

Development of the geodetic coordinate system in Antarctica

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Abstract Defining a universal geodetic coordinate system is one of the fundamental challenges of geodesy. We present a review of the basic general coordinate systems — the space rectangular coordinate system, the geodetic coordinate system, the topocentric coordinate system, and the plane coordinate system. We then look at the World Geodetic System WGS72 and WGS84 and the International Terrestrial Reference Frames ITRF2000 and ITRF2005, which were introduced when space technology became available. The history of international geodetic coordinate systems in the Antarctic region is briefly reviewed and the development of the geodetic coordinate systems in the Chinese Great Wall Station and Zhongshan Station in Antarctica is outlined. Finally, the issue of coordinate system transformation is discussed.

Keywords Antarctic, coordinate system, ITRF, GPS

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0 Introduction

To accurately describe a location in space, a suitable coordinate reference system and coordinate system have to be defined. A coordinate system is a system that uses one or more numbers, or coordinates, to uniquely determine the position of a point or a geometric element^[1]. The main task of geodesy is to measure and map the surface of the earth. To denote, describe, and analyze the results of the measurements, a geodetic coordinate system has to be defined. There are two types of geodetic coordinate systems: The earth-centered coordinate system and the local coordinate system^[2].

In practice, a coordinate system alone cannot determine the location of a point: The coordinate system has to be used in conjunction with a predetermined datum to form a coordinate reference system. The location of the point can then be defined by this reference system. A geodetic datum is a reference from which measurements are made. Strictly speaking, the datum is not equivalent to the coordinate re-

ference system, but the relationship between the datum and the coordinate reference system is very close and in many cases there is no clear distinction between the two. The extent and connotation of the coordinate reference system is wider than that of the datum. Although the definition of the coordinate reference system is very clear and strict, it is abstract and difficult to use. The coordinate reference system needs to be applied through a concrete form before it can be widely used. In practice, the coordinate reference system is constructed through a reference frame, which is a group of points under a corresponding coordinate reference system. The International Terrestrial Reference System (ITRS) is the most accurate and stable earth-centered coordinate system and is constructed through the International Terrestrial Reference Frame (ITRF).

At present, the earth-centered coordinate system is widely used all over the world. The geodetic coordinate system in China developed from the ellipse-centered coordinate system to the earth-centered coordinate system. The first Chinese geodetic coordinate system in the 1950s was the Beijing Geodetic Coordinate System 1954 (BJS54), which was an extension of the Pulkovo Coordinate System 1942 of the former Soviet Union. In the 1980s, the BJS54

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was replaced by the Xi'an Geodetic Coordinate System 1980 and the new BJS54. On 1 July, 2008, the China Geodetic Coordinate System 2000 (CGCS2000) was adopted as the new national geodetic coordinate system to replace the old systems, and it is still in use today. CGCS2000 is geocentric, the center of mass being defined for the whole earth including the oceans and atmosphere^[3-4].

The Antarctic geodetic coordinate system was developed through a similar course. In the second half of the 20th century, some countries established their own coordinate systems in different regions of Antarctica. With the development of geodetic techniques, the Antarctic Coordinate System, a geocentric system that refers to the International Terrestrial Reference Frame (ITRF), was established.

1 General coordinate systems

1.1 The Cartesian coordinate system

The Cartesian coordinate system, also named the space rectangular coordinate system, is a system in which the location of a point is given by coordinates that represent its distances from perpendicular lines that intersect at a point called the origin. A Cartesian coordinate system in a three-dimensional (3D) space has three perpendicular axes, the X axis, Y axis, and Z axis. If the origin, orientations of the three axes, and scale are determined, the space rectangular coordinate system in the 3D space is defined. In applications of surveying and mapping, the origin is usually located at the center of the earth, the Z axis is identical to the reference pole and parallel to the earth's rotation axis, the X axis lies on the reference meridian, and the Y axis completes the right-handed coordinate system.

