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Optimizing Gravity Forward Modeling through OpenMP Parallel Approach: A Case Study in Bawean Island

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Abstract

This study investigates the optimization of Gravity Forward Modeling (GFM) by implementing an OpenMP parallel computing approach, focusing on the synthetic model and topography of Bawean Island. The research addresses computational limitations in traditional GFM by utilizing parallel processing techniques to enhance efficiency and resolution. By modeling subterranean layers with rectangular prisms and using the Okabe equation for calculations, the study significantly improves computational speed and resource management. The practical application on Bawean Island includes a strategic distribution of observation stations to facilitate Bouguer Anomaly (BA) computations, providing a clearer understanding of subsurface density anomalies. Notably, the study demonstrates a 600% increase in efficiency for the synthetic case when OpenMP with 8 threads is applied to the utilized architecture. For the field model, computations spanning 400 square kilometers on Bawean Island, encompassing over 1.3 billion GFM calculations, are completed in just 143 seconds. Additionally, the gravity terrain values on Bawean Island exhibit a range of up to 65 mGal, which closely correlates with the high-resolution topographic map. These findings highlight the considerable advantages of parallel computing in enhancing the efficiency and feasibility of complex geophysical modeling tasks, offering substantial improvements for large-scale geophysical exploration.

Keywords: Gravity, Bouguer Anomaly, Parallel Computing, Forward Modeling

Abstrak

Penelitian ini mengoptimalkan *Gravity Forward Modeling* (GFM) dengan menerapkan komputasi paralel OpenMP pada model sintetik, dan topografi Pulau Bawean untuk mengatasi keterbatasan metode GFM konvensional dalam efisiensi dan resolusi perhitungan. Dengan memodelkan struktur bawah permukaan menggunakan prisma persegi empat serta menerapkan persamaan Okabe, penelitian ini berhasil meningkatkan kecepatan pemrosesan dan pemanfaatan sumber daya. Distribusi strategis stasiun observasi memungkinkan perhitungan Anomali Bouguer (BA) yang lebih akurat, memberikan pemahaman yang lebih mendalam mengenai variasi densitas bawah permukaan. Hasil eksperimen menunjukkan bahwa penggunaan OpenMP dengan 8 thread meningkatkan efisiensi komputasi hingga 600% pada model sintetik, sedangkan pada model lapangan yang mencakup wilayah 400 km^2 di Pulau Bawean, lebih dari 1,3 miliar perhitungan GFM dapat diselesaikan hanya dalam 143 detik. Nilai medan gravitasi di Pulau Bawean menunjukkan variasi hingga 65 mGal, yang berkorelasi erat dengan peta topografi beresolusi tinggi. Temuan ini menegaskan bahwa komputasi paralel dapat meningkatkan efisiensi dan kelayakan pemodelan geofisika yang kompleks, mendukung eksplorasi geofisika berskala besar secara lebih optimal.

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Kata Kunci: Gravitasi, Anomali Bouguer, Komputasi Parallel, Pemodelan Kedepan

I. INTRODUCTION

IN the subsurface Gravity Forward Modeling (GFM) domain, the Earth is conceptualized as a composition of density volume entities, with one prevalent representation being the employment of rectangular prisms [1, 2, 3, 4, 5, 6, 7, 8]. These prisms are organized to simulate subterranean layers and topographical features, with each layer possessing distinct volumes. These volumetric entities are subsequently subjected to computations using the GFM equation. The dimensions of the utilized prisms dictate the resolution of the resultant model, albeit at the expense of computational resources. Various strategies have been explored to mitigate this trade-off, including applying in the spectral domain [9] or adopting the discrete convolution algorithm [10]. However, this method is hampered by its substantial computer memory requirements and constraints on the spatial arrangement of gravity stations, necessitating their alignment on a single plane of uniform elevation. This poses a challenge, mainly when applying GFM computations for terrain gravity correction [11] to derive the Bouguer Anomaly (BA) or for deterministic [12] and stochastic gravity inversion [13]. BA computations mandate that the gravity stations be situated on the Earth's surface [14]. To address these limitations, we endeavor to leverage parallel computing techniques and assess their efficacy across different processor configurations. Furthermore, as a practical application of our research, we employ parallel GFM computations to model the gravitational effects of the topography of Bawean Island. In doing so, we strategically distribute observation stations across the island's surface to facilitate their utility in BA computations.

The demand for computational power has surged across various scientific and industrial domains, prompting the adoption of parallelization techniques to meet these escalating requirements [15, 16, 17, 18]. By exploiting the parallel processing capabilities of modern computing architectures, we can tackle increasingly complex computational tasks with greater efficiency and speed. Moreover, parallelization offers the potential to leverage the full capabilities of multi-core processors and distributed computing systems. Using parallel computing techniques represents a promising avenue for accelerating the computation process and handling the computational demands of large-scale modeling scenarios. By distributing the computational workload across multiple processing units, parallelization facilitates faster execution times and enhanced scalability, enabling us to tackle more ambitious modeling projects and achieve higher-resolution results.

