Environmental tests of the HXI spectrometer for the ASO-S mission

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ABSTRACT: The Advanced Space-based Solar Observatory (ASO-S) is the first Chinese solar mission and is scheduled to be launched in 2022. It is designed to study the solar magnetic field, coronal mass ejections, solar flares, and their relationships. The ASO-S includes three scientific payloads: the Full-disk vector MagnetoGraph, the Lyman-alpha Solar Telescope and the Hard X-ray Imager. As a key part onboard the ASO-S, the HXI will improve our understanding of solar flares during the 25th solar maximum. The HXI comprises three parts, namely a collimator (HXI-C), a spectrometer (HXI-S) and an electronics control box (HXI-E). Extensive environmental tests, such as mechanical and thermal tests are important for a space mission to ensure the design and performance are suitable for the severe challenges presented by the launch and on-orbit operations. This paper describes the procedures and results of environmental tests performed on the qualification model of the HXI-S. Functional tests of the spectrometer are reported as well. Test results show that the current qualification model fully satisfies mission requirements.

KEYWORDS: Overall mechanics design (support structures and materials, vibration analysis etc); X-ray detectors and telescopes; Detector design and construction technologies and materials

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1 Introduction

Solar flares and coronal mass ejections are two types of powerful activity of the Sun. Huge energies are released in short periods, which strongly affects the space environment. It is widely believed that the energetics of both types of eruption are from the magnetic field. It is therefore crucial to understand how the magnetic field links these two phenomena of the Sun. Dozens of space-borne missions such as YOHKOH and RHESSI [1, 2] have been launched during the past 50 years and so on. However, none of the onboard instruments observed solar flares, coronal mass ejections and the magnetic field simultaneously. It is expected that observing these three components at the same time on one integrated mission will clarify their relations. The Chinese solar physics community therefore proposed the Advanced Space-based Solar Observatory (ASO-S) mission in 2010. The ASO-S was formally approved in the autumn of 2017. It is scheduled to be launched in 2022 and will operate during the 25th solar cycle for no less than four years.

The ASO-S payload has three instruments: the Full-disk vector MagnetoGraph (FMG), the Lyman Alpha Telescope (LST), and the Hard X-ray Imager (HXI). A schematic view of the satellite is presented in figure 1. The mission science, instrument design, and software have been detailed in the literature [3]–[7]. The ASO-S will be launched on a CZ-2D rocket at Jiuquan launch center. The ASO-S will enter a Sun-synchronous orbit having an altitude of 720 km and inclination angle of 98.275°. This choice of orbit provides a balance between a relatively weak particle background for the HXI and little stray light for the LST. The pointing accuracy of the platform is better than 0.01° and the stability is better than 0.0005°/s. The total mass of the three instruments is about 350 kg while the mass of the satellite should be within 850 kg.
As one of the key instruments onboard the ASO-S, the HXI is a spatial modulation X-ray telescope designed to image the full solar disk in terms of hard X-rays between 30 keV and 200 keV. It adopts an imaging principle similar to those implemented by the Reuven ramaty High-Energy Solar Spectroscopic Imager (RHESSI) and the Hard X-ray Telescope on Solar-A mission (HXT). The HXI deploys three subsystems, namely the collimator (HXI-C), the spectrometer (HXI-S), and the electronics control box (HXI-E). Their locations are depicted in figure 1. The HXI-C modulates the incident X-rays with sub-collimators. The HXI-S records the photon count and measures their energy. The HXI-E acquires data and performs preliminary processing. Details of each subsystem are given in section 2.

A series of tests must be conducted to demonstrate the adaptability and performance of the instrument during launch and on-orbit operations. This paper focuses on environmental tests conducted for the HXI-S from December 2019 to March 2020. Mechanical and thermal tests were carried out on the Engineering Qualification Model (EQM). Functional tests were also performed with flight hardware and software. The test results are very important for the final optimization of the instrument design.

2 Instrument description

The HXI comprises three sub-detectors: HXI-C, HXI-S, and HXI-E. Unlike the HXI-C and HXI-S, which are mounted on the satellite payload platform, the HXI-E is located inside the spacecraft. The HXI-E manages the system’s operation, power supply, data collection and preliminary data processing [7, 8].

