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Current status and future prospects for the Antarctic geodetic datum construction

WANG Zemin[1,2], ZHANG Xiaohong[1,2*], ZHANG Baojun[1,2], ZHANG Shengkai[1,2], YANG Yuande[1,2] & KE Hao[1,2]

[1] Chinese Antarctic Center of Surveying and Mapping, Wuhan University, Wuhan 430079, China;
[2] Key Laboratory of Polar Environment Monitoring and Public Governance (Wuhan University), Ministry of Education, Wuhan 430079, China

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Abstract The Antarctic geodetic datum constitutes a specialized implementation of the modern geodetic reference system within the extreme polar environment. A high-precision, unified, and dynamic Antarctic geodetic datum serves as critical infrastructure for polar scientific research and engineering safety. This study reviews the composition, current status, and implementation pathways of the Antarctic geodetic datum through four dimensions: coordinate datum, height datum, gravity datum and sounding datum. Preliminary analysis reveals that the development of the Antarctic geodetic datum framework is severely lagging, thereby failing to meet the demands of both scientific expeditions and polar research. To address these challenges, this study proposes an implementation pathway leveraging the 5th International Polar Year (IPY-5) to pioneer regional high-precision geodetic datum in the China's key research sector covering the area between Amery Ice Shelf and Princess Elizabeth Land, specially highlighting the Prydz Bay–Amery Ice Shelf–Lambert Glacier–Dome A (PANDA) transect, by deploying multi-technique stations and μGal-level superconducting gravimeter networks; and then to integrate multinational observation resources to ultimately establish a high-precision, unified, and dynamic geodetic datum framework. This framework will deliver a spatiotemporal infrastructure for Antarctica to advance the strategic goals of "understanding, protecting, and utilizing Antarctica".

Keywords Antarctica, coordinate datum, elevation datum, gravity datum, depth datum, IPY-5

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1 Significance of the Antarctic geodetic datum

Geodetic datum consists of geodetic reference system and reference frame, which is a global or regional unified metric system established for determining geometric and physical geodetic parameters such as coordinates, gravity and elevation of geospatial points (Dang et al., 2015; Drewes, 2008; Yang and Ming, 2023). Geodetic datum can be classified into coordinate datum, height datum, gravity datum, and sounding datum according to their functions. By integrating multi-source geodetic data (e.g., space geodesy, Global Navigation Satellite System (GNSS)) and geoscientific observations, modern geodetic datums achieve high precision, stability, and sustainability. These unified frameworks deliver consistent geodetic products critical for socioeconomic development, national defense, disaster prevention and mitigation, global change monitoring, and geoscientific research (Avtar et al., 2019; Chuvieco et al., 2010; Otsubo et al., 2016; Sousa et al., 2021).

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[*] Corresponding author. ORCID: 0000-0002-2763-2548. E-mail: xhzhang@sgg.whu.edu.cn

Antarctica, as the most pristine, coldest, and most isolated continent on Earth, serves as a critical region for Earth system science research. Its unique geographical location and extreme environment provide irreplaceable scientific value for revealing the operational laws of Earth's systems and predicting climate change. Establishing a high-precision, unified Antarctic geodetic datum is an essential requirement for scientific research and engineering practices in Antarctica. Specifically:

(1) The establishment of a unified Antarctic geodetic datum can foster multinational scientific cooperation and ensures harmonized data for global research initiatives. A unified Antarctic geodetic datum can eliminate errors caused by disparate reference systems, resolve data inconsistencies resulting from national, regional, or temporal variations in benchmarks, and be in line with the data sharing principle of the Antarctic Treaty.

(2) The current Antarctic height datum cannot satisfy the high-precision monitoring of Antarctic sea level rise, glacier movement and crustal deformation, nor can it satisfy the construction of high-precision Glacial Isostatic Adjustment (GIA) model and ice-cap numerical model, and studies on ice-rock-ocean coupled dynamics.

(3) A stable, high-precision, maintainable geodetic datum guarantees the temporal comparability of monitoring data across different epochs. This continuity is vital for accurately quantifying environmental changes (e.g., ice-mass loss) and validating climate projections.

(4) With the rapid development of geodetic technology (e.g., GNSS, Gravity Recovery and Climate Experiment (GRACE)) and remote sensing, traditional geodetic datums cannot be able to meet the increasing requirements of modern technology on the accuracy and dynamics of datums. It is necessary to establish polar geodetic datums adapted to the new technology in order to give full play to the advantages of the new technology, enhance dynamic monitoring capabilities and optimize data acquisition efficiency.

Therefore, the Antarctic geodetic datum serves as critical infrastructure for resolving polar data fragmentation, enabling in-depth scientific research, and ultimately enhancing global climate change monitoring and prediction capabilities.

2 Composition of the Antarctic geodetic datum system

The Antarctic geodetic datum, an extension of the modern geodetic datum system to the Antarctic region, is essentially a concrete realization of the modern geodetic datum in the special geographic environment of the Antarctic. The Antarctic geodetic datum system comprises four core components aligned with its functional requirements, such as coordinate datum, height datum, gravity datum, and sounding datum.