II. LITERATURE REVIEW

A. Gravity Forward Modeling

Several equations can be used to calculate GFM using the rectangular prism model. Some commonly used ones include Sorokin, Plouff, Okabe, and Nagy approaches [19]. In previous research, we compared the efficiency of these methods, demonstrating that the Okabe method exhibits slightly superior performance [20]. Therefore, in this study, we utilized the Okabe equation, which can be expressed as equation (1).

$$g = -G\rho \sum_{i=1}^{2}\sum_{j=1}^{2}\sum_{k=1}^{2} \mu_{ijk} \times \left[x_i ln(y_i + r_{ijk}) + y_j ln(x_i + r_{ijk}) + 2z_k arctan \frac{x_i + y_j + r_{ijk}}{z_k}\right], \quad (1)$$

where,

$$x_i = x - \xi_i, \qquad y_j = y - \eta_i, \qquad z_k = z - \zeta_k, \quad (2)$$

and,

$$\mu_{ijk} = (-1)^i(-1)^j(-1)^k, \quad (3)$$

and g, G, ρ, (x, y, z), (ξ, η, ζ), r, are the gravity acceleration, gravity constant, density prism, station coordinate, and prism corner coordinate sequentially.

The BA is a geophysical measurement used in gravity exploration to correct gravity readings for various effects, such as the attraction of the Earth's crustal rocks, the elevation of the observation point, and the density of the terrain [21, 22, 23]. By removing the effects of topography and near-surface geology from gravity data, the BA provides a clearer picture of subsurface density anomalies. In calculating the BA, GFM is commonly employed in obtaining Bouguer and Terrain corrections, where, simplistically, the calculation of BA can be formulated as equation (4).

$$BA = G_{obs} - (G_t + FAC + BC - TC) \tag{4}$$

where G_{obs}, G_t, FAC, BC, dan TC, are the measured gravity acceleration corrected for tide and drift, theoretical gravity at datum, free air correction, Bouguer correction, and terrain correction, respectively.

B. Parallelization using OpenMP

Parallel computing is widely employed in various fields—such as scientific modeling, data analysis, image and video processing, and artificial intelligence—to leverage the capabilities of modern multi-core processors and distributed systems. For optimal performance, it is typically implemented using low-level programming languages such as C/C++ or Fortran, which allow direct memory access. The chosen parallelization strategy must also be compatible with the available hardware. In this study, we perform GFM computations using C++ with the OpenMP library, running on a computer system described in Figure 1. In a previous study, OpenMP was used to parallelize the 2.5D inversion of multiple gravity profiles, significantly reducing computation time in the fault detection workflow [24]. We chose OpenMP over MPI, as the latter is more appropriate for cluster computing environments, which are not compatible with our current setup.

TABLE I
THE HARDWARE AND SOFTWARE SPECIFICATIONS

CPU Name	Hardware/Software	Specifications
ENU8-02	Processor	12th Gen Intel(R) Core (TM) i7-12700 (20 CPUs)
	Memory	32,768 MB RAM
	Operating System	Windows 11 Educational 64-bit
	Compiler	Microsoft C++ (MSVC)
GTE2021	Processor	Intel(R) Xeon(R) Silver 4208 CPU @ 2.10GHz (16 CPUs)
	Memory	15,671 MB RAM
	Operating System	Ubuntu 20.04.4 LTS
	Compiler	gcc version 9.4.0 (Ubuntu 9.4.0-1ubuntu1~20.04.1)

The choice of parallelization approach, such as OpenMP or MPI, is often influenced by factors such as the nature of the computational task, the available computing resources, and the desired level of scalability. While MPI is well-suited for distributed memory architectures typically found in computer clusters, OpenMP offers a simpler and more user-friendly approach for shared memory systems, making it an attractive choice for many parallel computing applications, including gravity forward modeling.

III. RESEARCH METHOD

As a fundamental geophysical technique, GFM deciphers subsurface geology through gravity anomaly analysis. However, traditional GFM calculations face significant computational demands, particularly for extensive, high-resolution scenarios. This research addresses these efficiency constraints by leveraging OpenMP parallel computing to accelerate the GFM process. We employ a synthetic subsurface model constructed from rectangular prisms, calculated using the Okabe equation, to validate the approach's speed enhancement while preserving precision. The efficacy of the parallelized GFM is further confirmed through application to real-world gravity data from Bawean Island, demonstrating its capability for practical large-scale modeling. The following flowchart (Figure 1) outlines the comprehensive study workflow, including objective setting, synthetic model formulation, parallelization, and field data application.

