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Progress and prospects in Chinese Antarctic surveying, mapping and remote sensing studies

E Dongchen[1,2] & ZHANG Shengkai[1,2*]

[1]Chinese Antarctic Center of Surveying and Mapping, Wuhan University, Wuhan 430079, China;
[2]Key Laboratory of Polar Surveying and Mapping, SBSM, Wuhan 430079, China

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Abstract Antarctic surveying, mapping and remote sensing is one of the important aspects of the Chinese Antarctic geoscience research program that stretch back over 25 years, since the first Chinese National Antarctic Research Expedition (CHINARE) in 1984. During the 1980's, the geodetic datum, height system and absolute gravity datum were established at the Great Wall and Zhongshan Stations. Significant contributions have been made by the construction of the Chinese Great Wall, Zhongshan and Kunlun Stations in Antarctica. Geodetic control and gravity networks were established in the King George Islands, Grove Mountains and Dome Argus. An area of more than 200 000 km^2 has been mapped using satellite image data, aerial photogrammetry and in situ data. Permanent GPS stations and tide gauges have been established at both the Great Wall and Zhongshan Stations. Studies involving plate motion, precise satellite orbit determination, the gravity field, sea level change, and various GPS applications for atmospheric studies have been carried out. Based on remote sensing techniques, studies have been undertaken on ice sheet and glacier movements, the distributions of blue ice and ice crevasses, and ice mass balance. Polar digital and visual mapping techniques have been introduced, and a polar survey space database has been built. The Chinese polar scientific expedition management information system and Chinese PANDA plan display platform were developed, which provides technical support for Chinese polar management. Finally, this paper examines prospects for future Chinese Antarctic surveying, mapping and remote sensing.

Keywords **Antarctic, geodesy, remote sensing, geographic information system, digital mapping**

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0 Introduction

Antarctic surveying, mapping and remote sensing integrate modern geodesy, remote sensing, digital mapping, geographic information systems and related disciplines such as glaciology, oceanography, geology and environment sciences. This work aims to study Antarctic plate motion, describe topographic characteristics of the surface, monitor ice-snow-ocean dynamic processes, and build a digital polar framework using the spatial data and information. Therefore, this is a relatively new domain of study in Chinese polar science that builds on modern surveying science and spatial information technology.

Surveying and mapping for Chinese Antarctic expeditions have two main functions. One is to provide technical support for the expedition, including the provision of all sorts of maps and spatial geographic information platforms, etc. The other is to study changes in the polar environment (e.g., through mass balance) using modern surveying techniques. At the same time, because of the attributes of the surveying on the Antarctic continent *per se*, such as expanding map coverage, establishing ground control points, and the naming of geographic entities, the surveying and mapping has great significance for the maintenance of national rights and interests.

During the austral summer of 1984/1985, the first Chinese Antarctic National Research Expedition (CHINARE) established the Great Wall Station in West Antarctica and began an ongoing program of surveying and mapping that has been supported by the State Bureau of Sur-

* Corresponding author (email: zskai@whu.edu.cn)

veying and Mapping (SBSM) and the State Oceanic Administration (SOA). Advances in science and technology have led to the need to update traditional surveying methods to global Earth observations based on GPS, RS and GIS techniques. Great progress has been made in geodesy, environmental remote sensing, digital mapping and internet spatial information techniques in Antarctica.

1 Geodesy

Geodesy is the scientific discipline that deals with the study of the shape of the Earth and its motion. In the history of Antarctic research, the work of geodesists has led to the establishment of the coordinate system, the application of GPS technologies, and investigations of the gravity field, the geoid, crustal motion, and sea level change, etc.

