

Comprehensive analysis of noise in Macau Science Satellite-1 vector magnetometer data

SiShan Song¹, Fan Yin^{1*}, Qin Yan^{2,3}, Hermann Lühr⁴, Chao Xiong¹, Yi Jiang³, and PengFei Liu³

¹Department of Space Physics, School of Earth and Space Science and Technology, Hubei Luojia Laboratory, Wuhan University, Wuhan 430072, China;

²State Key Laboratory of Lunar and Planetary Sciences, Macau University of Science and Technology, Macao 999078, China;

³Macau Institute of Space Technology and Application, Macau University of Science and Technology, Macao 999078, China;

⁴GFZ Helmholtz Centre for Geosciences, Section 2.3 Geomagnetism, Potsdam, Germany

Key Points:

- Two types of artificial disturbances in VFM data from MSS-1A are identified: one is called the V-shaped chirp event in which the frequency decreases and increases with time; the other is the 5-Hz event with accompanying spiky signals whose sources are interfering magnetic fields from the satellite's attitude control subsystem.
- The noise level in the 1–25 Hz range of 50 Hz MSS-1A VFM data is lower in day-side than in night-side. The occurrence rate of V-shaped events plays a key role in periods of high noise levels.

Citation: Song, S. S., Yin, F., Yan, Q., Lühr, H., Xiong, C., Jiang, Y., and Liu, P. F. (2025). Comprehensive analysis of noise in Macau Science Satellite-1 vector magnetometer data. *Earth Planet. Phys.*, 9(3), 532–540. <http://doi.org/10.26464/epp2025031>

Abstract: The Macau Science Satellite-1 (known as MSS-1) is the first scientific exploration satellite that was designed to measure the Earth's low latitude magnetic field at high resolution and with high precision by collecting data in a near-equatorial orbit. Magnetic field data from MSS-1's onboard Vector Fluxgate Magnetometer (VFM), collected at a sample rate of 50 Hz, allows us to detect and investigate sources of magnetic data contamination, from DC to relevant Nyquist frequency. Here we report two types of artificial disturbances in the VFM data. One is V-shaped events concentrated at night, with frequencies sweeping from the Nyquist frequency down to zero and back up. The other is 5-Hz events (ones that exhibit a distinct 5 Hz spectrum peak); these events are always accompanied by intervals of spiky signals, and are clearly related to the attitude control of the satellite. Our analyses show that VFM noise levels in daytime are systematically lower than in nighttime. The daily average noise levels exhibit a period of about 52 days. The V-shaped events are strongly correlated with higher VFM noise levels.

Keywords: Macau Science Satellite-1; Vector Fluxgate Magnetometer; artificial disturbances; noise features

1. Introduction

The Macau Science Satellite-1 (MSS-1) mission was launched on 21 May 2023 into an ~41 degrees low-inclination orbit of about 450 km altitude (Kong DL, 2023), which makes it unique for its ability to monitor the South Atlantic anomalies. MSS-1 consists of two separate satellites, MSS-1A and MSS-1B. MSS-1A is dedicated primarily to high-precision geomagnetic field measurements; MSS-1B focuses on observing solar activity.

To achieve accurate measurement of the geomagnetic field, MSS-1A implemented a 4.5 m deployable boom for its magnetometers, similar to the European Space Agency (ESA) Swarm satellites, to minimize magnetic disturbances from the satellite body (Friis-Christensen et al., 2006; Herceg et al., 2017). The boom is tilted at an angle of about 17-degree with respect to the main

satellite body axis (see Figure 1). A scalar magnetometer, named Couple Dark State Magnetometer (CDSM), is placed at the end of the boom. A Vector Fluxgate Magnetometer (VFM) is rigidly mounted inside an optical bench, located 2.7 m away from the main satellite body, together with a star tracker, named Advanced Stellar Compass (ASC), which comprises three Camera Head Units (CHUs) (Zhang H et al., 2023).

In addition to the dominant geomagnetic core field and the moderate lithospheric magnetic field, the VFM on MSS-1A, with its high precision and resolution, can detect weak natural magnetic signals, e.g. from the equatorial plasma irregularities (Xiong C et al., 2012; Wu MJ et al., 2024), or from ionospheric and magnetospheric currents (Wang YB et al., 2023), or from the tidal signals (Ren ZY et al., 2025). Because the VFM samples data at a rate of 50 Hz, it is capable of investigating magnetic signatures from the Extreme Low-Frequency (ELF) range up to the Nyquist frequency (Xu CY et al., 2024).

However, geophysical magnetic signals of interest are unavoidably contaminated by spacecraft-generated disturbances even in the

First author: S. S. Song, songsishan@whu.edu.cn

Correspondence to: F. Yin, yinfan@whu.edu.cn

Received 26 DEC 2024; Accepted 07 MAR 2025.

First Published online 03 APR 2025.

©2025 by Earth and Planetary Physics.

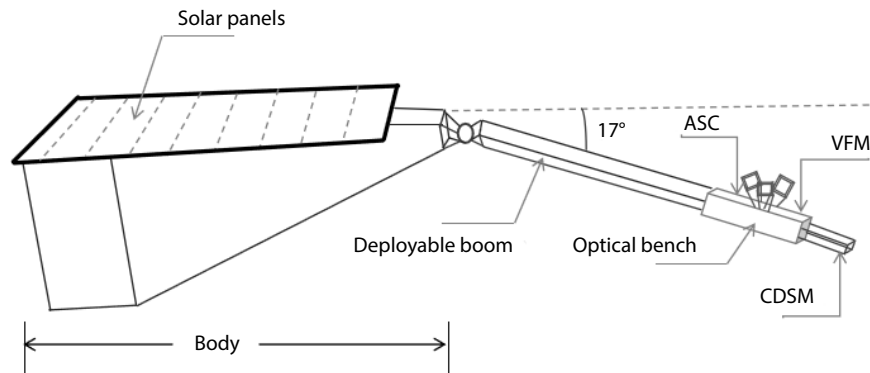


Figure 1. MSS-1A spacecraft schematic illustration.

presence of a satellite magnetic cleanliness control program. Spurious signals may originate from permanently magnetized materials, soft magnetic materials, or electric currents (Chen SW, 2009; Finley et al., 2023). For example, the 50 mHz signals in CHAMP magnetic field data could be traced back to an imperfect correction process applied to the magneto-torquer signals (Yin F et al., 2013). Some artificial magnetic disturbances in data from the China Seismo-Electromagnetic Satellite were caused by magnetorquer activation and by deformation of the satellite's boom (Yang YY et al., 2021). Swarm magnetometer data are known to have been contaminated by artificial signals, such as from Sun-driven thermo-magnetic disturbance fields (Tøffner-Clausen et al., 2016). Investigating the characteristics of different kinds of artificial signals is very helpful in identifying their sources and in improving data quality.

