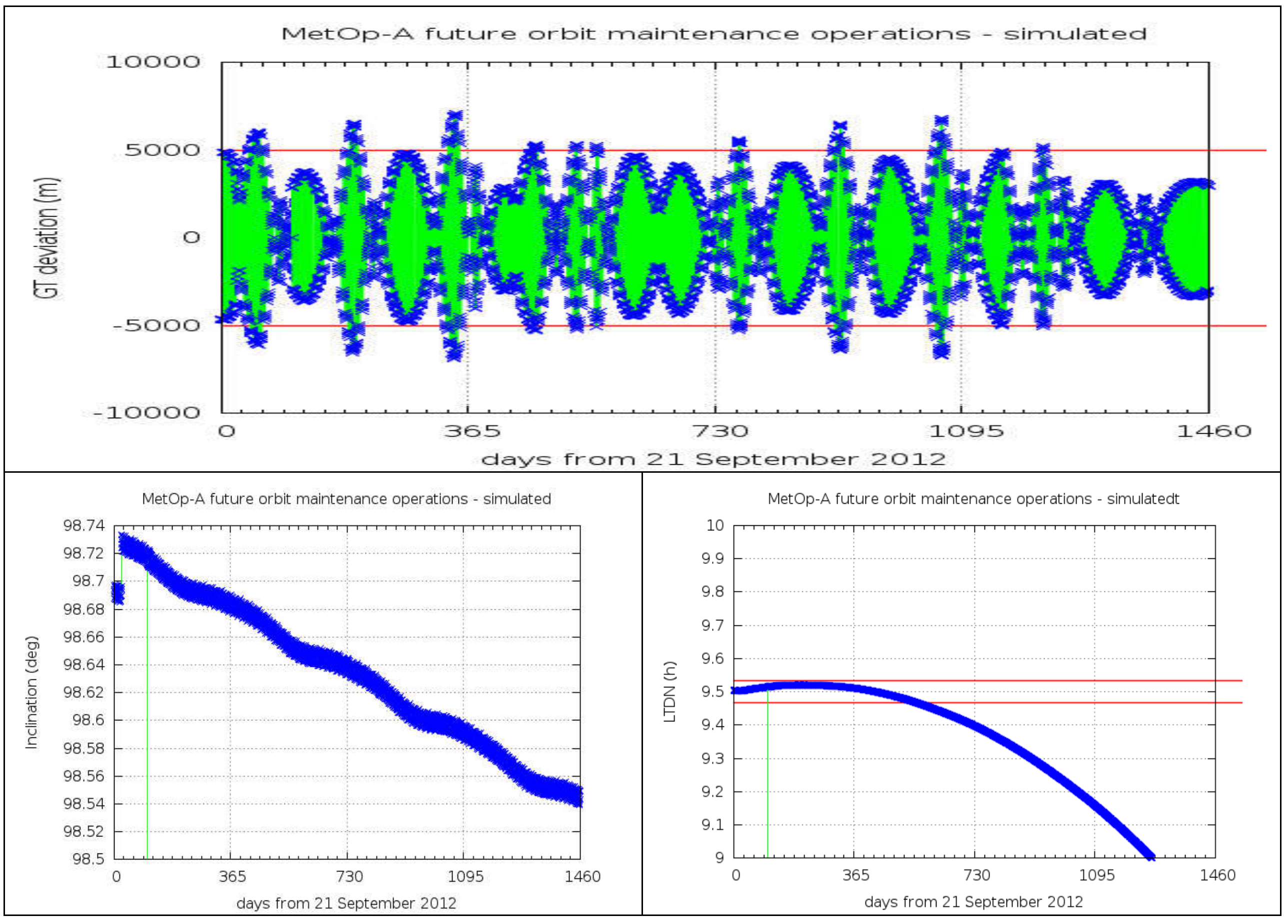

Figure 5: Simulated Metop-A GT deviation, Inclination (Mean of Date) and Local Time at Descending node evolutions from September 2012 until a potential EOL scenario

Finally, Metop-B has just been successfully launched from the Baikonur Cosmodrome in Kazakhstan on a Soyuz rocket on September 17, 2012. Its role is to ensure continuity of observations from polar orbit, service currently being provided by Metop-A, which has exceeded its nominal lifetime. The injection in orbit was targeted at 70 seconds earlier in local time and 35 milidegree higher in inclination than nominal values for allowing starting naturally a long MLST control cycle and saving with it an important amount of fuel. Figure 6 shows, for the same conditions, modelling and uncertainties as for previous Metop-A simulations, and using actual Metop-B state soon after launch, the planned evolution of Ground Track, inclination (wrt mean equator) and local time at descending node crossing for over 7.5 years. The full simulation takes less than one hour of CPU.