1.1 Early Chinese geodetic work in Antarctica

During the 1984/1985 austral summer season, China carried out the first Antarctic expedition and built the Great Wall Station in the King George Islands, West Antarctica. The first and foremost task undertaken was to accurately determine the location of the station. The TRANSIT system, also known as NAVSAT (Navy Navigation Satellite System), was used to determine the coordinates of the Great Wall Station: 62°12′59″S, 58°57′52″W, in the WGS72 system. The height system of the Great Wall Station area was established using a tide staff. Using traditional astro-geodetic surveying and gyroscopes, the orientation of the meridian was measured, and the coordinate system of the Great Wall Station was thereby established. Based on the geodetic datum, the distance and azimuth from the Great Wall Station to Beijing were calculated. At the same time, an engineering construction survey and lay out were undertaken[1–5]. In 1989, when the second Chinese Antarctic station—Zhongshan Station was established in the Larsemann Hills, East Antarctica, the same methods were used to build the coordinate system and undertake basic survey tasks[6].

From the late 1980s to the early 1990s, based on the techniques and funding available at that time, a geodetic control network was established, and relative gravimetry measurements, mapping etc. in the vicinities of the Great Wall and Zhongshan Stations were carried out by traditional methods. These activities initiated Chinese surveying in Antarctica and laid a good foundation for later geodetic studies across the continent.

1.2 Antarctic geodesy and crustal movement based on modern spatial techniques

With the development of modern surveying techniques, especially the Global Positioning System (GPS), the coordinates of any point on the Earth could be obtained conveniently and efficiently. Since 1993, GPS techniques have been applied in Antarctica by Chinese surveyors.

1.2.1 The geodetic control network

Before 1991, the geodetic control networks at the Great Wall and Zhongshan Stations were established by traditional ground traverse survey techniques. The control networks satisfied surveying and mapping requirements during that period. Since 1991, with the rapid development of GPS techniques, the geodetic control networks at the Great Wall and Zhongshan Stations, the Grove Mountains and Dome Argus (Dome A) were established one after the other. The coordinate systems for Chinese Antarctic expedition areas were united with the world geodetic system.

1.2.2 Crustal movement

During the austral summer of 1985/1986, a two-dimensional (2D) monitoring network was built in the vicinity of the Fildes Strait fault zone, West Antarctica, consisting of infrared laser ranging. In 1991, the monitoring network was updated to a three-dimensional (3D) monitoring network using GPS technology.

In the 1990s, GPS technology began being widely used in Antarctica. In 1994, the Geoscience Standing Scientific Group (GSSG), which is the former Working Group on Geodesy and Geographic Information (WGGGI) of the Scientific Committee on Antarctic Research (SCAR), carried out the Epoch GPS Campaigns. The GPS campaigns provided a valuable data set that is used to link Antarctica with the International Terrestrial Reference Frame (ITRF), and to gain the first detailed insights into the tectonic behavior of the Antarctic plate. The observation period of the GPS campaigns was between 20 January and 10 February each year. A tracking rate of 15 s was recommended to all participating countries. The minimum cut-off angle was set to 10°.

In 1995 and 1997, the Chinese Great Wall and Zhongshan Stations were involved in the GPS campaigns respectively. In 1997 and 2008, respectively, Zhongshan and Great Wall Station were rebuilt to permit year-round GPS data collection. Based on the multiyear GPS data, the horizontal velocity field of Antarctica was calculated (Figure 1).

1.3 Gravity measurements and height datum

Gravity data are indispensable for the study of the gravitational field and the shape of the Earth. The height datum plays a key role in many studies involving gravitation such as the development of a sea model of the South Ocean and the calibration and validation of altimetry data. However, because of the extreme climate and special geographic location, gravity measurements are difficult to be deployed in the Antarctic.

