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RAS Specialist Discussion Meeting on Geomagnetic Twin satellites MSS-1: Progress and Future plans

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RAS Burlington House, 10:30-15:30, 13-Oct-2023

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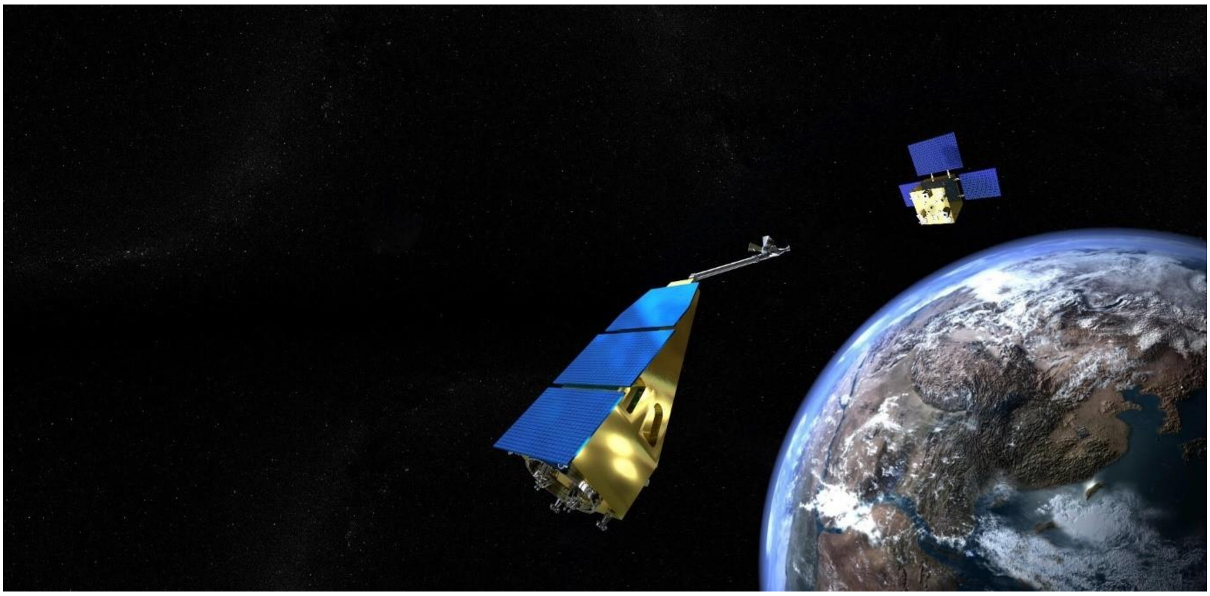

Background figure for the main page: Artist visualisation of the MSS-1A (foreground) and MSS-1B (background) in space

Overview

The study of Earth's magnetic field has always been data driven: from the invention of the compass by ShenKua in 1088 and its description in the west by Alexander Neckan (1175-1183) through to evidence for whole field reversals in the early 20th century and long-term measurements at modern ground-based observatories. The first satellite-borne magnetometers were launched by NASA as part of the Polar Orbiting Geophysical Observatory (POGO) missions in the mid-1960s. Another 15 years passed before a dedicated mission, MAGSAT, operated for six months between 1979 and 1980. After a longer hiatus, the Danish-led Oersted mission and the German-led CHAMP missions operated between 1999 and 2010, bringing forth a revolution in geomagnetism. In November 2013, the European Space Agency launched their mission of three magnetic field satellites called Swarm. These have operated for over 10 years providing a phenomenal source of magnetic, electric, and gravitational data for studying the planet and near-Earth space from the core, mantle, lithosphere, ionosphere and out to the magnetosphere.

The latest scientific mission dedicated to enhancing geomagnetic knowledge comes from Macau. An RAS Specialist Discussion Meeting to discuss the recently launched Macau Scientific Satellite (MSS-1) mission was held on the 13th October 2023 in Burlington House. The meeting was opened by David

Gubbins who welcomed the guests to the RAS and noted the long history of global collaboration in geomagnetic science.

Mission design

The mission Principal Investigator Keke Zhang, introduced the MSS-1 satellite mission, comprising a set of twin satellites (called A and B), which was successfully launched on 21st May 2023 into a near-circular orbit of altitude 450km with a low-latitude inclination of 41°. By 2026, a second set of twin satellites (MSS-2) are planned to be launched into a highly elliptical orbit of inclination 90° with a perigee of around 200km and apogee of 1500 km. The two MSS-2 satellites will orbit 180° apart allowing both poles to be surveyed simultaneously as the satellites pass through these regions. The four satellites will be in quite different orbits than any previous magnetic mission.

Professor Zhang highlighted how the magnetic field of Earth can be used to probe many different geophysical systems from the core to the magnetosphere. Taken together, the four satellites will achieve full local time coverage of the Earth every 2-3 months, which is particularly important for better understanding the dynamics in the magnetosphere and ionosphere. In addition, the equatorial orbit of MSS-1 will allow unprecedented coverage of the South Atlantic Anomaly (SAA), a locally weak spot in the intensity of the Earth’s internal field, while the low altitude perigee of MSS-2 will allow the lithospheric field of the Earth to be measured at the highest ever spatial resolution by a satellite.

