

Postprint of Calibration Testing for the Neutral Atom Imager

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Abstract

Neutral Atom Imager (NAIS-H) acquires high spatiotemporal resolution images that provide panoramic spatial particle distribution data for research on various mechanisms of geomagnetic storms and substorm processes in Earth' s space; it provides important data support for MIT scientific research missions such as magnetosphere-ionosphere coupling and magnetospheric energy dissipation. Detector calibration is an important technical step in the development process; it serves as the fundamental basis for future space detection data analysis and inversion.

Full Text

Calibration Testing of the Neutral Atom Imager

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The high temporal-spatial resolution images obtained by the Neutral Atom Imager (NAIS-H) provide panoramic spatial particle distribution data for studying various mechanisms of geomagnetic storms and substorms in Earth' s space environment, and offer crucial data support for MIT (Magnetosphere-Ionosphere-Thermosphere) scientific research tasks such as magnetosphere-ionosphere coupling and magnetospheric energy dissipation. Detector calibration constitutes a critical technical step in the instrument development process and serves as the fundamental basis for subsequent space detection data analysis and inversion.

Keywords: Energetic Neutral Atoms; Complete energy spectrum; Full Width at Half Maximum (FWHM); ADC threshold

The Neutral Atom Imager (NAIS-H) acquires high temporal-spatial resolution images that provide panoramic spatial particle distribution data for investigat-

ing various mechanisms and acceleration processes of geomagnetic storms and substorms, offering vital data support for MIT scientific research tasks including magnetosphere-ionosphere coupling and magnetospheric energy dissipation mechanisms [1]. Typical physics problems related to MIT scientific missions and NAIS-H detection data include:

- (1) Studying the evolution of the ring current during the main phase of magnetic storms;
- (2) Investigating the decay process of the ring current;
- (3) Detecting the fine structure of the ring current during magnetic storms;
- (4) Exploring the coupling between the plasmasphere, ring current, and radiation belts;
- (5) Investigating the influence of magnetosphere-ionosphere coupling under extreme interplanetary conditions on ring current dynamics.

Calibration of the detector energy spectrum represents a crucial technical step in instrument development, providing a quantitative description of the detector and associated front-end circuits' response to incident particle energy signals. Equipment capable of serving as calibration test particle sources is limited; the ideal source would be an ion cyclotron accelerator operating in the energy ion range ($0.1 \text{ keV} < E < 300 \text{ keV}$), which can produce neutral atom beams of specific energies through charge exchange by injecting inert gas tangentially to the cyclotron orbit [2]. During the prototype development phase, we typically employ radiation sources, simulated signal sources, or charged particle accelerators for instrument calibration. This paper describes the use of a simulated signal source for energy spectrum calibration of the detector front-end electronics system in the NAIS-H prototype, followed by radiation test verification of the calibrated detector energy spectrum using an electron accelerator.

1. Working Principle of the Neutral Atom Imager

The Neutral Atom Imager consists of sensors, electronic circuits, and mechanical structures. The electronic system includes a charge-sensitive preamplifier, main amplifier, peak-hold circuit, DPU (Data Processing Unit), output interface circuit, sensor characteristic detection circuit, power supply monitoring circuit, high-voltage power supply, and secondary power supply.

As shown in Figure 1 [Figure 1: see original paper], the NAIS-H employs 30 semiconductor sensors equally spaced across a radial 180° field of view, covering the full 4 solid angle through satellite spin. Within one satellite rotation period, the detector samples 128 azimuthal angles, with the satellite spin period being 6 seconds. Consequently, the integration time per sample for NAIS-H is 46.875 ms. During each sampling integration interval, particles are accumulated and

stored in 8 energy channels according to their incident energy. The instrument can record up to 8 images per satellite spin period, with each image comprising $30 \times 128 = 3840$ pixels.

The instrument sensor outputs charge pulse signals, which are converted to voltage signals by the charge-sensitive preamplifier. The preamplifier output signals pass through a pulse shaping circuit and are then further amplified by the main amplifier to facilitate acquisition and processing by the DPU unit. The DPU collects particle energy pulse heights and flux counts, performs pixel segmentation based on sensor identification and time-division signals, and outputs neutral atom imaging data.

2. Calibration Testing of the Neutral Atom Imager

The objective of pixel energy threshold calibration is to determine the instrument's energy channel division thresholds through calibration, providing a basis for setting pixel energy thresholds. The NAIS-H electronics have already performed pixel energy channel division according to scientific requirements and physical design specifications (Table 1). To obtain the thresholds for pixel energy channel division, calibration of both sensors and electronics is required.

Table 1: Energy Channel Settings for the Neutral Atom Imager
H (keV) | O (keV)

The optimal calibration source for pixel energy threshold calibration is an accelerator system capable of providing monoenergetic proton beams, which can equivalently simulate neutral hydrogen atom incidence when the imager's deflection high-voltage electric field is disabled. Due to limitations in accelerator calibration conditions, we first conducted sensor testing and electronics simulation calibration, followed by verification testing using relevant particle beams from an electron accelerator.

2.1 Simulation Calibration Principle

The Neutral Atom Imager comprises sensors and electronic circuits; therefore, the fundamental principle of electronics simulation calibration involves using electronic pulses to simulate accelerator-generated beams, achieving detector energy threshold calibration through separate calibration of sensors and electronic circuits. For pixel energy threshold calibration, the first step is to measure the sensor's actual thickness and dead layer information. Monte Carlo simulations then calculate the energy deposition value of particles in the sensor corresponding to each energy threshold, which serves as the pixel energy channel division threshold. Subsequently, a simulated signal source (pulse generator) emulates the pulse signals produced by this deposited energy in the sensor. The NAIS-H, operating in calibration mode, acquires the complete energy spectrum of the signals, and data processing yields the spectral peak channel, which corresponds to the pixel energy threshold. Simultaneously, the full width at half

maximum (FWHM) of the spectrum is recorded to calculate the instrument' s energy resolution at that energy point.