2.1 Coordinate datum

Modern coordinate datum theory is fundamentally constructed upon two core components: coordinate reference system and coordinate reference framework. Coordinate reference system defines the foundational geodetic parameters for coordinate computation, including origin orientation, scale, theoretical principles, mathematical models, and implementation methodologies. Coordinate reference framework serves as the physical realization of coordinate reference system, constituted by a network of geodetic stations with precisely determined coordinates and temporal evolution parameters (e.g., station velocity fields for crustal deformation) (Janssen, 2009; Jiang et al., 2022).

Coordinate reference framework can be categorized into long-term coordinate reference frame typically represented by station coordinates and velocities of geodetic stations at a reference epoch, and epoch coordinate reference frame defined by time series of station coordinates from continuous geodetic observations. The long-term reference frame is represented by the International Terrestrial Reference Frame (ITRF) established by the International Earth Rotation and Reference Systems Service. Its latest version, ITRF2020, was established by integrating four major technologies, namely, Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), GNSS, and Doppler Radio-Orbiting and Positioning System (DORIS). The spatial distribution of observation sites for these four technologies it adopts is illustrated in Figure 1, while the input data specifications for these stations are detailed in Table 1 (Altamimi et al., 2023; Rebischung et al., 2024). As the internationally recognized highest-precision and most stable global terrestrial reference framework, ITRF2020 provides a high-accuracy ground coordinate reference benchmark for geodetic observations, a globally unified basis for geodetic observation and Earth parameter estimation, and a high-precision, globally unified, and long-term stable coordinate reference for accurate monitoring of global change

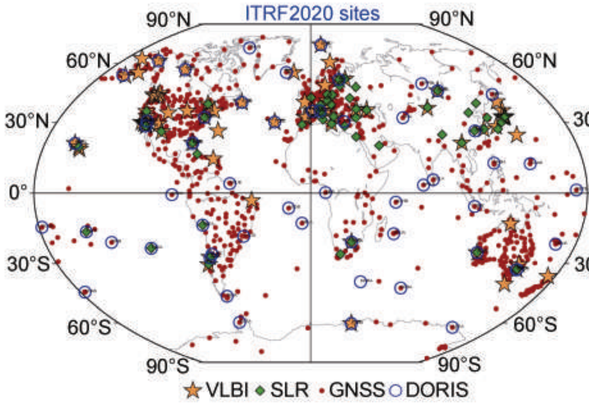

Figure 1 ITRF2020 network highlighting VLBI, SLR, and DORIS sites co-located with GNSS (Altamimi et al., 2023).

Table 1 ITRF2020 input data for each technology (Altamimi et al., 2022)

Technique center	Number of solutions	Time span	Number of stations	Theoretical frame origin
IDS/DORIS	1,456 weekly	1993.0–2021.0	87	Center of mass
IGS/GNSS/GPS	9,861 daily	1994.0–2021.0	1159	Center of network
ILRS/SLR	244 fortnightly 1,459 weekly	1983.0–1993.0 1993.0–2021.0	100	Center of mass
IVS/VLBI	6,178 session-wise	1980.0–2021.0	117	Center of network

phenomena as well as for precise positioning applications (Ming et al., 2023; Rebischung et al., 2024).

Coordinates obtained from GNSS observations in Antarctica are typically referenced to the WGS-84 (World Geodetic System 1984). However, the accuracy of coordinates in the WGS-84 is relatively low. For scientific research and crustal deformation monitoring, conversion to ITRF-based coordinates is essential to eliminate systematic errors and achieve high-precision results. Geodetic stations with ITRF2020 framework coordinates (and their temporal variations) constitute the realization of ITRF2020 coordinate reference in Antarctica. Through coordinate transformation parameters, ITRF2020 coordinates can be converted to other global or regional datums.

2.2 Height datum

Height datum serves as the reference benchmark for measuring the elevation of terrestrial points, defining the "zero elevation" reference. It establishes a terrestrial height datum through specific reference surfaces, such as the geoid or mean sea level (MSL), providing a unified elevation standard for topographic surveys, engineering construction, and scientific research (Ihde et al., 2017; Sánchez et al., 2016). The height datum surface typically adopts either geoid or MSL. Geoid is the gravity equipotential surface closest to the global MSL.

Regional height datum refers to a height reference system established using local MSL derived from tide gauge observations at one or multiple coastal stations over a specific period (Dang et al., 2022; Janssen, 2009; Li et al., 2017). The traditional height datum is realized by a level origin and a height control network, propagating elevation via precise leveling lines constrained to limited geographical coverage. Because they are based on local MSL from tide gauges and leveling networks covering local areas, these reference systems are referred to as regional height datum. A global height reference system established using the geoid as the height datum is called a global height datum. It can be realized by integrating multi-source gravity data (satellite, airborne, and terrestrial) to compute an ultra-high-degree gravity field model and derive a global geoid model that establishes explicit geometric-gravimetric relationships between Earth's geometric shape and its gravity field potential (Čunderlík, 2015; Xu, 2017).