2.1 HXI-C description

The HXI-C, shown in figure 2, is responsible for hard X-ray modulation: 91 pairs of grids (44 pairs of sin-cos sub collimators plus a set of three sub collimators) are mounted on the front and rear plates with different pitches and position angles. They supply enough u-v Fourier components for the reconstruction of images. A Solar Aspect System (SAS) was developed to improve the
pointing accuracy. The SAS is installed on the rear plate of the framework and includes the Solar Aspect (SA) and the Deformation Monitor (DM). The SA provides the location of the Sun’s center with accuracy of 2″. The DM monitors the relative displacement and distortion between the front and rear plates. The displacement precision can reach 2 μm and the twist precision is better than 3″ [7, 8].

Figure 2. Sketch of the HXI-C. Grids of 99 elements are located on the front and rear plate. The titanium framework supports the front and rear plate. The Solar Aspect System (SAS) is located on the rear plate and includes the Solar Aspect (SA) and Deformation Monitor (DM).

2.2 HXI-S description

The HXI-S records the photon count and measures the spectrum of the incident modulated X-rays from 30 to 200 keV. As shown in figure 3, there are 99 detector modules arranged in an 11 × 9 array: 91 are dedicated to observation of hard X-rays, five are used to measure the charged particle background, and the other three to record the background total flux. Each detector comprises a LaBr$_3$ scintillator coupled with a photomultiplier (PMT) and is assembled in a carbon fiber reinforced plastic (CFRP) case, which is also the interface with the satellite payload platform. The CFRP case protects the detector modules from potential damage during launch and on-orbit operations. Additionally, thermally conductive brackets (i.e., four copper brackets and eight aluminum straps) are located between the PMT bases and an aluminum-alloy Faraday panel. The front end electronics (FEE) and high voltage (HV) distribution system are also mounted on the Faraday panel.

2.2.1 Detector modules

The LaBr$_3$ scintillator can provide very fast light output, short decay time and excellent energy resolution and is thus very suitable for X-ray detection. Figure 4 is a cross-sectional drawing of the detector module. The LaBr$_3$ scintillator used in the HXI-S has dimensions of φ 25 mm × 25 mm (height). Wrapped with Teflon film and optical glue, each LaBr$_3$ scintillator is sealed in an aluminum case (Al shield) with a 3-mm-thick quartz window for light transmission. The R1924A-100 PMT has a super bi-alkali cathode that realizes an excellent energy resolution for X-rays at ~30 keV. The PMT is placed into a protective magnesium alloy shield (Mg shield) filled with Dow-corning Sylgard 170 silicone rubber. To reduce the gain variation of the PMT because of the geomagnetic
Figure 3. Exploded view of the HXI-S. The CFRP case is the main support of the HXI-S and has detector modules mounted inside. Thermal brackets are copper brackets and aluminum straps connected to the Faraday panel.

Figure 4. Profile of the HXI-S detector module.

field, three layers of perm-alloy sheets up to 75 μm thick are inserted between the PMT and the protective magnesium alloy frame. The LaBr₃ scintillator and the PMT are coupled with Dow Corning RTV615 and integrated with four M3 titanium screws.

2.2.2 CFRP case

The CFRP case is designed to support and protect the detector modules and electronics. The material should be as light as possible to reduce the total weight of the mission. The biggest challenge is that most of the weight budget is accounted for by the 99 small modules rather than the FEE or HV distribution system and the support plate. In fact, the total mass of the spectrometer is required to be within 54 kg, and the 99 detector modules and thermally conductive brackets already account for about 40% of this mass. Furthermore, the mass distribution is particularly centralized. Another constraint is the required alignment of the modules and front sub-collimators. This constraint requires the detector units to have precise sizes and locations.
According to the above requirements, we adopted CFRP as the main support material for the mechanical structure of the HXI-S. CFRP provides both high strength and stiffness while its density is relatively low. The schematic presented in figure 5 shows that the CFRP comprises three parts. The middle framework is glued to 99 cases that position the detector modules. The sidewall supports on the left and right have a ladder shape and are fabricated together. Closed by two carbon fiber face sheets, the sidewall provides better fixation with the middle section and a stronger support capability. The bottom is another support structure comprising 20 CFRP tubes. Inserts are embedded not only to interface with the satellite payload platform but also to improve the robustness and stiffness of the integrated structure.

