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# Precision gravity measurement facility



**Keywords** precision gravity measurement, large-scale scientific project, technological innovation, gravity reference, satellite gravity field measurement, gravity/gravity-gradient detection

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| **Project Legal Entity:** Huazhong University of Science and Technology |
| **Supervisory Authorities:** Ministry of Education; Hubei Provincial People's Government |
| **Co-establishing Authorities:** Chinese Academy of Sciences; Wuhan Municipal People's Government |
| **Participating Institutions:** Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences; China University of Geosciences (Wuhan); Sun Yat-sen University |

## 1 Overview of the precision gravity measurement facility

The Precision Gravity Measurement Facility (PGMF) is one of China's major national scientific and technological infrastructures. With a total investment of 859 million RMB and a five-year construction period, the project was supervised by the Ministry of Education of China and the Hubei Provincial People's Government, and jointly established by the Chinese Academy of Sciences (CAS) and the Wuhan Municipal People's Government. The application was initiated in 2010, approved in 2015, and construction began in 2018. Huazhong University of Science and Technology, China (HUST) serves as the legal entity, in collaboration with the CAS Innovation Academy for Precision Measurement Science and Technology, China University of Geosciences (Wuhan), and Sun Yat-sen University, China (Luo et al., 2016).

The facility aims to achieve breakthroughs in gravity reference, marine-airborne, and satellite gravity measurement technologies, enabling global milligal-level and reference microgal-level gravity data acquisition, evaluation, and application. The facility includes two main platforms—a gravity reference platform and a physical simulation platform—together with a 30,000 m$^2$ integrated research building and a renovated and expanded 6,000 m$^2$ underground laboratory. As shown in Fig. 1, the platforms comprise four subsystems: gravity reference traceability, gravity reference calibration and evaluation, physical simulation of marine-airborne gravity-gradient measurement, and physical simulation of satellite gravity measurement. These subsystems include 11 systems and 24 instruments (Liu et al., 2022).

The facility is supported by the Center for Gravitational Experiments, School of Physics, HUST. The team has conducted experimental investigations of gravitational and gravity-related physical laws for more than four decades. These efforts have yielded major advances in both fundamental research and applications of national relevance, earning the group the reputation of being a "World Center of Gravity". The team has independently developed a series of key technologies, producing significant scientific and engineering achievements. These include the world's state-of-the-art precise measurements of the universal gravitational constant $G$, all three of which have been included in the CODATA database. The findings were awarded as the "Top Ten Scientific Advances in Chinese Universities" and "Top Ten Advances in Chinese Science" in 2018. The team also independently developed a high-precision space electrostatic accelerometers for major space missions, a microgal-level cold atom absolute gravimeters for the earthquake sector. Additionally, they have developed several global gravity field models named after HUST, which have been included in the International Centre for Global Earth Models (ICGEM).

In October 2023, the facility passed the national acceptance evaluation. The evaluation concluded that all construction tasks approved by the National Development and Reform Commission were completed, all performance indicators met or exceeded the approved requirements, and the overall construction quality reached an interna-

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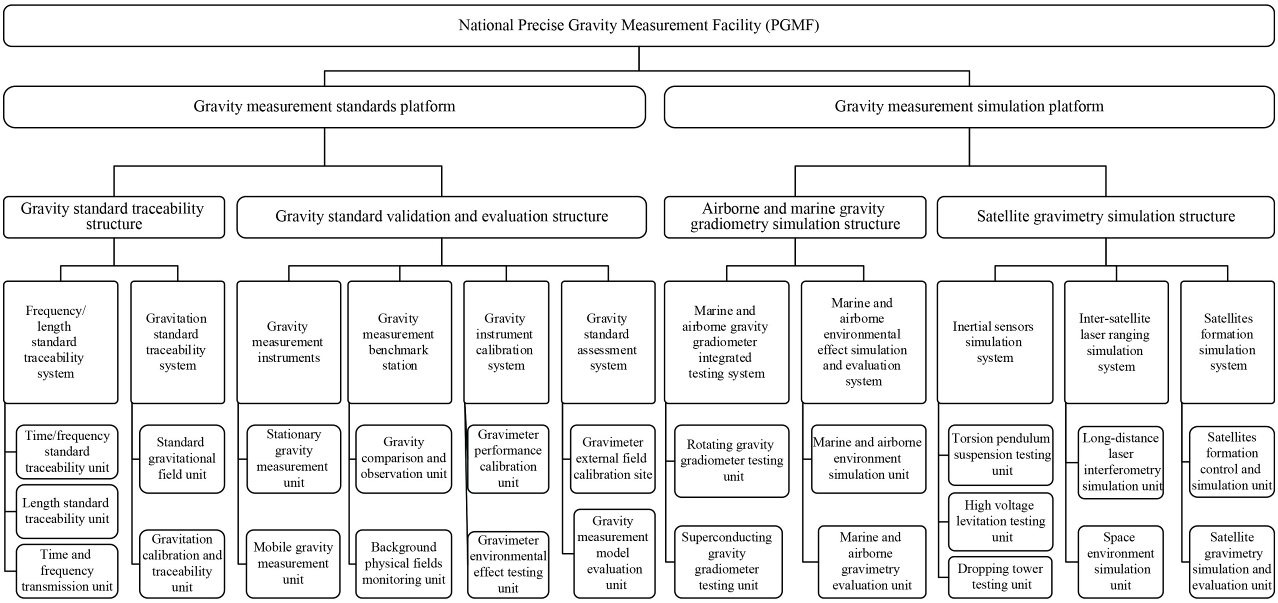


