In-orbit Operation and Calibration Postprint of the Insight-HXMT Satellite

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Abstract

The Insight Hard X-ray Modulation Telescope (abbreviated as Insight satellite, English name Insight Hard X-ray Modulation Telescope, abbreviated as Insight-HXMT or HXMT), launched on June 15, 2017, marks the birth of China' s first self-developed observatory-class X-ray telescope. Leveraging its comprehensive advantages of large effective area, broad energy band, high time resolution, and high energy resolution, the Insight satellite has opened a new research window for studies of hard X-ray rapid variability and broad-band spectral properties of black hole and neutron star systems. Having exceeded its design lifetime, the Insight satellite has been operating stably for over 8 years, is currently in good condition, and is expected to further extend its on-orbit service time. As of October 2024, the Insight satellite has publicly solicited observation proposals from the global scientific community on seven occasions, receiving a total of 334 valid proposals and formulating 2368 observation plans accordingly. Furthermore, the Insight satellite has released 13 batches of data to the public, with a cumulative data volume reaching 40 TB and a data release rate as high as 94%. The Insight satellite has also provided users with various versions of data analysis software and calibration databases, achieving an in-orbit calibration accuracy of approximately 2%, which meets the requirements for scientific analysis. Scholars from 17 international and 36 domestic research institutions have conducted scientific research using Insight data, publishing over 300 high-quality academic papers that have accumulated approximately 7300 citations.

Full Text

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Abstract

The Insight Hard X-ray Modulation Telescope (Insight-HXMT or HXMT), launched on June 15, 2017, marks the birth of China’ s first independently developed astronomical observatory-level X-ray telescope. Leveraging its comprehensive advantages of large detection area, broad energy band, high timing resolution, and high energy resolution, Insight-HXMT has opened a new window for studying rapid variability and broadband energy spectra of black hole and neutron star systems in hard X-rays. Having exceeded its designed lifespan, the satellite has been operating stably for over eight years, remains in good condition, and is expected to continue its extended mission. As of October 2024, Insight-HXMT has conducted seven rounds of observation proposal solicitations for the global scientific community, receiving 334 valid proposals and formulating 2,368 observation plans. Additionally, the satellite has released 13 batches of public data, totaling 40 TB, with a data release rate as high as 94%. Insight-HXMT provides users with various versions of data analysis software and calibration databases, achieving an in-orbit calibration accuracy of approximately 2%, which meets the requirements for scientific analysis. Researchers from 17 international and 36 domestic institutions have utilized Insight-HXMT data to conduct scientific research, publishing over 300 high-quality academic papers with approximately 7,300 cumulative citations.

Keywords: instrumentation: detectors, methods: data analysis, astronomical databases

1 Introduction

Insight-HXMT is China’ s first astronomical observatory-level X-ray satellite [1], successfully launched on June 15, 2017 from Jiuquan Satellite Launch Center into a 550 km altitude orbit with a 43° inclination. The satellite can conduct broadband, wide-field X-ray surveys to discover new high-energy variable sources and new activities of known celestial objects; perform pointed observations of short-timescale variability and energy spectra of high-energy objects such as black holes and neutron stars to understand their activity and evolution mechanisms; and simultaneously possesses all-sky monitoring capability for gamma-ray bursts.

The satellite carries three main scientific payloads: the High Energy X-ray Telescope (HE, 20–250 keV, 5,100 cm^2 geometric area) [2–3], the Medium Energy X-ray Telescope (ME, 8–35 keV, 952 cm^2) [4–5], and the Low Energy X-ray Telescope (LE, 1–10 keV, 384 cm^2) [6–7], as shown in Figure 1 [Figure 1: see original paper]. This detector configuration endows Insight-HXMT with a broad X-ray detection band and large detection area in the 20–250 keV range. Additionally, the three payloads feature high temporal and energy resolution, small dead time, and the low-energy payload exhibits no photon pile-up effects in the soft X-ray band. These capabilities enable Insight-HXMT to uniquely investigate rapid multi-band X-ray variability of celestial objects, allowing exploration of regions closer to black hole event horizons or neutron star surfaces than previously possible, thus opening a new window for studying rapid variability and spectral characteristics of black holes and neutron stars.

