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# THE USE OF GIS-BASED SPATIAL MULTI-CRITERIA EVALUATION IN THE SELECTION PROCESS FOR THE NEW SLOVENIAN GEOMAGNETIC OBSERVATORY SITE

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## *ABSTRACT*

*The study of geomagnetic field is one of the earliest studies in the field of geosciences. At present, measurement of the geomagnetic field is concerned with answering the fundamental questions about the Earth's deep interior, mantel conductivity, structure and thermo-mechanical properties of the crust, its lithosphere and the near-Earth environment. This paper presents a method that addresses a problem of site selection for a new geomagnetic field observatory in the Republic of Slovenia. The method relies on a multi-stage multi-criteria decision model. Geographic Information System (GIS) was used as a platform enabling the management of the criterion data, spatial analysis, cartographic modeling and production of map layers. Feasible areas were produced using Boolean overlay, followed by the application of multi-criteria evaluation (MCE) method on feasible areas to select the best area. Furthermore, preliminary measurements of geomagnetic fields were observed including the measurement of the total-intensity gradient of the magnetic field vector, the measurement of the geomagnetic field at a base-point, as well as the absolute and the three component measurements of the geomagnetic field.*

**Key words:** geophysics, geomagnetism, Geographic Information Systems (GIS), observatory, site selection, multi-criteria evaluation (MCE)

# USO DI VALUTAZIONE MULTICRITERIALE BASATA SU GIS NEL PROCESSO DI SELEZIONE DI UN SITO PER UN NUOVO OSSERVATORIO GEOMAGNETICO SLOVENO

## *SINTESI*

*Lo studio del campo geomagnetico è uno dei primi intrapresi nell'ambito delle geoscienze. La ricerca del campo geomagnetico è di fondamentale importanza per la comprensione dei processi in corso negli strati profondi della Terra, nella crosta terrestre e nell'ambiente circostante il pianeta Terra. L'articolo presenta un metodo per la selezione di un sito per un nuovo osservatorio geomagnetico in territorio sloveno. La scelta è basata sul modello decisionale della valutazione multicriteriale e multigraduale. Il Sistema Informativo Territoriale (GIS) è stato usato quale piattaforma per la definizione dei criteri, l'analisi spaziale, la creazione di modelli cartografici e la produzione di mappe pluristratificate. Aree potenzialmente adatte sono state evidenziate con l'uso del "Boolean overlay", seguito dall'applicazione del metodo della valutazione multicriteriale (MCE), al fine di scegliere l'area migliore. In tali aree sono state eseguite misurazioni preliminari dei campi geomagnetici, incluse misurazioni dell'omogeneità del gradiente dell'intensità totale del vettore del campo magnetico, nonché misurazioni assolute, di base e tri-componenziali del campo geomagnetico.*

**Parole chiave:** geofisica, geomagnetismo, Sistema Informativo Geografico (GIS), osservatorio, selezione sito, valutazione multicriteriale (MCE)

## INTRODUCTION

One of the essential tasks of the geomagnetic observatory is recording the short-term and long-term geomagnetic field variations in such a way that the recorded information is representative for a larger area (Wienert, 1970). The utility of the magnetic observatory records for the correct reduction of the surveyed data is reinforced if both spatial homogeneity of location and particular location anomalies including man-made and natural noises are assessed. It is important that the observatory site is magnetically representative of its region, both for the secular variation and for the short-term variations (Jankowski & Sucksdorff, 1996). This means that it is always convenient to set up a geomagnetic observatory in the environment free of or with limited electromagnetic contamination.

Electromagnetic radiation, which is constantly present in the environment, can be detected during the observation of the Earth's magnetic field as electromagnetic noise or interference. The noise may occur due to natural or artificial sources. Natural origins of the electromagnetic radiations are most often attributed to atmospheric phenomena and phenomena originating in the Universe. Unnatural or artificial electromagnetic noise is man-made; it originates in technological development and the electromagnetic applications. Due to technological growth, man-made electromagnetic noise is nowadays superimposed on natural noise almost everywhere on the Earth.