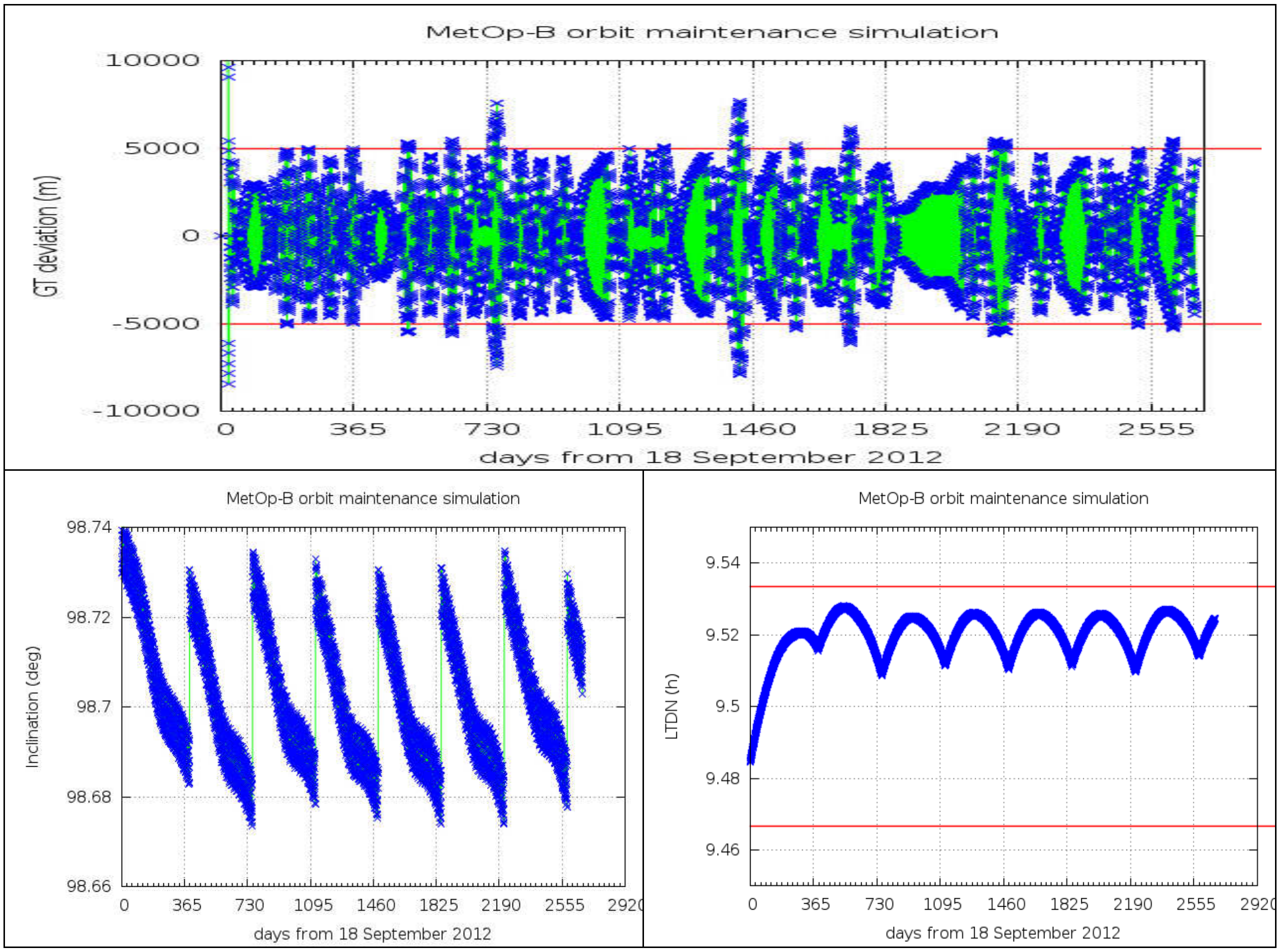

Figure 6: Simulated Metop-B GT deviation, inclination (Mean of Date) and Local Time at Descending node evolutions from 18 September 2012.

4. Sentinel-3

The future Sentinel-3 satellite is a Low Earth orbiting mission to support services relating to the marine and global land environment. Sentinel-3A is currently planned for a launch in 2014. It also flies a Sun-Synchronous repeating orbit, with repeat cycle 27 days (14+7/27). The mean local solar time at descending node shall be between 10:00 and 10:30 and it shall be controlled within 5 minutes. The actual satellite ground track shall differ from the nominal one by less than +/-1km maximum. The tight 1 km ground track control, at all latitudes, imposes the need to control both orbital period via in-plane maneuvers and inclination via out-of-plane maneuvers and for avoiding exceeding bounds at the northernmost (and southernmost) points in the orbit. By controlling the ground track tightly, the MLST can be easily, and implicitly, controlled.

Again, an end-to-end high fidelity modelling is performed, on the basis of Orekit-provided numerical propagator, 36x36 gravity field, MSAFE (average) atmospheric model... A number of uncertainties are modelled and in particular a 50% three sigma uncertainty on the air drag (implemented in same manner as in previous Metop simulations). No MLST control is used this time, since this was found not needed. Instead, same Ground Track control at equator crossings is used (for in-plane maneuvers) together with a simple inclination control. This inclination control consists simply in keeping the mean inclination (wrt to mean Earth equator) close enough to the reference inclination (9 milidegree, inducing <1km deviation at the northernmost point) with which reference ground track was computed. The eclipse constrain is kept.
Figure 7 shows the obtained results for ground track deviation as well as in-plane maneuver delta-V per cycle (30 days is used) and the resulting cumulated in-plane delta-V.

