# A STUDY OF SOIL MOISTURE VARIABILITY FOR LANDMINE DETECTION BY THE NEUTRON TECHNIQUE

by

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**This paper is focused on the space and temporal variability of soil moisture experimental data acquired at a few locations near landmine fields in the Tuzla Canton, as well as on the quantification of the statistical nature of soil moisture data on a small spatial scale. Measurements of soil water content at the surface were performed by an electromagnetic sensor over 1, 25, and 100 m$^2$ grids, at intervals of 0.2, 0.5, and 1 m, respectively. The sampling of soil moisture at different spatial resolutions and over different grid sizes has been investigated in order to achieve the quantification of the statistical nature of soil moisture distribution. The statistical characterization of spatial variability was performed through variogram and correlogram analysis of measurement results. The temporal variability of the said samples was examined over a two-season period. For both sampling periods, the spatial correlation length is about 1 to 2 m, respectively, or less. Thus, sampling should be done on a larger spatial scale, in order to capture the variability of the investigated areas. Since the characteristics of many landmine sensors depend on soil moisture, the results of this study could form a useful database for multisensor landmine detection systems with a promising performance.**

*Key words: landmine, neutron backscattering technique, soil moisture, spatial and temporal variability, variogram, correlogram*

## INTRODUCTION

At the moment, at least 110 million landmines are scattered across more than 70 countries, resulting in about 15 000-20 000 casualties per year, mostly civilians. At the current rate, clearing all existing mines could take 450-500 years. Bosnia and Herzegovina is the most heavily mined country in Europe. The country is still facing the problem of heavy mine contamination, more than a decade after the end of the war. Two years ago, The Bosnia and Herzegovina Mine Action Center (BHMAC) stated that there were 18 319 minefields. The recorded minefields represent only about 60% of the actual number of mined areas [1, 2].

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So far, only conventional methods have been applied in Bosnia and Herzegovina (B&H) for humanitarian demining. Metal detectors, dogs, and prodding techniques that have been used for finding, localizing, and identifying landmines are extremely dangerous, time consuming, and expensive. A wide range of mine detection techniques have been developed as an alternative to these conventional methods. However, none of the present sensors are capable of fulfilling all of the set goals. In order to improve the efficiency of landmine detection systems, innovative research and development are necessary.

A detection system should have a reasonable chance of being implemented and providing results within a reasonable span of time. One of the major problems in humanitarian demining is the separation of signals coming from landmines and those emitted by benign materials in the soil. Elemental analysis is the key to distinguishing explosives from other objects in the soil that do not contain explosives. The most common explosive materials found in landmines are rich in carbon, nitrogen, hydrogen, and oxygen, in variable concentrations. Therefore, their identification can be reduced to the identification of these light elements. Radiation based techniques can be useful for determining whether the anomaly in the soil, identified by non-nuclear means, contains an explosive material or not. Among available radiation interrogation approaches, neutrons are the most suitable candidates for providing non-intrusive composition information.

The most relevant neutron technique of practical use is the technique based on the detection of scattered neutrons, *i. e.* NBT (neutron backscattering technique) [3-5]. The NBT is based on the irradiation of contaminated ground with fast neutrons and the detection of backscattered low-energy neutrons whose yield depends on the concentration of hydrogen atoms in the irradiated volume. The presence of landmines in the soil causes an increased yield of low-energy neutrons. The use of neutron backscattering (NB) sensors, following terrain scanning with a metal detector (MD), would reduce the generation of "false" alarm signals in the inspection of contaminated areas considerably and, thus, improve the efficiency of the demining procedure. However, a limiting factor for the application of this technique is the density of hydrogen atoms contained in the soil due to moisture. Thus, an investigation of the NBT performance as a function of soil moisture in the contaminated area should be performed. Critical soil moisture is obtained when the density of the hydrogen atoms in the soil is equal to the sum of hydrogen atom density in the explosive and landmine casing. When this is the case, the landmine cannot be detected, since it is impossible to differentiate it from the background. For soil moisture lower than the critical value, the landmine is likely to produce an increased rate of backscattered neutrons in respect to the background.

The landmines found in the investigation areas are mostly buried, non-metallic or with a minimal metal content. Anti-personnel (AP) and anti-tank (AT) mines of different sizes and shapes have been found in the contaminated areas. AT mines contain a significant amount of explosives, a common charge having around 6 kg, whereas AP mines can weigh as little as 30 g of TNT, or tetryl. Critical soil moisture values for different types of landmines found in the Balkans, including B&H, mostly range from around 10% up to about 50%. These values have been calculated using a relation given in ref. [6]. Therefore, it is recommended that the soil moisture content for a NBT application does not exceed 0.1 kg/kg (10% mass).

