Low-noise read-out electronics design for a solar soft X-ray spectrometer onboard the MSS-1B satellite

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Abstract

The main scientific payload of Macau Science Satellite-1B is a solar soft X-ray detection unit. To obtain an accurate solar X-ray spectrum, we have designed low-noise, high-throughput electronics. Solar radiation is detected using a low-leakage silicon drift detector (SDD), which is cooled to $-30\ {}^\circ$C. The SDD output is processed using two parallel shaping amplifiers with peaking times of 315 ns and 65 ns. The amplifiers are designed using two-pole multiple-feedback active low-pass filters optimized to achieve a Bessel response. The differential output of the shaping amplifier generates a bipolar signal. The phase of the differential stage is tuned to ensure zero crossing corresponding to the peak of the shaping amplifier. A high-speed switch is inserted between the shaping amplifier and the peak-hold capacitor, and the peak value is maintained by turning off the switch. Fast and slow peak-hold circuits share a common ADC via time-division multiplexing. Both peak values are sampled for space-background rejection. Traditional pile-up detection methods cannot distinguish pulses that overlap in a fast channel. In this study, the differential of the "fast shaping" is selected, enabling the distinction of events separated by as little as 65 ns, which is crucial for solar flare detection. The energy resolution is measured to be 138 eV at 5.90 keV. The centroid drift is less than 3.6 eV between $-5\ {}^\circ$C and $20\ {}^\circ$C. Compared with other solar X-ray instruments, this study demonstrates improved energy resolution with a lower peaking time, indicating a higher solar flare detection capability.

Full Text

Preamble

Low-Noise Read-Out Electronics Design for a Solar Soft X-Ray Spectrometer Onboard the MSS-1B Satellite

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The main scientific payload of Macau Science Satellite-1B is a solar soft X-ray detection unit. To obtain accurate solar X-ray spectra, we have designed low-noise, high-throughput electronics. Solar radiation is detected using a low-leakage silicon drift detector (SDD) cooled to −30 °C. The SDD output is processed by two parallel shaping amplifiers with peaking times of 315 ns and 65 ns. These amplifiers employ two-pole multiple-feedback active low-pass filters optimized to achieve a Bessel response.

The differential output of the shaping amplifier generates a bipolar signal. The phase of the differential stage is tuned to ensure zero crossing corresponds to the peak of the shaping amplifier. A high-speed switch is inserted between the shaping amplifier and the peak-hold capacitor, and the peak value is maintained by turning off the switch. Fast and slow peak-hold circuits share a common ADC via time-division multiplexing. Both peak values are sampled for space-background rejection. Traditional pile-up detection methods cannot distinguish pulses that overlap in the fast channel. In this study, the differential of the "fast shaping" is selected, enabling distinction of events separated by as little as 65 ns, which is crucial for solar flare detection. The energy resolution is measured to be 138 eV at 5.90 keV. The centroid drift is less than 3.6 eV between −5 °C and 20 °C. Compared with other solar X-ray instruments, this study demonstrates improved energy resolution with a lower peaking time, indicating higher solar flare detection capability.

Keywords: Solar flare, X-ray detector, Energy resolution, Pile-up rejection, Spectroscopy

Introduction

X-ray astronomy is based on the detection of X-rays from celestial sources [**?**]. The Macau Science Satellite-1B (MSS-1B) is primarily responsible for monitoring solar activity, particularly solar flares, during Solar Cycle 25 [**?**]. Its main scientific payload is a solar X-ray detector (SXD) featuring a wide energy range and high count rate capability. The SXD consists of two soft X-ray detection units (SXDUs) with different aperture areas and two identical hard X-ray detection units (HXDUs). These four detection units are integrated into a single instrument. This study focuses on the electronic design of the SXDU.