1.3.1 Gravity measurements

During the late 1980s and the early 1990s, relative gravity measurements were made at the Great Wall and Zhongshan Stations by the Institute of Geodesy and Geophysics (IGG). Because there were no absolute gravity sites at the Chinese stations, high accuracy absolute gravity results could not be obtained. In January 2005, absolute gravity measurements were finally made at the Great Wall Station using an FG5 absolute gravimeter. At the same time, relative gravity measurements were deployed using Lacoste relative gravimeters at the Korean King Sejong Station and the Chilean Frei Station. In January 2008, three absolute gravity sites were measured using an A10 absolute gravimeter at Zhongshan Station, and a relative gravity network was set up in the Larsemann Hills of East Antarctica. The absolute gravimetry in Antarctica provides the gravity datum for aerogravity surveys, ocean gravity surveys and the gravity field studies[16–17].

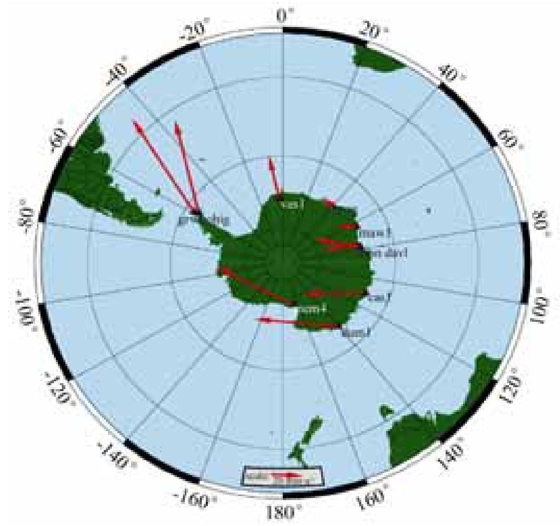

Figure 1 The horizontal velocity field of the Antarctic.

1.3.2 Height datum

A tide gauge was used to measure tides and also was the basic tool used to determine the height datum. In 1999, a pressure tide gauge was set on the sea bottom near Zhongshan Station, shared and jointly operated by Australia and China. In 2009, a new tide gauge was set up by China at Zhongshan Station using Norwegian Aanderaa equipment.

The geoid is the equipotential surface that would coincide exactly with the mean ocean surface of the Earth. In Antarctica, some countries routinely substitute a mean sea level derived from a tide gauge for the geoid to build their local height systems. Because the datum in each of the height systems corresponds to a different equipotential surface, there are height differences among the height systems. It is now very desirable to unite the various elevation systems of the Antarctica[18].

1.4 GPS applications in the atmosphere

Based on GPS data from the Zhongshan and Great Wall Stations, atmospheric characteristics such as meteorologic parameters and the spatial and temporal characteristics of the ionosphere have been obtained.

1.4.1 GPS applications in troposphere studies

GPS technology has been used in meteorological research work in recent years. The data from the SCAR Epoch GPS campaigns, including data from the Great Wall and Zhongshan Stations, were used to construct the GPS network. A high accuracy software package—GAMIT/GLOBK—has been used, and multiple schemes were adopted to obtain such properties as the tropospheric zenith all delay, zenith dry delay, atmospheric Precipitable Water Vapor (PWV), and zenith wet delay. The weather characteristics of the Great Wall and Zhongshan Stations can be extracted from the above analyses. For example, the PWV series from the Great Wall Station usually increased to 20 mm rapidly, with the precipitation occurring over 3–4 h. On the other hand, the PWV series from Zhongshan Station usually showed small and slow changes, which means that there are fewer opportunities to observe precipitation at Zhongshan Station. The results agree well with *in situ* meteorologic observations[19]. The conclusion can be drawn that GPS meteorology is a feasible and useful complement to weather forecasts in Antarctica.

1.4.2 Polar ionosphere characteristic study

Precise ionosphere Total Electron Content (TEC) values are derived from the GPS data from Zhongshan, Great Wall and Yellow River Stations. The characteristics of TEC associated with solar activities, the geomagnetic environment, and daily, annual and seasonal TEC variations have been studied.

