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Development Strategy of Quantum-Based Deep Geophysical Exploration Technology and Equipment

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Abstract: Quantum-based sensing and measurement technology is a disruptive technology that can realize fine detection of gravity and magnetic fields in deep Earth, and it has become a key development direction for geophysical exploration equipment worldwide. In this study, we focus on the frontier technologies for the quantum-based high-precision measurement of Earth's gravity and magnetic fields, summarize the development status of quantum-based geophysical exploration equipment, and analyze demand for the superconducting quantum-based electromagnetic detection system, magnetic vector gradient detection system, superconducting gravity detection system, and cold-atom absolute-gravity exploration system during deep resource exploration. Moreover, the international trend of quantum-based high-precision measurement technology as well as the development opportunities and challenges in this field are analyzed. To improve the core technology research, complete localization, and exploration application of quantum based geophysical exploration equipment in China, we propose the development goals, technical system, key tasks, and strategic planning for a new generation of quantum-based high-precision deep geophysical exploration equipment. These are intended to realize breakthroughs in superconducting quantum chips and high-sensitivity sensors, establish a collaboration model for the independent development of China's quantum-based geophysical exploration equipment, promote high-quality development of deep exploration equipment, and provide strategic support for solving major problems associated with deep mineral resource exploration and revealing of Earth's deep structure.

Keywords: mineral resources; deep detection; quantum-based high-precision measurement; superconducting quantum-based electromagnetic detection; superconducting gravity detection; cold-atom absolute-gravity detection

1 Introduction

The global clean energy transition has triggered a heavy demand for strategic minerals. The economy of China is turning from high-speed growth to high-quality development, and it will remain as the world's largest consumer of mineral resources. In view of the current situation, the major strategic mineral exploration capacity of China is weak, and the growth of production is relatively slow. It is difficult to satisfy the rapidly increasing demand for clean energy. Hence, the external dependence is increasing and security of mineral resources is becoming a matter of national strategy [1,2]. For energy-storage batteries, strategic mineral resources are indispensable materials, which are important to the development of new energy and carbon neutrality in the future. China's external dependence on major strategic mineral resources is as follows: copper and nickel are more than 70%, cobalt is up to 95%, and iron

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ore, copper concentrate, petroleum, and other resources are 50%–80%. Hence the dependence on all minerals exceed the national economic security warning line of 40%. In 2019, the external dependence on iron ore was 76% and that of copper concentrate was 84.6%. In 2020, the external dependence on iron ore was 77.3% and that of copper concentrate was 83.3% [3]. Before 2030, with the rapid development of information technology, equipment manufacturing, infrastructure, and other emerging industries, the demand for iron ore, copper ore, and other strategic minerals will rapidly increase and maintain a high trend. Additionally, China's proved reserves of mineral resources are seriously insufficient when compared with those of developed countries. China's mineral resources per capita is only one tenth of that of United States. According to incomplete statistics, the approved mineral resources rate at 2000 m underground is only one third, which is far lower than the average value of 60.5–73% in mining developed countries. In recent years, China's newly discovered metal mineral resources are mostly deposits with low grade, deep burial, and thick covering layer. Given that the metal mine exploration area is more complicated and depth of prospect area has deepened, the exploration of deposit with economic value is more difficult.

Quantum sensor is a disruptive technology in the field of sensing, which is described as the multiplier of industrial production and pioneer of scientific research [4]. Quantum geophysical exploration technology can effectively detect magnetic, gravity, and geoelectric fields based on quantum effects and quantum sensors. Quantum magnetic field sensors conduct high-precision measurement according to the influence of environmental magnetic field on the characteristics of quantum itself, including superconducting quantum interference device (SQUID), nitrogen vacancy (NV) centers in diamonds, cold atom magnetometer, and cesium photopump magnetometer [5–7]. In vacuum environment, quantum gravity sensors capture and control the quantum states of cold rubidium atoms via laser and magnetic field and obtain gravity field and gravity gradient field by measuring the atomic ratio of different energy levels. With the rapid development of SQUID chip, absolute gravity measurement technology of cold atoms, and quantum gravity gradient sensors, the deep geophysical exploration technology based on high precision magnetic field quantum sensors has become one of the disruptive technology in strategic mineral resources detection, volcanic activity monitoring, and Earth structure refinement. It has become the key development direction of international geophysical exploration equipment. Specifically, the United States, Germany, Japan, United Kingdom (UK), and other countries commenced research activities earlier in the field of quantum measurement technology and developed a state strategic plan to guide quantum sensing research and development (R&D), which focus on quantum sensor and quantum enhanced sensors in areas of industrial precision measurement, Earth exploration, geology and reservoir exploration, defense technology and navigation, and other fields. The research standards are, as usual, cutting-edge given long period of technology accumulation and equipment iteration, especially in geophysical exploration of gravity field, magnetic field, and electromagnetic field. The program on quantum sensors in China is still limited to industry or specific fields such as quantum communication and quantum computing. There is a gap with respect to a clear national strategic plan and satisfactory attention to the rapid development of quantum measurement and quantum sensing. Research studies on the quantum geophysical exploration technology and equipment in China are conducted relatively late. However, given the unremitting efforts of scientific researchers, significant progress has been made in the recent years, which has promoted the development of quantum deep geophysical exploration technology and equipment. This in turn has closed the technological gap with the developed countries.

In this study, the research status and development trend of quantum geophysical exploration technology in China and abroad are comprehensively investigated from a strategic perspective, and key issues in the development of detection technology and equipment in the fields of high-precision gravity field, magnetic field and electromagnetic field are analyzed. A series of challenges with respect to the development of key chip and core components in preparation technology, frontier key technology, and high-performance localization system are highlighted. The focus of the research task and overall development path of the quantum geophysical exploration technology and equipment in China are specified. In this study, we propose new ideas for the development of quantum geophysical deep detection technology and equipment in China. Furthermore, the discussion in this study can provide technical guarantee for the sustainable supply and strategic safety of mineral resource energy in China.

2 Research status of quantum geophysical exploration technology and equipment

Quantum-based geophysical exploration technology primarily focuses on high-precision observation of the Earth's magnetic and gravitational fields. Based on the type of parameters collected, the measurement systems can be classified into scalar total field, total field gradient, vector three-component, and tensor gradient system. According to the platform types, it can be classified into ground, aviation, well, ocean, and satellite platforms. More

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specifically, it can include ground and ocean, well, and ground-air superconducting quantum time-domain electromagnetic detection system, aviation superconducting quantum magnetic vector gradient detection system, aviation superconducting quantum magnetic vector gradient detection system, superconducting gravity system, aviation superconducting gravity gradient system, ground atomic absolute gravity, aviation atomic absolute gravity system, and aviation atomic absolute gravity gradient system (Fig. 1).

