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Construction and Research Progress of the Chinese Meridian Project in 2022–2023*

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Abstract The Chinese Meridian Project (CMP) is a major national science and technology infrastructure constructed in two steps. The first phase of the CMP has been operating for more than a solar cycle. From 2022 to 2023, utilizing the monitoring data collected by the CMP, scientists made major breakthroughs in fields of ionosphere, middle and upper atmosphere, and coupling between layers. The construction of the second phase of the CMP is nearly finished, and the project is expected to operate as a whole in 2025 after national acceptance of the second phase. The whole project was built in an architecture of so-called "One Chain, Three Networks and Four Focuses". It is promising to make a three-dimensional observation of the whole solar-terrestrial space. The science community is looking forward to the great contribution of the CMP to space weather and space physics research.

Key words Chinese Meridian Project (CMP), Magnetosphere, Ionosphere, Middle and upper atmosphere

Classified index P35

1 Introduction to the Chinese Meridian Project

Monitoring solar-terrestrial space and conducting related comprehensive research is crucial for humanity in the modern space age. In addition to satellite observation, ground-based detection is also an important and irreplaceable observation method. Ground-based space environmental monitoring has a long history, commencing with experiments such as geomagnetic surveys and auroral observations from ancient times. Due to its significant "5 C" advantages (continuous, convenient, controllable, credible, and cost-effective), ground-based monitoring has been widely adopted nowadays. Presently, ground-based monitoring is developing toward a networking trend, with research groups worldwide establishing numerous ground monitoring networks, such as SuperDARN, MAGDAS, and INTERMAGNET.

To monitor the huge span of the solar-terrestrial space with regions of quite different physical characteristics, including the solar atmosphere, interplanetary space, magnetosphere, ionosphere, and middle and upper atmosphere, a highly comprehensive capability is desired. The Chinese scientists proposed to construct the Chinese Meridian Project (CMP). The overall scientific goals of the CMP can be summarized as follows. (i) Tracing the propagation and evolution of space weather events from the solar atmosphere to near-Earth space and their impact on the space environment. (ii) Revealing regional characteristics of the space environment over different regions, and relationship between regions. (iii) Studying the coupling mechanism between different spatial layers and physical processes.

Construction of the CMP was divided into two stages, namely Phase I and Phase II. The CMP phase I

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was completed from 2008 to 2012 and entered the operational phase after 2012[1], and has accumulated data for more than a solar cycle. Significant research progress has been made utilizing the dataset[2]. The second phase, CMP phase II, with construction beginning at the end of 2019, is now waiting for final national acceptance. After the completion of CMP phase II, CMP can achieve a detection altitude range from near-Earth space to the solar atmosphere and has a rather full coverage of the territories of China's mainland and polar regions, providing a stereoscopic monitoring capability for the entire solar-terrestrial space.

This article aims to introduce the latest progress made between 2022 and 2023. Section 2 introduces the construction status of the CMP Phase II and outlines the facilities finally established. Section 3 will mainly introduce the research progress made using the facilities and data of the CMP Phase I, followed by some conclusions and future development prospects.

2 Construction Progresses of the CMP Phase II

2022–2023 is a critical two-year period for construction of the CMP Phase II. All the heavy works, such as laboratory experiments, on-site installation and debugging, were carried out during this period. After the construction was completed, each instrument was tested against design indicators under the witness of an expert group. On 3 June 2024, the project passed technique acceptance organized by Chinese Academy of Sciences and was put into overall trial operation. National acceptance is expected to be held by the end of 2024.

Each instrument started trial operation after completion of construction, so preliminary observation results have been accumulated, and related research is currently underway. Some preliminary open sharing and exchange activities are also carried out, such as the SuperDARN Beijing seminar held in June 2024.

According to the design, the CMP constructed three systems namely Space Environment Monitoring System, Data and Communication System and Scientific Application System. In the following paragraphs, a brief introduction of the constructed systems will be presented. For more detailed information, please refer to the "Chinese Meridian Project Special Collection" [3] published on the *Journal of Space Weather* or visit the website of the project (http://www.meridianproject.ac.cn).