1.5 Glacier movement studies

The Antarctic ice-sheet stores the majority of the Earth's freshwater, with the icecap containing almost 90% of the world's ice. As a result, changes in the mass balance of the Antarctic ice sheet would affect global sea level and global climate. Surface topography, ice velocities and height are important parameters for mass balance studies. In particular, investigations of glacier movement and dynamics based on spatial geodesy have been an area of great interest in Antarctic studies. Since the 1990s, ice velocities have been monitored along a traverse from Zhongshan Station to Dome A and the Amery Ice Shelf, East Antarctica. The ice velocities at the front on the Amery Ice Shelf vary from 800 to 1 200 $m \cdot a^{-1}$, with the flow directions pointing to the sea. The ice velocities along this traverse are shown in Figure 2. Horizontal ice velocities increase from the summit of the ice sheet to the coast. Near the dome area, the velocities are less than 10 $m \cdot a^{-1}$; in the plateau area, the velocities range from 8 to 24 $m \cdot a^{-1}$ and reach about 98.2 $m \cdot a^{-1}$ at a site (LT980) near the coast. The flow directions are roughly perpendicular to the contour lines of the ice sheet, mostly pointing toward the Lambert Glacier Basin[24–26].

2 Earth observation techniques in Antarctic studies

The establishment of the first meteorological satellite, launched by USA in 1960, marked a new period in the era of Earth observations. Over the last 50 years, Earth observation techniques have developed rapidly. Many techniques can now provide multi-spatial and/or multi-temporal resolution data quickly and accurately. These new techniques provide abundant data and information that cannot be obtained from terrestrially-based surveys and, of relevance to this paper, promote understanding of the Antarctic. Chinese scientists have used remote sensing and aerial photogrammetry techniques to map and study the dynamic process of the Antarctic.

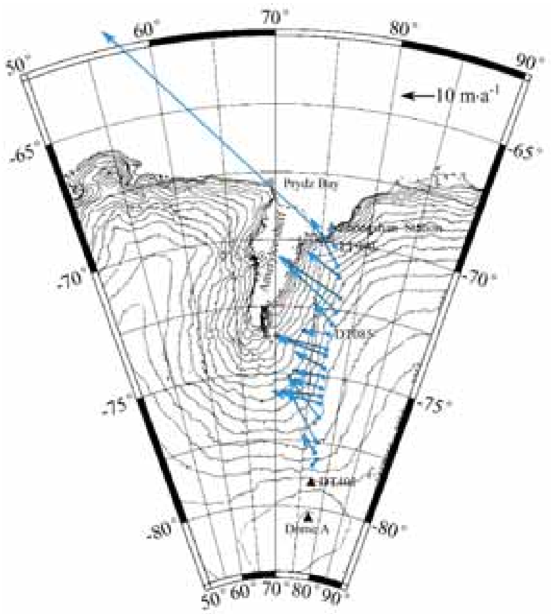

Figure 2 Horizontal ice velocities from Zhongshan Station to Dome A.

2.1 Remote sensing and aerial photogrammetry mapping in Antarctica

Topographic maps and small-scale image maps have been made using remote sensing and aerial photogrammetry methods for the foundations of the Great Wall, Zhongshan, and Kunlun Stations and also for the Chinese inland ice sheet expedition.

(1) A small format aerial photograph technique was developed to produce a topographic map of the Larsemann Hills at 1∶10 000 scale. A helicopter was used as the platform for a non-metric 120 camera used to take pictures. The method proved to be successful in Antarctica.

(2) Large range image maps from Chinese Antarctic expedition areas were made using the no ground control point method.

(3) Multi-purpose image maps of inland Antarctica such as the Grove Mountains and Dome A areas were made to satisfy with multi-disciplinary need[27–30].

2.2 Applications of Earth observation techniques in the snow and ice studies

With advancements in science and technology, techniques used for Earth observation have proven to be enormously advantageous in snow and ice studies associated with the main Chinese expedition areas (i.e., the Great Wall, Zhongshan, and Kunlun Stations, along with the Grove Mountains and Amery Ice Shelf). Progress has been made in the aspects that follow[31–35].

