GALILEO CONSTELLATION: EVALUATION OF STATION KEEPING STRATEGIES

Daniel Navarro-Reyes[(1)], Anna Notarantonio[(2)], Giacomo Taini[(3)]

[(1)] ESA, ESTEC Keplerlaan 1 Noordwijk The Netherlands, +31 71 5658313,
Daniel.Navarro-Reyes@esa.int

[(2)] Thales Alenia Space Italy, Via Saccomuro 24 Rome 00131 Italy, +39 064151 4137,
Anna.Notarantonio@thalesaleniaspace.com

[(3)] Thales Alenia Space Italy, Via Saccomuro 24 Rome 00131 Italy, +39 064151 2437,
giacomo.taini@thalesaleniaspace.com

ABSTRACT

Galileo is a Global Navigation System composed of 30 dedicated navigation satellites and a ground infrastructure with the main control centres in Europe and a network of dedicated stations deployed around the world.

The purpose of this work is to analyse three Station Keeping (SK) Strategies for Galileo. All three strategies are based on the optimisation of biases for inclination, RAAN, semi-major axis and argument of latitude in order to minimize the number of manoeuvres, taking into account other operational considerations.

A trade-off of the three Strategies will be presented in order to show the main advantages and the disadvantages of each of them, and the reasons to choose one of them for implementation in the Galileo System.

1. INTRODUCTION

Galileo is a Global Navigation System composed of 30 dedicated navigation satellites and a ground infrastructure with the main control centres in Europe and a network of dedicated stations deployed around the world. The Galileo Constellation has been defined as a Walker 27/3/1 and it is composed of 3 orbital planes in MEO orbit defined by the nominal inclination (56 degrees) and by differences of 120 degrees on RAAN.

The purpose of this work is to analyse the Station Keeping (SK) Strategies in order to select the orbital parameters for the In-Orbit-Validation (IOV) and Full Operation Capability (FOC) phase.

All the SK strategies are based on the selection of the biases and offsets for inclination, RAAN, semi-major axis and argument of latitude in order to maximise the time of the first and the second in-plane SK manoeuvres.

Three SK strategies have been defined and studied, using a preliminary launch schedule, in order to guarantee the in-plane (Argument of Latitude) and the out-plane (Inclination and RAAN) requirements of the constellation specification.

The First Strategy is based on the fully Relative in-plane and out-plane control while the Second of them uses the Relative maintenance for the out-plane and the Absolute control for the

Argument of Latitude. In the Third Strategy the fully Absolute orbit control is taken into account for the in-plane and the out-plane orbital parameters.

A trade-off of the Absolute and Relative SK Strategies will be presented in order to show the main advantages and the disadvantages of each of them, and the reasons to choose one of them for implementation in the Galileo System.

2. CONSTELLATION REQUIREMENTS

In the frame of the Galileo Project early studies, the Galileo constellation was defined as a Walker (27/3/1) constellation with an inclination of 56 degrees. This definition was based on a set of service performance levels defined in [1]. The constellation will have 27 active satellites, with 9 satellites in each of the three constellation planes (A, B and C plane). The planes are separated 120 degrees in RAAN value. In addition, each plane will have an in-orbit spare satellite located halfway two active satellites.

Reference [1] also established the maximum deviations from the satellites' nominal positions as to minimize the degradation of the service performance. These limits were adopted as Constellation SK requirements (these requirement identifiers below are only used within this paper for easy reading in the next sections):

- REQ_INC: The relative RAAN variations for each Satellite of the nominal Walker constellation shall be better than +/- 2°.

- REQ_RAAN: The inclination variations for each Satellite of the nominal Walker constellation shall be better than +/- 2°

- REQ_ALONG1: The relative along track orbit keeping between any two adjacent operational satellites in the same orbit plane shall be better than +/- 3°.

- REQ_ALONG2: The relative phasing variation between operational satellites in adjacent planes shall be better than +/- 3.0°.

In addition, in order to guarantee service availability, the number of service outages due to manoeuvres needed to be minimized. Initial studies showed that, thanks to the non-resonant nature of the Galileo orbit, one manoeuvre would be enough to fulfil the requirements above.

- REQ_MAXMAN: Initial biases on the orbit parameters of each operational satellite shall be optimized such as to satisfy tolerances on the Walker constellation parameters on a 12 year timeframe with one orbit keeping manoeuvre maximum per satellite life-time.

The radius of the orbit definition was originally defined in [1] as to have a repeat ground-track cycle of 5 revolutions in 3 days. This repeat cycle had the disadvantage of being affected by resonance effects due to the Earth non-spherical perturbation, which would have made the satellites drift away from each other, and not meeting REQ_ALONG1, REQ_ALONG2 and REQ_MAXMAN. A higher repeat cycle of 17 revolutions in 10 days was then chosen [2]. Such a repeat cycle, equivalent to an orbit with a radius of 29600 km, is not resonant, as numerical simulations have shown.

Clearly, these last requirements have to be associated with some sort of accuracy in the initial placement of the satellites (initial biases). Preliminary studies show that an accuracy in the achievement of the semi-major axis of 5 metres would suffice [3]. It is noted that such accuracy implies quite stringent orbit determination accuracy, which, in the case of S-band ranging, can be challenging to meet.

- REQ_SMA: The semi-major axis of the satellite orbit be corrected to within +/- 5 metres

3. PERTUBATIONS ANALYSIS

The analysis of perturbations has a three-fold goal:

- general perturbation theory will provide us with an insight of the dynamics dominating the evolution of the orbit in time;
- numerical (special) perturbation will allow us to select the degree of complexity needed for modelling the orbit dynamics;
- in addition, a combination of both general and special perturbation theories will provide us with an assessment of the orbit sensitivity to those model parameters that are not well known a priori, such as the SRP coefficients.

