



Tongji-GMMG2025C: A High-Resolution Global Gravity Field Solution Integrated from Heterogeneous Gravity Data via a Grid-based VCE Method

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Abstract: In this study, we present Tongji-GMMG2025C, a high-resolution global gravity field solution complete to degree and order (d/o) 2190. The solution combines GRACE and GOCE satellite gravity information with five marine gravity datasets derived from satellite altimetry, four topographic gravity field models, pseudo terrestrial observations generated from EGM2008 up to d/o 719, high-resolution Antarctic gravity anomaly grids (AntGG2021), and Arctic Gravity Project (ArcGP) datasets. Grid-level variance component estimation (VCE) is used to combine the marine and topographic datasets separately. The Tongji-GMMG2021S satellite-based full normal equation system is then combined with a terrestrial block-diagonal normal equation derived from global 5'×5' gravity anomaly grids. As a multi-source integrated solution, Tongji-GMMG2025C demonstrates lower residual statistics than single-source based solutions, exhibiting improvements of 0.01–0.21 mGal in measured free-air gravity anomalies and shipborne gravity anomaly enhancements of 0.08–0.54 mGal. Comparison with other existing gravity field solutions EGM2008, EIGEN-6C4, SGG-UGM-2, and XGM2019e reveals a good performance of our new combination solution Tongji-GMMG2025C and the closest agreement with XGM2019e. In oceanographic applications, Tongji-GMMG2025C achieves a root mean square error (RMSE) of 75.27 cm/s in geostrophic current determination relative to the DTU22MDT, outperforming EIGEN-6C4 by over 4.87 cm/s. Continental geoid evaluations in data-sparse regions yield accuracies of 38.94 cm (surrounding Brazil), 34.45 cm (surrounding Africa), and 50.60 cm (surrounding India), representing a 24% improvement over EGM2008 in the surrounding Brazil region. Validation against millions of shipborne gravity measurements indicates that Tongji-GMMG2025C performs favourably, particularly in the 0–10 km coastal zone, where it achieves an accuracy of 6.99 mGal, outperforming existing models by 9% to 24%. Similarly, the model establishes an accuracy improvement of approximately 40% compared to EGM2008 over Antarctica. These results demonstrate that Tongji-GMMG2025C may provide useful complementary gravity information in data-sparse regions. The Tongji-GMMG2025C solution is available at <https://doi.org/10.5281/zenodo.22667828> (Xuan et al., 2026).



1. Introduction

The Earth's gravity field, a fundamental physical property of the planet, arises from its material composition and structural dynamics. It serves as a crucial indicator of mass distribution and the interactions between Earth's systems (Kaula, 1966a; Wahr et al., 1998; Tapley et al., 2004; Hofmann-Wellenhof et al., 2006; Chen et al., 2022). High-precision and high-resolution global gravity field models provide detailed insights into the Earth's gravitational characteristics, facilitating interdisciplinary research in geodesy, oceanography, and geophysics (Ince et al., 2019; Kvas et al., 2021). Over the past two decades, advancements in global gravity field determination technologies, such as satellite gravimetry, satellite altimetry, and airborne gravity measurements, have revolutionized our ability to map the Earth's gravitational variations (Sandwell et al., 2014; Andersen et al., 2019; Varga et al., 2021). These breakthroughs have enabled the development of high-resolution gravity models (Ince et al., 2019), which are now widely applied in various domains, including mass change monitoring (Tapley et al., 2004; Han et al., 2006; Chen et al., 2006; Chambers et al., 2006; Rodell et al., 2018), unification of global or regional height reference systems (Rummel et al., 2012; Amin et al., 2019), regional geoid determination (Matsuo et al., 2020; Wang et al., 2021), precise satellite orbit determination (Bock et al., 2014; Shao et al., 2020), global mean dynamic topography and ocean circulation estimation (Knudsen et al., 2011), lithospheric structure modeling (Rathnayake et al., 2019), and crustal thickness and Moho depth determination (Bagherbandi et al., 2012; Shin et al., 2009).

The successful launches of dedicated gravity satellites, including the Challenging Minisatellite Payload (CHAMP), Gravity Recovery and Climate Experiment (GRACE), Gravity Field and Steady-State Ocean Circulation Explorer (GOCE), and GRACE Follow-On (GRACE-FO), have significantly advanced global gravity field models at medium- and long-wavelength scales to unprecedented levels (Han et al., 2002; Reigber et al., 2005; Pail et al., 2011; Floberghagen et al., 2011; Chen et al., 2019; Eshagh et al., 2024). To further improve spatial resolution, global gravity field models increasingly rely on multi-source data integration, as different gravimetric techniques capture Earth's gravity field from distinct perspectives, capturing signals across various spectral bands.

Theoretical and practical advancements in physical geodesy have demonstrated that the integration of multi-source data allows the complementary strengths of different datasets to be fully utilized. Pavlis et al. (2012) pioneered the creation of the EGM2008 model up to degree and order (d/o) 2190 by integrating the ITG-GRACE03s satellite-only solution with globally $5' \times 5'$ area-mean gravity anomalies derived from terrestrial gravity, satellite altimetry, and airborne gravity data. Subsequently, Förste et al. (2014) developed the EIGEN-6C4 model by incorporating GOCE



1 satellite observations, LAGEOS satellite data, DTU marine gravity anomalies, and terrestrial gravity
 2 anomalies computed from the EGM2008 solution. Similarly, Gilardoni et al. (2016) produced the
 3 GECCO solution by integrating GOCE data with the EGM2008 model, achieving improved accuracy
 4 compared to EGM2008. Liang et al. (2020) combined GOCE data, satellite altimetry and the
 5 EGM2008 model to compute the SGG-UGM series. The GOCO05c model employed regionally
 6 weighted $15' \times 15'$ terrestrial data to construct a full normal equation matrix up to d/o 720 (Fecher et
 7 al., 2017). Recent breakthroughs include XGM2016 (Pail et al., 2018) and XGM2019e (Zingerle et
 8 al., 2020), which incorporate $15' \times 15'$ global gravity anomalies from the National Geospatial-
 9 Intelligence Agency (NGA), significantly improving models in data-sparse regions. Recently,
 10 WHU-CASM-UGM2025 has also become available through ICGEM as a combined ultra-high
 11 degree model (Liu et al., 2026). Notably, these solutions primarily rely on single-source marine and
 12 topographic data to enhance global gravity anomaly grids. Although the EGM2008 solution uses
 13 distinct models for coastal and open ocean zones, the contributions of recently published
 14 heterogeneous gravity data (e.g., terrestrial, marine, and topographic gravity datasets, along with
 15 satellite observations) to gravity field estimation remain underexplored.

16 Variance component estimation (VCE) has been widely used in geodetic data combination to
 17 determine relative weights for heterogeneous observations or normal equations. Previous studies
 18 have applied VCE-related strategies to satellite gravity field regularization and the combination of
 19 gravity field solutions or normal equations, for example in satellite geodesy and GRACE monthly
 20 gravity field estimation (Koch et al., 2002; Kusche, 2003; Jean et al., 2018; Meyer et al., 2019).
 21 These studies indicate that relative weighting is a key issue when observations with different noise
 22 levels, spatial coverage, and spectral characteristics are combined. For marine and topographic
 23 gravity data distributed as gridded products, relative weighting can be performed at the grid level to
 24 prepare combined gravity anomaly grids for subsequent model determination.

25 Despite these advances, several challenges remain. First, the most fundamental limitation is the
 26 restricted availability of independent terrestrial gravity observations, which still constrains the
 27 recovery of high-frequency gravity signals over continental regions. Although EGM2008 and
 28 XGM2019e introduced important global terrestrial gravity anomaly information (Pavlis et al., 2012;
 29 Zingerle et al., 2020), many other combined models partly rely on EGM2008-derived information
 30 or use EGM2008 as an important background source. Therefore, the lack of newly available
 31 terrestrial gravity data remains a major obstacle to further improving high-resolution gravity field
 32 solutions. Second, integrating heterogeneous gravity data requires sophisticated methodologies to
 33 optimize the signal-to-noise ratio of gravity field models (Kaula, 1966b; Rapp, 1968). Third, high-
 34 frequency gravity signals in data-sparse regions are still poorly constrained, leading to discrepancies
 35 among models (Pail et al., 2018). Satellite altimetry and topographic observations provide valuable



1 datasets for retrieving high-frequency components of the gravity field (Sandwell et al., 2014; Hirt
 2 et al., 2017). Recently released marine gravity products, including those based on measurements
 3 from the Surface Water and Ocean Topography (SWOT) mission launched in 2022, provide
 4 additional information on short-wavelength marine gravity signals (Yu et al., 2024). Together with
 5 updated topographic and polar gravity datasets, these products provide a basis for updating high-
 6 resolution global gravity field models. Combining these datasets may improve the representation of
 7 short-wavelength gravity signals in global gravity field models, particularly in coastal and data-
 8 sparse regions.