The north-eastern part of B&H, the so-called Tuzla Canton, is infested with around 3140 minefields [7]. The map of the canton, along with the denoted mine fields, is presented in fig. 1. In the previous work [8], the results of the investigation of the physical properties of the contaminated soil in different areas of the Tuzla Canton, as well as the results of soil water content monitoring of selected soils from other regions in B&H, were presented. We have demonstrated that it was not appropriate to use an NBT with a system consisting of a neutron source and a single pixel detector for landmine detection in investigated areas of the Tuzla Canton, since the soil moisture contents exceeded the recommended value of 10% of the overall mass. However, we find it advisable to combine the NB method with similar methods, such as the ground penetrating radar (GPR) or infrared imaging (IR), in order to improve the performance of the detection system. Soil type and moisture also have a significant impact on GPR performance, IR, and NB imaging sensors [9].

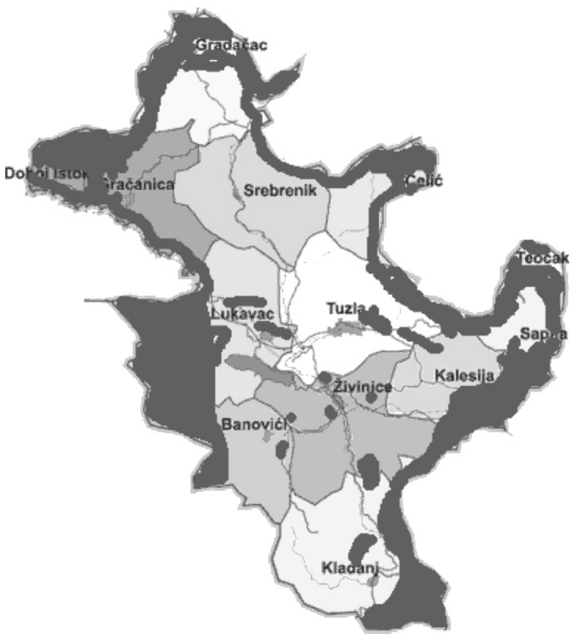


**Figure 1. Map of the Tuzla Canton with denoted minefields**

This paper deals with measurements of soil moisture at several locations next to the landmine areas in the Tuzla Canton and with correlation analysis of spatial and temporal variability of soil water distributions. The ability to characterize soil moisture spatial variability in different seasons is essential for the efficient monitoring of a particular area. Larger scale variations, such as slope and aspect, or smaller scale variations, having to do with microtopography, can influence spatial variations in soil moisture. Since our investigations were carried out close to the highly dangerous areas, the focus of our examination was on smaller spatial variations due to microtopography. Accurate quantification of the true statistical nature of the soil moisture field may be compromised if the moisture is not sampled at a fine enough resolution [10].

The goal of this work was to capture the natural statistical properties of soil moisture distributions at a few locations in the Tuzla Canton in hope of avoiding inconsistencies in the representation of soil moisture.

## CHARACTERISTICS OF MEASUREMENT LOCATIONS IN THE TUZLA CANTON

The first field experiment was carried out at four different locations in the Tuzla Canton. The soil water content was measured on a daily basis during August and September 2005, for 30 days. A total precipitation of 98.1 $1/m^2$ was measured between the first and last sampling campaign [11]. Measurement points have been chosen in areas neighbouring minefields. Measurements have been performed in different soil types with mostly grass vegetation cover and various ground configuration. Soil components and bulk density of the selected soil measured by standard methods are given in tab. 1 [12]. Volumetric content of moisture in the first sample has been monitored at location No.1 with GPS coordinates N 44 24'55.5", E 18 25'28.5" (village Musici), the second soil sample has been investigated at location No. 2 with GPS coordinates N 44 26'41.5", E 18 25'18.2" (village Jaruske), the third sample has been measured at location No. 3 (village Seona) with GPS coordinates N 44 26'07.7", E 18 23'16.1" and the fourth sample has been monitored at location No. 4 with GPS coordinates N 44 24'57.7", E 18 25'26.6" (village Pribitkovici).