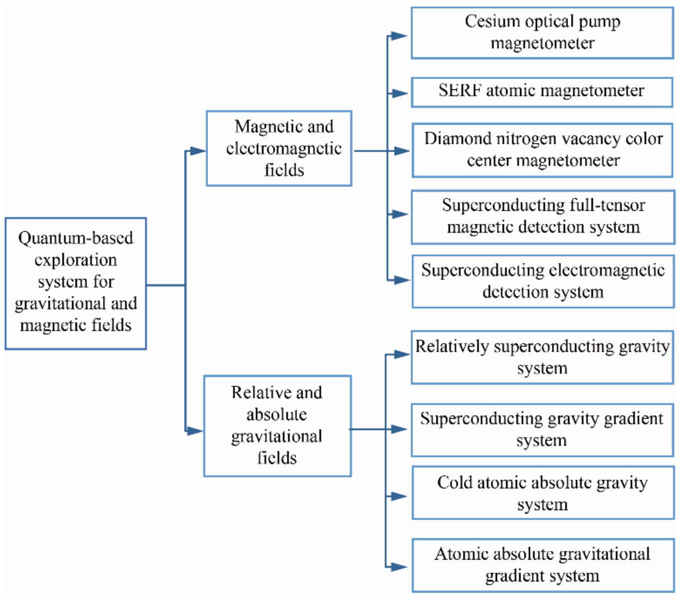

Fig. 1. Main equipment of quantum-based geophysical exploration.

2.1 Research status abroad

2.1.1 Aeronautical cesium optical pump magnetic total field detection system

In recent years, high-precision cesium optically pumped magnetic sensors have been widely used in the field of aviation magnetic measurement technology. Among the commonly used products, the most representative products are CS-3 (Scintrex Company, Canada) and G-824A (Geometrics Company, United States) with sensitivities of 0.6 pT/√Hz@1 Hz and 0.3 pT/√Hz@1 Hz, respectively. Currently, the United States and Canada stipulate that magnetometers with a sensitivity exceeding 20 pT are strictly prohibited for export to China [8]. In terms of the aeromagnetic total field detection system, the most representative product is the AARC510 data recording and compensation system (RMS company, Canada) with a resolution of 0.32 pT, system noise of 0.1 pT, and residual noise level of 10 pT after compensation (root mean square (RMS): 0.05–1 Hz) [9].

2.1.2 Aeronautical superconducting full tensor magnetic detection system

The Institute of Physics and High Technology (IPHT) located in Jena, Germany, in cooperation with Supracon, developed the first helicopter podded low-temperature hypernavigation space full tensor magnetic gradient system, named as Jessy Star. The flight experiment was conducted in South Africa, and it was reported that the system noise was better than 10 pT/m (RMS: 4.5 Hz bandwidth). In 2004, the Commonwealth Scientific and Industrial Research Organization (CSIRO) of Australia cooperated with China Minmetals to develop a high-temperature superconducting ground full tensor magnetic gradient measurement system, GETMAG, with a system noise of 2 pT/m/√Hz@10 Hz [10]. American Tristan Technology Corporation developed an aviation full tensor magnetic gradient system (T877) using high-temperature superconducting magnetic sensors with a system noise of 8 pT/m/√Hz. In 2020, IPHT developed a new generation of magnetic vector gradiometers with an intrinsic noise of 13 fT/m/√Hz using new technologies such as transformer-type coupling structures, submicron-sized Josephson junctions, and centimeter-scale pickup loops [11]. Following the first flight experiment in South Africa, the Jessy Star system has successively launched experiments in various places. It has conducted a range of applications in deep mineral exploration, including the successful detection of the HYPGEO pyrite belt in Spain, detection of a dolomite intrusion 800 m below ground in the Thuringian Forest in Germany, and detection of a dolomite intrusion in the central Lapland greenstone belt in northern Finland. A nickel-copper-platinum deposit with a depth of 1200m was discovered, and the distribution shape of the ore body was accurately explained.

2.1.3 Ground and oceanic superconducting electromagnetic detection system

The superconducting electromagnetic detection system is listed as one of the 38 innovative technologies that contribute to the global mining industry, and has become a highly advanced technology for detecting deep and large metal mines, geothermal oil reservoirs, and other resources. Germany, Japan, Australia, and other countries have long been committed to the development of high- and low-temperature superconducting quantum sensor chips. After nearly 30 years of research, high- and low-temperature superconducting quantum sensors have been successfully used in ground electromagnetic systems and well-based electromagnetic detection systems. The main technical indicators of the sensors are listed in Table 1. In 2007, CSIRO developed the high-temperature superconducting electromagnetic system, LandTEM, which discovered reserves of nickel sulfide deposits and other types of deposits worthy of more than six billion US dollars in the past 10 years of application [12,13]. In 2011, IPHT developed a low-temperature sub-micron DC SQUID and a sub-fT superconducting magnetic sensor. Furthermore, IPHT cooperated with Supracon to develop a world-leading ground low-temperature superconducting electromagnetic detection system. In 2013, Japan's Superconducting Sensing Technology Research Association (SUSTERA) developed a high-temperature DC SQUID chip and cooperated with the former Japan Metal Mining Corporation (now OGMEC) to develop the high-temperature superconducting electromagnetic system (SQUITEM). Its high-temperature superconducting technology level is at the highest advanced state in the world, and the detection depth reaches 1000–2000 m underground [14]. Furthermore, it has been applied in the detection of polymetallic ore in Japan, Thailand, Australia, Peru, and Chile. In 2017, the SQUITEM system detected underground polymetallic deposits of copper, silver, gold, lead, and zinc with a thickness of 150 m in the low-resistivity overburden in southern Australia, and the system successfully detected an oil reservoir at 2000 m below ground in Thailand in 2018 [15].

There also has been rapid development in marine superconducting electromagnetic detection technology, which has opened up new arenas for the exploration and development of strategic resources such as deep-sea resource detection and oil and gas reservoirs. In 2012, IPHT used the modular SQUID sensor and liquid helium refrigeration technology dedicated to the marine environment in the DESMEX project, developed two generations of SQUID marine time domain systems, and conducted high-resolution imaging of shallow geological features in shallow and deep seas. The measured effective detection depth can reach 1 km. In 2015, Joe Kirschvink proposed the technology involving the use of metal gallium to lubricate the cold pump. By improving the cooling efficiency of the cold pump and reducing the evaporation rate of liquid helium, the problem of short operation time and unstable operation of low-temperature SQUID in deep-sea exploration, which is due to the rapid evaporation of liquid helium [16], was solved. In 2016, Chwala et al. used the LTC SQUID system to scan the seabed magnetized targets along the Baltic Sea coast in the German coastal area and realized promising results in finding waste sediments and unexploded ordnance [17].

