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Postprint: Analysis of Search Strategies for Faint Space Debris Targets in GEO

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Abstract

Based on the characteristics of the geosynchronous orbit, the motion characteristics of space debris in geosynchronous orbit are introduced. For search strategies employed in observing faint space debris in geosynchronous orbit, considering the target's prediction error and field of view size, the success probabilities of concentric circle search and step-stare search are calculated respectively using mathematical methods, the features of both are analyzed based on the calculation results, and it is concluded that the concentric circle search strategy generally exhibits higher search efficiency.

Full Text

Preamble

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Analysis of Search Strategies for Faint Space Debris Targets in the GEO Region

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Abstract

Based on the unique dynamical characteristics of the geosynchronous orbit, this paper introduces the motion features of space debris in GEO. For observation search schemes targeting faint GEO space debris, we mathematically calculate the success probabilities of both concentric circles search and climbing stairs

search, taking into account target prediction errors and field of view size. Analysis of the computational results reveals that, in general, the concentric circles search strategy offers higher search efficiency.

Keywords: GEO space debris; optical observation; search strategy; search probability

1. Introduction

Space debris, also known as orbital debris, refers to all man-made objects in space other than operational spacecraft, ranging from intact satellites to powder produced by engine ignition [1]. Since the launch of the first artificial satellite, humanity has entered the space age. Over the past half-century, numerous countries have developed space assets, with nearly a thousand spacecraft currently in service. While space activities bring many benefits, they also create significant negative impacts, most notably the continuous increase in space debris. The vast majority of cataloged objects in Earth orbit are debris, with fragmentation events accounting for a large proportion of these objects [FIGURE 1].

Most space debris resides in Low Earth Orbit (LEO), with a substantial portion in Geostationary Earth Orbit (GEO). Unlike LEO, GEO lacks debris clearance mechanisms such as atmospheric drag [3], resulting in long orbital lifetimes for debris and potential hazards to space activities. GEO is an extremely valuable orbital resource, and space debris in this region has attracted significant attention from spacefaring nations [FIGURE 2].

Due to the r relationship between radar detection signal and distance [4], ground-based radar is generally only effective for LEO targets and cannot detect GEO space debris. Consequently, major space powers have applied ground-based optical equipment to GEO space debris observation and research. Optical observation of space debris primarily includes target detection and identification, precise positioning and orbit determination, and cataloging. Studying the physical characteristics of space targets has become a major research focus, treating space objects as extended bodies rather than point masses through photometric and multi-band observations [5].

2. GEO Space Debris Orbital Characteristics

The ideal geosynchronous orbit is circular with zero inclination ($i = 0^\circ$), an orbital period matching Earth's rotation, and a theoretical semi-major axis of 42,164 km at an altitude of 35,785 km. Due to various perturbations, GEO debris exhibits east-west and north-south drifts. The main perturbation factors include Earth's non-spherical gravitational perturbation, solar and lunar gravitational perturbation, and solar radiation pressure perturbation [6]. Earth's non-spherical gravitational perturbation causes the orbital angular momentum to precess with a period of approximately 26.5 years, leading to periodic variations in orbital inclination with an amplitude of about 15° [7]. Solar radiation

pressure induces a small eccentricity, causing radial distance variations. We define the GEO belt as a region with radius 42,164 km, width ± 150 km, and inclination $\pm 15^\circ$. In extreme cases, this variation can reach ± 75 km [FIGURE 3, FIGURE 4].

3. Search Strategy Analysis and Computational Results

For space debris on GEO, even ideal geostationary targets are moving relative to ground stations. Each target has corresponding orbital element-based ephemeris prediction data. General space debris observation equipment generates real-time guiding data matched to the telescope based on orbital prediction data and observatory coordinates to guide the telescope to the predicted position. When the telescope reaches the predicted position, the guide telescope's large field of view typically contains many stars. If the space target is visible, experienced observers can usually identify it manually, aided by some recognition algorithms [8]. During tracking using prediction data, the target remains relatively stationary in the field of view, enabling capture and tracking for more detailed photometric observations [9].

