An Introduction to the MSS Constellation

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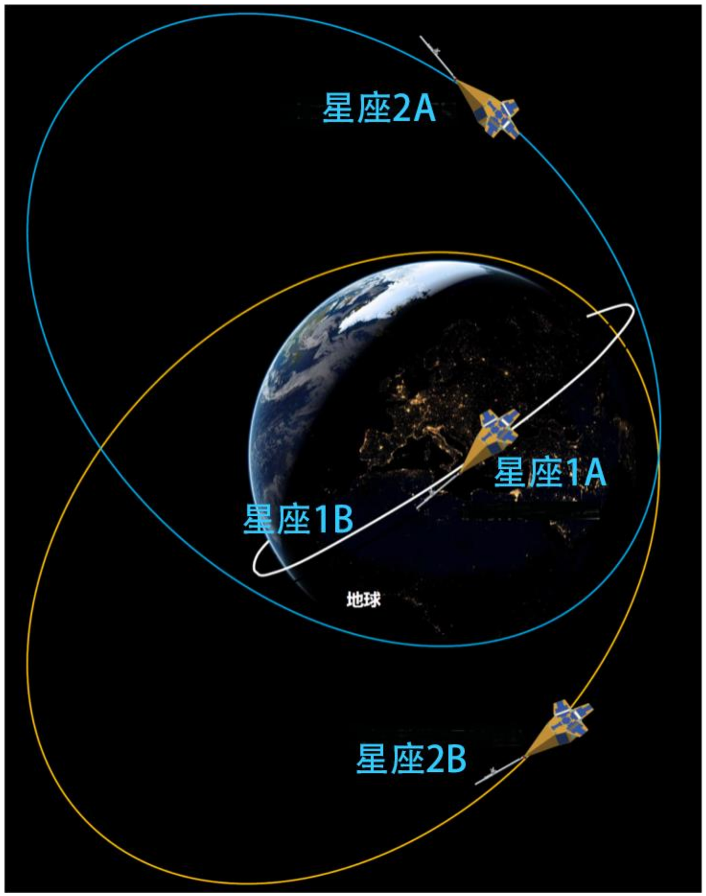
Outline of the Report

- **Background**
- **MSS Constellation: Macau Science Satellite 1A/B**
- **MSS Constellation: Macau Science Satellite 2A/B**
- **MSS Objectives: Near-Real-Time Modeling**
- **MSS-Swarm Cooperation**

MSS Constellation 1A



Orbits：

- (~40°) Low latitude
- Nearly circular
- Nearly ~450km (2-D measurements)

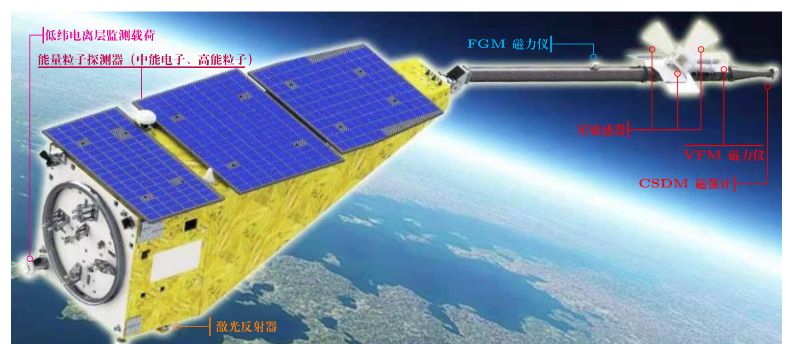
Payloads：

- Scalar Magnetometer
- Vector Magnetometer
- Star Camera and Optical Bench
- ….

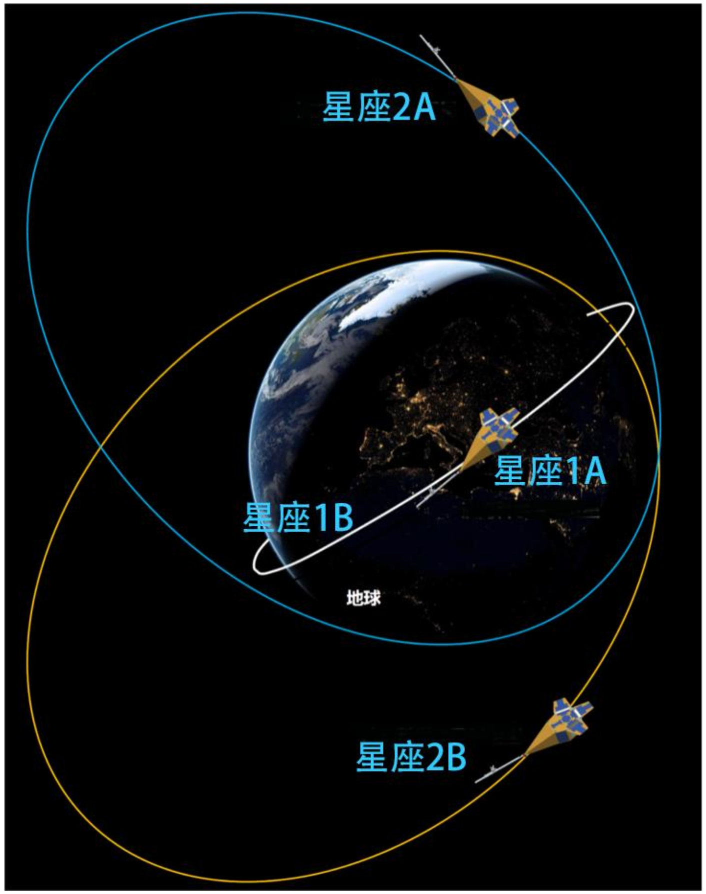
Objective:

- Measure low-latitude geomagnetic field and space parameters

Launch date： Launched on 21 May 2023



MSS Constellation 1B



Orbit:

- Inclination（~40°）、
- Nearly Circular：~450 km (2-D measurements)

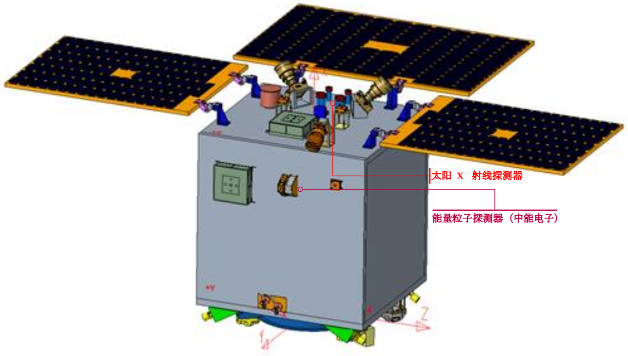
Payloads:

- Solar X-Ray Detector
- Charged Particle Detector
- ……

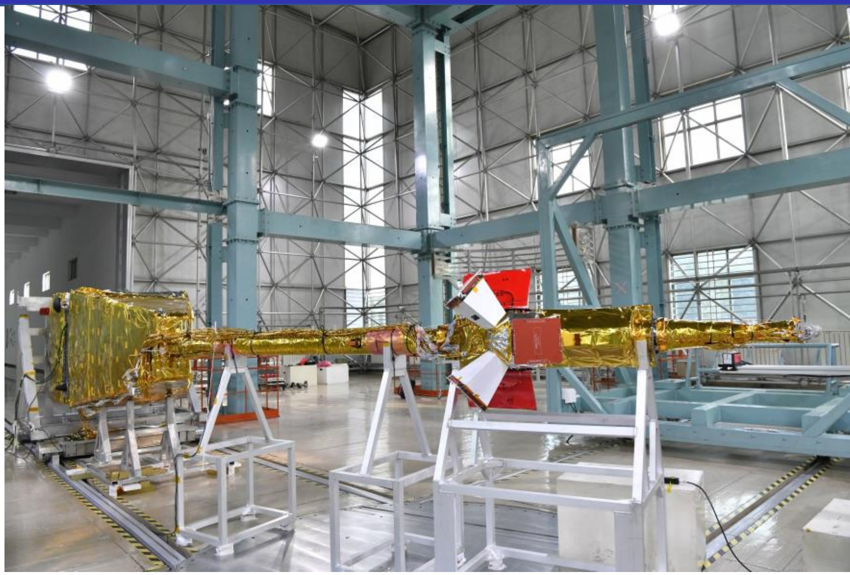
Objectives:

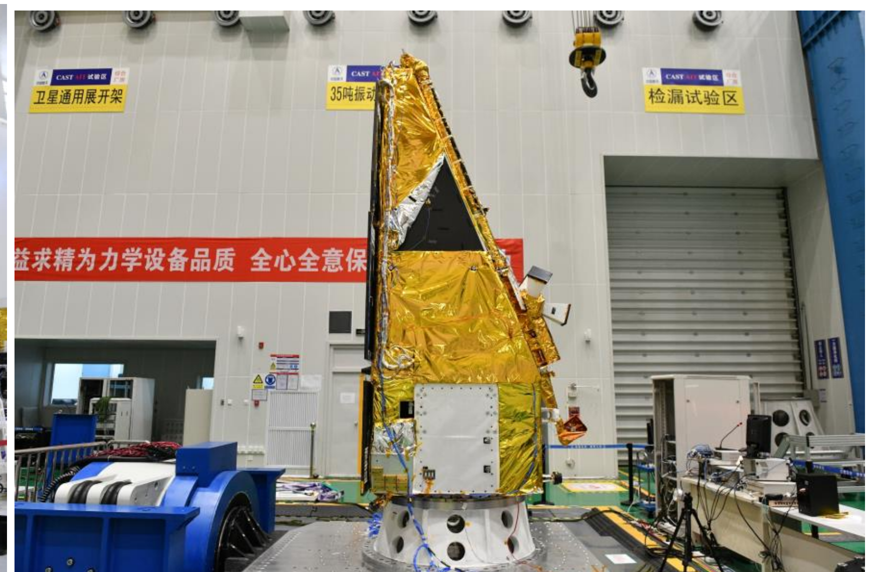
- Understand solar flares/winds and their interactions