The X-ray Sensor (XRS) on the GOES satellite provides continuous solar X-ray flux measurements, and the standard X-ray classification of solar flares is based on these measurements [?, ?]. However, this sensor lacks spectral resolution, which limits physical investigation of coronal emissions in the X-ray spectrum. The Solar Assembly for X-rays (SAX) on MESSENGER employs a Si-PIN detector with an aperture area of 0.03 mm^2. Its energy resolution is 598 eV at 5.9 keV, constrained by Si-PIN noise [?]. The Solar X-ray Spectrometer (SXRS) on the FY-2F mission monitors solar flares above the M1 level with an energy resolution of 185 eV [?]. The HEPP-X instrument onboard CSES is designed to monitor solar radiation from a wide field of view [?]. The X-ray spectrometer on MinXSS detects solar X-rays in the 0.8–12 keV range with a time cadence of 10 s [?]. The on-orbit energy resolutions for MinXSS-1 and MinXSS-2 at 5.90 keV are 240 eV for a 4.8 µs peaking time and 168 eV for 1.2 µs, respectively [?]. An improved instrument known as the Dual-Zone Aperture X-ray Solar Spectrometer employs a newer version of the SDD and a dedicated aperture design [?]. Its cadence time is set to 9 s, but solar observations are limited to flare levels below M3 due to detector saturation [?]. These CubeSats and instruments are designed using commercial off-the-shelf electronic devices, and one instrument was previously damaged by a single-event latch-up [?]. The Chandrayaan-2 Solar X-ray Monitor measures the 1–15 keV spectrum from lunar orbit with an energy resolution of 175 eV at 5.9 keV [?]. Its aperture area is limited to 0.367 mm^2, making it feasible for detecting flares up to the M5 class.

We enhanced the time cadence to 1 s using a dedicated X-ray signal processing design. The peaking times of the shaping amplifiers were optimized to improve energy resolution while achieving higher count rates. In particular, two soft X-ray detector units with different aperture areas were integrated to detect solar irradiation, targeting both the quiet Sun and solar flares up to the X-class level. The primary working principle of the SXD was presented by Shi et al. [?], whereas this study focuses on a detailed description of the SXDU' s electronic design and ground calibration results.

The remainder of this paper is organized as follows. Section II presents the basic principles, instrument composition, and specifications. Sections III–IV describe the design of the X-ray detector module and the analog electronic unit. Section V discusses the scientific data types, while Section VI covers spectral performance calibration. Finally, Section VII presents the conclusions.

Instrument Design

To distinguish emission lines from solar flares, the SXDU is designed with an energy resolution better than 200 eV across an energy range of 1–20 keV. The detector and electronics are identical for both SXDUs. Table 1 lists the specifications.

Table 1. Performance requirements of SXDU.

Parameter	Specification
Energy range (keV)	1–20
Energy resolution (eV)	< 200 @ 5.9 keV
Aperture area (cm^2)	0.17 and 0.005
Field of view (°)	$\geq 1 \times 10^5$
Time cadence (s)	1
Count rate (counts s^{-1})	100,000

Figure 1 [Figure 1: see original paper] presents a conceptual sketch of the SXDUs. The units consist of X-ray Detector Modules (XDMs), analog electronic units (AEUs), a data processing unit (DPU), and a power supply unit (PSU). Collimators positioned in front of the XDMs restrict the field of view and aperture area. The two XDMs and their associated AEUs share a common DPU and PSU. Detector power is supplied by low- and high-voltage power supplies within the PSU, which are interconnected with the AEU and DPU via a common bus board for signal transmission and power distribution. Additionally, two temperature sensors are mounted on the AEUs to monitor temperature fluctuations on the analog board.

A. SDD Detector

Silicon X-ray detectors are widely used in space applications, including silicon drift detectors (SDDs) [?], silicon photomultipliers [?, ?], silicon microstrips [?, ?], CCD detectors [?, ?], and Si-PIN detectors [?]. A 500 µm thick SDD is selected as the X-ray sensor. Its unique electrode structure provides ultralow capacitance, enabling operation at short peaking times that increase the count rate. Energy resolution is further improved using a thermoelectric cooler (TEC). The SDD, along with a CMOS charge-sensitive preamplifier, is mounted on the TEC. The detector is positioned behind a thin window composed of a 150 nm silicon nitride film covered with 250 nm aluminum. The two XDMs use the same type of SDD, but the aperture areas restricted by the collimator are 0.17 cm^2 and 0.005 cm^2, respectively. A passive graded shield surrounding the detector package protects against space background radiation and fluorescent photons from surrounding materials. Additionally, two ^{241}Am radioactive sources are mounted between the detector plane and collimator in both SXDUs for in-flight calibration and self-verification.