Since the orbital parameters that are constrained by the SK requirement are the RAAN, inclination and along-track phase (i.e. argument of latitude, u), the perturbation analysis focuses on these three parameters.

3.1 Earth Non-spherical Potential

The main effect of the Earth non-spherical gravitation field is the precession of the RAAN, the argument of perigee, and mean motion as expected by the effect of J2, J4, J6 and so on. One important effect that can be derived from the general perturbation theory is that the rate of argument of latitude depends on the inclination of the orbital plane through the effect of the zonal terms (Eq. 1 shows the effect of J2 only).

$$\left.\frac{du}{dt}\right|_{J_2} \cong \sqrt{\frac{\mu}{a^3}}\left[1+\frac{3}{4}J_2\left(\frac{R_\oplus}{a(1-e^2)}\right)^2\sqrt{1-e^2}\,(3\cos^2 i-1)+\frac{3}{4}J_2\left(\frac{R_\oplus}{a(1-e^2)}\right)^2(5\cos^2 i-1)\right] \quad (1)$$

In addition, numerical propagation has shown that the tesseral terms also introduce an additional, residual, but not negligible, drift in the argument of latitude. Numerical simulations show that a truncation of the Earth potential down to 12x12 is acceptable to retain enough accuracy for the purpose of SK analysis. As Table 1 shows, any improvement of the Earth Potential above 12x12 does not make much of a difference.

Differences wrt 12X12 **[km]**	**J2**	**4x4**	**36x36**	**70x70**
Along-Track	800	40	$3.5\ 10^{-4}$	$4\ 10^{-4}$
Radial	10	10^{-1}	10^{-7}	10^{-7}
Cross-Track	1	10^{-2}	10^{-7}	10^{-7}

Table 1: 10-year orbit propagation and comparison for several degrees of geopotential.

3.2 <u>Third-Body</u>

Equations from general perturbation theory show that the Sun and Moon effect on the orbit is mainly on the inclination and RAAN:

- The effect of the third body perturbation on the RAAN is a decrease in the RAAN drift, that is, the RAAN values decreases faster. The RAAN drift is -9.49 degrees per year due to J2, but the inclusion of the third body makes this value decrease to -10.09 degrees per year. This means a full precession of the orbital plane in 35.7 years.
- For Galileo orbits, the inclination rate has the same sign as $\sin(RAAN)$. This can be confirmed with numerical simulations. The inclination in each of the constellation planes evolves in different ways (see Fig. 1). After one RAAN cycle of 35.7 years, the inclination returns close to its original value. However, the inclination variation during the cycle is larger than 2 degrees, but smaller than 4 degrees. REQ_INC can be met by biasing the initial inclination (see Fig. 2, left).

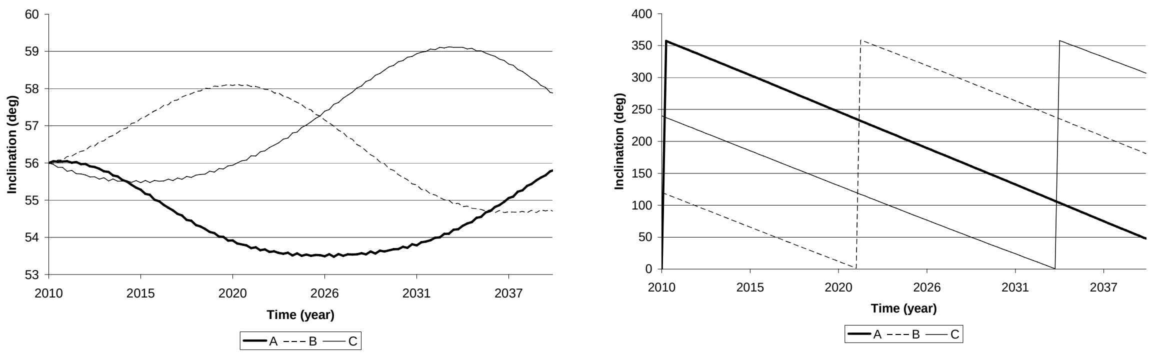

Fig 1. 20-year propagation. Inclination and RAAN values for satellites in each plane

The RAAN rate, being a function of the inclination, is also slightly different for each plane; the RAAN difference between two planes does not stay constant, increasing and violating REQ_RAAN. This can be avoided by biasing the initial RAANs. Fig. 2, the right plot shows an example of biasing of inclination and RAAN in order to fulfil the requirement.

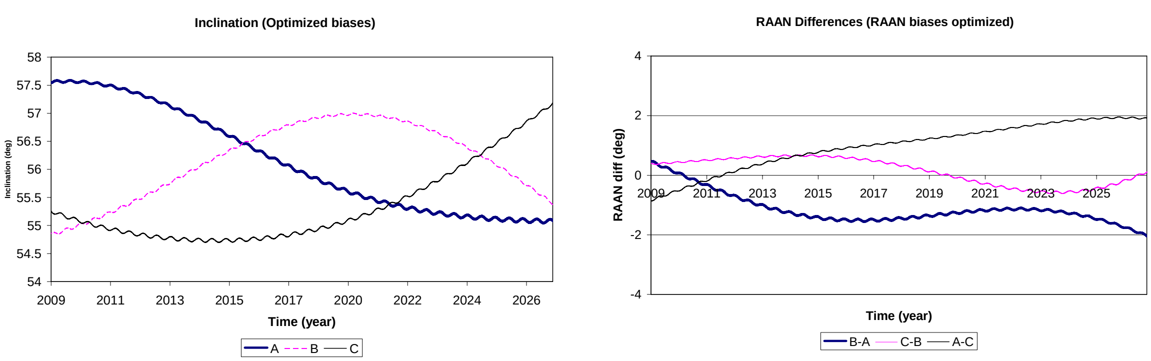

Fig 2. 20-year propagation. Inclination and RAAN values for satellites in each plane

As the inclination of satellites in different constellation planes will vary in different ways, their rate of argument of latitude will be also different (see Eq. 1), making REQ_ALONG2 difficult to meet.

