

In-orbit Validation of SEM-II onboard FengYun-3E

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Abstract The new generation of space environment monitor (SEM), SEM-II, onboard the Chinese meteorological satellite, FengYun-3E, has the abilities to measure the charged particles flux with the particle energy from 30 eV to 300 MeV in multi-directions, the satellite surface potential, the radiation dose in sensors, and the geomagnetic field variations. The space environment detections derived from SEM-II can be utilized for satellite security designs, scientific studies, development of radiation belt models, and space weather event monitoring or disaster warning. In this paper, we introduce the SEM-II's instrument characteristics, interpret the in-orbit calibration algorithm, perform the quantitative test to check the particle and the magnetic field detections' biases by the cross-calibration methods, and do the qualitative test to check if the radiation dose and the surface potential detections follow the nature law of space environment by comparing with the historical records. The results show that the uncertainties of the particle detections are less than 20%, the uncertainties of the magnetic field detections are about 1%, the radiation dose and the surface potential detections are coincide with the historical records and the space environment knowledge. The instruments' responses to the space weather events are also presented.

Key words FengYun-3E, Space Environment, Radiation Effects, Energetic Particles, Space Technology

Classified index V524.3

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1. Introduction

The space environment monitor-II (SEM-II) onboard FengYun-3E (FY-3E) meteorological satellite is an update version of the SEM-I onboard the previous FY-3 series satellites^[1-3]. FY-3E was successfully launched into orbit on July 5, 2021, which is the new Chinese operational

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meteorological satellite in Sun-synchronous polar circle Low-Earth-Orbit (LEO, about 830 km) with a 98° inclination, covering the dawn-dusk orbit. SEM-II booted up on July 10, 2021 and keeps in normal operation so far. This new generation of SEM, SEM-II, has the new abilities to measure the charged particles flux with the particle energy from 30 eV to 300 MeV in multi-directions, the satellite surface potential, the radiation dose in sensors, and the geomagnetic field variations. The measurements of the space radiation environment can be used in the area of satellite security designs, scientific studies, development of radiation belt models, space weather event monitoring or disaster warning, and the supporting for the Chinese manned spaceflight missions^[1].

In the period from July to December, 2021, we performed the in-orbit test of SEM-II to check the particle and the magnetic field detections' biases by the cross-calibration methods and if the radiation dose and the surface potential detections follow the nature law of space environment by comparing with the historical records. In this paper, we introduce the SEM-II's instrument characteristics in Section 2, demonstrating the calibration algorithm in Section 3, presenting the results of the in-orbit test in Section 4, and the conclusion and discussion are made in Section 5.

2. Instruments Description

FY-3E is observing the Earth from the Sun-synchronous orbit and passing the ascending node at LT (Local Time) 1740 and the descending node at LT 0540. The orbital period is about 102 minutes with the approximate altitude at 830 km. The SEM-II onboard FY-3E has the capacities to measure the flux of charged particles (protons and electrons) into the upper atmosphere, detect the geomagnetic field, and monitor the satellite surface potential and radiation dose in sensors.

It should be noted that, in FY-3E's satellite coordinate system, X is in the direction of the satellite velocity, Z is the direction to the Earth centre, Y is perpendicular to the XZ plane and points to the night side.

Table 1 The Instruments' Specifications of Fy-3E/SEM-II

Instrument Name	Observation Object	Installation Geometry	Sampling Rate	Sensitivity	Channels
High Energy Particles Detector	Integrated particle flux	3 directions in – X/Y/-Z with each direction's view field $\sim 40^\circ$	0.5 Hz	5% ($\Delta N/N$)	6 energy bands for proton in 3-300 MeV; 5 energy bands for electron in

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					0.15-5.7 MeV
Medium Energy Proton Detector	Integrated proton flux	18 directions with each direction's view field $\sim 20^\circ$	0.5 Hz	5% ($\Delta N/N$)	12 energy bands for proton in 30 keV-5000 keV
Medium Energy Electron Detector	Integrated electron flux	18 directions with each direction's view field $\sim 20^\circ$	0.5 Hz	5% ($\Delta N/N$)	8 energy bands for electron in 30 keV-600 keV
Radiation Dose Detector	Total radiation dose	3 probes installed on the interior surface of the outer wall of the satellite in X/Y/-Z	1/60 Hz	2 rad (Si)	Each probe has 2 channels: one's range is for 3×10^4 rad(Si), the other's range is for 5×10^3 rad(Si)
Surface Potential Detector	Surface potential	Relative Surface Potential Detector (RSPD) has 2 detectors: one faces to the night side, the other faces to the day side; Absolute Surface Potential Detector (ASPD)'s detail can be found in section 2.1.5	0.5 Hz	<15 V	RSPD has 2 channels; ASPD's channels are illustrated in Fig.3
Magnetic Field Detector	Magnetic field	6 sensors deployed on the satellite's truss	50 Hz	0.1 nT	Each sensor has three orthogonal channels to detect the magnetic field vectors.

2.1. Particle Detectors

The particle detectors have passed the ground tests using accelerator and radiation source, and meet the calibration requirements from the simulation signals during the prelaunch period^[4].

2.1.1. High Energy Particles Detector (HEPD)

SEM-II HEPD has two groups of detectors for detecting proton and electron, respectively. Each

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group contains three directional detectors which are pointing to -X/Y/-Z directions in the satellite coordinate. The proton detectors can measure the proton flux in 6 energy bands: 3-5(P1), 5-10(P2), 10-26(P3), 26-40(P4), 40-100(P5), and 100-300(P6) MeV. The electron detectors can measure the electron flux in 5 energy bands: 0.15-0.35(E1), 0.35-0.65(E2), 0.65-1.20(E3), 1.20-2.00(E4), and 2.00-5.70(E5) MeV.