In this article, we report two disturbance signals found in MSS-1A 50 Hz VFM data, present their characteristics, and try to trace their sources. In addition, we compare the noise levels of MSS-1A VFM data to those of Swarm A VFM data in the frequency range of 1 Hz to 25 Hz. Section 2 presents our data processing method and analysis approaches. Section 3 presents results and discussion of our investigation of two main disturbance signals and other phenomena. Section 4 gives conclusions and our suggestions for future research.

2. Data and Method

2.1 Data Processing

For the study presented here we have used vector magnetic field data from the MSS-1A VFM. These measurements were made from 01 October 2023 to 30 April 2024 with 50 Hz resolution. In the VFM coordinate system, the z-axis is aligned with the boom; it points in the flight direction at an angle of 17 degrees. The y-axis points sideways, lying in the horizontal plane. The x-axis is always sampling the downward component. The ambient geomagnetic field, along the satellite track of such a low-Earth orbit, is strong compared to the magnetic signatures of disturbances from the spacecraft, which are primarily transient and infrequent. For this reason, the mean background field is fitted by applying a smoothing cubic spline with appropriate parameters. The magnetic field residuals are then obtained by subtracting the smoothed signal from the original VFM readings, for each component. This operation is similar to suppressing the main contributions of the

geomagnetic field by a high-pass filter or by a geomagnetic field model. The choice of appropriate fitting parameters ensures that the residual magnetic field presents the signals from 1 Hz to 25 Hz, the Nyquist frequency. In this frequency range artificial perturbations can be easily identified (Yin F et al., 2015; Léger et al., 2015). Different from polar orbiting satellites, e.g. Swarm, MSS-1A has a low latitude orbit and flies through the complete 0–24 h local time zones in one orbit; its dayside/nightside observational distribution is also quite different from that of polar orbits (Tøffner-Clausen et al., 2016; Yang YY et al., 2021). Therefore, the appropriate cutting of residual parts is not by ascending/descending orbital arcs, but by daytime/nighttime orbital arcs. In this paper, the separation of daytime/nighttime is 06/18 Local Time (LT). Our analyses are based on these sections of magnetic field residuals; we use both time domain and frequency domain approaches. The upper panels of Figure 2 present an example (from 1 December 2023) of disturbances for a daytime arc, on the left, and on the right for a nighttime arc.

First of all, because of its good performance in weak signal detection (Yin F et al., 2015), we use Welch's method to calculate the PSDs of the day and night arcs. Spectra derived from long-time data sequences have greater frequency resolution than data from a single orbit, but such data cannot provide information about the temporal evolution of a disturbance event. Our approach is to select orbits in which disturbances are observed, and then to apply several different techniques of harmonic analysis to investigate the artificial signals. For each detected event we use two time-frequency analyses, the Short Time Fourier Transform (STFT) with Hamming window, and the Continuous Wavelet Transform (CWT) with Morse Wavelet function (Basis et al., 2013). Both spectral analysis methods can show the temporal evolution of small-scale disturbance events in the 1–25 Hz frequency range. The time and frequency resolution of the CWT has been adaptively adjusted according to the characteristics of the signal, so CWT can focus more on the time-frequency characteristics in the lower frequency range. Therefore, in this paper, we primarily employ the CWT method to analyze the spectral characteristics of disturbance events.

2.2 Event Detection Approach

We have identified magnetic fluctuation events such as those shown in Figure 2 by applying the method described in Yin F et al. (2019) with parameters chosen to fit MSS-1A data. We set

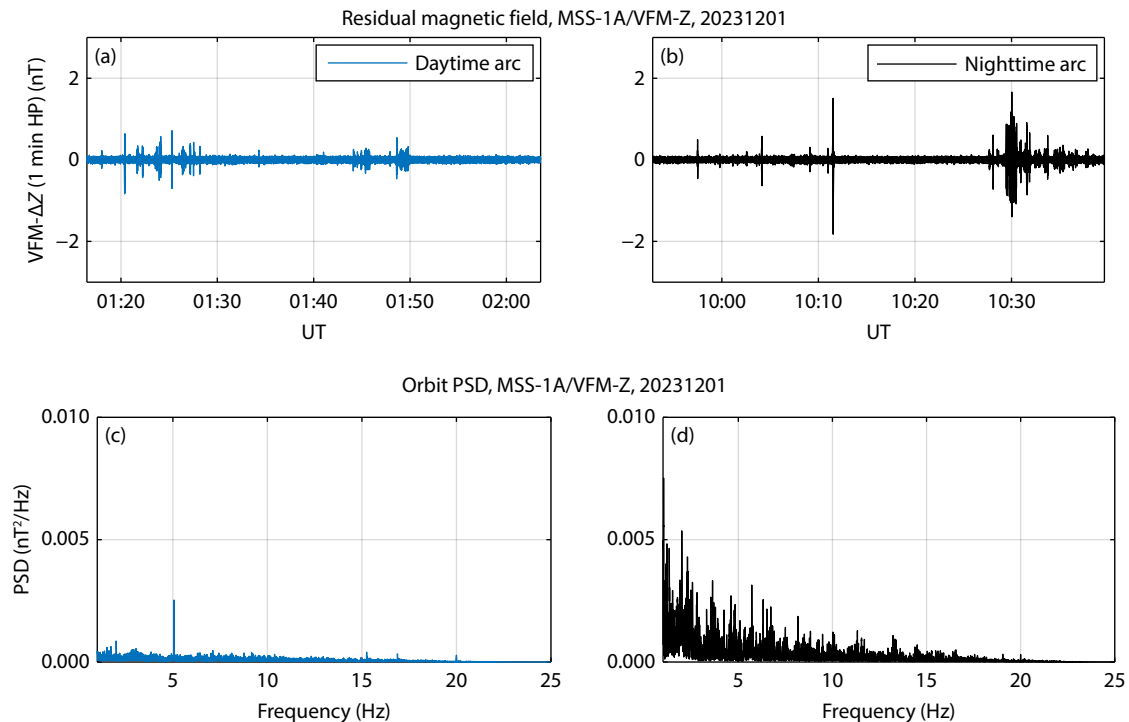


Figure 2. MSS-1A daytime and nighttime noise spectra, recorded on a day when a 5 Hz peak was observed: (a, c) Daytime arc. (b, d) Nighttime arc. (a, b) are the corresponding Z-axis residual magnetic field time series for each arc; (c, d) are orbit PSDs of B_z (in VFM).