The primary instruments on MSS-1A are the magnetometers which sit at the end of 4.5 m boom extending from the main body with a total length of 9 m. MSS-1B is a smaller (~3 m) cube-shaped satellite with instruments designed to measure plasma density and energetic electrons [Fig 1]. As a magnetic field satellite, MSS-1A will maintain a circular orbit for consistency of measurements, while MSS-1B will move to a slightly elliptical orbit (400-500 km) later to aid in sampling the ionosphere at different altitudes.

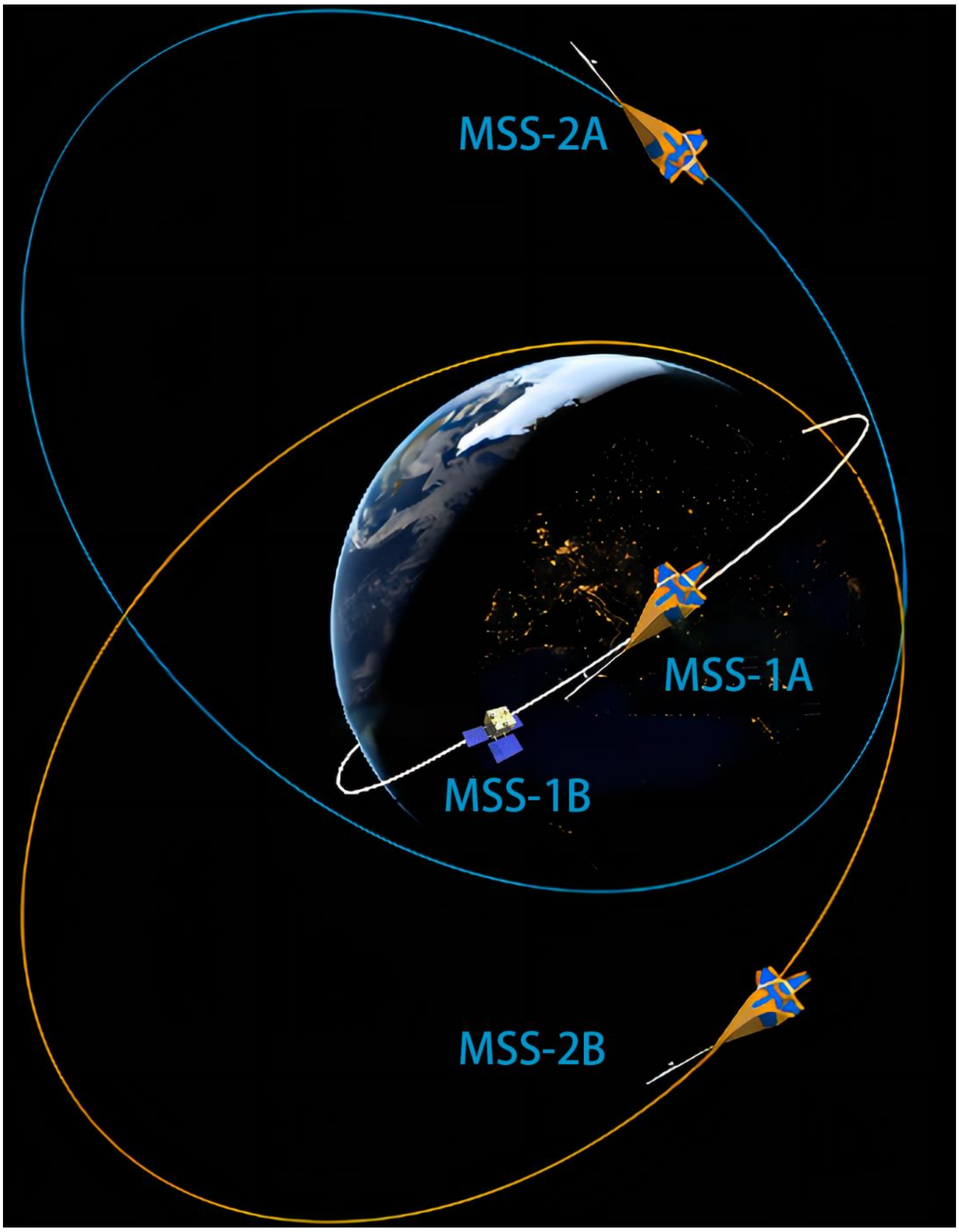

Figure 1: The MSS-1(A,B) satellites in a near-circular, 41° inclination, ~450km altitude orbit, were launched on May 21st 2023. The proposed MSS-2(A,B) satellites would complement this mission with their elliptical orbits with perigee of ~200km and apogee of ~1500km.

