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澳門空間技術與應用研究院

Macau Institute of Space Technology and Application



THE EUROPEAN SPACE AGENCY



2025 DRAGON 6 SYMPOSIUM

14-18 JULY 2025

PROJECT ID. 95341

The MSS constellation of Geomagnetic Survey Satellites: Progress and Initial Scientific Results

Keke Zhang¹ and Phil Livermore²

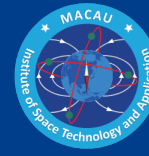
Presented by: Hongbo Yao¹ (on behalf of Keke Zhang)

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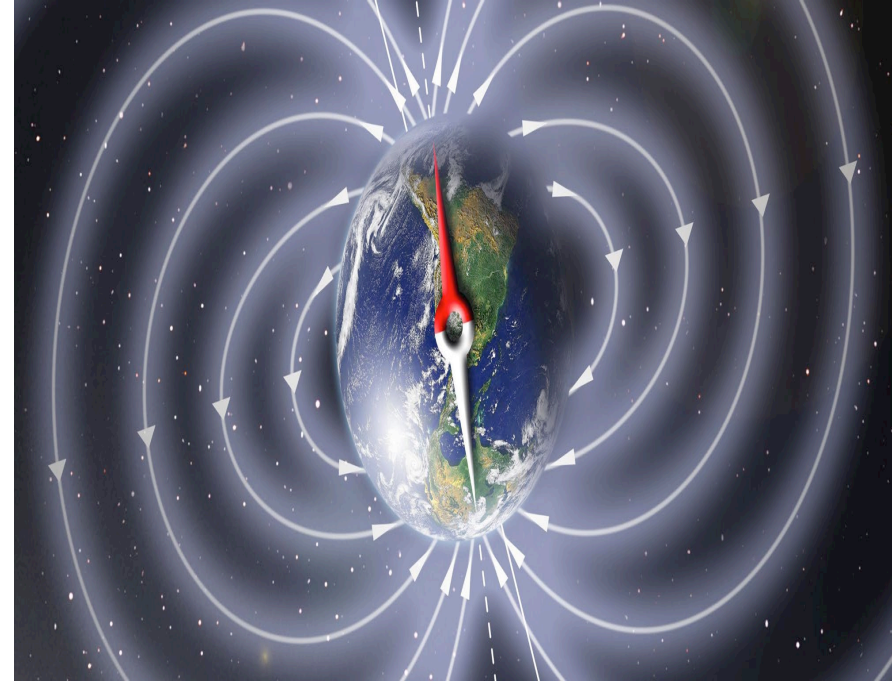


Outline of the Talk

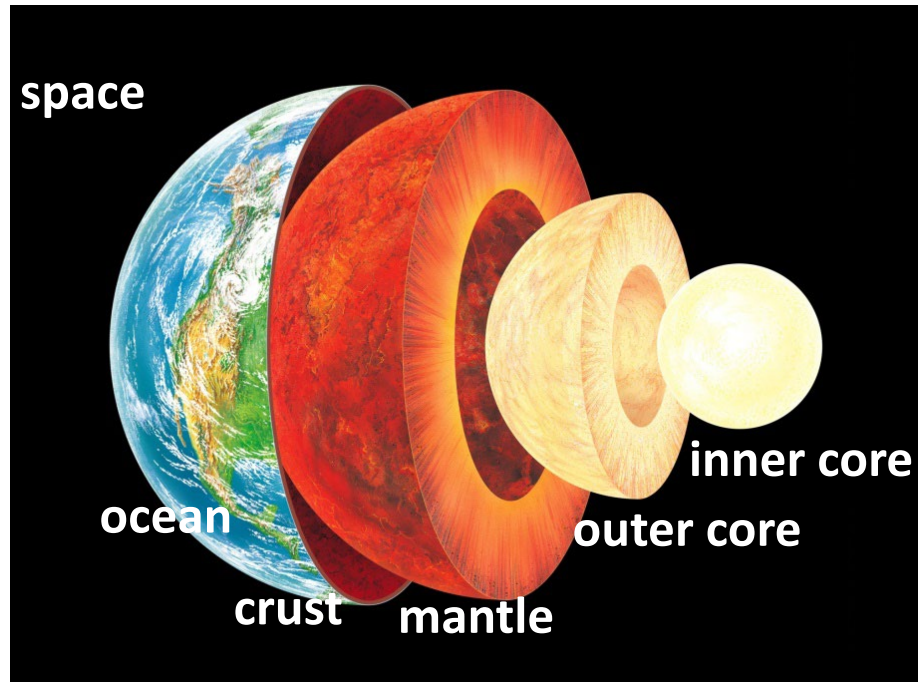


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- **Background**
- **MSS Constellation: Macau Science Satellite 1A/B**
- **MSS Constellation: Macau Science Satellite 2A/B**
- **MSS Constellation: Scientific Results**
- **MSS International Cooperation**