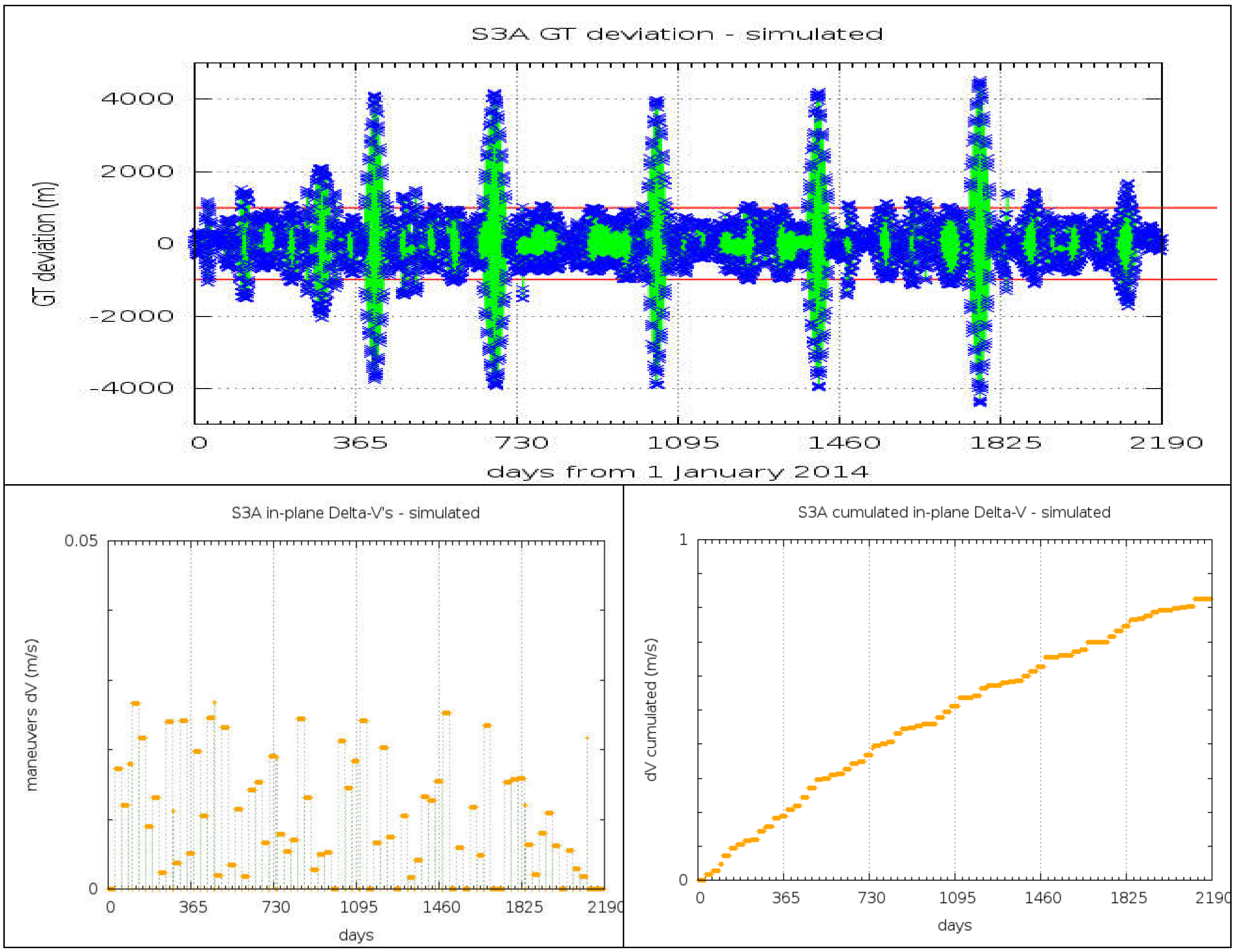

Figure 7: Sentinel-3A In-plane control performance simulation (GT deviation, delta-V per cycle and cumulated delta-V)

The first thing which is noticed quickly is large GT boundary violation soon after some out-of-plane maneuvers. In fact, a simple investigation shows that out-of-plane maneuvers occur every 3-4 months and are implemented as pure inclination maneuvers with no in-plane component. A change in inclination has however non-negligible effects on node rotation with an impact on the ground track evolution. In the unlucky situation in which an out-of-plane maneuver occurs nearby the eastern boundary of the ground track window, this produces a quick violation of this boundary and until next in-plane maneuver opportunity arrives. This was not so clearly visible in the Metop simulated cases due to the larger ground track window for control. In this case however, it clearly shows that inclination maneuvers shall either be performed close to the western boundary of the ground control window and/or performed with an in-plane component that compensates the effect on node rotation.

Figure 8 shows the same case but with no air drag uncertainty (perfect predictability) and perfect out-of-plane control. It shows the decreasing in-plane delta-V per cycle as consequence of the decreasing solar activity, which was no so visible in previous simulation. The total cumulated delta-V results in 0.68 m/s. From Fig. 7, total delta-V when accounting for all effects was 0.83 m/s, showing a penalty of 0.15 m/s over 6 years.

