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Impact assessment of perturbations on the orbit control in a Near-Zero Inclination Geosynchronous Synthetic Aperture Radar

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Abstract. The Near-Zero Inclination Geosynchronous Synthetic Aperture Radar (NZI-GEOSAR) concept enables high-frequency observations with stable geometry for interferometric applications. However, orbit stability at GEO altitude is strongly affected by perturbative forces that challenge the control strategy efficiency. This work quantifies the relative contribution of lunisolar gravitational effects, solar radiation pressure, Earth's non-sphericity to the orbit maintenance of a NZI-GEOSAR mission implementing the Tangential-Normal (TN) control strategy proposed in [1]. Simulation results show that the lunar gravitational perturbation dominates the ΔV budget, accounting for about 85% of the total control effort, while solar and geopotential effects have minor influence. Moreover, a 14% ΔV increase between epochs is observed, driven by the 18.6-year lunar node regression cycle.

Introduction

Earth Observation missions increasingly rely on advanced spaceborne Synthetic Aperture Radar (SAR) systems to provide high-resolution, all-weather imaging for scientific and civil applications. Within this framework, the GEOSAR concept - proposed since 1978 in several configurations - offers the unique capability of wide-swath, near-persistent observation from geostationary orbit, enabling revisit intervals of 24 hours or less over continental scales due to its synchronicity with Earth's rotation. Recent developments confirm the growing interest in this architecture: China's Ludi-Tance 4-01 satellite, launched in August 2023 on a 16° inclined GEO orbit, represents the first operational GEOSAR mission [2], while ESA's Hydroterra+ concept, shortlisted under the Earth Explorer 12 call, envisions a C-band Near-Zero-Inclination (NZI) GEO system for twice-daily monitoring of Europe and the Mediterranean [3].

A key requirement for such systems - especially in NZI configurations - is the implementation of an orbit control strategy that preserves spatial and temporal coherence for interferometric SAR (InSAR) applications. Maintaining small cross-track baselines and stable Doppler bandwidth overlap is challenging at GEO altitude, where even small orbit deviations induce significant ground-projection errors. Perturbative accelerations due to Solar Radiation Pressure (SRP), Earth's oblateness, and lunisolar gravity can destabilize the orbit and degrade imaging performance even over short timescales. To meet these constraints, tailored control strategies have been proposed in [1], with the Tangential-Normal (TN) approach emerging as the most efficient trade-off between interferometric performance and propellant consumption. Such previous analyses, however,

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considered all perturbations simultaneously, without isolating their individual contributions. This limits the understanding of the physical origin of the ΔV demand in GEOSAR configurations.

The present work aims to identify and quantify the dominant perturbative sources affecting orbit stability and InSAR coherence in NZI-GEOSAR systems, clarifying how solar, lunar, and geopotential effects drive ΔV consumption over different epochs. The analysis compares multiple simulation scenarios in terms of ΔV budget and fuel usage, providing physical insight into orbital distortion mechanisms, useful for the optimization of control strategies for GEOSAR missions.

This paper is organized as follows. Section I explains the methodology behind the conducted orbit perturbation, Section II provides the simulation setting and the results, discussing the impact of them on the TN control strategy.

Orbit Perturbations Analysis

The efficient applicability of the Tangential-Normal control strategy [1] can be appreciated from two different perspective in Fig. 1 by comparing the drifting behaviour of the perturbed orbit and the stable behaviour of the controlled one. In the analyses that have been already conducted, the orbit control simulations are performed in totally perturbative orbit environments in GMAT software [4]. This implies that Earth gravitational potential up to 21 degree and order, Moon and Sun gravitational attractions, and SRP are activated in the orbit propagator to take into account all the perturbing accelerations acting on the system in the reference epoch (i.e., 15th March 2036 00:00:00 UTCG). Spacecraft mass is 2000 kg, the exposed area to the Sun is nominally 50 m^2, thus leading to 0.025 kg/m^2 of area to mass ratio A/m; the reflectivity coefficient C_r is 1.8. This simulation setting enabled the estimate of a realistic total ΔV budget that has to be allocated for orbit maintenance tasks.