2.1.2. Medium Energy Proton Detector (MEPD)

SEM-II MEPD has the abilities to detect the medium energy proton flux in situ in 18 directions in the satellite coordinate (see the details in Fig. 1). The proton energy is from 30 keV~5 MeV in 12 energy bands: 30-48(P1), 48-80(P2), 80-120(P3), 120-170(P4), 170-240(P5), 240-350(P6), 240-350(P7), 350-500(P8), 500-800(P9), 800-1500(P10), 1500-3000(P11), 3000-5000(P12) keV. There are two parts in the MEPD design: low energy part and high energy part. The energy bands from P1 to P6 belong to low energy part while other energy bands belong to high energy part. The designers set P6 and P7 as the overlap channels (240-350 keV) to check the consistency of detection.

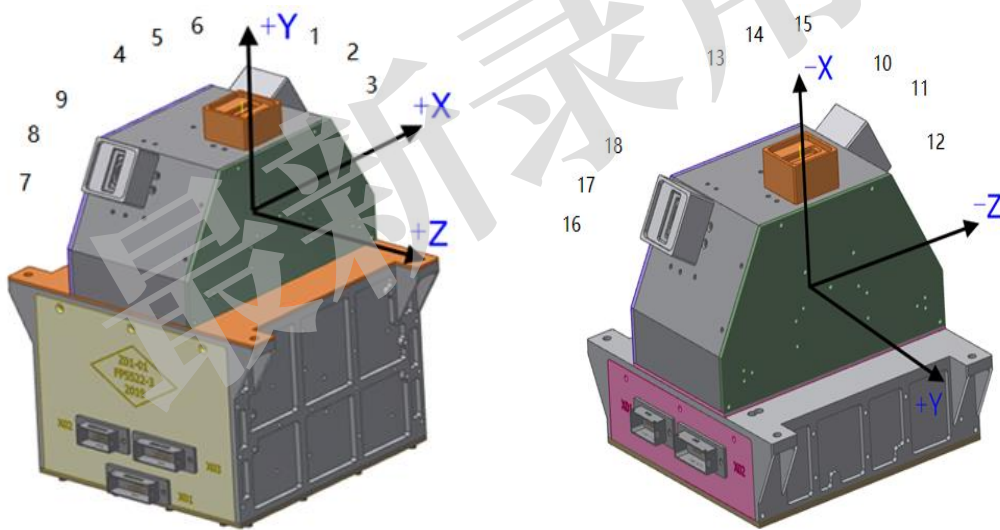


Fig. 1 SEM-II MEPD Directions Map

2.1.3. Medium Energy Electron Detector (MEED)

SEM-II MEED has the abilities to detect the medium energy electron flux in situ in 18 directions in the satellite coordinate (see the details in Fig. 2). The electron energy is from 30~400 keV in 8 energy bands: 30-40(E1), 40-60(E2), 60-90(E3), 90-130(E4), 130-190(E5), 190-280(E6), 280-410(E7), 410-600(E8) keV.

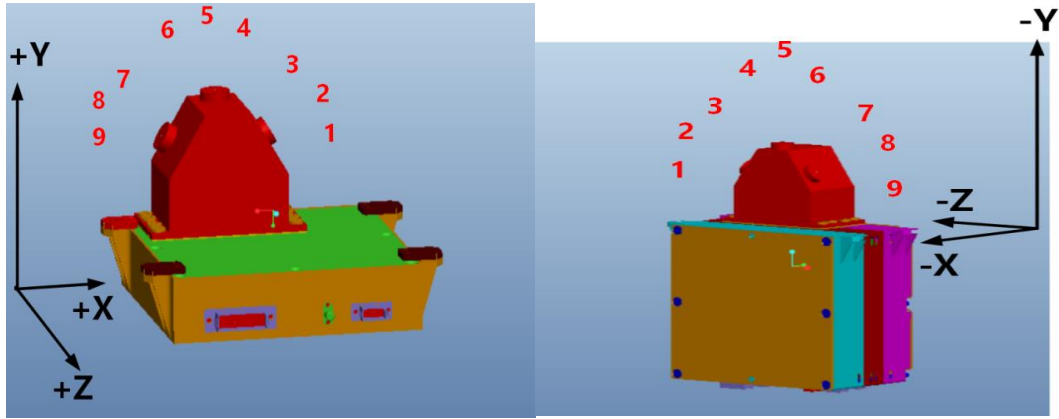


Fig. 2 SEM-II MEED Directions Map (Left is Sensor 1; Right is Sensor 2).

2.1.4. Radiation Dose Detector (RDD)

SEM-II RDD has the abilities to detect the radiation dose in situ in X/Y/-Z directions in the satellite coordinate with two channels in each direction. The detection sensitivity is better than 2 rad (Si) and the measurement uncertainty is within 10% based on the prelaunch calibration test.

2.1.5. Surface Potential Detector (SPD)

SEM-II SPD contains two parts: Relative Surface Potential Detector (RSPD) and Absolute Surface Potential Detector (ASPD). These detectors have the abilities to detect the surface potentials of the satellite on both dayside and nightside (see Fig. 3). The relative surface potentials are retrieved from the volt changes in the detectors and the absolute surface potentials are derived from the energy spectrums (30 eV-30 keV) of the plasma surrounding the satellite. The potential detections uncertainty is within 20% based on the prelaunch calibration test.

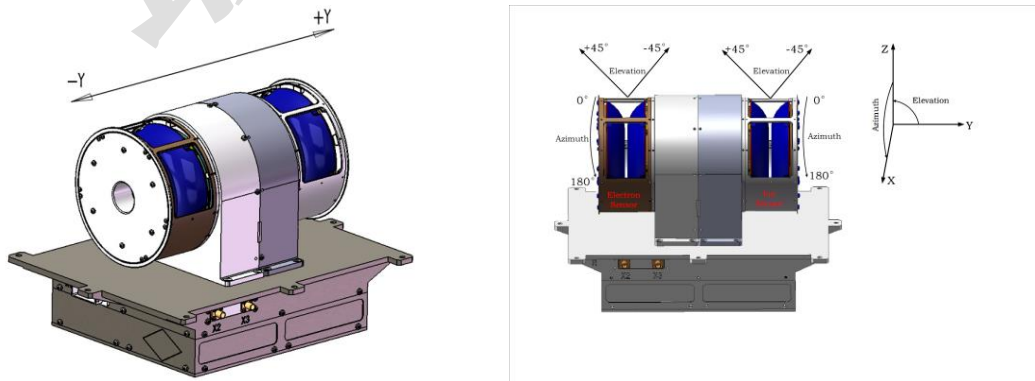


Fig. 3 SEM-II ASPD Directions Map.

