SPATIAL PATTERN OF GLOBAL STRONG SEISMICITY: A FRACTAL-GRAVITY INTEGRATED ANALYSIS

Boyko Ranguelov, Rosen Iliev

Space Research and Technology – Bulgarian Academy of Sciences
e-mail: branguelov@gmail.com, ilievrosen@space.bas.bg

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Abstract: *Understanding the spatial relationship between lithospheric heterogeneity and strong seismicity is important for global geodynamic studies. This study investigates the nonlinear spatial association between gravity anomalies and strong earthquakes using a variogram-based fractal dimension (FD) approach. High-resolution global Bouguer, Free-Air, and Isostatic gravity anomalies from the World Gravity Map 2012 were analyzed and compared with a global catalog of 5162 earthquakes of M ≥ 6.0 recorded between 1990 and 2025. Spatial statistical analyses, including Moran's I, bivariate Moran's I, Pearson correlation, and local cluster analysis, reveal a strong spatial association between earthquake epicenters and gravity-anomaly fractal dimensions. Most strong earthquakes occur in areas with FD values of 1.0–1.6, while events of M ≥ 8.0 are predominantly associated with FD values below 1.4 across all gravity anomaly types. These results indicate that fractal characteristics of gravity fields can capture tectonic complexity and lithospheric discontinuities associated with strong seismicity. The proposed methodology provides a framework for characterizing tectonically complex zones associated with strong seismic activity and may contribute to the spatial analysis of cascading multi-hazard events within the "Space and Ground Technologies for Studying Cascading Multi-hazard Events – Models, Applications, Precursors (SPARC)" project.*

ПРОСТРАНСТВЕНО РАЗПРЕДЕЛЕНИЕ НА ГЛОБАЛНАТА СИЛНА СЕИЗМИЧНОСТ: ИНТЕГРИРАН ФРАКТАЛЕН И ГРАВИМЕТРИЧЕН АНАЛИЗ

Бойко Рангелов, Росен Илиев

Институт за космически изследвания и технологии – Българска академия на науките
e-mail: branguelov@gmail.com, ilievrosen@space.bas.bg

Резюме: *Разбирането на пространствената връзка между хетерогенността на литосферата и силната сеизмичност е важно за глобалните геодинамични изследвания. В настоящата работа е изследвана нелинейната пространствена зависимост между гравитационните аномалии и силните земетресения чрез фрактална размерност, изчислена посредством вариограмен анализ. Анализирани са глобални данни от World Gravity Map 2012 за аномалиите на Буге, свободен въздух и изостатичните аномалии, сравнени с каталог от 5162 земетресения с M ≥ 6.0 за периода 1990–2025 г. Пространствено-статистическите анализи, включващи Moran's I, двувариантния Moran's I, корелацията на Пиърсън и локален клъстерен анализ, показват силна положителна пространствена зависимост между епицентрите и фракталната размерност (FD) на гравитационните аномалии. Повечето земетресения са концентрирани в области с FD = 1.0–1.6, докато най-силните събития (M ≥ 8.0) преобладават при FD < 1.4 за всички изследвани типове аномалии. Резултатите показват, че фракталните характеристики на гравитационното поле могат да отразяват тектонската сложност и литосферните неоднородности, свързани със силната сеизмичност. Предложеният подход предоставя методическа рамка за пространствено характеризиране на зони, свързани със силна сеизмична активност, и може да подпомогне анализа на каскадни мултирискови събития в рамките на проекта „Космически и наземни технологии за изследване на каскадни мултирискови събития – модели, приложения, прекурсори" (SPARC).*

Introduction

Understanding the spatial complexity of Earth's lithosphere and its relationship with seismicity remains a central challenge in geophysics. Natural surfaces and tectonic structures commonly exhibit scale-invariant properties that can be described using fractal geometry (Voss, 1988; Turcotte, 1997). Among the approaches used to quantify spatial complexity, variogram-based methods provide an effective means of estimating local fractal dimension (FD) from raster data (Oliver & Webster, 2014).

In seismology, FD can characterize the spatial complexity and structural heterogeneity of fault systems, with higher values generally associated with more irregular and multi-segment fault structures and tectonically complex environments capable of generating strong earthquakes (Aydindag & Kirci, 2021; Chauhan & Dixit, 2024; Zhao et al., 2025). High-resolution FD mapping can therefore contribute to the characterization of tectonic environments and the identification of zones associated with strong seismic activity, particularly along convergent and divergent plate boundaries. In this study, intraplate earthquakes are not considered because they are relatively rare and commonly occur within more spatially homogeneous crustal environments.