![Figure 5. View of the main support. The left diagram is an exploded drawing of the CFRP case while the right diagram shows the detail of the sidewall support.](image)

3 Test philosophy and procedure

Various tests need to be conducted in different phases of the fabrication of space instruments. A series of environmental tests are usually performed after the development of a qualification model to verify the adaptability from the launch to on-orbit operations. To make the tests more realistic, the HXI-S EQM is based on the same drawings, materials, tooling, manufacturing processes, and integration process as the flight model. However, to reduce the costs and time required in constructing the EQM, 39 of the 99 detector modules are replaced by dummy models having the same mass distribution and power consumption. The EQM is thus equivalent to the flight article in terms of mechanical and thermal properties. Mechanical tests were performed first, and thermal tests were performed afterward.

3.1 Mechanical tests

Mechanical tests include sinusoidal and random vibration tests. Before and after each run of vibration, a model survey is conducted to find possible structural degradation resulting from the tests, and ensure the needed stiffness is preserved.
The model survey adopts sinusoidal sweeping from 5 to 300 Hz in horizontal (x/y) directions and from 5 to 500 Hz in the vertical (z) direction. The test acceleration magnitude is set as 0.1 g with a sweeping rate 2 oct/min as a typical value for space instruments.

The sinusoidal vibration is used to verify the instrument survival capability against low frequency vibration while the random vibration allows investigation of the structural response in a wide frequency band from 20 to 2000 Hz. As prime evidence of the HXI-S passing the vibration test, the natural frequency variation in the model survey before and after the test should be within 5%, especially in the case of random vibration. Meanwhile, the instrument needs to continue working normally after the mechanical test.

Detailed test levels are summarized in tables 1 and 2. For the lowest frequency range of sinusoidal vibrations, the displacement amplitude of the vibrating table is employed as the test parameter. The remaining test levels are determined by acceleration levels of the EQM. The sweeping rate in this qualification phase is 2 oct/min.

Table 1. Sinusoidal vibration test parameters (where g stands for acceleration of gravity).

| Freq./Hz | Magnitude | X direction |
|----------|-----------|-------------|
| 5~10     | 15.20 mm  | 6g 9g 3g    |
| 10~14    | 23.75 mm  | 6g 9g 3g    |
| 14~25    | 10.13 mm  | 4g 8.5g 10g |
| 25~100   | 10.13 mm  | 4g 8.5g 10g |

| Freq./Hz | Magnitude | Y direction |
|----------|-----------|-------------|
| 5~8      | 10~25     | 25~100      |
| 8~10     | 23.75 mm  | 6g 9g 3g    |
| 10~25    | 10.13 mm  | 4g 8.5g 10g |
| 25~100   | 10.13 mm  | 4g 8.5g 10g |

| Freq./Hz | Magnitude | Z direction |
|----------|-----------|-------------|
| 5~10     | 10~40     | 40~50 50~75 75~85 85~100 |
| 10~14    | 23.75 mm  | 6g 9g 3g    |
| 14~25    | 10.13 mm  | 4g 8.5g 10g |
| 25~100   | 10.13 mm  | 4g 8.5g 10g |

Table 2. Random vibration test parameters.

| Freq./Hz | Magnitude | 9.06 g RMS in each direction, Duration time, 120 s for each direction |
|----------|-----------|---------------------------------------------------------------------|
| 20~100   | +3 dB/oct | 0.1 g^2/Hz -9 dB/oct                                                  |
| 100~600  |           |                                                                      |
| 600~2000 |           |                                                                      |

The mechanical tests were performed in January 2020 at the Sushi Guangbo Environmental Reliability Laboratory in Suzhou, China. The EQM was installed on a vibrating table via a fixture in the same way as it will be mounted on the satellite payload platform. The fixture was rigid enough to eliminate potential resonance with the EQM. To control the test magnitude and measure the instrument’s response, several tri-axial accelerometers were positioned on the surface of the model and the fixture. The average value for the four monitoring points on the fixture was adopted for the control strategy. Figure 6 presents the distribution of the accelerometers applied in these tests. There were four control points and ten measuring points in total. Table 3 summarizes the acceleration results and the locations of the accelerator sensors. All responses were fully recorded without exception.

