China Seismo-Electromagnetic Satellite search coil magnetometer data and initial results

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Abstract: Four levels of the data from the search coil magnetometer (SCM) onboard the China Seismo-Electromagnetic Satellite (CSES) are defined and described. The data in different levels all contain three components of the waveform and/or spectrum of the induced magnetic field around the orbit in the frequency range of 10 Hz to 20 kHz; these are divided into an ultra-low-frequency band (ULF, 10–200 Hz), an extremely low frequency band (ELF, 200–2200 Hz), and a very low frequency band (VLF, 1.8–20 kHz). Examples of data products for Level-2, Level-3, and Level-4 are presented. The initial results obtained in the commission test phase demonstrated that the SCM was in a normal operational status and that the data are of high enough quality to reliably capture most space weather events related to low-frequency geomagnetic disturbances.

Keywords: search coil magnetometer; CSES, data description; earthquake

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1. Introduction

As the first space-based platform in China for both earthquake observation and geophysical field measurement, the China Seismo-Electromagnetic Satellite (CSES; also called ZHANGHENG-1), was launched successfully on February 2, 2018. Ten days later, it began its global observation (Shen XH et al., 2018). During its five-year mission, it will provide nearly continuous data of natural electromagnetic (EM) field waveforms and spectra, in situ plasma parameters, electron density profiles and tomography, and energetic particle flux and energy spectra.

Seismo-electromagnetic phenomena before earthquakes from ground observation have been reported independently and intensively, especially as related to strong earthquakes, such as the Alaskan M 9.2 Earthquake of 1964 (Davies and Baker, 1965), the Bohai M 7.4 Earthquake of 1969 (Wang, 2007), the Tangshang M 7.8 Earthquake of 1978 (Zhao YL and Qian FY, 1994; Park et al., 1993), the Loma Prieta M 7.1 Earthquake of 1989 (Fraser-Smith et al., 1990), the Landers M 7.3 Earthquake of 1992 (Johnston, 1997), the Indonesia M 8.2 Earthquake of 1996 (Hayakawa et al., 2000), the Kobe M 7.2 Earthquake of 1995 (Nagao et al., 2002), and the Wenchuan M 8.0 Earthquake of 2008 (Huang O.H., 2011). Because these event data come from different observational systems, it is difficult to examine these cases in a unified data space. However, the advantage of space-based observation is that it enables quick and regular acquisition of all main seismic events (Parrot et al., 2006). This makes reliable statistical analysis for large earthquakes feasible (Tao D et al., 2018; Yan R et al., 2017; Zhang XM et al., 2014; Li M and Parrot, 2013; Parrot, 2012), especially since the first successful special satellite mission, DEMETER (Parrot, 2006), was launched for seismo-electromagnetic ionospheric effects observation. Before DEMETER, in contrast, just independent cases from different spacecraft were studied (see Parrot et al. (2006) and references therein).

CSES is flying on a polar, nearly circular orbit at an altitude of 507 km with an inclination angle of 97.4°. This orbit crosses the equator or close to 14:00 LT on the dayside. Normally, data acquisition is limited within the geographical latitude of 65°. In the past 6 months, hundreds of terabytes of data have been obtained, including the EM field, plasma, and energetic particles in the ionosphere. These data will benefit not only the study of ionospheric perturbations possibly associated with seismic activity but also geophysics, space science, radio wave science, and space weather monitoring.

The search coil magnetometer (SCM) is the one of the three EM field measurement payloads aboard CSES. It aims to measure the magnetic field fluctuation of low-frequency EM waves in the frequency range of 10 Hz to 20 kHz. Ground calibration results have indicated that SCM is advanced compared the current SCMs in other international space missions, particularly in terms of the ~3 dB measurement bandwidth, frequency resolution, and sensitiv-
ity (Cao JB et al., 2018). In this paper, the definitions of each level of the SCM data product are presented in Section 2. Processing algorithms are briefly reviewed in Section 3. In Section 4, some initial results of SCM are presented.