Satellite design, instrumentation and calibration

The detailed satellite design and initial calibration of the magnetic data was presented by Yi Jiang [Macau Institute of Space Technology and Application (MISTA)] and Shi Geng Yuan [China Academy of Space Technology]. The satellite body and subsystems were designed in conjunction with the China National Space Administration. The satellite heritage comes from an existing Chinese magnetic mission which allowed the platform to be built under stringent magnetic cleanliness conditions [Figure 2]. The primary magnetic instruments are the scalar Coupled Dark State Magnetometer (CDSM) [Figure 3] supplied by IWF, Graz (Austria) and the Vector Field Magnetometer and Star Camera Tracker provided by DTU Space (Denmark). After build and testing, magnetic interference from the body of the spacecraft was determined to be less than 0.1 nT at the end of the boom. The MSS-1 satellites were undergoing in-orbit tests to determine effects from roll manoeuvres and from on-board systems such as the reaction wheels. Initial analysis shows the magnetic data are of very high quality with RMS errors of around 0.5 nT between the scalar and vector magnetic instruments.

[Figure 2: image of the satellite being built in the workshop]

Figure 2: MSS-1A under construction (Zhang presentation). The satellite is 9m long with the boom deployed and has a mass of 570kg, carrying a payload of seven instruments.

The absolute scalar magnetometer was described by Dr Werner Magnes (IWF, Graz), who introduced the large team of partners in Austria and China who built the optically pumped magnetometer (OPM). A similar instrument flies on both the European Space Agency (ESA) Jupiter Icy Moons Explorer (JUICE) and China Earthquake Administration (CEA) China Seismo-Electromagnetic Satellite (CSES) satellite. The magnetometer is based on quantum effects, with ^{87}Rb gas in a small glass cell excited by a laser. The strength of the magnetic field is determined by observing the absorption of laser light through the cell via the Zeeman effect. The scalar magnetometer is a very stable instrument and, as well as making measurements directly, allows the accompanying vector magnetometer to be calibrated correctly in space: this removes effects such as temperature variation, optical bench deformation and electronic drift over time. One issue with OPMs is that they can have header errors (i.e., null zones) with respect to the orientation of the magnetic field. This uncertainty was determined at the Conrad Observatory (Austria) and found to be less than 0.2 nT. While in space, the opportunity was taken to examine cross-over orbits between MSS-1A and the ESA Swarm A satellite. Where the satellites cross paths the difference between the measurements has a mean of between 0-0.2 nT and a standard deviation of 0.5 nT, which is excellent agreement.

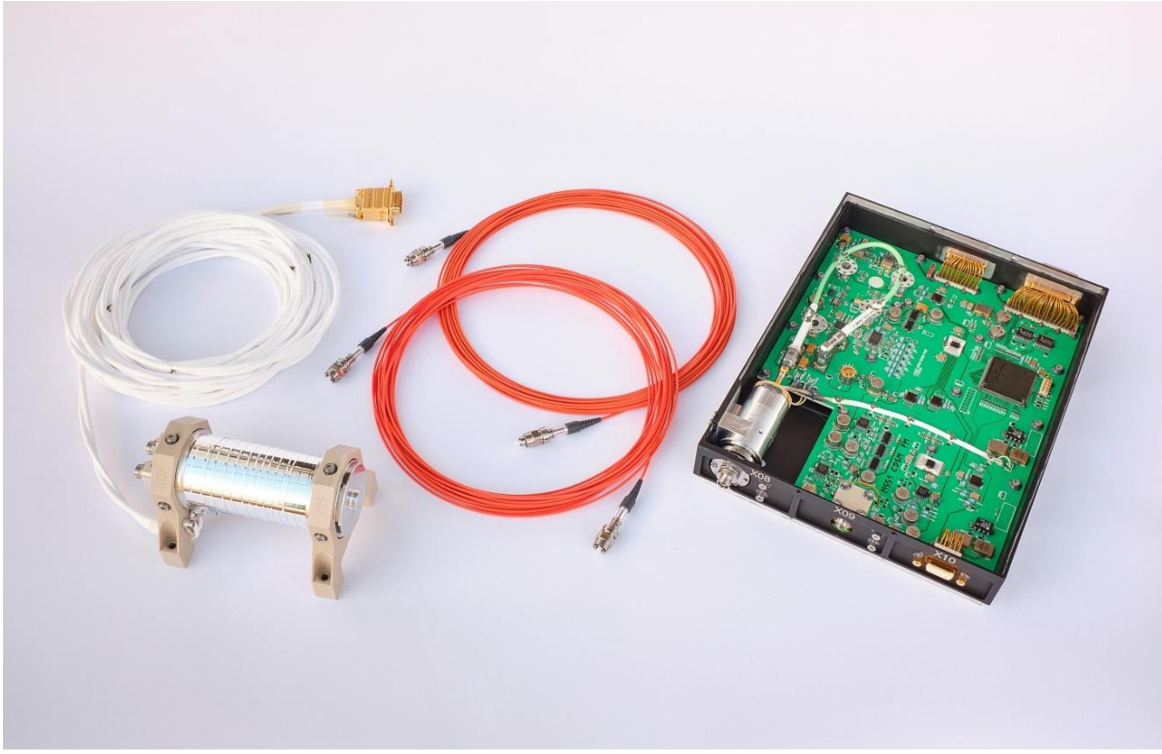

Figure 3: The Coupled Dark State Magnetometer from IWF, Graz. Sensor (left), optical fibres (middle) and front-end electronics (right) of the Coupled Dark State Magnetometer