Table 1. Comparison of main technical indicators of SQUID-TEM systems in China and abroad.

Unit/Parameter	Low-temperature DC SQUID (2011)	High-temperature DC SQUID (2007)	High-temperature DC SQUID (2015)
R&D Institutions	German IPHT	CSIRO Australia	Japan SUSTERA Association
noise level (fT/ √ Hz@10 kHz)	15	45	30
Slew rate ($\text{mT}\cdot\text{s}^{-1}$)	10	2.66	10
System bandwidth (MHz)	8	1	0.1

2.1.4 Ground and aerospace superconducting gravity systems

In the 1990s, Stanford University first conducted research on superconducting gravity gradiometers, which were used for basic physics research such as gravitational wave detection and space gravity measurement. In 2002, Paik's research group at the University of Maryland developed a ground-based superconducting gravity system with instrument noise of as low as 0.02 E/√Hz@0.5 Hz, which was 2–3 orders of magnitude lower than traditional gradiometers. British ARkex, Canada's Gedex, and Australia's Rio Tinto also committed to the development of aviation superconducting gravity gradiometers [18], aiming to break through the resolution limit of rotational accelerometer-type gravity gradiometers and obtain deeper resource exploration capabilities. However, the R&D of aeronautical superconducting gravity gradiometers has not been smooth. To date, there are no reports of aviation superconducting gravity gradiometers with comparable performance to rotational accelerometer-type gravity gradiometers.

As a new-generation technology, the ultra-navigation air gravity gradient system is the focus and hotspot of the current air gravity gradient exploration system research. Internationally, Stanford University took the lead in developing a low-temperature superconducting gravity gradient system, which was followed by various other research institutions. Currently, the equipment is in the final stages of production or is in the preparation stage for test flight, and it is similar to EGGTM aviation gravity gradient system developed by ARKeX company in the UK, HD-AGG aviation gravity gradient system jointly developed by Canadian Gedex company and University of Maryland (with actual flight measurement accuracy up to 20 E), and the VK-1 gravity gradiometer jointly developed by Australia's Rio Tinto Group and the University of Western Australia with an on-board measurement accuracy of 20 E.

2.1.5 Ground atomic absolute gravity and aeronautical atomic gravity gradient detection system

In the 1990s, Steven Chu's group at Stanford University first proposed the cold atom interferometric gravimeter [19]. In 2001, the uncertainty of gravimetric measurement reached 3.4 μGal, and in 2008, the measurement sensitivity was optimized to 8 μGal/√Hz. The research team at the Paris Observatory in France used the method of freely falling cold rubidium atoms to measure the gravitational acceleration. The uncertainty of gravity measurement was 4.3 μGal, and the measurement sensitivity was 8.9 μGal/√Hz [20]. In 2019, the California Institute of Technology Berkeley developed a vehicle-mounted mobile atomic gravimeter with a quasi-dynamic test measurement sensitivity of 0.5 mGal/√Hz and total measurement uncertainty of 40 μGal. The German Federal Institute of Physics and Technology developed a quantum gravimeter based on optical clock technology that can be used for precise measurements of the Earth.

In terms of the development of quantum gravity gradiometer, University of Birmingham first developed a prototype of the quantum gravity gradiometer. In 2018, the prototype test experiment of the quantum gravity gradiometer was successfully realized. In 2019, the measurement accuracy of the system's gravity field was improved to the order of 10–99 mGal, and the detection depth was expected to exceed several times that of the existing technology [21]. Currently, University of Birmingham (UK) is developing a miniaturized aerial gravity gradiometer mounted on an unmanned aerial vehicle. With respect to the research on the miniaturized atomic absolute gravity system, the Jet Propulsion Laboratory of the National Aeronautics and Space Administration completed the development of a laboratory prototype of the cold atom interference gravity gradient system. In 2019, the French ONERA team mounted the cold atom absolute gravity measurement system on an airplane for the first time [22], and the error of gravity value on the repeated measurement line and cross measurement point was 1.7–3.9 mGal. Furthermore, currently, there is still a big gap between the atomic interference type gravity gradient system and practical application of aviation. In 2022, researchers from the UK's National Centre for Quantum Technology successfully developed the world's first quantum gravity gradiometer outside of laboratory conditions and determined an outdoor tunnel buried 1 m below the surface under practical conditions. The event has been dubbed an "Edison moment" in sensing that will transform society, human understanding, and economic development as gravity-sensing technology matures. This in turn will enable underwater navigation and reveal the subsurface [23].

2.2 R&D status of quantum geophysical detection technology and equipment in China.

China has experienced several generations of long-term and unremitting exploration in the research of deep mineral resources exploration technology and equipment. By means of introduction, absorption, and innovation, China has made considerable progress and independently developed a series of quantum geophysical exploration equipment [24–27], which will lead to significant contributions to the improvement of the domestic exploration geophysical technology and equipment system. However, there is still a gap between the core indicators of certain self-developed quantum Earth detection equipment and advanced level realized by foreign countries. China is still highly dependent on chips and sensors for high-precision measurement of gravity and magnetic fields, such as cold atoms and superconducting quantum, on foreign countries, and its self-developed system is still in the prototype stage. Specifically, there is a paucity of R&D of the airborne superconducting gravity gradient system and airborne cold atom absolute gravity measurement system. Hence, more foreign imported equipment is applied in resource exploration. Furthermore, many technological challenges have to be resolved before the equipment independently developed by China can be fully localized and can truly realize the field detection capability.