2. SCM Data Description

Generally, the SCM data include three frequency band waveforms and/or power spectral density (PSD) data, i.e., ultra-low-frequency band (ULF, 10–200 Hz) data with a 1024-Hz sampling rate, extremely low frequency band (ELF, 200–2200 Hz) data with a 10.24-kHz sampling rate, and very low frequency band (VLF, 1.8–20 kHz) data with a 51.2-kHz sampling rate. The scientific data file uses the hierarchical data format (HDF), and their corresponding figures use the portable network graphics (PNG) format.

During onboard data processing, the output three analog signals from the three-axis search coil sensor, which represent the three components of the induced magnetic field \(B_x, B_y,\) and \(B_z\), are amplified by the preamplifier and digitized by analog-to-digital conversion. Then the digital processing unit processes the digitized signals and outputs the waveform and spectral data. The performance of the SCM, including its sensitivity, transfer functions, and calibration results, were checked in the paper of Cao JB et al. (2018).

Ground data processing, including data level definition and implementation of the main algorithms, is divided into four parts. Therefore, the parts corresponding to four levels are described in the following.

2.1 Level-0 Data

Level-0 data are defined as the data from CSES downlinked after descrambling, error correction, frame synchronization, and duplicate removal.

The Level-0 data files include time-alignment binary data in little-endian format, the on-orbit SCM calibration results, and the Level-0 processing report.

The contents of Level-0 binary data include the operation status of the SCM, satellite flight information, ULF (10–200 Hz) and ELF (200–2200 Hz) frequency band waveforms, and the VLF Fourier transformation spectrum (1.8–20 kHz) in survey mode or the VLF waveform in burst mode. Error-processing information is recorded in the processing report file.

2.2 Level-1 Data

Level-1 data are defined as the physical quantities calibrated after binary-to-decimal conversion, transferring function calibration, orthogonal correction of Level-0 data.

The Level-1 data files include time-alignment decimal scientific data and their figures, on-orbit calibration data, SCM on-orbit status data, and the processing report.

In the data processing from Level-0 to Level-1, transferring function calibration, orthogonal correction, and satellite altitude parameters are needed. The physical quantities of the three frequency bands in the HDF files organized by half-orbit are then illustrated in the PNG figure products. The data quality flag and error information are recorded in the Level-1 processing report file.

2.3 Level-2 Data

Level-2 data are defined as the physical quantities transformed from the sensor coordination system of Level-1 data into the geographic coordinate system labeled with geomagnetic coordinate system information and satellite altitude information.

The Level-2 data files include time-alignment decimal scientific data organized by half-orbit and their figures, on-orbit calibration data, SCM on-orbit status data, and the processing report.

In the data processing from Level-1 to Level-2, the PSD data are calculated from the Fourier spectral data in the Level-1 data files, and coordinate transformation matrices including sensor-to-satellite coordinate and satellite-to-geomagnetic/geographic coordinates are needed. The waveform and PSD data of the three frequency bands organized by half-orbit are then illustrated with geographic coordinate system information in the PNG figure products of the Level-2 HDF data. The data quality and error information are recorded in the Level-2 processing report file.

2.4 Level-3 Data

Level-3 data are defined as the time series data of the half-orbit generated after resampling from the Level-2 data.

In the Level-3 data, the time series data include the waveform and PSD of the latest orbit; the statistical quantities of its recursive orbits are included in the HDF file. The statistical quantities include the median, quantiles, mean, and standard deviation of the data of recursive orbits.

In the processing of Level-3 data, auxiliary data including space weather indices, such as \(K_p, Dst, F_{10.7}\), and \(AE\) indices, and the latest earthquake catalog are needed. Recorded in the Level-3 processing report file are HDF data files calculated for the median, quantiles, mean, and standard deviation; space intervals for resampling; flags beyond the threshold base for each statistical quantity; and other processing information.