2.1.6. Magnetic Field Detector (MFD)

SEM-II MFD has the abilities to detect the magnetic field vectors in situ in the satellite orbit without rods (see Fig. 4). After excluding the satellite remanence, we can retrieve the geomagnetic

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field changes from the detections. The time resolution of the detections is 1 s and the detections uncertainty is 1 nT based on the prelaunch calibration test.

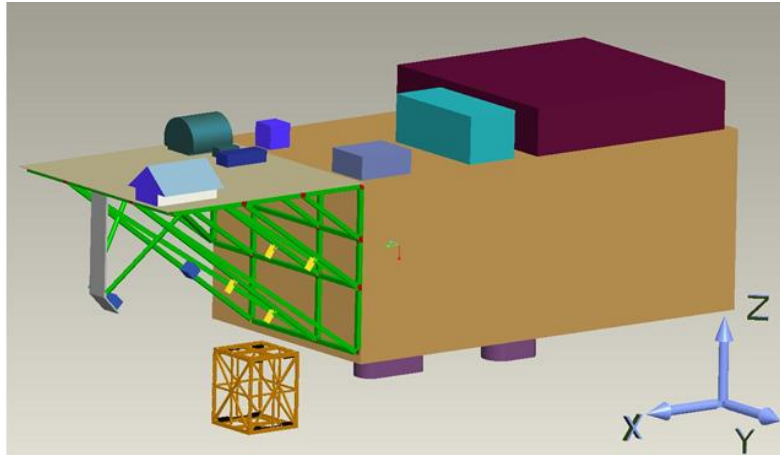


Fig. 4 SEM-II MFD Assembly Map, the yellow (GMR, Giant Magneto Resistive) and blue blocks (FGM, Flux Gate Magnetometer) on the satellite truss (green) mean where the six sensors are deployed.

3. In-Orbit Testing Approach

We apply the qualitative test and the quantitative test to identify the validity of SEM-II detections. To the qualitative test, we check if the SEM-II detections follow the space environment rules. To the quantitative test, we do the inter-comparisons with other satellites detections or model's results to check the validation of SEM-II detections.

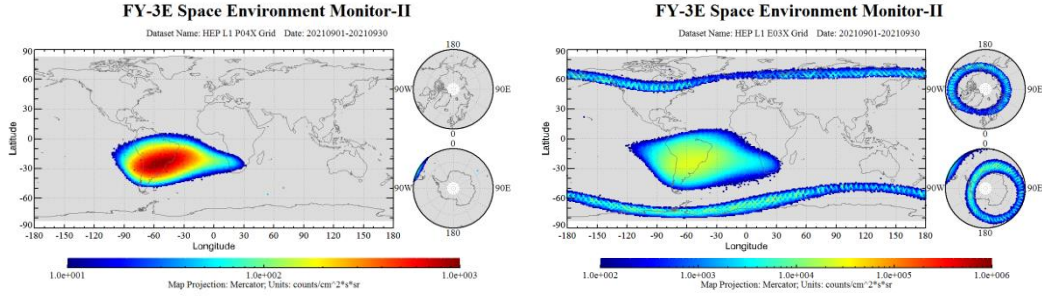
4. In-Orbit Testing Results

4.1. Energetic Particle Detections

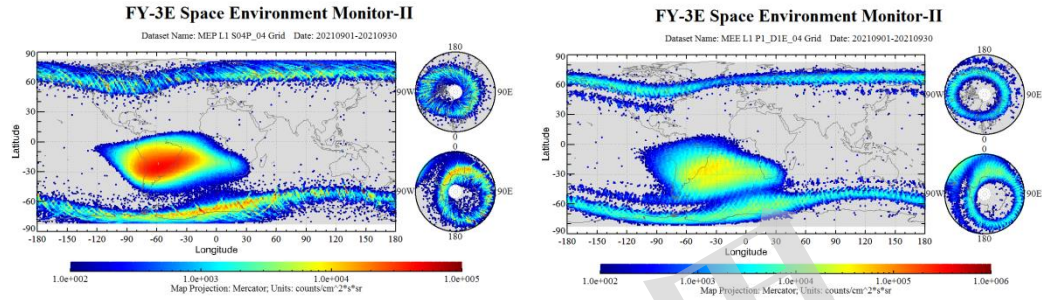
Energetic particle detections include the detections from HEPD, MEPD and MEED.

4.1.1. Qualitative Test

From Fig. 5, we can find that the particle detections from SEM-II show the South Atlantic Anomaly (SAA) region at low latitudes and the out radiation belt at high latitudes clearly. These radiation belt patterns and the particle directional flux distributions agree with our space environment knowledge well.



(a) Proton Global Map from HEPD; (b) Electron Global Map from HEPD



(c) Proton Global Map from MEED; (d) Electron Global Map from MEED

Fig. 5 The radiation belt detections from SEM-II: (a) is for the proton energy of 26-40 MeV in -X direction; (b) is for the electron energy of 0.65-1.20 MeV in -X direction; (c) is for the proton energy of 120-170 keV in the 4th direction of Fig.1; (d) is for the electron energy of 90-130 keV in the 4th direction of the sensor 1 in Fig.2. The approach for the maps generation: we generate a 360° (longitude) $\times 180^\circ$ (latitude) matrix, the data from the detection points located within a 0.5° range (i.e. a 1° grid) around each latitude and longitude point is averaged as the detection result for that latitude and longitude point, then, we plot these figures.