Launch date: launched on 21 May 2023



MSS-1 A before its launch

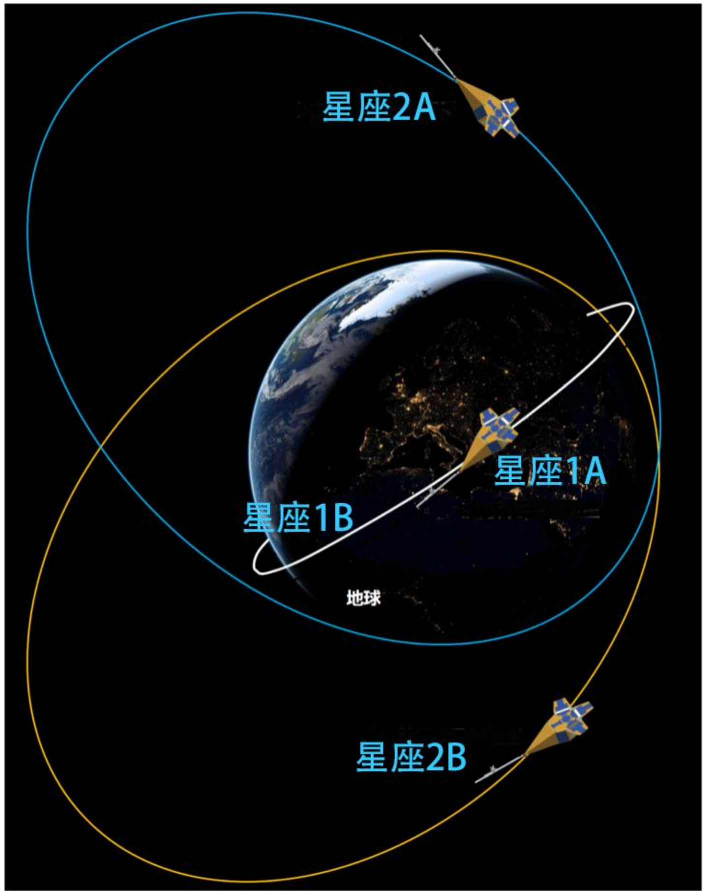




MSS-1 Twin Satellites Launching

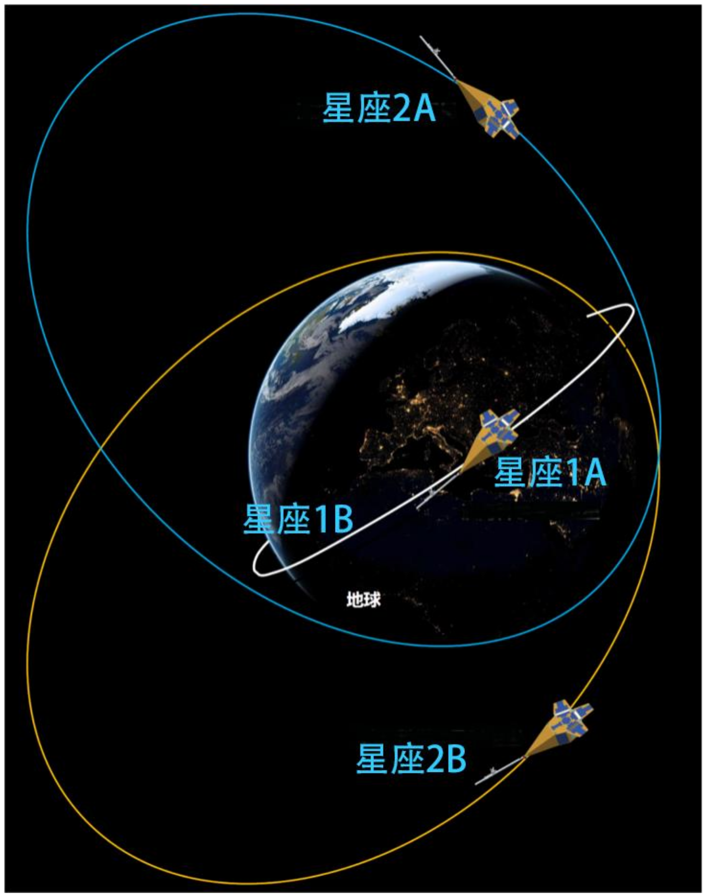
MSS-1 twin satellites were launched on 21 May 2023 while the in-orbit testing was largely finished by the end of 2023.

MSS-1 Data Calibration/Release



- The calibration of Scaler Magnetometer has been carried out by the MSS team and the Austria team (Completed);
- The calibration of Vector Magnetometer has been carried out by the MSS team and the Demark team (Just completed);
- The quality of the magnetic data, both scalar and vector, is satisfactorily high;
- All the magnetic data will be released, via a simple procedure, either this summer or before the end of 2024;
- Dr Jiang will talk about the magnetic data in detail tomorrow.

MSS Constellation 2A



Orbits：

- （~90°）Nearly polar orbits
- Highly elliptical
- Perigee 190-220km; Apogee 1500-2000km

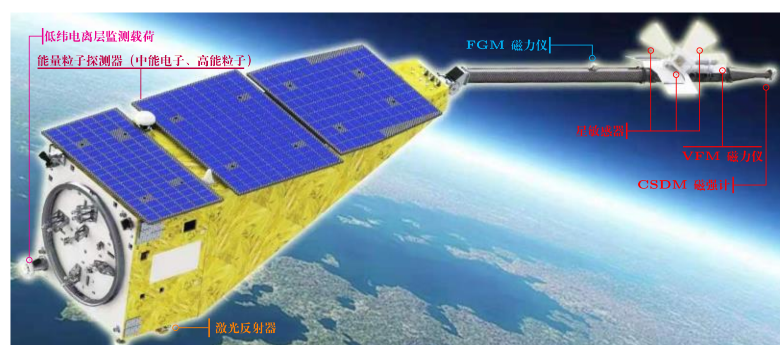
Payloads：

- Scalar Magnetometer
- Vector Magnetometer
- Star Camera and Optical bench
- ….