Troelz Denver [DTU Space] introduced the star trackers provided by DTU Space to the mission. The cameras are performing very well and show little shift in position, meaning the optical axis and focal planes have not been affected by vibration during launch. On the ground it is difficult to determine the magnitude of stars correctly (due to atmospheric extinction) so some further inflight monitoring of the camera gain settings may be required. There is presently no indication that the optical bench hosting the star cameras and vector magnetometer is deforming under thermal stress.

Peter Bauer [DTU Space] described the behaviour of the vector magnetometer in comparison to the scalar magnetometer. The data and timing integrity of the sensor are within expected levels. By examining the residual of the vector data, the levels of artificial disturbances can be found. Some small perturbations were found which are likely related to interference from other instruments affecting the sensor electronics rather than the sensor itself. Taking periods where interference is low, the instrument has a noise level of 11 pT/sqrt(Hz) at 1 Hz which is similar to the noise level measured on the ground and is comparable with that of the Swarm satellites.

Synergies with the ESA Swarm mission

A major goal of the meeting was to discuss how the MSS and Swarm scientists can work together.

Anja Stromme, Swarm mission manager, reported that the ESA three-satellite mission was in excellent health and has been in orbit for 10 years, with only a few signs of aging. The hope is to fly Swarm throughout the present solar cycle at least up until 2031. Swarm has good global coverage, but poor coverage in local time. By contrast, MSS-1 has very good local-time coverage and there is consequently a lot of scope for synergy. Collaboration between Swarm and MSS-1 scientists will undoubtedly lead to improvements in both data quality and processing pipelines for both missions.

Further details on the scientific synergies between Swarm and MSS-1 were presented by Nils Olsen [DTU Space]. Olsen remarked that the original Swarm proposal, submitted to ESA in 1998, was for 7 satellites comprising 6 polar satellites with an additional low inclination satellite. MSS now permits a realisation of this original concept – i.e., a true swarm of magnetic satellites.

Close encounters between the Swarm and MSS-1 satellites, which occur every 21 days, present a key opportunity to test the instrumentation and calibration in both satellite missions. There has been excellent agreement in magnetic intensity, with a discrepancy typically less than 1.5nT between Swarm A and MSS-1. However, the difference in measured intensity does not tend to zero with shrinking separation distance, which provides an interesting opportunity to improve the calibration of both Swarm and MSS-1 sensors.

The specific orbit of MSS-1 will promote much better understanding of the geomagnetic field in several ways. For internal field modelling (mantle conductivity, core, crust), better understanding of the external field (which needs to be removed from the measured signal) is the principal challenge. Better local-time modelling through the MSS-1 datasets can help improve these external field models. Lithospheric field models can hopefully be significantly improved by MSS-2, because its perigee of 200km is much lower than Swarm, even though it will spend only 7% of time at an altitude of less than 200km. Low altitudes are challenging because increased density and turbulence within the atmosphere causes satellite shaking, vibrating the sensor and star cameras, thus degrading pointing accuracy and performance.

Data access is important for ensuring full exploitation of any mission. Geomagnetic data from Swarm are freely available and the Python tools (vires-client) and an online virtual research platform (VirES) makes data discovery, download, manipulation, and visualisation particularly easy. MSS-1 data should become available to scientists in 2024 once calibration has been completed.

Some important results from the mission will be highlighted at the Swarm 10 Years Anniversary and science conference in Copenhagen (April 2024). Science results from MSS-1 and other magnetic missions including the Canadian ePOP satellite and CSES will also be presented there.

Modelling Earth's magnetic field with MSS-1 and Swarm data

While the general principles of the how Earth's geodynamo operates are understood, the detailed behaviour of the core field and how to model and forecast spatial and temporal changes are not. High quality measurements from satellite over the past two decades are revealing previously obscured features of the field particularly at equatorial regions.

Kuan Li (Macau Institute of Space Technology and Application) presented a first version of a core field model derived from two months of MSS magnetic data. As MSS-1 does not have a polar orbit no data are returned from latitudes higher than 41°. A global model cannot therefore be constructed from MSS-1 alone. Instead, Swarm magnetic data were used to supplement the missing regions and a snapshot model was created. This new model shows very good agreement with standard core field models such as CHAOS up to degree and order 14 (Figure 4). The external part of the field (e.g., the ring current) can also be modelled with the MSS-1 data when more data are available.