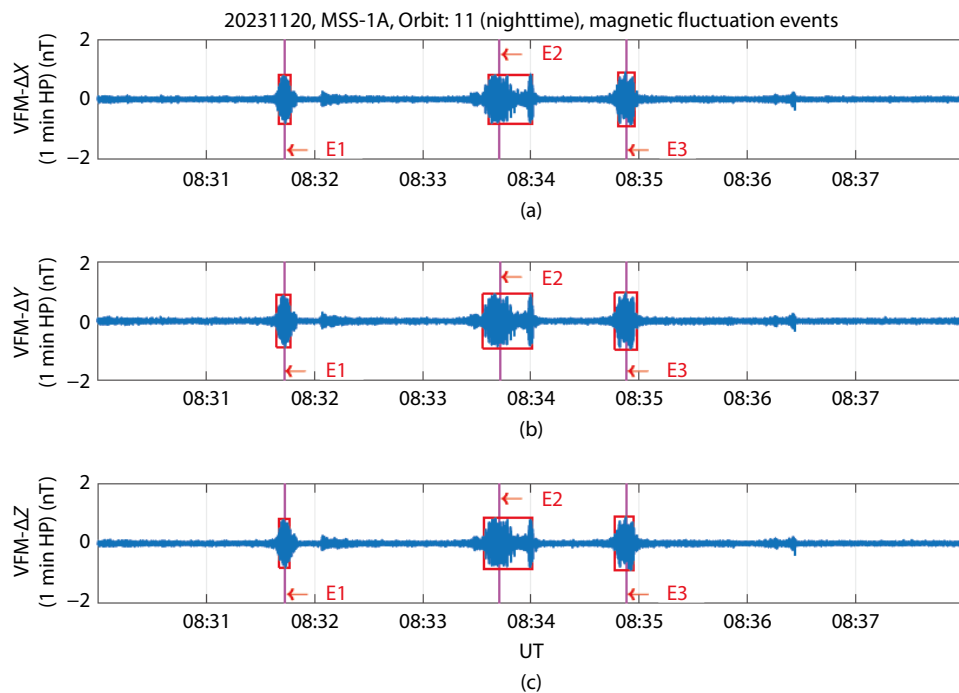


Figure 3. (a, b, c) An example of event detection in the X, Y and Z components. Red boxes mark the detected events.

± 0.15 nT as the threshold defining an event of magnetic intensity fluctuation. The justification for such a small value is that the VFM data of MSS-1A have a low noise level. Another parameter is the number of successive data points exceeding the threshold, which determines the duration of a valid event. A subevent is defined by a minimum of three successive points exceeding the threshold of the magnetic residuals. Moreover, if the interval between two

subevents is short, we combine the subevents. These defining parameters allow the procedure to detect valid disturbance events and derive magnetic fluctuation information in the time domain, e.g. the event's start and end times, prior to the event's detailed analysis. Figure 3 presents an example of the event detection approach, based on data from all three VFM components, observed during nighttime on 20 November 2023. Each

detected event is marked by a red box. Box widths represent the durations of the events; heights reflect the peak-to-peak amplitudes. A magenta line indicates the weighted center of each event's time duration, weighted by magnitude variation. Note that the three events in Figure 3 were detected on all three VFM axes and at the same amplitude.

3. Results and Discussion

3.1 V-shaped Events

The seven months of data we examined include a large number of detected events. Among them are many events characterized by a V-shape, detected in all three field directions, its components with almost the same amplitudes and temporal evolution of their consistent spectral shapes. These V-shaped signals were detected rather frequently in each day's data; they occurred 7564 times in total and exhibited a number of commonalities (see Figure 7c). Figure 4 presents spectral characteristics of a typical V-shaped event; its three upper lefthand panels (4a, 4b, and 4c) present the event's three VFM components over its 10 s duration. The amplitudes of the disturbance all show commonality, first rising and then decreasing, and all are in the range of ± 2 nT. In the frequency domain, the signal fluctuates rapidly at first, becomes slow later,

then returns to fast oscillation before disappearing. Its time sequence variation thus has the shape of a rhombus. The event's CWT time–frequency spectrum (Figure 4d) resembles a 'V', which is why we call such events "V-shaped". The oscillations of these events start at the Nyquist frequency and then quickly go to zero, rise up again to the initial state, and then disappear. We also found incomplete V-shaped events; an example is presented in the right hand panels of Figure 4, which clearly look like half of a complete V-shaped event. The event's lack of an initial quickly-rising part gives rise to its half 'V' appearance in the event's time-frequency panel (d).

We have surveyed statistical properties of the collection of detected V-shaped events. Figure 5, upper left panel, presents the distribution of events by latitude versus local time (LT frame), from which it can be seen that they are concentrated on the nightside and at higher latitudes. The upper right panel of Figure 5 shows the mean LT distribution of events. We can see more directly the characteristic of high nighttime occurrence. The MSS-1A has a low-inclination circular orbit, so its dwelling time is different in latitude projection, though showing an equatorial symmetric distribution but shorter in lower latitude while longer in higher latitude. The blue bars and the red line in Figure 5,