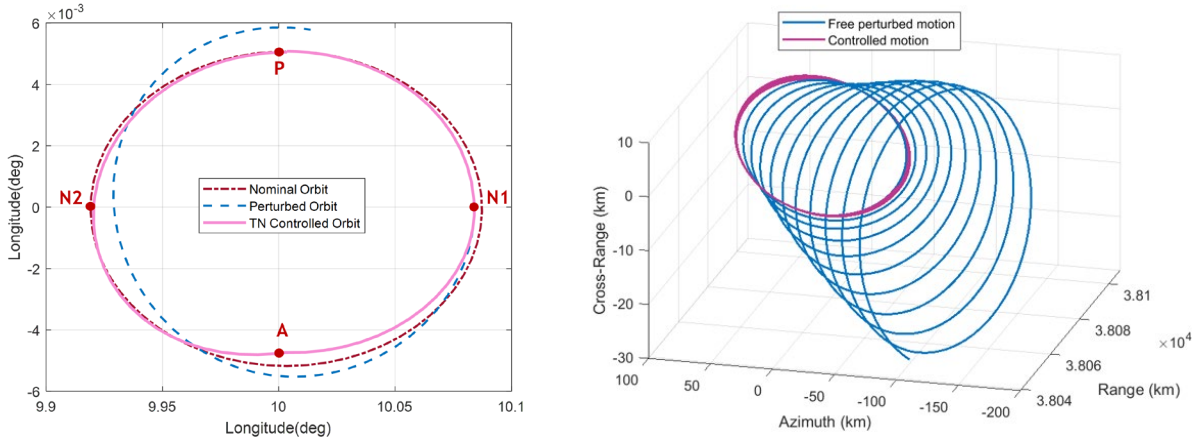


Figure 1 – Left: one-day comparison between the nominal orbit defined in [1], the perturbed orbit, and the TN controlled orbit from the ground-track point of view. P is perigee, A is apogee, N1 is the first orbit node, N2 is the second orbit node. Right: 10-days comparison between the free perturbed motion and the TN controlled motion in the topocentric Range-Azimuth-Cross-Range frame of a target placed at 16.75°E, 46°N, 0 km altitude

However, by switching to the analyses of the individual perturbations, it is possible to assess the impact of each force on the ΔV budget and the consequent fuel mass usage. Specifically, each perturbing force can be activated separately in the GMAT propagator so that its impact on the orbit stability and the maintenance cost can be properly appreciated and disentangled.

In general, the perturbative environment experienced by a GEOSAR satellite is governed by the complex gravitational interaction within the Earth-Moon-Sun system, which generates motions spanning a wide range of characteristic frequencies - from the daily Earth rotation to the lunar month, the solar year, and slow precessions of orbital planes and apsides extending up to tens of

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thousands of years. Each of these perturbations acts, when isolated, with distinct frequency signatures and affects different orbital components, thus requiring specific orbit control actions to be counteracted. Among these phenomena, the most relevant long-term perturbation is linked to the regression of the lunar nodes, which completes a full cycle every 18.6 years, accompanied by an apsidal precession of approximately 8.85 years [5]. The lunar orbit, inclined by about 5.15° to the ecliptic, combined with the 23.44° tilt between the ecliptic and the Earth's equator, leads to a variable apparent inclination of up to ± 28.6° with respect to the equatorial plane. In general, the 18.6-year regression of the nodes periodically changes the direction and magnitude of the lunar gravitational acceleration acting on the GEO spacecraft, modulating the out-of-plane component of the perturbing force and, consequently, the ΔV required for North-South orbit maneuvers. When the Moon reaches higher declinations, the normal component of its gravitational force increases, leading to a higher ΔV demand for the spacecraft inclination control; conversely, when the Moon is near the equatorial plane, this requirement is minimized.

The Sun, although less variable in apparent motion, also contributes to the perturbative environment. Its declination range (± 23.44°) and distance to Earth vary only slightly throughout the year, making its influence on out-of-plane dynamics nearly constant over time. Additionally, this gravity contribution also determines in-plane oscillations, driving periodic variations in eccentricity and argument of perigee with annual frequency [6]. Another relevant aspect is that the interaction between solar and lunar perturbations can produce short-term beating patterns that slightly modulate the needed ΔV, particularly when their declinations align constructively or destructively. The different trend of the declination of these third bodies (i.e., Moon and Sun) can be appreciated in Fig.2, where a temporal window of 20 years is considered to confirm the peculiar periodicity of the relevant motions.

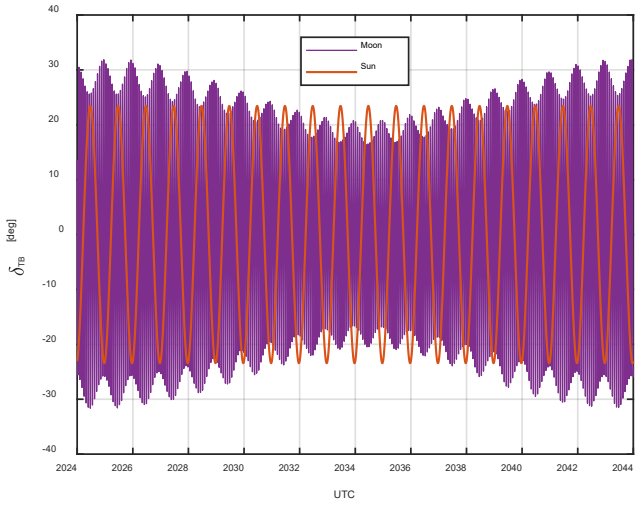


Figure 2 - Trend of the declination (δ_{TB}) of the involved third bodies (Moon, Sun) over a 20-year simulation period