Gravity anomalies provide important information on subsurface mass distribution and lithospheric density variations. The World Gravity Map 2012 (WGM2012) integrates satellite (GRACE, GOCE), terrestrial, and airborne gravity observations to produce global grids of Free-Air, Bouguer, and Isostatic gravity anomalies (Bonvalot et al., 2012). These datasets provide information on crustal and lithospheric structures, including rifts and subduction zones, many of which are associated with active tectonic deformation and seismicity.

The present study combines variogram-based fractal analysis, global gravity anomaly data, and seismicity records from the United States Geological Survey (USGS) to investigate the spatial relationship between gravity-field complexity and strong earthquake locations. Using a global catalog of earthquakes with M ≥ 6.0 recorded between 1990 and 2025, we examine whether spatial variations in the fractal dimension of gravity anomalies are associated with the distribution of strong earthquake epicenters. This approach provides a framework for investigating the relationship between lithospheric heterogeneity, tectonic complexity, and strong seismic activity.

Working methods, data and software

Variogram Method for Fractal Dimension Calculation

This study uses the variogram-based technique to assess fractal characteristics of gravity data, producing spatially explicit fractal dimension maps. The method is based on the idea that natural surfaces often show self-affine or scale-invariant features, which can be quantified through geostatistical measures like the variogram (Voss, 1984; Oliver & Webster, 2014). The analytical procedure used algorithm, implemented in Python within the QGIS environment, utilizing GDAL for raster I/O and NumPy for numerical computations.

For each selected window the following analytical steps were applied:

- Moving Window Analysis

Local fractal dimensions are calculated using a moving square window of fixed size 64 × 64 pixels. The window is shifted across the raster with a step of 16 pixels in both directions.

- Variogram computation and power-law scaling assessment

An experimental variogram is approximated using squared differences between pixel values for lag distances from 1 to 6 pixels. For computational efficiency, only horizontal and vertical pixel pairs are considered. For each lag h, the variogram value is computed as the average of squared differences in both directions and normalized by a factor of 1/4.

- Fractal dimension estimation

The local fractal dimension FD of the 2D surface was derived directly from the variogram slope using the well-established relation for self-affine fractional Brownian surfaces:

(1) $FD = 2 - (m / 2)$

Fractal Dimension (FD) near 2 indicates for higher gravity values variability, while values near 1 correspond to smoother gravity values variability.

Global Gravity Model WGM2012

The World Gravity Map 2012 (WGM2012) is a global gravity dataset developed by Bureau Gravimétrique International (BGI), integrating satellite gravity (GRACE, GOCE) with terrestrial and airborne gravimetric data (Bonvalot et al., 2012). WGM2012 includes grids of Bouguer anomaly, Free-Air anomaly, isostatic residuals, and crustal thickness at 1 arc-minute (~ 2 km) resolution. It refines the EGM2008 satellite gravity model by assimilating ground data and digital elevation models to better remove topographic effects (Pavlis et al., 2012). WGM2012 is widely used in geodynamic studies, calibrated with seismic and geophysical observations.

Tectonic boundaries were referenced using the digital plate boundary dataset by Bird (2003).

Seismic Data

Seismic analysis uses data from the USGS Seismic Hazard Program's global earthquake catalog (https://earthquake.usgs.gov/earthquakes/search/). A random seed–based selection was performed to generate a statistically representative sample of 5162 earthquakes with magnitude M ≥ 6.0 from the period 1990–2025.

Software

Spatial and statistical analysis within this study was performed in QGIS (python-based scripts) and GeoDa environment, an open-source GIS platforms widely used in Earth sciences.

Results and discussion

This analysis is based on a refined random sample of 5162 earthquakes with M ≥ 6.0, focusing on possible relationships between earthquake locations, gravity anomalies, and their fractal dimensions (FD) (Fig. 1). Gravity anomaly distributions provide critical insight for the subsurface mass structure surrounding the sampled earthquake locations.

