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Preface to the Special Issue of Initial Scientific Results of MSS-1

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Abstract: The scientific research of geomagnetism has been largely driven by new geomagnetic data that are available to scientists. Macau Science Satellite-1 (MSS-1) was successfully launched on 21st May 2023 into a near-circular orbit of altitude of about 450 km with a low inclination of 41°. After careful evaluation and calibration (7th June 2023 to 31st July 2024), the data of MSS-1 were released to the international scientific community on 1 August 2024, providing the highly accurate data of global geomagnetic field with an unprecedented local-time coverage to the community. This special issue of Initial Scientific Results of MSS-1, primarily driven by the new MSS-1 data, contains 27 research articles ranging from the MSS-1 design, satellite data analysis, outer core dynamics, mantle induction, lithospheric field modeling, ocean induced magnetic field, ionosphere and magnetosphere currents, to solar activities.

Keywords: geomagnetism; geodynamo; magnetometers; Macau Science Satellite-1

The scientific research of geomagnetism has been largely driven by new geomagnetic data available to scientists. The first satellite-borne magnetometer was first launched by NASA as part of the Polar Orbiting Geophysical Observatory missions in the mid-1960s; the Oersted mission and the CHAMP mission, which were operational between 1999 and 2010, provided high-precision global geomagnetic data for the study of geomagnetism; the European Space Agency launched in 2013 its Swarm mission of three geomagnetic field satellites which have accurately measured global geomagnetic fields for about 12 years; Macau Science Satellite-1 (MSS-1) mission, comprising a set of twin satellites (MSS-1A and MSS-1B), was successfully launched on 21st May 2023 into a near-circular orbit of altitude about 450 km with a low inclination of 41°, providing the highly accurate data of geomagnetic fields with an unprecedented local-time coverage. Macau Science Satellite-2 (MSS-2) is planned to be launched into an elliptical polar orbit with a perigee of around 200 km and will form, together with MSS-1, a geomagnetic satellite constellation, allowing the lithospheric field to be measured at the highest ever spatial resolution by a satellite and the first 3-D measurement of the geomagnetic field in near-Earth space (Zhang K, 2023).

The main scientific payloads on MSS-1A are a Fluxgate Magnetometer (FGM), a Coupled Dark State Magnetometer (CDSM), a Vector Field Magnetometer (VFM) and three Star Camera Trackers, which are placed on a highly stable optical bench. Note that the MSS-1A satellite is characterized by a nearly 4.5-meter-long boom with a total length of about 8.5 meters. The scalar magnetometer is based on quantum effects, directly measuring the strength of the geomagnetic field via the Zeeman effect and allowing the vector magnetometer to be calibrated. Under stringent magnetic cleanliness conditions with an optical bench nearly without temperature-induced deformation, the magnetic data measured by MSS-1A are of high quality with RMS error of less than 0.5 nT, providing an important source of accurate geomagnetic field data for studying Earth's interior and near-Earth space from the fluid core, mantle, lithosphere, oceans, ionosphere and magnetosphere. MSS-1B is a cube-shaped satellite with instruments designed to measure plasma density, energetic electrons, and solar activity. It should be particularly pointed out that opportunities were taken to carefully investigate the magnetic measurements at the cross-over orbits between MSS-1A and Swarm A satellites, showing an excellent agreement.

After more than one year (7th June 2023 to 31st July 2024) of careful evaluation and calibration, the data of MSS-1A and MSS-1B were released to the international community on 1st August 2024. Driven mainly by the new geomagnetic data of MSS-1, this Special Issue of Initial Scientific Results of MSS-1 contains 27 research articles, ranging from an introduction to geomagnetic measurements, the design of MSS-1A, satellite data analysis, outer core dynamics, mantle induction, lithospheric field modeling, ocean induced magnetic field, ionosphere and magnetosphere currents and solar activities. It should be especially emphasized that some studies in this special issue take advantage of both MSS-1 and Swarm measurements: MSS-1 is marked by excellent local-time coverage without the coverage of polar regions while Swarm has excellent global coverage with a poor coverage in local time. In

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other words, a combination of both Swarm and MSS-1 magnetic data will undoubtedly lead to a significant improvement in the quality of magnetic data and in the accuracy of geomagnetic modeling.