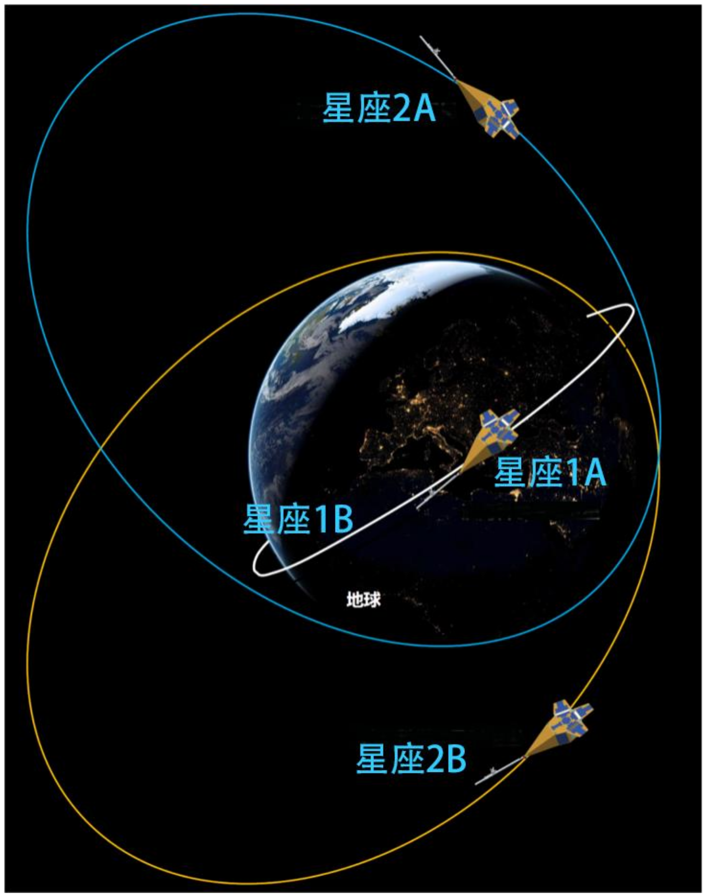
Objectives:

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

Launch date： Plan to be launched in 2026



MSS Constellation 2B



Orbits：

- （~90°）Nearly polar orbits
- Highly elliptical, different phases from 2A
- Perigee ~190-220km;Apogee 1500-2000km

- Nearly 180 degree difference in phase with 2A

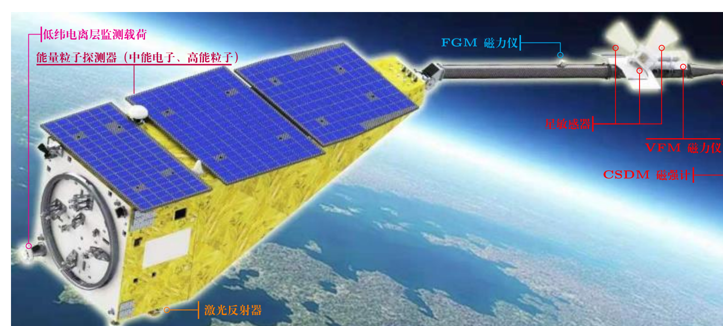
Payload：

- Scalar Magnetometer
- Vector Magnetometer
- Star Camera and Optical bench
- ….

Objective:

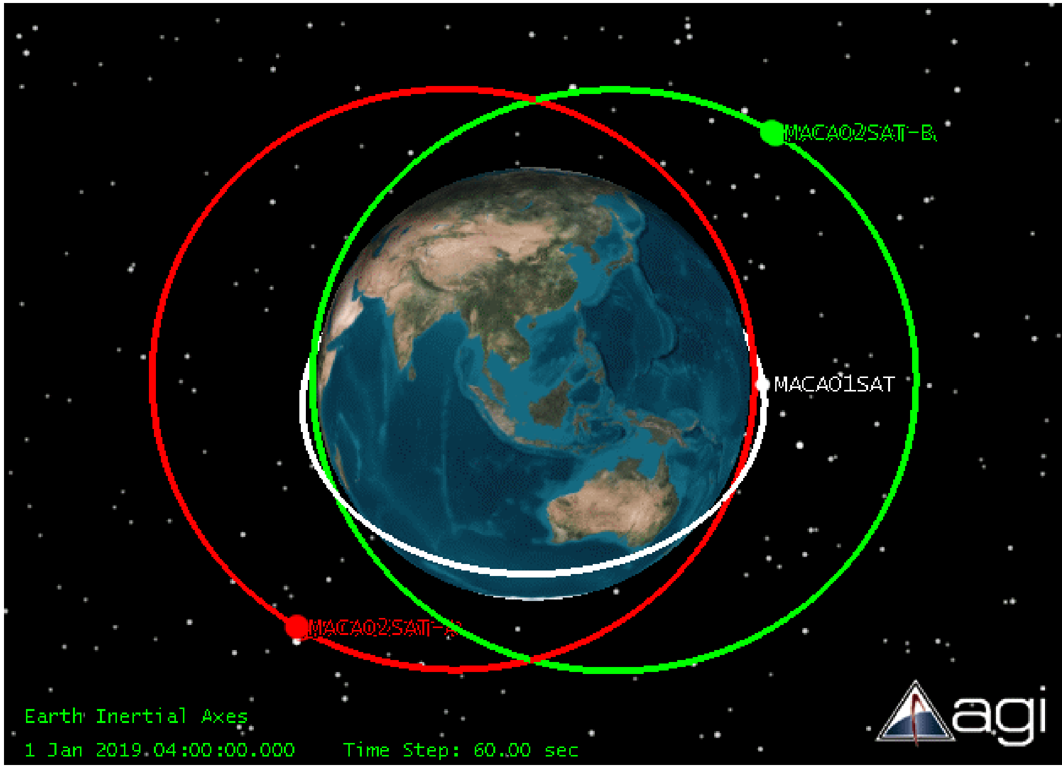
- Measure 3-D geomagnetic field and 3-D space parameters．