4.1.2. Quantitative Test

To the quantitative test of particle detections, we perform the inter-comparisons with the POES (Polar Orbiting Environmental Satellite) satellite particle detections from MEPED (Medium Energy Proton and Electron Detector) onboard POES N-19. We chose the same period (about a month) detections and, for each satellite, the data from the detection points located within a 0.5° range (i.e. a 1° grid) around each latitude and longitude point is averaged as the detection result for that latitude and longitude position. We compared two satellites detections at the same latitude and longitude position. Due to that the energy bands of MEPED are different from SEM-II, we do the power-law fitting^[5] to derive the particle's spectrum or combine the two datasets to the same energy bands. Considering the particle anisotropy and the differences of pitch angle between two

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datasets, we select the particles with close pitch angles (the pitch angle difference absolute value is less than 10°) in the inter-comparison works. The details of the data processing and testing methods can be found in Huang et al. (2012)' s work^[1]. We set F is the particle' flux (it is the linear flux not the logarithmic flux in the calculation) in a certain energy band and $\text{mean}()$ is the average operation on the dataset, set the standard deviation (STD) is $STD = \sqrt{\text{mean}(F_{FY3E} - F_{N19})^2}$, the average relative deviation (ASTD) is $ASTD = STD / \text{mean}(F_{N19})$. The comparison results are shown in Fig. 6. From Fig. 6, it can be calculated that the total relative biases of the particle detections between SEM-II and MEPED are less than 25%. The table 2 illustrates the specific statistical information of the test results in Fig.6.

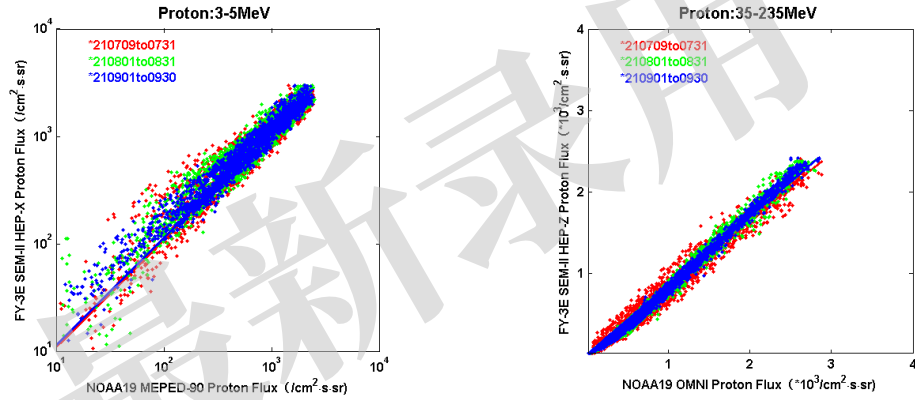
Table 2 Statistics for The Particle Inter-Comparisons (FY-3E vs. N-19) in Fig.6

FY-3E HEP -X vs. N-19 MEPED90: 3~5 MeV				
TIME	Correlation Coefficient	Slope	Average Relative Deviation (ASTD)	Spots Number
202107	0.94	1.10	20.22%	1971
202108	0.95	1.15	23.35%	1957
202109	0.96	1.15	20.39%	1953
FY-3E HEP -Z vs. N-19 OMNI: 35~275 MeV				
TIME	Correlation Coefficient	Slope	Average Relative Deviation (ASTD)	Spots Number
202107	0.99	0.93	19.92%	2065
202108	0.99	0.86	17.03%	2077
202109	0.99	0.85	17.74%	2077
FY-3E HEP -X vs. N-19 MEPED90: 0.1~1.1 MeV				
TIME	Correlation Coefficient	Slope	Average Relative Deviation (ASTD)	Spots Number
202107	0.96	1.14	23.46%	325
202108	0.98	1.19	24.60%	326
202109	0.99	1.17	24.41%	442
FY-3E HEP -X vs. N-19 MEPED90: 0.3~1.1 MeV				
TIME	Correlation Coefficient	Slope	Average Relative Deviation (ASTD)	Spots Number
202107	0.96	0.92	17.75%	325
202108	0.97	0.98	13.13%	326
202109	0.99	0.94	10.88%	442
FY-3E MEP -X vs. N-19 MEPED90: 80~240 keV				
TIME	Correlation Coefficient	Slope	Average Relative Deviation (ASTD)	Spots Number
202107	0.92	0.86	24.69%	1600

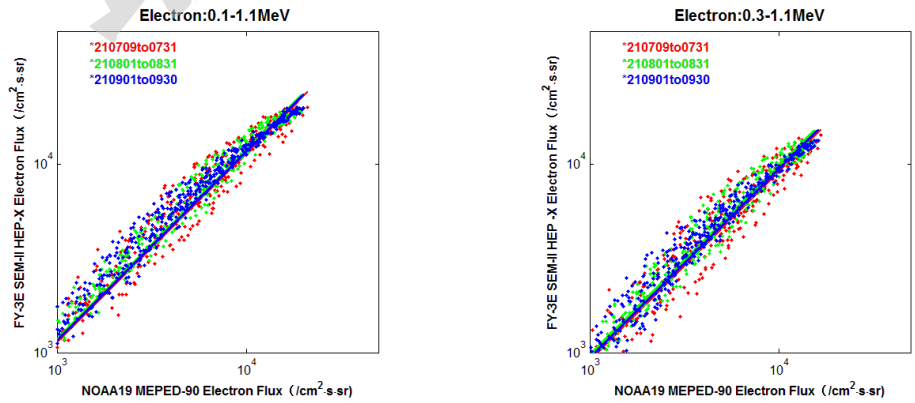
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202108	0.93	0.91	23.85%	1714
202109	0.94	0.93	21.38%	1837
FY-3E MEP -X vs. N-19 MEPED90: 240~800 keV				
TIME	Correlation Coefficient	Slope	Average Relative Deviation (ASTD)	Spots Number
202107	0.95	0.99	20.87%	2089
202108	0.96	1.05	20.04%	2040
202109	0.96	1.05	19.29%	2101
FY-3E MEE vs. N-19 MEPED00: 30~100 keV				
TIME	Correlation Coefficient	Slope	Average Relative Deviation	Spots Number
202109	0.97	0.99	13.2%	1231
FY-3E MEE vs. N-19 MEPED90: 100~300 keV				
TIME	Correlation Coefficient	Slope	Average Relative Deviation (ASTD)	Spots Number
202109	0.98	1.00	15.9%	1231