B. TEC Characteristics

Detector leakage current is sensitive to operating temperature, doubling for every 7 °C increase, as described by [?]:

$$I_0 = T^2 e^{-E_g/2kT}$$

where I_0 is the leakage current, T is the detector operating temperature, E_g is the silicon bandgap energy (temperature-dependent), and k is the Boltzmann constant. The TEC reduces electronic noise in the detector and preamplifier. Heat extracted by the TEC is dissipated through a mounting stud attached to a copper heat radiator. Figure 3 [Figure 3: see original paper] shows the TEC voltage and current at a room temperature of 25 °C. The SDD temperature decreases exponentially as TEC power increases, allowing the silicon detector to be cooled to −30 °C. Since the leakage current of the SDD increases after radiation exposure [?], the TEC temperature can be adjusted via command, and the TEC can be turned off if necessary. The voltage and current of the TEC driver are recorded every second.

C. Preamplifier Reset Rate

When detector leakage current accumulates in the preamplifier, the ramp output eventually saturates. To counter this, a reset pulse is applied to restore the detector anode to ground potential, as shown in Fig. 2 [Figure 2: see original paper]. The large transient caused by the reset pulse can interfere with signal processing; therefore, a window of 10 µs is implemented to eliminate its effects. The preamplifier periodically resets the charge accumulated on the feedback capacitance due to X-ray signals and leakage current:

$$I_0 = C_f V_{ramp} f_{reset}$$

where I_0 is the leakage current, C_f is the preamplifier feedback capacitance (typically 25 fF), V_{ramp} is the ramp voltage, and f_{reset} is the ramp-reset rate. The reset rate decreases exponentially with decreasing detector temperature and stabilizes at a nominal value of 12–13 Hz in the absence of incident radiation. However, it increases with higher incidence rates and deposited energy. To monitor variations in SDD leakage current following radiation exposure, the reset rate is recorded every second.

IV. AEU

The AEU comprises an SDD preamplifier driver, TEC power driver, and front-end readout electronics, as shown in Fig. 4 [Figure 4: see original paper].

A. SDD and TEC Drivers

The preamplifier driver circuit generates and filters power, sends reset signals to the preamplifier, and buffers and amplifies the preamplifier output to drive the front-end electronics. The TEC driver reads the temperature diodes inside the SDD package and supplies power to the TEC. The temperature diode is biased using a 160 µA current source. A proportional-integral-derivative (PID) control feedback loop maintains the SDD at the desired temperature, which is set via a digital-to-analog converter (DAC). TEC power is supplied by a high-efficiency DC-DC converter, with output ripple minimized using an LC-type filter. The voltage and current of the TEC driver, along with the set and measured temperatures, are converted using an ADC. These parameters, together with the ramp-reset rate, are used to assess the operational status of the SDD in orbit.

B. Shaping Amplifier

The preamplifier generates a ramp output composed of small steps. Its output is differentiated to measure the step voltage. The shaping amplifier, designed using two-pole multiple-feedback active low-pass filters [**?**] as shown in Fig. 5 [Figure 5: see original paper], enhances the signal-to-noise ratio. The amplifiers are optimized to achieve a Bessel phase response, ensuring constant group delay within the passband. The step response exhibits no overshoot or ringing, which is essential for spectrometer performance. While the rising edge of the shaping output is steep, the voltage decays exponentially back to the baseline. These exponential tails extend many times beyond the full width at half maximum (FWHM) duration. Pulses that overlap during this extended window cause pile-up, particularly at high count rates. Reducing the FWHM mitigates pulse pile-up but introduces additional noise.

Two parallel shaping amplifiers with different time constants are designed to serve distinct purposes. The first amplifier is optimized for better timing accuracy, while the second achieves higher spectral resolution. The shaping amplifiers with peaking times of 315 ns and 65 ns are referred to as "slow shaping" and "fast shaping," respectively. The fast-shaping channel improves double-pulse resolution and reduces pile-up but introduces more noise, consequently requiring a higher threshold set by a DAC. In contrast, the slow-shaping channel uses a longer peaking time to extract spectral information. When the amplitude of the slow-shaping channel exceeds the threshold, the peak value is held by the peak holder and digitized by an ADC.