In terms of optical pump sensor system, the cesium optical pump sensor, developed by the Aerospace Information Research Institute, Chinese Academy of Sciences (formerly Institute of Electrics, Chinese Academy of Sciences), has been tested by the National Institute of Metrology, China, with a sensitivity of $0.45\,\mathrm{pT}/\sqrt{\mathrm{Hz}}@1\mathrm{Hz}$. After many field tests, the residual noise level of the developed magnetic total field detection system, which is handled by magnetic compensation software, is 10 pT (RMS: 0.05–1 Hz). The digital airborne helium optical pump magnetometer and gradient meter, independently developed by Airborne Geophysical and Remote Sensing Centers, China, exhibit a sensitivity of $0.25\,\mathrm{pT}$ (effective value of unit bandwidth). In terms of the airborne high and low temperature superconducting full tensor magnetic detection system, the Shanghai Institute of Microsystem and Information Technology, Chinese Academy of Sciences, and Airborne Geophysical and Remote Sensing Center, China, jointly developed the airborne low-temperature superconducting full tensor magnetic gradient system. The system noise is $75\mathrm{fT/m}/\sqrt{\mathrm{Hz}}$, and the experimental flight test has been conducted. Jilin University and Airborne Geophysical and Remote Sensing Center, China, jointly developed the airborne high-temperature superconducting full tensor magnetic gradient system. The system noise reached $30\mathrm{pT/m}$ (RMS: 5 Hz bandwidth). The line flight tests have been conducted in Danyang, Jiangsu Province. Jilin University developed ground superconducting time-domain electromagnetic detection system and other equipment [28–30].

In terms of ground and airborne superconducting gravity systems, as early as 1970, China began to develop superconducting gravimeters. However, unfortunately, no system prototype was developed. In 2010, China restarted the R&D of superconducting gravity instruments. The Institute of Electrical Engineering of the Chinese Academy of Sciences was responsible for the development of superconducting gravimeters, and Huazhong University of Science and Technology was responsible for the development of aerospace superconducting gravity gradients, which involved the development of key technologies such as design, manufacturing, integration, and testing of superconducting gravimeters. The research group developed the principle prototype of superconducting gravity gradients. The noise level was $7.2\ \mathrm{E}/\sqrt{\mathrm{Hz}}$ in the laboratory. The 707 Research Institute of China Aerospace Science and Technology Corporation and Airborne Geophysical and Remote Sensing Center, China, jointly developed the airborne gravity gradient system in form of the rotary accelerometer, which realized the gradient measurement of horizontal component of gravity for the first time in China with an accuracy of 70 E.

In terms of the development of the ground atomic absolute gravity system, National Institute of Metrology in China, Huazhong University of Science and Technology, Innovation Academy for Precision Measurement Science and Technology of the Chinese Academy of Sciences, Zhejiang University of Technology, and other units performed the development of the quantum gravimeter. In 2017, four domestic units participated in the 10th International Comparison of Global Absolute Gravimeters and obtained effective comparison data. The specific indicators are listed in Table 2. The measurement sensitivity of the atomic gravimeter, developed by Huazhong University of Science and Technology, was $4.2\mu\mathrm{Gal}/\sqrt{\mathrm{Hz}}$, which realized the international leading level. It used a new quantum gravity micro-electro-mechanical systems (MEMS) chip with a sensitivity of $8\mu\mathrm{Gal}/\sqrt{\mathrm{Hz}}$ with a dynamic range of up to $8000\mathrm{mGal}$ [31]. In 2019, the University of Science and Technology of China developed an atomic gravimeter with a sensitivity value of g corresponding to $35.5\mu\mathrm{Gal}/\sqrt{\mathrm{Hz}}$ and $42.5\mu\mathrm{Gal}/\sqrt{\mathrm{Hz}}$, and the stability was as high as $0.8\mu\mathrm{Gal}/\sqrt{\mathrm{Hz}}$ and $1.3\mu\mathrm{Gal}/\sqrt{\mathrm{Hz}}$ after the integration time of $2000\mathrm{s}$ [32]. In terms of the development of mobile platform atomic gravimeter, the mobile atomic gravimeter system was jointly developed by Zhejiang University of Technology and Airborne Geophysical and Remote Sensing Center, China. The absolute gravity measurement was completed under the shipboard mooring environment for the first time in China in 2020, with a gravity measurement sensitivity of $16.6\mathrm{mGal}/\sqrt{\mathrm{Hz}}$. In 2022, a series of measurement experiments were conducted in a sea area in the South Sea, China. Under condition of speed of less than $2.1\mathrm{km/h}$, the absolute gravity measurement sensitivity increased from $300.2\mathrm{mGal}/\sqrt{\mathrm{Hz}}$ to $13.8\mathrm{mGal}/\sqrt{\mathrm{Hz}}$ based on the extended Kalman filter algorithm.

Table 2. Performance of atomic gravimeters in Chinese institutions and international comparison results.

Institution	Sensitivity and resolution	Uncertainty of measurement	International comparison results
Huazhong University of Science and Technology	$4.2\mu Gal/\sqrt{Hz}$, $0.5\mu Gal@100s$	$3.0\mu Gal$	$1.3\pm3.1\mu Gal$
National Institute of Metrology, China	$44\mu Gal/\sqrt{Hz}$, $0.2\mu Gal@3e4s$	$5.2\mu Gal$	$-2.4\pm4.6\mu Gal$
Innovation Academy for Precision Measurement Science and Technology of the Chinese Academy of Sciences	$30\mu Gal/\sqrt{Hz}$, $1\mu Gal@4e3s$	$10\mu Gal$	$-3.8\pm10.2\mu Gal$
Zhejiang University of Technology	$90\mu Gal/\sqrt{Hz}$, $4\mu Gal@1e3s$	$20\mu Gal$	$-11.4\pm14.1\mu Gal$
University of Science and Technology of China	AG02: $35.5\mu Gal/\sqrt{Hz}$, $0.8\mu Gal/\sqrt{Hz}@2e3s$ AG12: $42.5\mu Gal/\sqrt{Hz}$, $1.3\mu Gal/\sqrt{Hz}@2e3s$	—	—
National University of Defense Technology	$210\mu Gal/\sqrt{Hz}$, $5.1\mu Gal@3e3s$	—	—

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3 Challenges for the development of quantum geophysical exploration technology and equipment

Throughout the development status of China's quantum geophysical technology and equipment, the challenges are mainly reflected in the R&D systems, core technology, innovation ability, industrial application, etc.

3.1 Imperfections of the medium- and long-term systematic development system

Countries, such as Germany, Japan, and Australia, established a cutting-edge technology and future scientific research system, which focusses on the field of quantum precision measurement of the Earth's gravity and magnetic field, and conducted long-term research on the layout. The relevant research has been conducted for over 40 years, and the layout has been made in the development of ground, well, ocean, and airborne quantum geophysical equipment. The unremitting pursuit of technological leadership has formed a well, ground, sea, airborne three-dimensional detection system. Furthermore, a long-term cooperative development system for basic research and engineering application has been established. Specifically, IPHT in Germany has a long-term and stable cooperative relationship with Supracon. SUSTERA association in Japan has a very close cooperation with mining exploration JOGMEC. IPHT and SUSTERA and other national scientific research institutions mainly develop special chips, sensors, and detection systems for engineering applications. Supracon, JOGMEC, and other exploration enterprises conducted practical exploration applications and repeated system iterations and finally realized the engineering practicability of the detection system.