In the last decade man-made noise has increased dramatically over and above the natural noise in residential and business areas (Bianchi & Meloni, 2007). Typical electromagnetic interferences in the Earth's magnetic field in urban environments are caused by a number of sources: electricity grids and switches, building materials (mostly ferroconcrete structures), electromagnetic fields from telephony and other telecommunications, electric mains and transmission lines, and electrified railways, transport etc. Of these man-made noises the electric mains and transmission lines and direct current electrified railways have the biggest influence on measurements. In the history of the geomagnetic field observations some observatories, above all because of the high level of man-made electromagnetic noise, were moved from urban areas to countryside with a lower level of noise caused by artificial sources (Tsunomura & Tokumoto, 2005). The interference from electrified railways is so strong that the electromagnetic radiation spreads to a distance of several tens of km. In case of electric railways driven by alternation current, leakage currents do not have strong interference on measurements, as its frequency range is out of observation period range of geomagnetism, and leakage currents may not form large current loops beneath the ground because of the skin effect (Yanagihara, 1977). Nevertheless, AC-electrified railways still represent a significant source of noise, mainly because of the nature of its noise which has extremely complex variability and could not be entirely eliminated even with the modern techniques for noise removal (Fontes, 1988; Egbert *et al.*, 2000; Padua *et al.*, 2001).

Generally, it can be shown that the level of electromagnetic noise from artificial origins, measured at the various locations, is highly dependent on the distance from the origin of noise. It can also be proved that the level of electromagnetic noise from artificial origins is not constant in time and that both, its frequency and power also fluctuate. For that reason, the above-mentioned electromagnetic noise causes a lot of problems for observing the geomagnetic field. Many authors have pointed this out, quoting the problems in discovering, quantifying and eliminating the man-made electromagnetic noise (Harada *et al.*, 2004; Villante *et al.*, 2004; Masci *et al.*, 2007).

According to the researches described, the reasonable choice for a site location is a "quiet" rural area which has a lower level of man-made electromagnetic noise. In spite of its relevance, man-made noise, depending on frequency band, is on average 20–30 dB lower in "quiet" rural areas than in the business and residential areas. Of course, starting from the 1960's, satellite communication systems also contribute to man-made noise measurable on the Earth (CCIR/ITU, 1990; Bianchi & Meloni, 2007). Man-made noise can be mainly observed in the vertical component of a magnetic field.

During geomagnetic field observations, any changes in electromagnetic field as a result of seismic processes must not be neglected. Some researchers are inclined to believe that the *Sun–interplanetary space–magnetosphere–ionosphere–atmosphere–tectonosphere* chain should be considered as a very complex, dynamic and non-linear system in which high energy phenomena cause various complex processes on the Earth. In this context, the seismic processes in the Earth's crust and its upper mantle should be treated as a part of a physical process common to the Sun–Earth system (Bakhmutov *et al.*, 2007). A number of researchers have investigated the relation between the system's physical processes and seismic activities. The results of these studies are different from one researcher to the other. It is not possible to get unified results on this matter in the literature, and therefore it is not possible to establish the exact quantitative criteria for the evaluation of potentially adequate geomagnetic observatory locations. Although the researchers are not unanimous regarding the relation between the change in the geomagnetic field and the occurrence of seismic activities, the results they presented support the statement that such relation exists (Rulev, 1991; Sobolev *et al.*, 2001; Zakrzhevskaya & Sobolev, 2002; Bakhmutov *et al.*, 2007).

## MATERIAL AND METHODS

The above-mentioned facts prove that the area selection and choice of the final location for the geomagnetic observatory is a multi-stage multi-criteria decision process, as the location must meet a number of criteria that are related to its spatial and functional specifications, geological characteristics, the level of electromagnetic noise, topographic characteristics and other technical characteristics. Nevertheless, an important factor in bringing the final decision is also its social acceptability in the broader surroundings, both at local and personal level.

