Postprint: Methods for Estimating Observation Time of X-ray Astronomical Sources

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Abstract

The effective observation time of space detectors for X-ray celestial sources is primarily constrained by space environmental factors. The main factors limiting effective observation time include the solar avoidance angle, Earth occultation of the source, and the South Atlantic Anomaly region, among others; however, when the satellite is located in high particle background regions, the sunlit zone between the Sun and Earth, or when the field of view points close to Earth, the background level is extremely high and difficult to determine, rendering data from these periods also unusable. This paper employs the orbitTools function library to predict orbits, utilizes the attitude function library under HEAsoft to calculate space environment variables, uses these variables to estimate the observation time for sources, and demonstrates through comparison with actual observations that the observation time estimated by this method shows good consistency with actual conditions.

Full Text

A Method to Estimate the Observable Time of X-ray Sources

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Abstract

The effective observation time of X-ray celestial sources by space detectors is primarily constrained by space environmental factors. The main factors limiting effective observation time include Sun avoidance angle, Earth occultation of the source, and passage through the South Atlantic Anomaly (SAA). However, when satellites are in high particle background regions, in the sunlit area between the

Sun and Earth, or when the field of view points near Earth, the background level becomes very high and difficult to determine, rendering data from these periods unusable. This paper employs the orbitTools library for orbit prediction and the attitude library under HEAsoft to calculate space environment variables, which are then used to estimate the observation time for sources. Comparison with actual observations demonstrates that the observation time estimated by this method shows good consistency with real conditions.

Keywords: observation time, geomagnetic cutoff rigidity, observation constraints

The Hard X-ray Modulation Telescope (HXMT) satellite [1][2] was launched in June 2017, initiating China’ s observational research of celestial sources in the X-ray band. Currently, the Einstein Probe satellite [3] (EP) has been officially approved and is expected to launch in 2022, while the enhanced X-ray Timing and Polarimetry Observatory (eXTP) is in the pre-research phase. The orbital altitudes of these satellites are mostly within the Earth’ s inner radiation belt range [4], making satellite payloads vulnerable to the South Atlantic Anomaly (SAA) and geomagnetic field effects [5], resulting in poor data quality (high background with difficult-to-determine spectral shape) or even complete data loss. For instance, most satellites stop data acquisition or shut down directly when entering the SAA region. Simultaneously, an important task for these satellites is pointed observation of sources, whose visible time is mainly affected by the Sun and Earth: satellite thermal control prohibits pointing payloads at the Sun and requires maintaining a certain angular distance from it. For example, HXMT has a sunshade and simultaneously requires the satellite pointing to avoid the Sun, which dictates that observed sources must be positioned far from the Sun. Earth can also block the satellite’ s field of view, preventing source photons from reaching the payload.

Previous efforts to estimate observation time for celestial sources have focused primarily on visibility time estimation [6], typically by applying observation constraints where visible time represents the time remaining after screening with constraint conditions. These observation constraints include Earth occultation of the field of view, Sun and Moon occultation of the field of view and thermal control constraints, and periods passing through the South Atlantic Anomaly. In reality, these constraints are insufficient, as observation time must also exclude specific regions such as high particle background areas. These constraints are generally considered only during data analysis. For example, for low-orbit astronomical satellites like Swift [7] and Suzaku [8], their data analysis manuals specify screening ranges for geomagnetic cutoff rigidity (COR) [9] to exclude high background regions.

Thus, estimating observation time for an X-ray celestial source requires addressing both data quality (including background level and background shape uncertainty) and visibility time. However, data quality constraints are related to the payload' s operating mechanism and energy range, requiring different conditions for different instruments. For instance, HXMT' s Low Energy Telescope [10] experiences varying degrees of light leakage in its SCD (Swept Charge Device) array when the satellite is positioned between the Sun and Earth, necessitating exclusion of these time periods.

This paper focuses on the impact of the space environment on source observation time for low-orbit astronomical satellites, presenting estimation methods from both visibility time and data quality perspectives. This will facilitate observation planning, improve satellite utilization, and promote scientific output acquisition.

1 Analysis of Factors Affecting Astronomical Satellites

In observation time estimation, we consider only space environmental factors. While satellite pointing jitter and payload temperature variations also reduce observation time, these factors are related to telescope structural properties and are not discussed in this paper.

1.1 Earth Effects on Observation Time

Earth affects observation time in three main aspects: (1) Earth blocks the field of view, preventing source photons from entering; (2) When the satellite' s field of view approaches the atmosphere, scattered solar X-ray photons or visible light enter the field of view, making background estimation difficult; and (3) Source photons passing through atmospheric absorption also experience spectral distortion.