9 This study presents Tongji-GMMG2025C, a high-resolution global gravity field solution complete
 10 to d/o 2190, and describes its input datasets, model determination, and quality assessment. The
 11 solution incorporates satellite gravity information from GRACE and GOCE, marine gravity datasets
 12 from satellite altimetry, topographic gravity field models, gravity information from EGM2008, and
 13 polar gravity data from ArcGP and AntGG2021. Grid-level VCE is used to combine the marine and
 14 topographic datasets separately, and satellite and terrestrial normal equations are jointly adjusted to
 15 determine the model coefficients. The assessment examines the spectral and spatial characteristics
 16 of Tongji-GMMG2025C and its agreement with measured gravity anomalies, regional geoid models,
 17 and DTU22MDT-derived geostrophic currents. The subsequent sections of this paper are organized
 18 as follows. **Sect. 2** elaborates on dataset information, the optimized grid-level VCE methodology,
 19 and the integration approach for normal equations. **Sect. 3** outlines the data processing strategies
 20 employed for the Tongji-GMMG2025C solution. **Sect. 4** examines the contribution of the grid-level
 21 VCE integration. **Sect. 5** presents a comprehensive accuracy assessment of the Tongji-
 22 GMMG2025C solution through spectral and spatial domain evaluations using multi-source datasets.
 23 Conclusions are presented in **Sect. 6**.

24 **2. Data and Method**

25 **2.1. Grid Datasets and Preprocessing**

26 This study develops a high-resolution (d/o 2190) Earth gravity field solution by systematically
 27 integrating multi-source gravitational data on globally homogeneous $5' \times 5'$ resolution grids. The
 28 synthesis incorporates the GRACE and GOCE satellite data, EGM2008 model, marine gravity
 29 anomalies derived from satellite altimetry measurements, terrestrial and airborne gravity data, and
 30 topographic gravity field models. This multi-source approach ensures comprehensive spectral
 31 coverage, ranging from long-wavelength geopotential variations to short-scale terrain-induced
 32 gravitational signals. Specifically, the global gravity anomaly grids were constructed using three
 33 primary datasets: topographic, marine and polar gravity data (as detailed in **Table 1**). These marine



and polar datasets were resampled to $5^{\circ} \times 5^{\circ}$ grids at cell centers using bicubic interpolation.

Table 1. Datasets for the Tongji-GMMG2025C gravity field solution

ID	Data	References	Resolutions
T,1	RWI_TOPO_2015	Grombein et al., 2016	d/o 2190
T,2	dV_ELL_Earth2014	Rexer et al., 2016	d/o 2190
T,3	ROLI_EllApprox_SphN_3660	Ince et al., 2020	d/o 3660
T,4	EHFM_Earth_7200	Liu et al., 2025	d/o 7300
M,1	DTU17	Andersen et al., 2019	$1^{\circ} \times 1^{\circ}$
M,2	Grav32.1	Sandwell et al., 2014, 2021	$1^{\circ} \times 1^{\circ}$
M,3	GravSWOT03	Yu et al., 2024	$1^{\circ} \times 1^{\circ}$
M,4	SDUST2022GRA	Li et al., 2024	$1^{\circ} \times 1^{\circ}$
M,5	NSOAS24	Zhang et al., 2025	$1^{\circ} \times 1^{\circ}$
P,1	ArcGP	Kenyon et al., 2008	$5^{\circ} \times 5^{\circ}$
P,2	AntGG2021	Scheinert et al., 2024	$5\text{km} \times 5\text{km}$

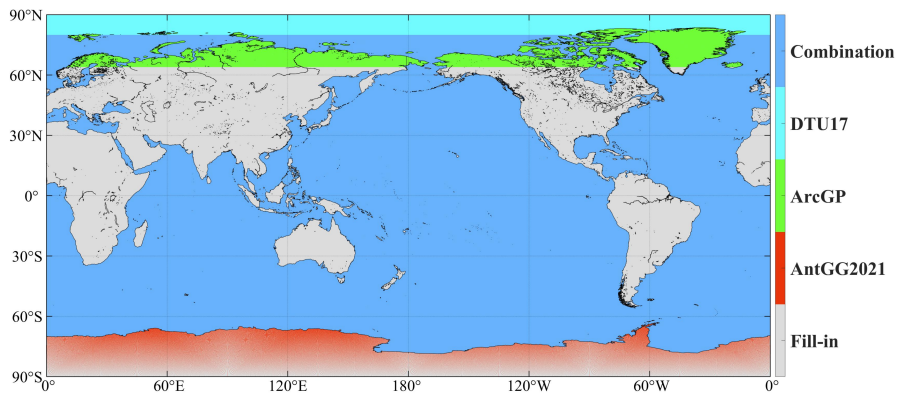


Figure 1. Global gravity data sources

Figure 1 illustrates the spatial distribution of various gravity data sources utilized in this study (see also **Table 1**). In **Figure 1** and **Table 1**, the marine gravity anomalies based on satellite altimetry were combined from five key models: DTU17, Grav32.1, GravSWOT03, SDUST2022GRA and NSOAS24. For topographic gravity data, we integrated four primary models: RWI_TOPO_2015, dV_ELL_Earth2014, ROLI_EllApprox_SphN_3660, and EHFM_Earth_7200. Note that the four



1 topographic gravity field models were truncated at d/o 2190 and transformed into ellipsoidal
 2 harmonic coefficients (EHCs). Subsequently, we computed gravity anomaly grids from these EHCs
 3 on the ellipsoidal surface before merging. The specific methodology to combine these models at a
 4 grid level will be detailed in subsequent sections. Notably, the DTU17 model provides exclusive
 5 coverage for Arctic marine regions above 80°N, where other marine models lack data. To address
 6 polar regions, we incorporated terrestrial and airborne gravity measurements from the ArcGP and
 7 AntGG2021. These polar datasets were processed using downward continuation (Ellmann, 2011)
 8 and resampling techniques to ensure compatibility with our global grids.
 9 For non-polar continental regions, we employed a hybrid spectral combination strategy to integrate
 10 the EGM2008 model with the combined topographic gravity field models. EGM2008 was truncated
 11 at d/o 719. This was done intentionally to reduce the dependence of the new solution on the high-
 12 frequency terrestrial information already contained in EGM2008 and to allow the contribution of
 13 the VCE combined topographic gravity grids to be assessed more independently. For the spectral
 14 band up to d/o 719, the non-polar continental gravity signal was obtained by a spectral combination
 15 of EGM2008 and the combined topographic gravity field models. This strategy involved: (1) for
 16 high-frequency components (d/o >719), direct substitution with topographic gravity solutions
 17 (Pavlis et al., 2007; Hirt et al., 2017); (2) for low-frequency components (d/o ≤719), adaptive
 18 weighted combination of EGM2008 and topographic gravity field models, computed as follows
 19 (Zingerle et al., 2019):

$$\sigma_n^2 = \frac{\sum_{m=0}^n [(C_{n,m} - C_{n,m}^{Ref})^2 + (S_{n,m} - S_{n,m}^{Ref})^2]}{2n+1}, \quad (1)$$

$$\omega = \frac{1}{\sigma_n^2}. \quad (2)$$

22 In Eqs. (1) and (2), $(C_{n,m}, S_{n,m})$ denote the spherical harmonic coefficients (SHCs) of either the
 23 EGM2008 or the topographic gravity field models for degree n and order m , while $(C_{n,m}^{Ref}, S_{n,m}^{Ref})$
 24 represents the coefficients of the d/o 719 priori solution named XGM2016 (Pail et al., 2018). The
 25 weighting factor ω is determined by the degree variances σ_n^2 .

26 2.2. Grid-level VCE for Gravity Field Integration

27 We used a multi-source data combination strategy that integrates marine gravity anomalies from
 28 satellite altimetry-derived models and topographic gravity anomalies from topographic gravity field
 29 models, respectively. These datasets are combined to construct global gravity anomaly grids. Unlike
 30 conventional VCE approaches typically applied to combine SHCs or normal equation systems in



1 the spectral domain (Jean et al., 2018; Meyer et al., 2019), this study uses a grid-level (spatial
 2 domain) VCE methodology. The observation equations governing this process are expressed as:

$$3 \quad \begin{cases} \mathbf{l}_{T,p} = \mathbf{g}_T + \mathbf{e}_{T,p} \\ \mathbf{l}_{M,q} = \mathbf{g}_M + \mathbf{e}_{M,q} \end{cases}, \quad (3)$$

4 where $\mathbf{g}_T$ and $\mathbf{g}_M$ represent the vectors of unknown gravity anomaly grids for topographic and
 5 marine datasets, respectively; $\mathbf{l}_{T,p}$ and $\mathbf{l}_{M,q}$ denote the gridded observations; $\mathbf{e}_{T,p}$ and $\mathbf{e}_{M,q}$ are
 6 the error vectors; and p and q indicate the IDs of the topographic or marine grid datasets, as listed
 7 in **Table 1**.