**Table 1. Soil components and bulk density of soil from different locations in the Tuzla Canton**

| Soil components | Sample No. 1 | Sample No. 2 | Sample No. 3 | Sample No. 4 |
|---|---|---|---|---|
| Clay [%] | 15.5 | 12.5 | 0.0 | 15.5 |
| Silt [%] | 33.3 | 44.3 | 15.5 | 43.6 |
| Sand [%] | 42.8 | 43.2 | 46.3 | 34.6 |
| Gravel [%] | 8.4 | 0.0 | 38.2 | 6.3 |
| Soil density [$10^3$ kg/m$^3$] | 1.91 | 1.80 | 2.02 | 1.83 |

Theta Probe type ML2x and Profile Probe type PR2/4 (Manufacturer Delta-T Devices, UK) [13, 14] have been used for measuring the soil surface moisture and soil moisture at the depths of 10, 20, 30, and 40 cm, respectively. The probes are electromagnetic sensors and since the soil dielectric properties are highly sensitive to the presence of water, soil moisture content can be obtained indirectly. During a sampling campaign, each time at each location, the surface soil moisture was measured at three points separated by 20 cm, within a surface area of 80 80 cm$^2$.

PR2/4 has an accuracy of 0.06 m$^3$/m$^3$ with generalised soil calibration in "normal" soil. In order to average out possible anisotropies in moisture distribution in the small soil volume, two further readings have been taken with the probe rotated through 120 , each time for all locations, at each depth. During the measurements, both probes were used with the manufactured calibration assumed for "normal" soil. PR2 and ML2x have been combined with a HH2 readout unit [15]. The results measured have shown that the values of soil moisture for different types of soil in the Tuzla Canton are often higher than the soil moisture critical value recommended for the NBT [8]. However, the results obtained in this work could be useful as a database for the integrated sensor system that requires information on the effects of local soil environment.

## SOIL MOISTURE VARIABILITY AND SAMPLING RESOLUTION

Without adequate resolution in the measurements, a lack of understanding of the nature of the variability of soil moisture at different scales can lead to significant inconsistencies in the representation of these variables. Therefore, we performed soil moisture measurements at different sampling resolutions and over different grid sizes, in order to determine the optimal spatial scale and sampling density at which these data should be represented. For statistical structure analysis, we have chosen one sample at location No. 2 with 44.3% of silt and the second sample at location No. 3 with 46.3% of sand. The type of soil with more sand at location No. 3 has a low water capacity and changes in moisture are fast and significant compared to the soil at location No. 2. Measurements of soil water content at the surface were performed by using the ML2x sonde with an accuracy of 3%, over 1, 25, and 100 m$^2$ grids, at intervals of 0.2, 0.5, and 1 m, respectively. Basic parameters of descriptive statistics for 3 sampling resolutions at location No. 2, for two sampling dates, Sept. 9, 2005 and Aug. 17, 2006, are given in tab. 2. Along with the sampling of soil moisture, visual observation of the presence of vegetation was made at each sampling point within the area of the study. Sampling resolutions of 0.2, 0.5, and 1.0 m at location No. 2, have been chosen to investigate microtopography effects on soil moisture distribution.

**Table 2. Basic parameters of descriptive statistics for three sampling resolutions at location No. 2, for two sampling dates: Sept. 9, 2005 and Aug. 17, 2006**

| Descriptive statistics | Step 0.2 [m] | | Step 0.5 [m] | | Step 1.0 [m] | |
|---|---|---|---|---|---|---|
| | 2005 | 2006 | 2005 | 2006 | 2005 | 2006 |
| Mean values [%] | 16.93 | 18.61 | 17.54 | 18.33 | 17.60 | 17.66 |
| Standard deviation [%] | 1.75 | 1.59 | 1.41 | 2.20 | 1.46 | 2.36 |
| Maximal moisture [%] | 21.22 | 21.50 | 21.11 | 22.77 | 21.34 | 22.06 |
| Minimal moisture [%] | 13.00 | 14.22 | 13.00 | 10.06 | 13.00 | 6.33 |
| Amplitude [%] | 8.22 | 7.28 | 8.11 | 12.71 | 8.34 | 15.73 |
| Coefficient of variation [%] | 10.32 | 8.56 | 8.00 | 12.00 | 8.31 | 13.38 |

