A Satellite-borne Miniature Ion Mass Spectrometer for Space Plasma Postprint

Authors: KONG Linggao, ZHANG Aibing, ZHENG XiangZhi, AN YaYa, WANG WenJing, TIAN Zhen, GUAN Yibing, LIU Chao, DING JianJing, Sun Yueqiang

Date: 2017-01-22T00:00:00+00:00

Abstract

The miniature design technology is an important trend in space exploration. Mass spectrometer is used extensively in the space environment detection. The miniature ion mass spectrometer utilizes a 127° cylindrical electrostatic analyzer accompanied with a Time of Flight(TOF) unit based on ultrathin carbon foil to measure the energy spectra and composition of space plasma. The Time of Flight technique has been used broadly in space plasma measurement. A new type of miniature method for the ion mass spectrometer is introduced. The total mass of the instrument is 1.8 kg and the total power consumption is 2.0 W. The calibration results show that the energy measurement range is 8.71~43550eV, the energy resolution is 1.86% and the ion mass from 1 amu(1 amu =1.67 x 10~(-27) kg) to 58 amu can be resolved by the miniature mass spectrometer. The miniature ion mass spectrometer also has a potential to be increased in the field of view by an electrostatic deflecting system to extend its application in space plasma detection. The miniature ion mass spectrometer has been selected for pre-study of Chinese Strategic Priority Research Program on Space Science.

Full Text

Preamble

A Satellite-borne Miniature Ion Mass Spectrometer for Space Plasma

Linggao Kong, Aibing Zhang, Xiangzhi Zheng, Yaya An, Wenjing Wang, Zhen Tian, Yibing Guan, Chao Liu, Jianjing Ding, Yueqiang Sun
National Space Science Center, Chinese Academy of Sciences, Beijing, 100190, China

Abstract

Miniaturization is a critical trend in space exploration, and mass spectrometers are extensively used for space environment detection. This miniature ion mass spectrometer employs a 127° cylindrical electrostatic analyzer coupled with a time-of-flight unit based on an ultrathin carbon foil to measure the energy spectra and composition of space plasma. The time-of-flight technique has been widely adopted in space plasma measurements due to its high performance, excellent mass resolution, and reduced mass. This paper reports a novel miniature design approach for an ion mass spectrometer. The instrument has a total mass of 1.8 kg and power consumption of 2.0 W. Calibration results demonstrate an energy measurement range of 8.71 eV to 43.55 keV, an energy resolution of 1.86%, and the ability to resolve ion masses from 1 amu to 58 amu. The miniature ion mass spectrometer also has the potential to increase its field of view through an electrostatic deflecting system, extending its applicability in space plasma detection. The instrument has been selected for pre-study under the Chinese Strategic Priority Research Program on Space Science.

Keywords: Satellite-borne; Miniature; Mass Spectrometer; Space Plasma

0 Introduction

Mass discrimination is a fundamental requirement for space particle exploration, particularly for space plasma ions. Common methods for determining ion mass in space particle instruments fall into two categories: spatial separation and temporal separation. Spatial separation typically utilizes electromagnetic fields, including static magnetic fields alone, combined magnetic and electric fields, and radio-frequency electric fields. Temporal separation employs time-of-flight measurements over a fixed flight path. Wüst provides a comprehensive review of typical ion mass discrimination methods [1]. In recent years, the time-of-flight method has become the most widely used technique in space exploration due to its high performance, excellent mass resolution, and lower mass requirements. Reviews of time-of-flight methods in space exploration can be found in works by Wüst [2] and Gloeckler [3]. Representative space missions employing time-of-flight techniques include MAVEN, STEREO, CLUSTER, CASSINI, SOHO, SELENE, CHANDRAYAAN-1, and YINGHUO-1 [4-11].