Establishing a high-accuracy MSL in Antarctica is challenged by the scarcity of tide gauge stations and limited long-term observational records. Historically, some research stations derived regionally approximate MSL from local tide gauge data and established regional height datums covering only the station vicinity through leveling-based height control networks (Xu, 1989). However, the Antarctic Ice Sheet's extensive ice cover prevents large-scale deployment of leveling networks, making it impossible to extend tide gauge-based regional datums inland. Therefore, establishing the Antarctic geoid model is the only viable approach to realize a unified vertical datum across Antarctica.

2.3 Gravity datum

Gravity datum serves as the foundational standard for calibrating (absolute) gravity values within a nation or region, forming the basis for gravity control surveys (Wziontek et al., 2021). Historically, three international gravity datums have been established: Vienna Gravity System (1900), Potsdam Gravity System (1909), and International Gravity Standardization Net 1971 (IGSN71). Currently, International Association of Geodesy (IAG) is advancing the International Terrestrial Gravity Reference System/Frame (ITGRS/ITGRF) initiative to establish a next-generation global datum (Wilmes et al., 2018; Wziontek et al., 2021). Gravity datum can be realized by terrestrial fundamental gravity network. A terrestrial fundamental gravity network is a precisely measured control framework comprising absolute and relative gravimetry points that operationalize a gravity datum by providing reference origins for regional surveys and calibration benchmarks for gravimeters. Antarctic gravity reference frameworks rely on hybrid measurements. Absolute gravimetry establishes primary datum points. Relative gravimetry surveys extend coverage through interconnected networks.

2.4 Sounding datum

Sounding datum serves as a reference plane for measuring ocean depth and tidal height. It is typically defined as a specific low-tide surface below MSL, ensuring vessels have sufficient navigable depth during low tide for safe passage. Common marine sounding datums include the theoretical minimum low tide, mean low water, and mean low water springs (Sjöberg, 2011). The determination of the sounding datum relies on long-term water-level observations from tide gauge stations. However, the spatially isolated distribution of these stations results in step-like discontinuity boundaries within the depth datum across adjacent coastal zones.

Establishing a sounding datum requires synthesizing ocean dynamic characteristics, tidal patterns, and surveying standards through multi-source data fusion and model iteration. For example, the theoretical minimum low tide can be derived via tidal harmonic analysis, integrating long-term tide gauge observations with celestial gravitational models; mean low water can be calculated as the arithmetic mean of all low-tide levels based on $\geqslant$19 a of continuous tidal data and achieved spatial extrapolation between sparse gauges through techniques like Radial Basis Function networks; mean low water springs focuses on syzygy spring tide extremes, with low-tide sequences within spring tidal cycles extracted using sliding window method and noise from short-term atmospheric disturbances eliminated using gaussian filtering (Bao et al., 2009; Shi and Myers, 2016).

3 Status of Antarctic geodetic datum construction

3.1 Coordinate datum

The distribution of observational stations contributing input data to ITRF2020 exhibits significant global inhomogeneity, with particularly sparse coverage across Antarctica (Figure 2). Antarctica hosts only 16 continuously operating GNSS stations (merely 1.3% of global), with the continental interior ice sheets remaining virtually unmonitored. Zero VLBI coverage beyond Syowa VLBI was achieved, and no SLR was adopted.

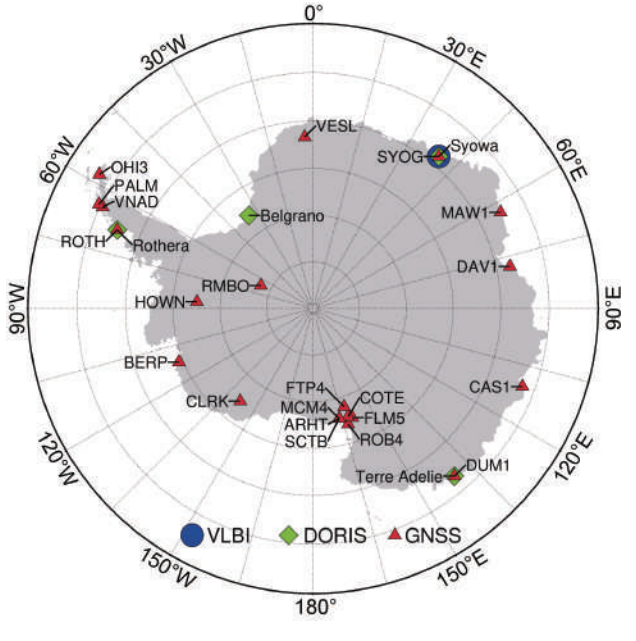

Figure 2 Sites used in the estimation of ITRF2020 across Antarctica.

The quantity and distribution of multi-technique co-located sites, along with the observational quality of local ties, significantly impact the effectiveness of inter-technique combination. Precise three-dimensional coordinate differences between co-located stations are typically incorporated as inter-technique constraints into observation equations to establish linkages across techniques. Although ITRF2020 enhanced framework stability by optimizing coordinate differences from 172 global co-located sites, Antarctica possesses only three available co-location sites. The scarcity of Antarctic co-located stations compromises local tie quality in this region, thereby limiting ITRF2020's precision. Theoretically, such errors propagate to station coordinates and may even distort the entire network geometry (Jiang et al., 2022).