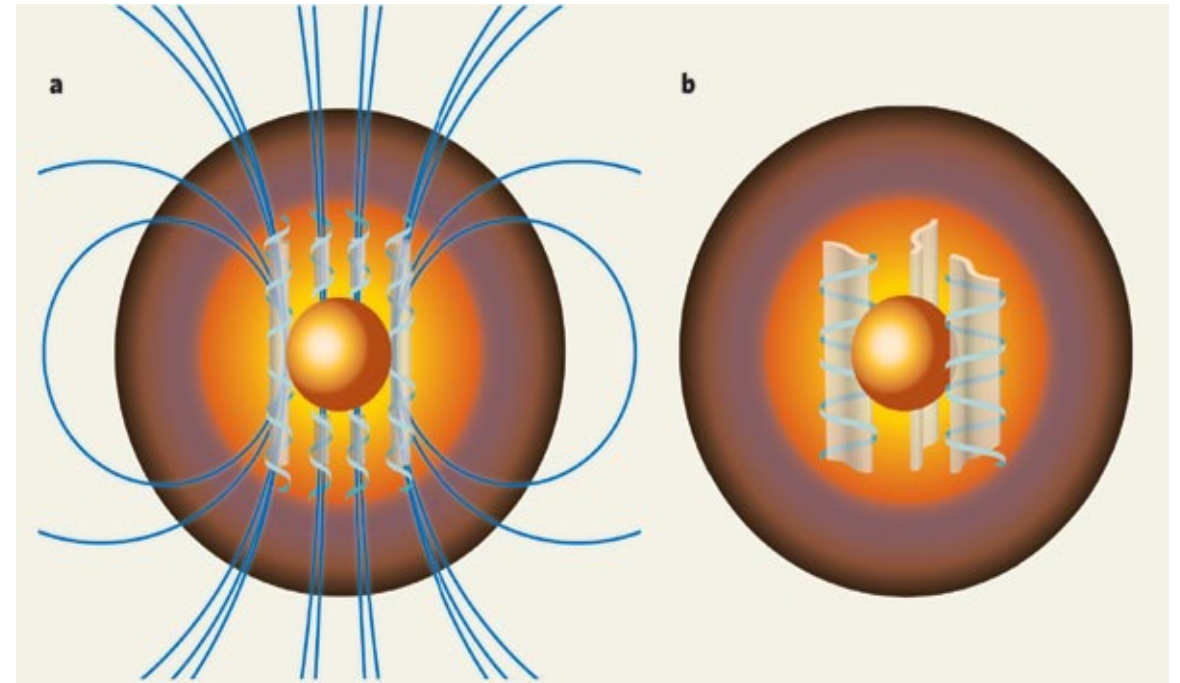


The Earth's interior

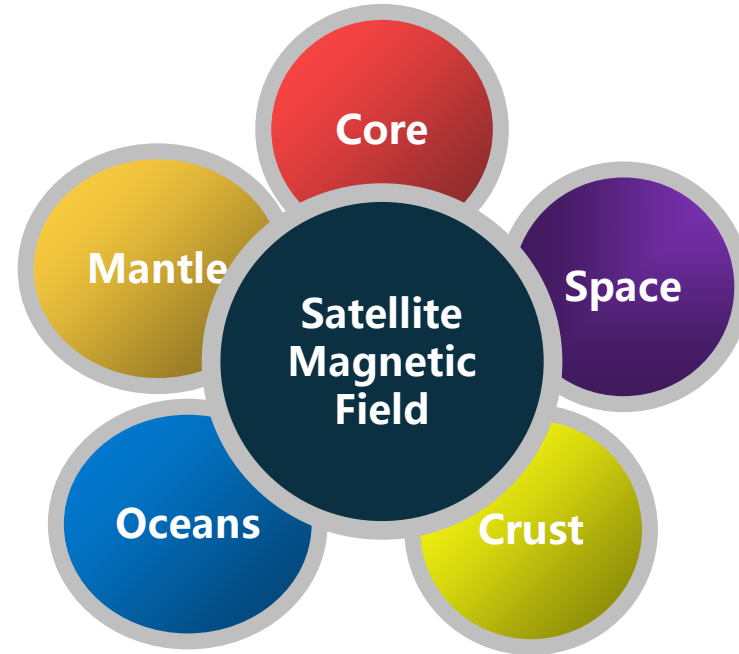
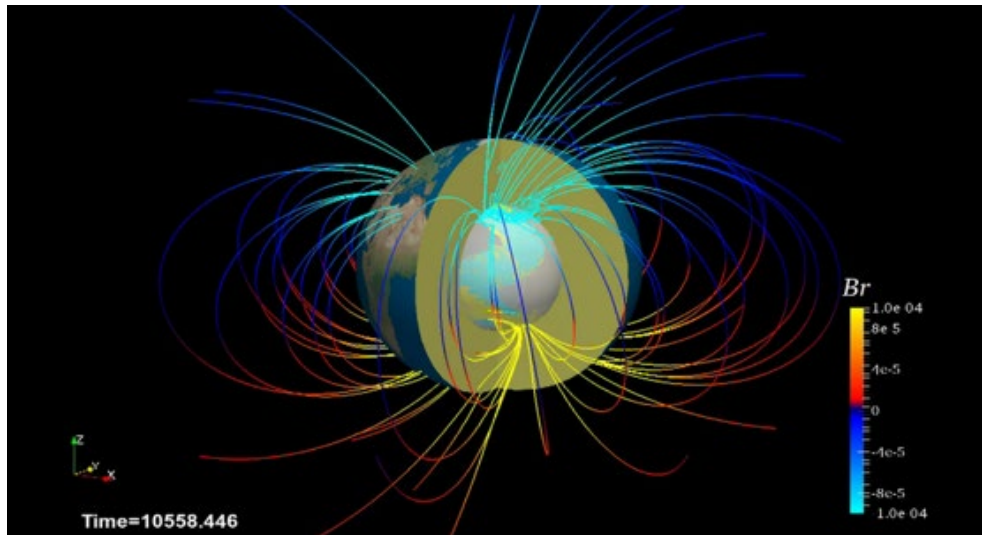


The geodynamo is located in
the liquid outer core of Earth

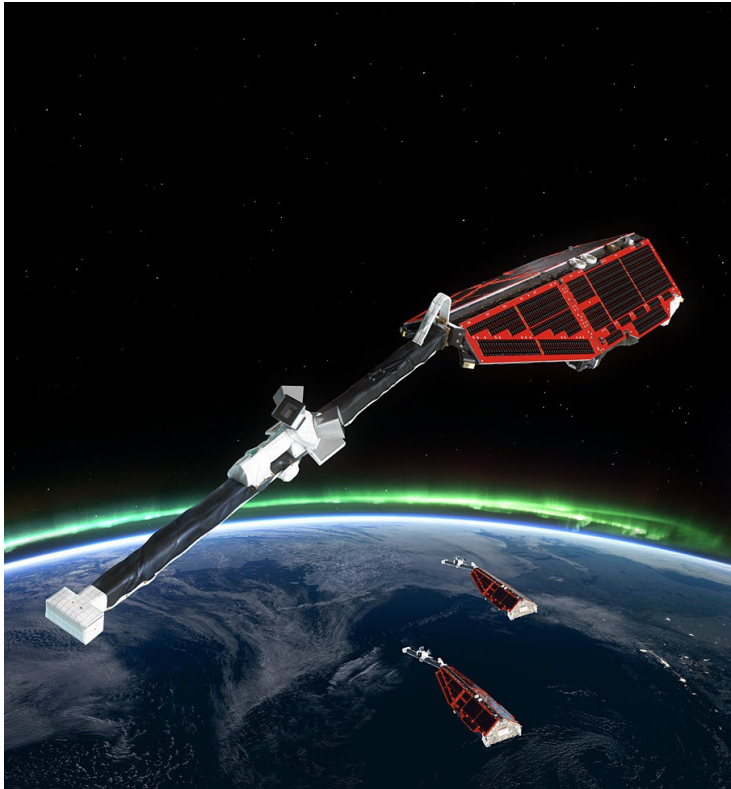
The geodynamo process



The geodynamo problem is highly
important but complicated



The measured Earth's magnetic field is the only geophysical parameter that includes the information of Earth's fluid core, mantle, crust, oceans, ionosphere and magnetosphere.



European Space Agency's Swarm
satellite constellation (polar orbit)
2013.11.25-



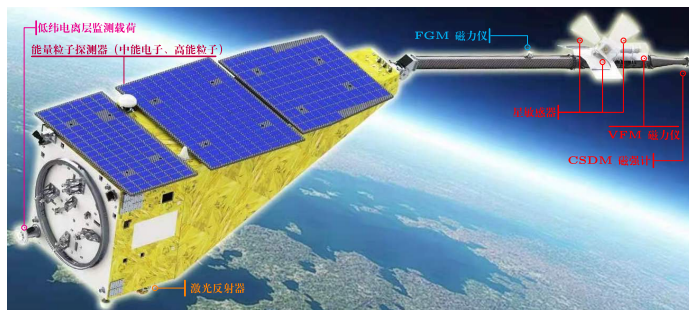
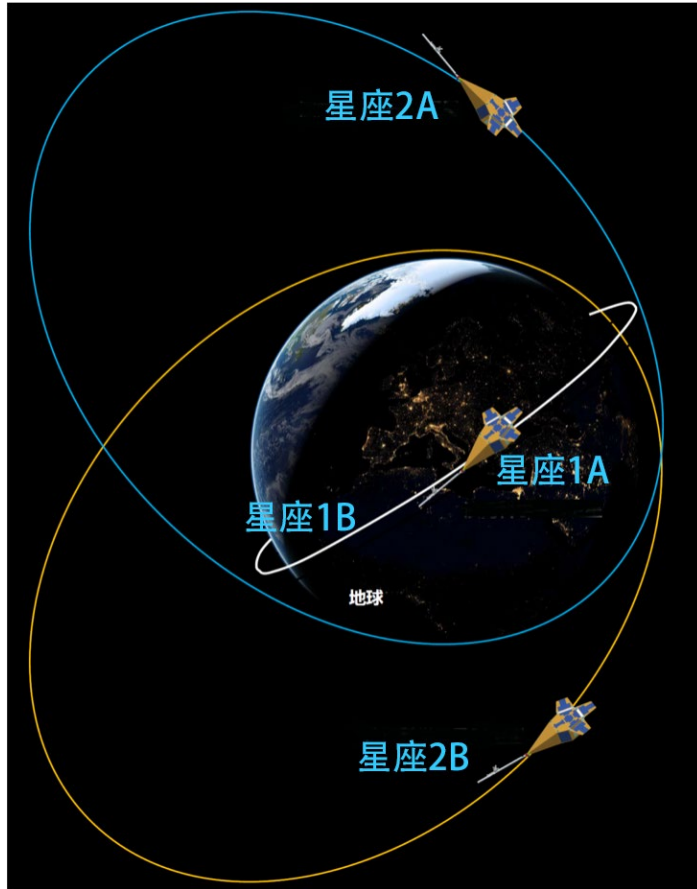
Macau Science Satellite-1 (MSS-1)
(the first low-inclination geomagnetic satellite)
2023.5.21-

Dragon 6 project 95341 - Exploring Earth's magnetic field using Swarm and MSS-1 data

MSS Constellation 1A



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Objective:

- Measure low-latitude geomagnetic field and space parameters

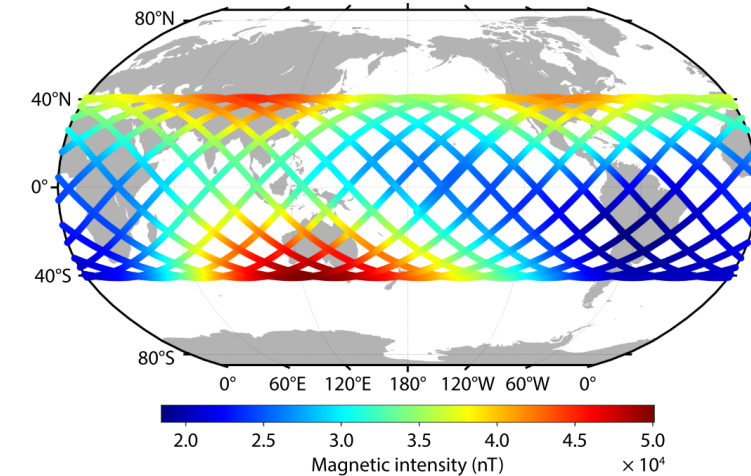
Orbits:

- ($\sim 41^\circ$) Low inclination, Low latitude
- Nearly circular
- Nearly $\sim 450\text{km}$ (2-D measurements)

Payloads:

- Scalar Magnetometer
- Vector Magnetometer
- A Star Tracker and an Optical Bench work together to precisely determine the spacecraft's orientation in space (attitude) and maintain its stability
-

Launch date: Launched on 21 May 2023

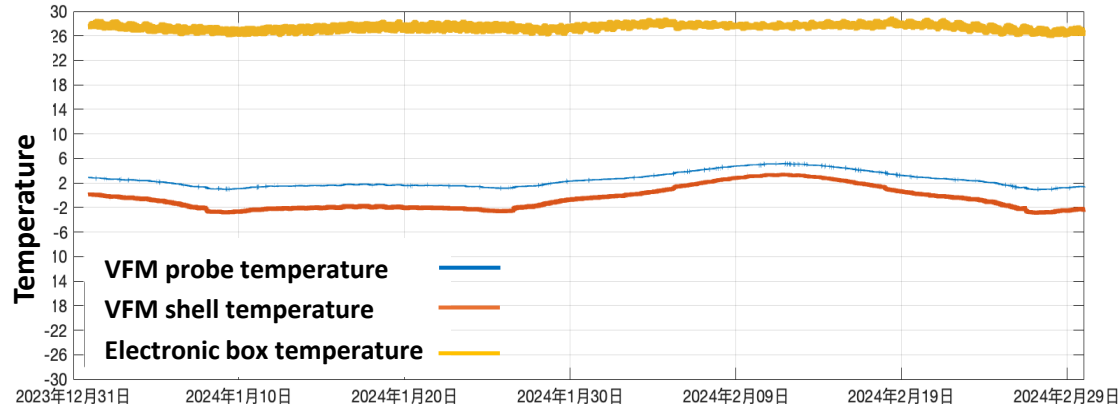


MSS Constellation 1A : The Optical Bench

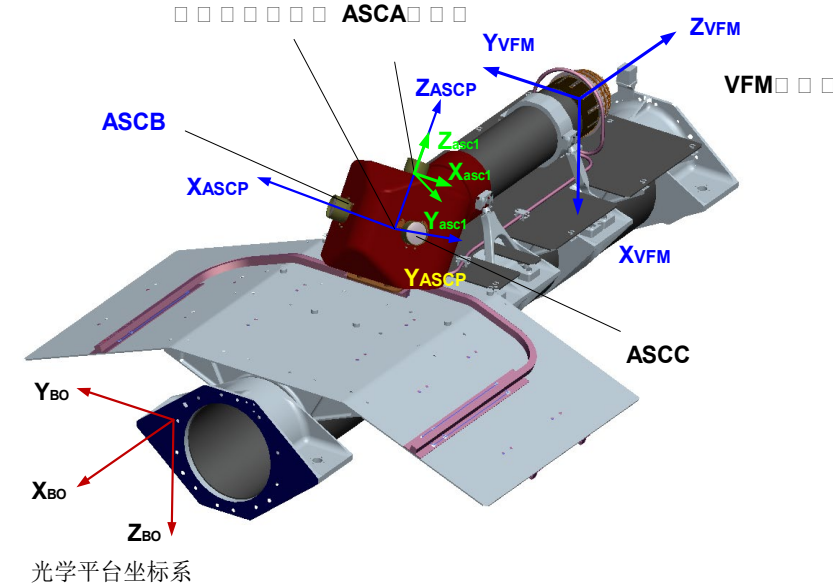
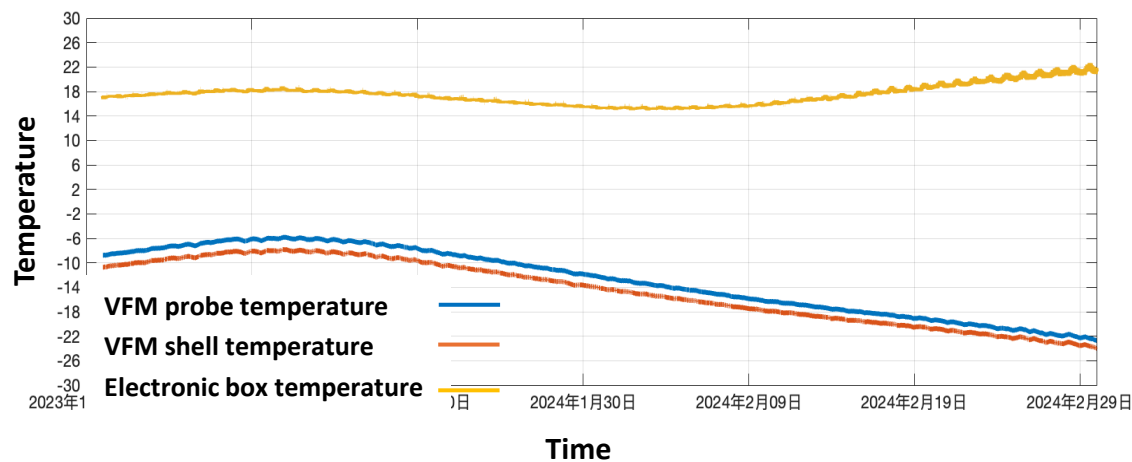


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Temperature monitoring curve of the Vector Field Magnetometer (VFM) on the optical bench of the MSS-1 satellite



Temperature monitoring curve of the VFM on the optical bench of the Swarm satellite

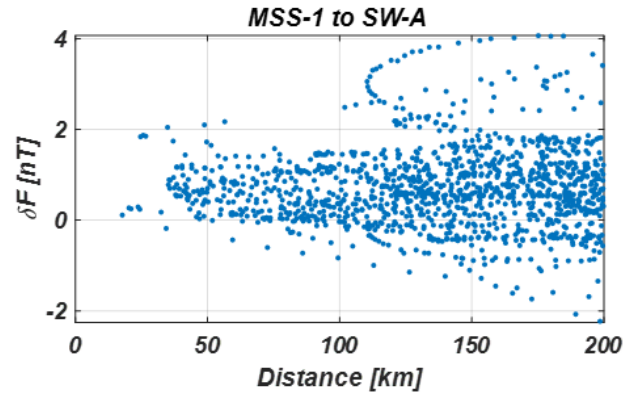


- Equipped with a highly stable optical bench and three non-magnetic star trackers;
- Nearly without the error induced by thermal deformation;
- Produce accurate measurements of geomagnetic fields.