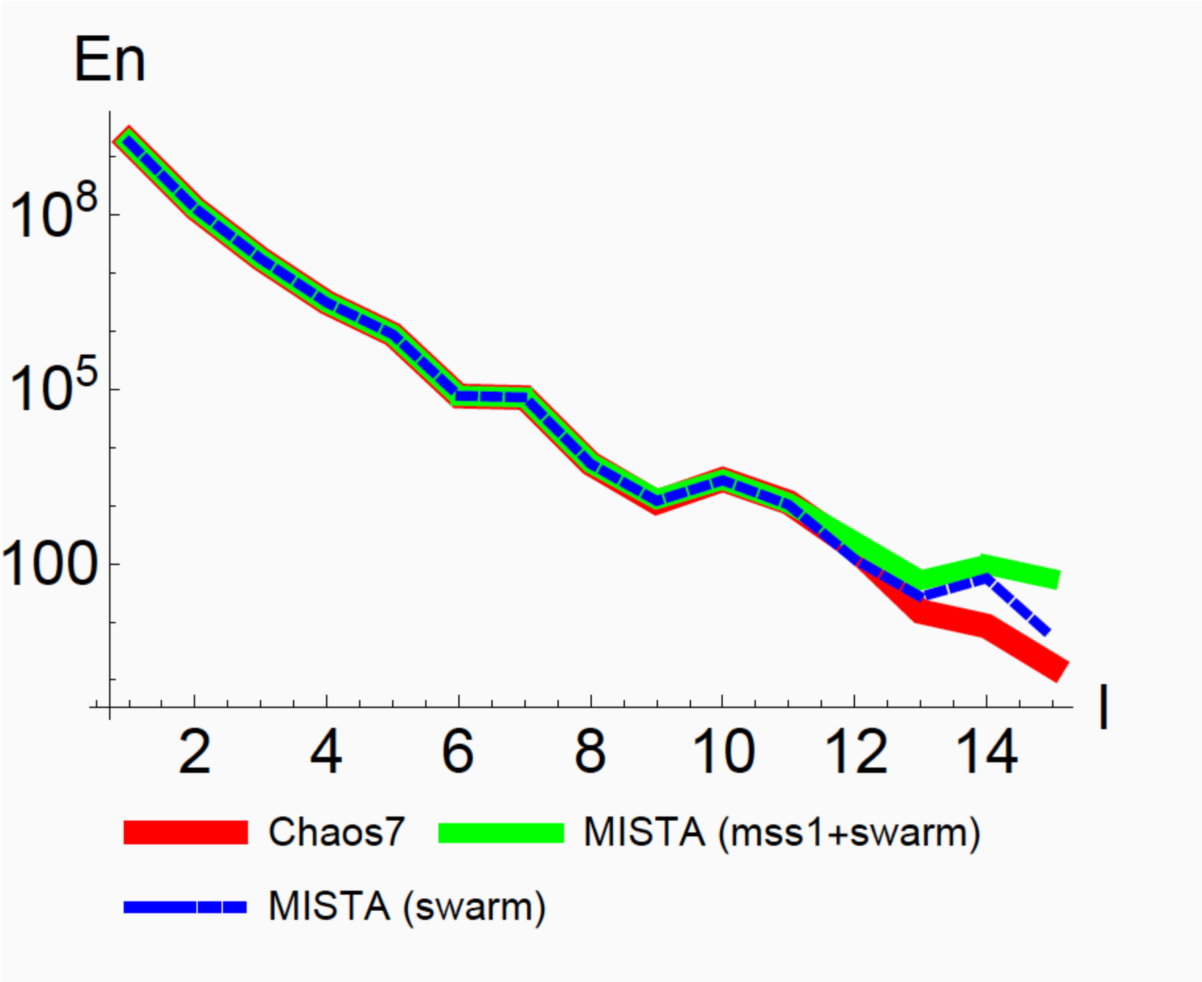

Figure 4: The spectrum of geomagnetic field models with spherical harmonic degree l, of the MISTA model (MSS-1 with Swarm data), compared to a similar model derived from Swarm data only and the CHAOS-7 model (Finlay et al., 2020).

Chris Finlay [DTU Space] spoke about the core mantle boundary magnetic field and opportunities for MSS-1 to improve our understanding of rapid time changes in this region. In particular, the low inclination of the satellite provides repeated samples of the weakest regions of the Earth's magnetic field. Over the past 25 year, the South Atlantic Anomaly (SAA) region of low total field strength (below 25,000 nT at Earth's surface) has expanded and deepened to cover South America, a large section of the south Atlantic and extended east into southwest Africa. The SAA has its origin in a large area of reversed flux patches on the core-mantle boundary where there is a lack of strong normal (outward pointing magnetic) flux compared to other parts of the hemisphere. The questions are: what controls these flux patches and why are they growing?

