MARINE GRAVITY ANOMALIES

CE678 PROJECT

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Abstract

This study examines marine gravity anomalies over the Mariana Trench using Sea Surface Height (SSH) data from SARAL satellite altimetry to reveal subsurface tectonic structures. Gravity anomalies, linked to variations in seafloor topography and subsurface density, are extracted through SSH data, analyzed, and mapped using advanced interpolation techniques. Calculations of slope, azimuth, xi, and eta, coupled with kriging interpolation, highlight detailed tectonic features. Findings improve geoid models, contributing to oceanographic, geophysical, and hydrocarbon exploration, underscoring SSH's significant role in marine geophysics.

Introduction

Marine gravity anomalies give information on changes in the gravity field over ocean basins. In other words, they are described as gridded gravity data, which have variations in subsurface structures, tectonic activities, and crustal density variations. Underwater topography and density heterogeneities result in variations in gravity anomalies, which allow scientists to identify ridges, trenches, and seamounts and thereby gain insights on ocean floor morphology and conditions of mantle convection along with those of subduction zones.

Traditionally, marine gravity data have been acquired using very high-accuracy shipborne gravimetry that was both spatially very limited and expensive. It is now possible with advances in satellite altimetry to revisit the field with global coverage and continuous updates of areas previously inaccessible. The most recent missions such as CryoSat-2, SARAL/AltiKa, and Jason yield very accurate gravity anomaly measurements from the SSH data, thus very high detail maps of these regions previously inaccessible.

Separation methods of gravity anomaly have also been subjected to some research. Hwang and Parsons (1996) laid a foundation in work of developing efficient deterministic and stochastic methods, and Hwang et al. (2002) improved the inverse Vening-Meinesz formula for noise reduction. Region-specific investigations include Annan and Wan 2021, in the Gulf of Guinea, and Nguyen et al. 2020, in the Gulf of Tonkin, which show the utilization potential of multi-satellite combinations. This study utilizes SARAL data to examine gravity anomalies in the Mariana Trench and enhances geoid models, making them even more useful for various practical purposes in geophysical research as well as resource exploration.

Mathematical Details

The project area is defined as follows-

- 12° x 12° grid data has taken for the analysis in Mariana trench region to study the marine gravity anomaly.
- Specified coordinates
- Southwest Corner: (5°N, 136°E)
- Southeast Corner: (5°N, 148°E)
- Northwest Corner: (17°N, 136°E)
- Northeast Corner: (17°N, 148°E)

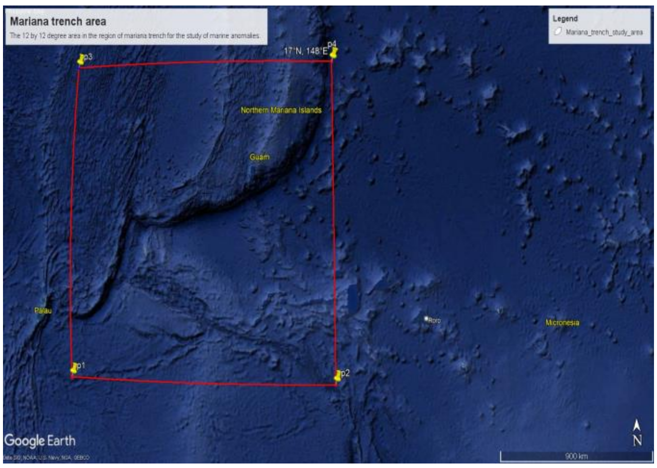

Fig.- Project area (Mariana Trench Region)

Information of the data is as follows-

- **SARAL** satellite data is used to find the marine gravity anomaly.

- Data is collected from **14th March 2013 to 4th July 2016.**
- Total **35 cycles** are from 001, 002 and so on to 035.
- In **1st cycle** there is only **34 passes.**
- From **2nd to 34th cycle** there is **36 passes.**
- In **35th cycle** there is only **18 passes**.