Launch date： Plan to be launched in 2026

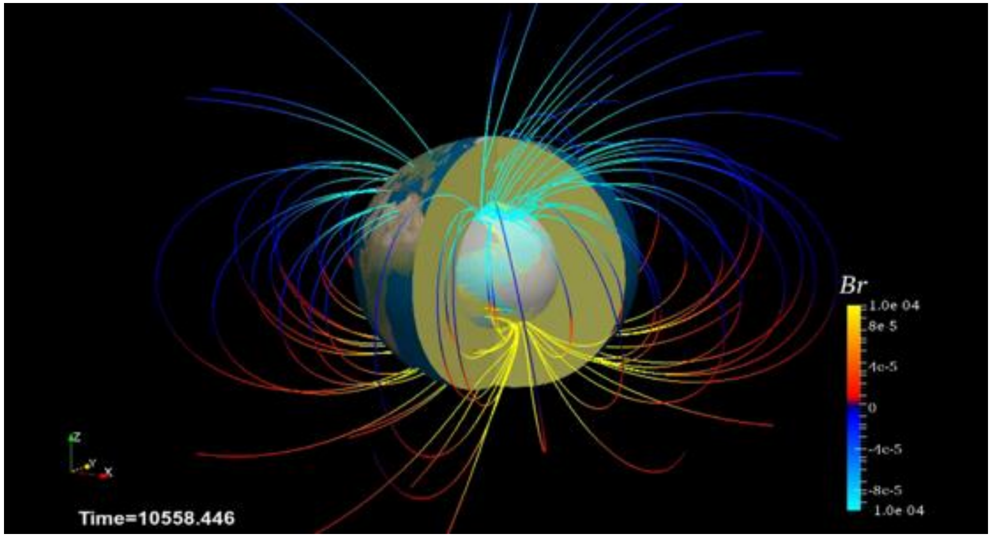


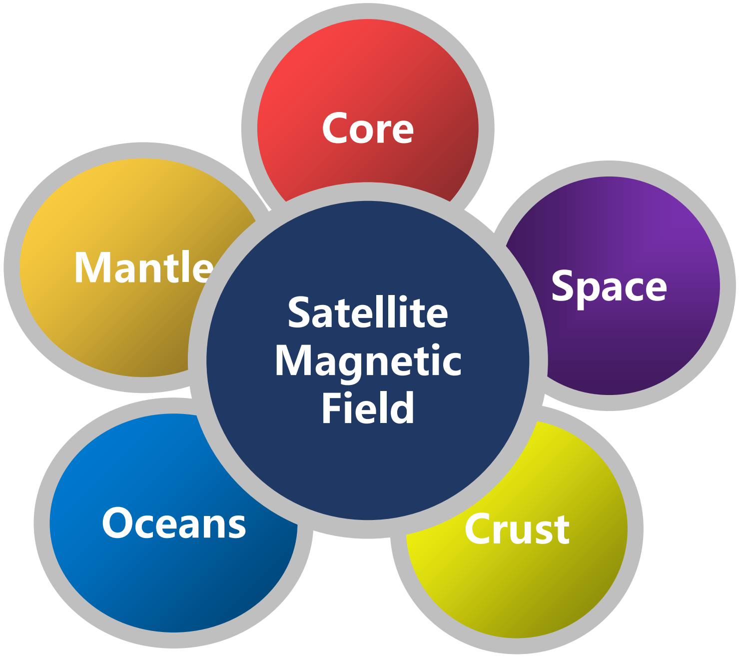
MSS Constellation: A combination of nearly circular and highly elliptical orbits

- Precessing Perigee and apogee;
- 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.



MSS Objectives: Near-Real-Time Modeling of the Earth's Magnetic Field.

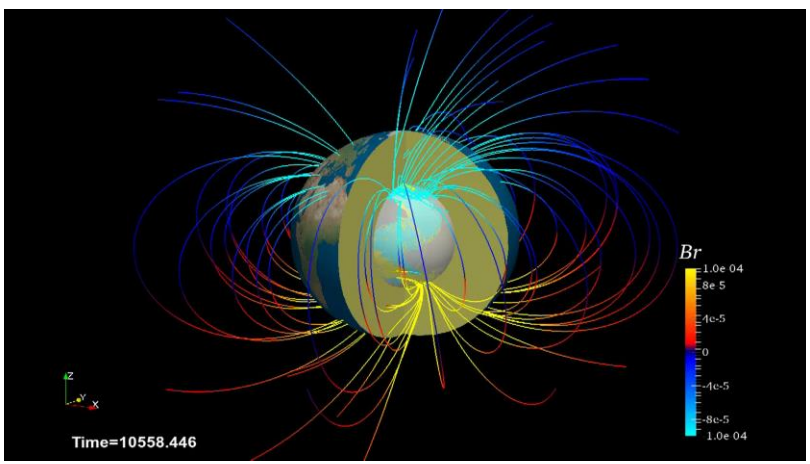




The measured Earth's magnetic field is the only geophysical parameter that includes the information of Earth's fluid core, mantle, oceans, crust, ionosphere and magnetosphere.