**Fig. 1** National Precise Gravity Measurement Facility (PGMF).

tionally advanced level. In 2024, the Ministry of Education has approved the establishment of the National Gravitation Laboratory, which is responsible for management and operation. The facility is now fully operational and open to the public, with six service platforms established to provide external scientific supports.

## 2 Technical and managerial innovations of PGMF

Internationally, no facility of comparable scale exists for precision gravity measurement. The construction of such an infrastructure was highly complex, presenting multiple technical challenges and lacking established acceptance standards. Since the approval of the PGMF project, the team has continually refined management models and optimized construction processes, ensuring efficient, high-quality completion. These efforts have also provided valuable experience for the planning and management of large-scale scientific infrastructures at Chinese universities.

At the level of technological innovation, the project team has advanced precision gravity measurement methods and technologies, achieving breakthroughs in cold-atom gravimetry, satellite gravity measurement, airborne gravity-gradient measurement, and global and regional gravity data processing and applications. Extensive land, sea, air, and space observations have been accumulated, enabling contributions to surveying benchmarks, resource exploration, environmental change assessment, disaster monitoring, and national security. These advances have markedly strengthened China's capacity for research, testing, and evaluation in gravity measurement technologies and promoted the development of advanced gravity instruments and equipment.

### 2.1 Microgal-level absolute gravity benchmark construction and key innovations

To address the long-standing challenge of traceability for precision gravimeters, the team pioneered two methods for measuring the universal gravitational constant $G$ under double-blind synchronization: the torsion balance time-of-swing method and the torsion balance angular-acceleration method. Both approaches achieved a record-breaking measurement precision of 11.6 ppm. Notably, the results obtained from the two methods were consistent within two standard deviations—a milestone that had never been achieved in global $G$-measurement research (Li et al., 2018). A *Nature* commentary, "Gravity measured with record precision", lauded the team's 2018 $G$-measurement work as "a model of exquisite craftsmanship in the field of precision measurement". Building on the advancements in high-precision $G$ measurements and torsion balance-based weak-force detection techniques, the team established a gravity measurement traceability system directly linked to the law of universal gravitation, thereby resolving the long-standing issue of gravimeter traceability.

Leveraging progress in quantum sensing technology, as shown in Fig. 2, the team also made a series of breakthroughs in cold-atom absolute gravimetry, including in-depth research on measurement mechanisms and modeling analysis, development of traceability and calibration methods, suppression of vibration and laser phase noise, evaluation of errors caused by Raman beam wavefront distortions, as well as systematic design and integration

(a) Gravimeter calibration equipment

(b) Reference-grade atom gravimeter

(c) Absolute gravimeter comparison field

**Fig. 2** Gravity benchmark construction.

optimization. These innovations culminated in the development of a microgal-level cold-atom absolute gravimeters with independent intellectual property rights. As the first instrument its kind deployed in China's earthquake monitoring sector, it marks the realization of independent and controllable high-precision absolute gravimetry in China.

### 2.2 Innovation in global satellite gravity field measurement technologies and methods

Satellite gravimetry is the only direct technique for acquiring global gravity field observations. High-precision global measurements require advancements in payload design and full-chain data processing methods. To this end, as shown in Fig. 3, the PGMF has advanced next-generation technologies, including ultra-high-precision inertial sensors, inter-satellite laser ranging, and satellite formation flying, while also developing refined full-chain gravity field modeling theories to support satellite gravimetry.

High-precision spaceborne inertial sensors are core to satellite gravity measurement. The team overcame challenges in sensitive probe fabrication, capacitive sensing and electrostatic control, and performance testing. Devices based on torsion pendulum suspension, high-voltage levitation, and free-fall methods were established, resolving critical testing difficulties for high-precision space accelerometers. These advances enabled the development of a spaceborne electrostatic accelerometer with a resolution of $10^{-12}$ m/s$^2$, supporting both China's first gravity satellite constellation and the Tianqin-1 satellite mission (Wang et al., 2023).

High-precision inter-satellite laser ranging systems are essential for satellite gravimetry. The team achieved breakthroughs in satellite-borne lasers and frequency-stabilization techniques, ultra-stable optical platform design, precision phase measurement and weak-light phase locking, and inter-satellite laser acquisition and pointing control. The laser interferometry system achieved nanometer-level (1 nm) resolution. An innovative 20 m baseline laser interferometry simulation platform was also established, enabling ground-based validation and integration testing of critical inter-satellite ranging technologies.