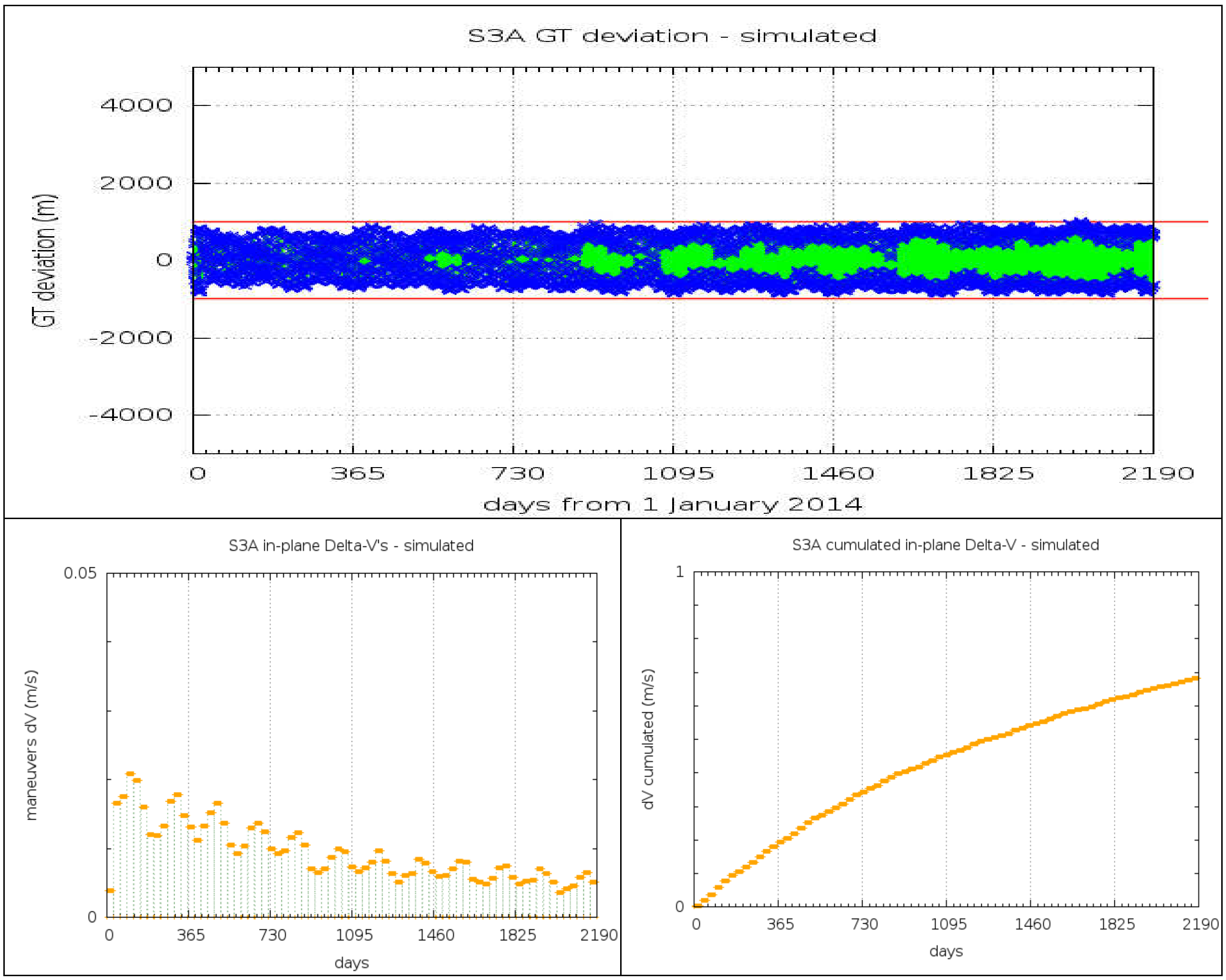

Figure 8: Sentinel-3A In-plane control performance simulation with no uncertainties and perfect out-of-plane control (GT deviation, delta-V per cycle and cumulated delta-V)

Actual operations may perform better, with better suited controls and fine-tuned operational algorithms. The current results give at least sufficiently realistic cases showing the range of performances that can be expected.

5. MTG

The MTG in-orbit configuration will consist of two different platforms, the MTG-I (imager) and the MTG-S (sounder), co-located within a ±0.1° longitude box. Unlike the previous first and second generation of Meteosat satellites, MTG will be based on a three-axes stabilised platform. Figure 9 shows an ideal configuration of these two satellites at around 0° longitude, using the longitude separation scheme for co-location. One year high fidelity propagation is shown, with no uncertainties and perfect controls, including sun-perigee pointing longitude control. As it can be seen, natural eccentricity circles for both satellites are not the same but similar, due to different masses. This ideal station keeping has been modelled on the basis of a 3-week fixed length station keeping cycles, with station keeping maneuvers occurring at cycle start. The obtained longitude drift control has 4 cm/s maneuver per cycle, which is in line with the known drift at that longitude position (0.66 m/s per year, see ref [8]).

