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SPATIAL CHARACTERIZATION OF GAMMA RADIATION ON THE SHUMEN PLATEAU: THE ROUTE TO THE FOUNDERS OF THE BULGARIAN STATE MONUMENT

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Abstract
Mobile georeferenced measurements provide an effective approach for investigating the spatial variability of environmental radioactivity. This study investigates the spatial distribution of gamma radiation along a pedestrian route in the Shumen Plateau Nature Park leading to the "Founders of the Bulgarian State" Memorial Complex, using a portable Radiacode 103G gamma-ray spectrometer. Statistical and spatial analytical techniques were applied to evaluate data distribution, spatial autocorrelation, and local clustering. The results provide insight into the spatial variability observed along the route and demonstrate the potential of mobile georeferenced measurements for detailed spatial gamma radiation characterization.

Keywords: environmental gamma radiation, dose rate, Shumen Plateau, spatial distribution, CPS, public exposure.

INTRODUCTION

Natural background radiation is an inherent component of the environment. Its measured levels may vary depending on geological composition, soil characteristics, topography, vegetation, and the presence of anthropogenic structures [1]. Spatial analysis of gamma radiation makes it possible to identify local variations and characterize its distribution within a defined area or along a specific route [2].

Shumen Plateau Nature Park is an area of considerable historical, cultural, and recreational significance. The route to the "Founders of the Bulgarian State" Memorial Complex is used by residents of Shumen and visitors for leisure walks, tourism, and physical activity [3]. This highlights the importance of evaluating the spatial variability of gamma radiation in an area with high public exposure.

Conventional environmental gamma radiation assessments are mainly based on static point measurements or surveys conducted using vehicle-mounted and airborne systems. Although these approaches provide valuable information over large regions, they do not always offer sufficient spatial resolution in areas that are primarily accessible on foot [4]. The development of compact, portable radiation detectors and their integration with global positioning systems (GPS) create opportunities for more detailed characterization of the radiation environment [5].

The aim of this study is to characterize the spatial variability of gamma radiation along a selected route on the Shumen Plateau Nature Park, leading to the "Founders of the Bulgarian State" Memorial Complex. Measurements were obtained using a

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portable Radiacode 103G detector. The resulting georeferenced data were subjected to statistical processing and spatial analysis to describe the measured values and investigate their distribution along the route.

EXPOSITION

The study was conducted along a route in the city of Shumen and leading to the Shumen Plateau Nature Park and the Memorial Complex "Founders of the Bulgarian State". The complex is situated at an elevation of approximately 450 m above sea level. It was built to commemorate the 1 300th anniversary of the founding of the Bulgarians state. The architectural and artistic composition consists of eight concrete structures arranged in a spatial formation. It also includes a large-scale mosaic triptych. Today, the complex is a site of national cultural and tourism significance. It is included in Bulgaria's list of 100 National Tourist Sites and is connected to the city of Shumen by a staircase of 1 300 steps [6].

Measurements and Investigated Parameters

Measurements were carried out on 20 September 2026, from 09:30:27 to 10:04:13, at 467 measurement points. The mean air temperature was 23.5 °C. The route includes three main locations: P1 – the Freedom Monument, marking the starting point of the route; P2 – the Memorial Complex "Funders of the Bulgarian state", reached via a monumental outdoor staircase; and P3 – The Astronomical Observatory "Prof. Diana Kyurkchieva", to which the route continues along a paved alley (Fig. 1). Measurements were performed using a portable Radiacode 103G gamma-ray spectrometer. The instrument uses a cerium-activated gadolinium aluminum gallium garnet (GAGG) scintillation detector, with a scintillator volume of approximately 1 cm^3, coupled to a silicon photomultiplier. According to the manufacturer's technical specifications, the energy resolution is 7.4 ± 0.3% (FWHM) for the ^{137}Cs line [7]. The energy range of registered photon radiation is 0.02–3.00 MeV. The instrument enables continuous recording of radiation levels and provides measurements of dose rate and count rate.