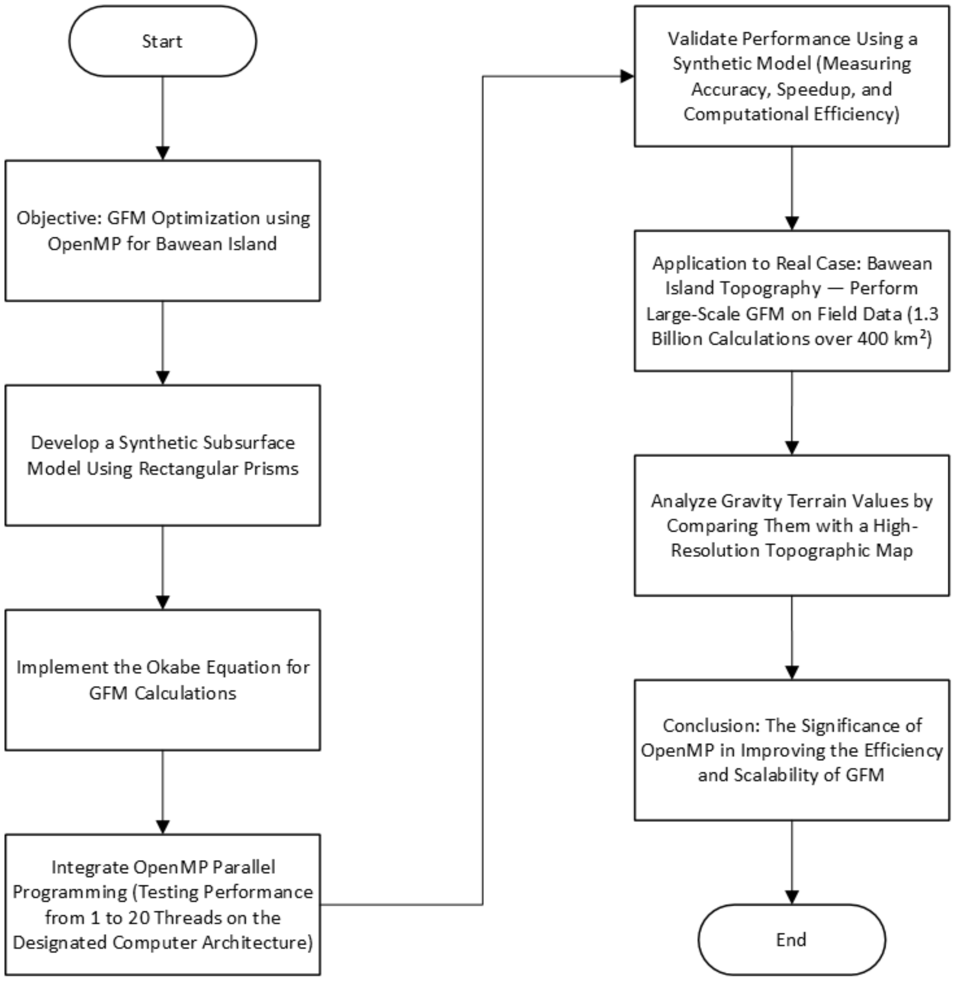


Fig. 1. Systematic workflow of the parallelized Gravity Forward Modeling (GFM) study, from objective definition and synthetic model development to OpenMP implementation and field application on Bawean Island data

A. Subsurface Model and Gravity Stations

The GFM calculation in equation (1) is performed for each prism and each gravity station (see Figure 2). Therefore, if subsurface modeling consists of M density prisms and N gravity stations, the total number of calculations will be M*N times. In modeling large areas to achieve high resolution, this significantly impacts the computation time. The complexity of the computations grows exponentially with the number of density prisms and gravity stations, making it crucial to optimize the calculation process for efficiency. In this study, we explore the application of parallel computing techniques, specifically leveraging the OpenMP library, to distribute the computational workload across multiple processor cores. This approach aims to reduce the overall computation time and improve the scalability of the gravity forward modeling process, especially when dealing with large-scale subsurface modeling scenarios. By harnessing the power of parallel processing, we endeavor to enhance the performance and feasibility of gravity forward modeling in geophysical exploration and research endeavors.

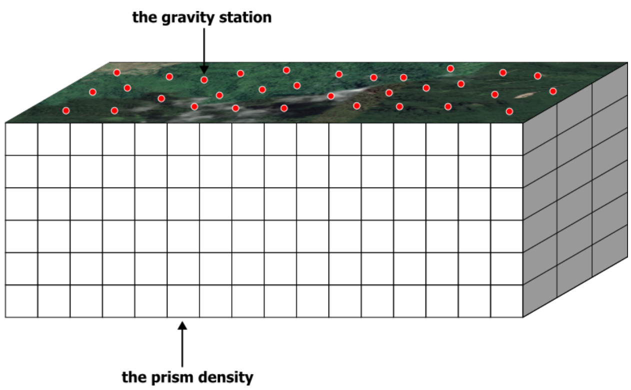
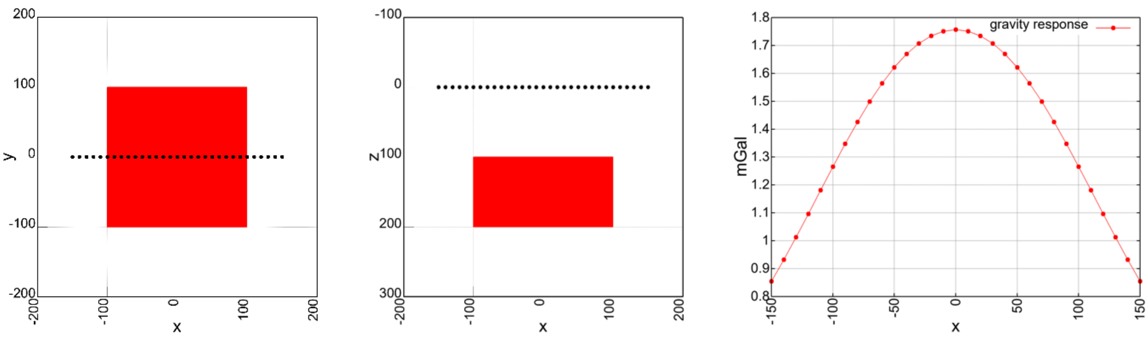