ELV, DYE_{ELV}, and NTE_{ELV} are commonly used to represent Earth' s effects. These represent the minimum angle between the field of view pointing and Earth, the minimum angle between the pointing and Earth' s bright region (the Sun-illuminated side), and the minimum angle between the pointing and Earth's dark region, respectively. If the latter two do not exist, they are generally set to 120° or 200°. Larger ELV and DYE_{ELV} values reduce Earth' s impact on observation but also decrease available observation time. For X-ray detectors operating at lower energy bands, ELV can be appropriately increased to reduce effects on the low-energy spectral range, while timing analysis may allow for lower ELV values. DYE_{ELV} primarily reflects the impact of solar diffuse X-ray background and visible light on instruments, which significantly affects CCD-type detectors.

1.2 Sun and Moon Effects

The Sun' s impact on satellites is substantial, primarily affecting thermal control. Solar X-rays also influence X-ray detectors, particularly low-energy detectors. Satellite attitude is generally constrained to keep payloads away from the Sun, with larger angles between the field of view pointing and Sun center (SUN_{ANG}) being preferable.

The Moon (represented by MOON_{ANG}, the angle between pointing and Moon) scatters solar X-rays and visible light, causing a 0.5° solid angle occultation effect on the field of view, with larger angles being preferable.

1.3 South Atlantic Anomaly Effects

The SAA region has extremely high particle background that severely damages payloads, which are generally shut down when passing through it. The SAA boundary is not distinct; particle background gradually increases when approaching the SAA, rendering this period unusable. When leaving the SAA region, satellite materials become activated by SAA particles, increasing activation background. However, this activation decays relatively quickly, and the time from SAA exit to when activation decays to an acceptable level is often also unusable.

SAA_{FLAG}, T_{SAA}, and TN_{SAA} [8] indicate whether the satellite is in the SAA, the time elapsed since exiting the SAA, and the time until the next SAA entry, respectively. These three quantities generally represent SAA effects, though it should be noted that they depend on the specified SAA region size.

1.4 High Particle Background Region Effects

Beyond SAA effects, some high particle background regions, such as high-latitude areas, also significantly impact data quality. COR describes Earth' s magnetic field' s ability to block cosmic rays; particles must have rigidity greater than the local geomagnetic cutoff rigidity to enter the geomagnetic field at a given location, typically expressed in minimum momentum units. Since cosmic rays increase instrument background, regions with lower COR exhibit higher background. Furthermore, payload background cannot be measured directly but is estimated using models. In low COR regions heavily affected by low-energy electrons and protons, background shape uncertainty is substantial.

When satellites are in high particle background regions, sunlit areas, or when the field of view approaches Earth' s limb, background levels are generally high and difficult to estimate, making acquired data unusable and causing significant differences between estimated and actual observation times.

2 Observation Time Estimation Method

Our objective is to estimate the observation time for one or multiple sources within a given time period. This implementation will facilitate optimization of observation efficiency (the ratio of observation time to total time) for multiple sources, enabling the development of high-efficiency operation plans.

We use the orbitTools [11] software package for satellite orbit prediction and the attitude software package under HEAsoft [12] for space environment parameter estimation. The orbitTools package is based on the SGP4/SDP4 model for orbit prediction of low- and high-orbit satellites, with inputs of two-line element sets (TLE) and reference time. Both packages use C/C++, facilitating integration.

2.1 Definition of Source Information and Constraint Conditions

In observation time estimation, source information is not particularly important; satellite pointing information is crucial, especially for off-axis observations. Therefore, the "source information" referred to here actually means satellite pointing information. We define in the J2000 coordinate system: the z-axis as the satellite pointing direction, and the y-axis as the direction of a certain satellite axis (such as the x-axis in the satellite body coordinate system) pointing toward the Sun.

To ensure the processing flow proceeds chronologically, we expand the SAA region, thereby simplifying T_{SAA} and TN_{SAA}. In practice, identifying the SAA solely through hardware triggering is problematic; as satellites approach the SAA region (without passing through it), payload counts also become distorted. The best approach is to accumulate substantial data and define the SAA through data analysis.

The parameters include RA, DEC, ELV, DYE_{ELV}, COR, SAA, MOON_{ANGLE}, and SUN_{ANGLE}, where RA and DEC represent the satellite pointing position, and SAA represents one of several SAA models that users can define.