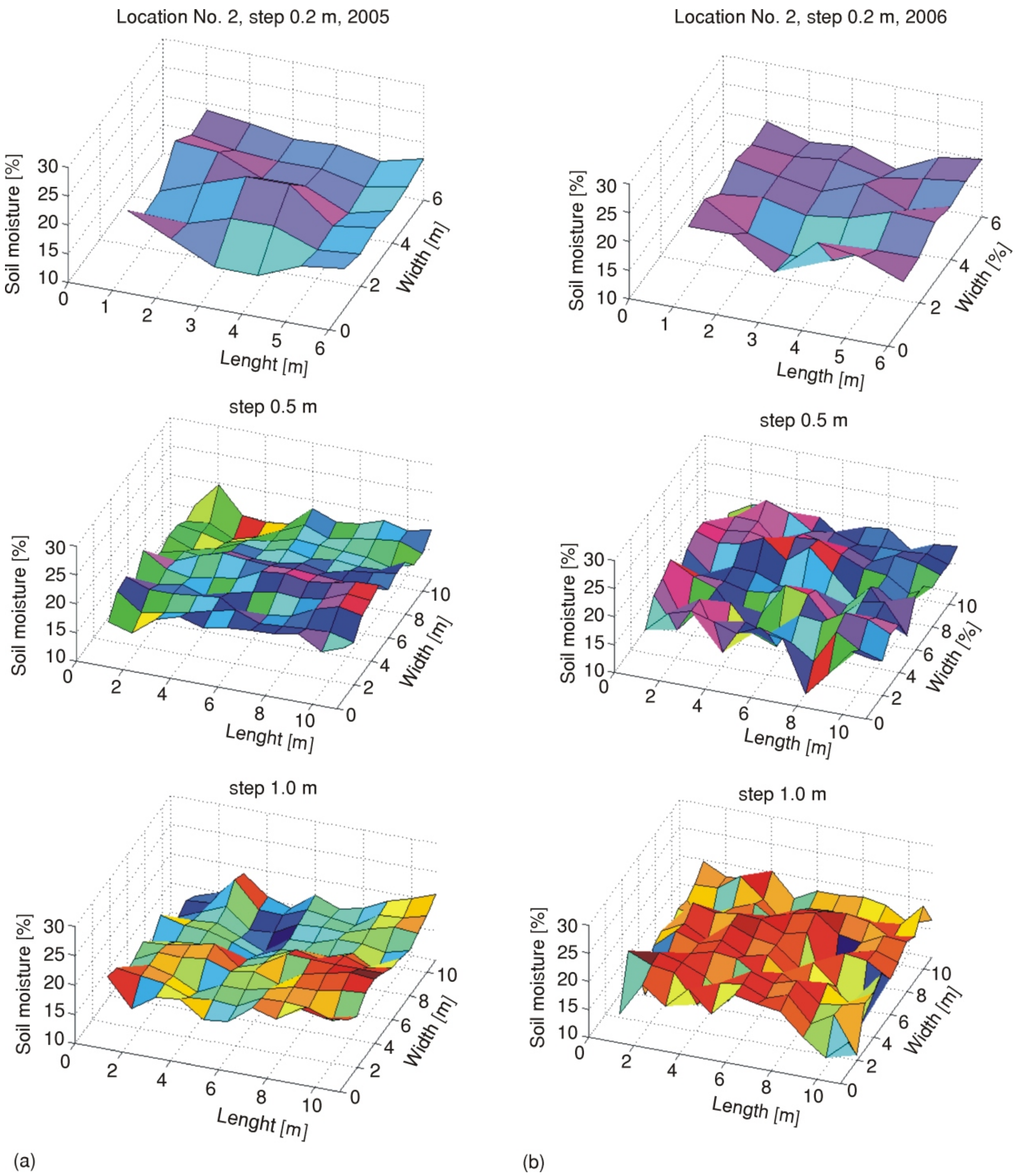


**Figure 2. A 3-D representation of soil moisture at location No. 2 with three sampling resolutions, for two sampling dates (a) 2005, (b) 2006**

The 3-D representation of soil moisture at location No. 2, given in fig. 2a and b, shows that, in agreement with expectations, the dispersion of soil moisture is not significant, since the grids are of relativelly small dimensions and the investigated areas are approximately homogenous. Basic parameters of descriptive statistics for 3 sampling resolutions at location No. 3, for two sampling dates, Sept. 9, 2005 and Aug. 8, 2006, are given in tab. 3. A 3-D representation of soil moisture at location No. 3 is given in fig. 3a and b for 2005 and 2006 sampling, respectively. It can be noticed that the mean soil moisture value does not vary significantly with spacing. However, the mean values of soil water distributions at location No. 2 are, on average, larger compared to those at location No. 3. For both locations, standard deviation increases slightly as the sam-