Fig. 2. The subsurface model shows the gravity stations and the density prisms.

B. *Synthetic Model for Parallelization Testing*

To comprehensively assess the performance of parallel GFM calculation, we constructed a synthetic model aimed at elucidating the impact of varying core/thread configurations on computation efficiency. The synthetic model refers to another study [25] that comprises a rectangular prism with dimensions of 200 x 200 x 100 meters in the x, y, and z directions, respectively, exhibiting a uniform density of 1000 kg/m^3. Positioned centrally at coordinates (0, 0, 150), the prism extends 100 meters below the surface, with a thickness of 100 meters, where positive z values denote depths towards the Earth's center. Along the surface, 31 gravity stations are distributed linearly, spanning from (-150, 0, 0.01) to (150, 0, 0.01), with a station spacing of 10 meters. Referencing Figure 3 provides a visual representation of this model configuration.



(a) (b) (c)

Fig. 3. The simple synthetic model of density prism in sections x-y (a), x-z (b), and the gravity response in the surface (c).

The parallelization strategy was systematically applied to compute this synthetic model across various scenarios. By examining the relationship between the number of iterations and the number of cores utilized, we aimed to discern the computational performance of GFM under different parallelization architectures. Through this analysis, we sought to identify the optimal core configuration that maximizes computational efficiency, thus providing invaluable insights for the application of parallel GFM to real-world field data. Seven distinct scenarios, spanning iteration counts of 1 to 10^6, were examined alongside 20 different core configurations, ranging from single-core to twenty-core setups. This comprehensive evaluation framework facilitated a nuanced understanding of the interplay between computational workload, parallelization efficiency, and hardware resources, ultimately guiding the selection of an optimal parallelization strategy for subsequent field data analysis.

Furthermore, each scenario was executed multiple times to ensure robustness and accuracy of the results, with statistical measures employed to assess the consistency and variability of computation times across iterations. Additionally, we conducted a comparative analysis of computational performance metrics, including speedup, efficiency, and scalability, to evaluate the efficacy of parallelization strategies across varying hardware configurations. Through meticulous experimentation and analysis, we aimed to elucidate the trade-offs and benefits associated with different parallelization approaches, thereby empowering us to make informed decisions when deploying parallel GFM algorithms in diverse computational environments. This systematic investigation not only advances our understanding of parallel computing methodologies but also contributes valuable insights to the broader field of geophysical modeling and data analysis.

C. Field Data

The terrain model used in this research was developed from topographic data derived from the Digital Elevation Model Nasional (DEMNAS) provided by the Indonesia Geospatial Portal. From this topographic data, we constructed a density model of the area using rectangular prisms that extend vertically from an elevation of 0 meters above sea level to the height of the surrounding terrain. This approach allows us to accurately represent the Bouguer and terrain corrections in the BA calculations.

Bawean Island, situated 160 km north of Surabaya, was selected as the study area due to its small, isolated nature, surrounded by the sea. This isolation minimizes external influences, allowing the gravitational field model calculations to concentrate on the effects of the island's terrain mass. Additionally, Bawean Island has comprehensive DEMNAS coverage, making it a suitable candidate for this study. Its relatively small area ensures the data set remains manageable for modeling purposes. The DEMNAS data for Bawean Island, with a horizontal resolution of up to 5 meters, encompasses over three million data records after excluding the surrounding sea area. To model this data using vertical rectangular prisms with a base dimension of 100 x 100 meters, more than 36,000 prisms would be required to calculate the gravitational acceleration at a given station point (the simpler terrain model using rectangular prism with 1000 x 850 meters base dimension illustration is presented in Figure 4). We spread more than 36,000 gravity stations on the surface with 100-meter spacing. Therefore, we need more than 1.3 billion GFM calculations. For the density values in our calculations, we used the average density of Earth's crustal rocks, which is 2670 kg/m^3.

This detailed modeling approach not only provides a precise representation of the island's terrain but also enhances the accuracy of gravitational studies conducted in the region. By focusing on Bawean Island, we leverage its isolated geographical setting to minimize the complexities often introduced by adjacent landmasses and varying topography. The high-resolution DEMNAS data ensures that even minor topographic variations are captured, which is crucial for refining the Bouguer and terrain corrections. Moreover, the selection of Bawean Island aligns with our objective of conducting focused gravitational field analyses without the interference of extraneous geological formations. The island's manageable size and the availability of high-resolution data allow for a comprehensive analysis within a reasonable computational scope. This research can serve as a model for similar studies in other isolated regions, providing valuable insights into the gravitational effects of localized terrain features.