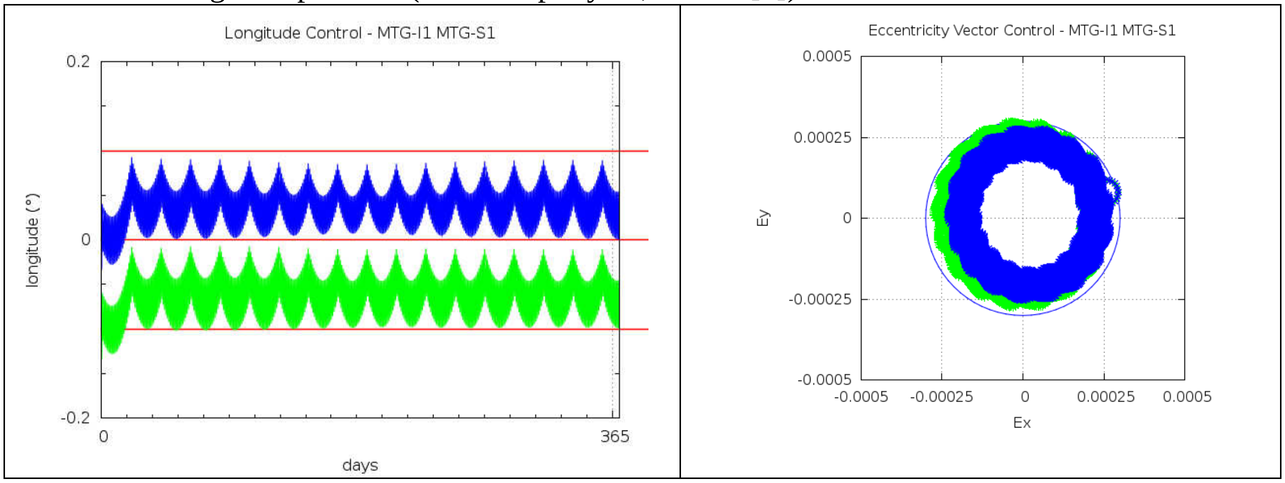

Figure 9: Ideal co-located MTG-I and MTG-S with longitude separation scheme: longitude and eccentricity control

Maintaining this same ideal scheme, more realistic simulations are performed assuming:

- inclination maneuvers within first day of cycle followed by longitude drift maneuver on next day for allowing orbit determination and cross-coupling correction in between
- cycles are synchronised between both satellites, i.e. maneuvers on same days
- single east-west maneuvers if eccentricity is kept within 4 10^{-4}, otherwise a double burn is planned for reaching a natural eccentricity circle of approximately 2.5 10^{-4}
- inclination is arbitrarily maintained at about +0.1° and -0.1° respectively for MTG-I and MTG-S satellites, with 2 to 4 m/s inclination maneuvers almost every cycle
- inclination maneuvers produce a deterministic 0.5% of its total delta-V along track and 0.2% in the radial directions, with additional 5% (3 σ) uncertainties (predictability) on these cross-coupling components
- maneuver uncertainties are 2% for inclination and 3% for east-west maneuvers (3 σ)
- 2% of the maneuvers are “missed”, implying a re-plan and execution for a day later
- negligible orbit determination uncertainties as well as propagation uncertainties (solar radiation pressure model)

Figure 10 shows these more realistic results for longitude and eccentricity control during 3 years.

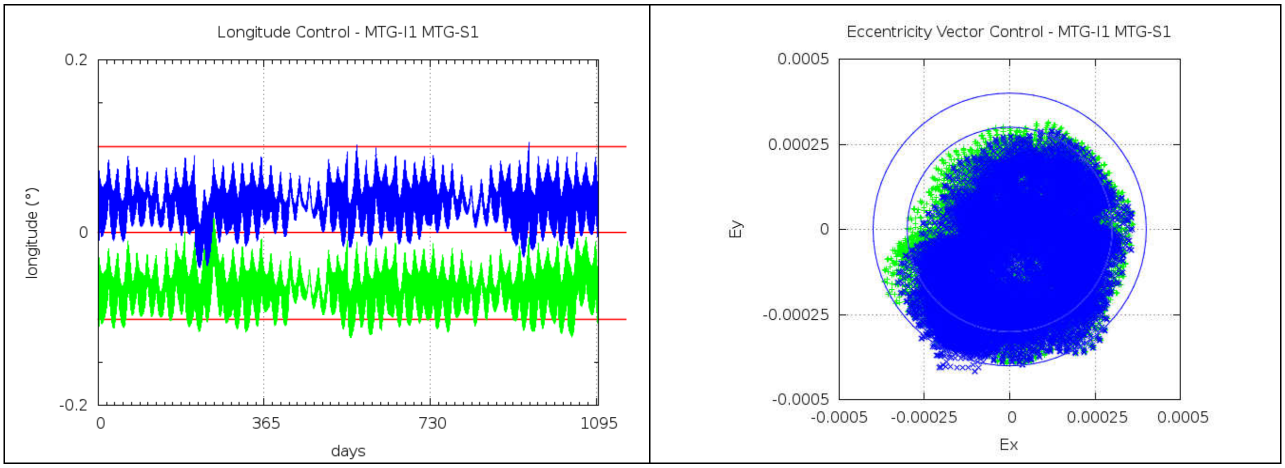

Figure 10: Simulated co-located MTG-I and MTG-S longitude and eccentricity control

The maneuver results are shown in Tab. 2. About 20% of the cycles require double burns for eccentricity control and there is less than 1 m/s penalty over the 3 years in longitude control with respect to the ideal case.