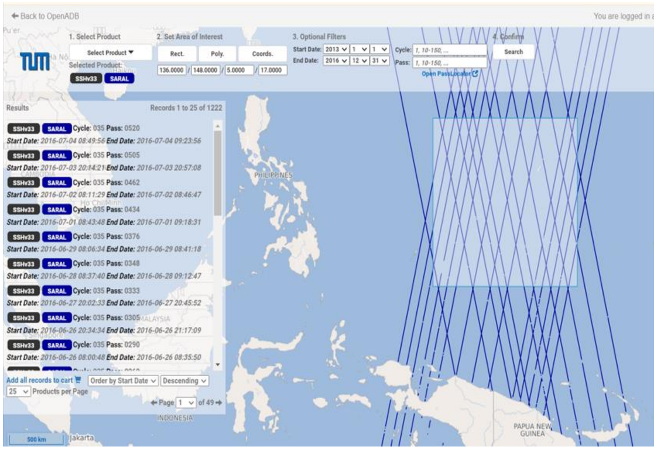

Fig.- Cycle Data from OpenADB website

Information of Ascend and Descend pass

Ascending passes are chosen for analysis, specifically focusing on passes in a 35x18 matrix format which represent 35 cycles with 18 passes each.

Calculating Ascending or Descending Pass-

Two time points are noted. Time 1 at a specific latitude and longitude (lat1, long1). Time 2 at another latitude and longitude (lat2, long2).

By comparing latitudes between these two points:

- If the latitude at Time 2 (lat2) is greater than at Time 1 (lat1), the pass is ascending, indicated as a positive difference.

- If the latitude at Time 2 (lat2) is less than at Time 1 (lat1), the pass is descending, indicated as a negative difference.

Thus, an ascending pass is defined by a positive change in latitude between two consecutive points along the satellite's path.

This method allows for distinguishing between ascending and descending orbits based on the satellite's movement direction relative to latitude.

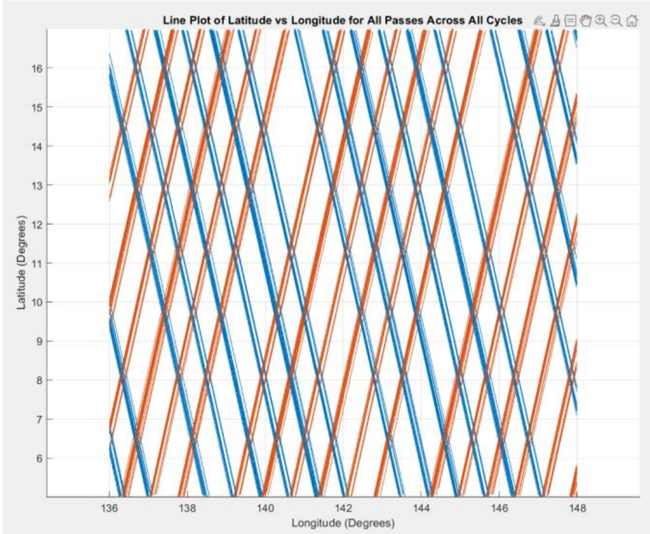

Fig.- All passes across all cycles

Sea Surface Height (SSH)

Sea Surface Height is the difference between the ocean surface height and a reference ellipsoid, typically measured via satellite altimetry. SSH data is essential for monitoring temporal changes at the ocean surface caused by tides, currents, and gravity anomalies from underwater topography and subsurface density variations. Changes in SSH reflect gravitational field variations across the ocean floor, making it valuable in marine gravity anomaly studies.

2D Plot: The 2D SSH plot displays sea surface height variations across the region, with latitude and longitude as axes. Darker areas indicate lower heights, and lighter areas show higher ones, potentially reflecting underwater features like ridges or trenches and aiding in identifying tectonic structures.

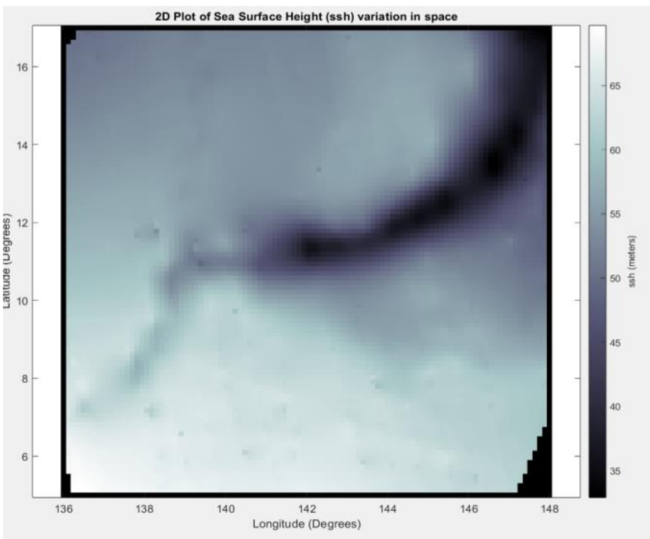

Fig.- 2D plot of SSH variation

3D Plot: The 3D plot represents SSH as the vertical axis, with latitude and longitude as horizontal axes, providing a dynamic view of SSH variations. Peaks and valleys in the plot correlate with underwater features like ridges and trenches, revealing geological and topographical influences on the ocean surface.