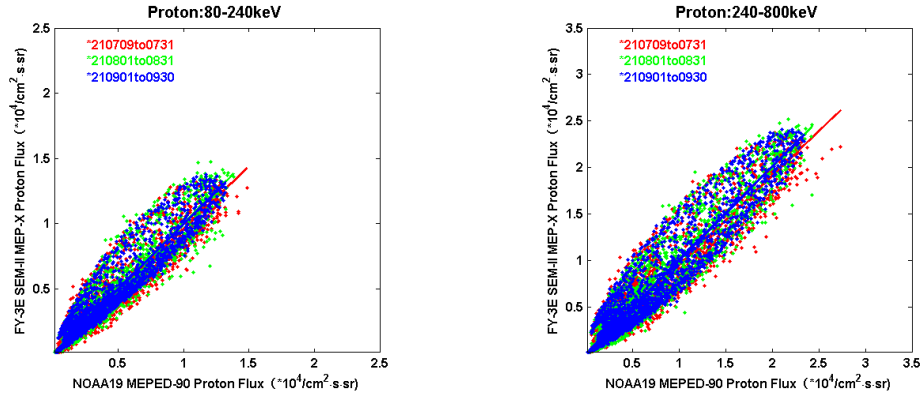
(a) Proton inter-comparisons of FY-3E_SEM-II_HEPD vs. N-19_SEM_MEPED



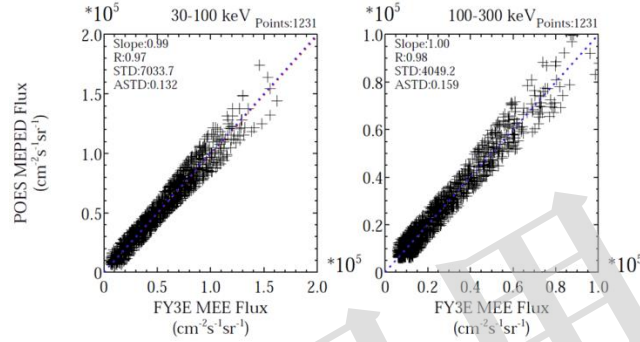
(b) Electron inter-comparisons of FY-3E_SEM-II_HEPD vs. N-19_SEM_MEPED

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(c) Proton inter-comparisons of FY-3E_SEM-II_MEPD vs. N-19_SEM_MEPD



(d) Electron inter-comparisons of FY-3E_SEM-II_MEED vs. N-19_SEM_MEPD

Fig. 6 The particle inter-comparisons of FY-3E vs. N-19: (a)-(c) are for the results of HEPD and MEPD where the different colors denote the different periods; (d) is for the results of MEED in September, 2021.

4.2. Magnetic Field Measurements

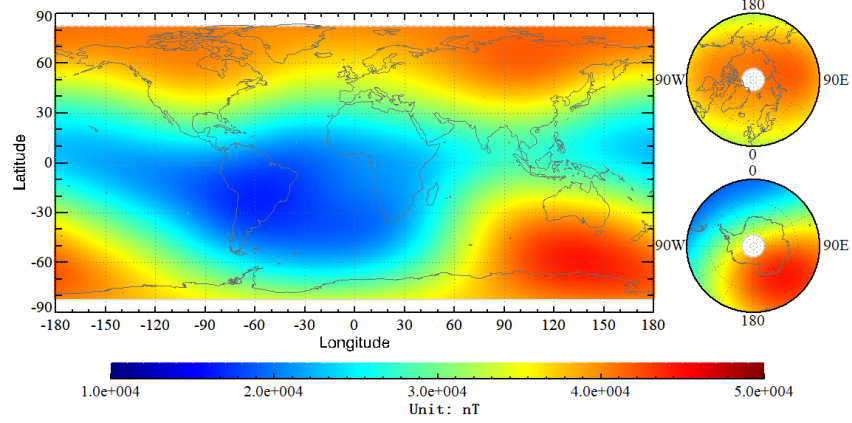
Magnetic Field measurements are derived from MFD.

4.2.1. Qualitative Test

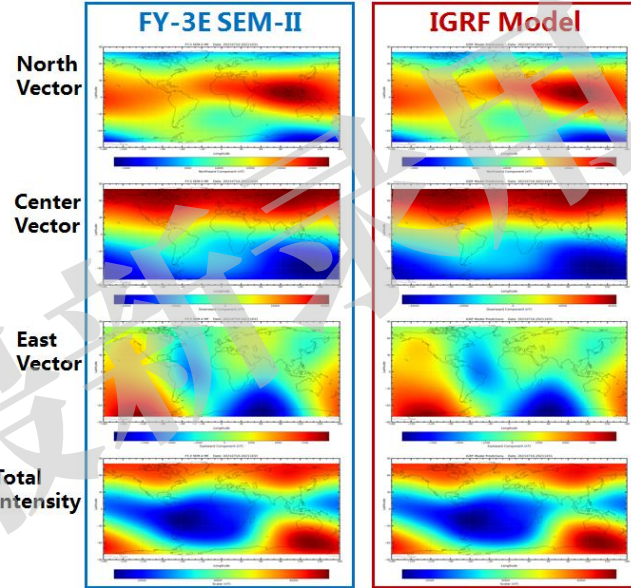
Fig. 7 shows the magnetic field intensities at FY-3E orbit and the magnetic field distribution coincides to our geomagnetic knowledge. The negative magnetic field region in SAA and the high value regions at high latitudes are clearly described in Fig. 7a. Fig. 7b shows the geomagnetic field distributions from SEM-II compared with IGRF13.

FY-3E Space Environment Monitor-II

Dataset Name: HMF BT Grid Date: 20210901-20210930



(a) The Global Geomagnetic Field Intensity Map from MFD which is generated by one month measurements.



(b) FY-3E SEM-II MFD vs. IGRF in different vectors and the total intensity.

Fig. 7 The geomagnetic field map from FY-3E_SEM-II_MFD compared with IGRF13. Unit: nT. The way for these maps' generation is like that in Fig. 5.