Usually the objective in applications involving cartographic modelling is to locate the area or areas where the given criteria apply. Thus, GIS was used as a platform enabling the management of the criterion data, the production of criterion layers, the spatial analysis and production of the maps needed in the evaluation process. When we are looking for a suitable location, the process actually includes the spatial evaluations according to different decision criteria. In a classification based on Boolean logic, an area is either accepted or rejected based on a given threshold value. The final outcome of those models is a map showing areas simultaneously fulfilling all the decision criteria. However, problems have been noted with methods that relay on classical Boolean logic (Carver, 1991). In situations where threshold value is not precise, loss of information or error propagation may occur. Additionally, the method does not offer any analytical possibility for examining which areas are the most appropriate or which areas are the best among the feasible areas (Stone, 2001).

In our case, the site evaluation process may be divided into three stages: collecting the necessary data, cartographic modelling including multi-criteria modelling, and preliminary on-site geomagnetic field observations.

The first stage consists primarily of collecting and preparing digital data that includes different thematic layers. Since our study area represents the entire territory of the Republic of Slovenia, most of the variables needed in the evaluating process were already available in digital format. Map layers describing these factors were obtained from Surveying and Mapping Authority of the Republic of Slovenia. All available map layers were in vector data format, so the accuracy and consistency of the data has not been questioned.

In the second stage, the cartographic modelling was applied in producing and combining spatial data describing decision variables. In this process, cartographic tools including buffering, filtering, dissolving features, to overlapping all map layers considering deterministic area factors. The areas not included in the area determined as

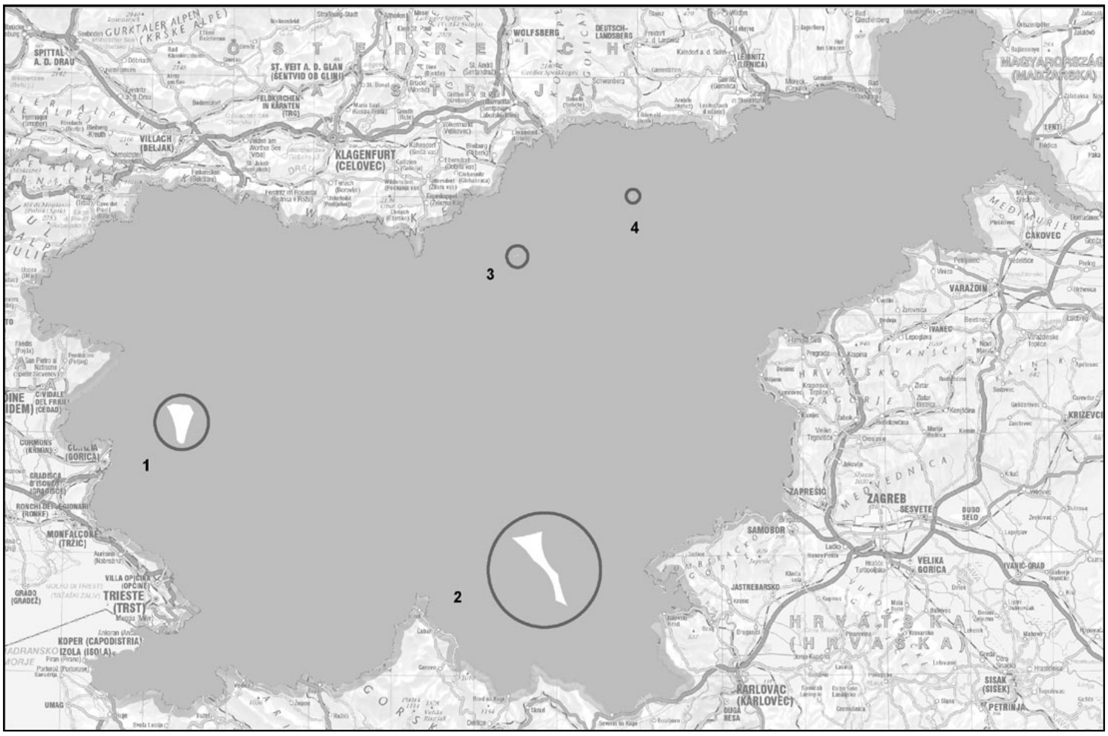


***Fig. 1: Map depicting areas simultaneously fulfilling all the conditions set in spatial criteria group.***
***Sl. 1: Prikaz lokacij, ki ustrezajo vsem postavljenim prostorskim kriterijem.***

gether with Boolean logic were used. Feasible area is produced using Boolean overlay, *i.e.*, by numerically being suitable by all deterministic criteria were excluded from further consideration. Since the Boolean logic does not offer any analytical possibility for examining which areas fulfilling the deterministic criteria are the most appropriate, the Multi-Criteria Evaluation (MCE) method has also been applied in decision process. The most frequently used MCE procedure in the GIS environment was used, *i.e.,* the weighted linear summation. This method is suitable for when we have to evaluate several criteria and consider their different levels of importance.