Time-of-flight mass spectrometers for space environment exploration typically consist of a front-end energy analyzer and a mass-resolving time-of-flight section. The front-end for ion instruments is generally some form of electrostatic analyzer (ESA) to determine the energy per charge (E/Q) of incident ions. The time-of-flight section measures ion velocity (v). Combining E/Q and v enables determination of mass per charge (M/Q). The two major types of electrostatic analyzers are cylindrical and spherical. Compared to spherical analyzers, cylindrical electrostatic analyzers offer simpler and more compact structures, making them well-suited for miniature mass spectrometer designs [12]. Their primary disadvantage is a much smaller intrinsic field of view, which can be addressed by adding an electrostatic deflector in front of the analyzer aperture to increase the field of view, as implemented in the miniature plasma instruments on Chandrayaan-1 and Yinghuo-1. Miniature cylindrical electrostatic analyzers are thus frequently employed on satellites with severely limited mass and power resources.

Time-of-flight systems can be categorized into two types: those based on ultrathin carbon foils and those based on multilayer reflecting coatings. The carbon foil type is more commonly used with top-hat spherical electrostatic analyzers and typically requires high voltage (above 15 kV) for post-acceleration to ensure ions have sufficient energy to transmit through the foil. Multilayer reflecting coatings are primarily used with cylindrical electrostatic analyzers in miniature mass spectrometers [12].

Mass spectrometer designs can be adapted according to varying requirements for temporal, spatial, and mass resolution. However, given spacecraft resource constraints, space instruments must be smaller, lighter, and consume less power, making miniaturization an important trend in space exploration [13]. This paper reports for the first time the use of an ultrathin carbon foil behind a cylindrical electrostatic analyzer in a miniature ion mass spectrometer.

1 Instrument Description

The miniature ion mass spectrometer comprises two main parts: the sensor assembly and the electronics unit.

The sensor assembly consists of a 127° cylindrical electrostatic analyzer (ESA) and a time-of-flight (TOF) unit.

1.1 Electrostatic Analyzer

The 127° cylindrical electrostatic analyzer provides superior focusing of particle trajectories at the ESA exit [12, 14, 15]. For space applications, solar photons can cause serious contamination in plasma instruments. Photons undergo at least two reflections within the electrostatic analyzer with the large 127° deflection angle, which effectively mitigates photon contamination and improves particle measurement quality. The instrument schematic is shown in Figure 1 [Figure 1: see original paper], and a mechanical drawing appears in Figure 2 [Figure 2: see original paper].

The 127° cylindrical electrostatic analyzer consists of two concentric semicylinders with an inner diameter of 100 mm and an outer diameter of 106 mm. The cylinder height is 16 mm. Entrance and exit apertures at the front and back of the analyzer collimate ion trajectories, each measuring 1 mm × 2 mm.

To establish an electric field for ion energy analysis, the inner cylinder is supplied with a 64-step sweeping high voltage from -1 V to -5000 V on a logarithmic scale. One complete waveform cycle is illustrated in Figure 3 [Figure 3: see original paper], while the outer cylinder is grounded, creating a uniform electric field between the cylinders.

Ions enter the electrostatic analyzer through the entrance aperture, and their energy is analyzed by this electric field. Only ions with energies satisfying Equation 1 can exit through the exit aperture. In this equation, E represents the energy of ions that successfully pass through the electrostatic analyzer, V is the sweeping high voltage applied to the inner cylinder, k is the electrostatic analyzer constant (k-factor), and q is the ion charge.

1.2 Time-of-Flight Unit

Before entering the time-of-flight unit, ions are accelerated by a post-acceleration voltage U__ACC of 15 kV applied to the TOF unit housing. This acceleration provides ions with sufficient energy to transmit through the ultrathin carbon foil (~9 nm) and generate secondary electrons. The carbon foil was purchased from Arizona Foil Company (AFC) in the USA. Ions lose energy E__loss when interacting with the carbon foil, with E__loss varying according to ion energy and mass. Secondary electrons are directed to strike the start microchannel plates (MCPs), generating the start signal. After passing through the carbon foil, ions continue flying until they strike the stop MCPs, generating the stop signal. The time interval between start and stop signals defines the time of flight . The flight length d is the 30 mm distance between the carbon foil and the MCP surface. For a given ion species, the energy of transmitted ions can be determined from the ESA, acceleration voltage, and energy loss theory. Thus, mass per charge (M/q) depends only on the time of flight , as given by Equation 2.