Table 2 lists the design parameters of the slow-shaping channel. The group delay is simulated to be constant in the passband at 853.8 ns, as shown in Fig. 6 [Figure 6: see original paper]. A pulse generator connected to the shaping amplifier input simulates X-ray events. Figure 7 [Figure 7: see original paper] shows the transient response of the slow channel, revealing no overshoot and no ringing. The rise time of the slow-shaping amplifier is measured to be 315 ns, the fall time is 945 ns, and the pulse width is less than 2.8 µs.

Traditional pile-up detection uses a fast/slow-channel approach [?] but cannot distinguish pulses that overlap in the fast channel. The differential of the shaping amplifier generates a bipolar output. As Fig. 8 [Figure 8: see original paper] shows, the pulse width of the differential signal is significantly smaller than that of the shaping amplifier. Therefore, the differential signals of the fast channel are selected for pile-up rejection.

The time interval of an X-ray photon can be described by an exponential distribution:

$$f(\tau) = \lambda e^{-\lambda\tau}$$

where τ is the dead time and λ is the average incoming rate, assumed to be 1×10^5 counts $\cdot$ s^{-1}. The dead time caused by the shaping amplifier is 2.8 µs for the slow channel. The probability of non-paralyzable pile-up can be calculated as:

$$P = \frac{\lambda\tau}{1 + \lambda\tau}$$

For the slow channel with $\tau = 2.8$ µs, the probability is 21.9%. This is reduced to 4.8% for the fast channel with a dead time of 0.5 µs. The throughput is significantly better, making it suitable for calculating the true input rate.

C. Peak-Hold Circuit

The rise time of the SDD output is a function of the incident position [?]. The peaking time of the slow channel is significantly longer than the variation in rise time, leading to pulse height loss due to ballistic deficit. Consequently, events originating far from the center could be rejected by comparing fast and slow amplitudes. Both peak values are sampled for space-background rejection.

The peak-hold circuit diagram is shown in Fig. 9 [Figure 9: see original paper]. A CMOS analog switch is inserted between the shaping amplifier and the hold-capacitor stage. When a pulse peak is detected, the peak value is held in the capacitor by turning off the switch until it is read out by a 16-bit ADC (only the 12 most significant bits are stored). The charge on the capacitor is reset by turning on the switch. The peak value from the capacitor is buffered by a unit-gain operational amplifier with low input-bias current. Low-leakage, low-dielectric absorption capacitors are essential. The fast-shaping amplitude peak value is obtained similarly, with both fast and slow peak-hold circuits sharing a common ADC. Figure 10 [Figure 10: see original paper] shows the ADC input waveform.

A CMOS analog switch selects a single channel. The switch features extremely high switching speed with a maximum transition time of 30 ns. Therefore, the slow-channel amplitude does not depend on event position. The flat-top duration of the fast channel is shorter than the rise time, ensuring break-before-make switching. Charge injection is less than 2 pC, which is crucial for high-precision peak-height capture.

Figure 11 [Figure 11: see original paper] shows the timing of the switches in the peak-hold circuit. The peak-hold signal durations "PH_F" and "PH_S" for the fast and slow channels are 150 ns and 200 ns, respectively. The ADC conversion signal "CNV" starts with delays of 100 ns and 150 ns for the two channels, respectively. At the end of each peak-hold signal, the switch changes state. Note that "PH_F" may be absent in some cases since the fast channel threshold is higher. Consequently, "PH_{MUX}" assertion is controlled by both "HOLD_S" and "PH_F" . Here, "HOLD_S" is the "HOLD" signal of the slow channel, while "HOLD_F" corresponds to that of the fast channel. At the rising edge of "HOLD_S" , if "PH_F" is high, then "PH_{MUX}" is asserted at the falling edge of "PH_F" ; otherwise, "PH_{MUX}" is asserted immediately.

The "HOLD" signal is generated by connecting the differentiating amplifier output to a comparator with hysteresis. "HOLD_S" and "HOLD_F" are generated using the same approach, as shown in Fig. 12 [Figure 12: see original paper] and Fig. 13 [Figure 13: see original paper]. The comparator U2 output, known as "HOLD" , switches high for input voltages greater than V_{HI} and does not switch low until the input voltage falls below V_{LO} (i.e., at zero crossing).

$$V_{HI} = (V_{CC} - 1)\frac{R1}{R1 + R2}$$

$$V_{LOW} = 0$$

where $V_{CC} = 5$ V, $R1 = 100\ \Omega$, $R2 = 10$ kΩ, and $V_{HI} = 40$ mV. The latch pin of U2 is connected to the output of U1. Therefore, "HOLD" remains in a low state unless the shaping-amplifier amplitude exceeds the threshold.