Near-Real-Time Modeling : the Geodynamo Field

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



Simulations with realistic geophysical parameters are still beyond reach.

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

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

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

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

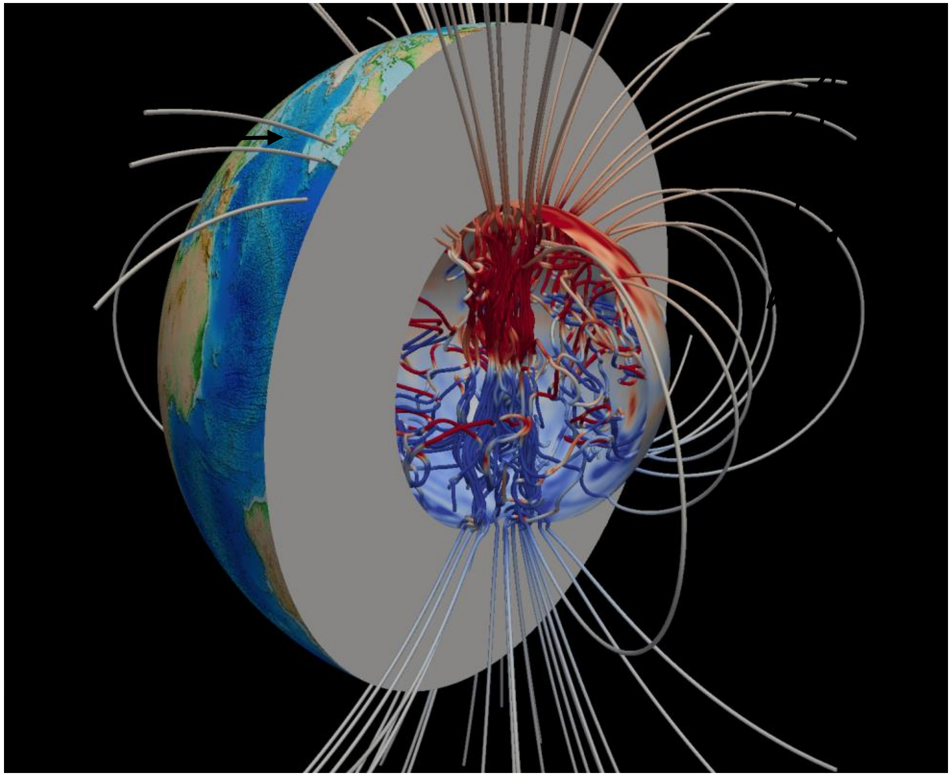
$$\nabla \cdot \boldsymbol{B} = 0$$

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

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

Near-Real-Time Modeling : Fluid Motion in Earth's Core

Use the accurate measurements to extract the information of mass motion in the Earth's fluid core via various hypotheses such as the frozen flux approximation the quasi-geostrophic approximation.



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

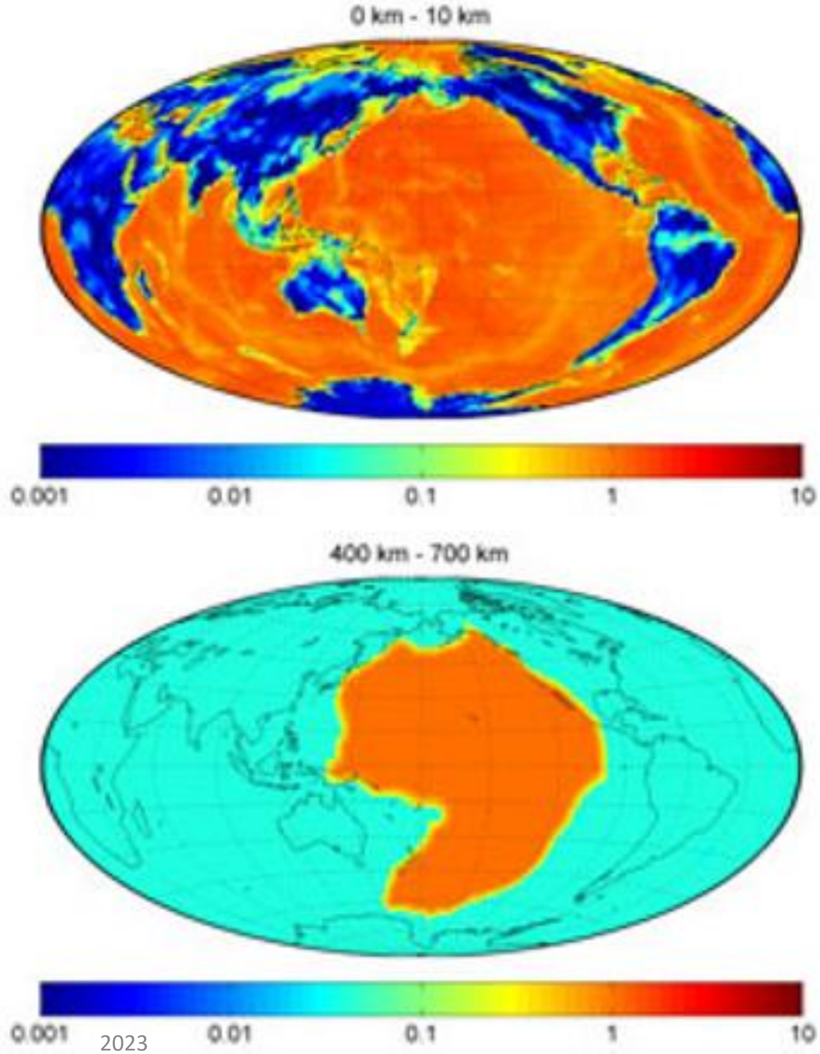
$$\frac{\partial \mathbf{u}}{\partial t} + 2\hat{\mathbf{z}} \times \mathbf{u} = -\frac{1}{\rho_0} \nabla P$$