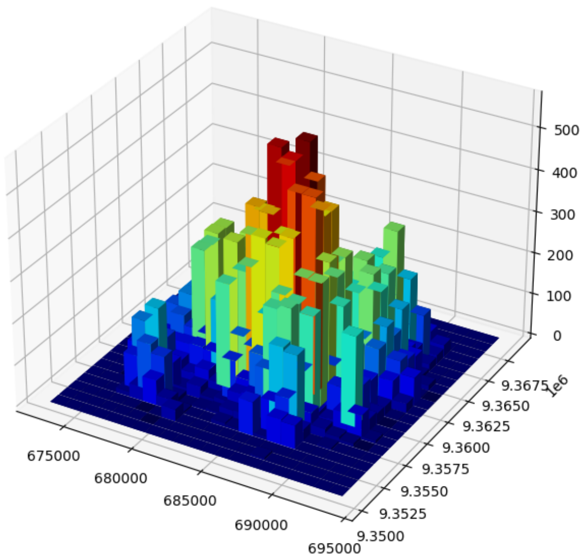


Fig. 4. The illustration of the Bawean island terrain model using rectangular prism with 1000 m x 850 m base dimensions. Unit in a meter.

IV. RESULTS AND DISCUSSION

A. Parallelization Testing

The synthetic model has undergone testing across several scenarios to examine the repeatability of calculations. Seven distinct scenarios, labeled from (a) to (g), were designed to vary the number of iterations, specifically 1, 10, 100, 1000, 10000, 100000, and 1000000 iterations, respectively. Each scenario was tested five times to ensure robustness and accuracy. The average execution times for each scenario, with varying numbers of threads, are presented in Table II and illustrated in Figure 5.

The results reveal that parallelization significantly impacts the GFM calculation only when the iteration count exceeds 100. This is demonstrated by the reduction in execution time as the number of threads increases, particularly in scenarios (c) through (g). Conversely, in scenarios (a) and (b), when the iteration counts below 100, adding more threads tends to increase the overall execution time. These findings suggest that for smaller iteration counts, the overhead of managing multiple threads outweighs the benefits of parallel processing. In scenarios with 100 iterations (scenario (c)), the introduction of additional threads generally reduces execution time. However, beyond a certain number of threads, this benefit diminishes, and in some cases, adding more threads can still lead to increased execution times. A similar pattern is observed in scenario (d) with 1000 iterations. The efficiency of parallelization becomes more stable and effective in scenarios with 10000 iterations and above (scenarios (e) through (g)), where the benefits of adding threads are more consistently realized.

To further analyze the data, we plotted the results on both a log scale and a log-log scale, as shown in Figure 5. These plots indicate that the reduction in execution time follows an exponential pattern up to the use of eight threads. Beyond eight threads, the addition of more threads does not yield exponential improvements in computational efficiency. This suggests a point of diminishing returns where the overhead associated with managing many threads negates the performance gains from parallelization.

This observation has important implications for the practical implementation of parallel computing strategies. It underscores the necessity of a balanced approach, where the number of threads is optimized to match the computational workload. Excessive threading can lead to resource contention and increased synchronization overhead, which in turn can degrade performance rather than enhance it. Therefore, careful consideration must be given to the architecture of the system and the nature of the tasks when designing parallel algorithms. While parallelization can significantly enhance the efficiency of calculations in the GFM model, this benefit is contingent on the number of iterations and the optimal number of threads. For iteration counts exceeding 10000, parallelization is consistently effective. However, using more than eight threads does not substantially improve performance and can even be counterproductive. This highlights the importance of optimizing thread usage to achieve the best computational efficiency. Future work could explore dynamic threading strategies that adapt to the computational load, thereby maximizing efficiency across a broader range of scenarios.

TABLE II
The Execution Time for Number Iterations in each Scenarios (a – g) in ENU8-02 Machine

Thread(s) used	Execution Time (µs) for number iterations						
	(a)	(b)	(c)	(d)	(e)	(f)	(g)
1	48	329	2,403	26,748	229,409	2,226,568	22,189,249
2	76	512	1,314	12,513	121,634	1,179,147	12,014,703
3	112	730	995	9,244	83,272	801,791	8,065,971
4	291	1,040	1,006	7,977	66,848	617,500	6,199,666
5	236	1,390	754	7,298	54,284	505,509	5,065,096
6	196	2,068	915	7,381	49,525	433,521	4,385,218
7	234	1,779	1,107	6,910	44,844	384,161	3,878,848
8	305	2,787	881	7,079	45,148	357,051	3,536,952
9	453	3,276	934	8,317	43,816	336,328	3,402,823
10	1,301	3,591	887	8,311	42,083	323,575	3,541,785
11	774	3,720	973	8,367	40,428	314,771	3,619,038
12	938	4,160	1,216	8,682	40,498	297,307	3,495,111
13	645	3,654	911	9,859	37,942	284,956	3,442,592
14	624	5,505	1,161	10,466	36,487	279,652	3,316,279
15	569	5,010	942	9,056	36,368	268,292	3,246,143
16	832	5,533	933	9,813	35,465	259,192	3,167,165
17	929	4,790	1,007	9,959	39,056	259,221	3,109,382
18	758	5,555	1,127	18,019	39,432	256,017	3,101,046
19	1,042	13,108	1,013	10,977	40,814	254,026	3,060,680
20	1,157	6,012	1,346	13,744	40,860	272,321	3,118,252