Table 2: Maneuver results for MTG-I1/MTG-S1 3-year longitude separation simulation

		Nbr	ΔV total	ΔV mean/cycle	Re-planned
MTG-I1	Longitude	63	2.713 m/s	0.051 m/s	2
	Inclination	46	147.238 m/s	2.778 m/s	0
MTG-S1	Longitude	62	2.813 m/s	0.053 m/s	0
	Inclination	46	146.919 m/s	2.772 m/s	2

Figure 11 shows the achieved angular separation between the two satellites, as seen from an antenna located in Usingen (Germany), and the inter-satellite distance. The angular separation is a key parameter for maintaining the antenna sharing operational concept and is shown to be maintaining in this case below 0.3 degree. The inter-satellite distance is kept above 40 km.

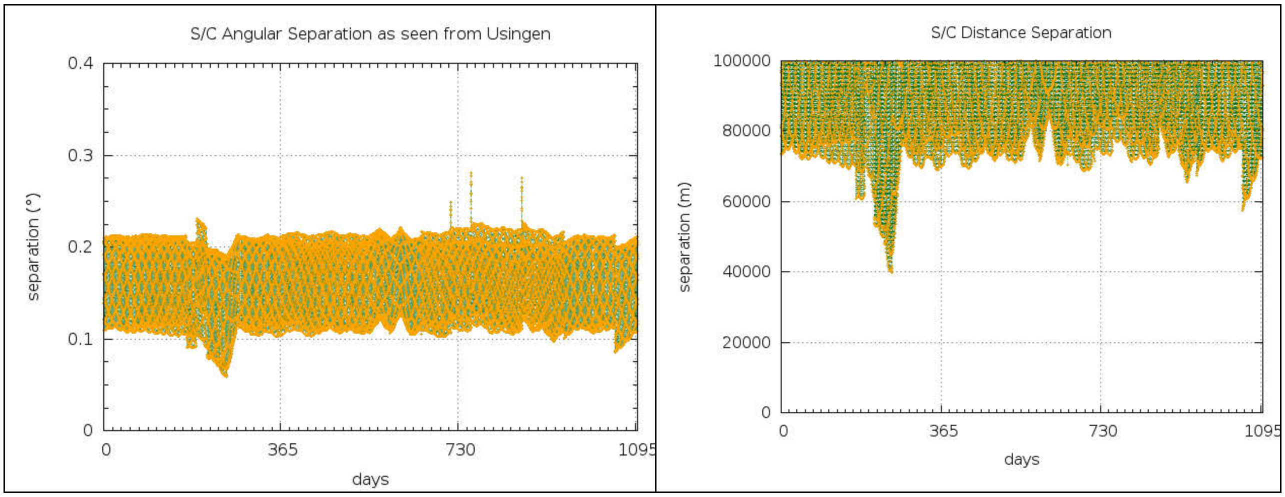

Figure 11: MTG-I1 and MTG-S1 angular separation as seen from Usingen, Germany and inter-satellite distance. Longitude separation scheme.

For comparison, a different simulation is performed using an eccentricity/inclination (e/i) separation scheme. In this case, both satellites are allowed to use the full 0.2 degree longitude window and the satellite separation is guaranteed in the radial and north-south directions, by appropriately selecting and maintaining the inclination and eccentricity vectors. In this case, the station keeping cycle length is set to 4 week, with the potential saving in maneuver numbers. All other configuration is kept, with the exception of the "missed maneuvers" which are now increased to 5%.

Figure 12 shows the evolution of the eccentricity and inclination equinoctial vectors, during the 3 years' simulation. Figure 13 shows the longitude evolution for each satellite. The impact of the higher eccentricity is visible in the larger longitude libration at specific seasons for each satellite.

The maneuver results are shown in Tab. 3. In this case, no double burns seem required and overall maneuver numbers as well as delta-V are smaller. The smaller delta-V in inclination control hints to a slight suboptimal control in the first simulation case (maneuver could have been better optimized to move inclination vectors along their mean drift line). The delta-V per cycle numbers cannot be directly compared since cycle lengths are different, 3 weeks for the first case (longitude separation), 4 weeks for the second case (e/i separation).