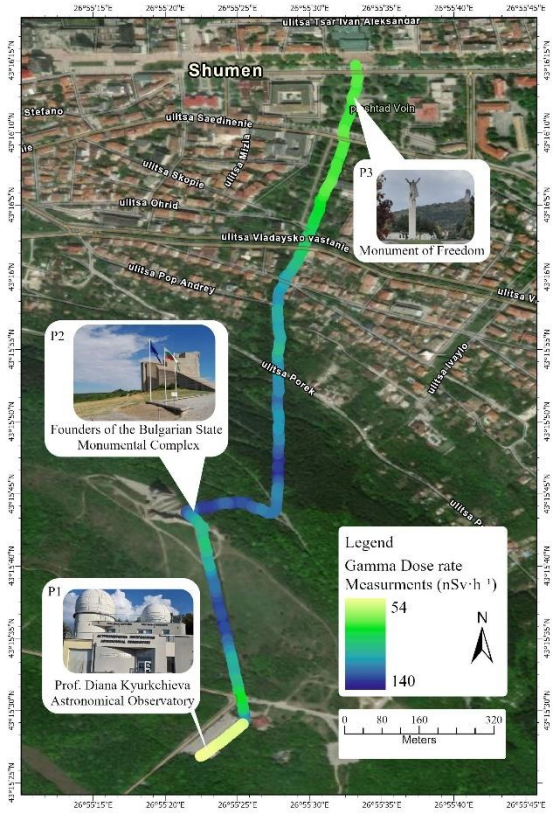


Fig. 1. *Spatial distribution of gamma dose rate measurements along the study route*

In the present study, two radiometric parameters were evaluated: count rate, expressed in counts per second (CPS), and dose rate, as directly recorded by instrument. The count rate represents the frequency of detected radiation events per unit time, whereas the dose rate measures the radiation dose per unit time, reflecting the instantaneous rate of dose accumulation.

The data were georeferenced using the instrument's built-in GPS allowing their integration into geographic information system (GIS) for subsequent statistical and spatial analyses along the surveyed route. The spatial distribution of the measured ambient gamma dose rate along the surveyed route is presented in Figure 1.

Statistical Analysis

Statistical analyses were performed using IBM SPSS Statistics, version 19. The aim was to characterize the spatial distribution and variability of the measured dose rate and to assess its correlation with the count rate.

Descriptive statistical analysis was conducted to characterize the distribution of the measured values. The mean dose rate was 105.38 nSv·h^{-1}, with values ranging from 54.30 to 136.00 nSv·h^{-1} (Table 1). In addition to the mean, the median and mode were determined. The mean was lower than both the median and the mode, which is consistent with a negatively skewed distribution. The interquartile range (IQR) was calculated as 29.50 nSv·h^{-1}. It characterizes the spread of the central 50% of the dataset and is less sensitive to extreme values than standard deviation [8].

Table 1. *Descriptive statistics of dose rate*

	Dose rate (nSv·h^{-1})
N	467
Mean	105.38
Median	111.00
Mode	127.00
Standard deviation	20.27
Skewness	-0.779
Kurtosis	-0.320
Minimum	54.30
Maximum	136.00
25th percentile (Q_1)	91.50
75th percentile (Q_3)	121.00
IQR (Q_3 - Q_1)	29.50

- **Dose Rate Distribution and Normality Assessment**

The distribution of the measured dose rate was evaluated using a histogram (Fig. 2). The plot exhibits a high concentration of measurements within the 110-130 nSv·h^{-1} range, alongside a smaller group of low values between 54.30 and 60.00 nSv·h^{-1}. The observed shape of distribution is consistent with negative skewness (-0.779), indicating a longer tail towards the lower values.

To statistically evaluated normality, the Kolmogorov-Smirnov test with Lilliefors correction and the Shapiro-Wilk test were applied. Both tests revealed a statistically significant deviation from a normal distribution (D=0.118, W=0.920, p<0.001).

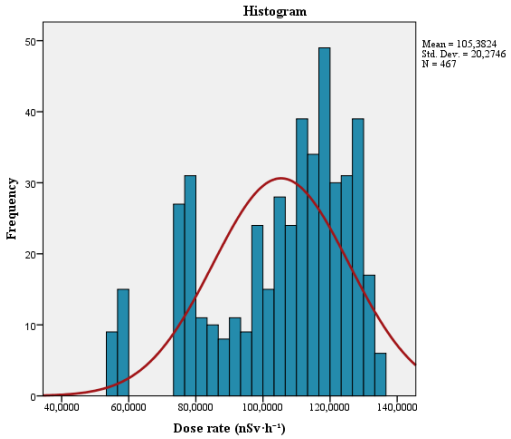


Fig. 2. *Frequency distribution of gamma dose rate values along the study route.*

- **Correlation analysis**

The relationship between CPS and dose rate was evaluated using Pearson's (r=0.927, p<0.001, N=467) and Spearman's correlation coefficient (ρ=0.855, p<0.001, N=467). Both metrics confirm a strong positive dependence between the two variables.