(1) Satellite remote sensing has been applied to study glacier dynamics. The dynamic processes of the Polar Record and Dark glaciers were determined from multi-period satellite images covering 17 years.

(2) The interferometric synthetic aperture radar (InSAR) technique was used to build a digital elevation model (DEM, Figure 3), and retrieve the distributions of blue ice and ice crevasses.

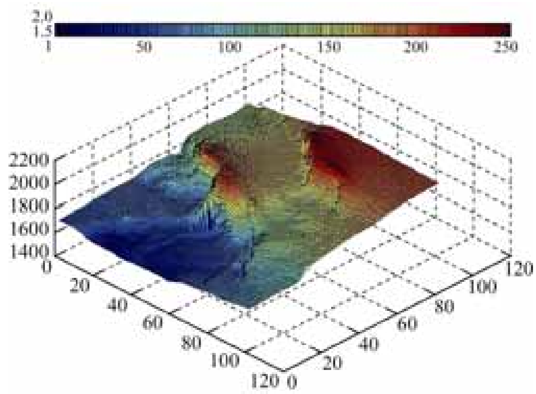

Figure 3 DEM of the core area from ERS tandem data, Grove Mountains.

(3) A satellite laser ranging technique was used to build the DEM of the ice sheet. The precise DEM along the traverse from Zhongshan Station to Dome A was built from the ICESat/GLAS data. The elevation variation of the Lambert Glacier—Amery Ice Shelf System was also calculated from the ICESat/GLAS data (Figure 4).

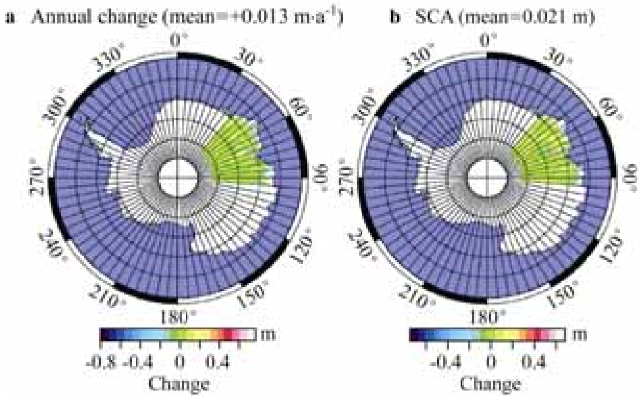

Figure 4 The elevation variation of the Lambert Glacier—Amery Ice Shelf System from ICESat/GLAS data.

(4) The mass balance of Antarctic ice sheet and its contribution to global sea level change was assessed from the Gravity Recovery and Climate Experiment (GRACE)

data (Figure 5).

(5) The ice velocities of the Lambert Glacier—Amery Ice Shelf System were calculated from a Landsat 7 ETM+ image and an Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) image.

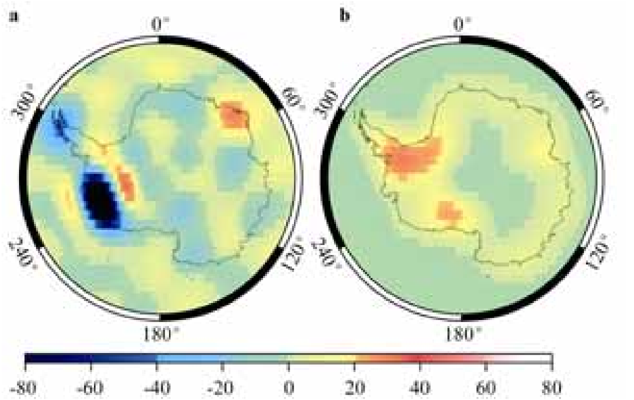

Figure 5 The mass balance of Antarctic ice sheets from GRACE data.

