GUEST EDITORIAL

Earth and Planetary Physics
7: 1–3, 2023
doi: 10.26464/epp2023027

Preface to the Special Issue on the Macau Science Satellite-1 Mission

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Citation: Kong, D. L. (2023). Preface to the Special Issue on the Macau Science Satellite-1 Mission. *Earth Planet. Phys.*, *7*(1), 1–3. http://doi.org/10.26464/epp2023027

Abstract: The Macau Science Satellite-1 (MSS-1) mission (https://mss.must.edu.mo/) is marked by a new high-precision constellation of satellites that will survey the Earth's geomagnetic and space environment. MSS-1 consists of two satellites that are to be launched in the near future. Since these two low Earth orbit (LEO) satellites will operate in circular orbits, with an inclination of about 41°, they are expected to provide essential measurements covering the Earth's lower-latitude regions—including, especially, the South Atlantic Anomaly (SAA). This special issue presents 18 articles to provide the international scientific community with details regarding the mission's goals, relevant scientific research, on-board payloads, and international collaborations. Contributors are members of the scientific and engineering groups involved in the mission. In this preface, we categorize the articles and give some brief comments or editor's recommendations.

Keywords: geomagnetic field; satellite geomagnetism; Macau Science Satellite-1

The Earth's geomagnetic field is a very remarkable phenomenon. The active geodynamo process operating in Earth's liquid core generates the predominant part of the planet's geomagnetic field—a globally quasi-dipolar external magnetic field caused by the core's turbulent magnetohydrodynamics under rapid rotation. This field interacts and interplays with the Earth's internal and external layers—e.g., its mantle, lithosphere, ocean, atmosphere, and magnetosphere—resulting in a variety of secondary magnetic sources that contribute to peculiar geomagnetic signatures. The overall geomagnetic field and its temporal-spatial variations are both scientifically important and rich in applications.

In recent decades, instruments carried by LEO satellites have provided unprecedented time-space data coverage of the Earth's global geomagnetic field. Satellite observations of geomagnetism have already greatly enhanced monitoring and understanding of the geomagnetic field (Olsen and Stolle, 2012). In the era of high-precision measurements, represented by the previous CHAMP mission and the current SWARM missions, vector field data can be precisely acquired not only in the sensor's frame of reference but also in the geographical coordinate system, thanks to the key design of optical benches that rigidly connect a vector magnetometer to a stellar compass (Herceg et al., 2017).

Adopting a similar architecture, the highly-stable optical bench of the Macau Science Satellite-1 (MSS-1) mission will make MSS-1 China's first satellite constellation with high-precision geomagnetic field measurements. MSS-1 consists of two separate satellites, Satellite A (Sat A) and Satellite B (Sat B), both of which are to be launched into near-circular orbits with an inclination of about 41° and an altitude of about 450 km. Sat A is mainly responsible for the geomagnetic surveying while its companion, Sat B, will focus on solar activity observations. Both satellites are equipped with energetic-electron spectrometers and hence are capable of mapping the near-Earth space environment. It is worth mentioning that the lower-latitude coverage of its orbits gives the MSS-1 mission a unique advantage in monitoring the South Atlantic Anomaly, which is of wide scientific interest.

The MSS-1 mission is funded jointly by the China National Space Agency and the government of the Macau Special Administrative Region of the People's Republic of China. The two MSS-1 satellites will be launched shortly. The 18 papers in this special issue are thus timely. They have been written by scientists and engineers participating in the MSS-1 mission. The papers are divided into three categories. Papers 1 to 12 present related scientific research; Papers 13 to 15 describe engineering aspects of the mission—payloads and the satellites; the remaining papers discuss relevant mission simulations and future perspectives. This special issue is intended to elucidate some of the matters that may concern the international geomagnetism community, and to help prepare future users for the scientific data that will soon start to become available from the MSS-1 mission.

The geomagnetic field measured at the satellite's altitude is made up of contributions from complex sources. In the opening article of this special issue, Zhang K (2023) comprehensively reviews the key MHD processes underlying geomagnetism and discusses recent achievements in understanding satellite geomagnetism, which will be extremely helpful in analyzing satellite data to identify contributions from different magnetic sources. Also presented is an overview of the scientific and applicational significance of high-precision geomagnetic field measurements. Zhang also proposes a novel concept of the next-generation geomagnetic constellation and explains its superior potential capability. The views and visions in Zhang's review article are elaborated and supported by the papers that follow.

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Received 02 JAN 2023; Accepted 04 JAN 2023.
Accepted article online 05 JAN 2023.