The reliability and correctness of Insight-HXMT data products and user data analysis software have been verified through compatibility tests with various analysis tools used by domestic and foreign users, as well as cross-comparisons with results from other satellites. Based on these data and software, researchers have achieved numerous original and significant results: participation in monitoring the electromagnetic counterpart of the first binary neutron star merger gravitational wave event (GW170817) and placing the most stringent constraints on the MeV emission from this event [11–12]; repeatedly breaking the record for direct measurement of the strongest cosmic magnetic field [13–14]; discovering the highest-energy quasi-periodic oscillations in black hole X-ray binary systems [15]; first confirming that fast radio bursts originate from magnetars [16]; and jointly with the GECAM telescope, precisely detecting the brightest gamma-ray burst to date [17].

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2.1 Observation Proposal Collection and Evaluation

To fully utilize Insight-HXMT data and promote scientific output, the Insight-HXMT Science Center regularly solicits observation proposals from the global astronomical community. Each proposal call is announced through an Announcement of Opportunity (AO) on the Insight-HXMT portal website. Our proposal solicitation covers not only annual observation proposals but also continuously accepts Target of Opportunity (ToO) proposals through the proposal website (http://proposal.ihep.ac.cn/proposal/index.jspx) to enable rapid response to transient astronomical events or observe temporarily available important scientific targets.

To date, Insight-HXMT has successfully conducted seven rounds of proposal solicitation. Detailed information for each round, including solicitation period, number of valid proposals received, observation requests, allocated observation time, and number of ToO targets, is recorded in Table 1 . The seven rounds have accumulated 334 proposals from various research institutions, with the distribution shown in Figure 2 [Figure 2: see original paper].

After the proposal submission deadline, the Science Center conducts technical feasibility assessments on all submitted proposals and invites expert panels to perform scientific reviews, ensuring that selected proposals align with Insight-HXMT' s observational capabilities and satisfy mission constraints. Following a thorough review process, the selected proposals are graded and ranked. To provide better user service and transparency, once proposal grading is completed, all review results are published on the proposal solicitation website, allowing applicants to promptly check the status of their proposals.

2.2 Observation Planning

To optimize Insight-HXMT' s observation plans and meet user requirements, the Insight-HXMT Science Center must formulate and execute observation plans while ensuring satellite safety and considering multiple influencing factors. Insight-HXMT' s observation targets primarily come from open solicitation of proposals from the international academic community or prompt celestial activities. These observation requirements include various types, such as small sky region scanning, short-term monitoring, joint observations, scheduled time observations, and ToO observations.

Insight-HXMT observation proposals are divided into three grades: A, B, and C. Higher-grade proposals are prioritized in observation planning, while joint and scheduled time observations are given preference within the same grade. When developing observation plans, the Science Center comprehensively considers proposal requirements, the South Atlantic Anomaly, Earth occultation, data downlink, and other factors while satisfying satellite observation constraints (Sun avoidance angle $>70°$), aiming to maximize observation efficiency. During proposal execution, Grade A proposals are guaranteed; any unexecuted observations are automatically postponed to the next cycle. Grade B and C proposals are scheduled as much as possible, but unexecuted ones are not postponed.

Based on these considerations, the Insight-HXMT Science Center first develops an overall annual observation mission plan, which is further refined into short-term observation plans executed every two days [10]. Additionally, to enable rapid response to transient celestial events, a fast-response mechanism has been established to handle such special observation requests (ToO observations). As of September 30, 2024, Insight-HXMT has formulated 1,346 short-term observation plans, 65 ToO plans, 244 parameter update plans, and 713 gamma-ray burst plans, successfully completing all observation requirements. Table 2 presents statistics of celestial sources observed by Insight-HXMT, including the number of different sources, observation counts, and exposure time information. The majority of Insight-HXMT' s pointed observation time is devoted to black hole and neutron star X-ray binaries, which are also the fields with the richest scientific output from the mission.

2.3 Data Product Production and Release

Given that Insight-HXMT observations are led by international astronomical users who are deeply involved in data analysis, the Science Center converts raw satellite data and auxiliary data into standard data products, provides instrument responses in the form of calibration databases, and designs standardized data analysis pipelines and algorithms, enabling users to focus on scientific analysis without needing to deeply understand instrument working principles and modes.

Insight-HXMT' s data product design accommodates scientific research, engineering monitoring, and quick-look science requirements, forming 13 levels of advanced data products totaling over 700 types. The project developed a "Data Template Library Software" to ensure consistency and traceability of data product files. The Science Center generates more than 60 TB annually, approximately over 2 million data product files at various levels, and has flexibly expanded more than 100 product types to meet scientific research needs.