Through a series of national key R&D projects during the 11th Five-Year Plan, the 12th Five-Year Plan and 13th Five-Year Plan, China began to develop high-precision quantum sensing detection technology and equipment for the Earth's deep gravity and magnetic field, mainly including ground superconducting electromagnetic detection system, ground superconducting gravimeter, airborne superconducting full tensor magnetic detection system, airborne quantum Cesium optical pump magnetic detection system, ground atomic absolute gravity system, airborne quantum gravity gradient system, and ship-borne quantum gravity gradient system. First, the domestic research commenced directly based on the tracking of the international advanced system, which was conducive to catching up with and surpassing the international advanced level. The engineering prototype of the quantum gravity and magnetic field detection system was initially realized, and certain key technologies were overcome. However, core technical indicators and maturity were significantly below the international advanced level, and the developed detection system cannot be used for the exploration of deep mineral resources. Second, there is a paucity of research and layout in frontier fields, such as deep well, ocean and airborne superconducting electromagnetic detection, airborne atomic absolute gravity and gravity gradient system, and airborne superconducting gravity system, in China. Furthermore, the development system of the systematization of quantum precision measurement deep-Earth detection equipment is in a scattered distribution state, which is not ideal. The phenomenon of patching and binding has been serious. The R&D of quantum precision sensing technology and detection equipment has been characterized by high technical difficulty and long cycle. For example, the superconducting application technology requires decades or hundreds of years of long-term continuous research before it can be extensively applied. Domestic research mainly has been relying on project funding. However, after the completion of most projects, the research foundation stagnates, research teams reorganize, there is a lack of long-term research planning and long-term goals, and a stable cooperation system between scientific research institutions and enterprises has not been formed, to date. At the national level, the medium- and long-term systematic development layout has been insufficient, and the construction of the quantum precision geophysical field detection system should be further improved.

3.2 Insufficient basic process capability of key chips and core components

In the field of leading-edge subversive technology, basic research requires more scholars to conduct free exploration according to their interests. It is very important to build a long-term tolerant research atmosphere, scientific and reasonable evaluation mechanism, and personal long-term development space. Given the instability of the R & D talent team in China, interruption of research is easy, and therefore, it cannot persist to the stage of fruitful output. Furthermore, for certain basic research teams, obvious application prospects cannot be immediately predicted even if the number of research members are small. Hence, the core team or core members should be retained. Additionally, research on basic technology and preparation technology, which is eager to follow the cutting-edge, extreme pursuit of higher performance indicators of quantum sensor or prototype system can lead to a gap in solid basic technology and basic process capability, innovation and cutting-edge basic research, and engineering practicality. This can lead to a situation wherein the key core technologies are highly dependent on foreign countries and cannot be fundamentally changed.

Application research in the field of quantum precision measurement is relatively independent in Germany. For the research of future science and predictive technology, the application market benefits have not been considered. This is due to the fact that there are significant uncertainties and unknowns in the application of basic research. For example, the giant magneto-resistance effect was not applied in nearly 20 years after it was discovered. Until it was applied in computer hard disks, it opened the door to the world of new technology. However, domestic R&D institutions lack sustainable basic research to a certain extent, especially the basic R&D capabilities in key chips and core components. Generally, after the new high-precision quantum or atomic magnetic field detection system has been developed internationally, it is determined that it can lead to good application prospects and potential. Subsequently, the research on high-precision quantum gravity and magnetic field detection system can be commenced as opposed to starting from the basic theory of superconducting quantum and atomic precision measurement of gravity and magnetic field. When it was determined that there was a gap between the main indicators of the domestic detection equipment and international advanced level, significant attention was focused on the basic technology of key chips and core components of the sensor. However, the basic theory of SQUID and cold atom measuring magnetic field is still unclear and the source is not clear. Hence, this led to technical problems of high-sensitivity SQUID chip design and sensors. Consequently, it is difficult to propose original research ideas.

3.3 Weak in leading-edge comprehensive key technology innovation ability

Most of the quantum gravity and magnetic field detection technology and equipment developed in China are weak in terms of the basic theoretical research of quantum gravity and magnetic field measurement. Furthermore, they mainly focus on tracking foreign ideas and technical methods, resulting in weak original innovation ability of leading-edge key technologies. Although there have been relevant reports on the development of low-temperature SQUID for magnetic field chips, SQUID for magnetic vector gradient chips, and cesium optical pump magnetic sensor in China, there is still a gap in their indicators when compared to the world's most advanced indicators in terms of noise level and sensitivity index. The high-precision index of a single chip or prototype does not imply that the key technologies have been overcome, and the small batch R&D capability has not been formed, to date. In China, the key technologies of high-performance SQUID sensor chips have not been completely solved, and the quantum gravity MEMS chips are still in the research and exploration stage. The deep-sea low-temperature liquid helium or liquid nitrogen insulation technology and elimination of motion noise requires further research. The suppression of vibration and external noise of superconducting gradiometer in airborne platform, ground vibration noise of quantum gravity gradiometer, Raman phase noise, and atomic detection noise require resolution of significant technical challenges.

Domestic research on the basic core technologies, such as low-temperature SQUID sub-micron Josephson junctions, high-temperature superconducting high-quality thin film preparation, long baseline lithography, superconducting constant temperature cooling, superconducting electromagnetic shielding, single quantum state generation of cold atomic system, laser cooling technology, three-dimensional magneto-optical well, and ion trap technology, is not sufficient and thorough. The improvement of chip and sensor indicators cannot be separated from the experience accumulated by repeated failures, and the core technology research requires long-term persistence. Nowadays, given the development of economic strength, future scientific basic research can be conducted in China. Thus, we need to aim at the subversive, forward-looking, strategic, and cutting-edge direction of quantum precision geophysical field detection, conduct research from multiple angles and multi-level underlying technologies, and experience repeated explorations to clarify the essence. Furthermore, we should adopt the spirit of searching for the truth and solving the current situation of basic research and key technologies.