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

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

Derive the 3-D core flow from geomagnetic inversion (Kloss and Finlay, 2019; Lin et al. 2023

Near-Real-Time Modeling: Induced Fields by Conductivity of the Earth’s Mantle



2023

- **The profile/magnitude of the secondary magnetic field can be used to estimate conductivity and heterogeneity of the mantle;**
- **It is closely connected with its physical/chemical properties, such as porosity, water, temperature and composition of the mantle.**

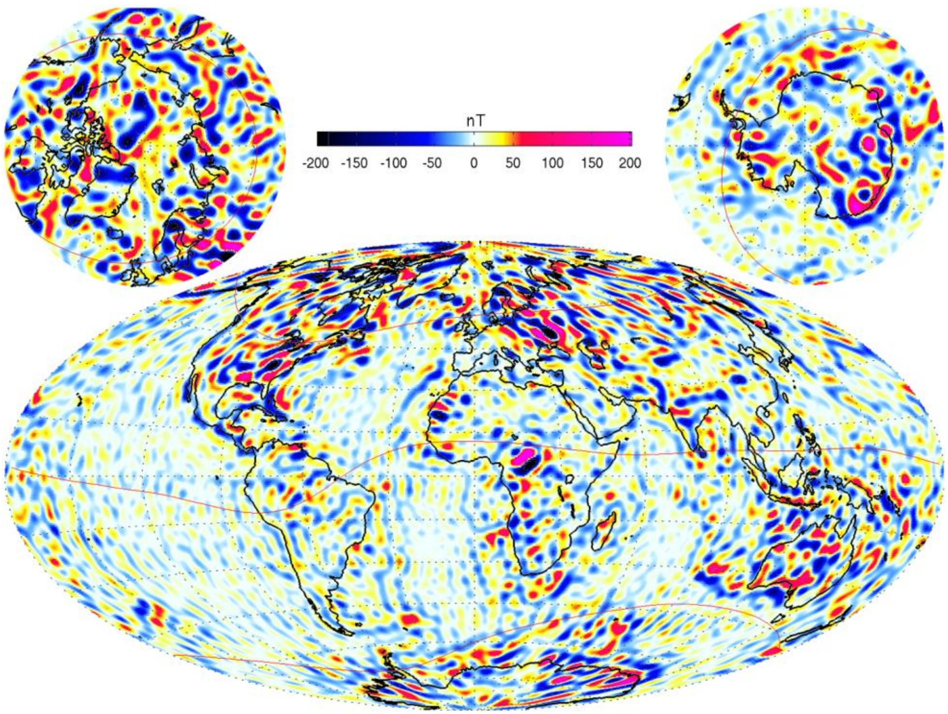
$$\frac{1}{\mu}\nabla \times \boldsymbol{B}(r,\theta,\phi) = \sigma(r,\theta,\phi)\boldsymbol{E}(r,\theta,\phi),$$

$$\mathrm{i}\omega\boldsymbol{B}(r,\theta,\phi) = -\nabla \times \boldsymbol{E}(r,\theta,\phi),$$

$$\nabla \cdot \boldsymbol{B}(r,\theta,\phi) = 0,$$

Kuvshinov, 2008; Yao et al. 2023

Near-Real-Time Modeling : Earth's Crustal Magnetic Field



- A broad spatial spectrum of the lithospheric magnetic field;
- Characterized by many sharp discontinuities;
- The low perigee of MSS offers a higher spatial resolution;
- Improve the current crustal model of the magnetic field.

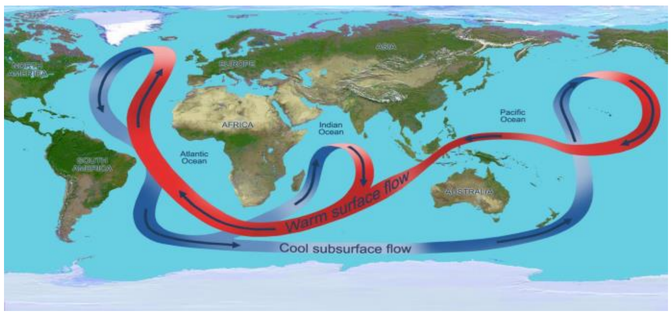
$$\Phi_e(\mathbf{r}) = r_E \sum_{l,m} \left(\frac{r_E}{r}\right)^{l+1} P_l^m \left(\tilde{g}_l^m \cos m\phi + \tilde{h}_l^m \sin m\phi\right),$$

$$\Phi_M(\mathbf{r}) = \frac{\mu}{4\pi} \int_{\tilde{V}} \left[\mathbf{M}(\tilde{\mathbf{r}}) \cdot \tilde{\nabla}\left(\frac{1}{\mathbf{r} - \tilde{\mathbf{r}}}\right)\right] d\tilde{V},$$

$$\mathbf{M}_0(\theta, \phi) = \sum_{l,m} \left(E_l^m \mathbf{Y}_{l,l+1}^m + I_l^m \mathbf{Y}_{l,l-1}^m + T_l^m \mathbf{Y}_{l,l}^m\right),$$