2.5 Level-4 Data

Level-4 data are defined as the global or regional space data retrieved from Level-2, in terms of variation between recursive orbits and disturbances observed according to the background field.

Level-4 spatial data include the global and regional waveforms and PSD data resampled from the latest single full recursive period of 5 days. The background of the latest recursive period is established from the data spreading over a time scope of \(>30\) days. The statistical quantities of the background are included in the Level-4 HDF files.

The Level-4 PNG figure product illustrates the global or regional map of the latest 5 days, the background, and the residuals of the former. Earthquakes with magnitudes \(>M\) 6.0 in the latest 5 days are plotted in the residuals map. The spatial intervals for resampling, flags beyond of threshold base for each statistical quantity, and other processing information are recorded in the Level-4 processing report file.

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3. Initial Results from the SCM Experiment

Examples of various data recorded by the SCM experiment are shown in Figures 1–4. All plots are drawn at the CSES mission center (Shen XH et al., 2018). Figure 1 displays the ELF magnetic spectrogram of the Level-2 data product along one half-orbit. It is a classical daytime half-orbit with a clear cutoff of waves at the proton gyrofrequency all along this half-orbit. At higher latitudes, more intense waves without any cutoff at the local proton gyrofrequency are observed. These are well-known characteristics of auroral emissions. High-altitude strong sources of ELF and VLF emissions have been identified in the auroral regions. At middle latitudes, many perturbations are seen in Figure 1 because of the unquiet day with a $|D_s|$ index of >30 nT. Figure 1 also shows the clear position of the geomagnetic equator.

As an example of a Level-3 product, Figure 2 shows a large geomagnetic storm starting at August 25, 2018. The $D_s$ index approached –200, as shown in the three lower left panels. In the middle latitude, significant disturbances (red line) exceeding the background were observed. The median of five recursive orbits in the latest month are plotted by the black line, and the upper and lower boundaries using the median and adding or subtracting the IQR of the five recursive orbits in the latest month are also plotted.

Figure 3 shows an example of a Level-4 product in which VLF transmitter emission from Australia’s NWC (19.8 kHz) station is observed (Parrot et al., 2006; Shklyar et al., 1992).

Balasis and Manda (2007) examined CHAMP satellite data to identify possible EM signatures related to the two mega earthquakes Sumatra $M_c 9.3$ of 2004 and $M_c 8.7$ of 2005 (Maus et al., 2002). The top panel of Figure 4 displays an example of an EM wave perturbation in possible relation with seismic activity with a ground-computed PSD during survey mode. Two earthquakes of magnitude 6.8 and 6.5 occurred on July 29 and August 5, 2018, at 01:07:02 Beijing local time (BJT) and 19:46:03, at locations defined by (Lat = –8.3°, Lon = 116.55°) and (Lat = –8.33°, Lon = 116.45°), respectively. The bottom panel is related to earthquakes “seen” by the satellite along the orbit. Most of the symbols in the earthquake panel have the same meaning as those from DEMETER data, except for the blue-filled square, which represents earthquakes occurring during the time range of the current orbit. The two red triangles in the middle earthquake information panel of Figure 4 correspond to the closest approach to the epicenter. The location of this earthquake corresponds to the Indonesia islands. It is a zone without land and, if we refer to the generation mechanism determined by Parrot et al. (2006), the only hypothesis that could explain such an ionospheric perturbation is a large gas release.

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**Figure 1.** ELF magnetic spectrogram recorded on June 1, 2018, along a half-orbit between 16:33:14 and 17:07:38 UT.
Conclusions

The SCM has been developed to measure the three magnetic components of EM waves from 10 Hz to 20 kHz. The objective of the CSES SCM is to provide high-sensitivity observations of EM waves to study preseismic VLF and ELF disturbances and to determine possible relative mechanisms. By combining the SCM data with data from the high precision magnetometer, which measures the three components of the absolute geomagnetic field in the DC frequency range to 15 Hz, we can produce a complete magnetic profile. The SCM will also be used to study human-made emissions and lithosphere conductivity.