3.4 Insufficient application ability in detection engineering with the localization system of quantum detection

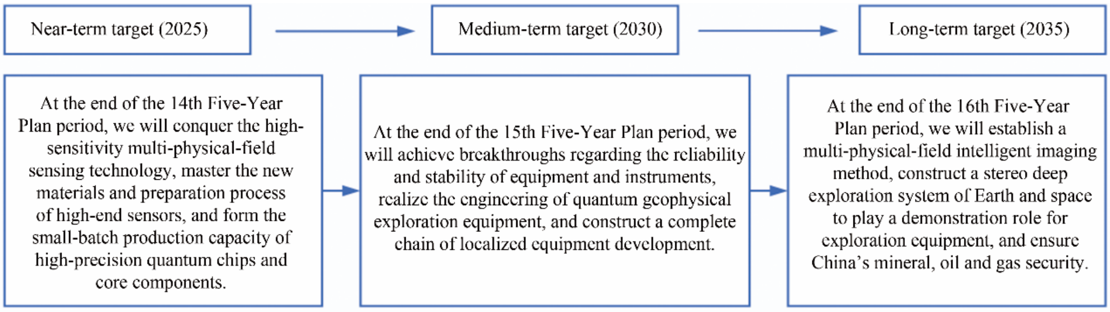
China has successfully developed the ground superconducting electromagnetic detection system, ground superconducting gravimeter, airborne superconducting full tensor magnetic detection system, airborne quantum cesium optical pump magnetic detection system, ground atomic absolute gravity system, airborne quantum gravity gradient system, and ship-borne quantum gravity gradient system. Most of the domestically developed quantum gravity and magnetic field detection systems are in the prototype stage. Although certain technical indicators have been realized, they are still in the R&D stage in terms of the key technologies of gravity and magnetic field measurement in the large dynamic range of the moving platform and shielding and shock absorption engineering technology. The practicability and maturity of the detection system are not very high. There are two main reasons leading to this phenomenon. First, the western countries have developed high-sensitivity SQUID chips. Unfortunately, embargoes have been imposed on China in the fields of high-precision gravity sensors and inertial devices. Second, the core technologies of airborne high and low temperature full tensor magnetic measurement and airborne gravity/gravity gradient measurement are mainly owned by Canada, Russia, the United States, and Germany. Hence, the actual field detection capability of the quantum geophysical detection system developed in China is insufficient along with the low degree of field exploration application. This in turn cannot satisfy the requirements of deep mineral resources exploration.

4 Key construction tasks and overall development path of quantum-based deep geophysical exploration technology and equipment

4.1 Key construction tasks

With the continuous development of quantum-based sensing and measurement technology, geophysical exploration equipment, with high precision, high resolution, high sensitivity, and high intelligence, will play an important supporting role in the development of mineral resources exploration in deep Earth, with broad development space and application prospects. Therefore, urgent resolution of the theoretical method of quantum-based high-precision measurement of physical field in deep Earth is required. Furthermore, development of chips for low- and high-temperature SQUID chips for deep Earth geophysics and quantum-based vector magnetic sensor of NV centers in diamonds with high sensitivity and resolution are required. Additionally, the measurement system of cold-atom, superconducting gravity, and gravity gradient, and establishment of an all-dimensional exploration system, involving deep quantum-based Earth geophysics of space, sky, Earth, and well, are required.

The key construction tasks of quantum-based deep geophysical exploration technology and equipment are shown in Fig. 2. There are near-, medium-, and long-term targets in three five-year plans of China. We will successively focus on the construction of high-sensitivity sensing technology, new materials and preparation process, technical bottlenecks of quantum-based chip production capacity, stability and reliability, complete chains of engineering and localization, multi-physical fields inversion imaging method, all-dimensional exploration system, and other aspects. Fig. 3 shows the specific construction tasks of quantum-based geophysical exploration technology and equipment. In three levels of high-sensitivity sensing technology, cutting-edge disruptive technology, and practical reliability technology, we propose suggestions and expectations for the specific construction tasks of quantum-based geophysical exploration technology and equipment from four aspects of gravity, magnetic field, electromagnetic field, and earthquakes.



At the end of the 14th Five-Year Plan period, we will conquer the high-sensitivity multi-physical-field sensing technology, master the new materials and preparation process of high-end sensors, and form the small-batch production capacity of high-precision quantum chips and core components.

At the end of the 15th Five-Year Plan period, we will achieve breakthroughs regarding the reliability and stability of equipment and instruments, realize the engineering of quantum geophysical exploration equipment, and construct a complete chain of localized equipment development.

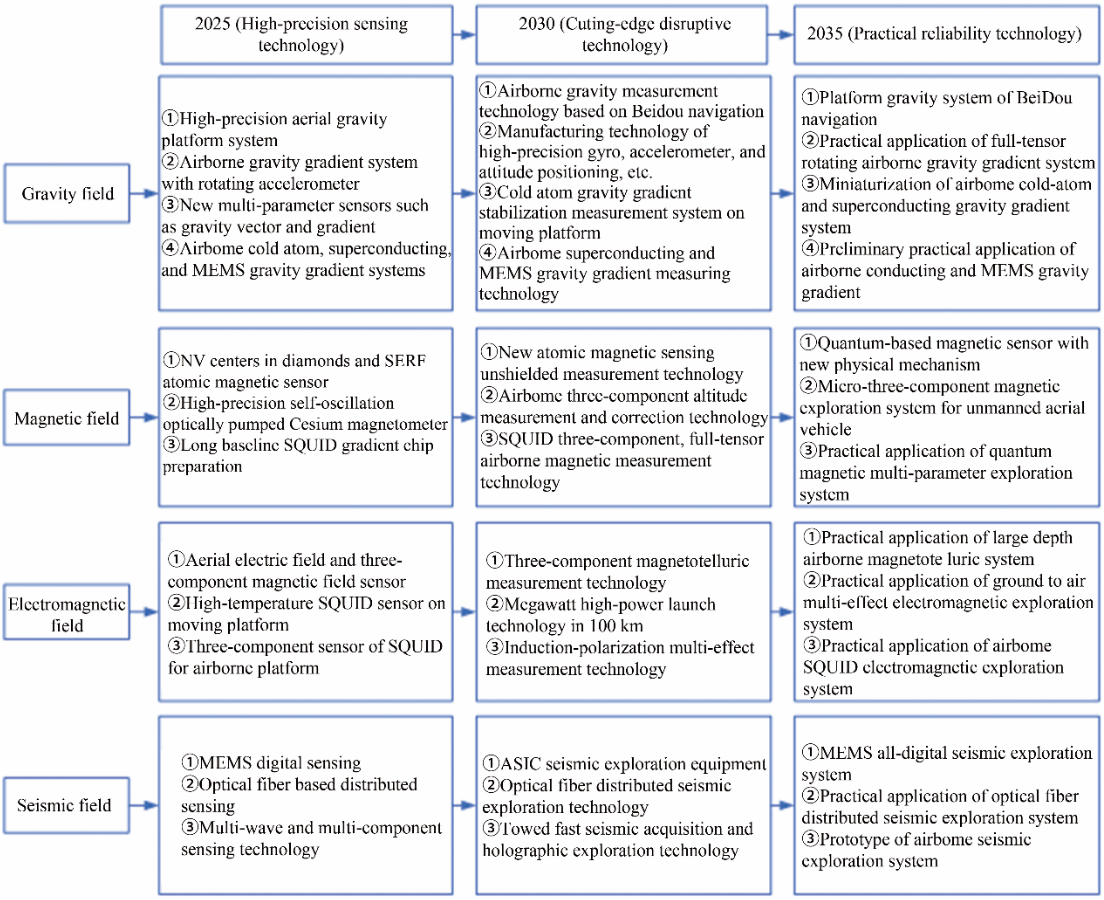
At the end of the 16th Five-Year Plan period, we will establish a multi-physical-field intelligent imaging method, construct a stereo deep exploration system of Earth and space to play a demonstration role for exploration equipment, and ensure China's mineral, oil and gas security.