The basic principle of using a simulated signal source (pulse generator) to emulate particle energy deposition in the sensor is as follows: particles lose energy in the sensor, generating charge signals proportional to the energy loss, which are then collected by the electronics. The simulation approach replicates the charge signals produced by particles in the sensor, accomplished through a pulse generator and input capacitor. Assuming a particle of definite energy produces energy loss E in the sensor, the resulting charge quantity Q is given by:

$$Q = \frac{E \cdot e}{\varepsilon}$$

where e is the elementary charge and ε is the average energy required to create an electron-hole pair. Using the pulse generator voltage (U) and input capacitance (C), the formula $Q = CU$ can simulate the charge signal corresponding to particle energy loss in the sensor. By selecting appropriate capacitance and pulse height values, it becomes possible to simulate energy deposition from particles across different energy ranges.

Assuming the energy at the i -th boundary point of the NAIS-H energy channels is E_i , and the corresponding converted voltage pulse height is V_i , the instrument acquires the complete energy spectrum when the pulse generator pulse height is V_i . Through spectral analysis, the spectral peak N_i is obtained as the threshold for the i -th energy channel, and the spectral half-width FWHM is recorded to determine the instrument' s energy resolution at that energy point:

$$\lambda = \frac{\text{FWHM}}{N_i}$$

The detector' s response in each energy channel under no-signal conditions reflects the background noise level, which defines the anti-interference capability and measurement precision.

2.2 Simulation Calibration Testing

The semiconductor sensor thickness is 300 μm . Monte Carlo simulations calculate particle energy loss in the sensor, presented in Table 2 , which serves as simulation input for energy channel range and precision calibration in electronics simulation calibration.

Table 2: Energy Channel Deposition Energy
Incident H Energy (keV) | Actual Deposited Energy (keV)

Simulation calibration results primarily include two components: energy channel threshold calibration and energy resolution calibration. We used a signal gener-

ator to sequentially simulate equivalent deposited energy signals corresponding to each energy channel, with a generator frequency of 1000 Hz.

Figure 2 [Figure 2: see original paper] presents the complete energy spectrum acquired from simulated signals of incident hydrogen atoms with energies of 40–300 keV, with the horizontal axis representing signal amplitude corresponding to ADC acquisition results and the vertical axis showing event statistics. Gaussian fitting (red curve in Figure 2) yields the spectral peak and full width at half maximum (FWHM), enabling calculation of the energy resolution corresponding to each energy channel.

Figure 3 [Figure 3: see original paper] shows the relationship curve between simulated incident particle energy and ADC threshold for simulated deposited energy, with the horizontal axis representing equivalent energy in keV and the vertical axis representing ADC sampling values.

The simulation calibration results are summarized in Table 3. Through simulation calibration, we obtained the ADC thresholds and energy resolutions for each energy channel of NAIS-H, which will serve as the basis for FPGA threshold settings in the instrument.

Table 3: Simulation Calibration Results

H Atom Energy Channel Threshold (keV) | Simulated Deposited Energy (keV)
| Energy Channel ADC Threshold | Energy Resolution
12.4% | 17.0% | 16.5% | 8.85% | 5.66% | 3.30% | 2.12% | 2.12%

2.3 Electron Accelerator Verification

Due to the lack of suitable proton accelerator test facilities domestically, an electron accelerator was employed for simulation testing. On December 25, 2015, accelerator calibration tests for the Neutral Atom Imager were conducted at the Huairou campus of the National Space Science Center, Chinese Academy of Sciences. The accelerator outputs high-energy electrons with continuously adjustable energy ranging from 100 keV to 2 MeV. Testing was performed according to energy channel division requirements, with partial test results shown in Figure 4 [Figure 4: see original paper]. Verification test results are presented in Figure 5 [Figure 5: see original paper] and Table 4.

Figure 4: Electron accelerator test signal energy spectrum for injected electron energies of 100–276 keV, with the horizontal axis representing signal amplitude corresponding to ADC acquisition results and the vertical axis showing event statistics; the red curve represents the Gaussian fit.

Figure 5: Fitting results of accelerator calibration energy spectrum response curve

Table 4: Accelerator Test Results for the Neutral Atom Imager

H Atom Energy E (keV) | Injected Electron Energy E (keV) | Fitted Spectral

Peak Position A | Energy Resolution
7.25% | 5.66% | 4.24% | 5.94%

3. Calibration Conclusions for the Neutral Atom Imager

Due to limitations in calibration test conditions, only electronics simulation calibration and partial energy channel verification tests using an electron accelerator have been performed on NAIS-H. From the two calibration result curves (Figures 3 and 5), both the instrument's electronics and sensors exhibit excellent linear characteristics within the calibrated energy range. Simulation calibration can effectively reflect the instrument's measurement linearity and energy response function; however, the actual instrument also suffers from sensor parameter errors and discrepancies between theoretical and actual values of particle-sensor interactions, among other factors. Therefore, proton accelerator calibration is required to refine the energy response function obtained from simulation calibration. Future ion accelerator calibration tests should be conducted when ion accelerator facilities become available.

Acknowledgments

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Abstract

The Neutral Atom Image System with High energetic particles (NAIS-H) developed for a Chinese mission of Magnetosphere Ionosphere and Thermosphere (MIT) is capable of obtaining the global map of plasma distribution with high temporal-spatial resolution in support of this mission. The calibration of the

detector was an important technical task in the development, which is the fundamental basis of data analysis and inversions.

Keywords: ENA; Complete energy spectrum; FWHM; ADC threshold

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

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