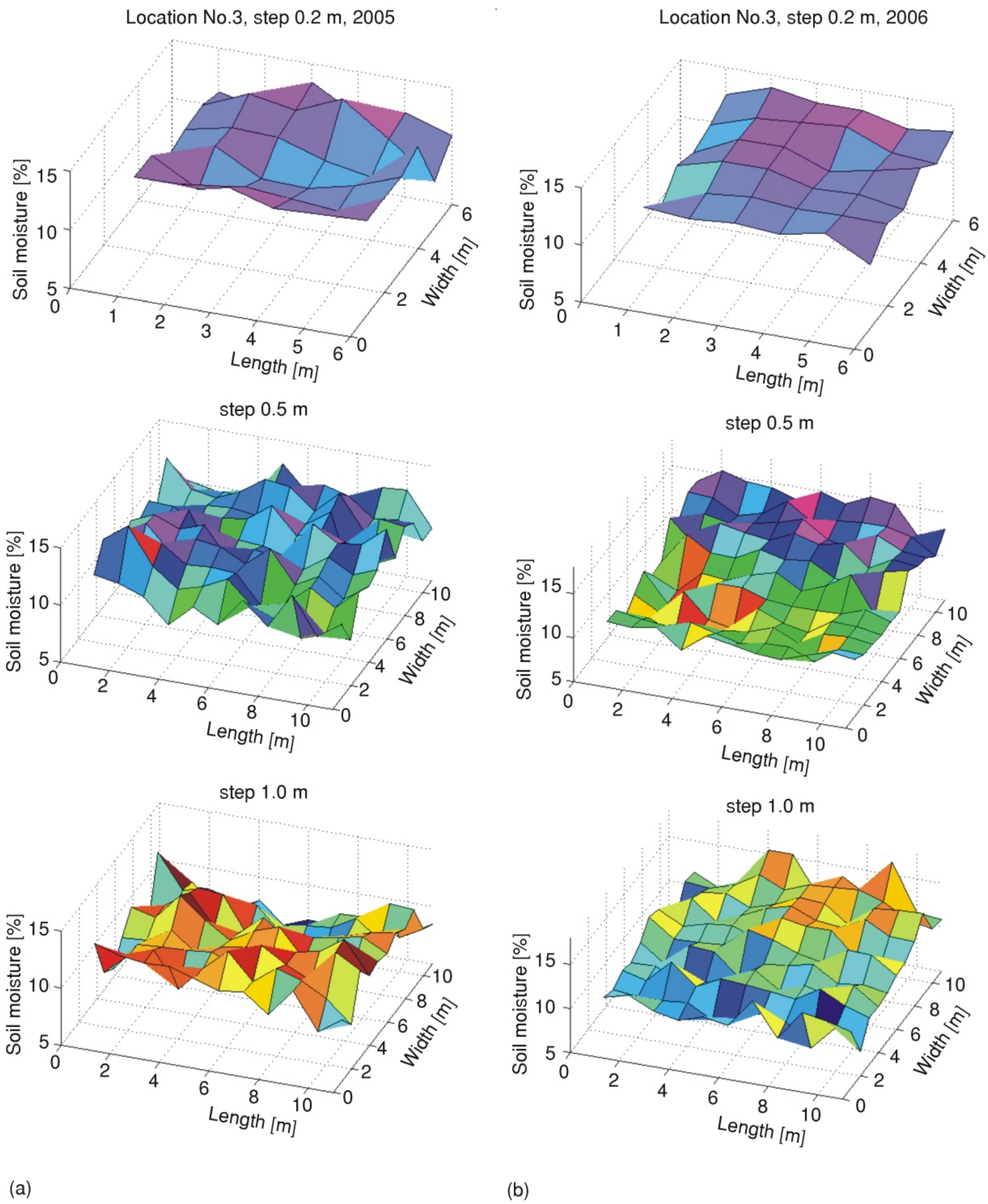


**Figure 3. A 3-D representation of soil moisture at location No. 3, for (a) 2005, (b) 2006 sampling**

ple spacing becomes coarser. The coefficient of variation (CV) is defined as the ratio of the standard deviation to the mean value. The coefficient of variation has the largest value for the grid with the step of 1 m, since individual sample points across the larger grid were, on average, closer to the mean soil moisture. The CVs ranged from 5.53 to 15.62%, indicating rather high variability in soil water content at different spatial scales during the two periods of measurements.