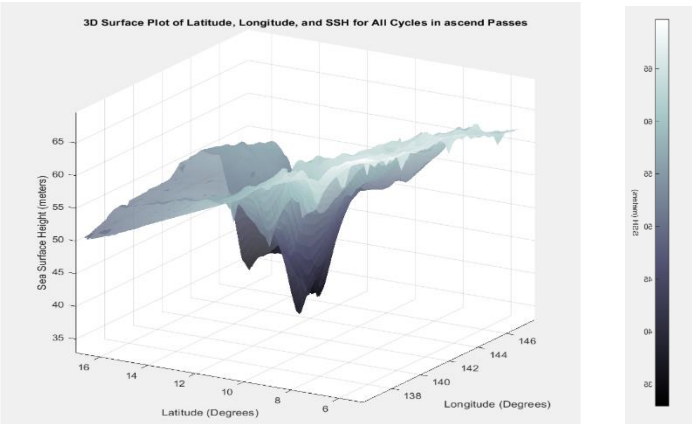

Fig.- 3D plot of SSH variation

Analysis of SSH Data

1. Mean: The average SSH value within each cell, indicating the typical surface height in that area.

2. Median: The middle value of sorted SSH data in each cell, providing a central tendency measure less affected by extremes.

3. Standard Deviation: Shows how spread out SSH values are around the mean, indicating variability within the cell.

4. Z-Score: Converts SSH values to a standardized format, showing deviations from the mean, making it easier to spot unusual values.

5. List of Outliers: Identifies SSH values that deviate significantly from the average, signaling localized variations or unique features.

6. Number of Outliers: Counts the outliers in each cell, indicating areas with frequent unusual values.

7. Percentage of Outliers: The proportion of outliers in each cell, helping locate regions with high anomaly concentrations.

Together, these metrics help to assess SSH variability and detect patterns or anomalies across the data grid.

Interpolation Using Nearest Neighbor Method

The nearest neighbor interpolation method is used for areas where SSH data is sparse or missing. This technique assigns values to empty grid cells based on the closest neighboring cell with available data, ensuring continuity across the grid without introducing artificial trends. Nearest neighbor interpolation is simple yet effective for spatial data, preserving original data values and filling gaps while maintaining overall data integrity.

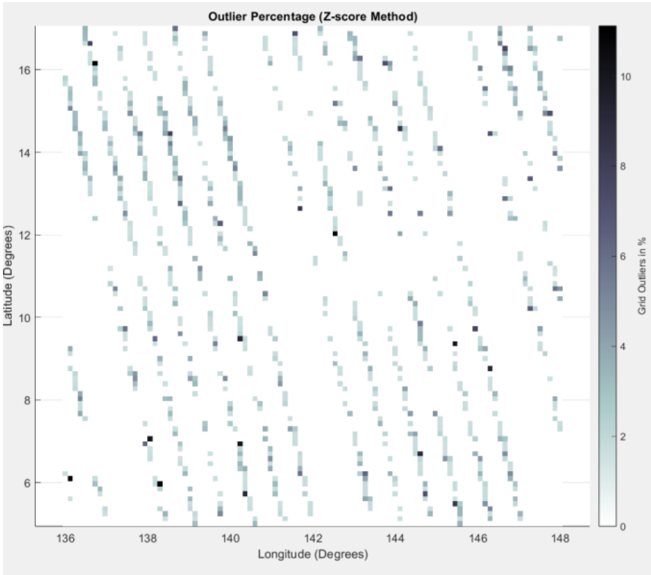

Fig.- Outlier Percentage of SSH data

Methods

Calculate Slope & Azimuth

For this project, we have a 100x100 grid, and we calculated the slope and azimuth values between points in the grid using the Haversine formula.

Slope calculation formula:

Calculate the Haversine formula component a_{hav}:

$$a_{\text{hav}} = \sin^2\left(\frac{\Delta\varphi}{2}\right) + \cos(\varphi_i) \cdot \cos(\varphi_j) \cdot \sin^2\left(\frac{\Delta\lambda}{2}\right)$$

where:

- $\Delta\varphi = \varphi_j - \varphi_i$: Difference in latitude between points i and j (in radians).
- $\Delta\lambda = \lambda_j - \lambda_i$: Difference in longitude between points i and j (in radians).
- φ_i and φ_j: Latitudes of points i and j (in radians).