The main problem with modelling the large scale, slowly varying core field is separating it from the other main sources of magnetism, the small scale but stationary crustal field and rapidly time-varying external field. The external field originates in ionospheric and magnetospheric currents and contains variations short as 1 hr or less. Using Swarm data to remove these external field sources suffers due to its poor local time coverage: this is where MSS-1 data can help. In future, new methods of co-estimation of core and crustal fields (using MSS-2 data) and making use of prior information from core dynamics and maps of magnetic minerals in the crust offer a chance to map the core field to significantly smaller scales.

Analysing the near-Earth space environment using satellite data

The effects of the variable solar wind on the Earth are collectively termed 'space weather'. Some of the most pronounced space weather impacts are on the ionosphere, which can affect transmission of GNSS timing signals, HF radio and over-the-horizon radars. The equatorial regions are particularly affected by anomalies due to their proximity to the equatorial electrojet and the configuration of the magnetic field.

Zhe Yang [Tongji University, China] described the team's work on ionospheric scintillation and equatorial plasma bubbles, which are an important atmospheric phenomenon as they affect GNSS and communications. The study of these irregularities uses the onboard Radio Occultation (RO) receiver that detects the propagation of transmitted GNSS radio waves through the atmosphere, particularly along the limb where they are strongly refracted. The low inclination orbit of MSS-1 is ideal for providing coverage over the equatorial zones where most plasma bubbles occur. First results confirm the local time dependence around post-sunset hours. The other region of focus is the zone of weak magnetic field strength around the South Atlantic Anomaly (see Figure 5). Using Empirical Orthogonal Functions (EOFs), a set of reduced basis functions was derived to describe the main modes of the behaviour of the ionospheric scintillation occurrence in time and space. A cross comparison with the NOAA Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC-2) mission provides confidence that the EOFs capture around 85% of the measured variation.

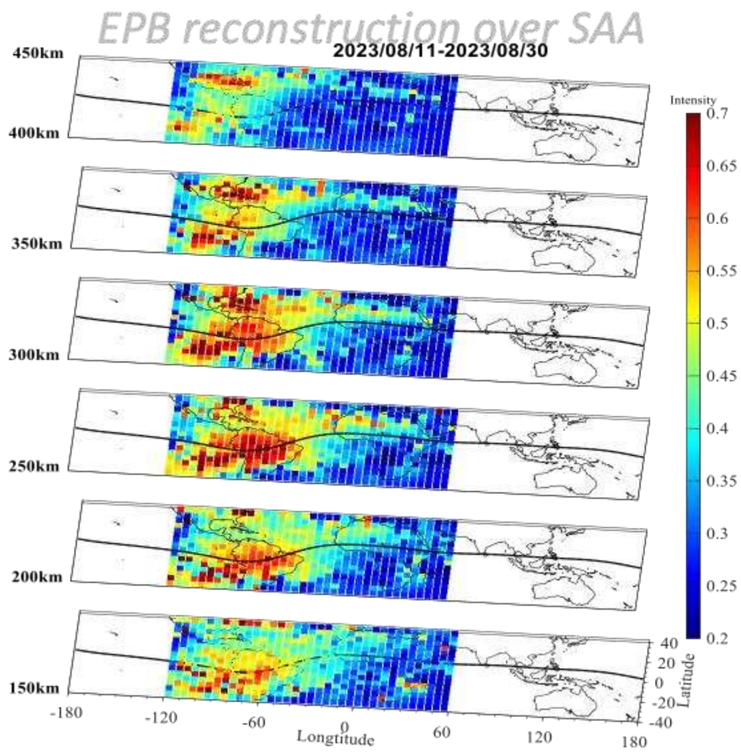

Figure 5: The reconstruction of the equatorial plasma bubbles (EPB) over the South Atlantic Anomaly using Empirical Orthogonal Functions based on data from MSS-1 and COSMIC-2. The colour scale shows normalised intensity of scintillations.

The study of energetic electrons using the two spectrometers on MSS-1A and MSS-1B was introduced by Hong Zou on behalf of Qiugang Zong [Peking University, China]. The Energetic Electron Spectrometer (EES) sensor on MSS-1A has 128 channels over a range of 60-2000 eV MSS-1A has 200keV to 3MeV while MSS-1B has 40-300keV. The first results of the distribution of high energy electrons on a per orbit basis were presented. The SAA was clearly visible, showing higher energy electrons penetrating to lower altitudes where the magnetic field is weakest. Finally, the influence of manmade transmitters on the energetic particles was observed, with the large transmitter in north-west Australia (NWC) being visible in the dataset at around 100 keV.

Probing mantle conductivity from space

An open question in deep Earth science is the heterogenous nature of the mantle. In particular, the electrical conductivity is a crucial geophysical parameter that constraints thermal, compositional and mineralogical structure. Satellite geomagnetism can provide constraints on the magnetic and electrical properties of the mantle. Lunisolar tidal forcing generates periodic flows in the Earth's oceans, which interact with magnetic field. These tidal signals are ideal source for probing interior structure. Longer period changes of the radiation belts and ring current penetrate deeper into the mantle providing sensitivity to lower regions.