2.2 Definition of Orbit and Operation Parameters

We use the orbitTools software package for orbit prediction, with inputs of two-line element sets (TLE). The parameters include t1, t2, stepsec, year, month, day, hour, min, second, mjd0, and output. Here, t1 and t2 represent cumulative seconds from the reference time, with the estimated observation period starting at t1 and ending at t2. The reference time is specified by year, month, day, hour, min, and second; for HXMT, these are 2012, 1, 1, 0, 0, 0, with second allowing floating-point values. mjd0 is the MJD time of the reference moment, which is 55927 for HXMT. Output is the name of the output file, designed in this work to use the astronomical data format FITS [13]. stepsec is the time step (integer) in seconds, indicating that observation efficiency is calculated every stepsec seconds.

All times in orbit prediction are cumulative seconds relative to the reference moment (UTC time). However, when calculating ELV and other quantities, these UTC times must be converted to MJD time, requiring consideration of leap seconds between the two systems.

Currently, some commercial software (such as STK) or institutions (Chinese

Academy of Sciences Space Center) can provide specialized orbit predictions. Orbit data can also use third-party sources, so the program should preferably be able to read FITS-format orbit files, which need to include time (TIME) and position (X, Y, Z) information in the J2000 coordinate system, consistent with the orbit coordinate system generated by orbitTools (though conversion from J2000 to Earth-fixed coordinates based on time is also possible).

2.3 Implementation Strategy

The software reads parameters via file input, designing source and constraint conditions, two-line element sets, and operation parameters into separate configuration files (source and constraint condition file, TLE file, and operation parameter file). To estimate observation time for multiple sources simultaneously, multiple source positions and their respective constraints can be written into the source and constraint condition file. If orbit prediction does not use the orbitTools library, orbit data can be read directly, with positions for points outside orbit data points calculated using linear interpolation.

The program first initializes by reading the aforementioned configuration files, establishing the correspondence between UTC and MJD, specifying the start and end times for efficiency calculation, initializing various orbitTools modules using TLE and MJD0, and simultaneously setting constraint condition values. It then calculates orbit points and their times within one time step (stepsec) (i.e., one orbit point per second), computes ELV, COR, and other values for these points, compares them with constraint conditions, and counts the number of points meeting the constraints. After completing judgment for all points in the time step, observation efficiency is the ratio of compliant points to total points (i.e., stepsec). If the time step is relatively small (e.g., 1s), the calculated observation efficiency will be either 0 or 100%. The time step should start from t1 and continue until exceeding t2. Finally, each segment's observation efficiency and its time (represented by midpoint time) are written to file.

COR is related to satellite orbit. We adopt results generated by IGRF2005 [9], which has a relatively wide latitude range, suitable for satellites with large inclination angles such as HXMT (satellite inclination 43°).

3 Prediction Results and Discussion

We compared our method with HXMT satellite' s High Energy Telescope observations of Crab from late August 2017, requiring ELV $> 10°$, COR > 8 GV, with RA and DEC of 255.705667 and -48.7896, respectively. [Figure 1: see original paper] shows the comparison between actual and predicted results, with time (in seconds) on the horizontal axis and, from top to bottom, Crab' s original observed light curve (NaI events, with Earth occultation and SAA region removed), light curve screened using HXMT user analysis software [14], and observation time (observation efficiency) predicted by our method. The original light curve comes from HXMT' s Level 1 data product. After screening, considerable time is removed, and the efficiency or usable time calculated by our method shows good consistency with the screened results. It should be noted that our method' s attitude assumes the satellite body coordinate system x-axis points toward the Sun, with attitude changing over time, whereas in actual observations, once attitude is determined, it remains unchanged throughout the observation.

Visibility time estimation differs from observation time estimation, as observation time must also consider data quality. This is particularly important for low-energy detectors such as CCD-type detectors, which may experience light leakage, making the DYE_{ELV} angle crucial. Considering COR and other factors makes efficiency directly reflect actual data usability.

However, orbit prediction accuracy is affected by TLE accuracy. Moreover, even with accurate TLE, long-term predictions are unreliable due to atmospheric effects and non-uniform Earth gravity.

Current satellite power supply is relatively abundant, generally allowing multiple attitude adjustments per orbit, which is crucial for improving observation efficiency. Based on this method, considering how to improve observation efficiency within one orbit is essential, particularly for maneuverable small satellites such as EP.

This paper does not consider observation time estimation for solar observation satellites, though the Sun itself is an X-ray celestial source. Additionally, this paper does not consider the impact of high-power ground facilities on satellite data.

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