The electronics unit comprises a preamplifier unit, time-to-amplitude converter (TAC) unit, high-voltage unit, housekeeping monitor unit, field-programmable gate array (FPGA) unit, power supply unit, and interface unit. The high-voltage unit supplies power to the ESA, TOF electrodes, and MCPs. Charge pulses from the MCPs, collected by anodes behind them, are amplified by preamplifiers. The TAC unit measures the time of flight. The housekeeping monitor unit tracks parameters for instrument health monitoring. The FPGA unit controls instrument operation, while the interface unit handles communication with peripheral equipment. The instrument operating principle is illustrated in Figure 4 [Figure 4: see original paper].

Figure 5 [Figure 5: see original paper] shows a photograph of the ion mass spectrometer prototype (without the top cover). The instrument volume is 170 mm × 150 mm × 136 mm, with a total mass of 1.8 kg and power consumption of 2.0 W.

2 Calibration Facility Description

The ion mass spectrometer was calibrated using a high-quality, stable ion beam facility under construction at the National Space Science Center, Chinese

Academy of Sciences. The ion source was imported from Peabody Scientific, USA, with subsequent modifications made in China. The ion beam' s intensity, energy, and species are adjustable. The experimental layout is shown in Figure 6 [Figure 6: see original paper].

The ion mass spectrometer was mounted on a platform such that the ion beam fully illuminated the instrument aperture. To ensure safe operation of the high voltages for both the ion source and mass spectrometer, the ion source, instrument, and platform were placed under high vacuum (~1.0×10 Pa). A photograph of the calibration facility appears in Figure 7 [Figure 7: see original paper].

The calibration facility specifications are listed in Table 1 .

Table 1 Specification parameters of the calibration facility

Parameter	Value
Beam energy range (adjustable)	100 eV–30 keV
Beam flux (adjustable)	10^3–10^1 cm ^{2}s ^{1}
Beam diameter	H , H , He , N , Ar
Ion species	

3 Calibration Results

The calibration aimed to determine the key performance parameters of the ion mass spectrometer, including the ESA k-factor, energy resolution, ion mass range, and mass resolution.

3.1 K-factor and Energy Resolution

For each measurement case, the ion beam' s energy, intensity, and species were fixed while a sweeping high voltage range was selected to match the beam energy. The instrument response was recorded as start counts, stop counts, and valid time-of-flight spectra versus time. The start signal counts for 20 keV H are shown as asterisks in Figure 8 [Figure 8: see original paper], with the solid curve representing the Gaussian fit to the measurement data. The sweeping high voltage value V__c at maximum count corresponds to the beam energy of 20 keV. From Equation 1, the ESA constant (k-factor) equals the beam energy divided by V__c. The instrument' s energy resolution is defined as FWHM/V__c, where FWHM is the full width at half maximum. In theory, the k-factor and energy resolution are independent of ion species and beam energy.

The instrument was characterized at four energy points: 4.8 keV, 9.5 keV, 15.3 keV, and 19.7 keV. The k-factor was determined by fitting Equation 1 to these measurement points using a least-squares method, as shown in Figure 9 [Figure 9: see original paper]. The slope of the fitted line gives a k-factor of 8.71. Given the ESA high-voltage supply range of 1 V to 5000 V, the instrument’ s energy range is 8.71 eV to 43.55 keV (Equation 1).

Energy resolution values at the four measurement points are listed in Table 2 , yielding an average energy resolution of 1.86%.