Hongbo Yao [MISTA] (presenting on behalf of Zhengyong Ren) described their work to determine mantle conductivity and ocean tide flow. They have initiated a series of studies using 3D electromagnetic modelling and trans-dimensional Bayesian analysis. Using one month of MSS-1 data, the recovered mantle conductivity falls with previous results estimated by using more than 6 years of satellite and observatory data (Figure 6). A more sophisticated model involving the 3D variation at different locations and depths containing information on ocean and land as well as deeper layers with anomalous conductivity will be constructed as more data are collected. The researchers also looked at solving for magnetic signal from the M2 lunar tide but one month of data is not a sufficiently long time series to recover such tidal signals. Further improvements will also require data from the polar orbiting MSS-2 satellites for global coverage.

Jakub Velimsky [Charles University, Prague] spoke about his research into using the tidal magnetic field to probe upper mantle conductivity using Swarm data. Drawing on electromagnetic induction equations in the frequency domain, the response of the magnetic field measured globally can be used to estimate the conductivity. A 3D model of the mantle is a very challenging problem particularly as large parts are 'masked' by the relatively conductive seawater layer. To 'see' through the oceans, a more sophisticated approach includes conductivity models of the oceans including the properties of sea floor sediments (e.g. thickness), and ocean flow. A new model (named WINTERC-E) with 10^4 – 10^5 parameters has been developed to capture the 3D structure of mantle conductivity in 13 separate layers (Fullea et al. 2021). Promisingly, inverse models produce maps of conductivity with depth, which shows some correlation with Large Low Shear Velocity Provinces (LLSVPs) as derived from seismology. In conjunction with Swarm and other missions, MSS-1 can improve coverage in low- mid latitudes and help identify additional source signals of non-ocean origin, especially from the ionosphere.

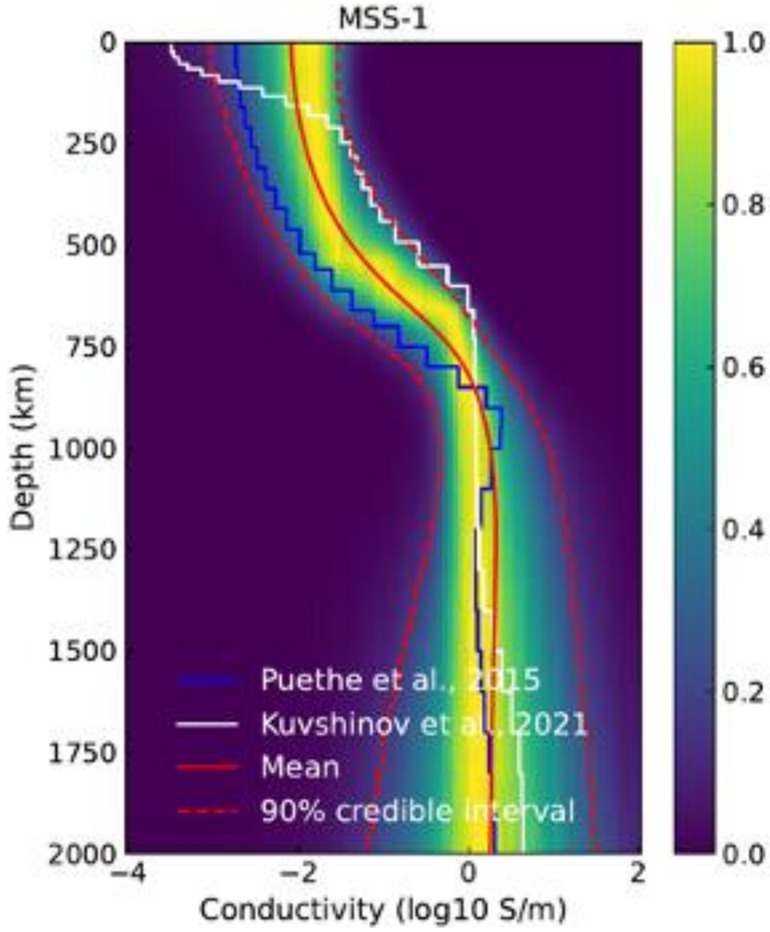

Figure 6: Comparison of recovered conductivity profile from one month of MSS-1 data to published models (Puethe et al., 2015, 10 years of satellite and observatory data; Kuvshinov et al., 2021, 6 years of Swarm, CryoSat-2 and observatory data)

Imaging the dynamics of Earth's core from space

Earth's magnetic field is generated by the swirling motion of electrically conducting fluid within the liquid core. Because it is so remote, some 3000km beneath the surface, understanding the dynamics of the core remain extremely challenging and require a combination of data and numerical models.

