Galileo Station Keeping Strategy

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ABSTRACT

This paper presents the analyses done for the design and implementation of the Maneuver Planning software of the Galileo Flight Dynamics Facility. The station keeping requirements of the constellation have been analyzed in order to identify the key parameters to be taken into account in the design and implementation of the software.

INTRODUCTION

The accuracy of position determination based on navigation signals depends mainly on the User Equivalent Range Error and the Dilution of Position. The former can be allocated to broadcast orbit and clocks accuracy, S/C payload and environment, atmospheric effect on the signal paths, and finally, the user receiver. The latter is a function of the constellation geometry. The objective of station keeping is to maintain the constellation in a configuration that allows ensuring the nominal level of service during its whole planned lifetime.

The station keeping strategy shall minimize the propellant utilization and the time the satellite is out of service during orbit correction maneuvers, while maintaining low the operational cost and complexity required. Actually, if satellite positions were not controlled, the constellation would completely lose its geometrical configuration because of the effects of orbital perturbations. To avoid the deterioration of the constellation geometrical pattern, it is imperative to outline the conditions and the criteria that define the orbit control strategies and the corresponding implementation constraints.

The Galileo constellation that is going to be analyzed in this section will be constituted by a MEO Walker constellation with the following parameters:

- ❑ Walker constellation 27/3/1 with an additional spare satellite in each orbital plane.
- ❑ Inclination: 56 degrees.
- ❑ Orbit altitude: 23222 km.

The station keeping requirements of the Galileo constellation are:

- ❑ Orbit inclination limits: nominal inclination ± 2 degrees.
- ❑ Relative spacing of nodal lines: nominal difference ± 2 degrees.
- ❑ Relative along-track phasing of adjacent S/C in one orbit plane: nominal phasing ± 3 degrees.
- ❑ Relative along-track phasing of S/C in adjacent orbit planes: nominal phasing ± 3 degrees.

ORBIT PERTURBATIONS

The analysis of the evolution of the S/C orbital elements is the first step to be carried out in order to characterize the constellation maintenance problem and then define an effective orbit control strategy. This analysis has been conducted comparing the effects of the main disturbance sources of a MEO constellation with a reference constellation that only considers the effects of the zonal terms of the Earth gravitational field.
The considered perturbations are:

- ❑ Earth Gravitational Field (6x6).
- ❑ Third-body attraction (Sun and Moon).
- ❑ Solar radiation pressure.

The analysis of the evolution of orbital elements has provided the following conclusions:

❑ Sun and Moon attraction is the perturbation that causes greater differences with respect to the reference case.

      a. Evolution of orbital inclination and Right Ascension of Ascending Node (RAAN) driven by the attraction of Sun and Moon. Due to the different orientation with respect to the ecliptic and the moon orbital plane, each constellation plane has a different inclination and RAAN evolution.

      b. Evolution of the argument of latitude (and therefore, relative phasing between satellite) is also driven by the attraction of Sun and Moon through the evolution in inclination and its effect on the mean motion due to zonal terms.

❑ The effect of tesseral terms of Earth gravitational field and solar radiation pressure, are smaller than the ones shown by Sun and Moon attraction.

STATION KEEPING STRATEGY

The reference constellation (Walker constellation 27/3/1) will represent the expected evolution of the constellation in order to assure the constellation nominal level of service during its lifetime. It is used to define the offsets of the orbital elements in order to fulfill the required station keeping requirements.

The reference constellation has the following characteristics:

❑ Earth Ground-track, 17 revolutions in 10 sidereal days, equivalent to a mean semi-major axis of 29601 km.

❑ Constant orbital inclination of 56 degrees.

