Postprint: Orbital Evolution Analysis of iHCO Satellites in the CAPS System

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Abstract

The Chinese Area Positioning System (CAPS) proposes to employ satellites in inclined Highly Circular Orbits (iHCO) that are 150 } 300 km higher than Geostationary Earth Orbit (GEO) to construct a navigation and communication constellation. The orbital evolution process of iHCO satellites under various perturbing forces and satellite orbit injection deviations is analyzed. This work can be applied to the optimization design of iHCOs, providing reference for establishing an excellent CAPS navigation and communication constellation using iHCO satellites.

Full Text

The Orbit Evolution of iHCO Satellites in the CAPS System

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Abstract: The Chinese Area Positioning System (CAPS) proposes to use inclined highly circular orbit (iHCO) satellites to form a navigation and communication constellation. This paper analyzes the orbital evolution of iHCO satellites under various perturbation forces and injection orbit biases. This work can be used to optimize the design of iHCO satellites and provides a reference for constructing an excellent CAPS navigation and communication constellation using iHCO satellites.

Keywords: Inclined Highly Circular Orbit (iHCO); perturbation force; injection orbit bias; orbit evolution

1. Introduction

The CAPS system, based on geostationary Earth orbit (GEO) communication satellites [1], plans to push end-of-life GEO communication satellites to an inclined highly circular orbit (iHCO) approximately 150-300 km above GEO to form the CAPS constellation [2]. During iHCO satellite operation, fuel is primarily used for attitude adjustment toward Earth, which significantly extends the satellite' s operational lifespan. Since iHCO satellites are positioned above GEO, their orbital angular motion lags behind Earth's rotation, causing them to drift westward relative to Earth without requiring longitude or latitude station-keeping. This westward drift can be exploited to achieve global navigation and communication coverage [3].

Under perturbation forces, the orbital parameters of iHCO satellites will evolve. The inclination gradually increases, which can improve the navigation constellation layout and enhance CAPS positioning performance. However, satellites cannot be injected into their designed orbits with perfect accuracy, resulting in injection biases between the actual and designed orbits. In engineering applications, these biases within allowable design tolerances can still cause non-negligible differences in orbital evolution under perturbation forces. This paper focuses on the orbital evolution characteristics of iHCO satellites under perturbation forces and the effects of injection biases, providing a reference for selecting appropriate iHCO design parameters to form a CAPS constellation with excellent navigation performance.

2. Orbital Evolution of iHCO Satellites

During spaceflight, satellites are primarily subject to Earth' s gravity, but also to perturbation forces including lunar and solar gravitational forces, atmospheric drag, and solar radiation pressure. These perturbations cause the orbital elements—semi-major axis a, eccentricity e, inclination i, right ascension of the ascending node (RAAN) Ω, argument of perigee ω, and mean anomaly M—to vary with time. For long-term stability analysis of high-orbit satellites like iHCO, atmospheric drag is negligible, and we primarily consider Earth' s non-spherical gravity, lunar/solar gravity, and solar radiation pressure.

Due to Earth' s non-uniform mass distribution, satellites experience non-spherical gravitational forces whose magnitude depends on satellite position and distance from Earth. Considering Earth' s non-spherical gravitational potential J_2, the long-term variation rates are primarily described by RAAN and the along-track angle λ (representing satellite phase). For semi-major axis, simple time translation and coordinate transformation show that satellites with identical eccentricity and inclination experience the same long-term variations in Ω and λ under J_2 perturbation. Therefore, while Earth' s non-spherical forces cause absolute phase and orbital plane changes in an iHCO constellation, the relative phase differences and orbital plane relationships remain unchanged, preserving the constellation's spatial geometry and global coverage performance

[4].

The perturbations from Earth's non-spherical forces and lunisolar gravity can be analyzed through high-precision orbital dynamics models, while solar radiation pressure effects depend on satellite surface reflectivity and area-to-mass ratio, typically simulated using ideal models. Using the Satellite Tool Kit (STK) with its High-Precision Orbit Propagator (HPOP), we analyzed the effects of these primary perturbation forces on iHCO satellites [5-6].

The initial iHCO parameters used were: semi-major axis a = 42,364.14 km, eccentricity e = 0°, inclination i = 7°, RAAN Ω = 0°, argument of perigee ω = 0°, and mean anomaly M = 0°. The calculations employed the 21\$×21*WGS*84/*EGM*96*gravitymodel*, *adual* − *coneEarthshadowmodel*, *andidealsolarradiationpressuremodelwithasolarradiationpressurecoefficientof*1. *to* − *massratioof*0.02*m*^{2}\$/kg.