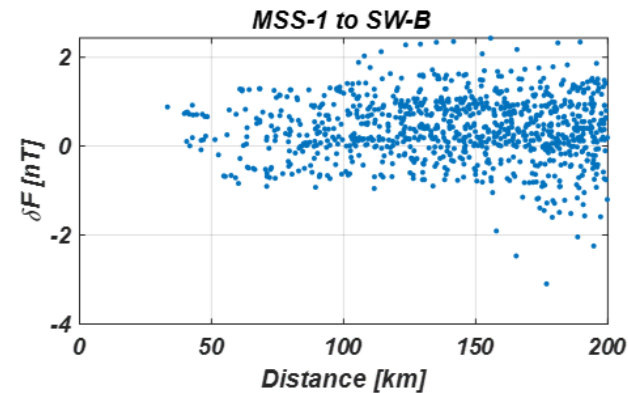
Comparison between Swarm and MSS-1



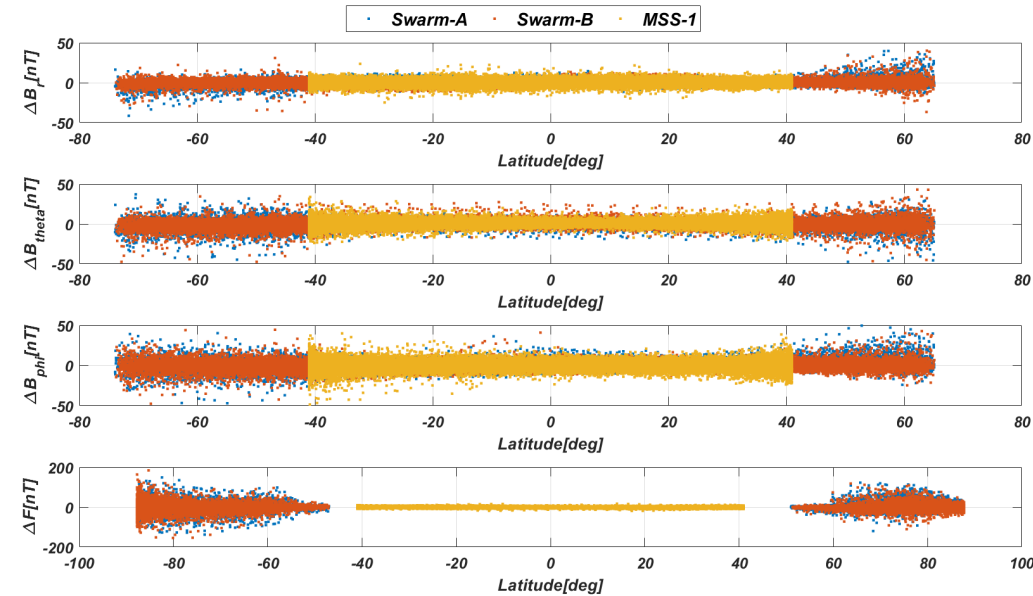
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Scalar field difference between MSS-1 and Swarm-A as a function of distance



Scalar field difference between MSS-1 and Swarm-B as a function of distance

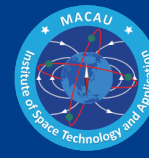


Residual between measurements and geomagnetic model predictions

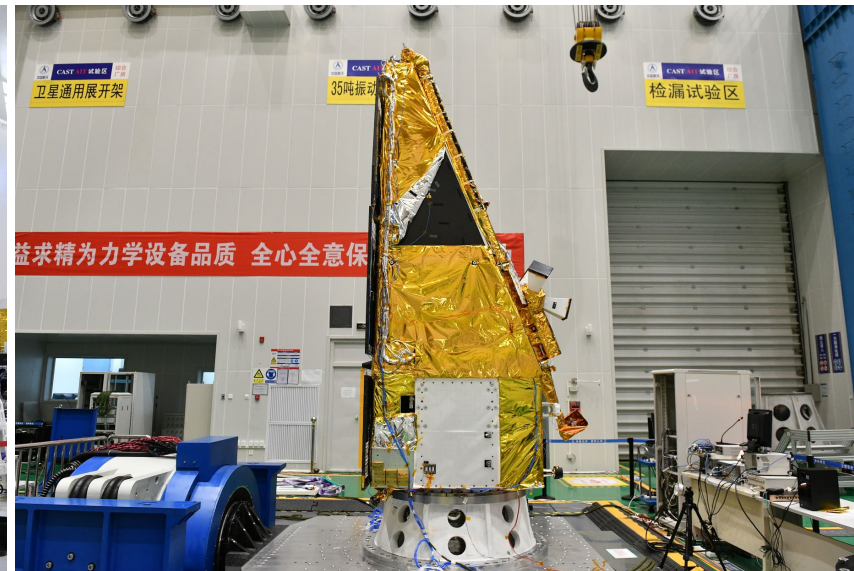
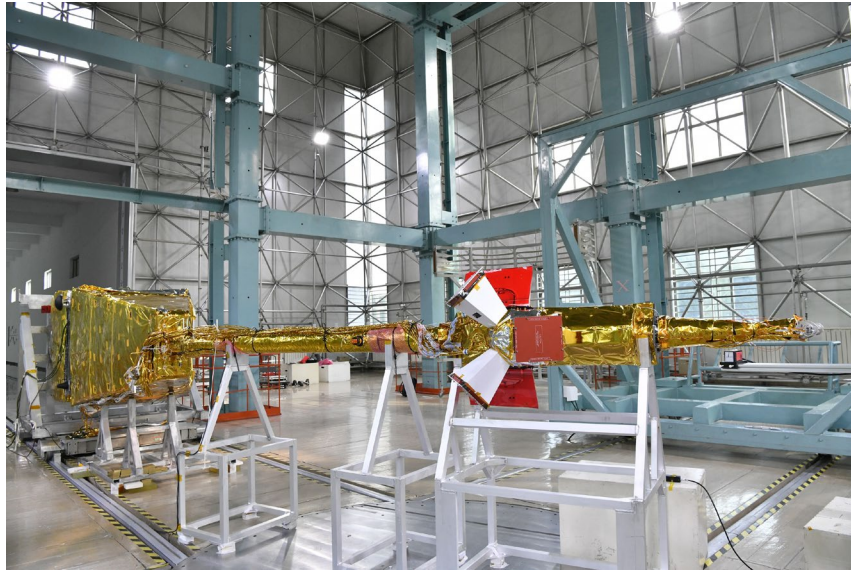
MSS-1 (2023.11.02 -2024.03.25)	Huber-weighted RMS error (nT)
In-flight determination of all parameters	0.2597
Pre-flight values (adjustment of offset, Scale value and Non-orthogonalities)	0.2573

Confirming the excellent data quality of MSS-1, with accuracy better than 0.5 nT

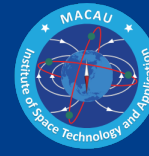
MSS-1A before its launch



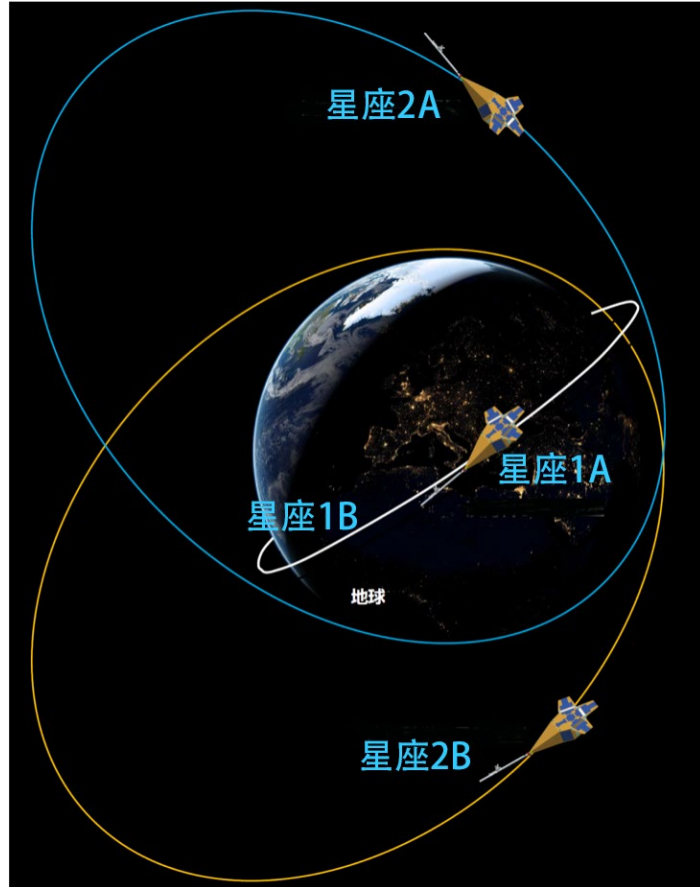
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MSS Constellation 1B



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Objective:

- Understand solar flares/winds and their interactions

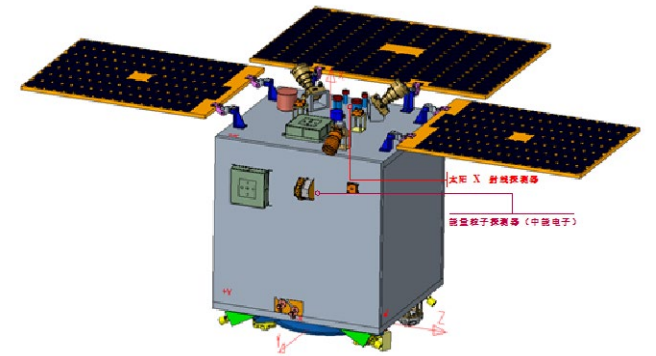
Orbits:

- Low inclination ($\sim 41^\circ$)
- Nearly Circular: ~ 450 km (2-D measurements)

Payloads:

- Solar X-Ray Detector
- Charged Particle Detector
-

Launch date: launched on 21 May 2023



MSS-1 Twin Satellites Launching



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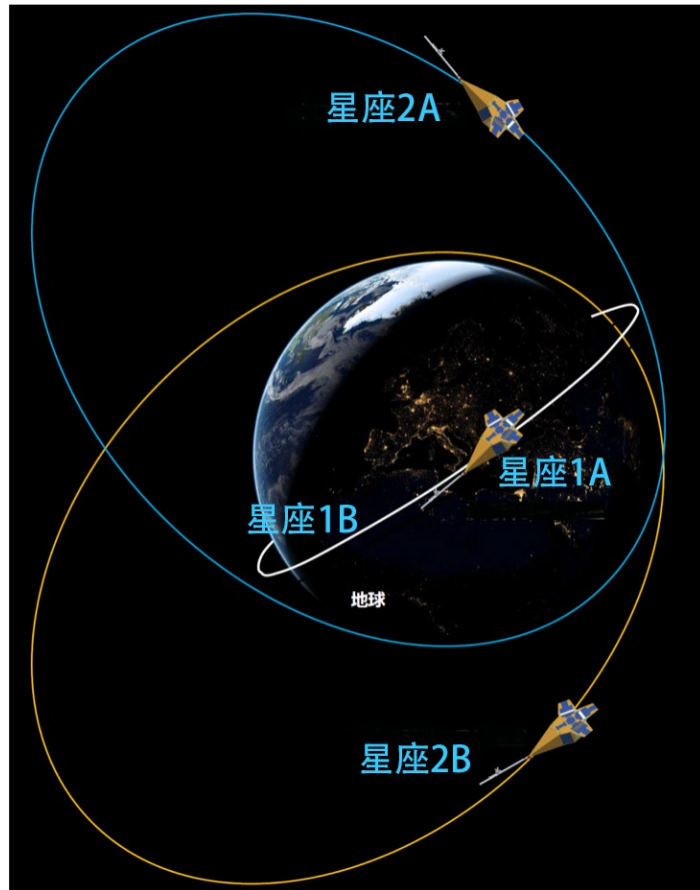


MSS-1 twin satellites were launched on 21 May 2023 while the in-orbit testing was finished at the end of 2023.

MSS Constellation 2A



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Objective:

- Measure 3-D geomagnetic field and 3-D space parameters

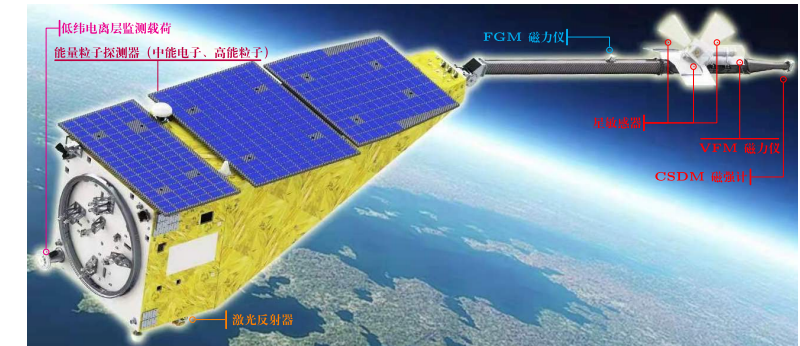
Orbits:

- ($\sim 90^\circ$) Nearly polar orbit
- Highly elliptical
- Perigee 190-220km, Apogee >1500km (3-D measurements)

Payloads:

- Scalar Magnetometer
- Vector Magnetometer
- Star Tracker and Optical bench
-

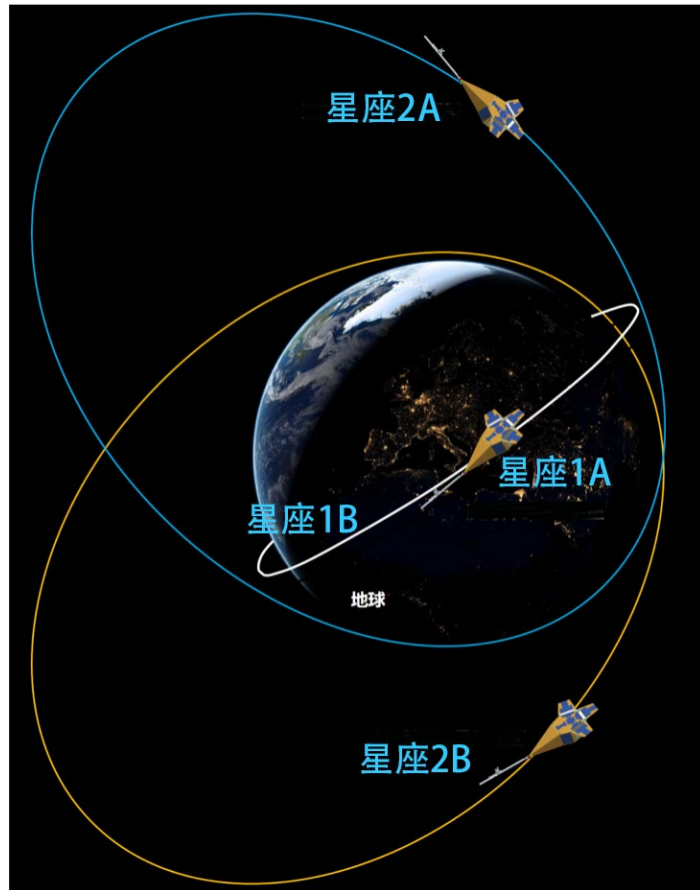
Launch date: Plan to be launched in 2028



MSS Constellation 2B



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Objective:

- Measure 3-D geomagnetic field and 3-D space parameters.

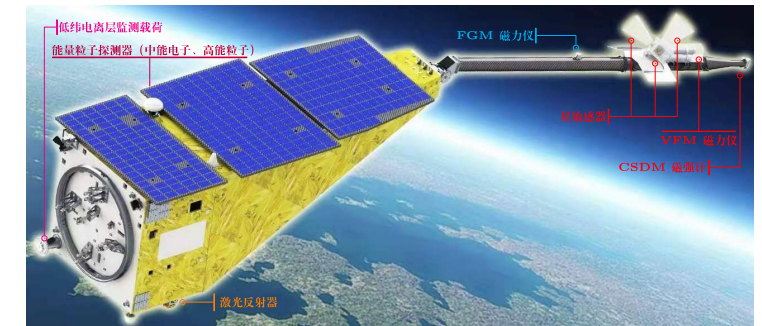
Orbits:

- ($\sim 90^\circ$) Nearly polar orbits
- Highly elliptical, different phases from 2A
- Perigee ~ 190 - 220 km, Apogee >1500 km (3-D measurements)
- About 180-degree difference in phase with 2A

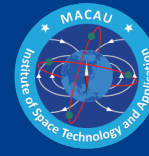
Payloads:

- Scalar Magnetometer
- Vector Magnetometer
- Star Tracker and Optical bench
-

Launch date: Plan to be launched in 2028



MSS Constellation: A Combination of Nearly Circular and Highly Elliptical Orbits



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- **Covering the whole Earth over 2-3 months;**
- **Providing 3-D geomagnetic field measurements;**
- **Probing disparities between north and south polar regions;**
- **Exploring the coupling zone between ionosphere and magnetosphere;**
- **Offering unprecedented accuracy of the crustal magnetic field measurements.**



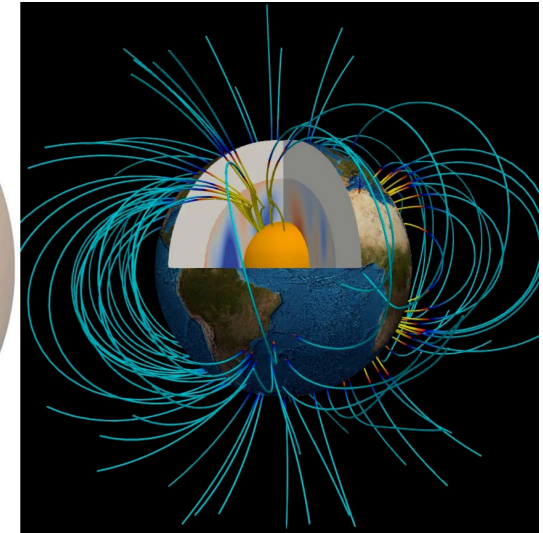
Determine fluid motion in Earth's geodynamo outer core

- Core fluid flow generates geomagnetic secular variation;
- Using accurate magnetic data and solving geomagnetic inverse problem to recover the core flow model ;
- Highly important for understanding geodynamo process.