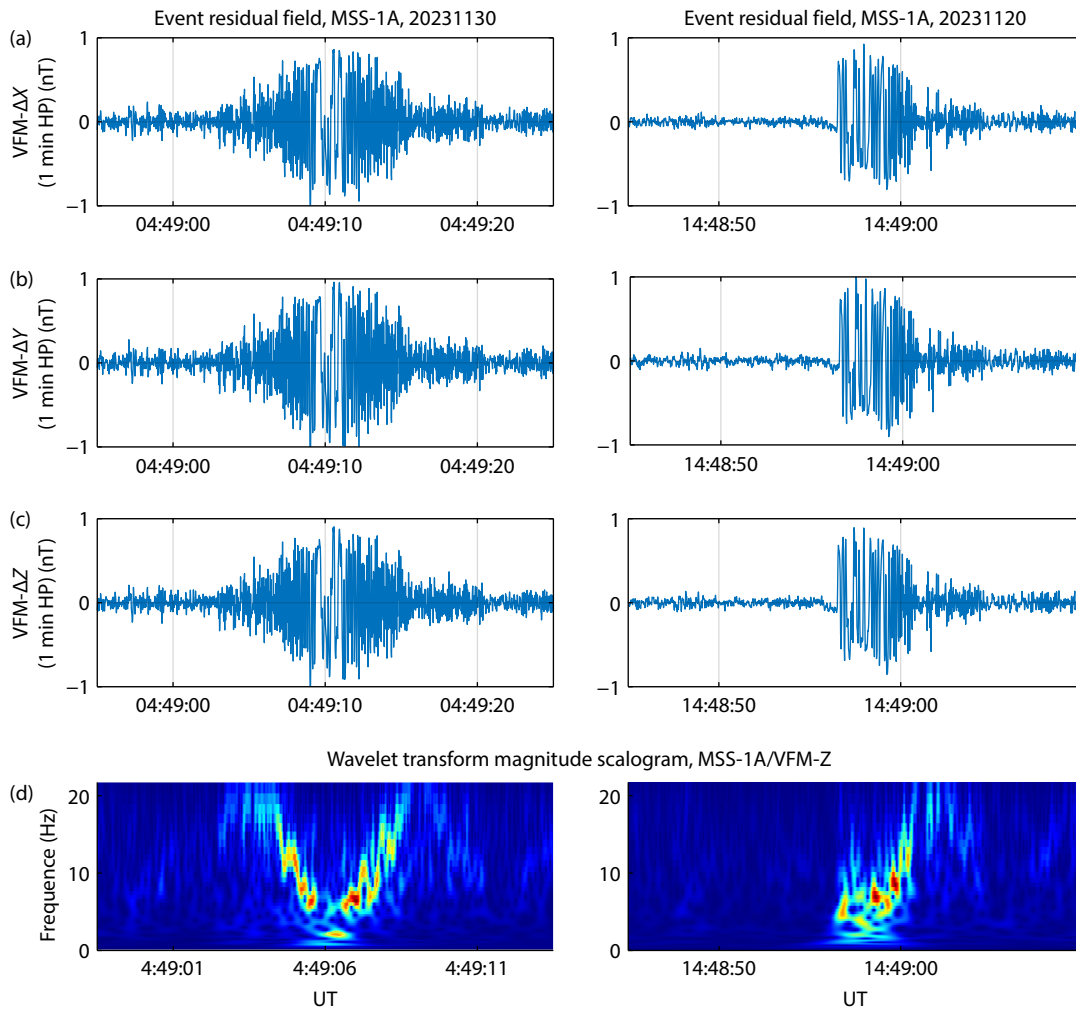


Figure 4. Left: An example of a V-shaped event. Right: An example of an incomplete V-shaped event. (a, b, c) X, Y, and Z components, respectively, of the temporal variations of the detected event. (d) The CWT of the event from the VFM Z component.