- **Linear Regression Analysis**

To quantitively evaluate the linear relationship between the parameters, simple linear regression analysis was applied. Figure 3 presents scatterplot illustrating the dependence between CPS and dose rate. The regression model is statistically significant, F(1.465)=2846.27, p<0.001 with an R^2 value of 0.860 [9]. This indicates that CPS explains 86.0 % of the variability in dose rate in the studied route.

Dose Assessment and Radiation Risk Level

Extrapolating the mean measured gamma dose rate of 105.38 nSv·h^{-1} over a full year yields an estimated annual dose of approximately 923 µSv (105.38 nSv·h^{-1}×8760 h year^{-1}).

To estimate exposure during regular recreational visit or physical activity, a scenario involving three weekly visits was considered. As visitors typically return to

Shumen along the same route, the path is traversed twice per visit, resulting in a total duration of approximately 68 minutes. Assuming 156 visit per year, the cumulative residence time along the route is 176.8 h year^{-1}, corresponding to an estimated annual dose of 18.63 μSv (105.38 nSv·h^{-1}×176.8 h year^{-1}).

For context, Council Directive 2013/59/Euratom establishes an annual effective dose limit of 1 mSv for members of the public from planned exposure situations [10]. The estimated dose for the considered scenario is substantially below this value. However, this limit is not a universal dose constraint for natural background radiation. Therefore, the comparison is intended for illustrative purposes only and does not constitute a formal assessment of regulatory compliance. Given the short duration of the measurement campaign, further monitoring across different seasonal and meteorological conditions is required to fully evaluate the spatial and temporal variability of the radiation background along the route.

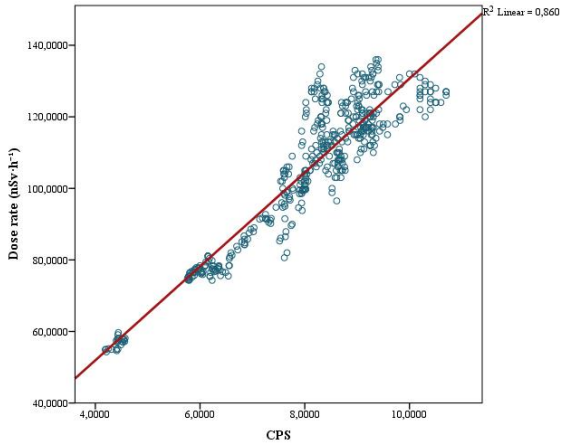


Fig. 3. *Scatter plot with linear regression line showing the relationship between CPS and gamma dose rate.*

Spatial Analysis and Geostatistical Modeling

Spatial analysis of the measured gamma dose rate was performed using ArcGIS Pro. To characterize the spatial structure of the data and identify underlying spatial patterns, Ordinary Kriging interpolation, global spatial autocorrelation (Global Moran's I), hot spot analysis (Getis-Ord Gi*), and local cluster analysis (Anselin Local Moran's I) were applied.

The geostatistical approach (Ordinary Kriging) models the spatial distribution of dose rate by accounting for spatial dependence between measurements and predicting values at unsampled locations.

The spatial dependence is evaluated using a semivariogram, which describes the variation in semivariance as a function of the distance between sampling points. The experimental semivariogram is fitted to a theoretical variogram model, which provides the mathematical foundation for calculating spatial predictions via kriging.

In the present study, a Stable variogram model was adopted, with the estimated parameters presented in Table 2. The Nugget parameter accounts for micro-scale spatial variation and potential measurement errors. The Partial Sill reflects the variance component associated with the spatial structure, whereas the Sill is the total variance level approached by the semivariogram [11]. The Range indicates the distance beyond which spatial dependence becomes substantially weaker.

Table 2. *Geostatistical and variogram model results for Ordinary Kriging.*

	Dose rate (nSv·h^{-1})
Model type	Stable
Lag size	0.0001638
Number of lags	12
Nugget	1.71
Partial Sill	157.66
Sill	159.37
Nugget/Sill ratio (%)	1.07
Range (degrees)	0.00145

The Nugget-to-Sill ratio (~1.07%) indicates that micro-scale variance and measurement error contributed minimally to the overall structural variance.