However, when targets are extremely faint, they cannot be directly seen in the guide telescope's field of view, making selection, tracking, and detailed photometric measurement impossible. GEO space debris often falls into this category, particularly smaller fragments that cannot be easily located in the guide telescope field. Therefore, searching the guide telescope field becomes necessary.

Due to prediction errors, the target may be located anywhere offset from the field center. Assuming prediction data has azimuth accuracy σ_x and elevation accuracy σ_y , and that errors follow a Gaussian distribution, the true target position deviation also follows a Gaussian distribution. For intuitive analysis, we convert angular prediction errors to distance values at the target location:

$$R = L \times \sigma$$

where R is the distance deviation at the target location, L is the distance from target to station, and σ is the angular error. This conversion yields deviation distance precision values in two directions. The true target position follows a two-dimensional Gaussian distribution centered at the predicted position:

$$p(x, y) = \frac{1}{2\pi\sigma_x\sigma_y\sqrt{1-\rho^2}} \exp \left\{ -\frac{1}{2(1-\rho^2)} \left[\frac{(x-\mu_x)^2}{\sigma_x^2} + \frac{(y-\mu_y)^2}{\sigma_y^2} - \frac{2\rho(x-\mu_x)(y-\mu_y)}{\sigma_x\sigma_y} \right] \right\}$$

where (x, y) is the true position, $p(x, y)$ is the probability density, (μ_x, μ_y) are the means, and ρ is the correlation coefficient. Since the two directional errors are independent, $\rho = 0$.

For space debris, insufficient observation data leads to low prediction accuracy, particularly for GEO debris. Calculating the probability of the true position falling within distance r from the center yields the distribution shown in [FIGURE 5, FIGURE 6]. The probability decreases with distance from the predicted center, with the uncolored regions representing extremely low probability areas (the total probability within the calculated 20 km radius approaches 1). Using $r = 3,000$ m, we compute the Gaussian probability distribution.

3.1 Search Strategies

After determining the position range and probability distribution, the main search schemes are concentric circles search and climbing stairs search [FIGURE 7, FIGURE 8]. Using a photometric field of view with radius 1,000 m at the target distance, we search the region with this smaller field of view, requiring longer exposure times.

Concentric Circles Search: This scheme starts from the search region center and proceeds outward along concentric circular trajectories. Each point represents a search position (circle center), with the search covering a circular area of radius 1,000 m. The search proceeds counterclockwise. The success probability P for each search is the integral of the probability density over the circular search area:

$$P_n = \iint_{(x-x_n)^2+(y-y_n)^2 \leq R^2} p(x, y) dx dy$$

where (x, y) is the search center and R is the search radius (1,000 m). Ensuring non-overlapping search areas, the single-step search probability decreases with distance from the center [FIGURE 9]. The cumulative probability increases with search steps, approaching saturation after about 12 steps (12,000 m from center), where additional steps yield negligible probability gain [FIGURE 10].

Climbing Stairs Search: This scheme follows a back-and-forth path [FIGURE 11]. Each point represents a search center covering a 1,000 m radius area. The distance from search areas to the center varies non-monotonically, causing fluctuating single-step probabilities. The cumulative probability increases with steps, reaching 0.7348 at step 11 and 0.7854 at step 25.

3.2 Comparison

Both schemes search the same total area, but their cumulative probabilities differ significantly. The concentric circles scheme maintains higher success probability for most steps and reaches peak efficiency faster. It achieves high cumulative probability (0.7340) by step 11, while the climbing stairs scheme only reaches 0.7348 at step 11 and 0.7854 at step 25. Therefore, concentric circles search is more efficient, achieving higher success probability with fewer steps.

4. Conclusion and Outlook

Assuming equal prediction accuracy in azimuth and elevation, the concentric circles search scheme is more efficient. Calculations show that after approximately 12 steps, cumulative probability becomes sufficiently high, while subsequent steps offer very low efficiency. In practice, when prediction error is roughly known, the optimal search region can be estimated using this method. When prediction accuracies differ between axes, carefully selecting the starting search point could improve the climbing stairs search efficiency, potentially making it superior. Future work should explore optimizing search strategies under anisotropic prediction errors.

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