The ephemerides of the Moon and the Sun are here generated through the JPL Horizons on-line solar system data calculator [7] considering the nominal fixed GEOSAR satellite point whose definition is provided in [1]. It is worth noting that, since the GEO observer is displaced from the Earth center, the apparent declination of the Moon reaches a maximum value that is slightly higher (± 31.7°) in absolute terms.

In addition to third-body effects, the Earth's non-sphericity - especially the equatorial asymmetry represented by the C_{22}, S_{22} geopotential spherical harmonics [8] - induces a longitudinal drift of the GEO point, causing an East-West motion that must be compensated by

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tangential maneuvers. This perturbation is time-invariant and geometry-dependent, defining two stable (75°E, 255°E) and two unstable (165°E, 345°E) equilibrium longitudes. Finally, SRP acts primarily along the radial and tangential directions, depending on the spacecraft attitude and Sun-spacecraft geometry [8]. The main effects are small periodic eccentricity variations and minor diurnal oscillations in the ground track. Although the SRP long-term impact on orbit stability is limited, it can slightly perturb the along-track position, especially, for example, during spacecraft attitude transitions.

Simulations and Results

The impact of the perturbing forces can be appreciated looking at the orbit evolution in the topocentric reference frame centered in target B5, whose geodetic coordinates are 16.75°E, 46°N, 0 km altitude [1]. Fig. 3 depicts the controlled orbit evolution for a 30-days simulation under different propagator settings.

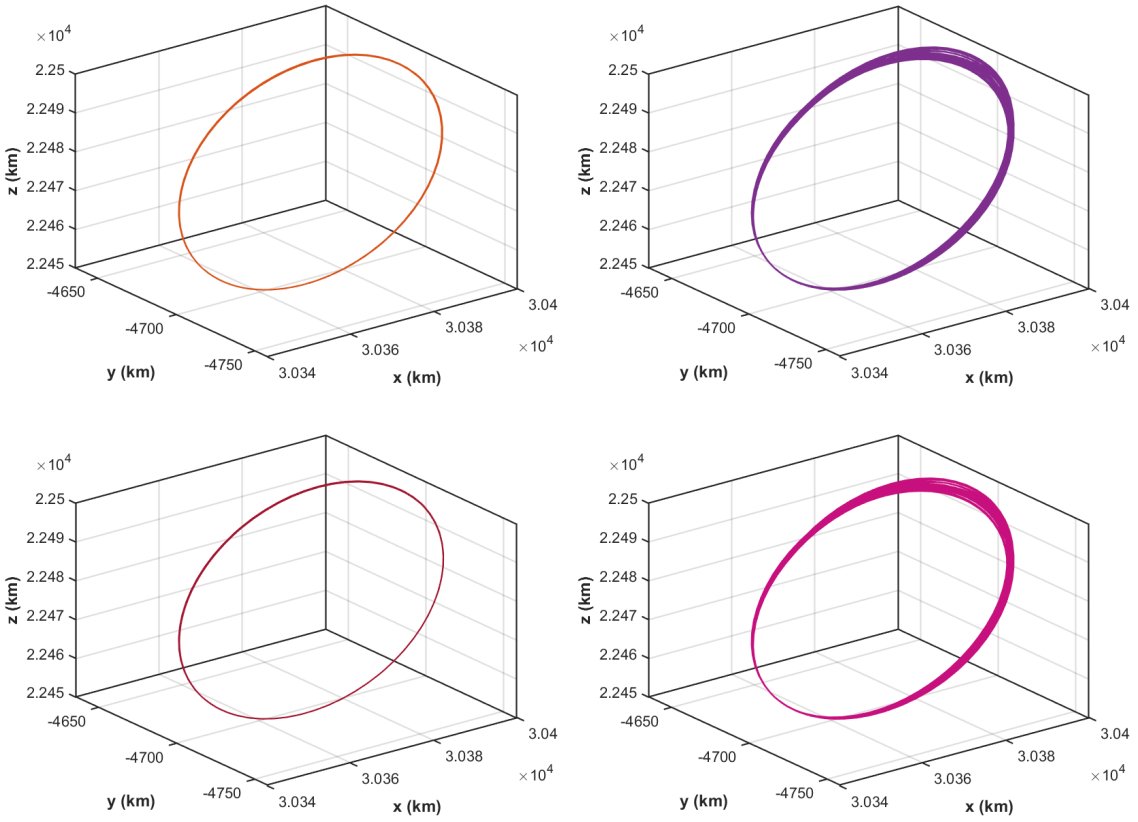


Figure 3 Controlled orbit evolution in the topocentric reference frame centered in beam B5, simulation of 30 days performed in GMAT activating different perturbing effects. Upper left: only Sun gravity is activated; Upper right: only Moon gravity is activated; Bottom left: only SRP and Earth non-sphericity are activated; Bottom right: all the perturbing forces are activated

