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Include Abstract (approximately 1000 words)
GALILEO Station Keeping Strategy

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 minimise the propellant utilization and the time the satellite is out of service during orbit correction manoeuvres, 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 station keeping requirements of the Galileo constellation are:

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

The analysis of the evolution of the S/C orbital elements is the first step to be carried out in order to characterise 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 w.r.t. the reference case.
  - 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.
  - 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.

The reference constellation (Walker constellation 27/3/1) will represent the expected evolution of the spacecraft orbits in order to guarantee the constellation nominal level of service during its lifetime. It is used to define the offsets of the orbital elements in order to fulfil the required station keeping requirements. The reference constellation has the following characteristics:

- Repeat 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.
- Constant RAAN regression of 9.45 deg/year.
- Dynamic model that considers the Central Body and \( J_2 \).
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. This way the required station keeping requirements can be fulfilled during the constellation lifetime without out of plane manoeuvres.

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 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.

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 optimisation of the spacecraft semi-major axis in order to minimise 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 w.r.t. its reference spacecraft within the absolute control deadbands ($\pm 1.5$ degrees) in order to fulfil the relative in-plane and inter-plane requirements ($\pm 3.0$ degrees).

After this optimisation, the phase difference of the full model constellation w.r.t. 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 manoeuvre has to be defined in order to bring the satellite inside the control box trying to maximise the time that the spacecraft will be inside the control box, return to initial offset.

The modification/optimisation of the initial orbital parameters to control the evolution of spacecraft phase has provided a possible absolute control strategy for each spacecraft. Nevertheless, the robustness of this strategy relies on a precise targeting of the semi-major axis, determined by the minimum manoeuvre delta-V (driven by the propulsion system design) and the orbit accuracy (driven by the tracking measurement errors and biases, orbit models, and tracking campaigns).