Gubbins et al., 2011; Olsen et al.2016; Finlay et al. 2017

Near-Real-Time Modeling : Fields Induced by Large-Scale Motion in Oceans

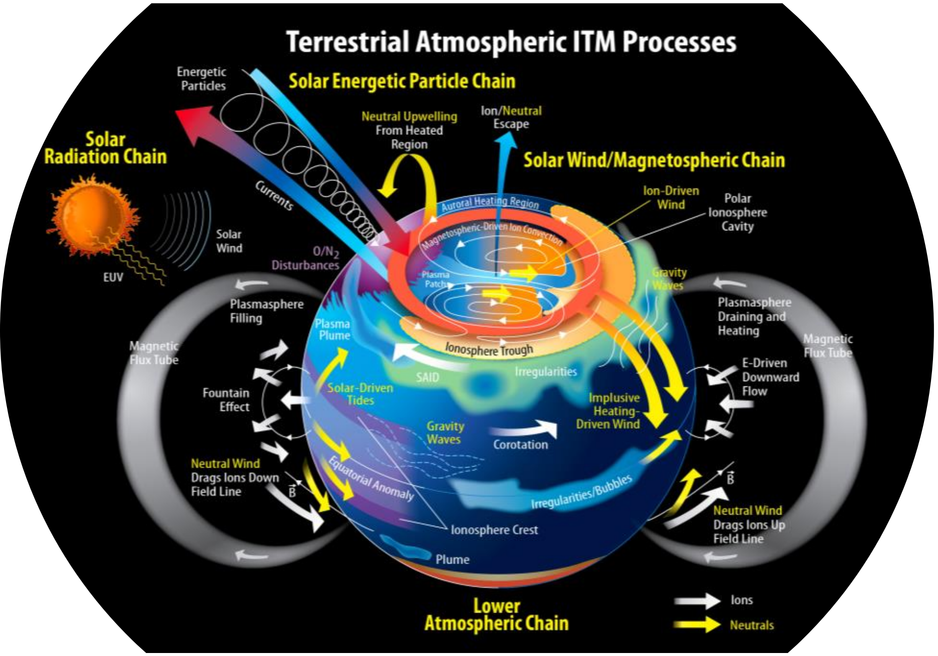


$$\frac{1}{\mu\sigma_{\text{ocean}}}\nabla^2 \boldsymbol{B}_{\text{i}}(r,\theta,\phi) - \text{i}\omega \boldsymbol{B}_{\text{i}}(r,\theta,\phi) = -\nabla \times [\boldsymbol{u}_{\text{ocean}}(r,\theta,\phi) \times \boldsymbol{B}(r,\theta,\phi)],$$

Sanford, 1971; Tyler et al. 2003

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

Near-Real-Time Modeling : Currents in Earth's Iono/magnetosphere



$$\frac{\partial \boldsymbol{u}_i}{\partial t} + 2\Omega \hat{\boldsymbol{r}} \times \boldsymbol{u}_i \cos\theta = -\frac{1}{\rho_i}\overline{\nabla} p_i + \frac{1}{\rho_i \Delta h} \boldsymbol{J}_i \times \boldsymbol{B},$$

$$(p_i, \boldsymbol{J}_i, \boldsymbol{u}_i)(\theta, \phi, t) \sim f_n^m(\theta) e^{im(\phi+\omega_i t)},$$

$$\boldsymbol{J}_i(\theta, \phi, t) \sim \nabla \times \left[\hat{\boldsymbol{r}}(\sigma_i \sin\theta\cos\theta)\, e^{i(\phi+t)}\right],$$

- **Earth's external magnetic environment mainly comprises its ionosphere(60km to 200km) dynamically coupled with its magnetosphere (>200km);**
- **Provide the data in the coupling region of the magnetosphere and the ionosphere;**
- **Provide the data for understanding the asymmetry between the Earth's polar regions;**
- **Offer an better magnetic separation of space and geodynamo sources.**

Kivelson and Russell 1995 Ganushkina et al. 2018

A Joint Swarm-MSS Conference in Macau

- The joint meeting will take place in Macau in the May of 2025;
- The organizers: A. Stromme, N. Olson, E. Qamili, Y. Jiang, K. Zhang;
- Some financial support is available if needed;
- Travelling between Europe and Macau is very easy.

The longest bridge in the world

MSS-Swarm Cooperation: what has been done

- The MSS agreement with the Swarm 18 research institutes;
- The MSS RAS London meeting (Oct 2023) with the Swarm team;
- The MSS scientific meeting in Macau 28-29 Nov at Macau;
- The Dragon 6 programme (with exchange between MSS and Swarm).