D. Pile-Up Rejection

If two pulses are too close in time, the height of the second pulse can be affected. Errors in measured pulse height may distort the spectrum. Overlapping pulses in the slow channel are identified using the differential signal of the fast channel, as described earlier. To obtain a clean spectrum, all overlapping pulses are rejected. The analog shaper exhibits an infinite impulse response. Even when the tail drops rapidly toward the baseline, a small contribution remains [**?**]. The dead-time window widths "WINDOW_S" and "WINDOW_F" for the slow and fast channels are 2.8 µs and 0.5 µs, respectively, as shown in Fig. 14 [Figure 14: see original paper]. If an event occurs during dead time, the dead time is reset, reducing throughput. Therefore, dead time can be described using a paralyzable model, as shown in Fig. 15 [Figure 15: see original paper] [**?**].

V. Operating Mode Design

The SXDU generates three types of observation modes in addition to the default standby mode. In standby mode, after power-on, the SXDU operates with the XDMs and AEUs powered off. A selected detector channel is powered by command. Following initialization, the SXDU switches to the selected observation mode.

The baseline noise observation mode enables detailed monitoring of detector performance, particularly for evaluating noise after radiation exposure. The signal amplitude is sampled every 10 ms, regardless of incident events.

In spectrometer histogram observation mode, each valid pulse height is stored in its respective channel to obtain a spectrum histogram with 2048 channels. The histogram depth is 3 bytes, generating 6 KB of histogram data every second.

The photonlist observation mode samples pulse heights in both channels sequentially using a 16-bit ADC. Data for each event consists of the detector number, trigger mode, time stamp, and pulse height data. Each transfer frame consists of 512 events, and data capacity is limited by the interface clock to a maximum of 40 frames per second.

VI. Spectral Performance

A linear energy response is desirable in solar spectroscopy. Before applying X-ray sources, a step signal generator is connected to the front-end readout electronics instead of an X-ray detector. The step voltage is attenuated 80 times using a small resistor to reject noise. The sampled peak values scale linearly with the input voltage, as shown in Fig. 16 [Figure 16: see original paper].

A miniature X-ray tube with a W target is used to obtain fluorescence lines from aluminum (1.49 keV), titanium (4.51 keV), manganese (5.90 keV), copper (8.05 keV), molybdenum (17.48 keV), and silver (22.17 keV). The emission line at approximately 13.94 keV from the ^{241}Am radioactive source is also included. Spectral performance is evaluated using the K$ $1 line centroid and width. During calibration, the detector temperature is maintained at −30 °C.

Figure 17 [Figure 17: see original paper] shows linear calibration using X-ray sources. Gain and offset are obtained by linear fitting. The gain is 5.9 eV/channel when operating in photonlist observation mode. The offset is approximately −233 eV with an error of 42 eV. The upper and lower limits of the energy range are 23.39 keV and 0.7 keV, respectively.

The fraction without loss is:

$$P(X > \lambda) = e^{-\lambda\tau}$$

Figure 18 [Figure 18: see original paper] shows the X-ray detector response to Mn fluorescence illumination. The 5.90 keV and 6.49 keV line complexes are clearly detected. Spectral lines are fitted with a Gaussian function to obtain the peak channel centroid and FWHM. The measured energy resolution is 138 eV at 5.90 keV, markedly better than the 200 eV requirement. Compared to instruments listed in Table 4 , this study demonstrates superior energy resolution with a lower peaking time, indicating higher sensitivity to solar flare levels and better spectral resolution.

As shown in Fig. 19 [Figure 19: see original paper], the centroid drift in the temperature range of −5 °C to 20 °C is less than 0.6 ADC bin, which calibrates to approximately 3.6 eV. These results demonstrate the low noise and high accuracy of the electronic readout design for solar X-ray spectrometers.