3 Digital cartography

Polar digital cartography is one of the branches of polar geosciences that plays a key role in polar expeditions. It is linked closely with geodesy, remote sensing and geography. Since 1984, more than 40 Chinese Antarctic maps covering approximately 200 000 km^2 have been published. More than 300 Chinese Antarctic place names have been released[36–39].

3.1 Multi-type, multi-scale maps covering all Chinese Antarctic expedition areas

In 1984, during the first Chinese National Antarctic Scientific Expedition, the first Chinese Antarctic map—the Great Wall Station map—was surveyed, and the first Chinese Antarctic place name—Great Wall Bay—was named. In 1987, a topographic map of Fildes Peninsula, King George Islands was surveyed by aerial photogrammetry. In 1992, the Larsemann Hills image map was made using the small format aerial photograph technique. In 1999 and 2005, topographic maps of the core areas of Grove Mountains and Dome A were surveyed using differential GPS methods. So far, more than 40 maps covering polar areas have been released, including Fildes Peninsula, Larsmenn Hills, Grove Mountains, Dome A, Great Wall Station, Zhongshan Station and the transect from Zhongshan Station to Dome A.

3.2 From simplex to multi-function map

With the development of the Chinese Antarctic expedition, series of maps such as thematic maps, evaluation maps and dynamic maps were compiled. Representative maps include: Great Wall Station—Fildes Peninsula—King George Island maps, Zhongshan Station—Xiehe Peninsula—Larsemann Hills maps, distribution maps of blue ice and meteorite locations in the Grove Mountains, and geology, geomorphology, and environmental frangibility maps of the Fildes Peninsula.

3.3 From paper to electronic maps

With the development of digital mapping, the quantity and quality of polar maps has greatly improved. Map services have changed from classic paper maps to four-dimension products, multimedia electronic maps, navigational electronic maps, online map services, etc. Products mainly include bipolar multimedia electric maps. For example, the transect from Zhongshan Station to Dome A can be navigated solely with electronic and online polar maps.

3.4 Methods and techniques of mapping changed from classic to full digital methods based on GPS, RS and GIS

Polar cartography has experienced the transition from hand mapping to remote sensing mapping and computer-aided drawing. Information sources for polar cartography have increased; however, the automatic degree of polar cartography has also improved, the period of time required to undertake polar cartography has shortened, and the quality of polar cartography products is improved remarkably. Cartography techniques based on the color map of desk publishing technology and map visualisation based on GIS technology are of special interest.

4 Geographic information system (GIS) studies

The development of GIS has been quick and was readily applied in Antarctic studies. In 1999, a Chinese internet-based prototype system for Antarctica GIS was established by the Chinese Antarctic Center of Surveying and Mapping at Wuhan University. In July 2000, the King George Islands GIS workshop, sponsored by SCAR WGGGI, was held at Wuhan University. Considering the rapid development of Chinese GIS studies, a Chinese internet GIS workshop, sponsored by the Chinese Arctic and Antarctic Administration (CAA) was held at Wuhan University in October 2002. The Chinese Polar Scientific Expedition management Information System, based on a GIS platform, was approved at this workshop.

In May 2004, a second SCAR WGGGI GIS workshop was held at Wuhan University. Experts from the USA, Canada, Germany, Italy, Poland and Russia attended the workshop. In 2006, Chinese representatives provided the geospatial information portal service for the Grove Mountains project. In 2009, the Prydz Bay, Amery Ice Shelf and Dome A Observatories program (PANDA) GIS system was developed by the Polar Research Institute of China and Wuhan University. The information system enabled 3D visualization of the Chinese Antarctic stations, route lines and resource distributions. Many kinds of spatial data including control points, raster maps, vector maps, 3D architecture models, remote sensing images and DEMs are integrated into the information system.

In general, Chinese Antarctic GIS integrates spatial data, application models and network services. The inter-operational Antarctic spatial information infra-structure has been developed step by step, providing information for Antarctic mapping, expedition management, and scientific studies. The current advances in digital Earth data are leading to the developmental changes in GIS from 2D to multi-dimensional. New group software technologies, network technology, multi-dimensional expressions, and distributed data support will be the main themes of GIS in the near future.