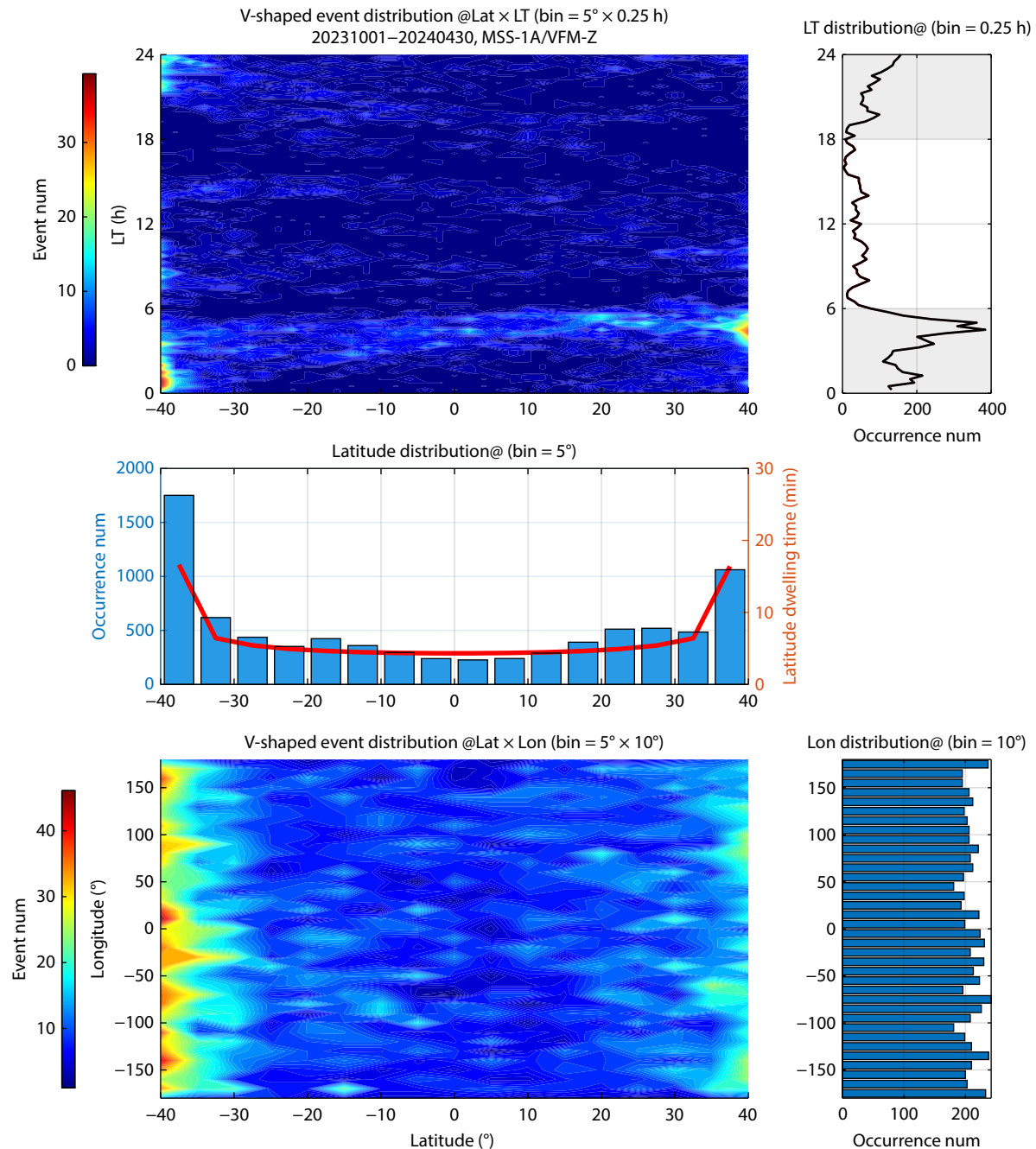


Figure 5. Statistics relating observed V-shaped events to the local time and the latitude and longitude of MSS-1A at the time of each observation. Upper left: V-shaped event distribution by latitude vs. local time. Middle: V-shaped event latitudinal distribution vs. MSS-1A latitude dwelling time. Lower left: V-shaped event latitude vs. longitude distribution. Upper right: Distribution of V-shaped events by local time (LT). Lower right: Distribution of V-shaped events by longitude.

middle, represent the V-shaped event latitudinal distribution and MSS-1A latitude dwelling time, respectively. From that it is obvious that the V-shaped event distribution is strongly related to the satellite dwelling time at a given latitude; many more events occur at higher latitudes, over the range of 35° to 41° in the southern hemisphere than in the northern. Furthermore, the events appear at clearly later times in the southern hemisphere. We believe that the higher occurrence of V-shaped events in high-latitude regions of the Southern Hemisphere is due to seasonal factors. Because the data we analyzed in this paper were collected

from October 2023 to April 2024, which covers the summer season in the Southern Hemisphere, summer in the Northern Hemisphere was not included. We believe that if our data had included an entire year of observations, the occurrence of V-shaped events in both hemispheres would be equal in high-latitude regions, because MSS-1A spent more time in the dark in the northern hemisphere during our study period from October 2023 to April 2024. Note that no longitude dependence was observed (see Figure 5, bottom).

V-shaped artificial magnetic disturbance events appear in Swarm

Absolute Scalar Magnetometer (ASM) data; they have been traced to interferences between the Swarm ASM and the 58-kHz square signal used by the Swarm spacecraft platform to operate heaters needed for thermal control of the ASM and its sensors (Léger et al., 2015). Each time one of the harmonics of the heater signal matches the ambient scalar field Larmor frequency, these perturbations occur. Yin F et al. (2015) also found V-shaped artificial signals in CHAMP FluxGate vector Magnetometer (FGM) Y-axis data when the readings go through zero. The authors relate it to a ringing of the analog-to-digital converter as the data approach the sign change at zero-crossing. The V-shaped events observed in Swarm and CHAMP data exhibit strong geographical distributions and occurred when the sensor readings of the ASM and FGM matched a specific value of the ambient magnetic field. Those observed in MSS-1A data are apparently different. Further discussion of V-shaped events appears in Section 3.3.

3.2 5-Hz Event

Analysis of the MSS-1A daily noise spectrum revealed a distinct peak around 5 Hz on some days (Figure 2c). By comparing the PSD magnitude of these events, we confirm that the 5 Hz peak is associated with another special event, shown in the top three frames of Figure 6, which in this paper we term “5-Hz events”. Different from the V-shaped events, which appear equally in all three field components, the size of 5-Hz events is commonly larger in the Y and Z components and the three components exhibit different temporal fluctuations, which suggests that the source may be stray magnetic fields generated by spacecraft subsystems. By searching through the sequence of the events in the residual fields, we find that there are distinct spiky signals appearing at intervals. When the 5-Hz events appear, four of the attitude Quaternions had obvious variation at the same time. This makes us believe the spiky signal may be caused by the MSS-1A’s attitude control system. Finley et al. (2023) illustrates oscillatory reaction wheel interference in magnetic field data of the CASSIOPE/Swarm-Echo spacecraft. Figure 6, lower four panels, show the quaternions needed for transforming the Celestial Reference Frame (CRF) into the North East Centre (NEC) frame during the 5-Hz event occurrence (the white area). All Quaternions exhibit clear deviations from a continuous change in that area. This suggests a non-nominal functioning of the Star tracker. Fortunately, the occurrence of 5-Hz events is not particularly frequent — just 103 instances in seven months, fewer than one per day. Figure 6d gives the CWT of an event. During the whole period of event, the oscillations around 5 Hz consistently appear in the spectrogram. They are accompanied by intervals of spiky signal down to 1 Hz.

3.3 Features of VFM Noise Level

For our analysis, the seven months of VFM data have been divided into LT sectors; for each sector the PSD has been calculated, orbit by orbit, to allow us to compare mean PSD noise levels between daytime and nighttime arcs. Based on the 213 days of PSD magnitude data that we analyzed, we find that daytime noise levels are significantly lower than in nighttime, which means that fewer disturbance events occurred in daytime — with a few exceptions, (e.g. 22 December 2023).

At first sight, we see in Figure 2 that the PSD is lower in daytime

than at nighttime; the upper two panels confirm that the residual magnetic field fluctuations are more violent at night. The distribution of V-shaped events as a function of LT, in Figure 5, further proves that the V-shaped events are the main contributors to the higher nighttime noise levels.

The MSS-1A employs the same type of magnetic field instruments and boom structure as the Swarm constellation. We compare the strongest of each satellite’s three magnetic field components (Zhang JN et al., 2022) — Z-axis VFM 50 Hz data from Swarm A to X-axis VFM 50 Hz data from MSS-1A. Since Swarm satellites are polar orbiting satellites but the MSS-1A has only a low-latitude coverage, we have truncated the Swarm data collected above 41 degrees in latitude, to ensure the comparability of the analysis. Since, there are V-shaped events in MSS-1A and some signals in Swarm A. For each satellite, we use a window of one minute in which no events are observed to get a piece of the data of each ascending and descending orbite arcs in one day. And then we calculate the PSD magnitude for all the pieces and take their average value as a representative of the instrument noise level for each day. Figure 7a gives the comparison of daily average noise levels in peace time between MSS-1A and Swarm A and the result show they are almost same. Disregarding the interference, we maintain that the instruments of both satellites is equally robust.