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

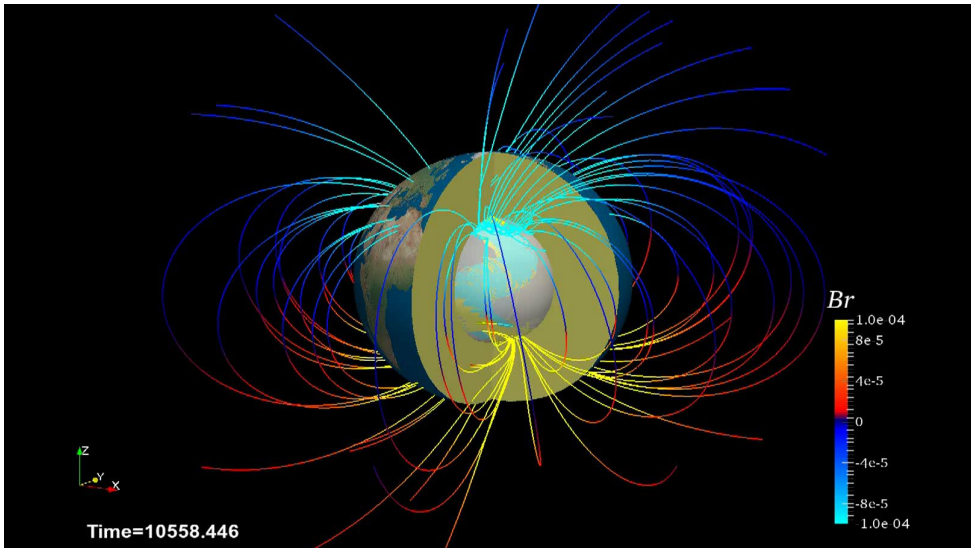
$$\frac{\partial \mathbf{u}}{\partial t} + 2\hat{\mathbf{z}} \times \mathbf{u} = -\frac{1}{\rho_0} \nabla P$$
$$\nabla \cdot \mathbf{u} = 0,$$

$$\mathbf{u} = \sum C_{mnk} \mathbf{u}_{mnk}$$



Help forecast short-term variation of the geodynamo field

- A combined analysis of accurate geomagnetic measurements and the geodynamo data assimilation;
- Forecasting the short-term variation of the geodynamo field with the modern AI technology and the data assimilation;



Simulations with realistic geophysical parameters are still beyond reach.

$$\rho_0 \frac{\partial \mathbf{u}}{\partial t} + \rho_0 (\mathbf{u} \cdot \nabla) \mathbf{u} + 2\rho_0 (\boldsymbol{\Omega} \times \mathbf{u}) = -\nabla P - \rho_0 \alpha T \mathbf{g} + (\mathbf{J} \times \mathbf{B}) + \rho_0 \nabla^2 \mathbf{u}$$

$$\frac{\partial T}{\partial t} + (\mathbf{u} \cdot \nabla) T_0 = \kappa \nabla^2 T$$

$$\frac{\partial \mathbf{B}}{\partial t} = \nabla \times (\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}$$

Terms representing feedback and coupling between the velocity, magnetic and temperature fields

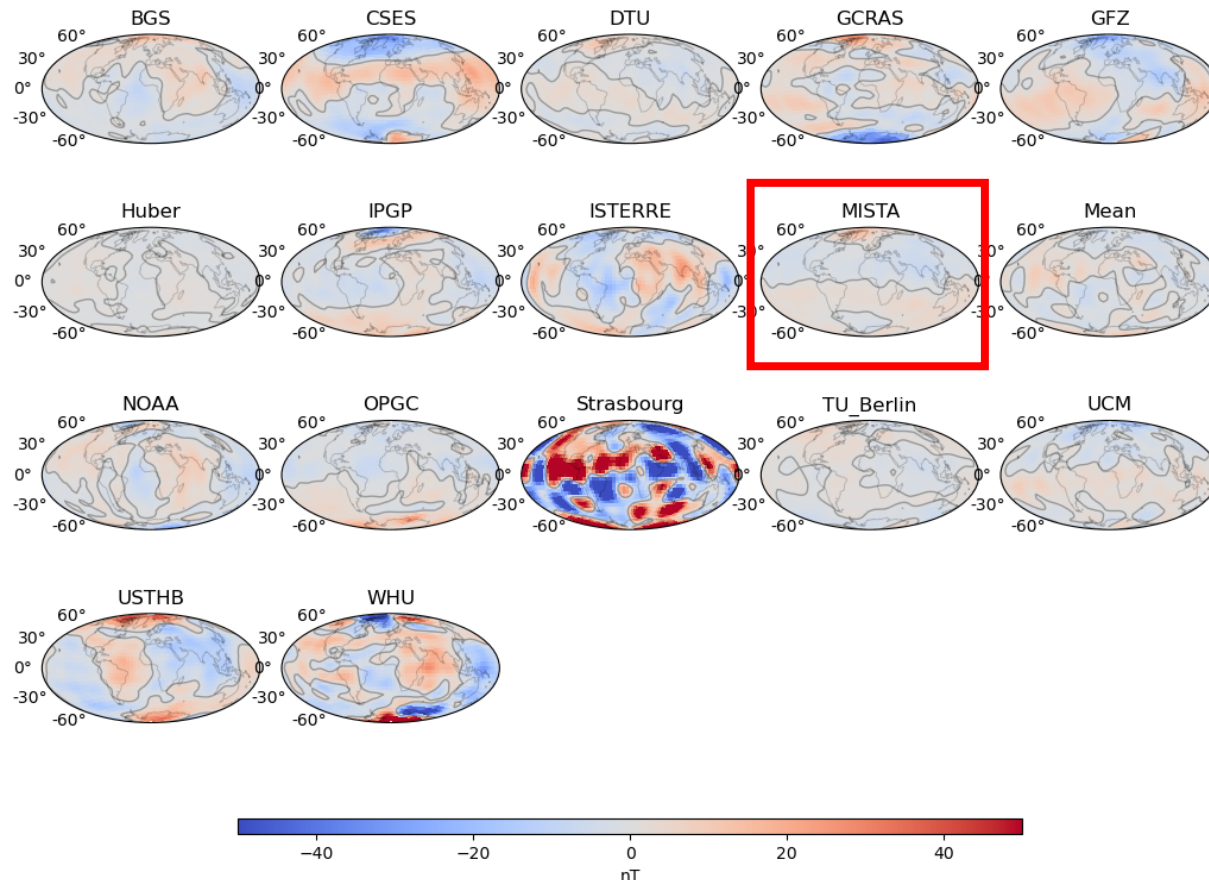
$$\nabla \cdot \mathbf{u} = 0$$

$$\nabla \cdot \mathbf{B} = 0$$

+ Boundary Flow, Thermal and Magnetic BC on ICB & CMB.