Calculate the central angle c:

$$c = 2 \cdot \operatorname{atan2}\left(\sqrt{a_{\text{hav}}}/\sqrt{1 - a_{\text{hav}}}\right)$$

Calculate the Haversine distance:

$$\text{distance} = a \cdot c$$

$$\text{slope} = \frac{h_j - h_i}{d_{ij}} = \frac{\delta N}{\delta s} + \epsilon$$

This approach allowed us to determine distances (sij) between latitude and longitude coordinates for each grid cell.

The slope and azimuth values are computed for each 0.12° x 0.12° box, with some values missing due to data gaps. Midpoints of latitude and longitude were also calculated in each grid cell.

Azimuth calculation formula:

$$\alpha = \arctan\left(\frac{\cos\varphi_j \sin(\lambda_j - \lambda_i)}{\cos\varphi_i \sin\varphi_j - \sin\varphi_i \cos\varphi_j \cos(\lambda_j - \lambda_i)}\right)$$

Calculation of Xi and Eta

The xi and eta values are calculated within every small grid using an adjustment computation method (observation equation method).

These parameters are measured in radians, and their values are typically within the range of 1e-4.

Each 0.12° x 0.12° grid may have varying numbers of observation equations (e.g., 36, 45, etc.).

- Total number of xi values: 3189
- Total number of eta values: 3189

Adjustment Computation Formula for Xi and Eta :

$$\frac{\delta N}{\delta s} + \epsilon = \xi \cos\alpha + \eta \sin\alpha$$

A line plot of xi and eta values is created to identify any irregularities or outliers in the data.

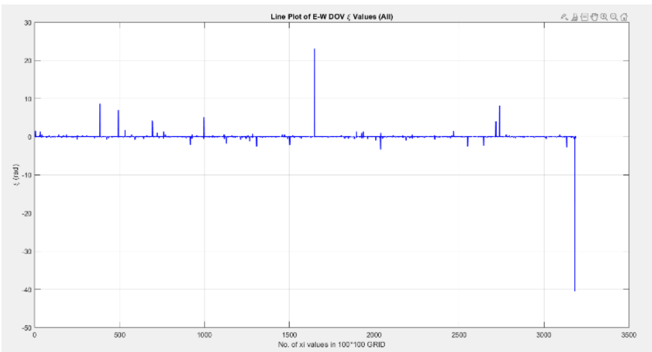

Fig.- Line plot of xi values with outliers

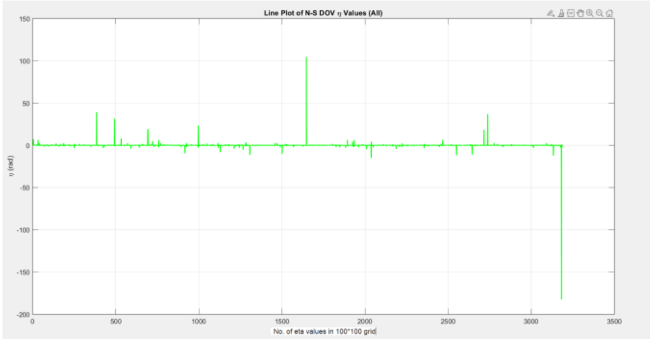

Fig.- Line plot of eta values with outliers

Analyze and Clean Xi & Eta Values

To ensure accurate interpolation, outliers in xi and eta values are removed if they exceed a threshold (abs(0.1)).

After cleaning, the data is re-plotted to verify uniformity across the 100x100 grid. This step ensures a smoother analysis and prepares the dataset for interpolation.

Outlier Removal:

Threshold check for outliers: abs(value) > 0.1

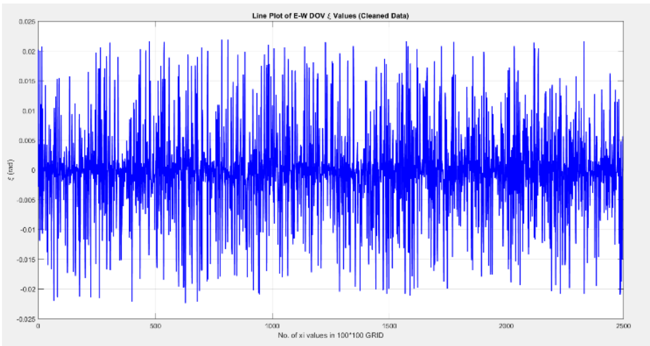

Fig.- Line Plot of xi values(cleaned)