## SEMIVARIOGRAM AND CORRELOGRAM ANALYSIS OF THE SOIL MOISTURE DATA

Sampling of soil moisture at different spatial resolutions has been investigated in order to achieve accurate quantification of the true statistical nature of soil moisture distribution. Statistical characterization of spatial variability has been performed through variogram and correlogram analysis of experimental

**Table 3. Basic parameters of descriptive statistics for three sampling resolutions at location No. 3, for two sampling dates: Sept. 9, 2005, and Aug. 8, 2006**

| Statistics | Step 0.2 [m] | | Step 0.5 [m] | | Step 1.0 [m] | |
|---|---|---|---|---|---|---|
| | 2005 | 2006 | 2005 | 2006 | 2005 | 2006 |
| Mean values [%] | 12.11 | 12.35 | 11.57 | 11.58 | 10.45 | 11.56 |
| Standard deviation [%] | 1.24 | 0.68 | 1.41 | 1.81 | 1.97 | 1.54 |
| Maximal moisture [%] | 14.55 | 13.86 | 15.59 | 15.39 | 14.11 | 16.38 |
| Minimal moisture [%] | 8.86 | 10.19 | 6.29 | 7.87 | 6.09 | 7.23 |
| Amplitude [%] | 5.69 | 3.67 | 9.30 | 7.52 | 8.02 | 9.15 |
| Coefficient of variation [%] | 10.23 | 5.53 | 12.20 | 15.62 | 14.26 | 13.35 |

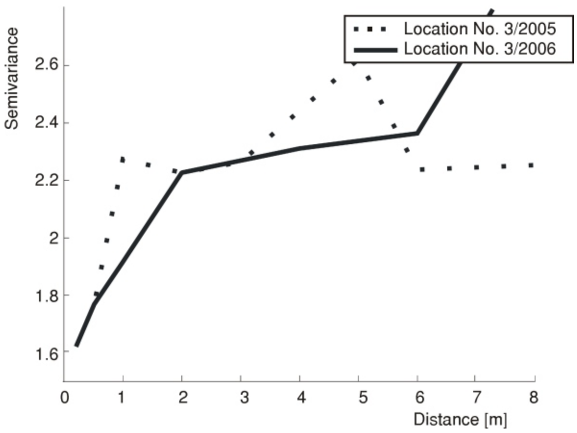


**Figure 4. The semivariance as a function of the distance at location No. 3 for the two sample periods**

data. A variogram is a plot of the semivariance at different distances, *i. e.* the average of the square of the differences between data values as a function of the separation distance (*i .e.* distance between sample points).

The semivariogram is defined as

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(x_i) - Z(x_i + h)]^2 \qquad (1)$$

where $h$ is the separation distance between sample points, $N(h)$ is the number of sample point pairs separated at distance $h$, $Z(x_i)$ is the observed value of soil moisture at point $i$, and $Z(x_i + h)$ is the observed value at point $i + h$. The range and sill are two parameters of the semivariogram used to describe the said data. The difference between the compared points becomes larger with the distance increasing. At some point, the semivariogram develops a flat region called the sill. The distance at which the sill is reached is called the range.

Figure 4 illustrates the semivariance as a function of distance at location No. 3 for the two sampling periods. The variogram shows that the variability increases with lag distance. The range indicates the extent to which sampled spatial values are similar, and for the 2005 data sampling, the distance at which the variogram reaches the plateau, when no further increase in variability occurs as the separation distance increases, amounts to about 1 m. As for the 2006 sampling data, the "range of influence" or "range of correlation" is about 2 m. Beyond this range, there is no more correlation between the sample and other values. It can be noticed that spatial dependence does not vary much during the course of a season as moisture conditions change. The spatial correlation length is about 0.5 and 1 m at location No. 2 for both sampling dates, respectively.

According to [16], the autocorrelation function (ACF) is a primary diagnostic tool which indicates if there is a spatial or temporal pattern of on-site sampled data. The effects of resolution and grid size on spatial autocorrelation should be examined to capture the natural statistical properties of the soil moisture field. Namely, accurate representation of soil moisture distribution may be obtained by an optimal sampling strategy.

Auto- and cross-correlation functions are used as geostatistical tools to describe the characteristics of spatial data distributions. Spatial autocorrelation analysis is based on the Moran I method, *i. e.* the calculation of the correlation coefficient $r(j)$ as the ratio of the covariance $c(j)$ and the total variance $s^2$ [16]

$$r(j) = \frac{c(j)}{s^2}$$

$$c(j) = \frac{1}{(n-1-j)} \sum_{i=1}^{n-1} [(x_i - \bar{x})(x_{i+j} - \bar{x})] \qquad (2)$$

$$s^2 = \frac{1}{(n-1)} \sum_{i=1}^{n-1} (x_i - \bar{x})^2$$

where $n$ is the number of these observations, $j$ the number of lags $h$ between observations used for the correlation, $x_i$ the variable at position $i$ and $x_{i+j}$ at position $i+j$, $r(j)$ are correlation coefficients for $j$ lags. Moran's I method of local spatial autocorrelation analysis was used in addition to the variogram to determine if there was any organization in the measured soil moisture field. This computation is achieved by dividing the spatial covariation by the total variation. The resulting values are in the range of approximately –1 to 1, with positive values suggesting positive spatial autocorrelation, and *vice versa*.