For investigate the long time evolution of the V-shaped event disturbance. We thus calculated PSD magnitude of 50 Hz Z-axis VFM data for each intact orbit in daytime and nighttime, and take their average of one day to present the daily variation. Figure 7b shows the MSS-1A daily average noise level variation over seven months. The blue line represents the daytime average PSD, while the night time is shown by black line. Over the entire period studied, the daily mean PSD in daytime is less than in the nighttime over the period. In addition, there are four high noise level periods in Figure 7b are observed, repeating at intervals of about 52 days and lasting for 8–9 days. In Figure 7c, we give the daily number of V-shaped event. We found that the number of distinct V-shaped events increases during the high noise level periods. Thus, we believe the high occurrence of the V-shaped event is the primary cause of high noise level. Figure 7d shows the 52-day repetition in the LT of the MSS-1A ascending/descending node, which indicates the recurrence period of high noise level days. The LT of ascending/descending node in high noise level days is always 06:00/18:00. The ASM-VFM scalar residuals in Swarm also show a periodic peak oscillation related to LT (Tøffner-Clausen et al. 2016). Please notice that the LT related large VFM residuals in Swarm are attributed to the Sun-driven disturbance field. However, the LT related high noise level of the VFM in MSS-1A occurs at night. Additionally, in Figure 7b, there appear 3 high noise periods spaced at 52 days, but the fourth one keeps away from spring equinox and comes later after 75 day at the end. It appears at the same local time as the earlier ones, but on up-leg. This means, now the noise source has jumped to the northern hemisphere data at roughly the time of the equinox. This coincides with the change from southern to northern summer.

In summary, the high noise periods are a summer, nighttime phenomenon appearing around 40° latitude. Around Solstice symmetric peaks come at the beginning and end of the disturbed period. Before Solstice the peak appears at the end of the distur-

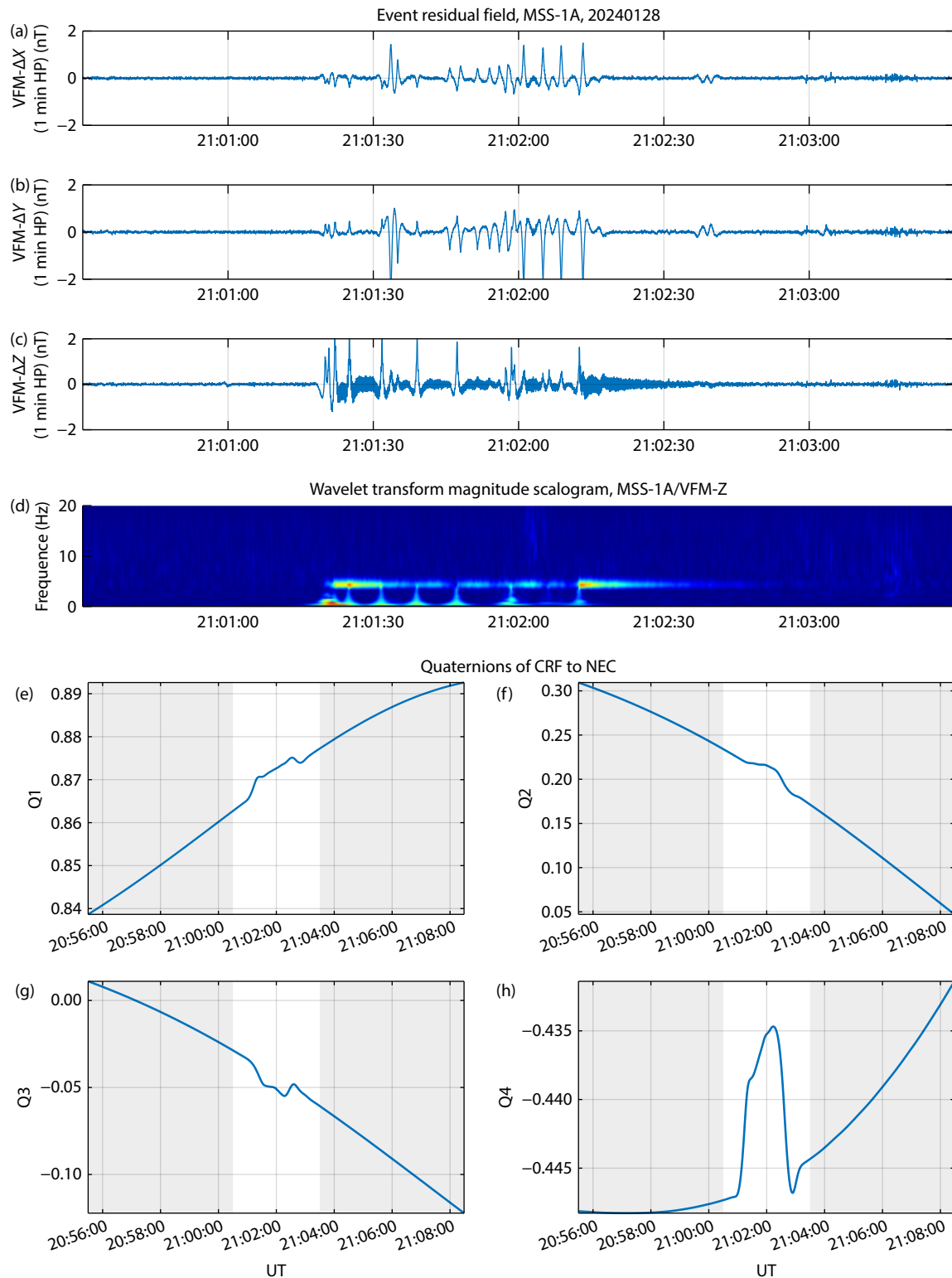


Figure 6. Example of a 5-Hz event. (a, b, c) Time sequential variations of the detected event's X, Y and Z components, respectively. (d) CWT of the event, given by the VFM Z component. (e, f, g, h) Quaternions of CRF to NEC frame (Q1, Q2, Q3, Q4 are four components of Quaternions).

bance and after Solstice at the beginning. All these characteristics make us believe that the thermal control of satellite platform may be the possible source.