The semivariogram plot exhibits a clear rise in semivariance with increasing distance between measurement points, ultimately leveling off into plateau (Fig. 4). The model was implemented without anisotropy,

assuming that spatial dependence does not vary with direction.

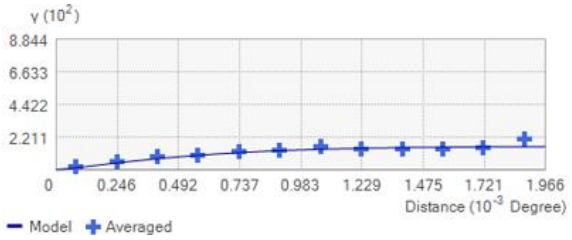


Fig. 4. *Semivariogram results for Ordinary Kriging*

The performance of the interpolation model was evaluated using leave-one-out cross-validation (LOOCV). Under this approach, each measurement point is successively excluded from the model, and its value is predicted using remaining measurements. The cross-validation results are presented in Table 3.

Table 3. *Cross validation results*

	Dose rate (nSv·h⁻¹)
Mean	0.04651
Root-Mean-Square (RMS)	2.18614
Mean Standardized	0.00998
Root-Mean-Square Standardized (RMSS)	0.85514
Average Standard Error (ASE)	2.53433

Overall, the Mean and Mean Standardized error values were close to zero, while the Root-Mean-Square (RMS) error was relatively low (2.186 nSv·h⁻¹) compared with the mean dose rate. These results indicate a small overall prediction error relative to the magnitude of the measured values. The close alignment between the RMS and Average Standard Error (ASE) further confirms the adequacy of the geostatistical model.

Global spatial autocorrelation was assessed using Global Moran's I. the index value was 0.9825, with an expected value of -0.0021 and variance of 0.0018 (z=23.093, p<0.001) [13]. the result indicates strong positive spatial autocorrelation, suggesting that measurement points located close to one another tend to have similar dose rate values. This finding indicates that the spatial distribution of dose rate is not random.

Local spatial patterns were examined using the Getis-Ord Gi* analysis. Of the 467 measurement points, 81 (17.34%) were identified as hot spots, whereas 86 (18.42%) were classified as cold spots. The remaining 300 points (64.24%) exhibited no statistically significant local clustering. Among the hot spots, 11 points were significant at the 99% confidence level (p<0.01), 46 at the 95% level (p<0.05), and 24 at the 90% level (p<0.10). For the cold spots, the corresponding count were 2, 23, and 37 respectively.

The Anselin Local Moran's I analysis complimented the assessment by identifying local cluster types and spatial outliers. A total of 98 points (20.99%) were classified as High-High (HH), indicating high values surrounded by high values, while 66 points (14.13%) were classified as Low-Low (LL), indicating low values surrounded by low values. No statistically significant spatial outliers of the High-Low (HL) or Low-High (LH) types were identified. The remaining 303 points (64.88) showed no statistically significant local spatial autocorrelation.

Taken together, the results of the three analyses characterize the spatial distribution of dose rate along the studied route. Global Moran's I identifies the overall tendency of similar values to cluster spatially, while Getis-Ord Gi* and Anselin Local Moran's I provide further information on the locations and types of local clusters.

CONCLUSION

This study investigated the spatial variability of gamma radiation along a walking route on the Shumen Plateau Nature Park using mobile georeferenced measurements obtained with a portable Radiacode 103G detector. The measurement dose rate ranged from 54.30 to 136.00 nSv·h⁻¹, with mean value of 105.38 nSv·h⁻¹. A positive correlation was observed between CPS and dose rate, indicating a consistent covariation between the two parameters.

Spatial analyses revealed strong positive spatial autocorrelation and local clusters of higher and lower dose rate values along the studied route. Ordinary Kriging was successfully applied to model the spatial distribution and predict dose rate values across unsampled locations. Cross-validation results indicated a low mean prediction error and minimal systematic bias. Furthermore, local spatial statistics complemented the overall characterization by identifying statistically significant spatial clusters of similar values.

The results illustrate the applicability of mobile georeferenced measurements for assessing the spatial variability of ambient gamma radiation along walking routes. However, due to the single-survey nature of the study, seasonal variability in the background radiation could not be evaluated, nor could general conclusions be drawn regarding the long-term radiation exposure of visitors. Additional monitoring across different seasons and under varying meteorological conditions will enable a more comprehensive assessment of temporal dynamics and the persistence of the identified spatial patterns.

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