8 After simply determining the diagonal weight matrix $\mathbf{P}$ based on the area of each grid cell, the
 9 complete normal equation system for the VCE-weighted iterative process can be derived as follows
 10 (Koch et al., 2002; Kusche, 2003; Jean et al., 2018):

$$11 \quad \begin{cases} \left(\sum_{p=1}^{K_T} \omega_{T,p}^{iter} \mathbf{P} \right) \mathbf{g}_T^{iter} = \sum_{p=1}^{K_T} \omega_{T,p}^{iter} \mathbf{P} \mathbf{l}_{T,p} \\ \left(\sum_{q=1}^{K_M} \omega_{M,q}^{iter} \mathbf{P} \right) \mathbf{g}_M^{iter} = \sum_{q=1}^{K_M} \omega_{M,q}^{iter} \mathbf{P} \mathbf{l}_{M,q} \end{cases}. \quad (4)$$

12 In the iteration scheme, the vectors $\mathbf{g}_T^{iter}$ and $\mathbf{g}_M^{iter}$ correspond to the combined gridded gravity
 13 anomalies for topographic and marine datasets, and K_T and K_M are the number of topographic
 14 and marine datasets. The weights (as inverse of variance components) $\omega_{T,p}^{iter}$ and $\omega_{M,q}^{iter}$ at the $iter$ -
 15 th iteration are determined by the residual vectors $\mathbf{r}_{T,p} = \mathbf{l}_{T,p} - \mathbf{g}_T^{iter}$ and $\mathbf{r}_{M,q} = \mathbf{l}_{M,q} - \mathbf{g}_M^{iter}$, respectively:

$$16 \quad \begin{cases} \omega_{T,p}^{iter} = \frac{\mathbf{r}_{T,p}^{iter}}{(\mathbf{l}_{T,p} - \mathbf{g}_T^{iter})^T \mathbf{P} (\mathbf{l}_{T,p} - \mathbf{g}_T^{iter})} \\ \omega_{M,q}^{iter} = \frac{\mathbf{r}_{M,q}^{iter}}{(\mathbf{l}_{M,q} - \mathbf{g}_M^{iter})^T \mathbf{P} (\mathbf{l}_{M,q} - \mathbf{g}_M^{iter})} \end{cases}, \quad (5)$$

17 where

$$18 \quad \begin{cases} \mathbf{r}_{T,p}^{iter} = N_{Grid} \left(1 - \frac{\omega_{T,p}^{iter}}{\sum_{p=1}^{K_T} \omega_{T,p}^{iter}} \right) \\ \mathbf{r}_{M,q}^{iter} = N_{Grid} \left(1 - \frac{\omega_{M,q}^{iter}}{\sum_{q=1}^{K_M} \omega_{M,q}^{iter}} \right) \end{cases}. \quad (6)$$

19 In Eq. (6), N_{Grid} denotes the number of grid points. The VCE algorithm requires only the values
 20 $\omega_{T,p}^0 = 1$ and $\omega_{M,q}^0 = 1$ to initialize the iterative algorithm, while achieving rapid convergence of the
 21 weights. This advancement enables adaptive weighting of identical spectral components, thereby



1 facilitating the estimation of gravity field signals from heterogeneous observations at the grid level.

2 2.3. Integration of Satellite and Terrestrial Normal Equations

3 Satellite gravimetry provides important long-wavelength gravity information and can strengthen the
 4 low-frequency part of the global gravity field solution. Our integration of multi-source datasets
 5 enables a recovery of full-spectrum gravitational information. The block-diagonal approximation of
 6 normal equations is a computationally efficient strategy because it simplifies the full matrix into
 7 independent blocks (Colombo, 1981), but this simplification to some extent reduces model accuracy.
 8 In contrast, the dense normal equation approach provides higher accuracy while requiring extremely
 9 large computational resources, with the computation of ellipsoidal dense normal equations up to d/o
 10 2159 needing about 150 TB of memory and significantly lower computational efficiency. To balance
 11 this trade-off between computational efficiency and model accuracy, this study modifies the hybrid
 12 adjustment scheme that combines the full satellite normal equation with the block-diagonal
 13 terrestrial normal equation. Considering the Earth's ellipsoidal geometry, both the combination and
 14 derivation of the normal equations are formulated on the ellipsoidal surface (Jekeli, 1988; Sebera et
 15 al., 2012; Li et al., 2017; Liang et al., 2020). The relationship between gravity anomalies $\Delta g_{i,j}$ and
 16 EHCs ($C_{n,m}^e, S_{n,m}^e$) can be expressed as (Hofmann-Wellenhof et al., 2006; Holmes et al., 2007; Pavlis
 17 et al., 2012):

$$18 \quad r_i \Delta g_{i,j} = \frac{GM}{R} \sum_{n=2}^{2159} (n-1) \sum_{m=0}^n \bar{P}_{n,m}(\cos \delta_i) [C_{n,m}^e \cos(m\lambda_j) + S_{n,m}^e \sin(m\lambda_j)]. \quad (7)$$

19 where r_i , δ_i , and λ_j represent the geocentric distance, reduced co-latitude, and longitude for the
 20 grid point at i -th latitude belt and j -th longitude belt, respectively. The geocentric gravitational
 21 constant is $GM=3.986004415 \times 10^{14} \text{ m}^3/\text{s}^2$ and the semi-major axis of the reference ellipsoid is
 22 $R=6.3781363 \times 10^6 \text{ m}$. $\bar{P}_{n,m}$ denotes the fully normalized associated Legendre function.
 23 Linearization of Eq. (7) leads to the observation equation as follows:

$$24 \quad \mathbf{L} = \mathbf{B}\mathbf{x} + \boldsymbol{\varepsilon}, \quad (8)$$

25 where $\mathbf{B}$ is the design (projection) matrix linking the EHCs, $\mathbf{x}$, to the observation vector $\mathbf{L}$ and $\boldsymbol{\varepsilon}$ is
 26 the error term. The following normal equation can be derived via the least-squares adjustment
 27 (Pavlis, 1988; Li et al., 2022):

$$28 \quad (\mathbf{B}^T \mathbf{P}^s \mathbf{B}) \mathbf{x} = \mathbf{B}^T \mathbf{P}^s \mathbf{L}, \quad (9)$$

29 with

$$30 \quad B_{i,j}^{\alpha_{n,m}} = \frac{GM}{R} (n-1) \bar{P}_{n,m}(\cos \delta_i) \begin{cases} \cos(m\lambda_j), & \text{if } \alpha = C^e \\ \sin(m\lambda_j), & \text{if } \alpha = S^e \end{cases}, \quad (10)$$



$$L_{i,j} = r_i \Delta g_{i,j}, \quad (11)$$

where elements $B_{i,j}^{\alpha n,m} (\alpha=C^e, S^e)$ and $L_{i,j}$ denote components of the design matrix $\mathbf{B}$ and the observation vector $\mathbf{L}$, respectively. To optimize the normal-equation matrix into a block-diagonal structure, we assume the weight matrix $\mathbf{P}^e$ to be identity, and reformulate the normal equation according to the “V” configuration described by Pavlis (1988):

$$\mathbf{B}^T \mathbf{P}^e \mathbf{B} = \begin{pmatrix} N_{C_{2,0}, C_{2,0}}^e & N_{C_{4,0}, C_{2,0}}^e & \cdots & N_{C_{2199,2199}, C_{2,0}}^e \\ N_{C_{2,0}, C_{4,0}}^e & N_{C_{4,0}, C_{4,0}}^e & \cdots & N_{C_{2199,2199}, C_{4,0}}^e \\ \vdots & \vdots & \ddots & \vdots \\ N_{C_{2,0}, S_{2199,2199}}^e & N_{C_{4,0}, S_{2199,2199}}^e & \cdots & N_{S_{2199,2199}, S_{2199,2199}}^e \end{pmatrix}, \quad \mathbf{B}^T \mathbf{P}^e \mathbf{L} = \begin{pmatrix} W_{C_{2,0}}^e \\ W_{C_{4,0}}^e \\ \vdots \\ W_{S_{2199,2199}}^e \end{pmatrix}, \quad (12)$$

when the element $N_{\alpha n,m, \beta r,s} (\alpha, \beta=C^e, S^e)$ of the normal-equation matrix $\mathbf{B}^T \mathbf{P}^e \mathbf{B}$ satisfies the condition specified by Colombo (1981), as shown in Eq. (13), thereby reducing the normal-equation matrix in Eq. (12) to a block-diagonal form:

$$\begin{cases} N_{\alpha n,m, \beta r,s} = \left(\frac{GM}{R}\right)^2 (n-1)(r-1) \sum_{i=1}^{N_{Lat}} \sum_{j=1}^{N_{Lon}} P_{n,m}(\cos \delta_i) \bar{P}_{r,s}(\cos \delta_j) \begin{cases} \cos(m\lambda_i) \cos(s\lambda_j), & \alpha = \beta = C^e \\ \sin(m\lambda_i) \sin(s\lambda_j), & \alpha = \beta = S^e \\ 0, & \alpha \neq \beta, m \neq s, \text{ or } n-r \text{ is odd} \end{cases} \\ W_{\alpha n,m} = \frac{GM}{R} (n-1) \cdot \sum_{i=1}^{N_{Lat}} \sum_{j=1}^{N_{Lon}} r_i \Delta g_{i,j} \cdot \bar{P}_{n,m}(\cos \delta_j) \begin{cases} \cos(m\lambda_j), & \alpha = C^e \\ \sin(m\lambda_j), & \alpha = S^e \end{cases} \end{cases} \quad (13)$$