Recent accelerated ice sheet melting and mass loss in Antarctica, driven by global warming, have established the region as Earth's most significant zone of surface mass redistribution. This mass redistribution has induced complex nonlinear crustal displacements, significantly impacting the nonlinear variations observed at Antarctic GNSS stations. Notably, the contributions to vertical nonlinear motions exhibit substantial regional heterogeneity across different stations (Pan et al., 2025). Antarctica's unique geographical environment and insufficient observational infrastructure have led to critical knowledge gaps of crustal density distribution and viscoelastic properties of the Earth's interior (Barletta et al., 2018; Nield et al., 2018; Scheinert et al., 2023). They compound the challenges in quantifying the contributions of nonlinear displacement of monument stations to the terrestrial reference frame. Critically, failure to account for nonlinear factors associated with geophysical processes—manifested as complex motions of monument stations—constitutes a primary obstacle preventing ITRF2020 from achieving millimeter-level precision.

The rapid mass loss of the Antarctic ice sheet inducing global mass redistribution, is significantly impacting Earth's geophysical dynamics. Polar ice mass variations have shifted geographic pole positions by ~3 m since 1900 (Göttl et al., 2021), and exerted millimeter-scale influences on both seasonal and long-term geocenter motions (Zhang and Sun, 2018). In addition, reduced moment of inertia due to ice sheet loss amplifies the deceleration of Earth's rotation (Agnew, 2024).

To achieve high-precision Antarctic coordinate datum realization and transfer, over 80 GNSS sites have been established across Antarctica (including Polar Earth Observing Network (POLENET), International GNSS Service (IGS), and other networks). Notably, China has deployed BeiDou-3 system-based continuous operation stations at Great Wall Station and Zhongshan Station, achieving autonomous positioning with horizontal accuracy of 1 cm (Zhao et al., 2022). Nevertheless, relative to the vast Antarctic continent, density of GNSS sites remains critically low, particularly in the interior ice sheet regions. This scarcity forces Antarctic expeditions to predominantly rely on GNSS devices outputting coordinates in the WGS-84 frame through single-point positioning (SPP) or standard positioning service (SPS), yielding meter-level accuracy for ground, marine, and aerial observations (Bouzinac, 2014; Frémand et al., 2023; Smith et al., 2020).

Satellite remote sensing observation data are also derived from coordinates in the WGS-84 coordinate system based on precise orbit determination data, with typical accuracy better than decimeter level. Such limitations introduce systematic biases between datasets acquired by different teams or distinct time periods, thereby compromising the reliability assessment of observational data, the effectiveness of multi-source platform data fusion, and the accuracy of critical parameter retrievals through cascading error amplification—exemplified by ice velocity and mass balance estimations. Ultimately, this may lead to systematic distortion of scientific understanding and risks in engineering safety decisions. A representative case is the >10-m coordinate deviations between multi-epoch mapping products in Grove Mountains region, where GNSS SPP was adopted as the initial reference. These inconsistencies severely hinder precise integration and mosaicking of geospatial products.

3.2 Height datum

To support the construction of research stations and facilitate scientific expeditions, temporary local height datums have been established at several Antarctic stations based on tidal observations. For instance, China's Zhongshan Station deployed the first permanent tide gauge in Antarctica, integrating GNSS and leveling observations to establish a regional height datum (E et al., 2013; Huang et al., 2012). The vertical deviation between the Zhongshan Station height datum and the global geodetic reference is −1.455 m, and its deviation from the Chinese National 1985 Height Datum is −1.759 m (Zhang et al., 2021). This provides a precise global-scale elevation reference for Antarctic geospatial information. Since the 39th Chinese National Antarctic Research Expedition, China's newly established year-round Qinling Station in the Pacific sector has deployed multi-source observation equipment (e.g., GNSS, tide gauges), aiming to establish a regional height datum. However, most Antarctic mapping activities currently rely solely on WGS-84 ellipsoidal heights due to the absence of a unified physical height system. Ellipsoidal heights represent geometric elevations relative to a reference ellipsoid, lacking physical meaning. The geoid undulation (i.e., the separation between the ellipsoid and geoid, as shown in Figure 3) causes negative ellipsoidal heights in some areas above sea level. When ellipsoidal heights are misinterpreted as orthometric heights in mapping, errors ranging from −66 m to +45 m are introduced. Figure 3 reveals a geoid undulation of approximately −60 m at Qinling Station. For its an actual orthometric height of ~10 m, ellipsoidal height at Qinling Station is about −50 m. This counterintuitive result (where a station above sea level exhibits a negative "elevation") conflicts with public perception and may lead to erroneous scientific interpretations.