Table 2 Energy resolution at four measurement points

Energy (keV)	Energy resolution
4.8	1.86%
9.5	1.87%
15.3	1.86%
19.7	1.84%
Average	**1.86%**

Theoretical calculations based on the cylindrical ESA geometry predict a k-factor of 8.58 and energy resolution of 1.94%, which are consistent with the calibration results.

3.2 Mass Range and Mass Resolution

Another important calibration objective was to determine the mass-per-charge range and resolution. Based on the operating principle shown in Figure 1, the time of flight for a given mass per charge depends only on the total energy (the sum of ion beam energy and post-acceleration energy). To compare results across different mass-per-charge values, the total energy was fixed at 22.7 keV/q throughout calibration. Figure 10 [Figure 10: see original paper] shows the time-of-flight spectrum for 22.7 keV H (M/q=1), H (M/q=2), He (M/q=4), and Ar (M/q=40). The results demonstrate that major ions from 1 amu to 40 amu are clearly resolved.

The upper mass limit is generally determined by the TAC circuit’ s time-of-flight range and the total ion energy after post-acceleration. The TAC circuit can measure time-of-flight values up to 1 ms, so it does not limit the upper mass range. Based on ESA calibration results, the total ion energy after post-acceleration is approximately 58 keV. For the 9 nm carbon foil used in this instrument, ions require at least ~1 keV/amu to penetrate the foil and generate sufficient secondary electrons [16]. Consequently, the maximum measurable mass is 58 amu, giving a mass range of 1–58 amu.

Both theory and the results in Figure 10 show that lighter ions exhibit better mass-per-charge resolution. For ions with $M/q < 4$, the mass-per-charge resolution ($\Delta M/M$) is approximately 0.5.

The mass-per-charge resolution is determined by several factors: (1) energy resolution of the electrostatic analyzer; (2) time-of-flight dispersion due to angular spread of ion trajectories from straggling in the carbon foil; (3) time-of-flight dispersion from energy straggling in the carbon foil; (4) time-of-flight dispersion from secondary electron noise; and (5) electronic noise [2].

The time-of-flight spectrum in Figure 10 shows crosstalk between adjacent peaks, likely due to the effects listed above. The dominant contribution is probably secondary electron noise, as no secondary electron trapping measures were implemented in this miniature design.

4 Conclusion and Discussion

The miniature ion mass spectrometer features very low mass and power consumption, making it suitable for small satellite platforms. The instrument maintains good energy measurement range and mass separation capabilities.

Key performance characteristics are summarized in Table 3 .

Table 3 Basic instrument characteristics

Parameter	Value
Energy range	8.71 eV–43.55 keV
k-factor	8.71
Energy resolution (ΔE/E)	1.86%
Mass range	1–58 amu
Mass resolution (ΔM/M)	0.5 (@ M/q < 4)

The miniature ion mass spectrometer employs a conventional cylindrical electrostatic analyzer and ultrathin carbon foil time-of-flight technique. To improve mass resolution, future work should implement measures such as secondary electron traps to mitigate secondary electron effects.

The calibration facility was still under development during the calibration campaign. The turntable and large vacuum chamber were not yet operational, so the field of view was not calibrated. This will be completed once facility upgrades are finished. Typically, space plasma measurements require a large field of view (~2 sr). The instrument described here has a small field of view (~2°×2°) according to simulations, but this can be expanded to 2 sr using an electrostatic deflector in front of the ESA entrance aperture, a technique successfully employed in other missions.

Future work on the ion mass spectrometer should focus on: (1) improving the time-of-flight unit to enhance mass resolution, and (2) implementing measures to enlarge the instrument' s field of view. With these improvements, the miniature ion mass spectrometer will have excellent prospects for space plasma measurements.

This work was supported by the Strategic Priority Research Program on Space Science of the Chinese Academy of Sciences (Grant Nos. XDA04071700, XDA04060202).

References

1. Wüst, M., David, S. E., & Rudolf, V. S. (2007). *Calibration of Particle Instruments in Space Physics*. Netherlands: ESA Publications Division, p. 51.