Fig. 2. Key construction tasks for quantum-based deep geophysical exploration technology and equipment.

4.2 Overall development path

4.2.1 Examining new physical effects or mechanisms of quantum-based sensing theory.

We establish a physical model for vector measurement of NV center based on the newest single-spin quantum-based magnetic sensor technology of NV center in diamond. Furthermore, the frequency shift mechanism of NV center under different magnetic field angles is analyzed. Additionally, we should study the control technology of ground state electron spin and nitrogen nuclear spin of NV center, precise regulation method of quantum-based state in diamonds via laser and microwave fields, readout technology of electron spin in quantum-based state based on optical transition, and noise suppression method based on dynamical decoupling protocol. By developing the quantum-based sensor with NV center in diamonds, the exploration method with high sensitivity and nanometer spatial resolution can be realized.



	2025 (High-precision sensing technology)	2030 (Cuting-edge disruptive technology)	2035 (Practical reliability technology)
Gravity field	①High-precision aerial gravity platform system ②Airborne gravity gradient system with rotating accelerometer ③New multi-parameter sensors such as gravity vector and gradient ④Airborne cold atom, superconducting, and MEMS gravity gradient systems	①Airborne gravity measurement technology based on Beidou navigation ②Manufacturing technology of high-precision gyro, accelerometer, and attitude positioning, etc. ③Cold atom gravity gradient stabilization measurement system on moving platform ④Airborne superconducting and MEMS gravity gradient measuring technology	①Platform gravity system of BeiDou navigation ②Practical application of full-tensor rotating airborne gravity gradient system ③Miniaturization of airborne cold-atom and superconducting gravity gradient system ④Preliminary practical application of airborne conducting and MEMS gravity gradient
Magnetic field	①NV centers in diamonds and SERF atomic magnetic sensor ②High-precision self-oscillation optically pumped Cesium magnetometer ③Long baseline SQUID gradient chip preparation	①New atomic magnetic sensing unshielded measurement technology ②Airborne three-component altitude measurement and correction technology ③SQUID three-component, full-tensor airborne magnetic measurement technology	①Quantum-based magnetic sensor with new physical mechanism ②Micro-three-component magnetic exploration system for unmanned aerial vehicle ③Practical application of quantum magnetic multi-parameter exploration system
Electromagnetic field	①Aerial electric field and three-component magnetic field sensor ②High-temperature SQUID sensor on moving platform ③Three-component sensor of SQUID for airborne platform	①Three-component magnetotelluric measurement technology ②Megawatt high-power launch technology in 100 km ③Induction-polarization multi-effect measurement technology	①Practical application of large depth airborne magnetote luric system ②Practical application of ground to air multi-effect electromagnetic exploration system ③Practical application of airborne SQUID electromagnetic exploration system
Seismic field	①MEMS digital sensing ②Optical fiber based distributed sensing ③Multi-wave and multi-component sensing technology	①ASIC seismic exploration equipment ②Optical fiber distributed seismic exploration technology ③Towed fast seismic acquisition and holographic exploration technology	①MEMS all-digital seismic exploration system ②Practical application of optical fiber distributed seismic exploration system ③Prototype of airborne seismic exploration system

Fig. 3. Specific construction tasks for quantum-based deep geophysical exploration technology and equipment.

To examine the response mechanism of the atomic spin of the spin-exchange relaxation free (SERF) atomic magnetic sensor to the external fluctuating magnetic field, the response model of the atomic spin to the external fluctuating magnetic field and high frequency modulation field in Bloch equation is established. To realize highly sensitive miniaturized gradient measurement of geophysical fields in unshielded environment, we should study atomic polarization uniformity, magnetic field response mechanism of each channel due to the difference in atomic polarization at different positions in the gas chamber, and modulation methods of pumped light intensity and frequency in unshielded geophysical field exploration. These methods can lead to solid foundations of geophysical quantum-based exploration. This in turn can lead to disruptive technologies of geophysical exploration in deep Earth.

4.2.2 Breaking through the key technology of preparation process and measurement application.

We should overcome the difficulties involved in developing the measurement of gravity gradient based on the cold atom interferometer, chip level cold atom absolute gravimeter sensor, small high repetition frequency cold atom physical probe, superconducting gravity sensor, and superconducting gravity gradient sensing probe. Furthermore, we should examine laser cooling technique in single quantum and ion trap technique in cold atom, high efficiency laser cooling atom and optically pumped quantum state preparation method, atomic free-fall measurement in short distance, and quantum-based absolute gravity measurement method. Additionally, we should resolve cross coupling noise reduction technology, common mode coupling noise reduction technology, and real-time elimination technology of common mode coupling signal on mobile platform. The ground vehicle-mounted measurement and airborne adaptability tests should be conducted, and the engineering prototypes of aviation gravity gradiometer and aviation cold atom interference gravity gradiometer should be realized.