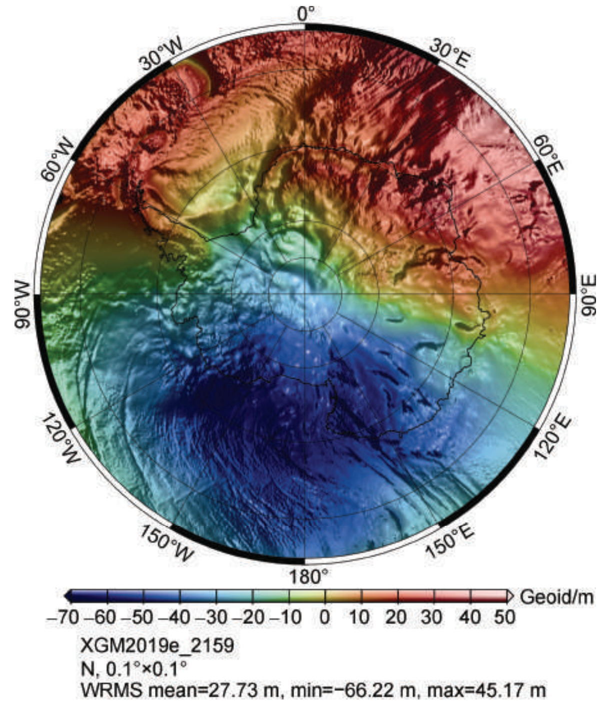

Figure 3 Grid calculation results for geoid of XGM2019e_2159 (Zingerle et al., 2020) from Calculation Service of International Centre for Global Earth Models at https://icgem.gfz-potsdam.de/.

The vast ice coverage across Antarctica renders large-scale height datum transfer via conventional leveling unfeasible, with only a dozen tide gauge stations currently operational on the continent—including China's installations at Great Wall, Zhongshan, and Qinling stations (Figure 4). These stations establish independent local height datums referenced to localized MSLs derived from short-term tidal observations, yet such fragmentation causes height datum discrepancies across research bases and renders observational data incompatible for fusion. That is, for an ice sheet exceeding 14 million km², the scarcity of tide gauges and isolated datums not only fails to meet high-precision elevation benchmarks for polar operations but also prevents continent-scale unification of the Antarctic height datum.

The establishment of digital height datums in Antarctica primarily relies on deriving gravity (quasi-)geoid models from ultra-high-degree gravity field models. These ultra-high-degree models are synthesized from multi-source datasets including satellite gravimetry, airborne gravity, shipborne gravity, terrestrial gravity, satellite altimetry, and topographic data. At present, the main international ultra-high-order gravity field models include EGM2008 (Pavlis et al., 2012), EIGEN-6C4 (Frste et al., 2014), SGG-UGM-2 (Liang et al., 2020), and XGM2019e_2159. Ultra-high-degree models exhibit distinct wavelength dependencies: satellite gravimetry primarily resolves long-wavelength signals (>400 km), surface gravity data reconstruct medium-to-short wavelengths (20–400 km), and

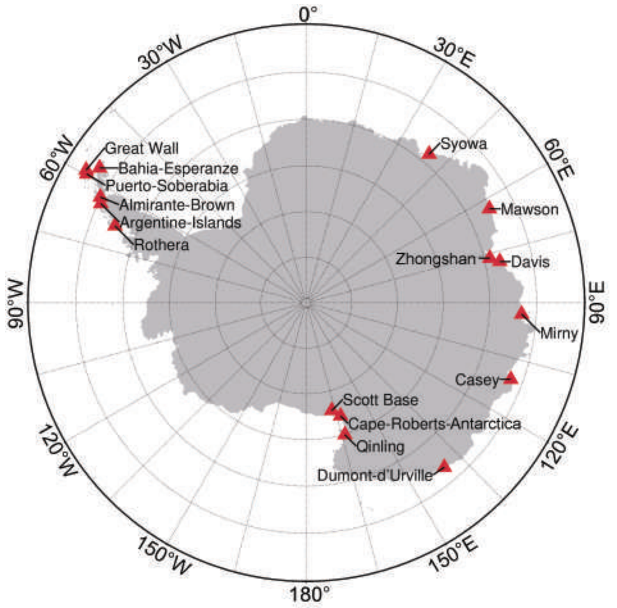

Figure 4 Distribution of Antarctic tide gauge stations.

topographic data constrain ultra-short wavelengths (<20 km). Airborne gravity surveys serve as the dominant source of terrestrial gravity data in Antarctica. International initiatives have acquired extensive airborne gravity coverage (Figure 5), with China's 2015–2019 campaigns specifically bridging critical data gaps in Princess Elizabeth Land, East Antarctica. However, significant limitations persist in contemporary Antarctic geoid modeling. Early global gravity field models such as EGM2008 and EIGEN-6C4 exclusively utilized satellite gravimetry over Antarctica, yielding geoid accuracies exceeding 1 m due to the absence of terrestrial gravity constraints (Frste et al., 2014; Pavlis et al., 2012). Subsequent models including XGM2019e incorporated airborne gravity data, yet achieved only 4-km spatial resolution with vertical errors of over tens of centimeters, constrained by sparse historical airborne surveys and suboptimal data quality (Zingerle et al., 2020). Compounding these deficiencies, accelerating ice mass loss under global warming induces dynamic geoid changes. The average geoid in Antarctic subsidence is at several millimeters per year, primarily driven by glacial isostatic adjustment and ice-mass redistribution estimated from GRACE/GRACE-Follow On (GRACE/GFO) satellite time-variable gravity with the methodology of Wahr et al. (1998). Consequently, static ultra-high-degree gravity field models cannot capture real-time height datum shifts, nor provide high-precision dynamic height datums.