Control points C01–C04 are on top of the fixture. The same one set of accelerator sensors is implemented in these tests.

Figure 7 shows a typical response along the vertical axis at the locations of M5 and M18. In this curve, M5 and M18 respectively denote accelerometers located on the crystal surface and
Figure 6. Layout of accelerometers (left) and the vibration setup along the Z direction (right).

Table 3. RMS acceleration as measured by accelerometers (see figure 6) during the random vibration test of the HXI-S.

| Number | Position                                      | x direction/g | y direction/g | z direction/g |
|--------|-----------------------------------------------|---------------|---------------|---------------|
| M5     | crystal surface (top)                         | 26.69         | 26.97         | 53.15         |
| M7     | crystal surface (middle)                      | 22.05         | 19.10         | 61.68         |
| M8     | crystal surface (bottom)                      | 13.62         | 15.46         | 43.26         |
| M13    | bottom support (+x, −y side upper part)       | 12.24         | 11.46         | 20.47         |
| M14    | sidewall support (−y side middle part)        | 17.21         | 18.94         | 27.78         |
| M15    | middle frame (+z side −y part)                | 29.80         | 26.34         | 43.79         |
| M16    | middle frame (+z side middle part)            | 33.46         | 16.14         | 63.82         |
| M17    | middle frame (+z side +y part)                | 30.90         | 26.46         | 45.08         |
| M18    | sidewall support (+y side middle part)        | 22.71         | 18.00         | 35.19         |
| M19    | bottom support (−x, +y side upper part)       | 11.98         | 11.53         | 31.84         |

main support. The results in figure 7a and 7b clearly show that the responses at these two points were similar. The difference between the responses was due to their locations. Additionally, the maximum amplitude amplification of sinusoidal test was 1.17 times in Y direction at the frequency of 100 Hz, where the amplitude was about 3.5 g. This is expected since the first natural frequency is higher than 200 Hz and the instrument is rigid enough in the test frequency range. In the model survey (7c), the variation of the first natural frequency was less than 1% (where the resonance frequency is about 255 Hz). The results suggest that the EQM fulfils the mechanical requirements and passed the series test.

3.2 Thermal tests

Passive thermal control is adopted for the HXI-S. Two types of thermal strap are deployed inside the spectrometer as shown in figure 8; i.e., four copper conductive brackets and eight aluminum frame
Figure 7. Responses of random vibration in the Z direction: (a) acceleration as measured during the sinusoidal vibration test by sensors M5 and M18; (b) random vibration spectrum profile (Power Spectral Density) as measured by the same sensors; (c) model survey results before and after the random test at these two points.

Figure 8. Thermal Vacuum test setup in the chamber (right) and thermistors on the thermal straps (left). RM1 to RM4 are the thermistors pasted on copper brackets (red) while RM5 to RM7 are those pasted on the aluminum straps (silver).

supports. Faraday plates with FEEs are then directly installed on the thermal straps with several screws. In this way, heat from the detector units effectively conducts to the Faraday plates, which are painted white and used as the system irradiative panel. The temperature differences among the 99 detector modules is expected to be kept as small as possible and in any case within 5°C to reduce gain disuniformities.