The main core field is very dynamic and changeable at different time scales, ranging from months to millions of years. How the geodynamo has been sustained has been a long-existing scientific puzzle. Li JF et al. (2023) apply a novel data assimilation method to investigate long term evolution and dynamics of the geodynamo. The study combines synthetic geomagnetic field data with numerical geodynamo simulations and shows that the data assimilation technique can reveal some key dynamics deep in the liquid core. Future MSS-1 data, which will provide better understanding of longitudinal variation of the geomagnetic field, can help further improve geodynamo research.

At decadal to sub-decadal time scales, there are interesting geomagnetic variations, such as secular variation, secular acceleration, and geomagnetic jerk. The causes of these variations have been identified as flows, oscillations, and waves at the top of the liquid core. Xu JY and Lin YF (2023) attempts to identify several primary dynamic modes in geomagnetic secular variation data. Li YJ et al. (2023) analyzes ground geomagnetic observatory data together with satellite geomagnetic data for the geomagnetic jerk events taking place in the 2010s. Continuous high-precision satellite geomagnetic data spanning the two decades since 2000 have been key to facilitating these time variation studies. Future MSS-1 data will provide continuity to these investigations and will increase their precision. In particular, unprecedented coverage of the SAA by the MSS-1 data can improve the resolution of the liquid core flow in that region.

The Earth's *mantle* is electrically conducting, though its conductivity is much lower than that of the planet's liquid metal *core*. Time-varying geomagnetic fields below or above the mantle can induce electrical currents within the mantle and hence produce magnetic signatures. A similar mechanism takes place in the ocean, which is also electrically conducting. At the MSS-1 satellite's altitude, the intensity of induced magnetic signatures (such as those of the mantle and the ocean) can be as low as just a few nano-Teslas (nT), very close to the accuracy level of SWARM and MSS-1 data. As a result, in order to effectively extract the corresponding magnetic signatures related to the mantle or the ocean, a detailed understanding of the field-inducing processes is necessary. Papers by Yao HB et al. (2023) and Yin L et al. (2023) are dedicated, respectively, to these two problems. Their theories and models will play an important role in future MSS-1 data analyses.

The magnetized *lithosphere* has its induced or remnant magnetic field, which can be utilized in geological study, resource exploration, and navigation. There are two kinds of lithosphere magnetic field models. One is regional and the other is global. Regional models are usually marked by high spatial resolution because the data are mainly obtained through ground, sea-borne, or air-borne observations. Spatial coverage is limited but accuracy can be high because the measurements are made near the field sources. On the other hand, global models depend on geomagnetic satellite data, which have good spatial coverage but limited accuracy because the measurements are made farther away from the field sources. In applications, regional models and global models can be used together. Feng Y et al. (2023) and Liu PF et al. (2023) discuss detailed procedures for constructing and utilizing regional and global models of lithospheric magnetism. Although the orbits of the MSS-1 satellites will limit their coverage primarily to the lower-latitude regions, their high-precision vector field data will benefit scientific studies of lithospheric magnetic fields, as well as practical applications.

The *atmosphere's* electrical conductivity increases gradually with altitude, as atoms and molecules are ionized by solar radiation and other mechanisms. Large-scale atmospheric wind within the Earth's main magnetic field will thus lead to the so-called atmospheric dynamo process, which operates mainly in the *ionosphere*. Ionospheric electrical currents can produce strongly time-varying magnetic fields. Yi SQ et al. (2023) discuss the ionospheric dynamo process, especially as observed in the SAA region.

At an even higher altitude is the Earth's *magnetosphere*, above the atmosphere, consisting of a plasma environment that is controlled jointly by the geomagnetic field and the solar wind. The magnetosphere's electrical current systems are complex and time-varying and thus can significantly distort the geomagnetic field. Magnetospheric activity can reach remarkable levels during geomagnetic storms. Wang YB et al. (2023) review these complicated current systems in magnetospheric space. The two papers of Yi and Wang are crucial to future interpretations of the MSS-1 data.

Both Sat A and Sat B of MSS-1 carry spectrometers designed to detect energetic electrons, in order to monitor the Earth's inner radiation belt. As is well known, the inner radiation belt reaches its lowest altitude above the Earth's surface in the SAA region, owing to the region's weak geomagnetic field intensity. The orbit configuration of the MSS-1 mission provides an excellent opportunity for improved studies of the inner radiation belt. Xiang Z et al. (2023) and Li YX et al. (2023) review the relevant research and discuss how the MSS-1 mission can contribute to inner belt studies.