2.1 Space Environment Monitoring System

Space Environment Monitoring System is composed of nearly 300 instruments in 31 comprehensive stations that are strategically located approximately along longitude 120°E, longitude 100°E, latitude 30°N, and latitude 40°N, effectively covering the Chinese Mainland and the polar regions. To achieve comprehensive and three-dimensional detection of the entire solar-terrestrial space, the CMP adopted a well-designed architecture namely "One Chain, Three Networks, and Four Focuses" (Figure 1[3]). The so-called "One Chain" is formed by optical, radio, Interplanetary Scintillation (IPS), and cosmic ray instruments, covering the entire space chain from the solar surface to interplanetary space, and further to the geospace. The "Three Networks" conduct grid-like monitoring for the ionosphere, middle and upper atmosphere, and geomagnetic field over the territory of China. Additionally, four key areas with special regional characteristics or serving as key nodes for the propagation of space weather disturbances have been identified, and large-scale instruments or powerful monitoring facilities have been established there to do more detailed observations. These key regions include the polar regions of high-latitude, the mid-latitude region in northern China, the low-latitude region at Hainan, and the Tibet Plateau region.

2.1.1 One Chain

The Sun serves as the primary source of disturbances in the solar terrestrial space environment. Monitoring the solar atmosphere and interplanetary space is crucial for understanding the mechanisms of solar eruptions and the transmission laws of matter and energy, as well as improving space weather forecasting performance. One Chain, the solar interplanetary monitoring chain, was established to monitor from the solar surface to near-Earth space.

To account for significant differences existing in the frequency of electromagnetic radiation across various regions, the chain employs a multitude of detection methods, including optics, radio, InterPlanetary Scintillation (IPS), and cosmic rays. This comprehensive approach forms a full chain with tracking and monitoring capability for solar eruption activities from the solar surface to near-Earth space. The main monitoring instru-