1.2 The geodetic system

The geodetic system is established based on the geodetic datum, also called the ellipsoidal coordinate system. The geodetic datum is a set of parameters that are used to define the reference ellipsoid of the Earth. The parameters include the size and shape of the ellipsoid, the orientation of the minor semi-axis of the ellipsoid, and the locations of the center of the ellipsoid and the prime meridian. The geodetic coordinates are described as the geodetic longitude (L), geodetic latitude (B), and geodetic height or ellipsoidal height (H). The geodetic longitude is the angle between the prime meridian and the meridian that passes through the point. The geodetic latitude is determined by the angle between the normal of the spheroid and the plane of the equator. The geodetic height is the distance from the point to the reference ellipsoid along the normal (Figure 1).

1.3 The topocentric coordinate system

The origin of the topocentric coordinate system is located at the observation site. It has two forms: the topocentric rectangular coordinate system and the topocentric polar coordinate system. It is usually described as point P (N , E , U). The origin is located at the observation site P; the U axis is

along the normal of the reference ellipsoid that passes through point P and points to the zenith. The N axis is perpendicular to the U axis and points to the semi-minor axis. The E axis is perpendicular to the U and N axes, and completes the left-handed coordinate system.

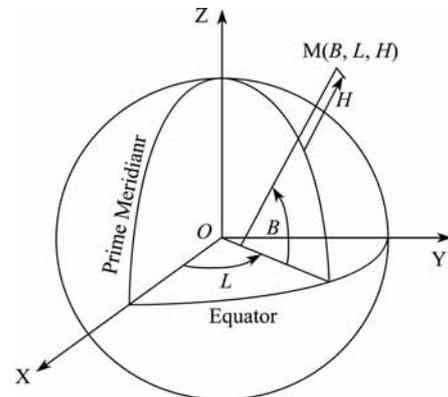


Figure 1 Definition of the geodetic system.

1.4 The plane coordinate system

The plane coordinate system is established by the projection of the geodetic coordinate system; it is also called the grid coordinate system. The projection is a mapping function between the spherical coordinates and the plane coordinates and can be described as follows:

$$\begin{cases} x = f_1(B, L) \\ y = f_2(B, L) \end{cases}$$

Where x and y are the coordinates of the plane coordinate system, B is the geodetic latitude, L is the geodetic longitude, and f_1 and f_2 are the mapping functions. The Transverse Mercator Projection and Gauss Projection are widely used in surveying and mapping because they retain shape similarity after the projection.

2 The international terrestrial reference systems and reference frames in Antarctica

2.1 The World Geodetic System 1972 (WGS72)

With the development of space technology the World Geodetic System was established by the United States Department of Defense as a geocentric coordinate system that answered the needs of global mapping. It has a series of versions including WGS60, WGS72, and WGS84. The origin of the WGS72 is located at the center of the earth, the Z axis is identical to the Conventional Terrestrial Pole (CTP), the X axis passes through the prime meridian, and the Y axis completes the right-handed coordinate system.

The geodetic parameters of the WGS72 are:

Semimajor axis of the ellipsoid: $a = 6\,378\,135$ m

Flattening of the ellipsoid: $f = 1/298.26$

Earth's gravitational constant:

$GM = 3.986\,008 \times 10^{14} \text{ m}^3 \cdot \text{s}^{-2}$

Angular velocity of the earth:

$$\omega = 7.292\ 115\ 147 \times 10^{-5} \text{ rad}\cdot\text{s}^{-1}$$

2.2 The World Geodetic System 1984 (WGS84)

The World Geodetic System 1984 (WGS84) is a reference system composed of a global geocentric reference frame, a series of models, and a relevant geoid. WGS84 was developed by the National Imagery and Mapping Agency in the middle of the 1980s, and replaced WGS72 in 1987. WGS84 is a conventional terrestrial reference system and right-handed coordinate frame; it is defined as follows (Figure 2):

(1) The origin is located in the center of mass of the Earth.

(2) The Z axis is identical to the reference pole defined by the International Earth Rotation Service (IERS) and is associated with the conventional pole of the Bureau International de l'Heure (BIH) in the 1984.0 epoch.

(3) The X axis lies in the IERS reference meridian (IRM).

(4) The Y axis completes the right-handed Earth-centered and Earth-fixed orthogonal coordinate system.