From the engineering point of view, a highly-stable optical bench is key infrastructure on a high-precision vector field geomagnetic satellite. The MSS-1 optical bench offers a rigid connection between the stellar compass and the vector magnetometer such that the vector components measured in a satellite sensor's reference frame can be reliably converted to an inertial reference frame. Accurate vector data in the geographical reference frame can then be derived by virtue of the Earth Orientation Parameters (EOP). The stiffness and stability of the optical bench are critical to the ultimate accuracy of the MSS-1's vector magnetic field measurements, without which the sensor's precision would be lost in the reference frame conversions. It has been well known that a related problem in SWARM's optical bench was responsible for reducing data quality significantly before the problem was identified and calibrated (Tøffner-Clausen et al., 2016). In this special issue, (Zhang H et al., 2023), the team who manufactured the optical bench onboard the MSS-1 Sat A , discuss its advanced design and performance in tests.

The MSS-1 Sat B is oriented towards the Sun since one of its major tasks is to observe solar activities during Solar Cycle 25. Its main scientific payload is an X-ray detector. Shi YQ et al. (2023) describe how the payload will work and its expected scientific output, from the manufacture's and user's perspectives.

Throughout the MSS-1 mission, the two satellites will rely on their primary GNSS receivers to determine their instantaneous real-time position and velocity in the orbits. These fundamental data are vital in all scientific measurements and in satellite flight control. However, the MSS-1 satellites are going to operate repeatedly in the SAA region, where space weather conditions are known to be very challenging to any satellite or spacecraft. In case such conditions should cause the GNSS receivers to fail, the satellite is equipped with laser retro-reflector arrays that will become a backup means to determine the orbits of the satellites. Cheng ZE et al. (2023) explain the relevant designs of the payloads and their capacity in ground satellite laser ranging measurements.

Raw vector geomagnetic data, as detected by magnetometers, cannot be used straightforwardly in scientific research. They have to be adjusted with attention to many mechanical, thermal, and electromagnetic interferences or disturbances arising within themselves, from other payloads, or from the satellite's framework. Additional, unanticipated influences make in-flight calibration inadvisable. As a result, mission planners have chosen to carry out comprehensive simulation studies, together with ground calibration work, before the satellites are deployed in their orbits. Li XZ et al. (2023) present a detailed mission simulation. The focus is to create a virtual testbed of a geomagnetic satellite, in which the outputs of various payloads under their mutual interferences and disturbances could be simulated as close to reality as possible. The testbed can be used for mock data calibrations and as a building block of an automatic problem diagnostics system. Yan Q et al. (2023) present a preliminary result on the implementation of an estimation algorithm of the Euler angles of the vector magnetometer sensors onboard MSS-1 Sat A.

In the opening article of this special issue, Zhang K (2023) proposes a novel next-generation geomagnetic constellation. Besides the MSS-1 Sat A that flies in a near-circular, near-equatorial orbit, two additional satellites are proposed, operating in elliptic polar orbits whose perigee altitudes Zhang suggests might reach as low as 200 km while their apogee altitudes could extend to as high as 5,000 km. A fantastic feature of such an orbit is that the perigee is latitude ergodic, due to the Earth's non-spherical gravitational field. As a result, under the Earth's rotation, the 200 km perigee can cover the whole globe. Such unprecedentedly low-altitude orbit coverage would bring drastic improvement in the range of geomagnetic field measurements. Jiang Y et al. (2023) conduct an end-to-end simulation to demonstrate convincingly the superiority of such a satellite constellation. These two papers unveil a promising future in satellite geomagnetism.

The MSS-1 satellites will be launched soon. Access to and use of MSS-1 data products are regulated by the MSS-1's Data Policy and are subject to acceptance of specific Terms and Conditions. All users who accept the Terms and Conditions will have free anonymous access to all MSS-1 Level 2 and Level 3 data products.

Acknowledgments

The guest editor wishes to thank all the authors and the reviewers for their efforts, as well as the EPP editors who helped us a lot in the editorial work. The support from National Natural Science Foundation of China (grant No. 12250013) is acknowledged.