Correlation coefficients as a function of the distance between spacing points for experimental data sampled at location No. 3 in 2005 are given in fig. 5. A maximal value of the auto-correlation coefficient of 0.4 has been obtained at the distance of 1 m, which is in agreement with the value obtained by variogram analysis.

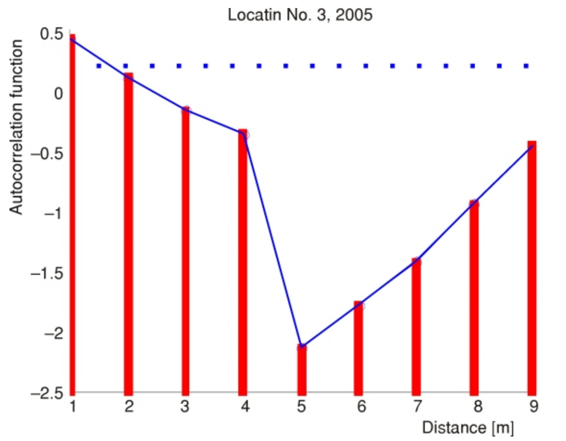


**Figure 5. Auto-correlation coefficients as a function of the distance**

The distribution of the correlation coefficients $r$ is rather complex, but it is, still, possible to form a new variable with a simpler distribution. The formula

$$t = \frac{r\sqrt{n-2}}{\sqrt{1-r^2}} \quad (3)$$

is used for testing whether $r = 0$ or not. The result is compared to a $t$-distribution with $(n-2)$ degree of freedom to return a probability value (2-tailed).

The critical value of the correlation coefficient is 0.1786 for a statistical significance of 95%. It is obvious, in fig. 5, that the correlation coefficient at the distance of 1 m is larger than the critical value, which means that the soil moisture experimental data at distances smaller than 1 m do not show significantly different water content at a confidence level of 95% ($\alpha = 0.05$).

When the sample size is only moderately large ( 10), we can compare whether the difference between the two non-zero correlation coefficients is significant. Fisher developed a transformation of $r$ that tends to become normal quickly as $n$; *i. e.* the sample size increases. This distribution is called the Fisher r to z transformation. The transformation is

$$z = \frac{1}{2}\ln\frac{1+r}{1-r} \quad (4)$$

where $r$ is the sample correlation. Then, each $z$ is approximately normally distributed with a mean value

$$\mu_z = \frac{1}{2}\ln\frac{1+\rho}{1-\rho} + \frac{\rho}{2(n-1)} \quad (5)$$

where $\rho$ is the actual or population value of the correlation coefficient, with a variance

$$\sigma_z^2 = \frac{1}{n-3} \quad (6)$$

By using the Fisher-z transformation, the correlation coefficient $r = 0.3994$ is in the confidence interval of 0.2379 to 0.5394, with a statistical significance of 95%.

In recent years, statistical literature has examined the properties of resampling as a means to acquire information about the uncertainty of statistical estimators. A histogram of the result obtained by the bootstrap procedure (fig. 6) to establish the uncertainty of the correlation coefficients represents a powerful quantitative evidence that the data set is positively correlated. The histogram shows the variation of the correlation coefficient across all the bootstrap samples. Most of the bootstrap results lie close to the value of 0.4, suggesting that the value of the correlation coefficient of 0.4 is statistically significant. Figures 5 and 6 indicate moderate spatial autocorrelations at resolution, or spacing of 1 m, which is in agreement with the value obtained by variogram analysis for experimental data sampled at location No. 3 in 2005.