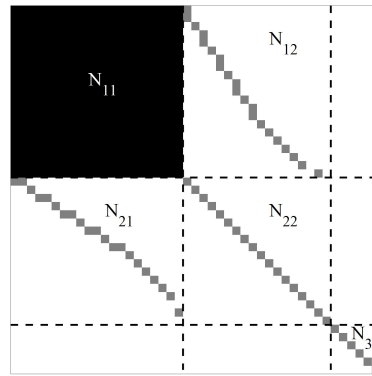
where $N_{\alpha n,m, \beta r,s} (\alpha, \beta=C^e, S^e)$ is an element of the normal-equation matrix $\mathbf{B}^T \mathbf{P}^e \mathbf{B}$; $W_{\alpha n,m} (\alpha=C^e, S^e)$ corresponds to the element of the right-hand vector $\mathbf{B}^T \mathbf{P}^e \mathbf{L}$; N_{Lat} and N_{Lon} indicate the number of latitude and longitude grids, respectively; and r and s represent degree and order, respectively. The computation of terrestrial normal equation can be accelerated through parallel processing and Fast Fourier Transform (FFT) techniques.

The integration of satellite and terrestrial normal equations necessitates reorganizing the normal matrix into the pattern through sequential ordering (Lemoine et al., 1998): (1) $n \leq n_{Sat}$, $m \leq n_{Sat}$, (2) $n > n_{Sat}$, $m \leq n_{Sat}$, (3) $n > n_{Sat}$, $m > n_{Sat}$ (n_{Sat} is the maximum degree of satellite normal equation). As shown in **Figure 2** for a simplified example, when merging a 4 d/o satellite normal equation with a 6 d/o terrestrial normal equation system, the submatrix N_{11} corresponds to the superposition of the full satellite normal equation and the block-diagonal terrestrial component. As shown in Eq. (13), the elements in group (3) are independent of those in groups (1) and (2). Therefore, the submatrix N_{33} allows direct inversion of the block-diagonal subsystem. Specifically, submatrices N_{12} , N_{21} , N_{22} , and N_{33} contain exclusively terrestrial information, where N_{12} and N_{21} represent covariances between groups (1) and (2), exhibiting irregular rectangular structures, and N_{22} retains a block-diagonal form. Due to computational limitations at the time, it was challenging to rigorously



1 implement this joint methodology (Lemoine et al., 1998). In this study, we derive streamlined exact
 2 solutions for groups 1) and 2), specifically optimized for modern high-performance computing
 3 frameworks.

4



5

6 **Figure 2.** Schematic diagram of combined 4 d/o satellite full normal equation (black elements) and 6 d/o terrestrial
 7 block-diagonal normal equation (gray elements), from left to right and top to bottom, corresponding to groups (1),
 8 (2), and (3) in the text

9

10 By rearranging Eq. (9) using the symmetrically distributed normal equation formulation mentioned
 11 above, we established the following equation to estimate the EHCs $\mathbf{x}=(\mathbf{x}_1 \ \mathbf{x}_2 \ \mathbf{x}_3)^T$ for groups (1), (2)
 12 and (3) (Lemoine et al., 1998):

$$13 \quad \begin{pmatrix} N_{11} & N_{12} & \mathbf{0} \\ N_{12}^T & N_{22} & \mathbf{0} \\ \mathbf{0} & \mathbf{0} & N_{33} \end{pmatrix} \begin{pmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \mathbf{x}_3 \end{pmatrix} = \begin{pmatrix} \mathbf{W}_1 \\ \mathbf{W}_2 \\ \mathbf{W}_3 \end{pmatrix}. \quad (14)$$

14 The purely block-diagonal component $N_{33}\mathbf{x}_3=\mathbf{W}_3$ can be solved directly, while groups (1) and (2)
 15 are reformulated as:

$$16 \quad \begin{cases} N_{11}\mathbf{x}_1 + N_{12}\mathbf{x}_2 = \mathbf{W}_1 \\ N_{12}^T\mathbf{x}_1 + N_{22}\mathbf{x}_2 = \mathbf{W}_2 \end{cases}. \quad (15)$$

17 Building upon Eq. (15), we can readily derive:

$$18 \quad \begin{cases} (N_{11} - N_{12}N_{22}^{-1}N_{12}^T) \cdot \mathbf{x}_1 = (\mathbf{W}_1 - N_{12}N_{22}^{-1}\mathbf{W}_2) \\ N_{22} \cdot \mathbf{x}_2 = (\mathbf{W}_2 - N_{12}^T\mathbf{x}_1) \end{cases}. \quad (16)$$

19 The block-diagonal matrix N_{22} allows for straightforward inversion. The sparse structure of the
 20 matrix N_{12} enables computationally efficient operations using the Intel Math Kernel Library's
 21 (MKL) sparse matrix routines, significantly reducing memory overhead. The most memory-
 22 intensive step involves the inversion of the matrix $N_{11}-N_{12}N_{22}^{-1}N_{12}^T$, where a 300 d/o full normal
 23 equation system requires approximately 60 GB of memory (or ~30 GB with triangular storage), a



manageable demand for modern computing architectures.

3. Computation of Tongji-GMMG2025C Gravity Field Solution

Using the global $5' \times 5'$ grids built above, we constructed a 2159 d/o terrestrial ellipsoidal harmonic block-diagonal normal equation system. To facilitate the joint derivation with the 300 d/o unconstrained satellite-only normal equation named Tongji-GMMG2021S generated by incorporating GRACE and GOCE data (Chen et al., 2024), we implemented three preprocessing steps as follows: (1) Parameter synchronization: the reference ellipsoid parameters and reference gravity field model were synchronized between satellite and terrestrial systems (Meyer et al., 2019); (2) Spectral transformation: the satellite normal equation was reformulated into ellipsoidal harmonic domain using rigorous spherical-to-ellipsoidal spectral conversion (Jekeli, 1988; Liang et al., 2020); (3) Weight optimization: optimal combination weights were determined based on a priori error statistics.

The transformed satellite full normal equation was then combined with the terrestrial block-diagonal system via least-squares adjustment, yielding the 2159 d/o EHC gravity field solution. The final d/o 2190 SHC solution Tongji-GMMG2025C (GMMG = Gravity field Model from Multi-Gravity observations) (Xuan et al., 2026) was derived through backward analytical transformation (Jekeli, 1988). To validate the marine and topographic contributions of our combination strategy described in Sect. 2.2, we developed a parallel solution entitled Tongji-GMMG2025T (Tongji-GMMG2025 Test). While maintaining identical data sources and derivation procedures, this test version used the DTU17 marine gravity anomalies and the dV_ELL_Earth2014 topographic gravity data (using data sources analogous to XGM2019e), instead of VCE outcomes, to construct the terrestrial normal equation.

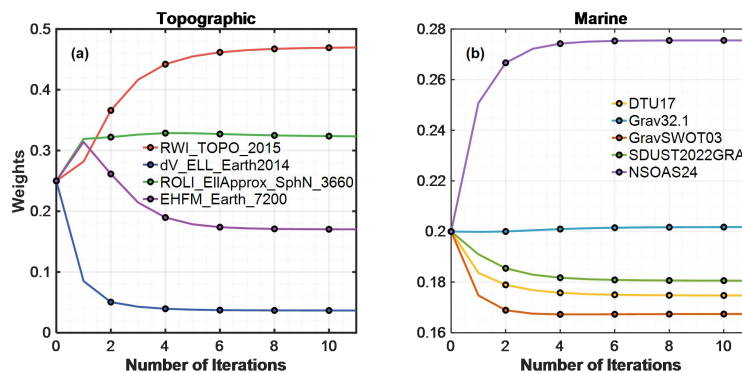
4. Contribution Analysis of Grid-level Multi-source Data Integration Approach

The topographic and marine datasets were combined by using the grid-level VCE method. Figure 3 depicts the variation of model weights with iteration count, demonstrating that the weighting coefficients converge to stable values after approximately 10 iterations. The resulting weights (Table 2) indicate that the RWI_TOPO_2015 dominates the topographic component, while the NSOAS24 exhibits the highest weight for marine data. For topographic models, spatial root mean square error (RMSE) values between the highest-weighted model (RWI_TOPO_2015) and the other three are 1.16 (dV_ELL_Earth2014), 0.49 (ROLI_EllApprox_SphN_3660), and 0.64 (EHFM_Earth_7200) mGal, whereas the corresponding values for the lowest-weighted model (dV_ELL_Earth2014) are 1.16, 1.08, and 0.98 mGal. Regarding marine models, the spatial RMSE values between NSOAS24 (highest weight) and the other four models are 2.28 (DTU17), 2.24



1 (Grav32.1), 2.64 (GravSWOT03), and 2.28 (SDUST2022GRA) mGal, while values for
2 GravSWOT03 (lowest weight) are 3.01, 2.32, 2.96, and 2.64 mGal. The superior spatial consistency
3 of RWI_TOPO_2015 and NSOAS24 with other models demonstrates the effectiveness of the grid-
4 level VCE approach at weighting consistent datasets higher.