According to Insight-HXMT' s data management policy, data beyond the proprietary period must be made openly available to all users, accessible through the Insight-HXMT website (http://archive.hxmt.cn/proposal). As of October 2024, 13 batches of Level 1 data products for scientific users have been publicly released, totaling 40 TB, with a data release rate of 94%. The remaining 6% of unreleased data are primarily within the proprietary period. The data release status for each proposal round is shown in Figure 3 [Figure 3: see original paper], which also displays the number of ToO observation IDs in each round.

2.4 User Data Analysis Software

The development of the Insight-HXMT Data Analysis Software package (HXMTDAS) follows in-depth research into Insight-HXMT' s data analysis pipelines, algorithms, and data products, aiming to provide a data processing tool highly compatible with the internationally used HEAsoft package. HXMTDAS incorporates efficient intelligent data identification algorithms to address issues such as glitches caused by high-energy particle events, multi-pixel discharge, instrument radiation damage, and dramatic space environment changes. These algorithms can automatically identify high-quality data, correct instrument responses, and automatically match instrument backgrounds, significantly improving the automation level and accuracy of data processing.

HXMTDAS employs a hierarchical architecture design that supports multiple payloads sharing a common underlying layer, thereby possessing excellent scalability and inheritability. The software features low memory consumption, high computational speed, and good compatibility, making it convenient to install and run on servers and personal computers with different operating systems.

Since its release, the Insight-HXMT data analysis software has been operating stably for over six years. The Science Center continuously optimizes and updates the software based on user feedback and suggestions, having released nine versions to date, all available for download from the official Insight-HXMT website (http://hxmten.ihep.ac.cn/software.jhtml). The software has gained wide recognition from users both domestically and internationally, providing crucial technical support for scientific research with Insight-HXMT. Meanwhile, the framework and some common interfaces of HXMTDAS have been successfully applied to the data software development for the follow-up telescope of the Einstein Probe satellite, demonstrating its potential for application in other astronomical satellite projects.

3 In-orbit Calibration

Monitoring payload performance and timely updating calibration databases constitute one of the primary tasks of the Science Center during Insight-HXMT’ s operation. The Science Center monitors payload performance at multiple levels, including payload working parameters, quick-look analysis of detection data, and celestial source monitoring analysis, achieving high-precision monitoring of detector performance and effectively ensuring normal observation and operation of the satellite.

Insight-HXMT’ s detectors include three types: compound crystals (18 units), semiconductors (1,728 units), and Swept Charge Devices (96 units), with large quantities and varying responses. Their performance changes with time and space environment during in-orbit operation, posing challenges for high-precision calibration. To address these challenges, a high-precision detector performance response model has been established for dramatic space environment changes, combining ground and space approaches. On the ground, accurate satellite mass models, interaction processes, and space environment models are constructed to extensively simulate and compare in-orbit operation and ground calibration experimental results, ensuring the effectiveness of payload simulation. After satellite launch, time- and temperature-dependent detector response models have been established based on satellite working parameters and measured detector performance, with calibration parameters verified through joint observations [18].

To date, all 18 NaI(Tl) and CsI(Na) compound crystal detectors of the HE payload are operating normally. However, due to radiation damage from the space environment, some hot detectors, excessively noisy detectors, and damaged detectors in the ME and LE payloads have been turned off. Specifically, among the 1,728 SiPIN pixels in the ME payload, 298 have been deactivated; and among the 96 CCD detectors in the LE payload, 8 have been turned off. The remaining number of detectors continues to meet scientific observation requirements.

3.1 Payload Gain and Energy Resolution

Insight-HXMT’ s operation has provided valuable data to help us deeply understand the evolution and development of detector performance. We previously published the temporal evolution of performance over five years for Insight-HXMT' s three payloads in the journal *Radiation Detection Technology and Methods* (RDTM) [3, 5, 7]; in this work, we provide updates on the in-orbit performance of the three payloads.

When the satellite observes empty sky regions or enters Earth occultation zones, four background spectral lines appear in the measured energy spectra of the HE payload due to activation of detector materials [3, 18], which can be used to calibrate HE gain. Since NaI(Tl) crystals experienced moisture degradation during ground storage, all detector units have worse resolution than during ground calibration. The width of the 31 keV line in orbit can be used to calibrate and evaluate energy resolution changes in the 18 detector units. Additionally, we monitor the temporal evolution of gain and energy resolution for each unit using the 59.5 keV peak position and width from the onboard 241Am radioactive source and the 191 keV background line, as shown in Figures 4 [Figure 4: see original paper] and 5 [Figure 5: see original paper], respectively. After three months in orbit, gain and energy resolution changes in all units are small, with most units showing a gradual improvement in energy resolution over time.