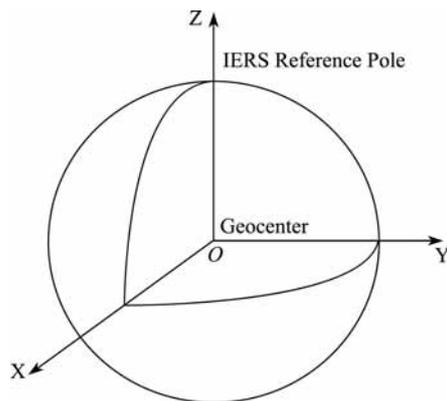


Figure 2 Definition of WGS84.

The ellipsoidal parameters of WGS84 are as follows:

Semimajor axis of the ellipsoid: $a = 6\ 378\ 137\ \text{m}$

Flattening of the ellipsoid: $f = 1/298.257\ 223\ 563$

Earth's gravitational constant:

$$GM = 3.986\ 004\ 418 \times 10^{14} \text{ m}^3\cdot\text{s}^{-2}$$

Angular velocity of the earth:

$$\omega = 7.292\ 115 \times 10^{-5} \text{ rad}\cdot\text{s}^{-1}$$

2.3 ITRF2000 and ITRF2005

The International Terrestrial Reference Frame (ITRF), a realization of the International Terrestrial Reference System (ITRS) includes the positions and velocities for a set of global tracking sites. The coordinates and velocities of these sites are derived from space geodetic techniques such as Very Long Baseline Interferometry (VLBI), Lunar Laser Ranging (LLR), Satellite Laser Ranging (SLR), the Doppler Orbitography and Radio positioning Integrated by Satellite (DORIS), and GPS. ITRF is established and maintained by the IERS. Since 1988, IERS has published ITRF88, ITRF89, ITRF90, ITRF91, ITRF92, ITRF93, ITRF94, ITRF96, ITRF97, ITRF2000 and ITRF2005. ITRF2000 and ITRF2005 have been widely used over the last ten years.

ITRF2000 is defined as follows^[5].

(1) Origin: The ITRF2000 origin is defined by the earth's center of mass sensed by Satellite Laser Ranging (SLR).

(2) Scale: The ITRF2000 scale and scale rate are defined by a combination of Very Long Baseline Interferometry (VLBI) and Satellite Laser Ranging (SLR) estimates.

(3) Orientation: The ITRF orientation and its drift are defined by alignment with historical earth orientation measurements and the condition of no net drift with respect to the plate motion model NNR-NUVEL1A.

ITRF2005 is the updated version of ITRF2000; the stations used for the TRF computation are shown in Figure 3. ITRF2005 is defined as follows^[6-7].

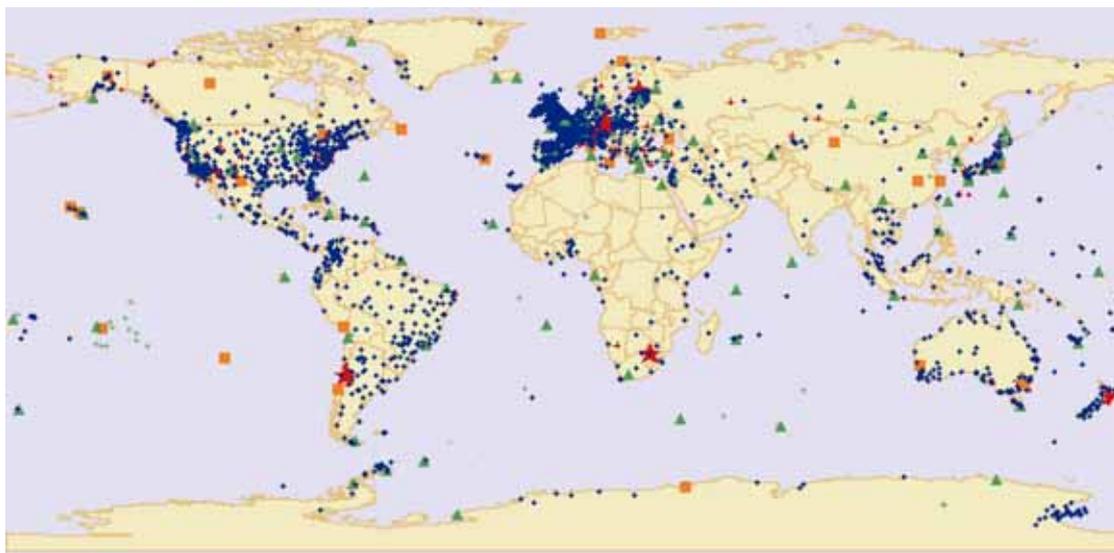


Figure 3 The global geodetic stations map of ITRF2005.