[Figure 1: see original paper] shows the orbital parameter evolution under Earth' s non-spherical forces, lunisolar gravity, and solar radiation pressure. As shown in [FIGURE:1(a)], the semi-major axis exhibits short-period variations. Since Earth' s non-spherical forces and lunisolar gravity are conservative forces, no long-term term exists for semi-major axis. Solar radiation pressure, under ideal models without Earth shadow effects, is also conservative and causes no energy dissipation, resulting in minimal variation magnitude. Therefore, iHCO satellites can maintain near-circular orbits long-term without considering the long-term stability of argument of perigee.

[FIGURE:1(c)] shows that orbital inclination experiences significant long-term variation, increasing by approximately 0.75° per year. The semi-annual and semi-monthly periodic variations are caused by solar and lunar gravity, respectively, making lunisolar gravity the primary factor for inclination change, with negligible effects from Earth' s non-spherical forces and solar radiation pressure. This continuous inclination increase under perturbation forces significantly improves the CAPS constellation' s spatial layout and navigation performance.

[FIGURE:1(d)] shows RAAN experiences long-term and long-period variations of about 1° per year from lunisolar gravity, plus secular perturbation from Earth' s non-spherical forces. Thus, the stability of iHCO satellites under these perturbations is primarily manifested in inclination and RAAN drift, which can be used to describe orbital stability.

3. Effects of Injection Orbit Bias

During constellation deployment, satellites cannot be injected into their designed orbits perfectly. The deviation between actual and designed orbits is called injection orbit bias [7]. While typically within design tolerances, these biases cause non-negligible differences in orbital evolution under perturbation forces.

Assuming initial iHCO parameter biases of Δa, Δe, Δi, $\Delta\Omega$, and $\Delta\lambda$, the long-term perturbation variations in RAAN and along-track angle under the J_2 term are:

$\Delta\Omega$ = -7/2 ($\Delta a/a$) + 4Δe - sin(i_0)Δi
$\Delta\lambda$ = -7/2 ($\Delta a/a$) - 3 tan(i_0)Δi

where i_0 is the designed nominal inclination value. Semi-major axis bias causes mean angular velocity deviation, resulting in long-term along-track variation:

$\Delta\lambda$ = -3/2 ($\Delta a/a$) n (t - t_0)

where t_0 is the initial time. These equations show that long-term orbital changes under J_2 depend only on semi-major axis and inclination biases. For near-circular iHCO satellites, injection bias causes long-term variations in RAAN and along-track angle, but Earth' s non-spherical forces do not alter constellation geometry. However, when a constellation comprises iHCO satellites with identical semi-major axis, eccentricity, and inclination, injection biases change satellite relative positions, affecting constellation geometry and coverage performance.

For an iHCO satellite with semi-major axis a = 42,364.14 km, we calculated phase and orbital plane changes for semi-major axis biases of 100 m, 200 m, and 500 m, assuming an inclination bias of 0.1°. shows these effects, where "combined effect" represents the total impact of Δa and Δi. The results demonstrate that semi-major axis bias is the primary factor causing along-track angle drift, requiring strict design tolerance compliance.

[Figure 2: see original paper] further examines how inclination and semi-major axis biases affect RAAN and along-track angle variations within one year. [FIGURE:2(a)] and [FIGURE:2(c)] show that for a given inclination, long-term perturbations in RAAN and along-track angle increase with inclination bias. [FIGURE:2(b)] and [FIGURE:2(d)] show that different inclination and semi-major axis biases have varying long-term effects. Inclination bias is the main factor affecting RAAN change, while semi-major axis bias causes dramatic along-track angle variations that increase linearly with time.

4. Conclusions

Based on our analysis of iHCO orbital evolution and injection bias effects, we conclude:

1. Under perturbation forces such as lunisolar gravity, iHCO satellite inclination continuously increases, optimizing CAPS spatial layout and improving navigation performance.
2. When CAPS uses a constellation of iHCO satellites with identical semi-major axis, eccentricity, and inclination, the relative geometric structure remains unchanged, maintaining global coverage performance but causing regional drift under perturbations.

3. Since each satellite' s injection bias is random, satellite phase and orbital plane changes under Earth' s non-spherical, lunisolar, and solar radiation pressure perturbations affect constellation geometry. Therefore, iHCO injection biases must be considered in CAPS constellation design.
4. Semi-major axis injection bias is the primary factor causing actual orbits to deviate from designed orbits.

When constructing a CAPS constellation using iHCO satellites, the orbital evolution characteristics under perturbation forces must be fully considered, particularly exploiting the increasing inclination feature to enhance navigation coverage. Using iHCO satellites with identical semi-major axis, eccentricity, and inclination maintains constellation geometry stability, while injection bias effects on satellite phase and orbital plane must be accounted for to determine appropriate design parameters that ensure CAPS navigation performance meets mission requirements.

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Note: Figure translations are in progress. See original paper for figures.