Consequently, Antarctica lacks a universally recognized, unified, high-precision, and high-resolution height datum. Scientific datasets and products commonly used in the region employ heterogeneous reference frames. For example, Bedmap 2 and the newly released Bedmap 3 adopt the EIGEN-GL04C geoid (Fretwell et al., 2013; Pritchard et al., 2025); BedMachine utilizes the EIGEN-6C4 geoid (Morlighem et al., 2017); REMA and satellite altimetry products (e.g., CryoSat-2, ICESat, ICESat-2) are directly referenced to the ellipsoidal surface (Bouzinac, 2014; Howat et al., 2019; Smith et al., 2020). This inconsistency in height datums complicates multi-source data fusion. Unification of datums is prerequisite for integration, yet residual errors from disparate reference systems cannot be fully eliminated, introducing additional uncertainties. Furthermore, geodetic observations based on regional datums are confined to local applications. Merging results from different regions is infeasible, hindering their utility for monitoring global-scale processes, such as climate change dynamics, mass redistribution, sea-level variability, ocean circulation patterns and natural hazard assessments. Such fragmentation severely impedes global data interoperability and scientific advancement.

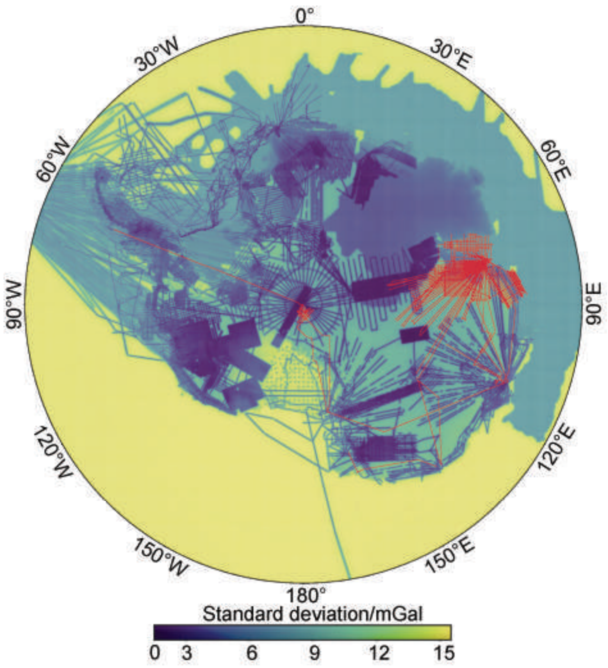

Figure 5 Distribution of Antarctic airborne gravity data. Standard deviation map of free-air gravity anomalies from AntGG2021 (Scheinert et al., 2024) is color coded from 1.5 mGal (blue) to +15.5 mGal (yellow). Standard deviations of 15 mGal indicates regions that are not covered by terrestrial gravity measurements (Charrassin et al., 2025). Red flight lines depict the ground tracks of airborne gravity surveys conducted by the Chinese National Antarctic Research Expedition during 2015–2019 (Cui et al., 2020a, 2020b; Frémand et al., 2023).

3.3 Gravity datum

As illustrated in Figure 6, the establishment of gravity reference frames via absolute gravity measurements across Antarctica has been predominantly confined to coastal regions (Fukuda et al., 2021; Kazama et al., 2013; Mäkinen et al., 2007; Yang and Li, 2022). China has progressively expanded these efforts to its research stations, filling critical

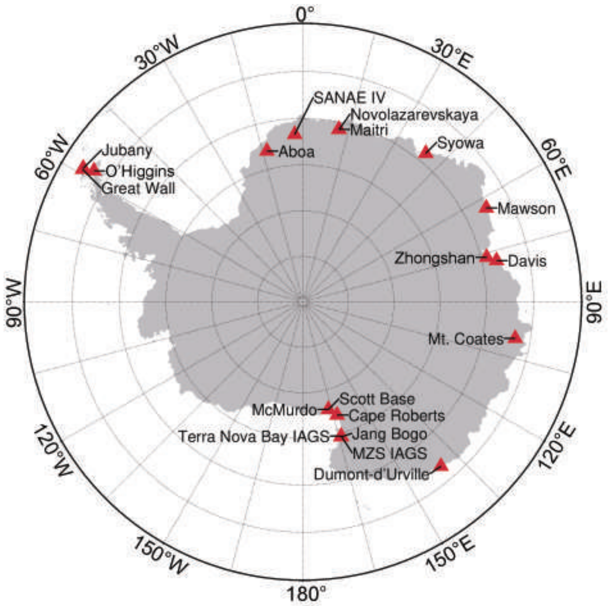

Figure 6 Distribution of Antarctic absolute gravity measurements.

gaps in the gravity datum framework. During the 21st Chinese National Antarctic Research Expedition (2005), the FG5 absolute gravimeter (Micro-g LaCoste FG5 Free-Fall Absolute Gravimeter) was deployed at Great Wall Station to conduct absolute gravity measurements (Zhang et al., 2007). The 25th Chinese National Antarctic Research Expedition (2009) utilized the portable A10 gravimeter (Micro-g LaCoste A10 Portable Absolute Gravimeter) for measurements at Zhongshan Station and the adjacent Larsemann Hills (E et al., 2011).