Thermal tests usually include thermal cycles (TC) and thermal vacuum (TV). The TC test reveals latent material defects or rosin joints on printed circuit board by circulating environmental stress. It is always performed at atmospheric pressure. Meanwhile, the TV test is the most realistic ground simulation of the space environment. The performance in this test therefore is the most direct evidence that we can use to judge whether the space equipment will operate regularly in orbit.
The TV test for the HXI-S was performed at the Shanghai Institute of Space Power-Sources in March 2020. The HXI-S was mounted at the center of the vacuum chamber, the diameter of which was 2 m. Test cables were connected by several electric connectors on the flange provided by the chamber. Fifteen thermistors, located on the surface of the detector modules and the thermal straps, were readout during the TV test. Four were used as feedback probes to control the environment temperature inside the chamber. Once any one of these four thermistors reached the target temperature (i.e., extreme hot or extreme cold), the temperature inside was maintained for four hours. The remaining thermistors measured the temperature. The spectrometer underwent 6.5 cycles in the TV test.

The TC test was performed by the same laboratory that performed the mechanical test. The TC test was carried out similarly to the TV test. Furthermore, the HXI-S went through 25.5 cycles in this test.

The profile of the TC and TV tests is shown in figure 9 and the test parameters are described in table 4. They comply with the requirements of the ASO-S and take into account the thermal environment experienced by the HXI-S once in orbit. They also account for components sensitive to extreme temperature, such as the PMT.

![Profile of the thermal test](image)

**Figure 9.** Profile of the thermal test. A full cycle is the period between two adjacent points with the same temperature containing an extreme hot stage and an extreme cold stage. The extreme hot stage has a temperature of 40°C and the extreme cold one has a temperature of −20°C. The TC test includes 25.5 cycles whereas the TV test lasts 6.5 cycles.

| Item | Pressure | Extreme Hot Temp. | Extreme Cold Temp. | Holding time of Extreme Temp. | Cycles |
|------|----------|-------------------|-------------------|-----------------------------|--------|
| TC   | Room Pres. | +40°C               | −20°C             | 4 h                         | 25.5   |
| TV   | <1.3e-3 Pa | +40°C               | −20°C             | 4 h                         | 6.5    |

As mentioned above, an electrical functional test was conducted throughout the TC and the TV tests except in the first and last loops, during which the turn-on/turn-off functions of the instrument were tested. Figure 10 shows temperatures as measured during the TV test, including those of the feedback probes and the thermistors on the crystals, the Faraday plate, and the thermal straps.
The temperature distribution of the detector modules is obtained from the thermistors affixed to the thermal straps. It is important to confirm whether there is temperature uniformity within 5°C.

Figure 10. Temperature monitored by sensors located on the instrument during the TV test: (a) environment-control sensors on the surface of two crystals (C1 and C3) and two Faraday plates (C2 and C4); (b) monitor sensors on the Faraday plate (M1) and on other crystals (M2–M4); (c) thermistors RM1-RM7 on thermal straps (see figure 8); (d) temperature of thermistors RM1-RM7 during the first balanced extreme stages including hot and cold stages.

Results are shown in figure 10. Panels (a), (b), and (c) start from the beginning of the operations within the chamber and show good results of the TV test, with the curves and magnitudes being similar. Temperature disuniformities of thermistors displayed in panel (b) and panel (c) are within 3°C at the same time. Panel (d) depicts the temperatures on thermal straps during the first balanced extreme stages. Data in this figure have been taken for one hour periods of the extreme hot and cold stages. The temperature homogeneity is around 1.3°C in the hot stage and 2.3°C in the cold stage. This suggests that the requirement that the temperature differences is less than 5°C was met. The fact that temperature differences are smaller in the hot stage than in the cold one is beneficial to the HXI-S, whose temperature is indeed expected to run between 17 and 27°C.

All along TC and TV tests the HXI-S was also observed to take data smoothly, apart during the first and last cycles when the switching ON/OFF functions were tested. Overall, thermal tests have thus shown that the thermal design of the spectrometer meets the temperature uniformity requirements of the detector modules.
4 Functional tests

The major properties of the instrument, such as the energy resolution and integral non-linearity (INL), were carefully tested before and after the environmental tests. The criterion for a successful environmental test of detector performance is that the change in energy resolution before and after the test is less than 2% with the absolute value being no worse than 27% at 32 keV. The change in energy non-linearity in this case should be smaller than 10%. The requirement on the absolute energy resolution originates from the physics aims of the mission, while the request on its variation takes the uncertainties on the measurements and environment into account.