3.3 Solar Radiation Pressure (SRP)

The effect of the SRP (cannonball model) is not negligible and it must be taken into account in the simulations. From a practical point of view, what is more interesting is to know the propagation errors due to not knowing with enough accuracy the effective area to mass ratio (because of the satellite attitude law) and the reflectivity coefficient. Numerical simulations show that an error of 10% on the effective area to mass ratio introduces an error of 0.3 degrees in argument of latitude after 12 years of propagation.

3.4 Effects on Constellation Requirements

As presented above, the major impact of the perturbations on the orbit are:

- A differential RAAN rate that makes the RAANs of each plane drift from each other, not respecting REQ_RAAN.
- A different evolution of the inclination that may not meet REQ_INC, and that, in addition, introduces a differential rate in the argument of latitude between the planes such that REQ_ALONG2 is not met.
- REQ_ALONG1 seems to be easy to meet if satellites in the same plane all have the same initial inclination and mean semi-major axis.

4. CANDIDATE STRATEGIES

An SK keeping strategy is needed in order to establish an operational schema of the deployment of the satellites. Such a strategy will establish the way the satellite orbit will be selected and controlled in order to fulfil the SK requirements.

Note that a Walker 27/3/1 will have three orbit planes separated 120 degrees in RAAN, however, the RAAN value of the first plane ($RAAN_0$), for a particular epoch (T_0), is not specified yet. Something similar happens with the argument of latitude of the first satellite in the first plane (u_0). The argument of latitude selection is shown not to affect the SK results, and will be left free to be chosen according to other criteria that are outside the scope of this paper.

The SK tolerances are defined in relative terms based on the difference of orbital parameters of any two satellites (except for the inclination, REQ_INC, which is an absolute tolerance with respect to 56 degrees inclination). This “relative” nature of the requirements brings up the possibility of establishing schemes that tackle the problem by using relative SK techniques, controlling each satellite of the constellation taking into account the orbit of the other satellites. However, there is also the possibility of dealing with the requirements in terms of absolute tolerances. By using absolute SK, a reference is defined for each satellite that guarantees that the differences between the satellites’ orbital parameters will meet the requirement. But only the difference between each satellite and the reference is controlled. A generic discussion about the advantages and disadvantages of each approach can be found in [4].

The way the SK requirements are defined also allows to decouple the optimization of in-plane orbital parameters (argument of latitude) from the out-plane ones (Inclination and RAAN). The control of the out-of-plane orbital parameters by using SK manoeuvres is very costly propellant-wise. As a matter of fact, this is not needed if the right biases in inclination and RAAN are achieved by the launch vehicle. The control of in-plane parameters is then left for in-orbit manoeuvres. First a drift will be necessary to bring the satellites from the location where the launch vehicle has injected them to the location within the constellation where the satellites have been assigned. Secondly, a series of fine tuning, or fine positioning, manoeuvres are performed to leave the satellites with the optimized biases in argument of latitude and semi-major axis such that the orbit perturbation are compensated and the requirements fulfilled. In most cases, later manoeuvres, SK manoeuvres will be needed to further compensate for the perturbation as the following analyses show.

Three strategies have been considered. All three are based on the selection of the biases and offsets for inclination, RAAN, semi-major axis and argument of latitude and on the maximization of the time of the first and the second in-plane SK manoeuvres.

SK Strategy	Out-of-plane	In-plane
Strategy 1	Relative	Relative
Strategy 2	Relative	Absolute
Strategy 3	Absolute	Absolute

Table 2. Summary of the three strategies

The maximization of the time for the second manoeuvre is intended to satisfy REQ_MAXMAN, searching for those constellation configurations that will not need a second manoeuvre earlier than 12 years after injection of the satellite. The maximization of the time for the first manoeuvre is intended to search for solutions that would not need manoeuvres earlier than 12 years in some satellites. This will improve the service availability. As the results show, these solutions depend on $RAAN_0$.

4.1 <u>Strategy 1: Fully Relative SK</u>

This first strategy is based on a relative optimization to fulfil the SK requirement the way they have been defined, that is relative SK. Therefore, apart from a reference inclination of 56 degrees, the RAAN difference and argument of latitude differences are the parameters to control. We say then that this strategy performs a relative out-of-plane control and a relative in-plane control. This strategy is described in [5].