The last stage includes magnetic field survey at selected site, activities with the purpose of ensuring social acceptability in broader and narrower surroundings, searching for an appropriate plot, etc.

### Evaluation criteria

The criteria for spatial evaluation were classified into three groups: spatial characteristics, technical-practical aspects, and social-global characteristics. In the spatial characteristics group, all the decision criteria are deterministic. Their threshold values have been defined as a result of literature review from the introduction of this paper, and evaluated according to field expert suggestions. In the two other groups we can find all other, subjective decision criteria, which are also important in setting up a permanent observatory of geomagnetic field (Wienert, 1970; J. Rasson, *pers. comm.*).

In the first stage, cartographic tools including buffering, filtering, dissolving features, together with Boolean logic were used. The model was designed using the *ArcMap 9.3 Software Package*. The aim of this procedure was to identify potentially appropriate sites, which would be acceptable in relation to the first group of criteria. The areas simultaneously fulfilling all the decision criteria from the first group are shown on the map as feasible areas (Fig. 1).

The next step was the evaluation of four potential sites according to decision criteria classified in the second and third group. Some of the selected parameters from the second and third group are not as exact and unique as the parameters from the first group. For some decision criteria the adjustment of interests on-site is of key importance, and these criteria could not be treated equally on each site. At this point, the multi-criteria evaluation method has been applied on feasible areas selected in the first stage. The method requires setting a degree of advantage (weight factors) for each parameter, and a relative significance of a single parameter in comparison to other parameters which are used in the selection process. Each parameter was evaluated in relation to its degree of advantage with rank from 1 to 5, where the rank 1 means a very inappropriate location and rank 5 means a very suitable location. This ensured that the important parameters could not be lost in the mean value and that the significant advantages of a potential site with high-rated main parameters would not be cancelled out by its lower scores for some less important parameters. For this model the importance of a parameter was evaluated with rank from 1 to 5, where the most important parameter was given the rank 5 and a parameter of very low importance was given the rank 1 (Tab. 2).

Evaluation of the sites using the weighted linear summation method showed that the most suitable site for the selected parameters was Site 1, which is in the vicinity of Predmeja village. Site 2 and Site 3 were less-suitable since neither of them is easily accessible, but the key parameter for a low score is their small area size. The data for the site evaluation in relation to parameter 3–a (social acceptability) were not available for all potential sites and therefore this was not taken into consideration at this stage of evaluation. Site 2 also obtained a

***Tab. 1: Definition criteria/parameters for potentially appropriate sites.***
***Tab. 1: Kriteriji za vrednotenje potencialno primernih lokacij.***

| | |
|---|---|
| SPATIAL CRITERIA (spatial evaluation in relation to the criteria that exclude any sites with a potentially high level of artificial electromagnetic radiation) | Distance from electrified railways, 30 km at least |
| | Distance from non-electrified electric railways, 10 km at least |
| | Distance from 110, 220 and 400 kV transmission lines, 10 km |
| | Outside of areas with high seismic risk (greater than 7 according to MSK-64 seismic intensity scale) |
| | Distance from the border, 10 km at least |
| TECHNICAL-PRACTICAL CRITERIA | Vicinity of a settlement (availability of power for measuring instruments) |
| | Geometrical-central location |
| | Easy access to the location |
| SOCIAL AND GLOBAL ASPECTS | Social acceptability |
| | Inclusion in the regional observatory network |
| | Appropriate plot (plot size, possibility of agreement with the owner) |
| | Possibility to safeguard the site |