A team at MISTA, led by Yufeng Lin, are investigating how to employ satellite data from MSS to better determine outer core flow. The main approach is to assimilate measurements of the magnetic field into computational representations of the geodynamo. The problem remains that the measurements are only at the outer core surface so other assumptions (for example, the inertial mode behaviour of the fluid) must be made to allow the deeper flow to be inferred. Their method is adapted from Kloss and Finlay (2019) with an update to reduce the number of modes in combination with a physics-informed neural network. As there is not yet a full year of data to compute the annual secular variation, the data from MSS was supplemented with predictions from the CHAOS model. Preliminary results reveal the distinct east-west hemispheric division of the core flow (see Figure 7), with flows in the Atlantic hemisphere being largely westward and largescale, whereas flows in the Pacific hemisphere are relatively small-scale with a weak columnar structure.

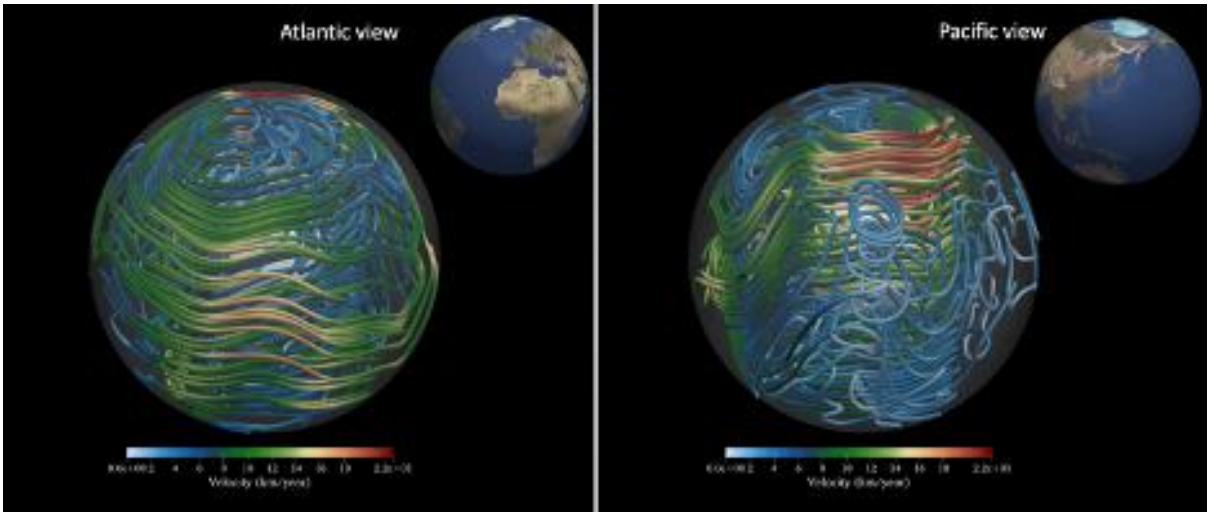

Figure 7. Streamlines of a reconstructed 3-D core flow using geomagnetic data from Swarm and MSS-1.

Nicolas Gillet [Grenoble, France] spoke about new types of waves detected in the core from satellite magnetic data. Due to the rapid rotation of the Earth (one Earth day is very much less than the centennial timescale of core convection), the core is likely to be strongly influenced by the Coriolis force which imparts strong structural constraints on the fluid motion. Although this makes simulations of the core challenging, it allows the theoretical prediction of various classes of waves. From Swarm data, torsional waves have been identified which produce a very small magnetic signal on the order of 2nT/yr and have a 6yr timescale. Another type of recently observed waves are magneto-coriolis waves, which have been identified at low-latitudes, despite being previously believed undetectable. These waves have a speed of 1000 km/yr, much larger than the typical speed of the core convection that generates the magnetic field.

The observation of waves in Earth's core provides crucial constraints on the otherwise unobservable background state on which they ride: for instance, the strength of the magnetic field interior to the core, or the density stratification profile of the fluid outer core. Better constraints from satellite data, particularly in equatorial regions, are therefore a crucial element to understanding the generative process of Earth's magnetic field.

Outlook

Like most geophysical datasets (e.g., climate records), magnetic data has a long 'half-life' and good quality measurements generally become more useful with age. Magnetic surveys have a long history, dating from the 15th century, when the main purpose was navigation, through the 19th century when they were used to discover minerals, to now, when our main research concerns are space weather hazards to other satellites and potential harm to humanity from the weakening dipole field.

International collaboration was developed in the latter part of the 20th century by the International Association of Geomagnetism and Aeronomy (IAGA), which endorses the International Geomagnetic Reference Field (IGRF), a standard baseline for magnetic mapping. Since the 1980s the IGRF has been dominated by satellite data. A number of satellites have been launched by different countries or groups of countries since the 1960s: USA, Denmark, Argentina, Germany, and the European Space Agency. The latest constellation, Swarm, will be joined and possibly succeeded by the MSS constellation. Thus China, over 1,000 years after inventing the compass, re-enters magnetic surveying with some of the highest quality instrumentation ever developed.

In this meeting, the early results from MSS-1 and the importance of a future MSS-2 mission were discussed. This new mission should fundamentally improve our knowledge of the magnetic environment and provide continuous global monitoring for decades to come.