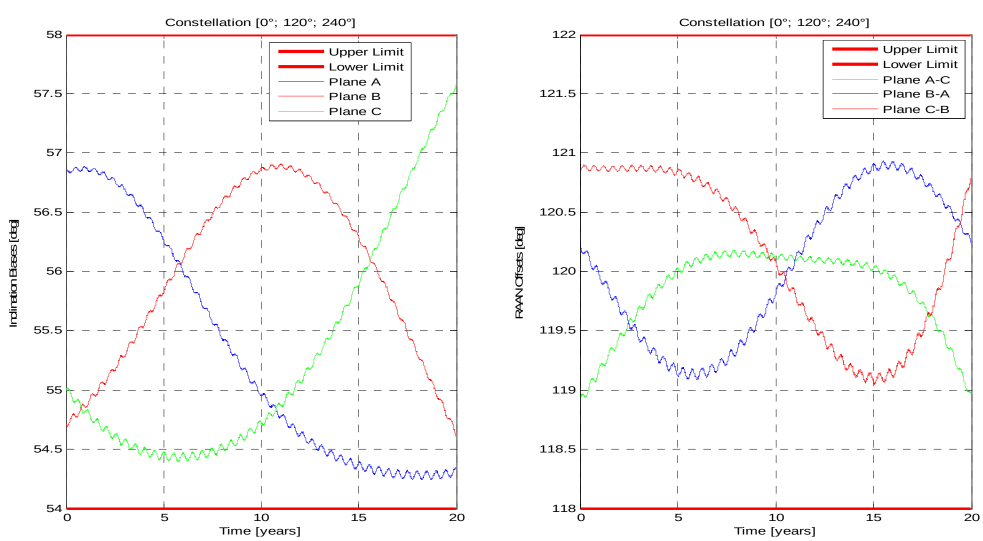

Fig. 3. Strategy 1. Example of optimized inclination and RAAN for 20 years

Given an initial RAAN value for the first plane (plane A), the strategy optimises the initial values of inclination and RAAN biases as to fulfil the out-of-plane requirements for the constellation design life of 20 years. As such, what is optimised is the inclination of each plane, that is, each satellite in that plane will fly such that its inclination and RAAN is the same. This is needed as to guarantee that the difference of RAAN is maintained even for new satellites launched in the constellation (see Fig. 3).

The same principle applies to the in-plane problem. The argument of latitude evolutions of satellites in different planes is optimized such that the differences are within the SK tolerance. The parameters optimised are first the semi-major axis, and second the argument of latitude (see Fig. 4). New satellites will have to be injected in the same optimized parameters; in the corresponding values for that epoch.

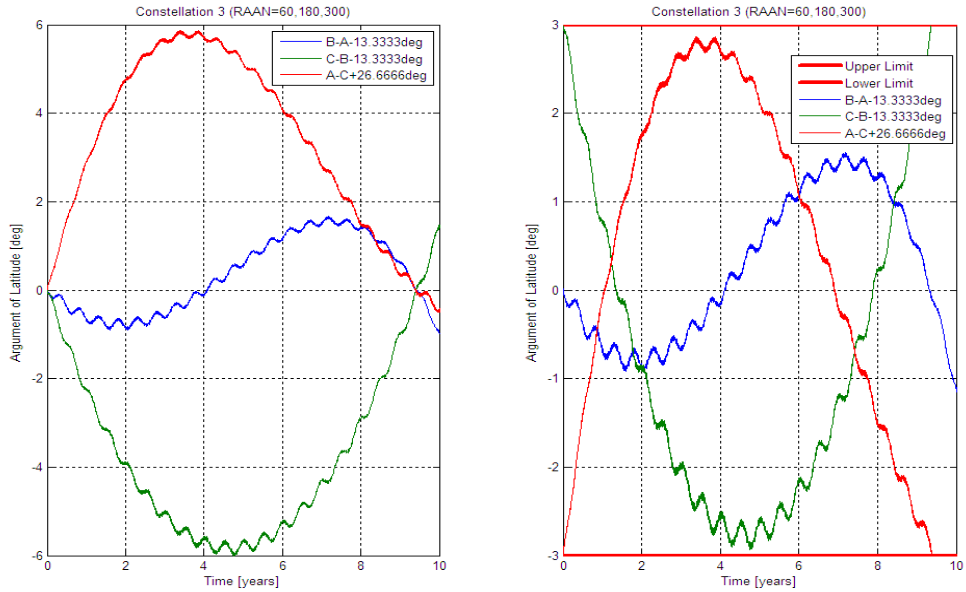

Fig. 4. Strategy 1: Argument of latitude differences, intermediate optimization step (left) and optimised (right)

Simulations done using this strategy show that for a range of initial RAAN0 values, the REQ_MAXMAN can be fulfilled in the sense that a second manoeuvre will be needed later than 12 years after constellation start time (see Fig. 5). Note that the manoeuvre time will essentially be the same for all satellites in one plane, regardless of when they were injected in the constellation.

This strategy is very elegant in the sense that deals directly with the original SK requirements, fulfilling all them. However, the strategy presents one disadvantage: It considers that all satellites will undergo exactly the same orbital perturbations. This will not be the case, in particular for the SRP. It is very likely that the constellation will be made up of satellites from several manufacturers, or even different satellite designs from the same manufacturer. This difference will mean that the argument of latitude of different satellites will diverge.

In addition, the strategy optimises the orbital parameters for a window of 20 years since this is the constellation operational life. However, it could be foreseen that the constellation is maintained for a longer time.

