Postprint: Analysis of the Detection Capability of Ground-based Electro-optical Telescopes for GEO Space Debris

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Abstract

The continuous increase of space debris has posed a serious threat to the safety of human space activities. To avoid the threat posed by space debris to on-orbit spacecraft, it is necessary to acquire information such as the positions of space debris and spacecraft through observations for collision early warning, thereby providing references for spacecraft to implement evasive maneuvers. Ground-based electro-optical telescopes possess absolute advantages in the observation of high-orbit space debris. Based on the detection signal-to-noise ratio formula, the size of the minimum detectable space debris by the telescope is calculated, the size calculation formula is verified through observation experiments, the influencing factors of equipment detection capability are analyzed, and the capability of equipment to detect geostationary orbit space debris under two observation modes is analyzed. The quantitative relationship between aperture and exposure time on detection capability is obtained, which can provide references for the construction of space debris observation equipment.

Full Text

Preamble

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Analysis of Detection Ability for GEO Region of Ground-Based Electro-Optic Telescope

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Abstract

The continuous increase of space debris has seriously threatened the safety of human space activities. To avoid the threat of space debris to spacecraft, observation is needed to obtain position information of space debris and spacecraft for collision warning, providing reference for spacecraft avoidance maneuvers. Ground-based electro-optical telescopes have absolute advantages in observing high-orbit space debris. Based on the detection signal-to-noise ratio formula, we calculate the minimum detectable size of space debris, verify the size calculation formula through observation experiments, analyze the influencing factors of equipment detection capability, and analyze the capability of equipment to detect geostationary orbit space debris in two observation modes. We obtain the quantitative relationship between aperture and exposure time on detection capability, which can provide reference for space debris observation equipment construction.

Keywords: space debris, electro-optical telescope, GEO region debris

Main Text

The proliferation of space debris poses an increasingly severe threat to spacecraft operations. To mitigate collision risks, continuous monitoring of debris positions is essential for effective collision warning systems. Ground-based electro-optical telescopes offer unparalleled capabilities for observing objects in the Geostationary Earth Orbit (GEO) regime.

The detection capability of these systems can be quantified through signal-to-noise ratio (SNR) analysis. The minimum detectable debris size is derived from the fundamental SNR equation:

$$SNR = \frac{\eta\gamma ATMS_0^{2.512}D}{r_{dout} \cdot scale^2 \cdot Q(m)}$$

where represents the system quantum efficiency, γ denotes the optical transmission, A is the collecting area, T is the atmospheric transmittance, M is the object magnitude, S_0 is the solar flux, D is the telescope aperture diameter, r_{dout} is the readout noise, scale is the pixel scale in arcseconds per pixel, and Q(m) is the sky background brightness.

The simulation parameters used in this analysis are summarized in , which includes telescope aperture size, pixel dimensions, field of view, exposure time, quantum efficiency, optical system efficiency, dark current, readout noise, pixel scale, object albedo, and atmospheric transmittance.

[Figure 1: see original paper] illustrates the variation of minimum detectable debris size as a function of sky background for different exposure times, while [Figure 2: see original paper] shows its dependence on aperture size under various exposure conditions. These relationships demonstrate that detection sensitivity improves with longer exposures and larger apertures, though with diminishing returns under bright sky conditions.

Two primary observation modes are considered: sidereal tracking, where the telescope tracks at stellar rates, and debris-targeted tracking, which follows the predicted motion of specific objects. The detection performance differs significantly between these modes, with debris tracking offering superior sensitivity for known objects at the cost of reduced search capability.

[Figure 3: see original paper] depicts the relationship between minimum detectable size and exposure time for various aperture diameters, revealing that detection limit scales approximately with the square root of exposure time. [Figure 4: see original paper] shows the aperture size dependence, indicating that detection capability improves linearly with telescope diameter for fixed exposure durations.

The quantitative analysis yields specific performance metrics: for a 0.5-meter telescope operating in sidereal tracking mode with 20-second exposures, the minimum detectable debris size is approximately 0.82 meters at 21 mag/arcsec^2 sky brightness. In debris-tracking mode, the same system achieves 0.56-meter detection limits, representing a 32% improvement. For a 1-meter telescope, these values improve to 0.41 meters and 0.35 meters respectively.

These results provide critical design parameters for future space debris monitoring networks, demonstrating that aperture size and exposure time must be optimized based on the intended observation mode and typical sky conditions at the site.

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