To reduce interference from the satellite platform, the distance from the magnetic antenna to the platform is set as 4.5 m. SCM can work in burst mode, survey mode, or calibration mode. Under

Figure 2. A geomagnetic storm starting on August 25, 2018, was observed by SCM. In the top three panels, huge disturbances were recorded in the accumulative spectrum of the current orbit (red line), exceeding the background. The black line denotes the median of five recursive orbits in the latest month. Also shown are the upper and lower boundaries using the median and adding or subtracting the interquartile range (IQR) of the five recursive orbits in the latest month.

4. Conclusions

The SCM has been developed to measure the three magnetic components of EM waves from 10 Hz to 20 kHz. The objective of the CSES SCM is to provide high-sensitivity observations of EM waves to study preseismic VLF and ELF disturbances and to determine possible relative mechanisms. By combining the SCM data with data from the high precision magnetometer, which measures the three components of the absolute geomagnetic field in the DC frequency range to 15 Hz, we can produce a complete magnetic profile. The SCM will also be used to study human-made emissions and lithosphere conductivity.

To reduce interference from the satellite platform, the distance from the magnetic antenna to the platform is set as 4.5 m. SCM can work in burst mode, survey mode, or calibration mode. Under
calibration mode, it can simultaneously produce standard signals with frequencies of 625 Hz and 10 kHz.

Every day the CSES mission center receives data from the ground receiving center (see Shen XH et al., 2018) and produces Level-0 to Level-4 data. At the same time, it downloads a seismic file from the China Earthquake Network Center (CNEC) that contains date, hour, location, magnitude, and depth of earthquakes as well as some space weather index files recorded the day before. These files are combined with the CSES Level-2 to Level-4 data products and will be used for the statistical analysis.

The first data results have shown that SCM data are of good quality and usable for scientific analysis. However, much reliable conclusions about earthquakes are needed to perform a statistical analysis.

The CSES data management regulations were jointly released by the China National Space Administration (CNSA) and the China Earthquake Administration (CEA) on May 10, 2018. They encourage much international scientific collaboration and cooperation all around the world. Two days after the release, an agreement among the Institute of Crustal Dynamics, CEA, and the IUGG Inter-IAGA/IASPEI/IAVCEI working group on EM studies of earthquakes and volcanoes was signed on May 12, 2018, ten years after the Wenchuan M 8.0 earthquake. This agreement should encourage people and institutes around the world to promote the broad applications of CSES data.

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Date: 2018-08-22 Orbit Type:1
Produced at 2018-08-28 02:14:27 v1.0
Current Background Residual

VLF Bx PSD (nT2Hz-1)

VLF By PSD (nT2Hz-1)

VLF Bz PSD (nT2Hz-1)

Figure 3. Emission from Australia’s VLF transmitter NWC (21.78°S, 114.15°E) was recorded in the SCM data. The top, middle, and lower panels show the $B_x$, $B_y$, and $B_z$ components of the accumulative inducted magnetic field, respectively. The figures in the left column represent the data of all the orbits in one recursive period (i.e., 5 days) using a 2.5° × 5° grid size for spatial interpolation. The figures in the middle column represent the background using the orbits of the last five recursive periods (i.e., about one month).
Figure 4. Possible disturbances related to earthquakes observed by SCM onboard CSES. The top three panels show the accumulative magnetic spectrum of the VLF and corresponding statistical quantities for the three inducted magnetic field components, respectively, recorded on August 18, 2018, along a half-orbit between 18:13 and 18:47 UT. The middle panel shows earthquakes with a distance of <2000 km between the epicenter and CSES and occurring in the latest month using different colors, which also are marked on the lower right panel. The lower left three smaller panels show the space weather indices (i.e., Dst, Kp, and F10.7) one month before the orbit. The lower right panel shows the CSES footprint projected on the world map (blue line) and the neighboring 1000 km earthquakes (red pentagram) that occurred in the latest month.
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