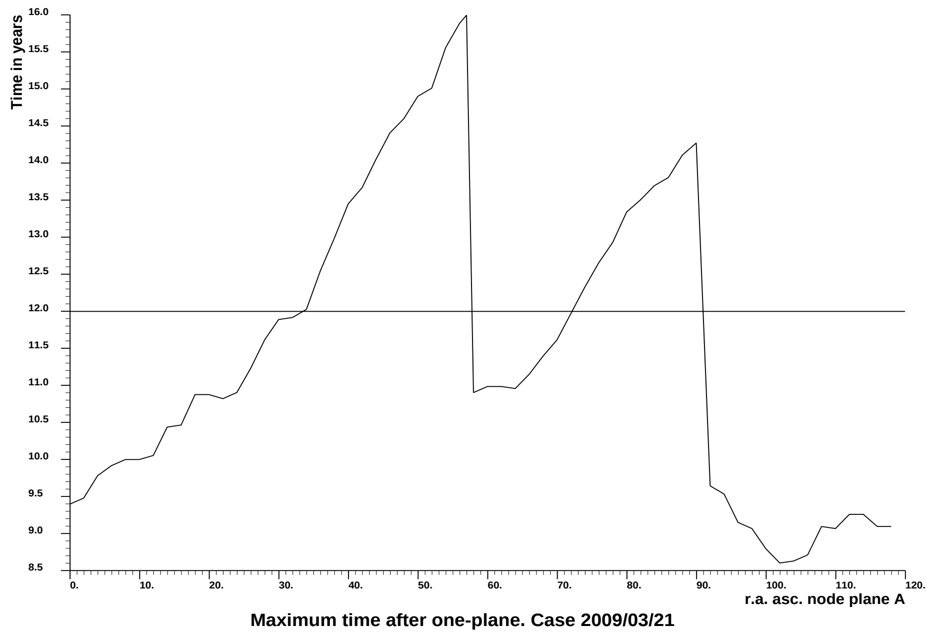

Fig. 5. Strategy 1: Time of second SK manoeuvre as function of $RAAN_0$. This figure has been taken from [5].

4.2 Strategy 2: Relative Out-of-Plane with Absolute In-plane SK

This second strategy applies the same principle for the out-of-plane optimization, but optimises the in-plane evolution in an absolute manner: a reference is established for the argument of latitude of every satellite (Eq. 2), and each satellite is controlled independently so as to stay within a deadband of +/- 1.5 degrees around its reference. This strategy is very similar to the one presented in [6], except that in that paper the in-plane optimization was done by minimizing the evolution of the mean difference in argument of latitude rate for a pre-defined period of time. The strategy presented in this paper optimizes the argument of latitude by utilising the whole deadband for the maximum time possible, something that [6] does not guarantee.

The reference argument of latitude can be defined in different ways, for instance propagating the orbit using two-body plus J2 effect. However, a kinematic definition, based on a constant nominal drift, is used in this paper.

$$u = u_o + 40 \cdot (slot - 1) + \frac{360}{13} \cdot (plane - 1) + D_{NOM} \cdot (T - T_0) \qquad (2)$$

The parameter $slot$ represents the position of the satellite within one plane; it can take values from 1 to 9. The parameter $plane$ represents the constellation plane, it can take the values 1 to 3 (A to C). The parameter T_0 is the initial time of the constellation, and it should be fixed for the whole constellation. In the present paper, this time is 00:00:00 UTC on 21 March 2010. Reference [6] uses the same expression for the reference, however D_{NOM} is computed there to fulfil 17 revolutions in 10 (sidereal) days taking into account the orbital plane precession due to J2 only. This paper uses the additional precession due to the Sun and the Moon.

Fig.6 shows an example of in-plane optimization of three satellites in different planes, with respect to their reference, with a deadband of +/- 1.5 degrees. The lower plot shows the difference in argument of latitude, with a deadband of +/- 3 degrees as per REQ_LONG2.