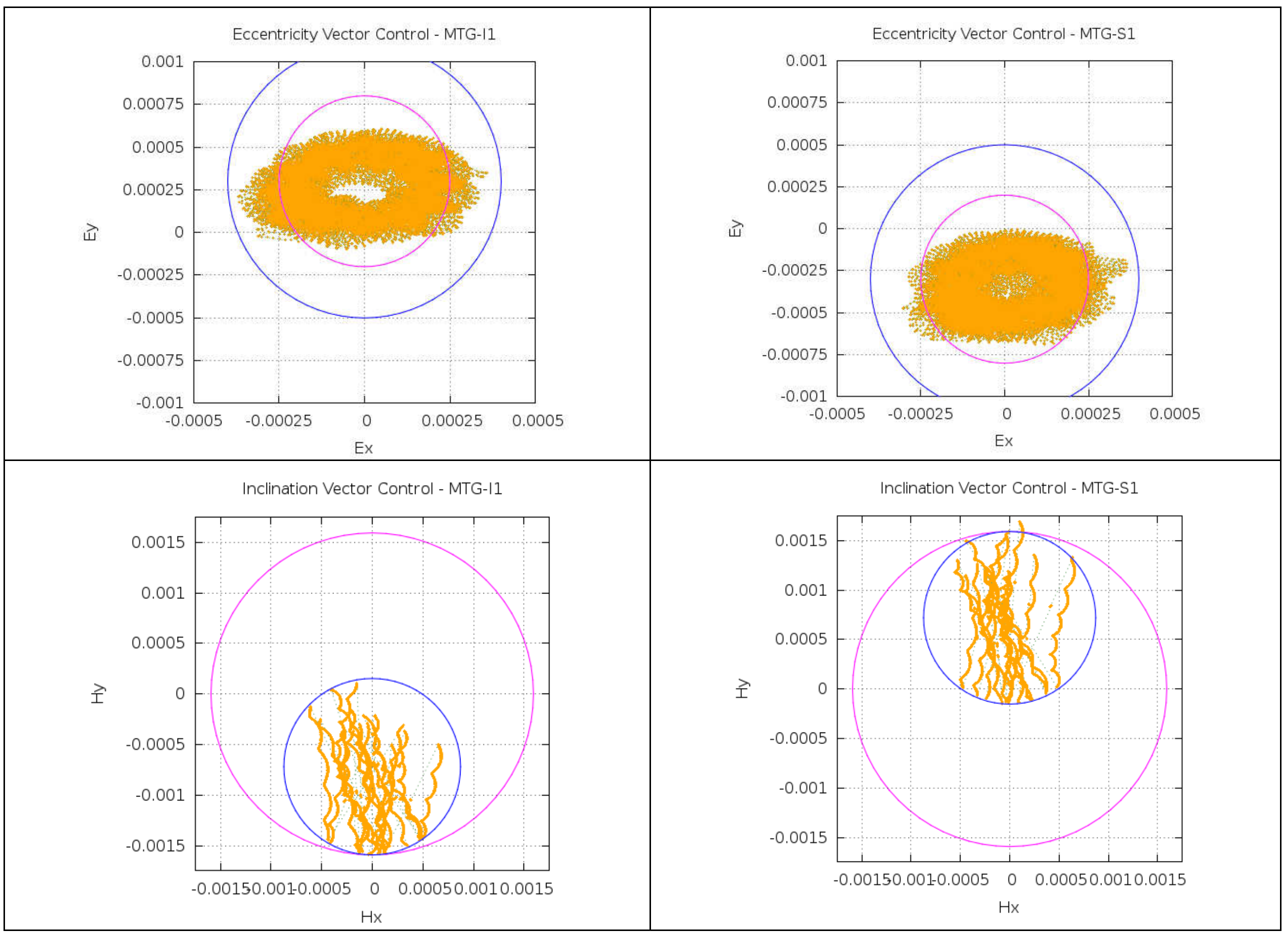

Figure 12: Simulated MTG-I1 and MTG-S1 eccentricity and inclination control. Equinoctial elements used:

$e_x = e \sin(\omega+\Omega)$, $e_y = e \cos(\omega+\Omega)$, $H_x = \tan(i/2) \sin\Omega$, $H_y = \tan(i/2) \cos\Omega$