5



6

7 **Figure 3.** The relationship between weights and the number of iterations in the grid-level VCE method for (a)
8 topographic and (b) marine gravity datasets
9

10

Table 2. Gravity data weights for grid-level VCE integration

Topographic data	Weights
RWI_TOPO_2015	0.47
dV_ELL_Earth2014	0.04
ROLI_EllApprox_SphN_3660	0.32
EHFM_Earth_7200	0.17
Marine data	Weights
DTU17	0.17
Grav32.1	0.20
GravSWOT03	0.17
SDUST2022GRA	0.18
NSOAS24	0.28

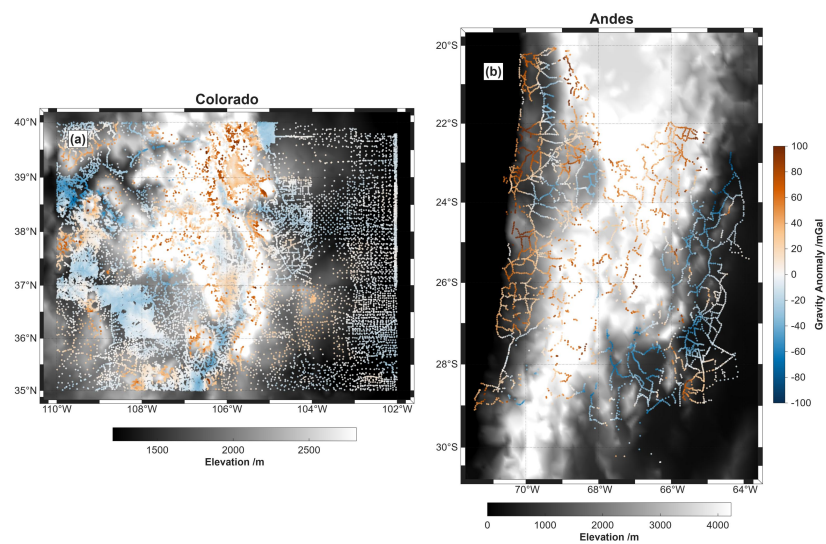
11

12 The spatial integration of marine and topographic gravity data is expected to enhance the quality of
13 the derived gravity field models. This section systematically evaluates the accuracy improvements
14 in gravity field modeling through our grid-level multi-source data integration approach. To evaluate
15 the performance of this approach, we computed SHC gravity field models complete to d/o 2190



1 using the topographic gravity models listed as IDs T,1~4 in **Table 1**. These models are hereafter
 2 referred to as Tongji-RWI, Tongji-Earth, Tongji-ROLI, and Tongji-EHFM, respectively. For
 3 independent accuracy assessment, we utilized measured free-air gravity anomalies and shipborne
 4 gravity datasets, which are widely recognized as benchmark references in gravity field model
 5 validation (Hirt et al., 2019; Zhang et al., 2025). The free-air gravity anomalies in **Figure 4** comprise:
 6 (1) 40,774 points in the Colorado acquired from the USA National Centers for Environmental
 7 Information (NCEI); (2) 4,728 points across the Andes obtained from NCEI.

8



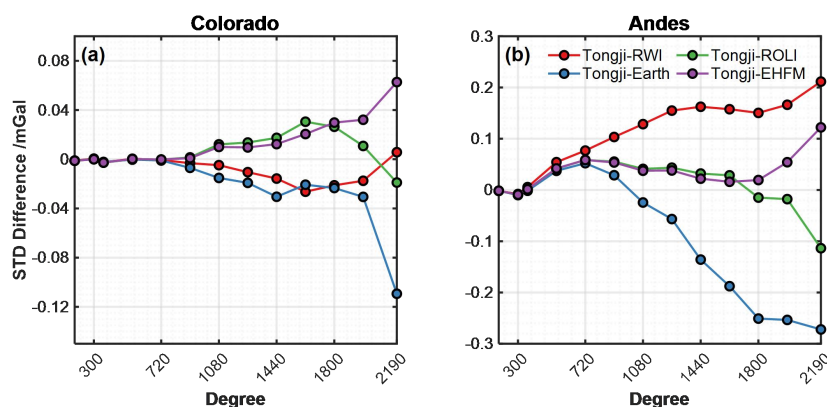
9
 10 **Figure 4.** The free-air gravity anomaly observation locations in the (a) Colorado, USA, and (b) Andes, South
 11 America
 12

13 **Figure 5** presents the standard deviations (STDs) of free-air gravity anomaly discrepancies between
 14 observations shown in **Figure 4** and gravity field solutions truncated at various degrees. The values
 15 shown in **Figure 5** are relative to the Tongji-GMMG2025C reference solution. The performance of
 16 the gravity field solutions is largely consistent across the study regions up to degree 720. At degree
 17 2190, Tongji-Earth shows the smallest STD in these areas, indicating that dV_ELL_Earth2014
 18 performs particularly well for these two validation datasets. However, the relatively low VCE
 19 weight assigned to dV_ELL_Earth2014 should not be interpreted as evidence of low external
 20 accuracy. Instead, it mainly reflects its lower spatial consistency with the other topographic gravity
 21 field models used in the grid-level VCE. Compared with the single-source solutions, Tongji-
 22 GMMG2025C does not always provide the smallest STD, but it remains close to the best performing
 23 solutions and shows relatively stable behaviour in both regions. At degree 2190, Tongji-



1 GMMG2025C shows accuracy improvements of 0.01 mGal (Tongji-RWI) / 0.06 mGal (Tongji-
 2 EHFm) in the Colorado, and 0.21 mGal (Tongji-RWI) / 0.12 mGal (Tongji-EHFm) in the Andes.
 3 The accuracy enhancements demonstrated above confirm that combining multi-source topographic
 4 gravity data not only effectively increases the sensitivity of gravity field solutions to high-frequency
 5 gravitational signatures but also yields more robust gravity field estimates.

6



7

8 **Figure 5.** STD performances between measured free-air gravity anomalies and gravity field solutions in (a)
 9 Colorado and (b) Andes (relative to the Tongji-GMMG2025C reference solution; negative values indicate higher
 10 accuracy than the reference solution, and positive values indicate lower accuracy)

11

12 The shipborne gravity anomalies were acquired from the NCEI. These datasets were validated
 13 against the DTU17 model using a 3-sigma criterion. Following this, systematic biases for each track
 14 were removed, computed as the mean difference between every gravity field solution and the
 15 shipborne data. The validated dataset comprises 6,504,091 points globally (**Figure 6**), including
 16 67,368 points in the Mariana trench (Region A) and 162,837 points in the Tonga trench (Region B).
 17 Following the same methodology, we computed five additional 2190 d/o SHC gravity field models
 18 using the marine datasets corresponding to IDs M,1~5 in **Table 1**. These are designated as Tongji-
 19 DTU, Tongji-Grav, Tongji-GravSWOT, Tongji-SDUST, and Tongji-NSOAS, respectively.

20

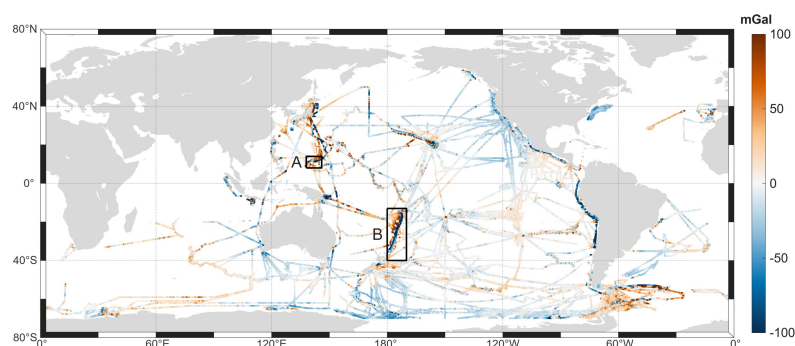


Figure 6. Shipborne gravity anomalies over the global ocean (A: Mariana trench, B: Tonga trench)

Figure 7 presents the STDs of the differences, relative to the Tongji-GMMG2025C reference solution, between shipborne gravity anomalies and values derived from gravity field solutions across various degrees. A key finding is that beyond degree 1440, where significant STD divergence begins, Tongji-GMMG2025C demonstrates superior accuracy across all regions up to degree 2190, relative to the individual (test) solutions. The improvements are quantified as follows: in the Mariana trench, RMSE reductions of Tongji-GMMG2025C are 0.54 mGal (vs. Tongji-DTU), 0.19 mGal (Tongji-Grav), 0.20 mGal (Tongji-GravSWOT), 0.08 mGal (Tongji-SDUST), and 0.42 mGal (Tongji-NSOAS). Corresponding improvements in the Tonga trench are 0.25 mGal, 0.39 mGal, 0.14 mGal, 0.15 mGal, and 0.23 mGal, respectively. Shipborne gravity assessments demonstrate that our grid-level VCE technique integrating multi-satellite altimetry datasets significantly enhances high-degree accuracy in gravity field modeling, better than the solutions based on the individual ocean datasets.