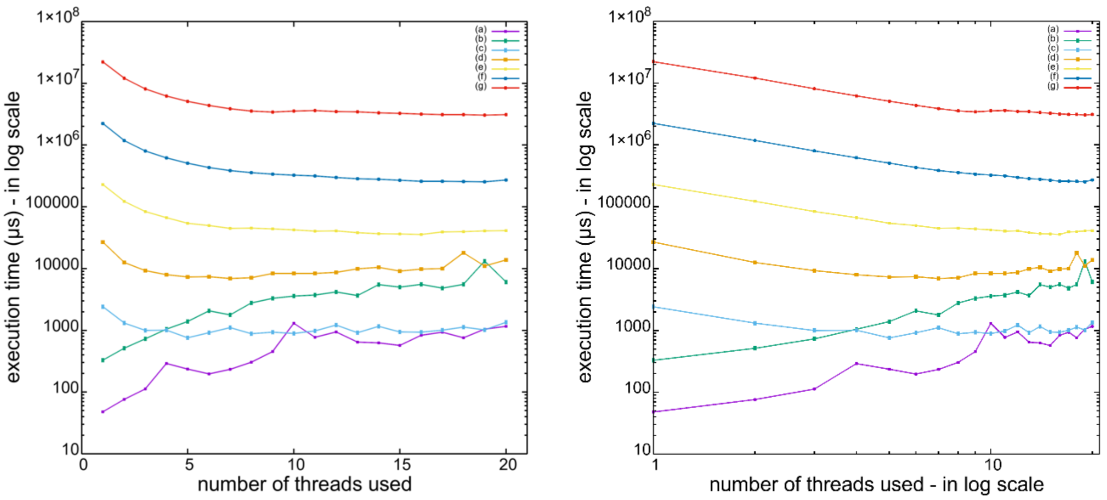


Fig. 5. The execution time versus the threads used in log plot (left) and log-log plot (right)

B. Field Application

Based on the outcomes from the GFM calculation experiment on the synthetic model, we applied the GFM calculations to field data using an 8-thread parallelization architecture. This method was chosen due to its high efficiency, achieving over 600% improvement compared to a non-parallelized approach. Our results show that the total number of GFM calculations performed exceeded 1.3 billion, which were completed in about 143 seconds. These findings highlight the importance of using parallelized architecture for GFM calculations, especially in large-scale field applications.

The comparison between the topographic distribution and the terrain gravity distribution patterns is illustrated in Figure 6. The provided figure is a gravity terrain map of Bawean Island, illustrating the variations in gravitational acceleration across the region. The color scale ranges from -5 to 65 miliGals (mGal), representing different gravity values. The central part of the map, highlighted in red and orange, shows the highest gravity values, reaching up to 65 mGal. This area suggests the presence of elevated topography. Surrounding this central zone are regions with moderate gravity values, indicated by yellow and green colors, ranging from 25 to 45 mGal. These zones show a gradual decrease in gravitational acceleration moving outward from the center. The outer edges of the map, depicted in blue and purple, represent the lowest gravity values, from -5 to 15 mGal, likely corresponding to lower elevations.

This distribution reflects a correlation between high gravity values and high elevations, consistent with the principle that greater topographic heights are associated with increased gravity. Conversely, lower gravity values align with lower elevations. The central high gravity region may indicate elevated landmasses, while the gradient from high to low gravity provides insights into the subsurface structures. Qualitatively, this demonstrates that the GFM calculations are consistent with the fundamental principles of gravity calculation, where the magnitude of gravitational acceleration is related to the volume and distance of the density object being measured.

The significant efficiency improvements not only reduce computation time but also enable more comprehensive and detailed analyses. Utilizing this method enhances our understanding of the relationship between topographic features and gravitational anomalies, leading to more precise geological and geophysical interpretations.