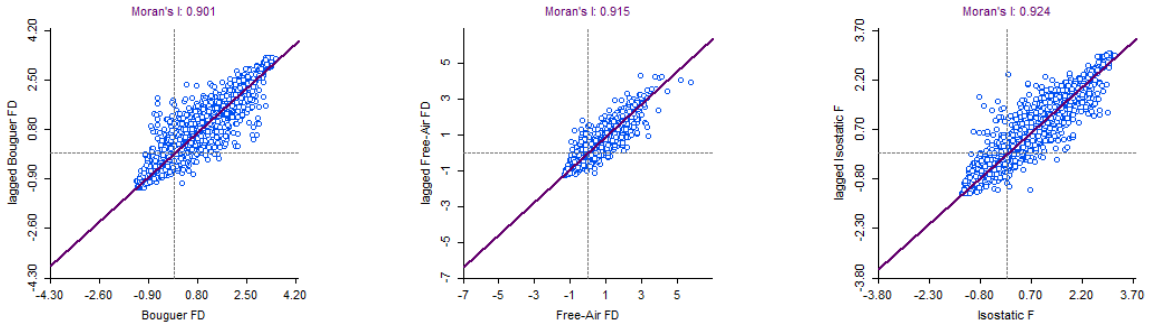
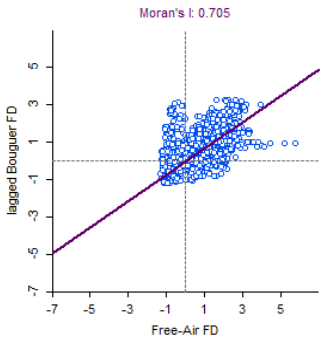
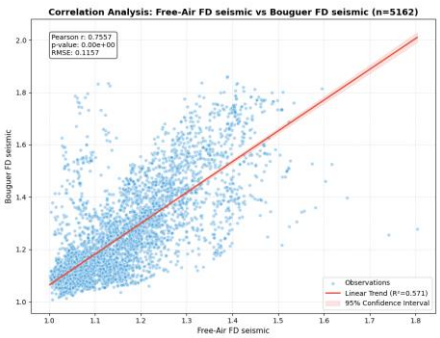
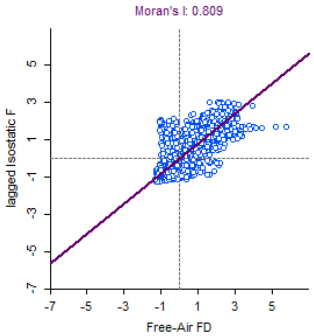
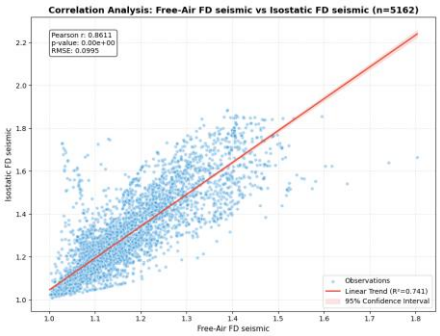


Fig. 1. Univariate Moran's I spatial autocorrelation analysis of strong earthquakes locations and corresponding gravity FD

The results in Figure 1 confirm the positive spatial autocorrelation of earthquakes with the values variation of gravity anomalies, expressed through the fractal dimension. The Moran's I values for all three types of anomalies are above 0.9, which is an indicator of a very strong relationship.

The statistical analysis (Bivariate Moran's I and Pearson Correlation) from Figure 2 indicates that M ≥ 6.0 seismic locations have a positive spatial autocorrelation with local FD gravity anomalies. Bivariate Moran's I analysis show very strong spatial autocorrelation between earthquakes and FD gravity anomalies, between 0.7 and 0.8 for three gravity types. The Pearson Correlation shows even stronger correlation (between 0.7–0.9), while the most prominence is the relation between earthquakes and corresponding Bouguer-Isostatic FD (r = 0.9135).

	Bivariate Moran's I	Pearson Correlation
Bouguer FD vs Free-Air FD		
Free-Air FD vs Isostatic FD		

Isostatic FD vs Bouguer FD

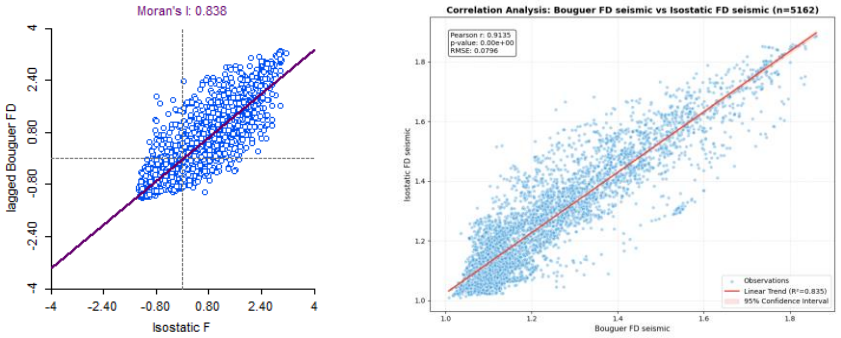
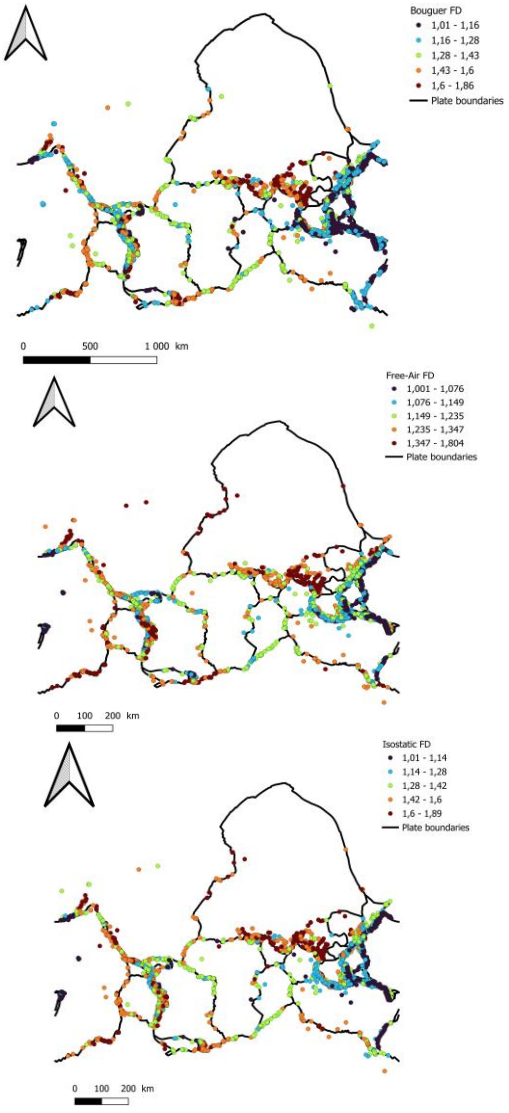