This special issue covers a broad range of research topics in connection with the newly released data of MSS-1A and MSS-1B. Gubbins (2025) first provided an important review on the fundamental advantages and disadvantages of different possible magnetic measurements; Li Y et al. (2025) discussed the innovative design of MSS-1A with a highly stable optical bench and an ultra-high magnetic cleanliness control that ensure a minimum measurement error in the magnetic field's three components; Olsen (2025) studied a combination of magnetic data from both the MSS-1 and Swarm mission, unveiled the complementary nature of polar-orbiting (Swarm) and low-inclination (MSS-1) satellites in geomagnetic modeling and confirmed the excellent data quality and agreement of the two missions during the close encounters between MSS-1 and Swarm satellites; Qiu YX et al. (2025) focused on the in-flight calibration of MSS-1A's FGM with the CHAOS-7 geomagnetic field model, revealing that the FGM magnetic data exhibit good agreement with the VFM data; Rang XY et al. (2025) performed a comprehensive evaluation of the MSS-1A magnetic data, demonstrating that the data effectively capture primary features of the magnetospheric and ionospheric currents; Song SS et al. (2025) carefully studied contamination sources of the VFM magnetic data at different frequencies and revealed that VFM noise levels in daytime are systematically lower than in nighttime; Yao HB et al. (2025a) investigated the quantitative impact of different data selection criteria on internal geomagnetic field modeling and found on reports that the uncertainties introduced into a model by different data selection criteria can be significantly larger than the measurement accuracy of modern geomagnetic satellites; Yao HB et al. (2025b) incorporated the ocean circulation-induced magnetic field into geomagnetic field modeling and demonstrated that neglecting the circulation-induced field in the modeling results in leakage into the core field model; Gao Y et al. (2025) identified, by integrating the MSS-1 magnetic data with the data from different missions, new interesting geomagnetic features of the South Atlantic Anomaly, a broad region of low magnetic field intensity over the southern Atlantic; Li JF et al. (2025), making use of physics-informed neural networks and incorporating the latest magnetic data from Swarm and MSS-1, derived a core-surface flow revealing persistent large-scale circulation linked to geomagnetic westward drift, significant temporal variations in the equatorial Pacific, and distinct jet-like structures at the poles; Ren ZY et al. (2025a) presented preliminary results of tidal-induced magnetic field signals extracted from 9 months of the magnetic data measured by MSS-1 (from November 2023 to July 2024), underscoring the strong potential of MSS-1 data in large-scale ocean-tidal modeling; Ren ZY et al. (2025b), taking advantage of MSS-1's unique 41-degree inclination and high-density observations across wider local times, investigated Earth's internal conductivity structure and water content distribution, and report compelling evidence supporting the hypothesis of a deep water cycle within the Earth's interior; Gu Y et al. (2025) used a nonlinear inversion method to recover the tidal flow velocity from its magnetic signals extracted from the MSS-1 data, demonstrating good agreement between the HAMTIDE model in low- and mid-latitude regions and the flow velocity derived from the MSS-1 data; Williams et al. (2025) performed an analysis of the MSS-1 magnetic data for modeling Earth's lithospheric magnetic field and demonstrated the value of MSS-1's unique orbital configuration in complementing existing magnetic field measurements; Yin L et al. (2025) proposed, based on the cubed-sphere, a new numerical method for global and regional modeling of the lithospheric magnetic field and performed several numerical tests with the MSS-1 and Swarm data to validate the accuracy and efficiency of both forward modeling and inversion procedure; Liu PF et al. (2025) carefully evaluated the MSS-1 magnetic data to reveal that the data capture the broad magnetic structure over the North Atlantic Ocean with the trend of magnetic stripes being consistent with the age frame of oceanic crust; Du JS et al. (2025) proposed an alternative