(1) Origin: The ITRF2005 origin is defined in such a way that there are null translation parameters at epoch 2 000.0 and null translation rates between the ITRF2005 and the ILRS SLR time series.

(2) Scale: The ITRF2005 scale is defined in such a way that there is a null scale factor at epoch 2 000.0 and a null scale rate between the ITRF2005 and the IVS VLBI time series.

(3) Orientation: The ITRF2005 orientation is defined in such a way that there are null rotation parameters at epoch 2 000.0 and null rotation rates between the ITRF2005 and ITRF2000.

3 The geodetic coordinate system in Antarctica

3.1 International geodetic coordinate systems in Antarctica

The coordinate systems in Antarctica were established by different countries and were locally based rather than having one coordinate system for the whole continent. Because several countries carried out expeditions in the same area, one region could have different coordinate systems. These coordinate systems were based on arbitrary reference ellipsoids according to the needs of each expedition^[8-9]. Therefore, in the gazetteer and map database of the Scientific Committee on Antarctic Research (SCAR), some features are defined by different coordinates. Antarctic geoscience scientists needed to establish a united geodetic coordinate system for the whole continent.

In the 1970s, the Antarctic coordinate systems were mainly established by using satellite Doppler techniques. In 1976, SCAR tried to unify the Antarctic coordinate systems, but due to logistic limitations, the plan was not successful. In the late 1980s, with the development of GPS, the Antarctic coordinate systems were unified into the global reference frame and the WGS84 was adopted universally. In 1990, the GPS technique was first applied in Antarctica during the SCAR90 Program. In 1991, the SCAR91 Program continued the GPS Campaign. In 1994, the Geoscience Standing Scientific Group (GSSG) of SCAR initiated the SCAR Epoch GPS Campaigns. Due to the particular circumstances of Antarctica and because of logistical needs, the observation period of the GPS Campaigns had to be scheduled for the Austral summer season. It was decided to define a core observation period of three weeks between January 20 and February 10 every year. The GPS Campaign has been ongoing since 1994 with more than 30 stations participating in the campaign. So far, 11 Antarctic GPS stations have been established as IGS permanent stations and have made contributions to the ITRF series: PALM, OHI2, OHI3, ROTH, VESL, SYOG, MAW1, DAV1, CAS1, DUM1 and MCM4^[10-12].

3.2 The coordinate system in Great Wall Station

China carried out its first Antarctic expedition during the

1984/1985 austral summer and set up Great Wall Station in the Fildes Peninsula, King George Island, West Antarctica. Surveying was carried out primarily to support the establishment of Great Wall Station^[13]. The Doppler satellite positioning technique was used to establish a geodetic coordinate system at Great Wall Station and provide the geocentric coordinates in WGS72. The coordinates of Great Wall Station were established as: $X=1\ 536\ 848.80 \pm 1.63$ m, $Y=-2\ 554\ 169.62 \pm 0.86$ m, $Z=-5\ 619\ 835.53 \pm 0.53$ m. The mean square position error of this station was within ± 1.9 m.

A local height system was established at Great Wall Station. The datum was the mean sea level determined by direct reading of a tide staff during a period of a little over one month. Several bench marks were laid; these bench marks were connected by geometric leveling and served as height control points for various construction surveys and topographic leveling. Gravity connection observations were made along the route of the Ushuaia–Great Wall Station–Punta Arenas by using relative gravimeters ZF-I and ZF-II on the voyage from Tierra del Fuego in South America to King George Island and back. The gravity value of Great Wall Station was 982 208.83 mgal. An azimuth determination from the astronomic station to an azimuth station was made by two methods: gyro-bearing and astronomic observation. The gyro systems JT15 and WILD GK1 were used for gyro-bearing. The plane coordinates for the topographic mapping were obtained by converting the geocentric coordinates of the Doppler station by using the Gauss Kruger projection. The distance and azimuth of the geodetic route of the communication between Beijing and Great Wall Station was calculated. After two years of continuous measurement, the geodetic reference system was established at Great Wall Station, including a geodetic coordinate system, a height system and a gravity system^[14-15].