4. Conclusions and Summary

We have analyzed characteristics of high-resolution MSS-1A 50 Hz

magnetic field data, in detail, to assess the quality of the data. By using a special event selection approach, we have detected a large number of artificial signal events, separated them by type, and investigated their features for statistical significance. We report two main kinds of artificial disturbances with distinct features. The largest number of artificial signals are "V-shaped

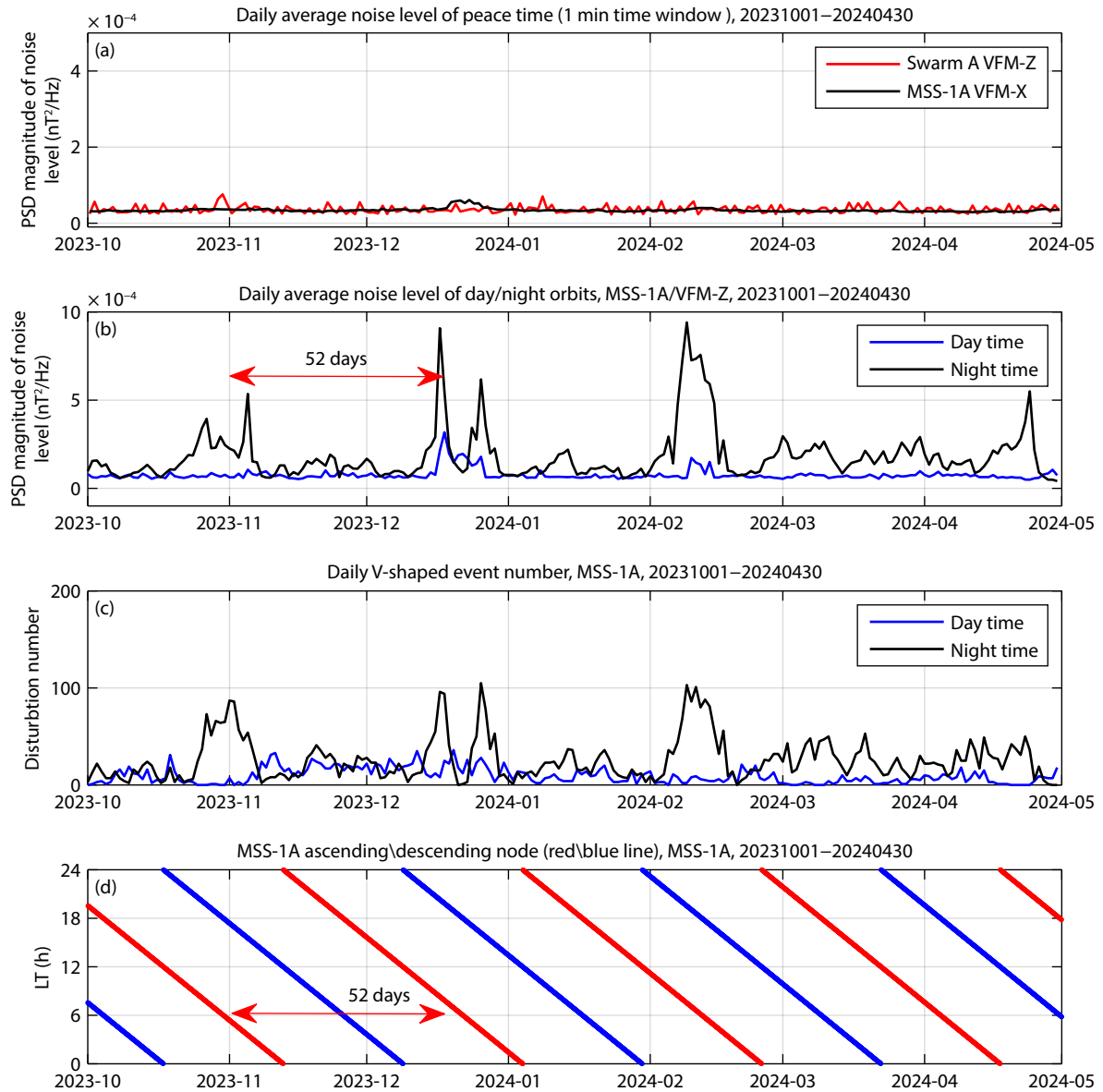


Figure 7. The daily average noise level of VFM data over seven months. (a) Comparison of daily average noise level between MSS-1A and Swarm A in peace time. (b) MSS-1A daily average noise level, separately for daytime and nighttime. (c) Daily number of V-shaped disturbance events. (d) Orbital local times of MSS-1A when crossing the equator in the two directions.

events”, which appear almost equally in all three field components, in the range of $\pm 2 \text{ nT}$. We observe a sweep through the whole frequency range, first downward to zero frequency then upward back to the Nyquist frequency. The resulting disturbance signal thus has a spectral shape resembling a ‘V’, hence the term we use for this type of disturbance, whose occurrence probability is uniformly distributed in terms of time and geographical location, but higher in the summer hemisphere and at night. Less frequently observed were “5-Hz events”, characterized by a marked 5 Hz peak in the PSD analysis. These events are typically strongest in the Z component; they were observed only 103 times in seven months and did not appear more than once per day. The 5 Hz peak in the spectrogram was consistently accompanied by broad-band signal in the 1 s interval. We find that these intervals of spiky signal are related to the satellite attitude control subsystem, when using thrusters.

In this study we reveal that the noise level in 1–25 Hz frequency range is lower, in general, during daytime than nighttime. We believe the high average noise level is caused by the V-shaped events, with their high occurrence at night. For the MSS-1A daily average noise level during the considered seven months, we obtain a mean PSD of about $0.0001 \text{ nT}^2/\text{Hz}$ in the range of 1–25 Hz. Exceptions are the three noisy periods, with durations of about 8–9 days each, in which the LT at ascending/descending node is around 06:00/18:00. The LT 52-day repetition period of the satellite ascending/descending node is related both to the concentrated distribution of V-shaped events and to the high average noise level. We also compared the daily averaged noise levels between the Swarm A and MSS-1A satellites. For MSS-1A we find, during undisturbed periods, almost the same average PSD levels as in comparable Swarm A data. This confirms the intrinsic high resolution and low noise level of VFM data from MSS-1A.

Although we provide detailed analysis of two types of noise distributions appearing in the MSS-1A data we studied, we need more house-keeping data to trace the source of the V-shaped events. Future work will focus on analysis of other types of disturbance features, eventually classifying and analyzing all different disturbance events in MSS-1A data.

Acknowledgments

We acknowledge the MSS-1A data processing team at Macau University of Science and Technology for their support. We also acknowledge ESA for providing the Swarm A data. This work is supported by the National Key R&D Program of China (Grant 2022YFF0503700) and the National Natural Science Foundation of China (42474200 and 42174186).