We should resolve manufacturing and processing technology of high precision SQUID sensor, three component high-temperature and low-temperature SQUID sensor, array high purity Germanium detector, and atomic vector magnetic sensor. Furthermore, we should conduct more research on silicon microfabrication technology of chip level

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atomic magnetometer, diamond design and processing technology for magnetic field measurement of quantum coherence with long life and high sensitivity, structural models and optimization methods for superconducting Josephson crystal boundary, thermal noise, eddy pinning, hysteresis and flux entrapment in geomagnetic environment with magnetic fluxion interference [33,34], and influence mechanism of different application scenarios such as unsourced magnetic field and active excitation electromagnetic field on the performance of high-temperature SQUID chips. By studying the fabrication process of YBCO superconducting thin films for high-temperature SQUID chips, we can reveal the effects of pulsed laser deposition temperature, particle size, and density of heterophase, chemical composition in plume, target normal direction angle, and laser energy on the quality of high-temperature superconducting thin films and noise level of high-temperature DC SQUID chips [35]. Additionally, we should examine preparation technology of high-temperature superconducting magnetic measurement chip and low-deformation low-temperature packaging technology [36,37], overcome the difficulties involved in the preparation technology of high-temperature superconducting chips [38], and develop a fully localization magnetic vector gradient chip for aviation flight platform. We should realize the localization of high-temperature SQUID chip in the field of geophysical exploration, improve the application level of SQUID chip in the field of magnetic method, electromagnetic method and gravity measurement, and enhance China's deep resources exploration ability.

4.2.3 Constructing the practical engineering system of quantum-based exploration technology and equipment in deep Earth.

To realize the requirements of intelligent and refined exploration of multi-physical attributes in deep Earth, establishment of the geophysical exploration technology system of various mobile platforms, such as aviation, well, ocean and satellite, which can reach the international leading level, is urgently required. It has become the development trend of high-resolution and fine geophysical technology and equipment for developing multi-parameter measurement technology and equipment, such as total gravitational and magnetic fields, three-component, gradient, full gravity, electromagnetic field, relative gravity and absolute gravity on moving platforms, and improving the sensitivity and depth of mineral resources exploration on various mobile platforms.

Mobile platform measurement should focus on vibration noise processing method of gravitational and magnetic fields and motion control technology. Furthermore, studies on real-time measurement and adaptive processing method of vibration noise should be conducted. Additionally, we should examine moving base motion attitude measurement and real-time feedback control technology of the inertial stability platform, attitude control method of quantum gravity measurement system, high sampling rate, moving motion noise suppression, and environmental adaptive technology of cold atom gravity gradiometer. Furthermore, we should resolve the key technology of ground mobile measurement of cold atom gravity gradiometer, breakthrough ground mobile measurement, position and vibration control technology in airborne adaptation experiment, airborne electromagnetic exploration technology based on superconducting quantum sensor, and unmanned aerial vehicle ground to air exploration technology.

5 Suggestions

5.1 Formulating the national development strategic plan for quantum Earth gravity and magnetic multi-field precision detection technology and equipment

As the top-level program for quantum sensor rests on local government level and lack of clear national guidance in China, it is suggested that China should launch a national strategic planning for quantum science and technology the soonest possible, improve cutting-edge technology of quantum sensor rapidly and in a healthy manner, and concentrate on the development of quantum device fabrication technology and quantum sensing technology for geophysical fields. For basic research studies on new mechanisms, such as SERF atomic magnetometer and NV centers in diamonds magnetometer, it is recommended that they should be examined a multi-point and sporadic manner. Hence, they can be researched in long-term in all directions. The development of airborne cold atom interference gravity and gravity gradient system is suggested as the critical, cutting-edge, and subversive technology given that it has a large gap toward practical applications. Furthermore, the measurement and experimental object of mobile platform can be extended to the field of satellite gravity measurement at the same time. For high- and low-temperature airborne superconducting magnetic vector detection system of aviation and ocean mobile platforms, realization of high maturity and practicality in short order is required. Simultaneously, we should focus on the choking technology of gravity and magnetic field mobile measurement with the goal of engineering practical development and aim to break the technological encirclement of developed countries such as Europe and the United States.

5.2 Establishing quantum geophysical field high-precision sensing and detection projects

Research on domestic engineering instrument and experiment should be encouraged, especially in areas superconducting quantum chip and sensors, the cold atomic absolute gravity gradient system, and NV centers in diamonds magnetometer. Special support on experiment and engineering technique should be established. Reliability and stability experiment and instrument test for a typical region should be conducted. This should be aimed to break the unusable situation of domestic instrument. Bottleneck technologies are finally reflected in engineering applications. Although there are many studies on domestic instruments and equipment, there is a paucity of their applications. The fundamental reason for reluctance in use of domestic instruments is that they are not usable. Furthermore, they are designed solely to pursue the breakthrough of performance indexes. Therefore, according to the demands of deep mineral resources, unconventional oil and gas energy, and other major strategic demand, it is suggested that we should focus on integration of superior resources and technological strength such as domestic superconducting quantum chip and sensors, the cold atomic absolute gravity gradient system, and NV centers in diamonds magnetometer. The R&D system for quantum precision geophysical exploration instrument should be created. In the aspect of basic research, the original new theory of large depth detection method should be explored. In terms of key equipment technologies, the bottleneck technologies should be resolved toward the development of special chip preparation for Earth’s gravity and magnetic field, superconducting quantum magnetic field and magnetic vector gradient field sensor, atomic magnetometer, and atomic gravimeter. The performance of quantum sensors, such as sensitivity, resolution, measurement limit, swing rate, and dynamic range should be improved. By conquering the key technologies of motion platform and measurement of Earth’s magnetic field in shielding environment, we can improve the geophysical field quantum exploration ability and high-precision measurement technology, realize the localization and practical application of quantum high-precision geophysical field exploration system, and create a new environment of geophysical deep exploration equipment independently developed by China. Furthermore, we should improve the deep intelligent and fine standard of geophysical equipment. Thus, it can serve deep mineral, oil, and gas exploration and realize national energy independence and control.

5.3 Improving model and evaluation mechanisms of multidisciplinary engineering talents

Due to the long development cycle of instruments, it is necessary to establish a new evaluation mechanism for personnel evaluation and professional-title evaluation, which are more suitable for scientific and technological innovation of geophysical instruments and more conducive to the stability and development of scientific and technological personnel teams. The engineers engaged in the R&D of instruments and other engineering applications can obtain corresponding development space by setting a series of senior craftsmen and engineers titles and establishing a third-party evaluation mode in terms of the localization and practicality of the R&D of geophysical instruments. It is suggested that engineers from domestic scientific research institutions should conduct multidisciplinary visits and exchanges to promote interdisciplinary integration and technological innovation. By setting up international cooperation projects, engineers and technicians are actively encouraged to participate in international cooperation, and thereby, a group of talented individuals, working on the R&D of geophysical instruments, will be cultivated in China.

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