These results collectively demonstrate that the grid-level VCE technique, through its optimal integration of diverse gravity data sources, enables the Tongji-GMMG2025C solution to achieve superior accuracy compared to solutions derived from traditional single-source methodologies.

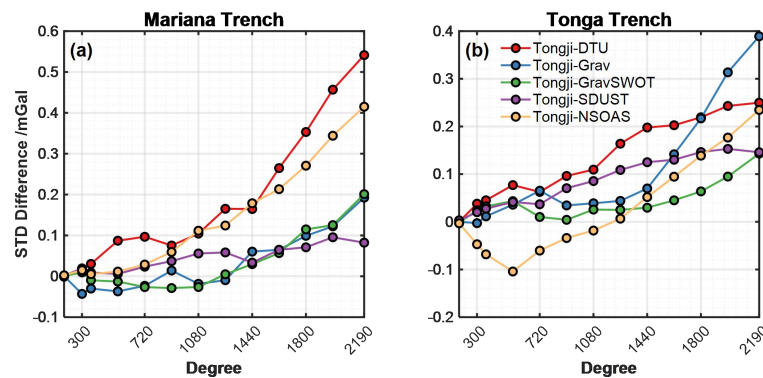


Figure 7. STD differences between shipborne gravity anomalies and gravity field solutions in (a) Mariana trench and (b) Tonga trench

5. Accuracy Assessment

To comprehensively validate the feasibility of our approach, we conducted a comparison between four 2190 d/o gravity field solutions (i.e. EGM2008, EIGEN-6C4, SGG-UGM-2, and XGM2019e) and the derived Tongji-GMMG2025C/T, with all spatial analyses performed on the ellipsoidal surface.

5.1. Analysis in Spectral-Spatial Domains

Using XGM2019e as a reference (Zingerle et al., 2020), we evaluated the spectral consistency of the gravity field solutions under consideration through geoid degree variance analysis. It should be noted that XGM2019e is used here only as a comparison model rather than as error-free truth. Therefore, smaller degree variances indicate closer agreement with XGM2019e, but do not necessarily imply higher accuracy. As shown in **Figure 8**, key findings can be found: (1) Tongji-GMMG2025C demonstrates superior spectral alignment with XGM2019e, exhibiting the smallest geoid degree variances across most spectral bands. (2) Below d/o 100, SGG-UGM-2 exhibits smaller variances due to the shared use of ITSG-Grace2018s low-frequency information with XGM2019e (Liang et al., 2020; Zingerle et al., 2020). (3) Between d/o 301 and 720, model discrepancies are minimal, as all solutions incorporate EGM2008 terrestrial data to varying degrees, except for XGM2019e (Förste et al., 2014; Liang et al., 2020; Zingerle et al., 2020). (4) Above d/o 720, Tongji-GMMG2025C maintains closer consistency with XGM2019e. EIGEN-6C4 and SGG-UGM-2 show similar variances due to their EGM2008-based ground infilling (Förste et al., 2014; Liang et al., 2020).

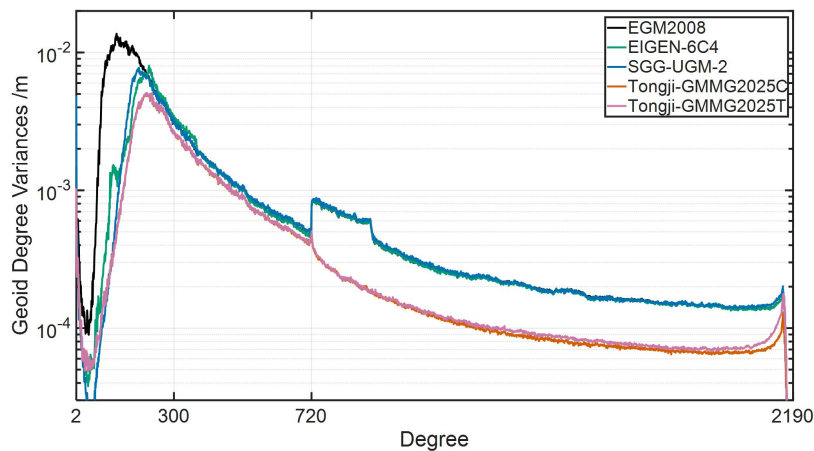


Figure 8. Geoid degree variances of gravity field solutions with respect to XGM2019e

We further evaluated gravity anomaly discrepancies using four statistical metrics: maximum deviation (MAXD), minimum deviation (MIND), mean absolute deviation (MEAND), and RMSE. As shown in **Table 3**, Tongji-GMMG2025C demonstrates the closest alignment with XGM2019e (besides Tongji-GMMG2025T), exhibiting the narrowest discrepancy range (-196.56 to 217.71 mGal) among all compared models. Notably, XGM2019e achieves the lowest MEAND (2.65 mGal) and RMSE (5.66 mGal), demonstrating its superior spatial consistency with the Tongji-GMMG2025C reference field.

Further spatial analysis (see **Figure 9**) reveals that the discrepancies between Tongji-GMMG2025C and both XGM2019e and Tongji-GMMG2025T exhibit distinct topographic correlations, particularly in orogenic belts such as the Tibet Plateau and the Andes Mountains. This spatial pattern primarily arises from differential processing of high-frequency signals (Hirt et al., 2019). Notable discrepancies are observed in the Tibet Plateau, Amazon Basin, and central-southern Africa regions, likely due to the use of distinct gap-filling data sources in Tongji-GMMG2025C compared to the EGM2008 solution; meanwhile, GOCE data were not utilized in EGM2008. Furthermore, the incorporation of updated AntGG2021 Antarctic data in Tongji-GMMG2025C has led to substantial differences compared to other models.

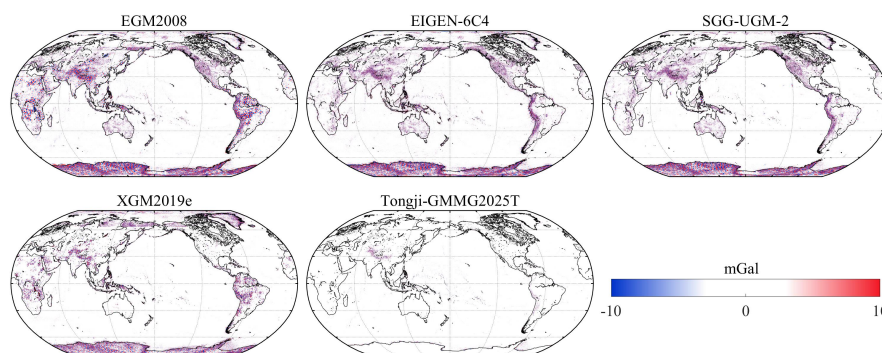
Table 3. Statistics of global gravity anomaly discrepancies with respect to Tongji-GMMG2025C (unit: mGal)

Model	MIND	MAXD	MEAND	RMSE
EGM2008	-307.19	329.22	3.15	7.21
EIGEN-6C4	-299.59	314.31	3.05	6.90



SGG-UGM-2	-303.19	316.98	2.73	6.75
XGM2019e	-196.56	217.71	2.65	5.66
Tongji-GMMG2025T	-67.55	134.68	0.62	1.21

1



2

3

Figure 9. Global gravity anomalies of gravity field solutions with respect to Tongji-GMMG2025C

4

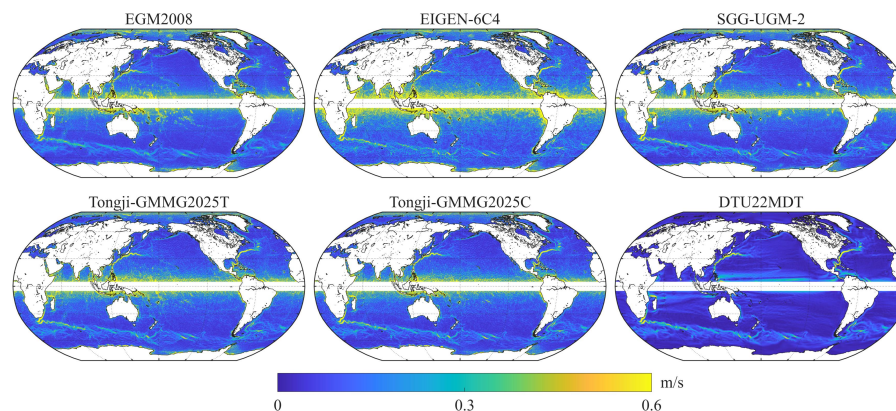
5 5.2. Geostrophic Current Comparison

6 This study introduces a data combination framework that integrates multi-source marine gravity
7 observations, with emphasis on incorporating the latest SWOT satellite data. The synergistic
8 integration is expected to improve the accuracy of gravity field estimation over oceans, thereby
9 enhancing the determination of geostrophic currents. Following the methodology described in
10 Knudsen et al. 2018, we utilized the DTU21MSS model (Andersen, 2023) as the mean sea surface
11 reference to compute unfiltered mean dynamic topographies with gravity field solution-derived
12 geoids. Geostrophic currents were then derived from these mean dynamic topographies. For
13 rigorous validation, we used the geostrophic current calculated from the high-quality DTU22MDT
14 model (Knudsen et al. 2023) as the benchmark.