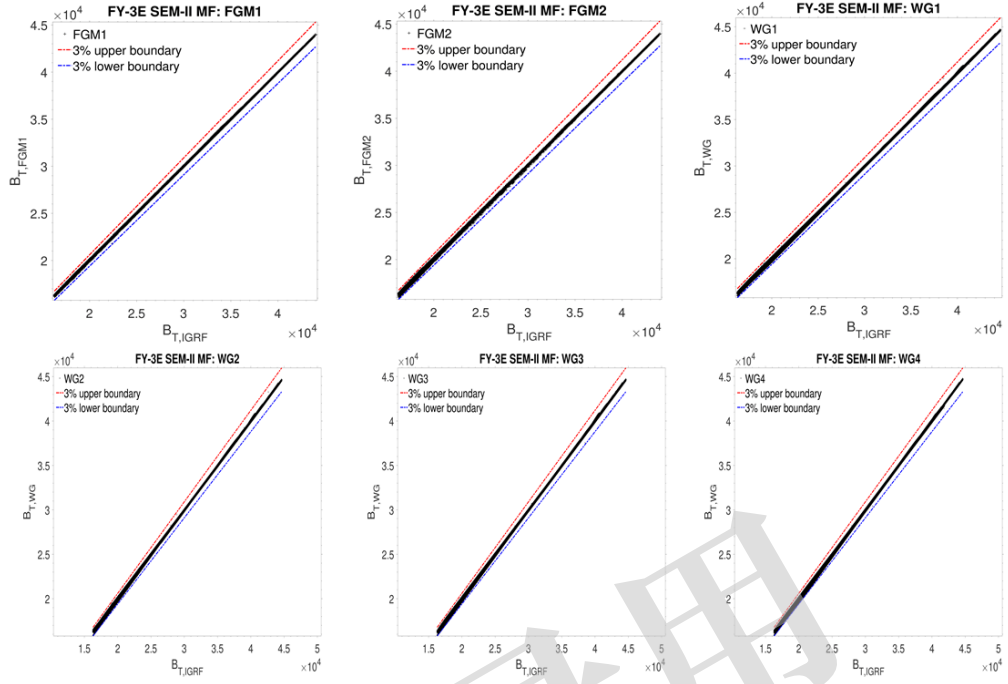
4.2.2. Quantitative Test

To the quantitative test of magnetic field measurements, we compare the measurements from SEM-II with IGRF13 (International Geomagnetic Reference Field 13th) model. We use IGRF13 as a reference and output the model calculation values of IGRF13 at each detection point (spatial position) for comparison with the magnetic field detection data of FY-3E. We use the total field data, B_T , and set the $\text{Bias} = (B_{T, \text{Sensor}} - B_{T, \text{IGRF}}) / B_T$ to calculate the bias between FY-3E/SEM-II and IGRF13. The dataset period is in August, 2021 and the samples size is about 2.2×10^6 (exact 1 Hz

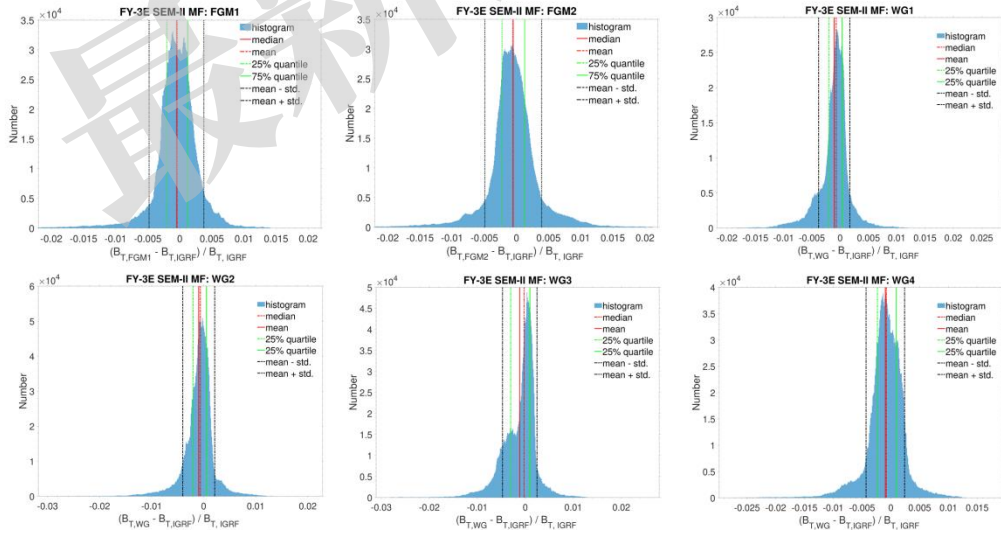
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samples from the 50 Hz detections). The results are shown in Fig. 8 and it is found that the total biases between SEM-II and IGRF13 are approximately 1%.



(a) The detections from 6 sensors of MFD vs IGRF, FGM_x denotes the sensors based on flux-gate magnetometer technology and WG_X denotes the sensors based on GMR (Giant Magneto Resitive) technology. Unit:nT.



(b) The statistics of the geomagnetic field intensity (B_T) relative to IGRF for 6 sensors of MFD, the meanings of FGM_x and WG_X are as shown in (a).

Fig. 8 The quantitative comparisons of the total intensity between FY-3E_SEM-II_MFD and IGRF in August, 2021. IGRF is used as the reference and the bias is calculated by $(B_T, \text{Sensor} - B_T, \text{IGRF}) / B_T, \text{IGRF}$, 3% in (a) is the deviation_check line.

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4.3. Radiation Effect Observations

Radiation effect observations include the detections from RDD and SPD.

4.3.1. Qualitative Test

Fig. 9 shows the radiation dose increasing. It is found that the radiation dose increasing rates are different in different directions. The increasing rate in Y direction is fastest. This situation coincides to the space radiation theory due to that the particle intensity is higher in Y direction with the pitch angle is close to 90° . The radiation dose increasing rate shows good responses to several geomagnetic storms occurred at the end of August/2021, the end of October/2021, and the middle of January/2022.