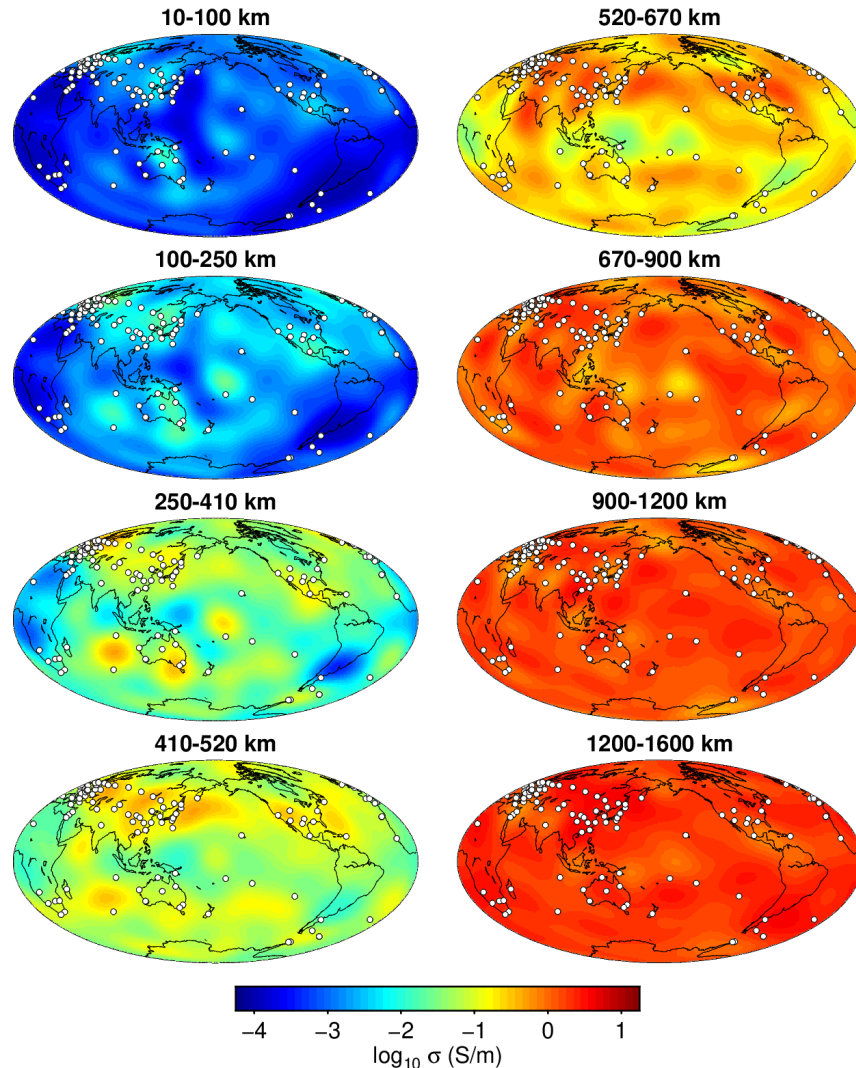
Contribute to the 14th generation of International Geomagnetic Reference Field (IGRF)

Radial magnetic field difference between various models
and official IGRF-14 model



- IGRF is the model of Earth's main magnetic field and its secular variation due to geodynamo;
- It is widely used in scientific studies and practical applications;
- Our candidate model derived from MSS-1 data shows excellent agreement with the official IGRF-14 model.

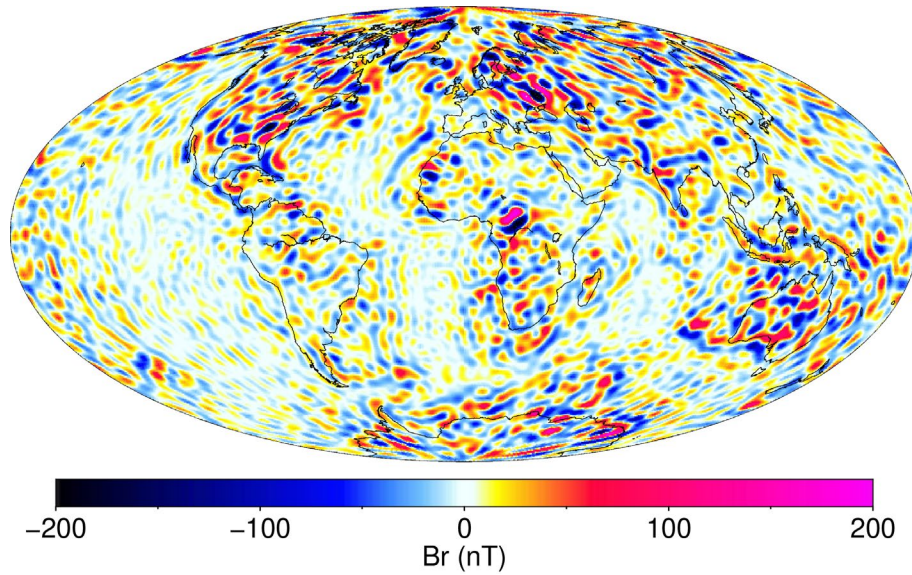
Probe the 3-D conductivity/heterogeneity of Earth's mantle



- Magnetic field due to electromagnetic induction in the mantle;
- Can be used to estimate conductivity and heterogeneity of the mantle;
- It is closely connected with mantle physical/chemical properties, such as water content and temperature;
- More sensitive to water content compared to seismic velocity

$$\frac{1}{\mu} \nabla \times \mathbf{B}(r, \theta, \phi) = \sigma(r, \theta, \phi) \mathbf{E}(r, \theta, \phi),$$
$$i\omega \mathbf{B}(r, \theta, \phi) = -\nabla \times \mathbf{E}(r, \theta, \phi),$$

Improve the model of Earth's crustal magnetic field

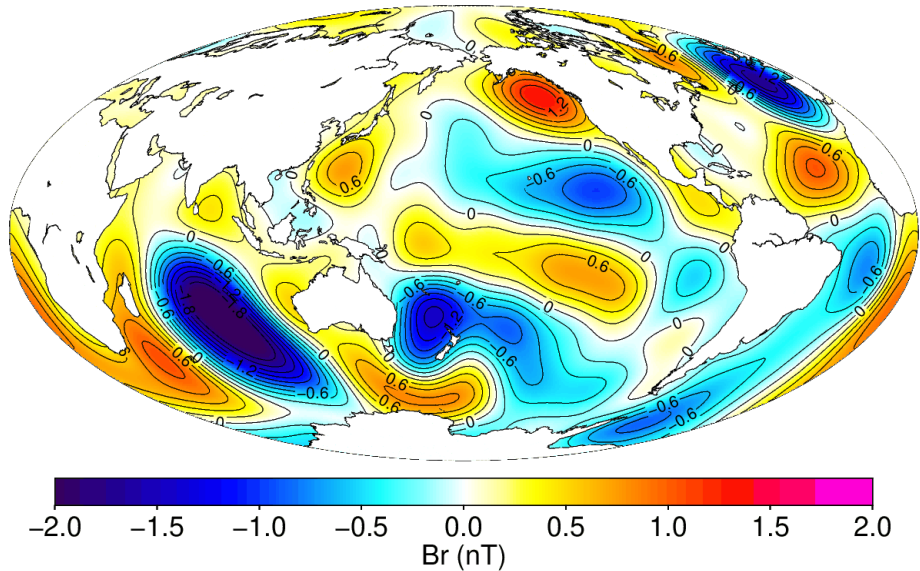


- Magnetic field due to crust magnetization;
- Characterized by many sharp discontinuities;
- The low perigee of MSS will offer a higher spatial resolution;
- Improve the current crustal magnetic field model.