5 Prospects

According to the medium and long term plans of Chinese Antarctic expeditions, we should aim to be at the frontier of international polar science, make use of the most advanced techniques of modern surveying, mapping and remote sensing, exploit a wide range of study areas and applications, and be innovative in new peripheral disciplines and cross disciplines. The key goals are as follows.

(1) Develop technical systems for basic surveying and survey engineering in Antarctica.

The integration of aerial, space-based, and ground-based observation systems should be emphasized to provide efficient, quick mapping and a platform of shared services.

(2) Strengthen physical geodesy and geodynamics in the Antarctic.

A high-precision geodetic reference system in Chinese polar expedition areas should be established and linked with the ITRF. The precise geoid of Antarctica and the relationship of the ice load to the characteristics of polar topography should be studied based on continuous GPS data, absolute and relative ground gravity data and aerogravity data. Further study is also needed in satellite orbit determinations and orbit reverse issues, GPS applications in the troposphere and ionosphere, and Antarctic Plate motion. For example, based on GRACE satellite gravity data, we can understand the mass balance of the Antarctic ice sheet more clearly than before[44–45].

(3) Develop a sea surface topography model and monitor variations in the Southern Ocean.

A digital sea surface topography model of the Southern Ocean can be used to monitor and evaluate sea level change around Antarctica. Improvements to such a model could be established by multi-satellite altimeter data and tide gauge data. With the development of Earth observation techniques, available data covering Antarctica are becoming more and more abundant. Among other things, this can support the development of a high-resolution sea surface topography model to monitor the mass balance of the Antarctic ice sheet and study Southern Ocean dynamics.

(4) Monitor and assess high-resolution snow and ice environment and ecology at a range of temporal and spatial scales.

The cryosphere in the polar regions is closely related to global climate and environmental change. Through the latest Earth observation techniques, using multi-source spatial data, variations in the ice environment and mass balance can be monitored and a digital 3D terrain model could be established.

Because of its extreme location and climatic characteristics, the Antarctic environment is transitional, fragile and sensitive. The activities of human beings in Antarctica have a significant effect on the fragile Antarctic ecology and environment. So, we plan to establish monitoring areas in East Antarctica to measure such effects.

a) The monitoring areas include Zhongshan Station, the Grove Mountains, Amery Ice Shelf, Dome A and all of the Chinese expeditions in East Antarctica.

b) The monitoring objectives include ice sheets, ice shelves, glaciers, coastlines, the geoid, subglacial lakes, and subglacial topography.

c) The technical systems used for monitoring are based on a modern integrated technical platform. They include satellite-based platforms, airborne radar, airborne laser ranging, airborne gravity, and ground-based 3D visualization survey platforms. Observations of periodic, operational and secular data should: (i) improve the temporal and spatial resolution of the monitoring data sets, (ii) enable the establishment of an Antarctic environmental information monitoring system framework, (iii) accumulate Antarctic ecological and environmental information, (iv) obtain key parameters of environment change, (v) describe the rules of dynamic variation in the Antarctic environment, and (vi) provide a scientific foundation for Chinese ecological and environmental protection and management.

(5) Build a 'Digital Antarctica', by establishing a polar spatial information grid sharing on a global scale.

The sharing of information will be a key part of future Antarctic expeditions involving multiple countries and multiple crossed disciplines. Grid techniques will make the sharing and integration of information possible. The functions of Digital Antarctica are to:

a) Integrate environmental change parameters, describe the polar dynamic variation quantitatively and solve scientific problems.

b) Facilitate data acquisition and sharing, and provide a scientific platform for multi-disciplinary teams who obtain polar data and resources and analyze polar environmental changes.

c) Provide the management and decision support for responsible departments and agencies, provide more scientific and efficient survey support, and share GIS services for Chinese polar expeditions.

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