❑ Dynamic model that considers the Central Body and J_2.
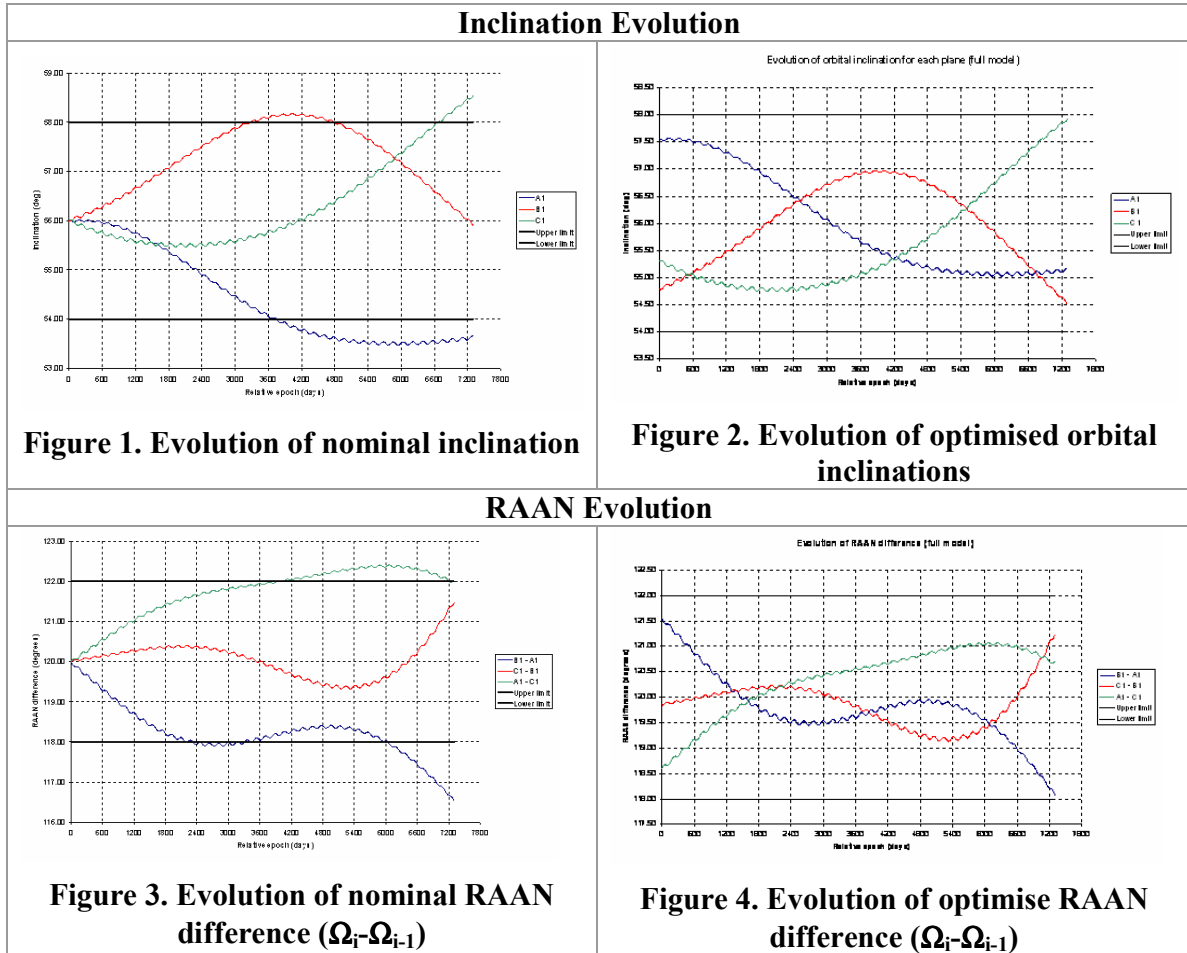
Inclination and RAAN control

Considering the evolution of the inclination and RAAN due to the orbital perturbations it is possible to define the initial offsets for each constellation plane. In this way, the required station keeping requirements can be fulfilled during the constellation lifetime without out of plane maneuvers. The Figures 1 and 3 show the evolution of the nominal inclination and RAAN of three satellites of the constellation, they show that the inclination control box and RAAN control box are violated.

The initial value of the inclination is modified in order to have an average value of the orbital inclination during the considered period of time equal to the reference one. The offset introduced to the initial inclination takes also into account any violation of the predefined control deadbands (see Figure 2).

Considering the influence of the orbital inclination in the evolution of the right ascension of the ascending node when the J_2 model is considered; an average value of the inclination around the reference inclination could help to have similar drifts in the Right Ascension of

the Ascending Nodes of the different constellation planes and then minimize differences among them when the full model is considered. Figure 3 shows that initial RAAN for each plane must be modified in order to assure that the evolution of relative phasing of nodal lines is within the predefined thresholds (± 2 degrees). Figure 4 shows the evolution of the RAAN difference after modifying the initial values

Inclination Evolution	
Figure 1. Evolution of nominal inclination	Figure 2. Evolution of optimised orbital inclinations
RAAN Evolution	
Figure 3. Evolution of nominal RAAN difference ($\Omega_i - \Omega_{i-1}$)	Figure 4. Evolution of optimise RAAN difference ($\Omega_i - \Omega_{i-1}$)

The control strategy of orbital inclination and relative phasing of nodal lines introduced has been applied to the definition of the initial parameters of the constellation, but it is also applicable to correct possible injection errors in order to assure that those parameters evolve during the constellation/satellite lifetime without exceeding the pre-defined thresholds. The correction of orbital inclination and RAAN is applicable to all the spacecraft located in the same plane.

Argument of Latitude control

The evolution of the orbit along-track phase (argument of latitude) depends on the semi-major axis and inclination (considering a J_2 model). The initial value of the inclination (and practically its evolution during the satellite life) is "fixed" once the launch vehicle target has been defined; then, the only degree of freedom to tune the orbit phase evolution is the semi-major axis.

In order to control the spacecraft phase two different steps can be identified. The first one corresponds to the optimization of the spacecraft semi-major axis in order to minimize the difference between the evolution of the mean phase rate of the reference orbit and the mean phase rate of the "real" orbit during a pre-defined period of time. The second step represents the computation of the initial offsets in order to keep the absolute differences for each spacecraft with respect to its reference spacecraft within the absolute control deadbands ($\pm$ 1.5 degrees) in order to fulfill the relative in-plane and inter-plane requirements ($\pm$ 3.0 degrees).