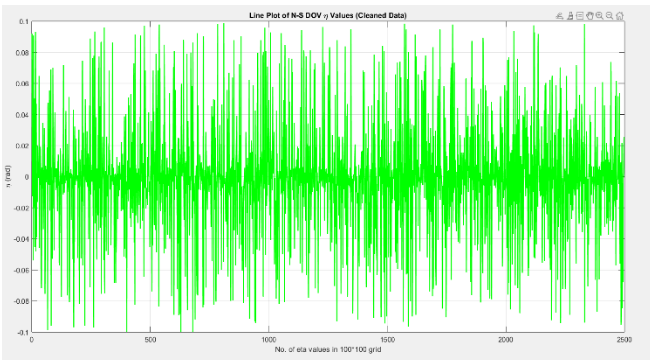

Fig.- Line Plot of eta values(cleaned)

1.Percentage of values removed in xi: 3.857

2.Percentage of values removed in eta: 10.7244

Interpolate Xi & Eta Values

Gaussian Random Process (GRP) interpolation, or Gaussian Process Regression (GPR), estimates values by modelling data as a continuous Gaussian process based on spatial correlations.

It uses a covariance function (kernel) to define relationships between points, fitting the model to known data to create a smooth, interpolated surface.

GPR predicts values across the area, providing both estimates and uncertainty measures for each location, making it effective for sparse data.

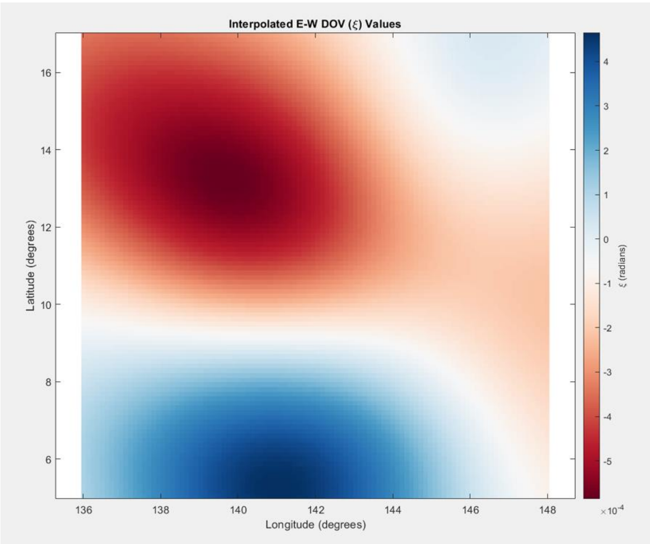

Fig.- Interpolated xi values

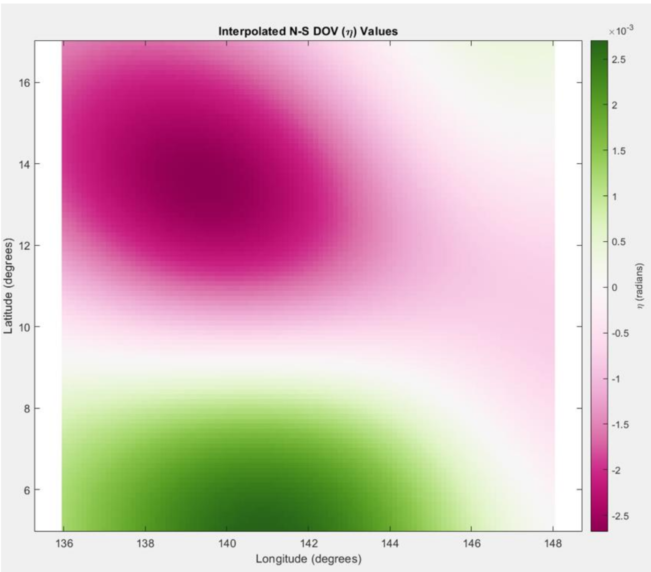

Fig.- Interpolated eta values

Results

Calculate Normal Gravity for 100x100 Grid

Using ellipsoid parameters and the Somigliana-Pizzetti formula, normal gravity (γ) is calculated for each point within the 100x100 grid.

This calculation accounts for the latitude of the grid center, ensuring an accurate gravity model.