Gubbins et al., 2011; Olsen et al. 2017; Yin et al. 2025

$$\Phi_M(\mathbf{r}) = \frac{\mu}{4\pi} \int_{\tilde{V}} \left[\mathbf{M}(\tilde{\mathbf{r}}) \cdot \tilde{\nabla} \left(\frac{1}{\mathbf{r} - \tilde{\mathbf{r}}} \right) \right] d\tilde{V},$$
$$\mathbf{M}_0(\theta, \phi) = \sum_{l,m} (E_l^m \mathbf{Y}_{l,l+1}^m + I_l^m \mathbf{Y}_{l,l-1}^m + T_l^m \mathbf{Y}_{l,l}^m),$$

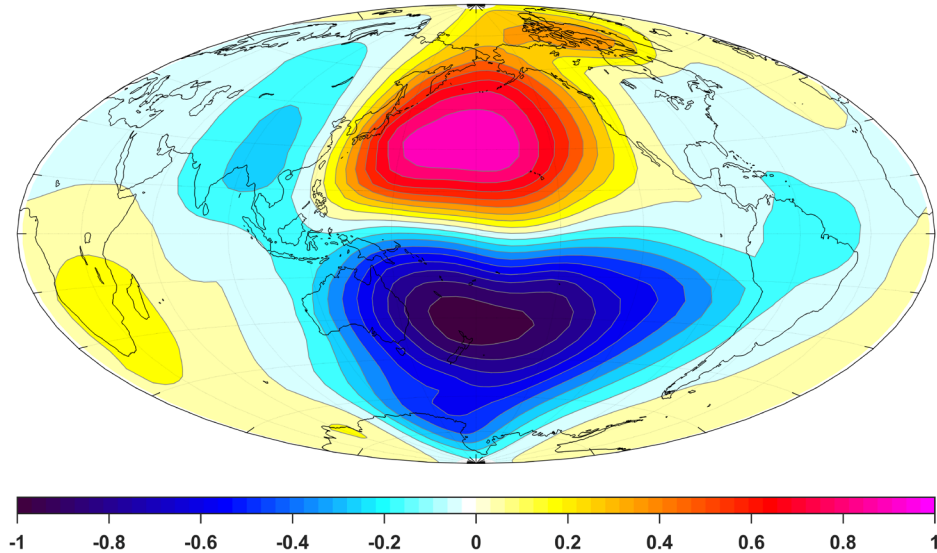
Reveal Induced Magnetic Fields by Large-scale Fluid Motion in Oceans



- Earth's oceans are made of an electrically conducting fluid;
- Large-scale salty water moving through the core geodynamo field induce electric currents;
- Induced magnetic fields are measurable by high-precision geomagnetic satellites;
- Extract contributions from ocean-induced magnetic fields.

$$\frac{1}{\mu\sigma_{\text{ocean}}}\nabla^2\mathbf{B}_i(r, \theta, \phi) - i\omega\mathbf{B}_i(r, \theta, \phi) = -\nabla \times [\mathbf{u}_{\text{ocean}}(r, \theta, \phi) \times \mathbf{B}(r, \theta, \phi)],$$

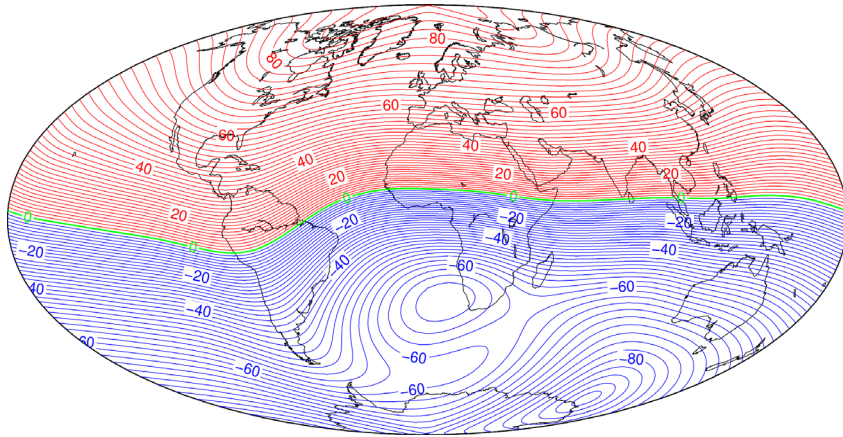
Reveal the Current Structure in Earth's Ionosphere



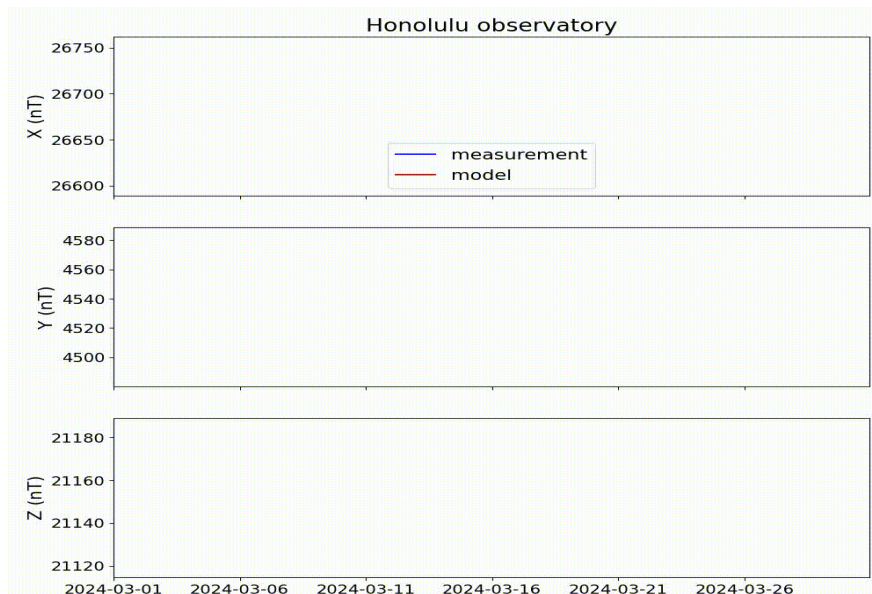
- Earth's external magnetic environment mainly comprises its ionosphere (60km to 200km) coupled with its magnetosphere (>200km);
- Providing the accurate magnetic data for understanding the current structure in near-Earth space;
- Leading to better magnetic separation of space and geodynamo sources.

$$\frac{\partial \mathbf{u}_i}{\partial t} + 2\Omega \hat{\mathbf{r}} \times \mathbf{u}_i \cos \theta = -\frac{1}{\rho_i} \bar{\nabla} p_i + \frac{1}{\rho_i \Delta h} \mathbf{J}_i \times \mathbf{B},$$
$$(p_i, \mathbf{J}_i, \mathbf{u}_i)(\theta, \phi, t) \sim f_n^m(\theta) e^{im(\phi + \omega_i t)},$$
$$\mathbf{J}_i(\theta, \phi, t) \sim \nabla \times [\hat{\mathbf{r}}(\sigma_i \sin \theta \cos \theta) e^{i(\phi + t)}],$$

Construct the Real-Time Model of Earth's Changing Magnetic Field

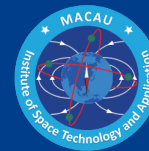


- Construct a real-time model of the Earth's magnetic field;
- Include important physics of the geodynamo, mantle, crust, oceans, ionosphere and magnetosphere;
- Have a wide range of applications in science and society.



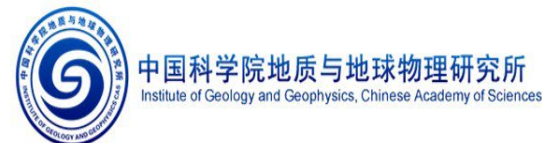
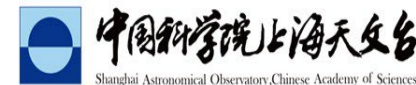
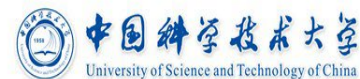
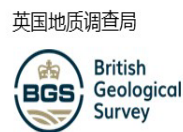
Comparison between observation (blue) and
model prediction (red)
Yao et al. 2025, PEPI, EPP

International Cooperation

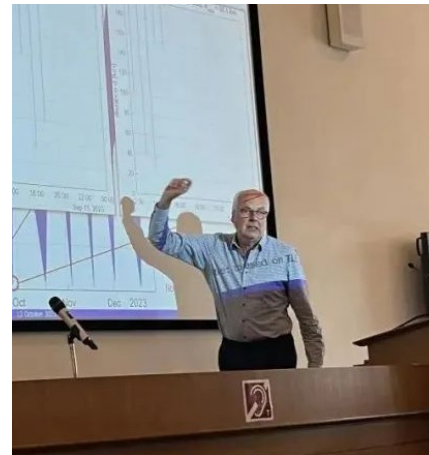


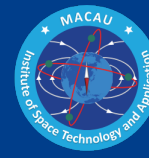
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- Cooperation with 18 international research institutes;
- Cooperation with more than 10 Chinese research institutes.



- The MSS agreement with the ESA DISC 18 research institutes;
- The MSS scientific meeting in Macau (Nov 2019);
- The MSS Royal Astronomical Society (RAS) London meeting (Oct 2023);
- The ESA Swarm-MSS joint meeting in Macau (May 2025);
- The MSS RAS London meeting (March 2026);
-





Thank you for your attention!

**You can learn more information and download the
MSS-1 data from our website:**

<https://mss.must.edu.mo/>

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