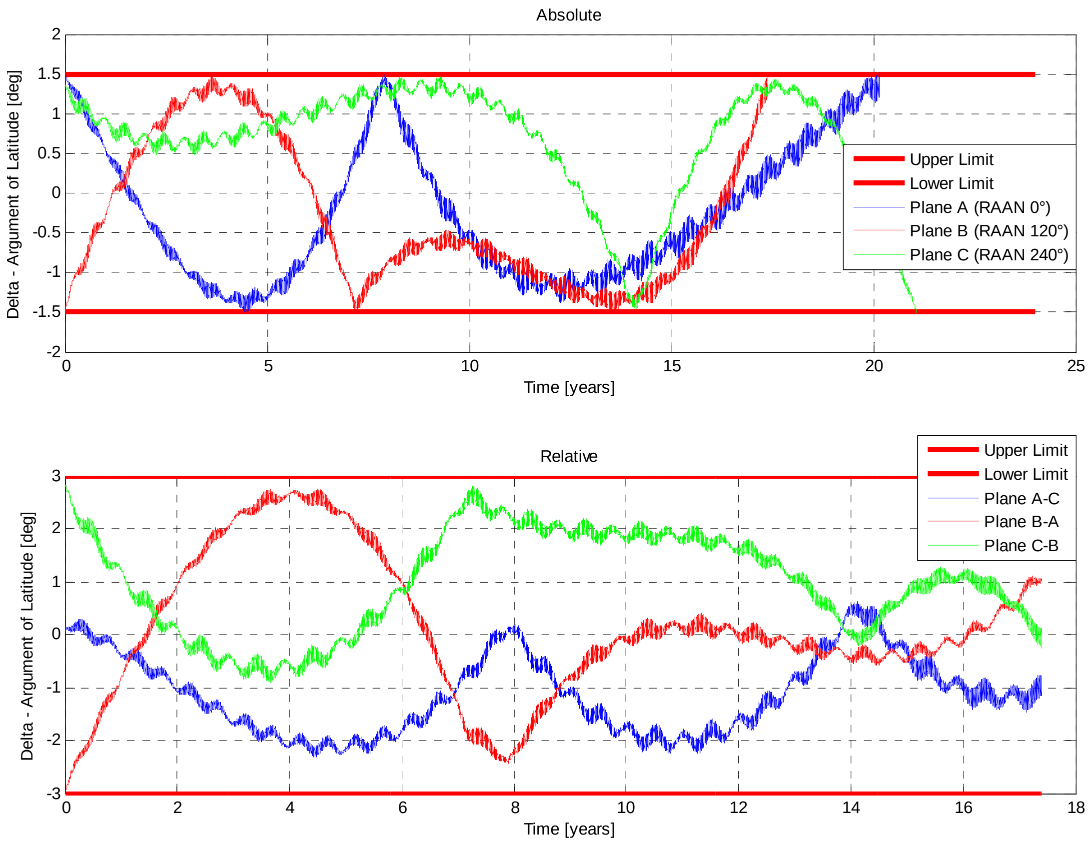

Fig. 6. Strategy 2: absolute in-plane optimization (up) and relative argument of latitude (down).

The numerical simulations show that there is a range of RAAN0 for which some satellites wouldn't need a manoeuvre (more details are provided in strategy 3).

The out-of-plane optimization is still done in a per-plane basis; the satellites have to be placed in the same inclination and RAAN values as the satellites already present in each of the planes. This has the disadvantage, as in strategy 1, that in case the constellation operational life is extended, the satellites will violate the out-of-plane requirements.

4.3 Strategy 3: Fully Absolute In-plane SK

A third strategy has been analysed. The objective to this strategy is to solve the issue of having a longer constellation operational life and make the SK independent of when the satellites are launched and how they are designed. Using a similar approach as for the in-plane optimization done in strategy 2, each satellite's RAAN is maintained within +/- 1 degree with respect to a reference RAAN, which is defined as a liner function of time (Eq. 3).

$$RAAN_{REF}(T) = RAAN_0 + 120 \cdot (plane - 1) + DRAAN \cdot (T - T_o) \quad (3)$$

The RAAN drift value ($DRAAN$) has been computed such that it represents the average of the RAAN precessions for a set of sample satellites. The parameters $plane$ and T_o are the same as in Eq. 2. $RAAN_0$ is a design parameter.

Since the out-of plane optimization is done per satellite, the time horizon is only 12 years, the satellite lifetime. Fig 7. shows an example of the absolute out-of-plane optimization for three satellites launched at the same time, one in each plane.

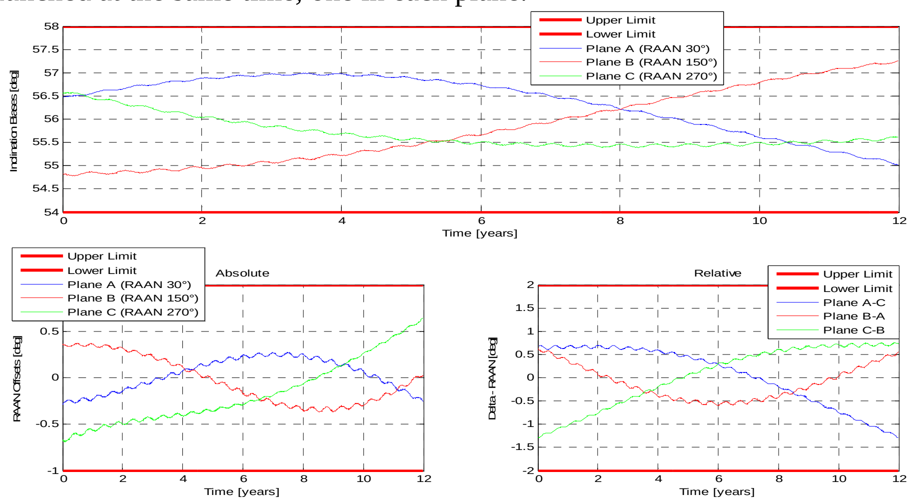

Fig. 7. Out-of-plane absolute optimization. Inclination (above). Absolute RAAN optimization (below left). RAAN differences between planes (below right).

The in-plane optimisation is done the same way as strategy 2. The results in terms of number of manoeuvre are similar as well.

4.4 Trade-off among candidates. Selection of strategy and associated parameters

In the sections above, the advantages and disadvantages of each strategy have been described. The full absolute strategy is recommended because of the flexibility it offers in terms of accommodating a longer constellation operational life, sparse satellites launch time, and difference satellite designs. Therefore, strategy 3 has been adopted as the baseline in the Project.

There are still two parameters to choose, the $RAAN_0$ and u_0. The latter does not affect the performance of the strategy; its value has been set to zero to simplify the analyses. The former has a strong influence on the number of manoeuvres needed. We tried to find which value of $RAAN_0$ minimises the number of SK manoeuvres needed: We have simulated a series of launches in different years (from 2010 to 2014) in different test constellations (each test constellation has a different value of $RAAN_0$). Then we compute how long after launch an SK manoeuvre will be needed. Fig. 8 shows that a plane (plane C in the plot) with RAAN values between 250 and 280 degrees will not require an SK manoeuvre earlier than 12 years after satellite launch (meaning that no manoeuvre will be needed at all). $RAAN_0$ should be set to a value between 10 and 40 degrees.