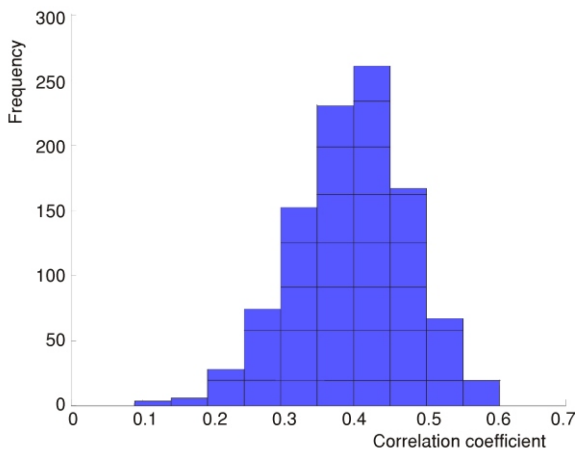


**Figure 6. A bootstrap histogram of correlation coefficient distribution**

## CONCLUSION

Measurements of soil moisture near the landmine fields in the Tuzla Canton, as well as the analyses of the statistical structure of experimental data, represent the first phase of the long-term research activity that is indispensable in the investigation of the applicability of advanced nuclear methods in the demining process. Experimental results relating to the Tuzla Canton presented in this paper indicate that soil water distributions are highly variable. This variability arises from a complex interaction of many geophysical parameters such as soil type, topography, vegetation, and climate. An accurate characterization of the true statistical nature of soil moisture distribution requires a proper sampling approach specific to the investigated site. Sampling of soil moisture at different resolutions and over different grid sizes was examined in order to improve the reliability of the field's representation. Since the measurements were performed near landmine fields, the investigation of soil moisture distributions was limited to smaller spatial scales and micro-topographic effects.

Statistical characterization of spatial variability was performed through the analysis of statistical structure, variograms, and autocorrelation of experimental data. The basic parameters of descriptive statistics for the three sampling resolutions of 0.2, 0.5, and 1 m at location No. 2 with 44.3% of silt and at location No. 3 with 46.3% of sand, both in the Tuzla Canton, were calculated for the two sampling dates. Results show that the seasonal mean soil moisture value does not vary significantly with spacing, but that the standard deviation increases slightly as the sample spacing becomes coarser. The temporal variability of the same samples was examined over a period of two seasons. The results, obtained by the autocorrelation function as a primary diagnostic tool that indicates a spatial or temporal pattern, have shown that measurement points at both locations are spatially correlated at resolutions of around 1-2 m or less during both sampling periods, respectively. As the mean does not change significantly, the sampling should be done on a larger scale in order to really capture the variability of the site as a whole. Results indicate that sampling does not need to be done at an extremely fine resolution, but larger area coverage could be more useful for the accurate representation of soil moisture distributions.

Since the performance of a few individual landmine sensors varies strongly with soil properties, incorporating information about the local soil environment into the integrated sensor system has the potential to greatly improve the performance of multisensor landmine detection systems [17].

The results obtained concern the quantification of soil moisture variability near a few landmine fields in the Tuzla Canton and determine the optimal spatial scale at which the said data should be represented. This study is a contribution to the establishment of a soil bank with basic information on soil properties and soil moisture variability that could be a valuable input for site-specific applications, such as the use of multisensor systems for landmine detection.

The next stage of our research program will include experimental studies of soil moisture in other areas of B&H, spectral and wavelet analysis of the spatial and temporal variability of soil moisture and their influence on landmine detection by neutron backscattering techniques.

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**Сенада АВДИЋ**

## ИСПИТИВАЊЕ ВАРИЈАБИЛНОСТИ ВЛАЖНОСТИ ТЛА РАДИ ДЕТЕКЦИЈЕ МИНА НЕУТРОНСКОМ ТЕХНИКОМ

Овај рад усмерен је на експериментално испитивање просторне и временске варијабилности влажности тла на неколико локација у Тузланском кантону, као и на квантификацију статистичке природе влажности тла на мањим просторним скалама. Мерење садржаја воде у површинском слоју тла извршено је помоћу електромагнетног сензора на мрежама површине 1, 25 и 100 m$^2$, и интервалима од 0,2, 0,5 и 1 m, респективно. Узорковање влажности тла на различитим просторним резолуцијама и за мреже различитих димензија испитивано је да би се постигла квантификација статистичке природе расподеле влажности. Статистичка карактеризација просторне варијабилности урађена је коришћењем вариограм и корелограм анализе резултата мерења. Временска варијабилност истих узорака испитивана је током два периода. За оба датума узорковања, просторна корелациона дужина износи приближно 1 и 2 m, респективно, или мање. Отуда, узорковање треба извршити са већом резолуцијом да би се обухватила варијабилност испитиваних подручја. Пошто карактеристике неколико индивидуалних сензора за детекцију мина зависе од влажности тла, резултати ових испитивања могли би се користити као корисна база података за мултисензорске детекционе системе који имају боље перформансе.

*Кључне речи: мине, неутронска техника, влажност тла, просторна и временска варијабилност, вариограм, корелограм*