Fig. 10.a and 10.b shows the time series and the global distribution of the observations from RSPD. During the in-orbit testing period, the surface charging volt reaches -180 V and the charging events concentrate in the outer radiation belt at high southern latitudes. These features of RSPD onboard FY-3E agree well with the previous detections from FY-3D (Fig.10.c). Fig. 11 shows the plasma particle detections from ASPD vs. AE (Auroral Electrojet) index which is used to describe the activity level of the geomagnetic field. From Fig. 11, we found that the plasma particle spectrums present good responses to the geomagnetic activities in the polar regions. These results coincide to the natural law of space environment.

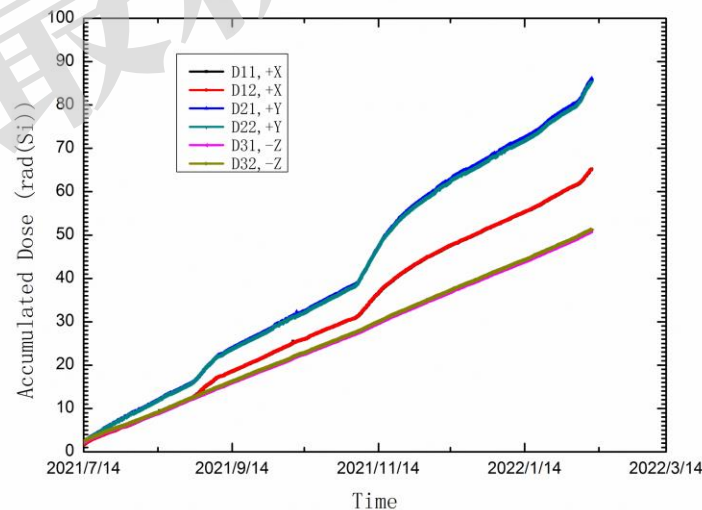
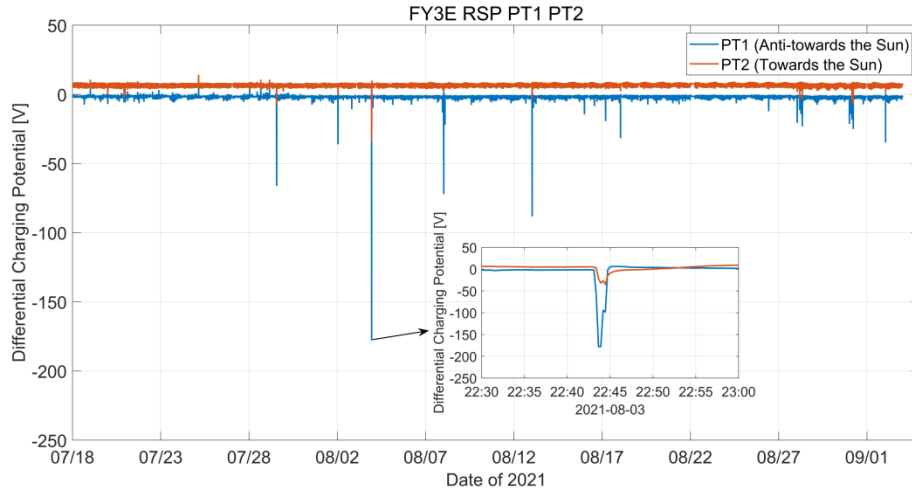
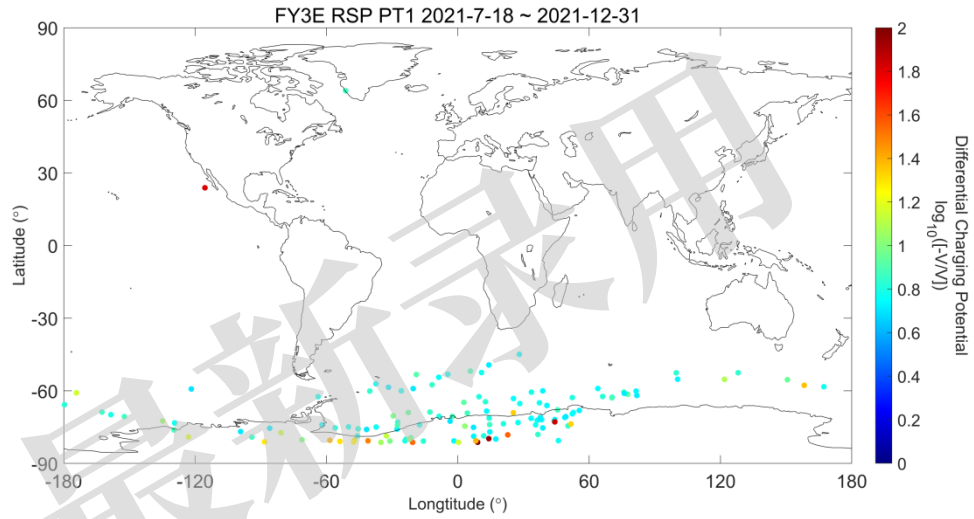


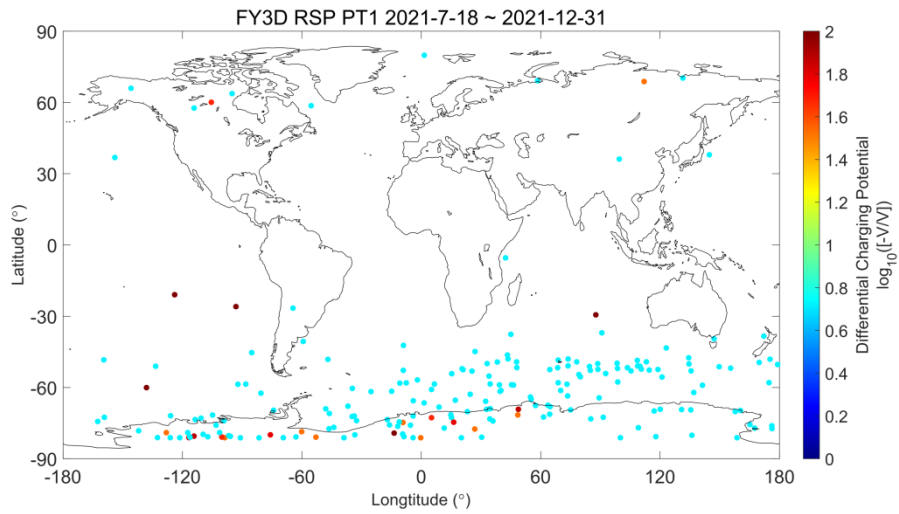
Fig. 9 The radiation dose detected by FY-3E_SEM-II_RDD, the different colors denote the accumulated radiation dose from the different sensors in X/Y/-Z directions.