Each ME module carries two onboard 241Am radioactive sources that illuminate eight SiPIN pixels. By accumulating spectra of the radioactive source during empty sky observations and using ground-calibrated gain coefficients, the central values and widths of source spectral lines can be obtained; pixels not illuminated by the source can be calibrated and monitored using the silver line peak position (22.5 keV) during empty sky observations [5]. The gain and energy resolution variations of ME are shown in Figures 6 [Figure 6: see original paper] and 7 [Figure 7: see original paper], respectively, demonstrating that ME gain variation does not exceed 1.5% and energy resolution variation does not exceed 3%. Such variations have minimal impact on data analysis, so ground-calibrated gain and energy resolution values are still used in orbit.

LE uses spectral lines from observations of the supernova remnant Cas A and background lines from empty sky observations to verify the gain calibrated on the ground. Using XMM-Newton (X-ray Multi-Mirror Mission) MOS (Metal Oxide Semiconductor) detector observations of Cas A, theoretical energies of Cas A' s emission lines are obtained. If ground-calibrated gain coefficients are applied to Cas A line peak energies, the gain is found to continuously decrease over time, as shown in Figure 8 [Figure 8: see original paper]. This indicates that LE gain has been declining due to radiation damage since launch. We use quadratic functions to describe the temporal evolution of different peak positions, allowing peak positions at any observation time to be obtained from the evolution function. When Cas A cannot be observed due to Sun avoidance angle constraints, we can also predict gain changes from preceding and following observations. LE energy resolution degradation can similarly be characterized by the temporal evolution of Si, S, and Fe line widths, as shown in Figure 9 [Figure 9: see original paper]. Affected by radiation damage, LE energy resolution has also been continuously degrading.

3.2 Energy Response Matrix and Effective Area

The Crab Nebula, with its stable flux, high brightness, and simple power-law spectrum in the 1-100 keV range, is frequently used as an in-orbit calibration source for hard X-ray telescopes. As a collimated telescope with relatively high background levels but no detector pile-up effects, Insight-HXMT can also use the Crab for calibration. The energy resolution obtained after subtracting in-orbit background [19–21] is shown in Figure 10 [Figure 10: see original paper], which is then used to simulate the in-orbit effective area. The net counts from Crab observations for the three payloads are shown in Figure 11 [Figure 11: see original paper], with in-orbit background levels indicated by orange points. Finally, an empirical function method is used to correct the simulated effective area, with the ratio distribution between corrected data and model shown in the bottom panel of Figure 11. Residuals for the three payloads are within 2% across most energy bands, with the structure of this ratio indicating inaccuracies in effective area simulation and background estimation. Joint NuSTAR (Nuclear Spectroscopic Telescope Array) observations of the Crab have also verified the calibration parameters and systematic errors.

3.3 Timing Accuracy

Based on the design characteristics of Insight-HXMT' s timing system, which leverages the long-term stability of standard second signals and short-term stability of payload timing signals, an iterative calibration algorithm combining long-term and short-term timing signals effectively improves the timing accuracy of detected events. To address the new problem of prolonged loss of standard second signals during satellite operation, the timing algorithm has been updated. The algorithm' s effectiveness and systematic errors have been verified through pulsar observations, forming an integrated workflow comprising the onboard timing system, ground algorithms, and celestial source calibration. Currently, Insight-HXMT' s timing system achieves a solution accuracy better than 16 s, comparable to the intrinsic timing stability of calibration pulsars [22]. Table 3 lists the timing offsets and systematic errors of various international X-ray astronomical satellites.

4 Summary and Outlook

As China' s first astronomical observatory-level space X-ray telescope, Insight-HXMT has opened a new window for studying rapid variability and energy spectra of black holes and neutron stars in hard X-rays, achieving multiple significant scientific results and providing an important astrophysical research platform for scientists both domestically and internationally, with profound impact on the development of China' s space science and astronomy. Since its successful launch in 2017, Insight-HXMT has been operating stably in orbit for over eight years (designed lifetime of four years), remains in good condition, and will continue its extended mission.

Since its launch and operation, Insight-HXMT has conducted over 300 joint observations with domestic and international space, ground-based optical, and radio telescopes, promoting the development of multi-messenger astronomy and obtaining large amounts of high-quality observational data on gamma-ray bursts, X-ray binary systems, supernovae, and more. Joint observations have demonstrated that Insight-HXMT' s data format is correct, calibration procedures are accurate, and error estimation is reasonable, with cross-validation of Insight-HXMT' s spectral and timing analysis results.

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