forward formula of global lithospheric magnetic field modeling that accounts for an arbitrarily high maximum degree of the inducing field and for a magnetic lithosphere of variable thickness, showing that the alternative formula can be employed as a valuable tool for quantitatively interpreting the global lithospheric magnetic field through an inverse or forward modeling; Sun SD et al. (2025) compared the forward-calculated lithospheric magnetic anomaly from an oceanic remanent magnetization model with MSS-1 magnetic data, showing that the magnetic anomalies over the normal oceanic crust regions at satellite altitude are mainly contributed by the high-intensity remanent magnetization corresponding to the Cretaceous magnetic quiet period; Zhang JX et al. (2025) constructed a lithospheric magnetic field model by combining data from CHAMP, Swarm-A, and MSS-1 and demonstrated that the MSS-1 data effectively and accurately capture fine-scale lithospheric magnetic field signals in mid-to-low latitude regions; Lin YX et al. (2025) developed a high-degree lithospheric magnetic field model by using gradient data from MSS-1, CHAMP, Swarm A/C satellites and revealed that the unique orbital characteristics of MSS-1 enable its near east–west gradient data to provide significant contributions to accurate global lithospheric modeling in the mid- to low-latitude regions; Zhang P et al. (2025) constructed, based on a spherical cap harmonic method, a high-resolution lithospheric magnetic field model of China and surroundings by incorporating 5-km resolution aeromagnetic data together with rigorously processed magnetic data from CHAMP, MSS-1, and other satellites; Gui JS et al. (2025) investigated how to mitigate, by adopting an alternative regularization, the problem of non-uniqueness and instability in the inversion of a spherical equivalent-source method, and constructed an equivalent-source regional model of lithospheric magnetic field over Africa and surroundings; Li WB et al. (2025) developed the first Sq geomagnetic field model that is directly built on the physical mechanism of the ionospheric dynamo driven by solar tidal waves, and successfully tested it using the MSS-1 data; Du JH and Yang Z (2025) used the radio occultation observations from MSS-1 to study the ionospheric response to the May 2024 G5 geomagnetic storm within the South Atlantic Anomaly region and confirmed the role of prompt penetration electric fields in driving ionospheric disturbances; Xu JY et al. (2025) constructed an averaged model to characterize F-region currents using the MSS-1 and Swarm data, which accurately reproduces the localized inter-hemispheric field-aligned currents observed in mid and low latitudes during solstices; Li JP et al. (2025) employ the soft X-ray spectra data from MSS-1 to study a main solar flare taking place on 22nd June 2023, suggesting that the entire shift of soft X-ray lines may occur during the process of solar chromospheric evaporation; Ji HS et al. (2025), after analyzing the MSS-1 measurements of rapid spectral evolution of the X-ray irradiance of solar flares during a series of X-class flares in October of 2024, suggest that there exists a close relationship between the duration and class of the solar flares and the associated geomagnetic storms.

Finally, it is worth noting that the International Geomagnetic Reference Field, which has been a standard baseline for large-scale global geomagnetic field mapping, was recently updated with its fourteenth generation by the International Association of Geomagnetism and Aeronomy via the substantial inclusion of newly measured MSS-1 geomagnetic field data. It is also worth pointing out that, after the Song Dynasty scientist Shen Kuo first introduced the concepts of Earth's magnetic poles and true north, and discovered geomagnetic inclination and declination more than 1000 years ago, China now returns to global geomagnetic surveying with some of the highest quality magnetic data-provided by MSS-1. In particular, the new geomagnetic constellation — formed by MSS-1 and MSS-2 from the year of 2028 — will significantly improve our knowledge of the Earth's magnetic environment and offer continuous global geomagnetic monitoring to the international community for decades to come.

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