15 Subsequently, the derived geostrophic currents from both gravity field solutions and the
16 DTU22MDT are presented in **Figure 10**. **Figure 10** demonstrates that both the gravity field and
17 DTU22MDT-derived geostrophic currents exhibit similar characteristic distribution patterns. The
18 detailed comparison highlights model-specific distinctions: EIGEN-6C4 shows globally distributed
19 bubble-like errors, while SGG-UGM-2 displays concentric errors in marine regions such as western
20 Mexico and eastern India. Notably, Tongji-GMMG2025C effectively reduces these systematic
21 errors. Furthermore, **Table 4** quantifies the deviation between geostrophic currents derived from
22 DTU22MDT and those from the gravity field solutions. Quantitatively, Tongji-GMMG2025C
23 achieves an RMSE of 75.27 cm/s with respect to DTU22MDT, representing noise reductions of 1.72



1 cm/s over EGM2008, 4.87 cm/s over EIGEN-6C4, and 2.44 cm/s over SGG-UGM-2. Importantly,
2 this improvement persists even when compared to the marine DTU17-based Tongji-GMMG2025T,
3 confirming the added value of our data integration method.



5
6 **Figure 10.** Geostrophic currents from d/o 2190 gravity field solutions and DTU22MDT (XGM2019e was
7 excluded in the comparison since DTU22MDT used its geoid). DTU22MDT data courtesy of DTU Space.

8
9 **Table 4.** RMSEs of geostrophic currents from gravity field solutions with respect to DTU22MDT-derived model

10 (unit: cm/s)

Model	EGM2008	EIGEN-6C4	SGG-UGM-2	Tongji-GMMG2025T	Tongji-GMMG2025C
RMSE	76.99	80.14	77.71	75.58	75.27

12 5.3. Geoid Modeling

13 The geoid, as a geometric-physical representation of the Earth's mean sea level, constitutes the
14 fundamental reference surface for physical geodesy datums (Hofmann-Wellenhof et al., 2006).
15 When integrated with GNSS-derived ellipsoidal heights, this reference surface provides critical
16 geospatial datum support for modern engineering surveys. To validate the accuracy and performance
17 of the Tongji-GMMG2025C gravity field solution, this study employs multi-source refined geoid
18 models from the International Service for the Geoid (ISG), including: (1) the MAPGEO2015 model
19 for the surrounding Brazil region (Blitzkow et al., 2015), which integrates 947,953 terrestrial gravity
20 points, SRTM, and EIGEN-6C4 datasets; (2) the AFRgeo2019 model for the surrounding Africa
21 region (Abd-Elmotaal et al., 2020), incorporating 126,202 terrestrial gravity points, AFH16S30 and
22 AFH16M03 digital terrain models, and the EIGEN-6C4 model; and (3) the IndGG-LSMSA2021
23 model for the surrounding India region (Goyal et al., 2021), which integrates GETECH terrestrial



1 gravity anomalies, MERIT digital elevation model, EGM2008, and GO_CONS_GCF_2_DIR_R5
2 models. These geoid models, which incorporate terrestrial gravity anomalies, provide robust
3 validation datasets for gravity field model evaluation. The selected regions are recognized as critical
4 data-deficient areas during the development of EGM2008, making them ideal testbeds for assessing
5 the capability of various gravity field models in retrieving high-frequency gravity field signals.

6 The STDs between geoid models and gravity field solution-derived geoids over land regions are
7 summarized in **Table 5**. Due to orographic effects in regions such as the Andes and Himalayas,
8 along with limited observational data, the accuracy of geoid determination varies significantly
9 across the study regions (STDs ranging from 34.22 to 55.00 cm). These challenges reflect the
10 difficulty of accurately representing complex geoids in data-sparse environments. Key findings
11 from **Table 5** include: (1) Tongji-GMMG2025C demonstrates significant STD reductions across all
12 three study regions compared to EGM2008, thanks to its incorporation of GOCE satellite gravity
13 gradients and multi-source integration strategies; (2) In the surrounding Brazil region, Tongji-
14 GMMG2025C reduces STD by 24% over EGM2008 (38.94 cm vs. 51.29 cm), achieving
15 performance nearly on par with the best-performing XGM2019e solution (38.28 cm) in this region;
16 (3) In Africa, the AFRgeo2019 fills data gaps with EIGEN-6C4 (STD: 34.7 cm), yet Tongji-
17 GMMG2025C demonstrates superior modeling capability with an 11% improvement over
18 EGM2008; (4) For surrounding India, the IndGG-LSMSA2021 integrates terrestrial datasets with
19 EGM2008 and GOCE data (GO_CONS_GCF_2_DIR_R5). Tongji-GMMG2025C achieves a lower
20 STD than XGM2019e (8% improvement). These results validate the effectiveness of our high-
21 frequency terrain gravity combination method, especially in mountainous and data-scarce regions.
22 Unlike conventional approaches, Tongji-GMMG2025C provides a data complementation strategy
23 that achieves comparable or even enhanced accuracy over existing solutions in these challenging
24 environments.

25

26 **Table 5.** STDs between geoid models and gravity field solutions over land regions (unit: cm)

Model	EGM2008	EIGEN-6C4	SGG-UGM-2	XGM2019e	Tongji-	Tongji-
					GMMG2025T	GMMG2025C
MAPGEO2015	51.29	39.79	40.38	38.28	38.92	38.94
AFRgeo2019	38.54	34.22	34.34	35.69	34.46	34.45
IndGG-LSMSA2021	53.03	50.16	49.21	55.00	50.74	50.60

27



5.4. Validation by Measured Gravity Data

Leveraging the high precision and spatial resolution of shipborne gravity data (Li et al., 2024), we assessed the accuracy of gravity field models across distinct regions (**Table 6**): the global ocean (6,504,091 observations), open ocean (6,187,737 observations), and coastal zones of 0~10 km (120,394 observations) and 10~20 km (195,960 observations). Tongji-GMMG2025C achieves optimal RMSEs in the global ocean (3.73 mGal) and open ocean (3.50 mGal). In coastal zones, it addresses the longstanding challenge of accuracy degradation. Specifically, in the 0~10 km coastal zone, the model attains an RMSE of 6.99 mGal, representing a significant accuracy improvement of 9% to 24% over established global models. This superior performance is maintained in the 10~20 km coastal zone, with improvements ranging from 7% to 17%. Crucially, when compared to its single-source predecessor (Tongji-GMMG2025T), the model shows consistent though modest accuracy gains (0.25 mGal and 0.15 mGal in the two coastal zones, respectively). These results confirm that the data integration method used in this study effectively enhances model performance.