VII. Conclusion

This study presents the design and ground calibration of a solar soft X-ray detection unit on the MSS-1B satellite. The core component of the X-ray module is a silicon drift detector, chosen for its excellent energy resolution. The detector is nominally cooled to −30 °C using a TEC. The preamplifier output voltage is processed by two parallel shaping amplifiers with peaking times of 315 ns and 65 ns. The slow-shaping channel, optimized for spectroscopy, operates with a longer peaking time, while the fast channel is used for pile-up rejection. Linearity response was validated using an electronic signal generator and various X-ray sources. The measured energy resolution is 138 eV at 5.90 keV, with a centroid drift of less than 3.5 eV over a temperature range of −5 °C to 20 °C. Compared with other on-orbit solar X-ray instruments, this study demonstrates improved energy resolution with a lower peaking time, enabling higher sensitivity to solar flare levels and better spectral resolution. These results highlight the low-noise, high-accuracy readout electronics design of the solar X-ray spectrometer.

Table 3. Energy resolution calibrated by various X-ray sources.

<table>
<tr><th>X-ray Source</th><th>Energy (keV)</th><th>FWHM (eV)</th><th>Error (eV)</th></tr>
<tr><td>Al-Kα</td><td>1.49</td><td>152</td><td>3</td></tr>
<tr><td>Ti-Kα</td><td>4.51</td><td>140</td><td>2</td></tr>
<tr><td>Mn-Kα</td><td>5.90</td><td>138</td><td>2</td></tr>
<tr><td>Cu-Kα</td><td>8.05</td><td>142</td><td>3</td></tr>
<tr><td>^{241}Am</td><td>13.94</td><td>145</td><td>4</td></tr>
<tr><td>Mo-K$ 1|17.48|148|5||$Ag-K$ $1</td><td>22.17</td><td>155</td><td>6</td></tr>
</table>

Table 4. Energy resolutions of solar X-ray detectors.

<table>
<tr><th>Instrument</th><th>Sensor</th><th>Sensor Area</th><th>Energy Range</th><th>Field of View</th><th>Energy Resolution</th><th>Peaking Time</th><th>Count Rate</th><th>Cadence</th></tr>
<tr><td>SXRS [?]</td><td>Si-PIN</td><td>7 mm^2</td><td>1.5–24.8 keV</td><td>$±26°|1850 eV@5.88keV$|±30°×$$±50°|175 eV@5.90keV|1.0s|80kcps
| —
|2.05s||HEPP−
X[?]|SDD|7mm^{2}$</td><td>keV</td><td>|10kcps|—
||SXM[?]|SDD|30mm^{2}$</td><td>keV</td><td>||MinXSS[?]|SDD|25mm^{2}$</td></tr>
<tr><td>This study</td><td>SDD</td><td>25 mm^2</td><td>0.7–23.97 keV</td><td>-</td><td>138 eV @ 5.90 keV</td><td>315 ns</td><td>100 kcps</td><td>1 s</td></tr>
</table>

References

[1] S.F. Wang, Y.N. Zhang, W. Cui, X-ray tomography of hidden matter in the Universe. *Sci. Bull.* 86, 3120–3123 (2023). doi: 10.1016/j.scib.2023.11.033

[2] K.K. Zhang, A novel geomagnetic satellite constellation: science and applications. *Earth Planet Phys.* 7, 4–21 (2023). doi: 10.26464/epp2023019

[3] A. Reinard, S. Hill, S. Bailey et al., Report on GOES SXI/XRS calibration effort. In: Fineschi S, Viereck R A, eds. *Proceedings of Solar Physics and Space Weather Instrumentation II*, San Diego, California, USA, 6689, 66890J (2007) DOI: 10.1117/12.734268

[4] P.C. Chamberlin, T.N. Woods, F.G. Eparvier et al., Next generation X-ray sensor (XRS) for GOES-R Satellite Series. In: Fineschi S, Fennelly J A, eds. *Proceedings of Solar Physics and Space Weather Instrumentation III*, San Diego, California, USA, 7438. 743802 (2009). DOI: 10.1117/12.826807

[5] B.R. Dennis, K.J.H. Phillips, R.A. Schwartz et al., Solar flare element abundances from the Solar Assembly for X-Rays (SAX) on MESSENGER. *ApJ.* 803, 67 (2015). DOI: 10.1088/0004-637X/803/2/67