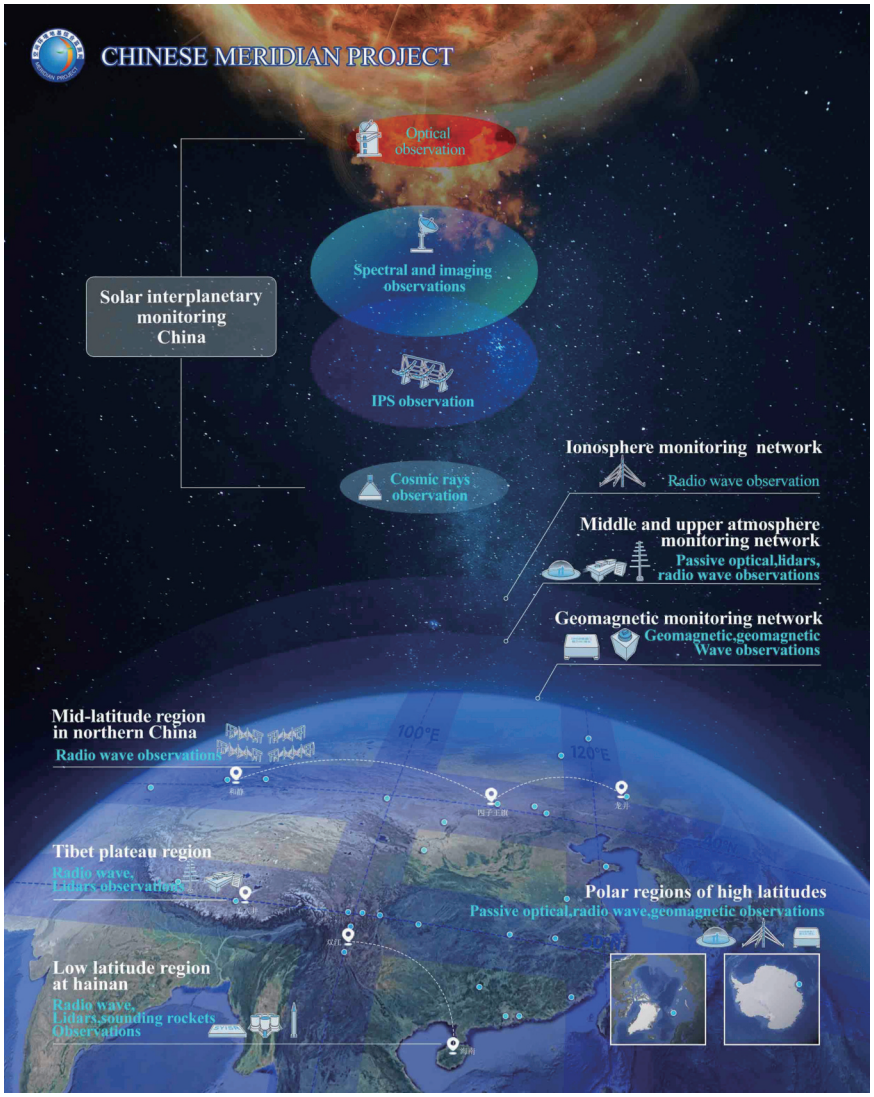

Fig. 1 Schematic diagram of the CMP's space environment monitoring system

ments include Solar Magnetism and Activity Telescope, Solar Full-disk Multi-layer Magnetograph, Solar Disk Chromosphere Telescope, Spectral Imaging Corona Graph, Spectrometers and radio heliographs in multiple frequency bands (*e.g.*, Figure 2), IPS telescope (Figure 3), Moun telescope and neutron counter.

2.1.2 Three Networks

A comprehensive network of instruments was deployed to monitor the near-Earth space environment. These instruments are approximately located along the meridians (120°E and 100°E) and latitude lines (30°N and 40°N). This layout enables thorough monitoring of the rich longitude and latitude variations and regional characteristics of the near-Earth space environment over China.

The Geomagnetic Monitoring Network deployed more than 100 geomagnetic (and electrical) instruments to detect long-term changes, rapid changes, and fluctuations in the geomagnetic field and near-surface electric fields. Instruments include fluxgate magnetometers, fluxgate theodolites and Overhauser magnetometers, magnetic field wave monitors, geoelectric field detectors, and so on.

The Middle and Upper Atmosphere Monitoring Network comprises various radio radars (meteor radars, Mesosphere-Stratosphere-Troposphere radars, with Figure 4 showing one of them), airglow monitoring instruments (airglow imagers, airglow interferometers), and LiDARs. These instruments collectively measure atmosphere density, wind, temperature, as well as ionospheric irregularities. The network can measure various

Fig. 2 Circular array solar radio telescope (150−450 MHz)

Fig. 3 IPS telescope array (the main station)

parameters from an altitude of 0.3 km up to more than 110 km with a horizontal station spacing of hundreds kilometers.

The ionospheric monitoring network consists of 17 ionospheric digital altimeters, 41 GNSS ionospheric TEC and scintillation monitors, and 16 high-frequency Doppler monitors. The network monitors key ionospheric parameters, the total electron content (TEC) and amplitude scintillation and phase scintillation information. In the second phase of the CMP, four high-frequency Doppler shift monitoring arrays were constructed near 120° east longitude. Each array consists of a transmitter and three receivers that is able to measure the three-dimensional motion velocity of the ionosphere.

2.1.3 Four Focuses

In the four key regions, *i.e.*, the polar regions of high-latitudes, the mid-latitude region in northern China, the low-latitude region at Hainan Island, and the Tibet Plateau region, powerful monitoring facilities or large-scale instruments have been deployed there.

For the polar regions of high-latitudes, the CMP utilizes existing scientific stations established by China in the polar regions or takes advantage of international cooperation, to deploy instruments monitoring the ionosphere, middle and upper atmosphere, auroras, and geomagnetic field waves. Stations include Zhongshan Station (76.4°E, 69.4°S) and Great Wall Station (59.0°E, 62.2°S) in Antarctica, and Longyearbyen Station (16.0°E, 78.2°N) in the Arctic.