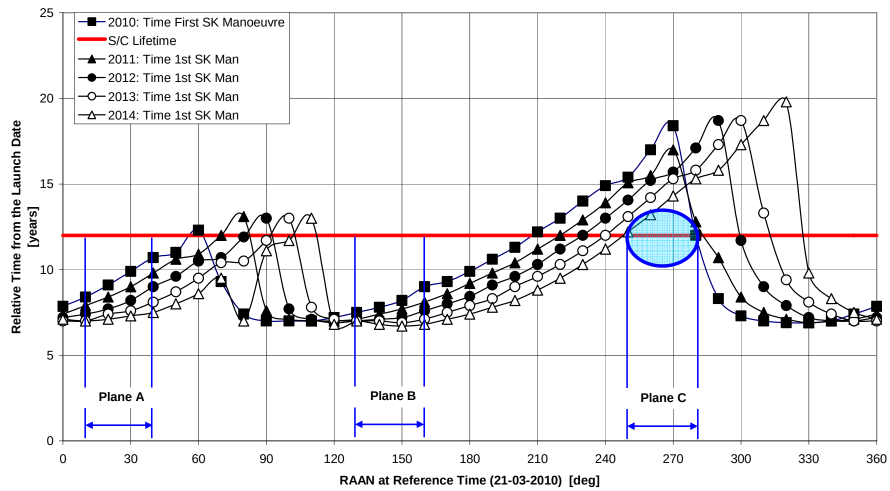

Fig 8. Time after launch for the first SK manoeuvre. Note that the abscise is RAAN value at T_o.

Similarly, the Fig. 9 shows the time for the second manoeuvre, for any value of RAAN, all satellites will need a second SK manoeuvre more 12 years after launch, therefore meeting REQ_MAXMAN.

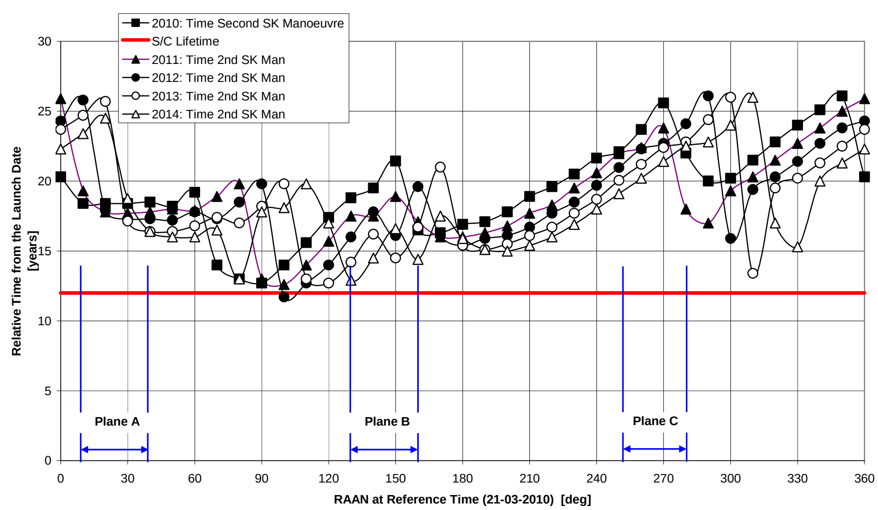

Fig 9. Time after launch for the first SK manoeuvre. Note that the abscise is RAAN value at T_o.

5. FUTURE REFINEMENTS

5.1 Semi-major axis accuracy

REQ_SMA allows for a 5 meter error in the achieved semi-major axis with respect to the target semi-major axis. This error has two sources: orbit determination uncertainty and propulsion system minimum thrust. The effect of this error is easy to see by taking an optimized in-plane solution, adding the error, and propagating (see Fig. 10). In the case of an overshot, the satellite leaves the SK much earlier than the optimized solution, coming back in to follow a turn-around behaviour. In case of an undershot, the satellite leaves the SK deadband a bit earlier than expected, needing an earlier SK manoeuvre. The latter case is preferred, and the optimization should take this into account. For example, in Fig. 10, the optimized solution has to be modified as to follow the one with a semi-major axis 5 metres lower. The utilization of the deadband is lower, but this guarantees that the satellite will stay in the deadband.

Further analyses will be done in the near future as to improve the optimizing algorithm and provide a solution that is robust against errors in the semi-major axis. This could mean Fig. 8 and Fig. 9 will be modified to show the range of RAAN values that will not need manoeuvres.

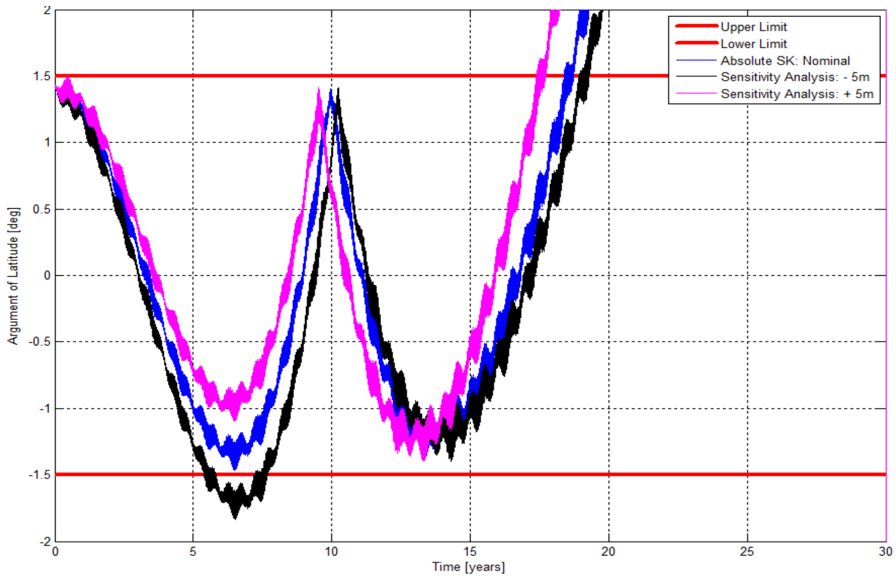

Fig. 10. Absolute in-plane optimization: Sensitivity to errors in semi-major axis