Somigliana-Pizzetti Formula for Normal Gravity

$$\gamma = \frac{a\,\gamma_a \cos^2\varphi + b\,\gamma_b \sin^2\varphi}{\sqrt{a\cos^2\varphi + b\sin^2\varphi}}$$

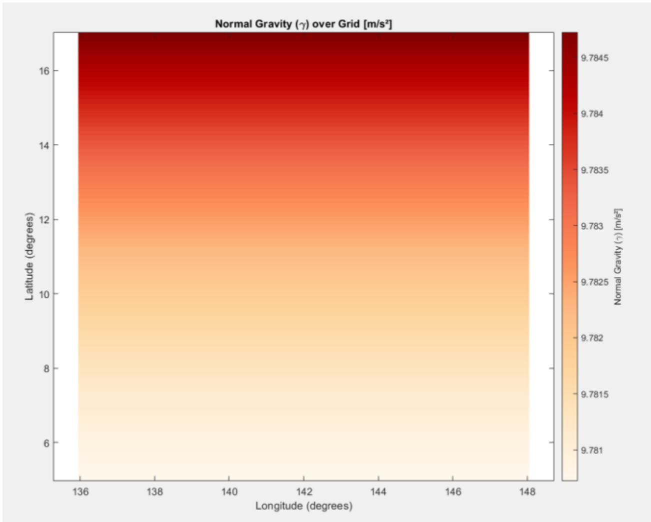

Fig.- Normal Gravity over grid.

Calculate Gravity Anomaly Using Vening Meinesz Formula

$$\Delta g = \mathcal{F}^{-1}\left\{-\iota\frac{\gamma}{|k|}\left[k_x\mathcal{F}(\xi) + k_y\mathcal{F}(\eta)\right]\right\}$$

The Vening Meinesz formula is employed to compute gravity anomalies across the grid.

These anomalies reveal subsurface density variations essential for geological interpretation.

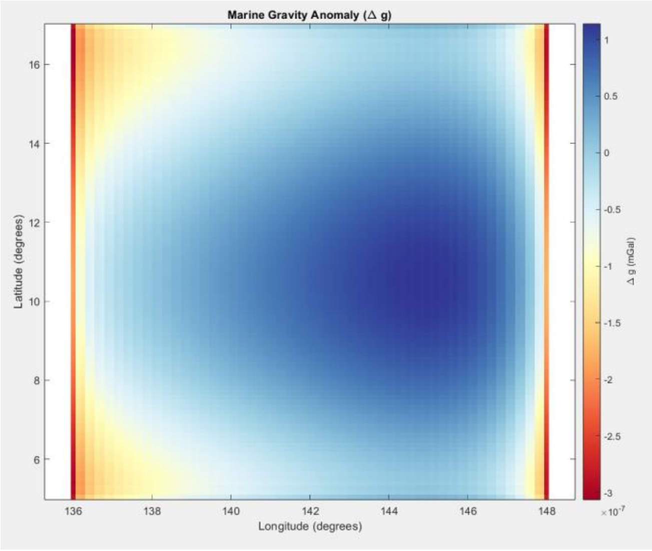

Fig.- Marine Gravity Anomaly

A plot of the gravity anomalies across the grid provides insights into subsurface density features. This visual representation aids in identifying geological structures in the study area.

Discussion

This study used Sea Surface Height (SSH) data provided by the altimetry of the SARAL satellite in order to map anomalies of marine gravity in the Mariana Trench, characterized by outstanding, fully expressed tectonic features and subsurface variations of density. Advanced interpolation techniques, including kriging and GRP interpolation, have been applied to map SSH variations with good accuracy as well as calculated slope, azimuth, xi, and eta values. This identified gravity anomaly yields an understanding of geological structures like ridges and trenches; however, its use is significant with regard to satellite altimetry for even high-resolution mapping over vast oceanic regions inaccessible with traditional shipborne gravimetry. Application of multiple statistical analyses, including Z-scores and outlier detection, allowed a highly precise anomaly identification step to contribute both to theoretical geophysics and practical application, like hydrocarbon exploration.

Conclusion

This study successfully mapped the marine gravity anomalies in the Mariana Trench thus significantly improving tectonic and oceanographic dynamics. It evaluated innovative data processing, which enabled a sophisticated use of SSH data toward subsurface features, making it productive for such detection purposes. In general, the research outcomes underline satellite altimetry's essential role in geophysical research and provide a valuable framework for future research in other oceanic regions, ultimately helping the scientific exploration and resource identification process.