The comparison among the different cases demonstrates that orbits propagated under lunar-only perturbations (Fig. 3 Upper right) closely reproduce the deviations observed when all perturbations are active (Fig. 3 Bottom right). This further confirms that lunar gravity is the primary driver of orbital plane distortion. Indeed, the Sun gravity contribution (Fig. 3 Upper left) is less impactful than the Moon one, causing smaller deviations of the orbit. When only SRP and Earth's non-sphericity are activated (Fig. 3 Bottom left), the orbit is very stable, remaining tightly bound around the nominal position, with very minor oscillations mostly confined to the along-track direction.

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Beyond the geometric orbit representations, a quantitative comparison in terms of ΔV budget is performed to assess the effect of each perturbation source. Two distinct simulation epochs are selected to capture the temporal variability of the lunar gravitational influence, which - as previously discussed - is expected to dominate the long-term evolution of the orbital dynamics. Specifically, two epochs separated by approximately nine years are selected, corresponding to the phases of minimum and maximum lunar declination within the 18.6-year nodal regression cycle. According to the declination trends in Fig. 2, 15 March 2033 00:00:00 UTCG and 15 March 2042 00:00:00 UTCG are chosen as the initial epochs for one-year controlled simulations in GMAT.

Table 1 summarizes the resulting ΔV and propellant consumption (i.e., fuel mass usage, m_{fuel}), assuming a 2000 kg spacecraft equipped with a chemical propulsion system of specific impulse of 300 s. The results clearly indicate that the Moon's gravitational perturbation is the dominant source of instability for the NZI GEOSAR configuration, whatever the selected epoch is. When only the lunar attraction is active, the required ΔV accounts for approximately ~85 % of the total control effort, while the solar contribution remains below ~35 %. Additionally, the combined ΔV of the Sun and Moon acting separately slightly exceeds the total ΔV obtained when both perturbations are applied simultaneously. This behavior reveals a geometric partial compensation between the lunar and solar accelerations: depending on their relative phase and declination, the normal components of their perturbative forces can partially counteract each other, reducing the total control effort required. In contrast, when third-body effects are neglected, the ΔV requirement drastically drops to ~6 m/s, confirming that SRP and Earth's non-sphericity have a limited impact on long-term orbit stability.

Table 1 – ΔV budget and fuel usage comparison

Epoch	Active Perturbations	ΔV [m/s]	m_{fuel} [kg]
2033	ALL	87.55	61.11
	ONLY MOON	74.97	52.44
	ONLY SUN	32.45	22.86
	NO THIRD BODY	6.35	4.49
2042	ALL	102.15	71.13
	ONLY MOON	87.13	60.82
	ONLY SUN	32.41	22.84
	NO THIRD BODY	6.37	4.51

The comparison between the epochs reveals a ΔV increase of about 14%, in 2042 epoch, which can be directly attributed to the 18.6-year regression of the lunar nodes modulating the inclination of the Moon's orbital plane relative to the Earth's equator. In 2042, when the lunar declination reaches its maximum amplitude, the normal component of the perturbative acceleration is increased, leading to a larger ΔV associated with out-of-plane maneuvers. Conversely, in 2033, the smaller lunar declination corresponds to a dynamically favorable configuration requiring less control effort. As expected, the Sun's gravitational influence remains nearly constant across epochs due to the quasi-stationary geometry of the Earth-Sun system.

Conclusions

A detailed analysis of the perturbative accelerations on a NZI GEOSAR orbit has been conducted through high-fidelity GMAT simulations implementing the Tangential-Normal control strategy. Each perturbation source has been individually activated to quantify its contribution to orbit stability and control effort. Results confirm that the lunar gravitational attraction is the dominant disturbance, responsible for nearly 85% of the total ΔV required for orbit control. The comparison between 2033 and 2042 epochs shows a ΔV increase of about 14%, consistent with the 18.6-year

lunar node regression cycle that modulates the Moon's declination and strengthens its out-of-plane effect during maximum inclination phases. Overall, the study demonstrates that third-body geometry and epoch selection can relatively influence orbit-keeping efficiency. These results highlight the need for third bodies geometry-dependent control planning and propellant allocation strategies in future GEOSAR missions to ensure long-term interferometric performance with minimized fuel consumption.

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