In 1995, Great Wall Station was involved in the SCAR Epoch GPS Campaigns and the WGS84 coordinate system was applied to the surveying and mapping at Great Wall Station. In 2009, the GPS site at Great Wall Station was updated to a continuous GPS site.

3.3 The coordinate system in Zhongshan Station

During the 1988/1989 austral summer, China carried out the first expedition in eastern Antarctica and established Zhongshan Station in the Larsemann Hills. The coordinate system of Zhongshan Station was determined by satellite Doppler technique and WGS72 was adopted. The coordinates of the geodetic origin of Zhongshan Station were measured as follows: (1) the location of the geodetic origin was determined by satellite Doppler technique; (2) the coordinates of the geodetic origin were calculated using a traverse survey. The coordinates of the geodetic origin of Zhongshan Station are as follows: $B=69^{\circ}22'28.345''$, $L=76^{\circ}22'22.434''$. The plane coordinates for the topographic mapping were obtained by the Gauss Kruger projection. The height system was established from tide gauge meas-

urements and the heights of the control points were obtained by leveling surveying^[16]. After four years of continuous measurements beginning in 1988, the geodetic control network in the Larsemann Hills was completed. In 1997, Zhongshan Station took part in the SCAR Epoch GPS Campaigns and WGS84 was applied in the surveying and mapping^[17].

4 The coordinate transformation

Various transformations between the different coordinate systems are useful in geodesy and other fields. The Cartesian coordinate system (X, Y, Z) can be transformed into the geodetic system (B, L, H) or into the topocentric coordinate system (N, E, U); the geodetic system (B, L) can be transformed into the plane coordinate system (x, y), and vice versa^[1,18-19].

The different reference systems can be transformed using the Seven Parameters method. There are two common models, the Bursa model and the Molodensky model. The 7 parameters include 3 rotation parameters, 3 translation parameters and 1 scale parameter. Theoretically, the transformation results of the Bursa and Molodensky models are the same. In fact, there is a small difference in the transformation results between the two models. The Bursa model is usually used in global datum transformations or in transformations of large areas.

The different ITRF frames can also be transformed. The IERS published the transformation parameters between ITRF2005 and ITRF2000, between ITRF2000 and former ITRF versions, and between ITRF and WGS84. After the 7 parameter transformation, the difference between WGS84 (G730) and ITRF92 is within 10 cm, WGS84 (1150) is identical to ITRF2000 within 1 cm. If the measurement adopts broadcast ephemeris, the results belong to WGS84, if the measurement adopts precise ephemeris, the results belong to ITRF. With the development of the analysis method and data processing technique of the IERS analysis center, the difference between the later ITRF versions are at mm level. ITRF2005 thus substituted ITRF2000 and was widely used in the geodetic studies.

When Great Wall and Zhongshan Stations were set up in the 1980s, Chinese surveyors used WGS72. Based on WGS72, multi-scale maps were made in the two stations and other Chinese Antarctic expedition areas. Because of the limitation of the satellite Doppler technique, the accuracies of the control points were at decimeter or meter level. During that period, the geodetic coordinate systems based on WGS72 provided the support to the basic surveying and mapping. More than 300 Chinese Antarctic place names were created, establishing the Chinese presence in the Antarctic region.

In the 1990s, the GPS technique was widely used in Antarctica and the geodetic coordinate systems of Great Wall and Zhongshan stations were transited to WGS84. Permanent GPS sites were established in both Great Wall and Zhongshan stations and precise coordinates of these

two sites within the ITRF frame were obtained. The geodetic control networks of the two stations were measured again using GPS, which resulted in an improvement in the accuracies of the control points to cm level; the multi-scale maps were updated accordingly.