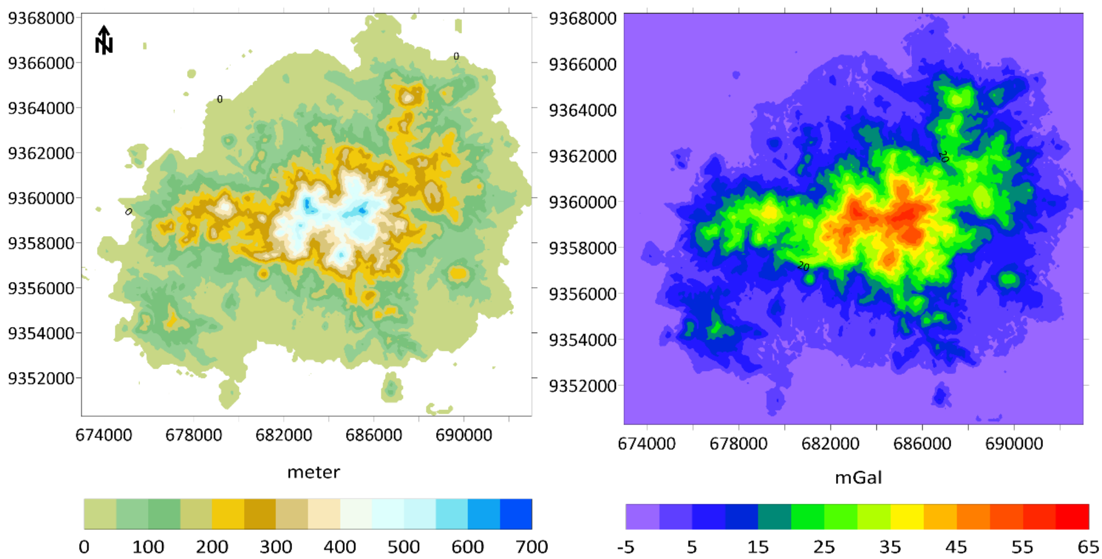


Fig. 6. The Bawean Island topography map (left) and its terrain gravity (right).

V. Conclusion

This research highlights the substantial benefits of parallel computing, specifically through OpenMP, in enhancing GFM. By applying this method to the synthetic model and topographic study of Bawean Island, the study successfully demonstrates that parallelization accelerates computational processes and improves the overall efficiency of resource usage. Employing rectangular prisms and the Okabe equation in GFM effectively generated high-resolution models, providing valuable insights into subsurface density anomalies. The strategic placement of observation stations facilitated accurate BA calculations, contributing to a more detailed understanding of the subsurface geological structures. These results affirm the potential of parallel computing techniques to revolutionize geophysical exploration, offering a powerful solution to the computational challenges faced by traditional GFM methods. Overall, this research underscores the importance of adopting advanced computational approaches to enhance the precision and scope of geophysical investigations.

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References

[1] G. Gavriilidou, C. Gerlach, and D. Tsoulis, Analytical computation of local gravitational effects of mountain glacier mass change from polyhedral and prismatic modeling - test case Vernagtferner, Austrian Alps, *Global and Planetary Change*, vol. 234, p. 104378, Mar. 2024, doi: 10.1016/j.gloplacha.2024.104378.

[2] H. Xu, Y. Tian, J. Yu, O. B. Anderson, Q. Wang, and Z. Sun, Comparative Study on Predicting Topography from Gravity Anomaly and Gravity Gradient Anomaly, *Remote Sensing*, vol. 16, no. 1, p. 166, Dec. 2023, doi: 10.3390/rs16010166.

[3] Y. Liu, J. Wang, F. Li, and X. Meng, Estimation of Antarctic Ice Sheet Thickness Based on 3D Density Interface Inversion Considering Terrain and Undulating Observation Surface Simultaneously, *Remote Sensing*, vol. 16, no. 11, Art. no. 11, Jan. 2024, doi: 10.3390/rs16111905.

[4] H. Xu, J. Yu, Y. Zeng, Q. Wang, Y. Tian, and Z. Sun, Predicting bathymetry based on vertical gravity gradient anomaly and analyses for various influential factors, *Geodesy and Geodynamics*, vol. 15, no. 4, pp. 386–396, Jul. 2024, doi: 10.1016/j.geog.2023.12.006.

[5] Y. Liu, J. Guo, M. Lin, L. Chang, X. Chang, and X. Liu, Refining regional gravity anomalies and vertical deflections of high-degree earth gravity model from residual terrains based on the spatial domain method, *Earth, Planets and Space*, vol. 77, no. 1, p. 37, Mar. 2025, doi: 10.1186/s40623-025-02168-y.

[6] L. Wan, S. Li, R. Ye, Y. Wang, Z. Ma, and T. Lin, Three-dimensional gravity forward modelling based on rectilinear grid and Block–Toeplitz Toeplitz–Block methods, *Geophysical Prospecting*, vol. 73, no. 2, pp. 459–470, 2025, doi: 10.1111/1365-2478.13658.

[7] A. M. León-Sánchez, E. L. Flores-Márquez, and A. Tejero-Andrade, Three-dimensional joint inversion of potential field datasets constrained by cross-gradient and depth weighting, *Acta Geophys*., vol. 73, no. 4, pp. 3385–3404, Aug. 2025, doi: 10.1007/s11600-025-01561-1.

[8] H. Xu, Q. Wang, J. Yu, O. B. Anderson, Y. Tian, and N. Xu, Topography prediction from marine gravity and satellite imagery and ship soundings, *Geophysical Journal International*, vol. 241, no. 2, pp. 919–933, May 2025, doi: 10.1093/gji/ggaf075.

[9] W. Chen and X. Tan, An efficient algorithm for gravity forward modelling (GFM) with masses of arbitrary shapes and density distributions, *Geophysical Journal International*, vol. 239, no. 3, pp. 1485–1516, Dec. 2024, doi: 10.1093/gji/ggae343.