[6] F. Wei, X.X. Zhang, B.Q. Zhang et al., Pre-flight calibration and the first results for the solar X ray spectrometer (SXRS) onboard FY-2F satellite. *Chin. J. Geophys.* (in Chinese). 57, 3812–3821 (2014). DOI: 10.6038/cjg20141135

[7] X.Q. Li, Y.B. Xu, Z.H. An et al., The high-energy particle package onboard CSES. *Radiat. Detect. Technol. Methods.* 3, 1–11 (2019). DOI: 10.1007/s41605-019-0101-7

[8] C.S. Moore, A. Caspi, T.N. Woods et al., The instruments and capabilities of the miniature X-ray solar spectrometer (MinXSS) cubeSats. *Sol. Phys.* 293, 21 (2018). DOI: 10.1007/s11207-018-1243-3

[9] J.P. Mason, T.N. Woods, P.C. Chamberlin et al., MinXSS-2 cubesat mission overview: improvements from the successful MinXSS-1 mission. *Adv. Space Res.* 66, 3–9 (2020). DOI: 10.1016/j.asr.2019.02.011

[10] B.D. Schwab, R.H.A. Sewell, T.N. Woods et al., Soft X-ray observations of quiescent solar active regions using the novel dual-zone aperture X-ray solar spectrometer. *ApJ.* 904, 20 (2020). DOI: 10.3847/1538-4357/abba2a

[11] T.N. Woods, B. Schwab, R. Sewell et al., First results for solar soft X-ray irradiance measurements from the third generation miniature X-ray solar

spectrometer. *ApJ* 956, 94 (2023). DOI: 10.3847/1538-4357/acef13
[12] H.E. Spence, A, Caspi, H. Bahcivan et al., Achievements and lessons learned from successful small satellite missions for space weather-oriented research. *Space Weather.* 20, e2021SW003031 (2022). DOI: 10.1029/2021SW003031
[13] N.P.S. Mithun, S.V. Vadawale, A. Sarkar et al., Solar X-ray monitor on board the Chandrayaan-2 orbiter: in-flight performance and science prospects. *Sol. Phys.* 295, 139 (2020). DOI: 10.1007/s11207-020-01712-1
[14] Y.Q. Shi, L.S. Li, J.W. Chen et al., Design of the solar X-ray detector for the macau science satellite-1B. *Earth Planet Phys.* 7, 125–130 (2023). DOI: 10.26464/epp2023018
[15] F. Zhang, H.Y. Wang, W.X. Peng et al., High resolution solar soft X-ray spectrometer. *Chin. Phys. C.* 36, 146–150 (2012). DOI: 10.1088/1674-1137/36/2/008
[16] F. Wei, S.J. Wang, J.B. Liang et al., Next generation Space Environment Monitor (SEM) for FY-2 satellite series.(in Chinese). *Chin. J. Geophys.* 56, 1–11 (2013) DOI: 10.6038/cjg20130101
[17] X.H. Fu, C.L. Li, G.L. Zhang et al., Data processing for the Active Particle-induced X-ray Spectrometer and initial scientific results from Chang' e-3 mission. *Res. Astron. Astrophys.* 14, 1595 (2014) DOI: 10.1088/1674-4527/14/12/008
[18] E.L. Chen, C.Q. Feng, S.B. Liu et al., Readout electronics for a high resolution soft X-ray spectrometer based on silicon drift detector. *Nucl. Sci. Tech.* 28, 14 (2016). DOI: 10.1007/s41365-
[19] J.X. Wen, X.T. Zheng, J.D. Yu, et al., Compact CubeSat Gamma-ray detector for GRID mission. *Nucl. Sci. Tech.* 32, 99 (2021). DOI: 10.1007/s41365-021-00937-4
[20] Y.P. Liu, P. Dang, X.B. Tang et al., Performance analysis of LYSO-SiPM detection module for X-ray communication during spacecraft reentry blackout. *Nucl. Instrum. Meth. A* 1013, 165673 (2021). DOI: 10.1016/j.nima.2021.165673
[21] J.J. Wei, J.H. Guo, Y.M. Hu et al., Characterization of silicon microstrip sensors for space astronomy. *Nucl. Sci. Tech.* 31, 97 (2020). DOI: 10.1007/s41365-020-00811-9
[22] Y.X. Cui, X. Li, S. Wang et al., Simulation of DAMPE silicon microstrip detectors in the Allpix2 framework. *Instrum. Meth. A* 1057, 1168685 (2023). DOI: 10.1016/j.nima.2023.168685
[23] Y. Tan, X.L. Cao, W.C. Jiang et al., In-orbit performance of ME onboard Insight-HXMT in the first 5 years. *Radiat. Detect. Technol. Methods* 7, 15–24 (2023). DOI: 10.1007/s41605-023-00395-z
[24] Y.G. Ye, H. Zou, Y.F. Wang et al., A cross-type imaging electron spectrometer. *Sci. China Tech. Sci.* 66, 641–653 (2023). DOI: 10.1007/s11431-022-2103-7
[25] Y.H. Guo, S.W. Peng, F. Wei et al., Design and simulation of Soft X-Ray imager on SMILE satellite (in Chinese). *Chin. J. Geophys.* 61, 4348–4355 (2018). DOI: 10.6038/cjg2018L0734
[26] Y. Chen, W.W. Cui, W. Li et al., The Low Energy X-ray telescope (LE)