Fig. 2. Analysis of spatial and statistical relationship of FD gravity anomalies and strong earthquakes epicenters

The results in Figure 2 show that, above all, the fractal dimension of gravity anomalies can serve as a predictor of global strong seismicity. Fractal model of gravity anomalies captures sharp transitions in the Earth's crust and marks areas of tectonic dislocations. The fractal dimension is an indicator of sharp transitions, but can specific FD ranges be identified where seismic foci are concentrated? Figure 3 shows that strong earthquakes are concentrated in areas with fractal dimension of gravity anomalies, in ranges between 1.0–1.6 (95% of cases) for Bouguer, 1.0–1.5 (98% of cases) for Free-Air, and between 1.0–1.5 (98% of cases) for Isostatic anomaly. This distribution indicates low to moderate gravity values variation. The studied earthquakes have FD mean value 1.23 for Bouguer, 1.14 for Free-Air and 1.26 for Isostatic gravity anomaly.



	Bouguer FD
FD min	1.00
FD max	1.86
FD mean	1.23
StdDev	0.17

	Free-Air FD
FD min	1.00
FD max	1.80
FD mean	1.14
StdDev	0.11

	Isostatic FD
FD min	1.00
FD max	1.88
FD mean	1.26
StdDev	0.19

Fig. 3. Gravity FD ranges and strong earthquakes spatial concentration (Plate boundaries: Bird, 2003)

As shown in Figure 3, clear spatial patterns are evident in the distribution of FD gravity values. Earthquakes along the Alpine-Himalayan collision belt and the eastern Pacific Ring of Fire are generally associated with the highest FD values, whereas the western Pacific Ring of Fire and adjacent Indo-Australian Plate show lower values. Divergent plate boundaries are generally characterized by moderate FD values of approximately 1.3–1.4.

Cluster analysis indicates positive spatial autocorrelation between earthquake epicenters and all three gravity-anomaly FD types in approximately 97% of cases. Only 2.7% of earthquakes show no significant spatial correlation, predominantly in the Indian Ocean and eastern Pacific, while negative spatial autocorrelation occurs in only about 0.2% of events.

The strongest earthquakes ($M \geq 8.0$) are consistently associated with relatively low gravity FD values. Mean FD values are 1.22 for Bouguer, 1.15 for Free-Air, and 1.25 for Isostatic anomalies, with most values below 1.4 and predominantly within the 1.1–1.3 range. Spatially, the lowest values occur mainly along the western Pacific and Java trench regions, while somewhat higher values characterize the eastern Pacific.

No significant relationship was identified between gravity-anomaly FD values and earthquake magnitude or focal depth.

Conclusion

The constructed model reveals a positive spatial autocorrelation between the fractal dimension of gravity anomalies (Bouguer, Free-Air, and Isostatic) and strong seismic events ($M \geq 6.0$), located along the boundaries of divergent and convergent tectonic plates. The nonlinear behavior is confirmed by the calculated fractal dimensions and may serve as an important indicator for the occurrence of strong earthquakes. These results are consistent with the global distribution of strong earthquakes, which is well established in geodynamics and plate tectonics theory. Future local and regional studies, as well as more detailed investigations applying the same methodology, could help extract additional information from a geodynamic perspective.

Acknowledgements

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