Fig. 4 One of the MST radars (Qinzhou Station)

For the mid-latitude region in northern China, a high-frequency radar array was built at three observation stations located in the northern region of China: Longjing (129.4°E, 42.8°N), Siziwang (111.6°E, 41.8°N), and Hejing (83.7°E, 42.9°N) (Figure 5). Each station is equipped with two high-frequency Radars, one facing northeast and the other facing northwest. The combination of the two radars forms a fan-shaped scanning region with an angle of approximately 158°. As a result, the combination of the detection region of the three stations is about 10000 km in the east-west direction and over 3500 km in the north-south direction. This huge coverage literally links domestic monitoring with polar region monitoring.

For the low-latitude region at Hainan Island, multiple large-scale radio wave and optical monitoring instruments were established to detect the fine spatial structure of the middle and upper atmosphere, ionosphere, and inner magnetosphere, spanning altitudes from 80 kilometers to thousands of kilometers. Among the instruments, Very High Frequency (VHF) radars in Danzhou, Hainan, and Shuangjiang, Yunnan, detect the distribution and movement of ionospheric irregularities. A low latitude high-frequency radar built in Dongfang, Hainan, explores the horizontal characteristics of magnetic field lines in the low latitude region by detecting ionospheric irregularities in the east and west directions. A parabolic mechanically steering incoherent scattering radar (ISR) was constructed in Qujing, Yunnan, during the first phase of the CMP, and a phased array incoherent scattering radar system (SYISR) was built in the second phase, with transmitters and receivers located in Sanya (Figure 6), Danzhou, and Wenchang, Hainan Is-

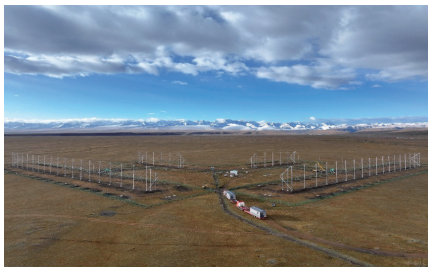

Fig. 5 Mid-latitude high-frequency radar (Hejing station)

Fig. 6 Multi-static incoherent scattering radar (the main station)

land. An Array Type Large-Aperture LiDAR (Figure 7) built in Danzhou integrated multiple optical telescopes to detect metastable helium density in the altitude range of 200–1000 km and atmospheric density, temperature, and sodium atom density within an altitude range of about 30–105 km.

For the Tibet Plateau region, the Yangbajing Station (90.5°E, 30.1°N, 4290 m) was established to accommodate a multitude of instruments consisting of an MST radar, an Atmosphere Wind Temperature Lidar, and a Millimeter-Wave and Infrared Imager. These instruments monitor atmospheric temperature, wind field, density, metal layer, and other parameters in an altitude range from the surface up to the lower thermosphere.

2.2 Data and Communication System and Scientific Application System

The data and communication system includes the data network transmission subsystem, data processing and management subsystem, and data service subsystem, with core functions of data collection, processing, storage, and user services. To ensure security, the system has established a VPN network that connects all monitoring instruments to the data center. Most monitoring data can be transmitted to the data center and made publicly available within 15 minutes.

Fig. 7 Array-type large aperture lidar

The Scientific Application System was constructed to efficiently manage monitoring instruments of the Space Environment Monitoring System, and promote scientific research using monitoring data. The system includes the Scientific Operation Subsystem, Research Support Subsystem, Forecast Support Subsystem, and Application Demonstration Subsystem.

Both the Data and Communication System and the Scientific Application System are built in the CMP Information and Operation Control Center Building in Huairou, Beijing (shown in Figure 8[3]).

3 Research Progresses

3.1 Overview

For CMP Phase-II, although its construction has not been fully completed, preliminary observations have been obtained and published in journals. For example, Hou *et al.*[4] reported a type-II radio burst observed by the Rongcheng solar radio spectrometer, and Yue *et al.* [5] presented an ionospheric pre-sunrise uplift event captured by the Sanya incoherent scatter radar. During the construction of CMP Phase-II, a series of equipment introduction articles and research papers were published, such as on interplanetary scintillation observation and space weather modeling[6], active phased array[7], and data acquisition, correction and retrieval[8]. In particular, a special introduction collection on conventional instruments was published in the *Chinese Journal Review of Geophysics* and *Planetary Physics*. Some introduction articles of large-scale monitoring instrument have been published in *Space Weather* as a special collection.