In a milestone achievement, the 36th Chinese National Antarctic Research Expedition (2020) employed China's domestically developed NIM-3C absolute gravimeter to perform absolute gravity observations at Zhongshan Station, sustaining continuous measurements for over 30 d (Su et al., 2021).

Domestically and internationally, continuous observations with stationary gravimeters, particularly superconducting gravimeters, have been deployed in Antarctica to monitor solid Earth geophysical parameters and variations in the Antarctic gravity datum. These efforts track gravity changes induced by glacial dynamics, environmental shifts, and solid Earth tides. Innovation Academy for Precision Measurement Science and Technology, Chinese Academy of Sciences, has conducted continuous gravity observations at Antarctica's Great Wall Station and Zhongshan Station over multiple years to study gravity tides and their variations (Liu et al., 2016, 2018; Xu et al., 2001). Germany's Alfred Wegener Institute (AWI) conducted a pioneering short-term deployment of the iGrav superconducting gravimeter at Neumayer Station III in 2015, validating instrument functionality at temperatures as low as −40 ℃ with a precision of 0.1 μGal. However, sustained operation was impeded by logistical barriers in liquid helium replenishment. Japan's National Institute of Polar Research attempted superconducting gravimeter-based monitoring of subglacial lake hydrodynamics in East Antarctica in 2018. This initiative recorded anomalous low-frequency noise attributable to critical current degradation in superconducting coils under persistent −30 ℃ conditions, which limited signal-to-noise ratios for lake-level inversion. China's recent procurement of an iGrav superconducting gravimeter by Wuhan University marks the advancement of long-term continuous gravity reference high-precision monitoring at Zhongshan Station in Antarctica.

Absolute gravity observations in Antarctica are predominantly concentrated in coastal regions, rendering them exceptionally sparse relative to the continent's vast area of 14 million km^2. Antarctic gravity observations face three critical constraints. The extreme Antarctic environment, with summer temperatures plunging below −40 ℃ in Antarctic interior zones, prohibits direct outdoor deployment of conventional gravimeters (e.g., FG5, A10) typically designed for room-temperature operation. Rapid mass depletion across the West Antarctic Ice Sheet drives gravity reductions exceeding $(-12.3\pm2.1)\ \mu\text{Gal}\cdot\text{a}^{-1}$ derived from GRACE/GFO satellite time-variable gravity with the methodology refers to Baur and Sneeuw (2011), primarily linked to accelerated glacial flow and oceanic forcing. Current surveys implement repeat measurements at intervals of multiple years, obscuring transient signals associated with subglacial hydrology or glacial isostatic adjustment. To maintain a high-precision gravity datum requires continuous monitoring its changes. Furthermore, the absence of long-term environmental monitoring—including air temperature, barometric pressure, and tidal variations—at gravity reference stations impedes accurate gravity reduction and subsequent geophysical interpretation.

3.4 Sounding datum

The establishment of a sounding datum for Antarctic marine areas remains largely uncharted territory. Currently, only Ke et al. (2020a, 2020b) from the Chinese Antarctic Center of Surveying and Mapping at Wuhan University have pioneered localized continuous sounding datum models near China's Great Wall and Zhongshan stations, leveraging long-term tide gauge data to define transformation relationships between sounding datums and reference ellipsoid. However, with intensifying polar research and burgeoning Antarctic tourism, diverse vessels—including research icebreakers, supply ships, cruise liners, and recreational yachts—now navigate Antarctic waters. Concurrently, coastal infrastructure projects (e.g., station piers, desalination plants) and subsea installations (e.g., seabed observatories, mooring systems) along Antarctica are burgeoning. Precise bathymetric mapping of Antarctic peripheral seas is imperative for these activities, and establishing a unified sounding datum has thus become an urgent geodetic imperative for the Antarctic region.

Significant challenges persist in establishing an Antarctic sounding datum. Firstly, sparse observational data and model uncertainties constrain sounding datum construction. At present, sounding datum remains largely undefined across Antarctic coastal zones due to severe scarcity of tide gauges, insufficient observation periods, and data discontinuity. There are fewer than 20 permanent stations operating along the entire Antarctic coastline, and most of them operate <19 a, the minimum requirement for statistical reliability. Meanwhile, sparse gauge distribution prevents effective spatial interpolation for datum unification. The limited distribution of long-term tide gauges along the Antarctic coast introduces substantial errors in calculating the theoretical minimum low tide. Secondly, maintaining datum stability amid dynamic mass redistribution remains unresolved. Cryospheric dynamics, glacial isostatic adjustment, and sea-level anomalies driven by climatic events necessitate real-time corrections via high-resolution models. Thirdly, the absence of unified international protocols impedes coordinated efforts. Collaborative frameworks under IHO-SCAR (International Hydrographic Organization and Scientific Committee on Antarctic Research) joint initiatives are critical to standardize measurement practices and enhance global consistency through bipolar conjugate observations.

4 Future perspectives for Antarctic geodetic datum establishment and maintenance

Establishing a high-precision, dynamically unified Antarctic geodetic datum is the prerequisite for resolving the “Babel Dilemma” of polar scientific data, and constitutes critical infrastructure for achieving the temperature control targets of the Paris Agreement. Only through integrating multinational observational resources and advancing ice sheet dynamic modeling technologies can a high-accuracy Antarctic geodetic datum be established, thereby providing a precise Antarctic data infrastructure for global sustainable development.