First of all, the semi-major axis of the spacecraft will be modified in order to have an average value of the mean phase drift equal to the reference model one (considering J2 model) during a pre-defined period of time. The first considered period of time was the satellite lifetime, but the relative phasing between spacecraft of adjacent planes is not within the requested control deadbands. This implies that it is not possible to optimize the semi-major axes and initial values of argument of latitude in order to avoid performing station keeping maneuvers. If the considered period of time is 7 years, it is possible to apply offsets to initial values and fulfill the relative phasing requirements. This period of time implies that this station keeping strategy will implement one control maneuver during the satellite lifetime.
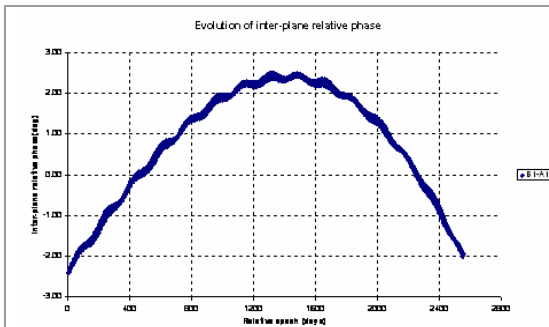

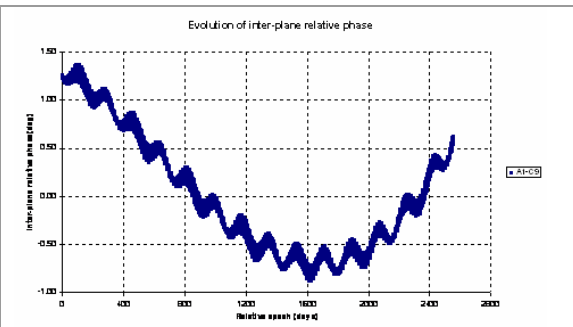| **Figure 5. Evolution of relative phase for two S/C (planes 1 and 2)** | **Figure 6. Evolution of relative phase for two S/C (planes 1 and 3)** |

After this optimization, the phase difference of the full model constellation with respect to the reference one could be monitored to check that the evolution of the phase is within the control deadbands. If control deadbands are violated, then the corresponding maneuver has

to be defined in order to bring the satellite inside the control box trying to maximize the time that the spacecraft will be inside the control box.

The definition of the modification/optimization of orbital parameters (semi-major axes and mean anomalies) to define the evolution of spacecraft phase has introduced a possible strategy to define the initial parameters of the constellation and could define the absolute control strategy for each spacecraft. This strategy depends on the considered satellite and then must be applied to all the satellites of the constellation. Nevertheless, the robustness of this strategy relies on a precise targeting of the semi-major axis, determined by the minimum maneuver ΔV (driven by the propulsion design and calibration) and the orbit accuracy error (driven by the ranging measurement errors and bias, orbital models, and ranging campaigns).

Definition of satellite operational orbits

The satellite operational orbits are defined to avoid performing out-of plane maneuvers and minimizing the number of in-plane ones during the considered period of time. It is possible to select different end epochs to define/optimize out-of-plane and in-plane parameters. These operational orbits are defined as follows:

Table 1. Optimised orbital mean elements definition

Initial mean element	New initial mean element
a (semi-major axis)	$a + \Delta a^{offset}$
e (eccentricity)	e
i (inclination)	$i + \Delta i^{offset}$
Ω (Right Ascension of the Ascending Node)	$\Omega + \Delta \Omega^{offset}$
$\phi = \omega + \nu$ (argument of latitude)	$\phi + \Delta \phi^{offset}$

The parameters of the initial mean state vector which are going to be optimized are:

❑ Inclination: The optimisation of initial inclination is performed individually for each satellite by comparison with reference and limit inclinations.

❑ Right Ascension of Ascending Node: The optimisation of initial RAAN is performed for each set of three satellites at different planes and at the same slot. The three relative RAANs are compared with the reference and limit ones.

❑ Semi-major axis: The optimisation of initial semi-major axis is performed individually for each satellite, and the method tries to make mean operational and reference phase drift equal.

❑ Argument of latitude: The optimisation of initial argument of latitude is performed individually for each satellite, and the method centres the evolution of the operational argument of latitude with respect to the reference one, given by the reference orbit.

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It is important to take into account the order of the parameter in the optimization process, because the optimization of one of them affects the other ones. In the following table it is shown the optimization sequence for the out-of-plane and in-plane parameters.

Table 2. Sequence of orbital parameter optimization

Order	Kind of parameter	Parameter
1st	Out-of-plane	i (inclination)
2nd		Ω (Right Ascension of the Ascending Node)
3rd	In-plane	a (semi-major axis)
4th		$\phi = \omega + v$ (argument of latitude))

CONCLUSIONS

The analyses presented in this paper were the starting point for the design of the Maneuver Planning software of the Galileo Flight Dynamics Facility. The constellation station keeping requirements are fulfilled by selecting adequate initial offset of the orbital parameters for each satellite of the constellation and performing only in-plane station keeping maneuvers.