The $^{133}$Ba radioactive source provides four characteristic X-rays at 32, 81, 302, and 356 keV. The detector modules were tested one by one with a single source in the laboratory. The source was attached at the center of the aluminum window of the detector module. Data were acquired from the FEE, which are the same as the FEE used in orbit. Obtaining sufficient data in the performance test for each module takes only five minutes owing to the high activity of the source. The environment temperature was maintained from 21°C to 22.5°C during the test to guarantee the validity of results.

Figure 11 presents the energy spectrum of a typical detector module from functional tests before and after all of the environmental tests. The module is located in the middle of the HXI-S where M7 is shown in figure 6. The spectrum peaks are near 356, 302, and 81 keV due to X-rays from $^{133}$Ba in the radioactive source, and at 32 keV due to a combination of X-rays from $^{133}$Ba and $^{138}$La isotopes in the scintillator, respectively. Least squares fits have been carried out utilizing Gaussian profiles to determine the positions and widths of these peaks. The estimated parameters, before and after the environmental tests, are listed in table 5. The energy resolution is evaluated as the ratio between peak widths and positions. It remains around 21% at 32 keV, 12% at 81 keV, 6% at 302 keV and 5.5% at 356 keV. The maximum variation is less than 1.2% that is still covered by uncertainty caused by the fitting process. This result suggests that the function of the instrument keeps almost no change during the environmental tests.

![Energy spectrum($^{133}$Ba) of a typical detector module](image)

Figure 11. Energy Spectrum ($^{133}$Ba) of a typical detector module. Red dots indicate the spectrum pre-test and blue dots the spectrum post-test.
Table 5. Differences of the measured parameters in functional tests, the errors in the table like “6.60 ± 0.14” are only from fit procedure without other systematic errors.

| Item     | Before test | After test |
|----------|-------------|------------|
| Energy /keV | FWHM of peak /keV | Energy resolution |
| Energy resolution | FWHM of peak /keV | Energy resolution |
| 32       | 6.60 ± 0.14  | (20.63 ± 0.44)%  | 6.98 ± 0.09  | (21.81 ± 0.27)%  |
| 81       | 9.58 ± 0.18  | (11.83 ± 0.22)%  | 9.87 ± 0.18  | (12.19 ± 0.22)%  |
| 302      | 17.86 ± 0.77 | (5.91 ± 0.25)%  | 18.25 ± 1.43 | (6.04 ± 0.47)%  |
| 356      | 18.91 ± 0.56 | (5.31 ± 0.16)%  | 20.10 ± 0.63 | (5.65 ± 0.18)%  |

Figure 12. Typical dependence of the response of detector modules on the energy of the incoming radiation (top), and its deviation from a linear behavior (bottom).

Figure 12 shows that the maximum INL is about 5.8% with the charge input ranging from 32 to 356 keV. The change in the INL between the pre-test and post-test is too little to identify. This result meets the requirement on the dynamic range in the HXI-S.

Overall, no damage or degradation is observed from the results of the functional tests.

5 Conclusion

The ASO-S, as the first dedicated solar mission of China, is in phase C (detailed design and fabrication of the EQM) study and will transition into phase D (construction of the flight model) in the fall of 2020. As an important instrument onboard the ASO-S, the HXI-S was required to undergo a series of environmental tests. These tests were performed to identify the ability of the payload to survive the launch and to operate normally in on-orbit environments and to verify the
detector performance under the same conditions. From December 2019 to March 2020, the HXI-S successfully passed environmental tests conducted with the EQM.

In this paper, we reported the results of mechanical and thermal tests conducted for the HXI-S. The test results show that the mechanical and thermal characteristics of the HXI-S satisfy or exceed the mission requirements. The performance of the spectrometer remained high, with little variation before and after the environmental tests. The HXI-S worked successfully during TV and TC tests. Consequently, the present study illustrates that the design and manufacture of the HXI-S instrument is such that the detector is expected to operate normally in the space environment.

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