References

Cheng, Z. E., Tang, K., Zhang, Z. P., Zhang, H. F., Li, P., and Long, M. L. (2023). Design and analysis of the Macau Science Satellite-1's laser retro-reflector array. *Earth Planet. Phys.*, *7*(1), 131–135. https://doi.org/10.26464/epp2023008

Feng, Y., Li, Y. J., Zhang, J. Y., Liu, S., Nasir, A., and Huang, Y. (2023). Study of the geomagnetic field's regional gradients in Chinese continent using three-dimensional surface Spline model. *Earth Planet. Phys.*, *7*(1), 74–83. https://doi.org/10.26464/epp2023013

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

Jiang, Y., Olsen, N., Ou, J. M., and Yan, Q. (2023). Simulation for MSS-2 low-perigee elliptical orbit satellites: an example of lithospheric magnetic field modelling. *Earth Planet. Phys.*, *7*(1), 151–160. https://doi.org/10.26464/epp2023021

Li, J. F., Lin, Y. F., and Zhang, K. K. (2023). The effect of model errors in ensemble sequential assimilation of geomagnetic field. *Earth Planet. Phys.*, *7*(1), 22–31. https://doi.org/10.26464/epp2023006

Li, X. Z., Li, L. G., Tang, K., Wang, Y. B., Cheng, J. X., Yan, Q., and Huang, Z. (2023). Numerical simulation of the sensor output on Macau Science Satellite-1. *Earth Planet. Phys.*, *7*(1), 136–143. https://doi.org/10.26464/epp2023014

Li, Y. J., Feng, Y., Zhang, S. Q., Liu, S., Zhang, J. Y., and Wei, G. C. (2023). The study of geomagnetic jerk from 2010 to 2021 based on hourly mean data from global geomagnetic observatories. *Earth Planet. Phys.*, *7*(1), 39–48. https://doi.org/10.26464/epp2023016

Li, Y. X., Yue, C., Liu, Y., Zong, Q. G., Zou, H., and Ye, Y. G. (2023). Dynamics of the inner electron radiation belt: A review. *Earth Planet. Phys.*, *7*(1), 109–118. https://doi.org/10.26464/epp2023009

Liu, P. F., Jiang, Y., Yan, Q., and Hirt, A. M. (2023). The behavior of a lithospheric magnetization and magnetic field model. *Earth Planet. Phys.*, *7*(1), 66–73. https://doi.org/10.26464/epp2023025

Olsen, N., and Stolle, C. (2012). Satellite geomagnetism. *Annu. Rev. Earth Planet. Sci.*, *40*, 441–465. https://doi.org/10.1146/annurev-earth-042711-105540

Shi, Y. Q., Li, L. S., Chen, J. W., Zuo, F. C., Zhang, X. P., Mei, Z. W., Wang, L., and Zhang, K. K. (2023). Design of the solar X-ray detector for the Macau Science Satellite-1B. *Earth Planet. Phys.*, *7*(1), 125–130. https://doi.org/10.26464/epp2023018

Tøffner-Clausen, L., Lesur, V., Olsen, N., and Finlay, C. C. (2016). In-flight scalar calibration and characterisation of the Swarm magnetometry package. *Earth Planets Space*, *68*, 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

Xiang, Z., Ni, B. B., Liu, Y. X. Z., Gu, X. D., Fu, S., Xu, W., Cao, X., Ma, X., Guo, D. Y., … Hu, J. L. (2023). Modeling the energetic electron fluxes in the inner radiation belt based on a drift-source model. *Earth Planet. Phys.*, *7*(1), 100–108. https://doi.org/10.26464/epp2023012

Xu, J. Y., and Lin, Y. F. (2023). Dynamic mode decomposition of the geomagnetic field over the last two decades. *Earth Planet. Phys.*, *7*(1), 32–38. https://doi.org/10.26464/epp2023026

Yan, Q., Ou, J. M., Suo, L., Jiang, Y., and Liu, P. F. (2023). Study on the estimation of Euler angles for Macau Science Satellite-1. *Earth Planet. Phys.*, *7*(1), 144–150. https://doi.org/10.26464/epp2023017

Yao, H. B., Ren, Z. Y., Pan, K. J., Tang, J. T., and Zhang, K. K. (2023). A global mantle conductivity model derived from 8 years of Swarm satellite magnetic data. *Earth Planet. Phys.*, *7*(1), 49–56. https://doi.org/10.26464/epp2023011

Yi, S. Q., Xu, X. J., Zhou, Z. L., Chang, Q., Wang, X., Luo, L., He, P. S., and Li, H. (2023). Theoretical study of the ionospheric dynamo region inside the South Atlantic Anomaly. *Earth Planet. Phys.*, *7*(1), 84–92. https://doi.org/10.26464/epp2023015

Yin, L., Ren, Z. Y., Yao, H. B., and Yang, C. (2023). A finite volume method for global electromagnetic induction forward modeling on collocated unstructured grids. *Earth Planet. Phys.*, *7*(1), 57–65. https://doi.org/10.26464/epp2023007

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, K. (2023). A novel geomagnetic satellite constellation: Science and applications. *Earth Planet. Phys.*, *7*(1), 4–21. https://doi.org/10.26464/epp2023019