(a) The time series of the detections from RSPD onboard FY-3E, the little window shows a significant charging event occurred on 2021-08-03.



(b) The global distribution of the charging events detected by RSPD sensor 1 onboard FY-3E in 2021 where the different colors denote the level of the charging events.

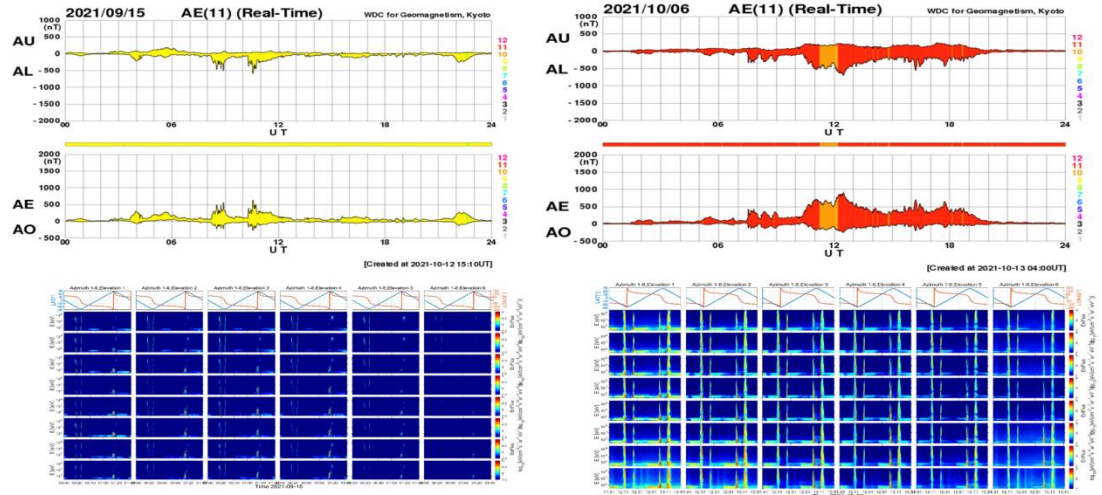


(c) The global distribution of the charging events detected by RSPD sensor 1 onboard FY-3D.

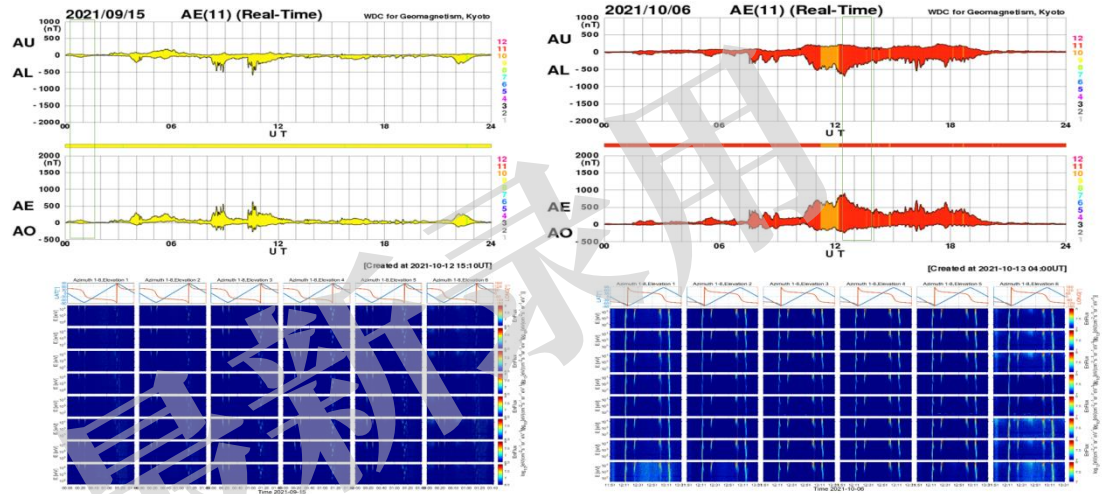
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Fig. 10 The charging events observed by RSPD onboard FY-3E and FY-3D.



(a) The electron spectrum responses to the geomagnetic activity detected by ASPD



(b) The proton spectrum responses to the geomagnetic activity detected by ASPD

Fig. 11 The plasma spectrum responses to the geomagnetic activity detected by ASPD onboard FY-3E, each little window shows the particle spectrum derived by ASPD in eight azimuths and six pitch angles which are shown in Fig.3, these detections show good correlations to the AE index.

4.3.2. Quantitative Test

Due to that it is difficult to find available quantitative data source to perform the inter-comparisons of radiation effect detections, we didn't carry out the quantitative test. More detailed discussions for the validation of the radiation dose measurements can be found in Dr. Zhang's work^[6].

5. Conclusions and Discussions

The cross-calibration methods are applied in the in-orbit calibrations and validations of SEM-II. To the particle detectors, we compared the particle detections from SEM-II with the particle

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manned spaceflight missions. The particle detections of space environment also help to develop the radiation belt model, such as AP8/AE8 which are developed to explain the mechanism of Van Allen radiation belt^[10,11], in the 1970s. However, it is known that AP8 and AE8 models only provide static-average- isotropic particle flux while the geomagnetic field migrates 0.3° every year. Therefore, the outputs of AP8/AE8 models may not be suitable for the requirements in the modern space missions.

Many satellite missions are developed for detecting the radiation belt^[12-15]. Currently, the National Oceanic and Atmospheric Administration (NOAA) Polar Orbiting Environmental Satellite (POES) series and China Meteorological Administration's FY-3 series provide the operational measurements of space environment in polar and Sun-synchronous orbits. The information about space environment can be used in space weather forecast and warning, satellite security designs, satellite malfunction analysis, and scientific studies. We hope that the data of SEM-II may be applied in more aspects of space science in the future.

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