4.1 Coordinate datum

In the Antarctic region, the establishment of geodetic datums must balance global uniformity with regional specificity. To address the scarcity and uneven distribution of input data for global reference frame solutions in Antarctica, it is essential to deploy an increased number of more evenly distributed observation stations integrating the four core techniques: VLBI, SLR, GNSS, and DORIS. Particular emphasis should be placed on multi-technique co-located stations to enhance local network tie accuracy in Antarctica, thereby improving the precision of the global reference frame to advance towards a 1-mm level. Leveraging the 5th International Polar Year (IPY-5) framework, we could establish VLBI and SLR observatories at Zhongshan Station and Kunlun Station along the Prydz Bay–Amery Ice Shelf–Lambert Basin–Dome A (PANDA) transect. These stations, combined with existing Antarctic VLBI/SLR facilities, will form an integrated observation network to support high-precision global coordinate datum establishment.

In regions of Antarctica with sparse GNSS continuously operating reference stations (CORS), expanding the network—particularly across the ice sheet interior—to establish a more uniformly distributed GNSS geodetic infrastructure serves dual critical purposes. On one hand, through expanded observations, we aim to monitor and understand the complex movements of observation stations induced by Antarctic Ice Sheet mass changes under global warming, thereby enhancing the contribution of the Antarctic Plate to the establishment and maintenance of the terrestrial reference frame. On the other hand, these monitoring stations will establish a readily accessible datum station network for Antarctic expeditions, providing precise and unified reference services. This enables high-precision positional monitoring to serve broader scientific domains, such as subglacial lake water-level variations and tidal dynamics, as well as isostatic adjustment of the crust. We propose deploying a dozen uniformly distributed CORS along the PANDA transect in the coming IPY-5. This infrastructure will provide precise geodetic services for scientific expeditions in the PANDA region, enabling dynamic positioning accuracy at the centimeter or even sub-centimeter level. Simultaneously, it will furnish high-precision, continuous observational data for ice sheet dynamics and geoscientific research in the region.

4.2 Height datum

In terms of height datum, two parallel strategies are essential. First, deploying continuously operating tide gauges in regions lacking such infrastructure to construct regional height datums. These will support Antarctic expedition facility construction and scientific activities while monitoring sea-level changes around Antarctica for global change research. Second, conducting targeted airborne and terrestrial gravity surveys to refine local geoid models based on global geoid frameworks. This will enhance the accuracy and resolution of the geoid in key Antarctic research areas. Additionally, periodic updates of the Antarctic geoid are required to dynamically maintain the vertical reference framework and align it with the International Height Reference Frame. Leveraging the IPY-5, we propose implementing high-spatiotemporal-resolution airborne gravity surveys along the PANDA transect. Integrated with existing airborne gravity data in this region, these efforts will refine the geoid model over the PANDA transect, establish a centimeter-level accuracy height datum covering the area, and provide a reliable reference for fine-scale glacier dynamics studies.

4.3 Gravity datum

Advancements in quantum absolute gravimeters, superconducting gravimeters, and Antarctic logistics support technologies now enable continuous high-precision absolute gravity measurements in Antarctica. Future initiatives will establish a network of absolute gravimetry stations across the continent, conducting long-term continuous observations to build a high-accuracy, dynamic Antarctic gravity datum network. This infrastructure will provide foundational reference for satellite, airborne, terrestrial, and shipborne gravity surveys while enhancing capabilities for monitoring ice sheet mass balance and Earth system dynamics. Leveraging China's enhanced polar expedition capabilities, we propose deploying superconducting gravimeters at Zhongshan Station and Kunlun Station along the PANDA transect in the IPY-5. These instruments will provide continuous absolute gravity measurements with μGal-level accuracy, reinforcing China's gravity datum support in this critical region and propelling advancements in ice sheet mass balance monitoring and Earth system studies.

4.4 Sounding datum

For sounding datum, we propose an integrated approach combining multi-source observations and dynamic modeling to address the practical demands of Antarctic expeditions. This collaborative framework will generate regionally continuous sounding datum models tailored for critical applications such as ship dock site selection and scientific station construction projects. Concurrently, by leveraging global high-resolution mean sea surface and geoid models, we establish mathematical transformations between sounding datum and ellipsoidal height systems. This enables the development of an orthometric height-based sounding datum conversion model, achieving unified expression of marine sounding datum and terrestrial height datum. The integrated framework provides a consistent, centimeter-level accuracy vertical reference for comprehensive ice-sea-land geographic information integration across Antarctica.

In summary, Antarctic geodetic datum constitutes critical infrastructure underpinning polar scientific research and engineering endeavors. Historically constrained observational conditions coupled with the extreme environmental harshness of Antarctica have resulted in severely underdeveloped or even absent geodetic benchmarks within the region's geodetic framework. Such lagging-behind development fails to meet the operational demands of current Antarctic scientific expeditions nor can it satisfy the requirements of advanced polar research. We urge relevant national authorities to prioritize this initiative and advance its improvement at the earliest opportunity.

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