From 2022 to 2023, most research works were conducted using monitoring data from CMP Phase-I. These

Fig. 8 (a) Information and operation control center building, (b) the operation control center hall, and (c) the data and computing center facility

research works mainly involve near-Earth space regions, *i.e.* middle and upper atmosphere, ionosphere. For the sake of brevity, we will only introduce some of the highlights of our research works below.

3.2 Middle and Upper Atmosphere

The nonlinear interaction between waves in the atmosphere is an important topic for studying the physical mechanisms of the generation, evolution, and propagation of atmospheric waves. He *et al.*[9] reported a Rossby wave second harmonic generation event in meteor radar wind observations. Bicoherence and biphase analyses demonstrate that the 16-day signature in wind data is a Rossby wave normal mode, and its second harmonic generation gives rise to an 8-day signature. For the first time, the study confirmed the theoretically anticipated Rossby wave nonlinearity.

The global middle and upper atmospheric wind field is a very important dynamic parameter that is difficult to be measured. Its characteristics of variation have always been an important scientific issue in the study of the middle and upper atmosphere. Using meteor radar observations and satellite TIMED/SABER temperatures, Liu *et al.*[10] derived a global balance wind dataset from 2002 to 2019 and studied the relationships between global zonal wind and several impactors. It was shown that the responses of zonal winds to Quasi Biennial Oscillation (QBO) are approximately hemispheric symmetry and change from positive to negative with increasing height, and the responses of zonal winds to $F_{10.7}$ and ENSO are more prominent in the southern stratospheric polar jet region as compared to the northern counterpart. Using meteor radar measurements and the reanalysis data from 2011 to 2020, Gong *et al.*[11] for the first time investigated the characteristics of intraseasonal oscillations (ISOs) in the MLT region over Mohe (53.5°N, 122.3°E). They found a strong Intraseasonal Oscillation with a period of 40–60 days in the mesosphere and lower thermosphere, and suggested that it is likely associated with the equatorial Madden-Julian Oscillations in the troposphere and strong El Niño and the positive Indian Ocean Dipole indices may also contribute.

Metal layers are important components of the atmosphere and good tracers for studying the dynamics and photochemistry in the mesosphere and lower thermosphere. In addition to metal Na, the Lidar at the Beijing station has been upgraded to detect other metal components in the mesopause and lower thermosphere region. Jiao *et al.*[12] reported a Ca^+ layer event up to a height of 300 km, captured by the new Lidar. The thermosphere-ionosphere Ca^+ layer was likely formed by uplifting ions from sporadic Ca^+ at about 110 km, which was demonstrated by spread F occurred concurrently and strong sporadic E layers occurred before. Efforts were also made to improve metal layer models. Yu *et al.*[13] compared the WACCM-Na model against lidar observations and suggested that vertical transportation is underestimated in the model.

3.3 Ionosphere

The nighttime enhancement of electron density is a frequent phenomenon, but lacks a satisfactory and consistent explanation. Liu *et al.*[14] made case studies showing that the northern hemisphere GEO-TEC enhances in a limited latitudinal and longitudinal coverage usually with a hemispheric asymmetry at low latitudes. They suggested field-aligned transport and electric fields being possible regulator to the limited spatial scale of post-midnight enhancements in the low latitude ionosphere. The study also showed discrepancies between TEC and N_mF_2 as indicators for electron concentration.

Ionospheric plasma bubbles are a type of ionospheric irregularities that often occur in low latitude regions, referred to as Equatorial Plasma Bubbles (EPB) as well. Relative studies can help to understand ionospheric dynamics. Exploring measurements from an all-

sky airglow imager and a Very High Frequency (VHF) radar and eight digisondes, Sun *et al*.[15] reported the evolution process of an EPB event that was supposed to be controlled by multiple factors. The EPB was seeded by gravity waves, and evolved into topside ionosphere via gradient drift instability and T-R instability. This equatorward wind-induced $E \times B$ gradient drift instability continuously forced topside depletions to extend poleward, resulting in 3.2 m irregularities around midnight.