2. Wüst, M. (1998). Time-of-flight ion composition measurement technique for space plasmas. In R. Pfaff, J. Borovsky, & D. T. Young (Eds.), *Measurement Techniques for Space Plasmas: Particles* (Geophysical Monograph Series, Vol. 102, pp. 141–155). Washington, DC: American Geophysical Union.

3. Gloeckler, G. (1990). Ion composition measurement techniques for space plasmas. *Review of Scientific Instruments*, 61(11), 3613–3620.

4. Bougher, S. W., Cravens, T. E., Grebowsky, J., et al. (2014). The aeronomy of Mars: Characterization by MAVEN of the upper atmosphere reservoir that regulates volatile escape. *Space Science Reviews*, doi:10.1007/s11214-014-0053-7.

5. Galvin, A. B., Kistler, L. M., Popecki, M. A., et al. (2008). The plasma and suprathermal ion composition (PLASTIC) investigation on the STEREO observatories. *Space Science Reviews*, 136, 437–486.

6. Rème, H., Bosqued, J. M., Sauvaud, J. A., et al. (1997). The cluster ion spectrometry (CIS) experiment. *Space Science Reviews*, 79, 303–350.

7. Young, D. T., Berthelier, J. J., Blanc, M., et al. (2004). Cassini plasma spectrometer investigation. *Space Science Reviews*, 114, 1–112.

8. Hovestadt, D., Bochsler, P., Grunwaldt, H., et al. (1995). The charge, element, and isotope analysis system CELIAS on SOHO. *Solar Physics*, 162, 441–481.

9. Yoshifumi, S., Shoichiro, Y., Kazushi, A., et al. (2010). In-flight performance and initial results of plasma energy angle and composition experiment (PACE) on SELENE (Kaguya). *Space Science Reviews*, 154, 265–303.

10. Bhardwaj, A., Barabash, S., Sridharan, R., et al. (2010). Solar wind monitoring with SWIM-SARA onboard Chandrayaan-1. In S. S. Hasan & R. J. Rutten (Eds.), *Magnetic Coupling between the Interior and Atmosphere of the Sun* (Astrophysics and Space Science Proceedings, Part 4, pp. 531–532). Berlin Heidelberg: Springer.

11. Li, L., Wang, S. J., Zhang, A. B., et al. (2008). The plasma experiment of the YH-1 mission. In J. C. Fang & Z. Y. Wang (Eds.), *Seventh International Symposium on Instrumentation and Control Technology: Optoelectronic Technology and Instruments, Control Theory and Automation, and Space Exploration* (Proceedings, Vol. 7129, p. 7129-96). Beijing.

12. McCann, D., Barabash, S., Nilsson, H., et al. (2007). Miniature ion mass analyzer. *Planetary and Space Science*, 55(9), 1190–1196.

13. Young, D. T. (1998). Space plasma particle instrumentation and the new paradigm: Faster, cheaper, better. In R. Pfaff, J. Borovsky, & D. T. Young (Eds.), *Measurement Techniques for Space Plasmas: Particles* (Geophysical Monograph Series, Vol. 102, pp. 1–16). Washington, DC: American Geophysical Union.

14. Oshima, C., Souda, R., Aono, M., et al. (1985). Optimum angle of deflection electrodes of a cylindrical electrostatic analyzer. *Review of Scientific Instruments*, 56(2), 227–230.

15. Kong, L. G., Zhang, A. B., Wang, S. J., et al. (2012). Numerical simulation analysis of space plasma detector based on SIMION. *Chinese Space Science and Technology*, 32(4), 71–76.

16. Allegrini, F., Wimmer-Schweingruber, R. F., Wurz, P., & Bochsler, P. (2003). Determination of low-energy ion-induced electron yields from thin carbon foils. *Nuclear Instruments and Methods in Physics Research B*, 211, 487–494.

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

Source: ChinaXiv —Machine translation. Verify with original.