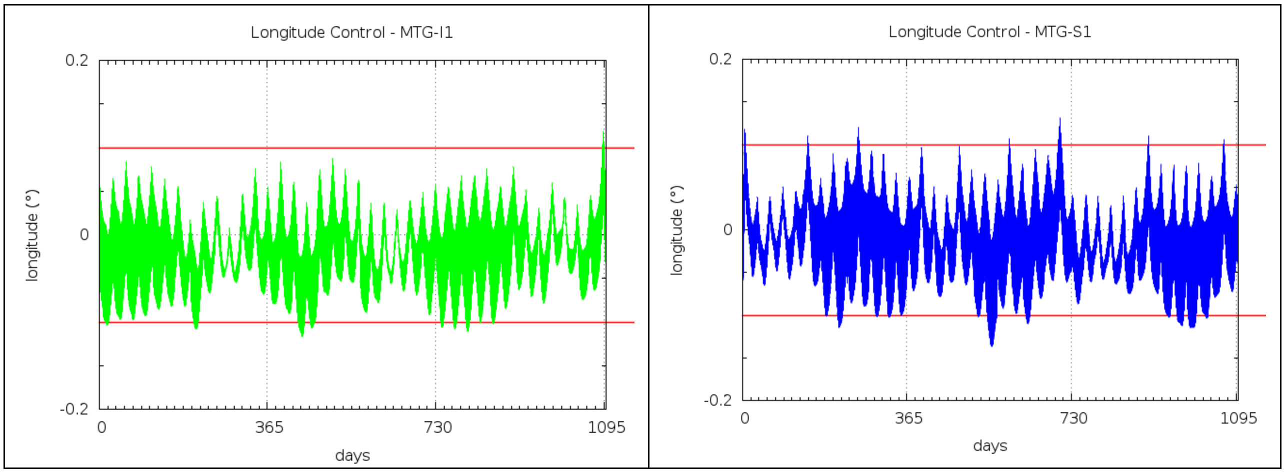

Figure 13: Simulated MTG-I1 and MTG-S1 longitude, using co-location scheme based on e/i vectors separation

Table 3: Maneuver simulation results for MTG-I1/MTG-S1, 3-year, e/i separation

		Nbr	ΔV total	ΔV mean/cycle	Replanned
MTG-I1	Longitude	38	2.296 m/s	0.057 m/s	3
	Inclination	42	139.308 m/s	3.483 m/s	2
MTG-S1	Longitude	37	2.434 m/s	0.061 m/s	3
	Inclination	41	134.755 m/s	3.369 m/s	2

Figure 14 shows the achieved angular separation, as seen from Usingen (Germany), and inter-satellite distance, for this last case. Angular separation is consistently kept below 0.4 degree, although sometimes close to zero (potential optical interference risk). Inter-satellite distance is normally kept above 20 km (one cycle getting below 15 km).

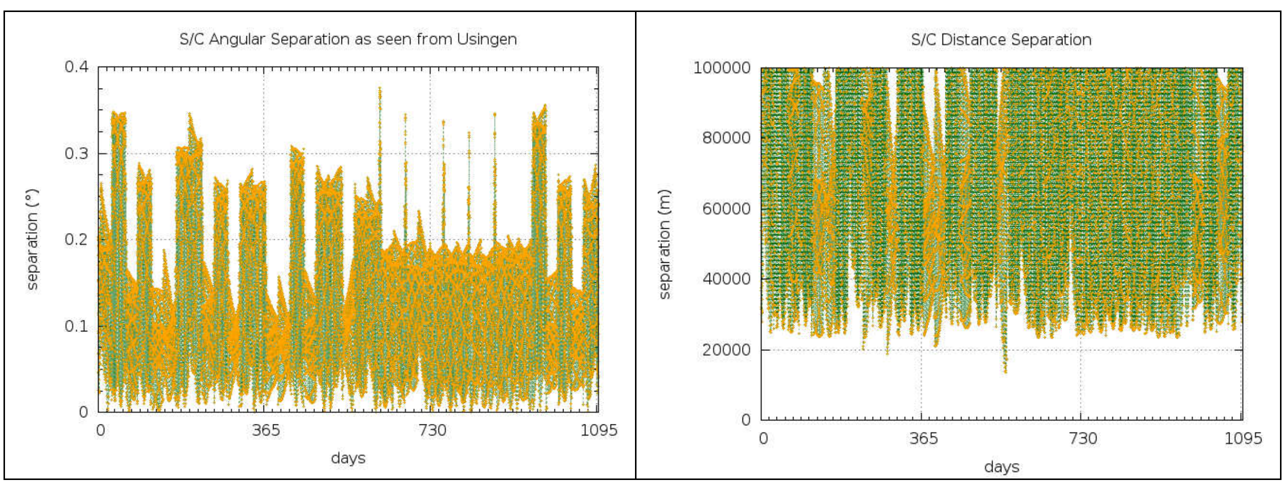

Figure 14: MTG-I1 and MTG-S1 angular separation as seen from Usingen, Germany and inter-satellite distance. e/i separation scheme.

Even though controls used here seem to perform at first sight in an effective and somehow efficient manner, a closer look shows quickly some room for improvement. Effectively, given the nature of GEO station keeping in which inclination maneuver times depend on the time of the year, when taking into account deterministic maneuver cross-couplings, their effects could be in principle anticipated. The simple controls implemented in the cases above, however, optimize single cycles not taking into account any predictions about the coming future and how this can impact for instance the control in eccentricity. A more sensible approach would be to introduce the concept of "rolling cycles" in the maneuver optimization, by which several (2 or 3) cycles are planned and optimized at each cycle (only first being actually implemented). This will be further explored in future works.

6. Conclusions

The approach used at EUMETSAT for modelling end-to-end high fidelity orbit maintenance operations has been shown. The concept is based on currently available technologies in the area of Space Flight Dynamics (Orekit and Apache Commons Math) and allows for accounting for the variability of the space environment, orbit determination uncertainties, maneuver predictabilities, time constraints and maneuver eclipse constraints and many more. The implementation approach has been demonstrated in a number of real application cases and in particular for LEO Sun-Synchronous and GEO current and future missions: Metop-A, Metop-B, Sentinel-3 and MTG system.

7. Acknowledgements

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