5 Conclusions and discussions

With the development of space geodesy, GPS stations, absolute gravity stations, and tide gauges were established in both Great Wall and Zhongshan stations. The Chinese Antarctic geodetic system changed from a 2D coordinate system to a 3D coordinate system and from a topocentric coordinate system to a geocentric coordinate system. In 2009, the third Chinese Antarctic station Kunlun Station was set up at Dome A, the summit of the Antarctic ice sheet and a GPS site was established there. Kunlun Station is the first Chinese Antarctic inland ice sheet station, thus extending the scope of Chinese Antarctic expeditions from coastal areas to the inland ice sheet. Chinese geodesists are planning to unify the geodetic coordinate systems of Great Wall, Zhongshan, and Kunlun stations, and establish a geodetic link between the Chinese Antarctic coordinate systems and the ITRF. The main tasks of the Chinese Antarctic geodesists is to maintain the stability and continuity of the Chinese Antarctic geodetic coordinate system while contributing to scientific advancement in the field including the new version of ITRF that IERS will be publishing in the near future.

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References

- 1 Li Z H, Huang J S. GPS surveying and data processing. Wuhan: Wuhan University Press, 2005.
- 2 Yang Y X. Main progress of geodetic coordinate system in China. *Bulletin of Surveying and Mapping*, 2005, (1): 6–9.
- 3 Wei Z Q. Proposal concerning China geodetic coordinate system 2000. *Journal of Geodesy and Geodynamics*, 2006, 26(2): 1–4.
- 4 Gu D S, Zhang L, Cheng P F, et al. Objectives of the geodetic datum in China. *Bulletin of Surveying and Mapping*, 2003, (3): 1–4.
- 5 Chen J Y. On the definition and adopted parameters of international terrestrial reference frame 2000. *Editorial Board of Geomatics and Information Science of Wuhan University*, 2005, 30(9): 753–756.
- 6 Zhu W Y, Xiong F W, Song S L. Introduction and elevation of the International Terrestrial Reference Frame 2005. *Progress in Astronomy*, 2008, 26(1): 1–14.
- 7 International Terrestrial Reference Frame. <http://itrf.ensg.ign.fr/>.
- 8 E D C, Zhang S K. Infrastructure and progress of international Antarctic geodetic reference framework. *Journal of Geodesy and Geodynamics*,

- 2006, 26(2): 104–108.
- 9 Manning J. SCAR Geodesy in Antarctica. Antarctic Geodesy Symposium (AGS'01) report, 2001.
- 10 E D C, Zhang S K, Zhou C X. Ten-year progress of Chinese polar geodesy: 1996-2006. *Advances in Earth Science*, 2007, 22(8): 784–790.
- 11 Dietrich R, Dach R, Engelhardt G, et al. ITRF coordinates and plate velocities from repeated GPS campaigns in Antarctica-an analysis based on different individual solutions. *Journal of Geodesy*, 2001, 74(11-12): 756–766.
- 12 National Aeronautics and Space Administration (NASA). International GNSS Service—Formerly the International GPS Service. <http://igscb.jpl.nasa.gov>.
- 13 E D C, Liu Y N, Guo X G. Surveying in Antarctica. *Acta Geodaetica et Cartographica Sinica*, 1985, 14(4): 305–314.
- 14 Xu S Q. Establishment of the surveying system in the Chinese Great Wall Station Area, Antarctica. *Chinese Journal of Polar Research*, 1989, 1(4): 57–64.
- 15 Xu S Q, Wang S D. Precise leveling in the Chinese Great Wall Station Area, Antarctica. *Science and Technology of Wu Ce*, 1988, 1: 31–33 (in Chinese).
- 16 Chen C M, E D C, Xu S Q. Establishment and Surveying of the Surveying Coordinate System in the Chinese Zhongshan Station//E D C. Study of the Antarctic modern crustal movement and mapping by remote sensing. Wuhan: Wuhan Technical University of Surveying and Mapping, 1996, 196–203.
- 17 Chen C M, E D C, Sang J Z. Geodetic network at Larsemann Hills, Antarctica. *Antarctic Research*, 1995, 7(3): 95–100.
- 18 Zhu H T. Common Geodetic Coordinate Systems and their Conversion. PLA Press, 1990 (in Chinese).
- 19 Bian S F, Chai H Z, Jin J H. Geodetic Coordinate System and Geodetic Datum. National Defense Industry, 2005 (in Chinese).