References

- Balasis, G., Daglis, I. A., Georgiou, M., Papadimitriou, C., and Haagmans, R. (2013). Magnetospheric ULF wave studies in the frame of Swarm mission: a time-frequency analysis tool for automated detection of pulsations in magnetic and electric field observations. *Earth Planet. Sp.*, 65(11), 1385–1398. <https://doi.org/10.5047/eps.2013.10.003>
- Chen, S. W. (2009). Control and measure of satellite magnetic cleanliness. *Prog. Geophys. (in Chinese)*, 24(2), 797–800. <https://doi.org/10.3969/j.issn.1004-2903.2009.02.061>
- Finley, M. G., Broadfoot, R. M., Shekhar, S., and Miles, D. M. (2023). Identification and removal of reaction wheel interference from in-situ magnetic field data using multichannel singular spectrum analysis. *J. Geophys. Res.: Space Phys.*, 128(2), e2022JA031020. <https://doi.org/10.1029/2022JA031020>
- Friis-Christensen, E., Lühr, H., and Hulot, G. (2006). *Swarm*: A constellation to study the Earth's magnetic field. *Earth Planet. Sp.*, 58(4), 351–358. <https://doi.org/10.1186/BF03351933>
- Herceg, M., Jørgensen, P. S., and Jørgensen, J. L. (2017). Characterization and compensation of thermo-elastic instability of SWARM optical bench on micro Advanced Stellar Compass attitude observations. *Acta Astronaut.*, 137, 205–213. <https://doi.org/10.1016/j.actaastro.2017.04.018>
- Kong, D. L. (2023). Preface to the special issue on the Macau science Satellite-1 mission. *Earth Planet. Phys.*, 7(1), 1–3. <https://doi.org/10.26464/epp2023027>
- Léger, J. M., Jager, T., Bertrand, F., Hulot, G., Brocco, L., Vigneron, P., Lalanne, X., Chulliat, A., and Fratter, I. (2015). In-flight performance of the Absolute Scalar Magnetometer vector mode on board the Swarm satellites. *Earth Planet. Sp.*, 67(1), 57. <https://doi.org/10.1186/s40623-015-0231-1>
- Ren, Z. Y., Huang, Y. P., Yang, C., Chen, C. J., and Zhang, K. (2025). Preliminary results suggest observations from Macau Science Satellite-1 system can improve knowledge of tidal-induced magnetic fields. *Earth Planet. Phys.*, 9(3), 586–594. <https://doi.org/10.26464/epp2025002>
- Tøffner-Clausen, L., Lesur, V., Olsen, N., and Finlay, C. C. (2016). In-flight scalar calibration and characterisation of the Swarm magnetometry package. *Earth Planet. Sp.*, 68(1), 129. <https://doi.org/10.1186/s40623-016-0501-6>
- Wang, Y. B., Zhang, Y., Wang, Y. J., Liu, P. F., Cheng, J. X., Li, X. Z., Tang, K., Li, L. G., and Duan, X. W. (2023). Influences of various space current systems on the geomagnetic field in near-Earth space. *Earth Planet. Phys.*, 7(1), 93–99. <https://doi.org/10.26464/epp2023010>
- Wu, M. J., Yue, H. Y., Guo, P., Ma, X., Li, H. G., Dong, J. J., and Zuo, F. F. (2024). The initial assessment of ionospheric radio occultation data of MSS-1 satellite and its applications in scintillation exploration. *Earth Space Sci.*, 11(9), e2024EA003695. <https://doi.org/10.1029/2024EA003695>
- Xiong, C., Lühr, H., Ma, S. Y., Stolle, C., and Fejer, B. G. (2012). Features of highly structured equatorial plasma irregularities deduced from CHAMP observations. *Ann. Geophys.*, 30(8), 1259–1269. <https://doi.org/10.5194/angeo-30-1259-2012>
- Xu, C. Y., Lühr, H., Xiong, C., Wang, F. J., and Zhou, Y. L. (2024). Coherence of compressional Pc3–4 pulsation driven by upstream waves in topside ionosphere observed by the Swarm constellation. *J. Geophys. Res.: Space Phys.*, 129(9), e2024JA032502. <https://doi.org/10.1029/2024JA032502>
- Yang, Y. Y., Zhou, B., Hulot, G., Olsen, N., Wu, Y. Y., Xiong, C., Stolle, C., Zhima, Z., Huang, J. P., ... Shen, X. H. (2021). CSES high precision magnetometer data products and example study of an intense geomagnetic storm. *J. Geophys. Res.: Space Phys.*, 126(4), e2020JA028026. <https://doi.org/10.1029/2020JA028026>
- Yin, F., Lühr, H., Rauberg, J., Michaelis, I., and Cai, H. T. (2013). Characterization of CHAMP magnetic data anomalies: magnetic contamination and measurement timing. *Meas. Sci. Technol.*, 24(7), 075005. <https://doi.org/10.1088/0957-0233/24/7/075005>
- Yin, F., Lühr, H., Park, J., Rauberg, J., and Michaelis, I. (2015). Noise features of the CHAMP vector magnetometer in the 1–25 Hz frequency range. *Sens. Actuators A Phys.*, 222, 272–283. <https://doi.org/10.1016/j.sna.2014.12.024>
- Yin, F., Lühr, H., Park, J., and Wang, L. (2019). Comprehensive analysis of the magnetic signatures of small-scale traveling ionospheric disturbances, as observed by Swarm. *J. Geophys. Res.: Space Phys.*, 124(12), 10794–10815. <https://doi.org/10.1029/2019JA027523>
- Zhang, H., Yu, C. Y., Suo, L., Luo, W. B., Yuan, D., and Ou, J. M. (2023). Thermal stability analysis of a satellite-borne optical bench based on quasi-kinematic support. *Earth Planet. Phys.*, 7(1), 119–124. <https://doi.org/10.26464/epp2023020>
- Zhang, J. N., Cheng, B. J., Tong, Y. Q., Miao, Y. Q., Zhou, B., Andreas, P., Zhu, X. H., Yang, Y. Y., Guo, X. C., ... Shen, X. H. (2022). Comparison of scalar magnetic field data of China Seismo-electromagnetic satellite and swarm bravo satellite. *Front. Earth Sci.*, 10, 866438. <https://doi.org/10.3389/feart.2022.866438>