Accurate full-chain data processing is vital for extracting reliable global gravity field information. The team addressed challenges in multi-mode gravity field modeling methods, integration of multi-source gravity data, and post-processing of satellite gravity data. These advances resulted in a comprehensive theoretical and methodological framework for satellite gravimetry data processing and applications. Several global gravity field models developed by the team have been included in the ICGEM, achieving accuracy superior to the most recent products released by official science data processing institutions (Zhou et al., 2024).

### 2.3 Innovation in gravity and gravity-gradient detection technologies and methods

The superconducting relative gravimeter is currently the most precise relative gravimeter available. The team established a cryogenic integration test system and a cryogenic support platform for superconducting gravity gradiometers, overcoming challenges in instrument integration, suppression of environmental disturbances, and cryogenic system design. These advances supported the development of a gravimeter (as shown in Fig. 4(a)) with a resolution better than 0.1 μGal and a gravity gradiometer with a static resolution reaching 1 E, thereby paving the way for the engineering application of superconducting gravimetry (Zhang et al., 2024).

Micro-electro-mechanical systems (MEMS) relative gravimeters, which have emerged as potential substitutes for conventional mobile relative gravimeters, have attracted increasing attention from research institutions worldwide. The team established micro/nano fabrication, inertial device testing, and gravity-source calibration systems, achieving advances in sub-Hz frequency structural design, bulk-silicon processing, and high-precision acceleration signal calibration. These efforts enabled the


(a) 20 m × 10 m laser interferometer (b) Space accelerometer

(c) Three-satellite formation simulation equipment (d) 24 m drop tower

**Fig. 3** Simulation system for satellite gravimetry.


(a) Superconducting gravimeter (b) MEMS gravimeter (c) Rotating accelerometer gravity gradiometer

**Fig. 4** Gravimeter and gravity gradiometer.

development of a MEMS relative gravimeter (as shown in Fig. 4(b)) with self-noise reaching 0.1 μGal/Hz$^{1/2}$ (Gao et al., 2023).

The rotating accelerometer gravity gradiometer is currently the only instrument successfully applied to gravity-gradient measurements on moving platforms such as aircraft and ships. The team established integration testing, motion simulation, calibration, and environmental simulation systems for the gradiometer, achieving advances in multi-accelerometer matching, motion-isolation platform integration, motion error compensation, and vehicle-mounted testing. These efforts supported the development of a rotating accelerometer gravity gradiometer (as shown in Fig. 4(c)) with a static measurement resolution of 10 E (Yu et al., 2024), laying the foundation for subsequent vehicle-, ship-, and airborne experiments.

### 2.4 Innovation in the management model of major scientific and technological infrastructure

During facility construction, an innovative hierarchical model was adopted in which the technical indicators of lower-level subsystems progressively supported the system-level indicators of higher-level units. Each subsystem was validated and accepted upon maturity, enabling an orderly, bottom-up acceptance process that ultimately ensured the facility's overall performance targets. This approach established a logically rigorous, verifiable, and traceable technical system, while also creating the capacity to acquire and apply gravity data across land, sea, air, and space domains. The construction process followed the principle of "simultaneous construction, acceptance, and operation". Equipment and instruments that reached the required operational standard were promptly placed into trial operation and opened for external services during the construction phase. This strategy enabled the facility to deliver early technical support and service capacity, providing strong support for gravity reference traceability, gravimeter calibration and validation, gravity-gradient measurement, satellite gravimetry, and the independent development of advanced instruments and equipment.

## 3 Conclusions

During the construction and operation of the PGMF, multiple challenges were encountered, including system complexity and the absence of established acceptance standards. Addressing these challenges generated valuable experience and enabled the exploration of a management model for comprehensive, research-oriented large-scale scientific infrastructure. This process produced a rigorous and effective management and assurance system. By establishing a complete technical system for gravity measurement and evaluation, developing the capability to obtain gravity observation data across land, sea, and air, and strengthening the construction of standards, the facility has provided robust technical support for gravity research in China. In several key areas, the project has achieved asymmetric advances, with some technical indicators reaching internationally leading levels. It has produced a series of important scientific achievements and established an integrated platform including the full suite of precision gravity measurement techniques, positioning itself as one of the internationally influential centers for gravity research. Its completion and stable operation mark a major breakthrough for China in the field of gravimetry. With continuous operation and future upgrades, the facility is expected to play an increasingly important role in Earth sciences, resource exploration, and environmental monitoring, advancing China’s gravity measurement technologies to new heights.

Looking ahead, the National Gravitation Laboratory will continue to strengthen original innovation and enhance the efficiency of shared services. The PGMF will be developed into a global frontier base for precision measurement physics, a fundamental research platform in Earth sciences, a research and development hub for high technology, a shared platform for international cooperation, and a leading center for cultivating outstanding innovative talent.

**Competing Interests** The authors declare that they have no competing interests.

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