[10] I. Gunawan, N. Prasetyo, and S. Alawiyah, A High Resolution of Terrain of Bandung Area, *ICGERE 2024, IOP Conference Series: Earth and Environmental Science*, 1437, 012014, 2024, doi:10.1088/1755-1315/1437/1/012014

[11] I. Gunawan, and S. Alawiyah, Terrain Correction in Gravity Data Processing using Hybrid Land Survey and Shuttle Radar Topography Mission Digital Elevation Model: A Case Study in Mount Pandan, Indonesia, *APS 2021, Journal of Physics: Conference Series,* 2243, 01012, 2021, doi:10.1088/1742-6596/2243/1/012012

[12] B. Sadraeifar, R. Ghanati, M. H. Rezayee, M. Abedi, S. H. Hosseini, and V. E. Ardestani, Joint interpretation of potential field data using independent Lpq norm inversion and geological modeling: Application to Iron targeting in Central Iran, *Physics of the Earth and Planetary Interiors*, vol. 362, p. 107347, May 2025, doi: 10.1016/j.pepi.2025.107347.

[13] Gunawan, I., Wahyudi, E. J., Alawiyah, S., Kadir, W. G. A., & Fauzi, U.. Annotation of Using Borehole Time-Lapse Gravity by Genetic Algorithm Inversion for Subsurface Modeling., *Journal of Engineering and Technological Sciences*, 52(2), 153–165, 2020, https://doi.org/10.5614/j.eng.technol.sci.2020.52.2.2

[14] Hinze, W. J., von Frese, R. R. B., & Saad, A. H., Gravity and magnetic exploration: Principles, practices, and applications. *Cambridge, Cambridge University Press*. 2012, https://doi.org/10.1017/CBO9780511843129

[15] A. Del Razo Gonzalez and V. Yutsis, Robust 3D Joint Inversion of Gravity and Magnetic Data: A High-Performance Computing Approach, *Applied Sciences*, vol. 13, no. 20, Art. no. 20, Jan. 2023, doi: 10.3390/app132011292.

[16] J. Bu et al., Marine gravity gradient model calculation based on wavelet numerical integration and CUDA parallel, *Computers & Geosciences*, vol. 196, p. 105852, Feb. 2025, doi: 10.1016/j.cageo.2025.105852.

[17] S. Dai, D. Zhu, Q. Chen, and H. Tian, Three-dimensional quasi-complete information numerical simulation of gravity anomalies and parallel computing on CPU-GPU, *Phys. Scr.*, vol. 99, no. 12, p. 125227, Nov. 2024, doi: 10.1088/1402-4896/ad8d39.

[18] C. Wu, X. Su, C. Xu, G. Jian, and J. Li, Seafloor topography refinement from multisource data using genetic algorithm—backpropagation neural network, *Geophysical Journal International*, vol. 238, no. 3, pp. 1417–1428, Sep. 2024, doi: 10.1093/gji/ggae229.

[19] X. Li, dan M. Chouteau, "Three-dimensional gravity modeling in all space." *Surveys in Geophysics*, 1998,19, 339-368.

[20] I. Gunawan, and S. Alawiyah, Simulasi Numerik untuk Menentukan GayaGravitasi Bawah Permukaan Pada ModelPrisma Segiempat. *Indonesian Journal of Computing,* 2018, Vol 1(2), pp. 47-56. doi:10.21108/indojc.2016.1.2.88

[21] F. Niu, S. Chen, Y. Li, H. Li, Y. Niu, and Y. Pan, "Simultaneous estimation of Bouguer gravity anomaly and near-surface density using Bayesian approach: A Yunnan case study," *Appl. Geophys*., Apr. 2025, doi: 10.1007/s11770-025-1202-3.

[22] Q. Wang et al., Enhanced Seafloor Topography Inversion Using an Attention Channel 1D Convolutional Network Based on Multiparameter Gravity Data: Case Study of the Mariana Trench, *Journal of Marine Science and Engineering*, vol. 13, no. 3, Art. no. 3, Mar. 2025, doi: 10.3390/jmse13030507.

[23] T. Banković, L. Brajković, A. Banko, and M. Pavasović, *The Impact of Gravity on Different Height Systems: A Case Study on Mt. Medvednica,* Applied Sciences, vol. 15, no. 10, Art. no. 10, Jan. 2025, doi: 10.3390/app15105680.

[24] X. Feng, L. Yang, J. Ma, C. Wu, and K. Liu, 2.5D Regularized Gravity Data Inversion for the Detection of Faults in Basement Rocks, *Pure Appl. Geophys.*, vol. 180, no. 9, pp. 3319–3338, Sep. 2023, doi: 10.1007/s00024-023-03326-7.

[25] M. E. Tokhey, M. Elhabiby, A. Ragheb, M. Shebl, Gravity and Density Relationship (Forward Modeling), *International Journal of Scientific & Engineering Research*, Vol 6(1), 2015, pp. 1359-1363.