Ionosphere modeling is not only crucial for prediction, but also helpful to understand physical mechanisms. Yu *et al*.[13] constructed an Es layer (sporadic E layer) climatological model based on S4 max data extracted from COSMIC satellite occultation measurements. This model can provide climatology of Es layer intensity as a function of altitude, latitude, longitude, universal time, and day of year.

3.4 Coupling between Layers

Some research was conducted on the coupling between solar wind, magnetosphere and ionosphere, using detection data of CMP. Liu *et al*. [16] found that the polar region ionosphere can be promptly affected by interplanetary shocks. Their study shows that the Ionosonde at Zhongshan station detected enhanced E region ionization and vertical plasma motion, and it is thought to be the result of Sudden Impulse (SI)-driven E-field drift-convergence and particle precipitation caused by an interplanetary shock. It was assumed the shock-triggered SI altered the dusk-to-dawn electric field that drives a brief downward plasma motion at the dayside polar ionosphere.

Ionospheric response to storms was studied. Tariq *et al*.[17] presented the longitudinal dependence of ionospheric responses during two intense geomagnetic storms of May and September 2017. Two ionospheric enhancements were observed in TEC measurements during the storm of May 2017, both can be attributed to Prompt Penetration Electric Field (PPEF) while with the maximum TEC enhancements located in different regions. Negative storm time ionospheric responses were observed on 30 May, allegedly caused by a change of the thermospheric composition as O/N_2 depletion.

Lithosphere-atmosphere-ionosphere coupling plays a crucial role in the dynamics of the whole near-Earth space. Volcanos and typhoons are two major sources of upward propagating disturbances. Multiple studies have been conducted about the 2022 Tonga volcano eruption. Zhang *et al*.[18] showed enhanced ionospheric irregularities with highly variable velocities after the Tonga volcanic eruption, with the maximum amplitude of the line-of-sight velocity of the ionospheric oscillation approaching 150 $m \cdot s^{-1}$ in the E layer. The study also showed magnetic field conjugation-related disturbances occurred much earlier than the arrival of surface air pressure waves. For typhoon-induced disturbance, Li *et al*.[19] presented an event in which a typhoon directly generated gravity waves in the mesopause region while the thermosphere was affected by the secondary waves generated by the dissipation processes in the mesopause region.

Stratosphere Sudden Warming (SSW) has been an important topic for studying coupling between different atmosphere layers and between the neutral atmosphere and ionosphere. From 2022 to 2023, many works using the CMP data were published on this topic. For example, Ma *et al*.[20] reported significant tide-like harmonics in the residuals of Total Electron Content (TEC) during SSWs. Their study shows that significant tide-like harmonics presented in the residuals of TEC were detected by five receivers at different latitudes during the 2018 SSW. After the SSW onset, the third harmonic enhanced and the fourth harmonic weakened for all receivers, while the second harmonic exhibited a response depending on latitude. Comparing TEC signals against mesospheric winds observed by four meteor radars showed good agreement, demonstrating the crucial role played by neutral winds in the formation of tide-like harmonics in the ionosphere.

4 Conclusion and Prospect

In this article, we reviewed the construction progress of CMP Phase II, including a brief introduction of established systems and instruments. The research progresses in the past two years using the monitoring data of the CMP Phase-I are also introduced. Recently, the second phase of the CMP has nearly finished construction and is expected to undergo national acceptance by the end of this year. The first phase of the project has been operating for more than a solar cycle. Utilizing the monitoring data, comprehensive research has made significant progress with topics varying from ionosphere, middle

and upper atmosphere, and coupling between layers. On national acceptance of the second phase, the two phases of Chinese Meridian Project will operate as a whole to realize the scientific objectives of the project. It is very promising that the CMP will continue contributing to innovation in the field of space science at an even much higher level.

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