5.2 <u>Extended SRP model: Y-bias effect</u>

The analysis presented in this paper is based on the assumption that the perturbing forces are well known such that starting with an accurate orbit determination, an orbit propagation will predict the real orbit evolution of the satellite. This assumption has been tested using GIOVE-B. This satellite has been flying thruster-free for nearly one year. A precise orbit determination based on L-band and SLR measurements has been done using a sliding window during this period of almost one year. Fig. 11 shows the difference in argument of latitude between the sliding window orbit determination and an orbit propagation based on the first orbit determination. The propagation uses 12x12, Sun and Moon gravity and SRP. Fig. 11 shows the results of this test: the difference in argument of latitude is about 0.3 degrees in less than a year. This has been a surprising result.

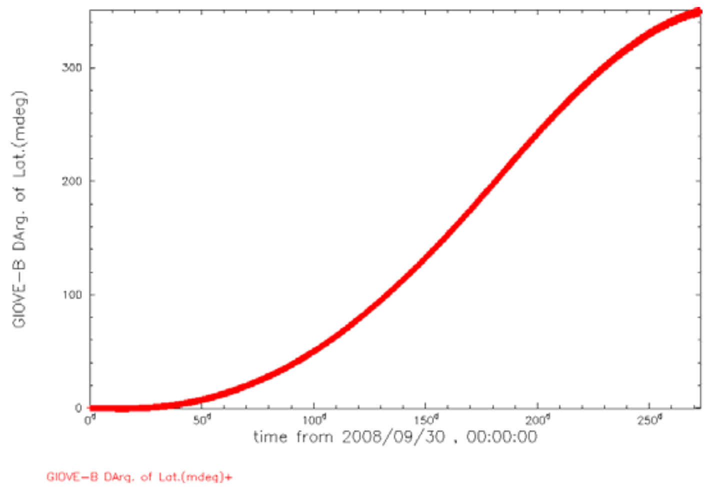

Fig. 11. Difference in argument of latitude between propagated orbit and sliding window orbit determination.

Further analysis has been done improving the dynamic model, introducing for instance an empirical extended SRP. Fig. 12 shows that using the so-called Y-bias, there is an improvement in the results.

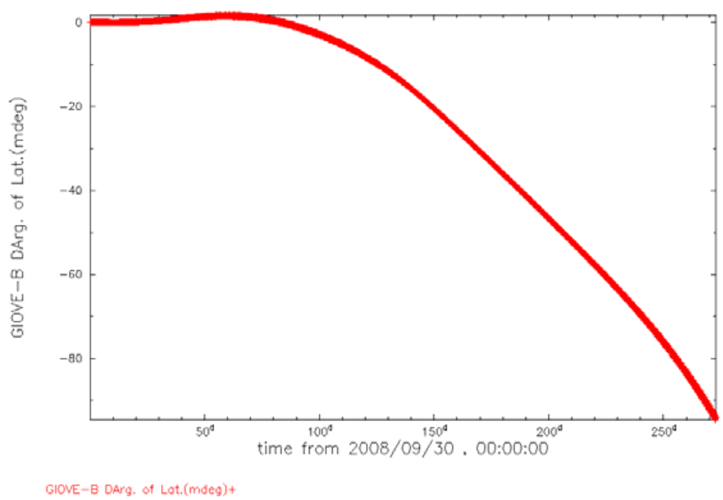

Fig. 12. Difference in argument of latitude between a propagated orbit (using a constant Y-bias) and a sliding window orbit determination.

The Y-bias is an empirical acceleration estimated in precise orbit determination of GNSS satellites, its direction is perpendicular to the sun-satellite vector, and it is aligned with the satellite y-axis, i.e. parallel to the rotation axis of the solar arrays. Since the satellites are practically symmetrical with respect the body XZ plane, there is no clear explanation for this asymmetry [7].

Further analyses are needed in order to assess the effect of this kind of perturbations, and developing procedures to take them into account when optimizing the orbits.

5.3 SK manoeuvre with drift

The analysis done so far has also assumed that the SK manoeuvre is made of one delta-V that changes the argument of latitude rate, but not the argument of latitude it self. However, there is the possibility that the deadband can be better utilized if the SK manoeuvre includes a small drift, no bigger than 3 degrees. Such a manoeuvre would take longer because it will need extra time for the drift. This may increase the unavailability time of that particular satellite, but it may allow to account for other errors (for instance the Y-bias mentioned above).

6. CONCLUSIONS

Three strategies have been presented to maintain the Galileo satellites within the tolerances established for the constellation. The third strategy, based on full absolute SK, has been chosen for the advantages it offers in terms of extension of constellation operational life and injection of satellites of different design. The constellation parameters have been chosen according to this strategy to minimize the number of manoeuvres assuming an initial deployment between 2010 and 2014.

However, further refinement of this strategy is needed in order to take into account errors in the semi-major axis, empirical SRP acceleration, and the possibility to drift the satellites within the deadband when doing the SK manoeuvres.

7. ACKNOWLDEGMENT

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