Table 6. RMSEs between shipborne gravity anomalies and gravity field solutions (unit: mGal)

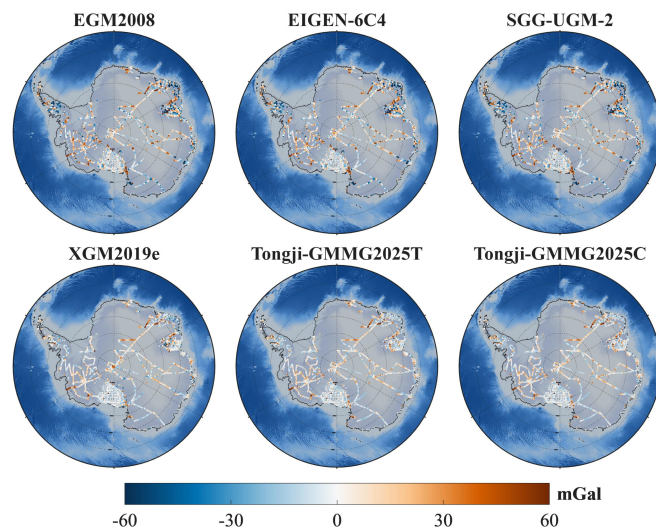
Region	EGM2008	EIGEN-6C4	SGG-UGM-2	XGM2019e	Tongji-	Tongji-
					GMMG2025T	GMMG2025C
Global ocean	3.79	3.78	3.75	3.83	3.74	3.73
Open ocean	3.55	3.54	3.52	3.56	3.51	3.50
Coastal 0~10 km	7.83	8.50	7.68	9.25	7.24	6.99
zones 10~20 km	6.68	6.82	6.09	6.30	5.82	5.67

As reported in Pail et al. (2018), significant discrepancies persist in Antarctic gravity anomalies among high-resolution gravity field solutions. To comprehensively assess model accuracy, we used gravity station data from the USA Defense Mapping Agency (DMA) provided by NCEI, selecting 13,764 terrestrial points across Antarctica. **Figure 11** presents the spatial distribution of gravity anomaly differences between modeled and observed values. Comparative analysis reveals that Tongji-GMMG2025C demonstrates superior consistency with ground-truth measurements in both West Antarctica (particularly the Antarctic Peninsula) and Northeast Antarctica compared to EGM2008, EIGEN-6C4, and SGG-UGM-2. Quantitative evaluation indicates that Tongji-GMMG2025C achieves a precision improvement exceeding 40% over EGM2008, with a 14.32 mGal reduction in STD. Two factors contribute to these advancements: (1) Unlike EGM2008, EIGEN-6C4, and SGG-UGM-2, which rely solely on low-frequency satellite gravity signals for



1 Antarctic interpolation, Tongji-GMMG2025C integrates AntGG2021 data with native 5 km
 2 resolution to capture full-spectrum gravitational signals; and (2) The ITG-GRACE03S model used
 3 in EGM2008 contains only 57 months of GRACE data (September 2002 to April 2007) (Mayer-
 4 Gürr et al., 2010). The Ice Sheet Mass Balance Inter-Comparison Exercise (IMBIE) reported that
 5 the mass change rate over the Antarctic ice sheet during 2002~2007 (-73 ± 53 Gt/yr) was
 6 substantially smaller than the long-term trend (-109 ± 56 Gt/yr) for 1992~2017 (IMBIE team, 2018).
 7 This implies that the GRACE-only static gravity field information for Antarctica used in EGM2008
 8 may insufficiently represent long-term static gravity signals, compounded by GRACE's 89° orbital
 9 inclination (Chen et al., 2019) that limits full coverage of Antarctica.

10



11

12 **Figure 11.** Discrepancies between gravity field solutions and measured gravity anomalies in Antarctica
 13 (STD values from left to right and top to bottom: 33.75 mGal, 33.54 mGal, 33.56 mGal, 20.49 mGal, 19.44 mGal
 14 and 19.43 mGal)
 15

16 6. Conclusion and Outlook

17 The rapid advancement of modern geodetic measurement technologies and the growth of
 18 observational datasets have opened unprecedented opportunities for advancing Earth's gravity field
 19 modeling, while simultaneously raising expectations for both model resolution and accuracy. This
 20 study introduces a data combination methodology based on grid-level VCE to effectively integrate
 21 multiple marine and topographic gravity datasets. Building upon this foundation, we further
 22 incorporated normal equations derived from GRACE/GOCE satellite observations, airborne, and



1 terrestrial gravity data, as well as the EGM2008 solution up to d/o 719, to establish a rigorous joint
 2 derivation framework. Using the multi-source data integration method, we developed Tongji-
 3 GMMG2025C, a high-resolution gravity field solution up to d/o 2190.

4 The grid-level VCE procedure found the highest weight 0.47 from RWI_TOPO_2015 among four
 5 topographic gravity models and 0.28 from NSOAS24 among five marine gravity models considered
 6 in this study. For performance benchmarking, we computed 2190 d/o single-source gravity field
 7 solutions, comprising solutions based on four topographic and five marine models. Validated against
 8 free-air gravity anomaly and shipborne gravity measurements, the multi-source integrated Tongji-
 9 GMMG2025C solution demonstrates statistically significant accuracy improvements along with
 10 enhanced solution robustness compared to the single-source models, showing improvements in free-
 11 air gravity anomalies from 0.01~0.21 mGal, with progressive marine gravity anomaly
 12 improvements beyond d/o 1440 culminating in 0.08~0.54 mGal gains at d/o 2190.

13 Comparative assessments against established global solutions (EGM2008, EIGEN-6C4, SGG-
 14 UGM-2, and XGM2019e) highlight the enhanced capabilities of Tongji-GMMG2025C. Through
 15 both spectral and spatial domain analyses, Tongji-GMMG2025C aligns most closely with
 16 XGM2019e, exhibiting a gravity anomaly difference of 5.66 mGal in spatial comparisons, which is
 17 significantly smaller than the 7.21~6.75 mGal deviations observed in other solutions. For
 18 oceanographic applications, the model achieves an RMSE of 75.27 cm/s in geostrophic current
 19 determination relative to the DTU22MDT-derived model, outperforming EIGEN-6C4 by over 4.87
 20 cm/s. Continental geoid evaluations in data-sparse regions (surrounding Brazil, Africa, and India)
 21 demonstrate terrestrial modeling accuracies of 38.94 cm, 34.45 cm, and 50.60 cm, respectively, with
 22 about 24% precision improvement over EGM2008 around Brazil. Validation against millions of
 23 shipborne gravity measurements confirms the superior performance of Tongji-GMMG2025C,
 24 which achieves an accuracy of 6.99 mGal in the 0~10 km coastal zone, outperforming existing
 25 models by 9% to 24%, and establishes an approximately 40% improvement over EGM2008 in
 26 Antarctica. As a pioneering 2190 d/o solution, Tongji-GMMG2025C addresses persistent challenges
 27 in gravity field determination for data-sparse regions and offers novel computational insights for
 28 global gravity field modeling.

29 Despite these encouraging results, several aspects of the present model still require further
 30 improvement. First, the construction of Tongji-GMMG2025C did not exhaust all globally available
 31 gravity datasets, especially recent terrestrial, airborne, shipborne, and regional gravity observations.
 32 The limited availability of terrestrial gravity data remains a major constraint for high-resolution
 33 gravity field modeling over continental regions. In this study, the spectral band above d/o 719 over
 34 non-polar land areas was mainly represented by topographic gravity field models. Although this



strategy provides a practical way to complement high-frequency gravity signals in data-sparse regions, it cannot fully replace direct terrestrial gravity observations and may introduce uncertainties related to the accuracy of terrain models, density assumptions, and topographic reduction procedures. Future work should therefore focus on incorporating more independent and recently released gravity datasets, improving the regional treatment of data-sparse areas, and developing more flexible weighting strategies that account for spatially varying data quality. These improvements are expected to further enhance the accuracy and reliability of future versions of the Tongji high-resolution gravity field model.

9 Data availability

The Tongji-GMMG2025C solution is available at <https://doi.org/10.5281/zenodo.22667828> (Xuan et al., 2026). We acknowledge the following institutions for providing the datasets. The topographic and gravity field models are available via the International Centre for Global Earth Models (ICGEM) at <https://icgem.gfz-potsdam.de/>. The DTU17 and DTU22MDT models can be downloaded from the Technical University of Denmark at <https://ftp.space.dtu.dk/>. The Grav32.1 and GravSWOT03 models are hosted by the Scripps Institution of Oceanography at <https://topex.ucsd.edu/pub/>. The SDUST2022GRA model from Shandong University of Science and Technology can be accessed at <https://doi.org/10.5281/zenodo.8337387> (Li et al., 2023). The NSOAS24 model was jointly developed by Northeastern University and China's National Satellite Ocean Application Service, and is available at <https://doi.org/10.5281/zenodo.12730119> (Zhang et al., 2024). Regional gravity datasets were obtained from the following sources: ArcGP and AntGG2021 are available at <https://earth-info.nga.mil/> and <https://doi.pangaea.de/10.1594/PANGAEA.971238> (Scheinert et al., 2024), respectively. Global shipborne gravity anomalies are provided by the NCEI at <https://www.ncei.noaa.gov/maps/trackline-geophysics/>. Regional gravity anomaly datasets for Colorado, the Andes, and Antarctica are archived at the NCEI via <https://www.ngdc.noaa.gov/mgg/gravity/>. Finally, the geoid models referenced in this study are available through the ISG at <https://www.isgeoid.polimi.it/>.

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28 Contributions

Jianhao Xuan designed the main technical workflow, constructed the Tongji-GMMG2025C solution, performed the validation experiments, wrote the original manuscript, and revised the manuscript. Qiujie Chen contributed to the conceptualization of the study, supervised the research, discussed the methodology and results, and revised the manuscript. Yunzhong Shen and Xingfu Zhang contributed to the theoretical discussion of gravity field modeling and reviewed the manuscript. Yun Xiao reviewed the manuscript. All authors read and approved the final manuscript.

34 Competing interests

The authors declare that they have no conflict of interest.

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