onboard the Insight-HXMT astronomy satellite. *Sci. China Phys. Mech. Astron.* 63, 249505 (2020). DOI: 10.1007/s11433-019-1469-5
[27] C.Zhang, Z.X. Ling, X.J. Sun et al., First Wide Field-of-view X-Ray Observations by a Lobster-eye Focusing Telescope in Orbit. *Astrophys. J. Lett.* 941, L2 (2022). DOI: 10.3847/2041-8213/aca32f
[28] H. Spieler, *Semiconductor detector systems.* (Oxford, Oxford University Press, 2005), pp. 1–42.
[29] B.Q. Zhang, F. Wei, S. Leng et al., Effect on characteristic of silicon drift detector by electron exposure (in Chinese). *J. Beijing Univ. Aeronaut. Astronaut.* 39, 235–238, (2013).
[30] E.D. Monte, Y. Evangelista, E. Bozzo et al., The effect of the displacement damage on the charge collection efficiency in silicon drift detectors for the LOFT satellite. *J. Instrum.* 10, P05002 (2015). DOI: 10.1088/1748-0221/10/05/P05002
[31] M. Shanmugam, Y.B. Acharya, S.V. Vadawale et al., Radiation effects on Silicon Drift Detector based X-ray spectrometer onboard Chandrayaan-2 mission. *J. Instrum.* 10, P09005 (2015). DOI: 10.1088/1748-0221/10/09/P09005
[32] M. Shanmugam, S.V. Vadawale, A. Patel et al., Investigation of radiation damage due to particle irradiation on Silicon Drift Detector for Chandrayaan-2 mission. *J. Instrum.* 15, P01002 (2020). DOI: 10.1088/1748-0221/15/01/P01002
[33] G. Prigozhin, K. Gendreau, J.P. Doty et al., NICER instrument detector subsystem: description and performance. In: Herder J A., Takahashi T, Bautz M, eds. *Proceedings of Space Telescopes and Instrumentation 2016: Ultraviolet to Gamma Ray*, Edinburgh, United Kingdom, 9905, 99051I (2016). DOI: 10.1117/12.2231718
[34] G. Blaj, C.J. Kenney, A. Dragone et al., Optimal pulse processing, pile-up decomposition, and applications of silicon drift detectors at LCLS. *IEEE Trans. Nucl. Sci.* 64, 2854–2868 (2017). DOI: 10.1109/TNS.2017.2762281
[35] G. Prigozhin, K. Gendreau, R. Foster et al., Characterization of the silicon drift detector for NICER instrument. In: Holland A D, Beletic J W, eds. *Proceedings of High Energy, Optical, and Infrared Detectors for Astronomy V*, Amsterdam, Netherlands, 8435, 845318 (2012). DOI: 10.1117/12.926667
[36] R.H. Redus, A.C. Huber, D.J. Sperry, Dead time correction in the DP5 digital pulse processor. In: *IEEE Nuclear Science Symposium Conference Record*, Dresden, Germany, 3416–3420 (2008). DOI: 10.1109/NSSMIC.2008.4775075
[37] S. Usman, A. Patil, Radiation detector deadtime and pile up: A review of the status of science. *Nucl. Eng. Technol.* 50, 1006–1016 (2008). DOI: 10.1016/j.net.2018.06.014

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