***Tab. 2: Evaluation of sites by using the weighted linear summation method.***
***Tab. 2: Vrednotenje lokacij po metodi utežene vsote.***

| | Parameter 2-a | Parameter 2-b | Parameter 2-c | Parameter 3-b | Parameter 3-c | Score for site suitability |
|---|---|---|---|---|---|---|
| Site 1 | 5 | 2 | 4 | 5 | 4 | 76 |
| Site 2 | 4 | 3 | 3 | 3 | 4 | 64 |
| Site 3 | 5 | 2 | 2 | 3 | 1 | 49 |
| Site 4 | 3 | 2 | 2 | 3 | 1 | 39 |
| Rank of parameter importance | 5 | 2 | 3 | 3 | 5 | |

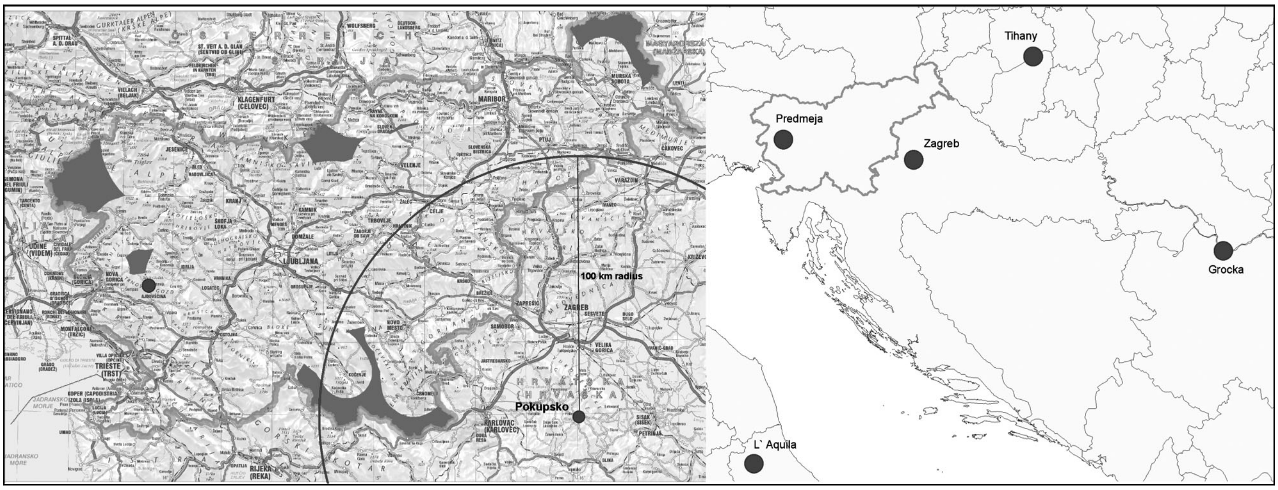


***Fig. 2: Placing the observatory in the existing INTERMAGNET network.***
***Sl. 2: Umestitev observatorija v obstoječo mrežo observatorijev INTERMAGNET.***

high score, but because of the lower score in relation to parameter 3–b (observatory in the territory of the Republic of Croatia is too close) it was treated as less suitable than Site 1 (Fig. 2).

The last stage of decision making process included on-site field observations, as well as informing the local community. The response of the Administration and the Local Community was positive. During field work, a microlocation was selected and sample measurements of geomagnetic field elements were carried out. Detailed results are presented in the next chapter.

## RESULTS

### Sample measurements of the geomagnetic field elements at the selected location

The Laboratory for Geomagnetism and Aeronomy together with the Geomagnetic Institute, Geomagnetic Observatory Grocka (GCK), Republic of Serbia, carried out a preliminary local survey of the homogeneity of the total-intensity gradient of the magnetic field vector, measurements of the geomagnetic field at a base-point, absolute and all three components (X, Y, Z) measurements of the geomagnetic field and measurements of the diurnal variations in elements of the geomagnetic field. The measurements were carried out in September 2008 using the following equipment: *MAGSON 11 3-axis Magnetometer* (accuracy 0.1 nT), *Overhauser magnetometer GSM-19* (Proton magnetometer - accuracy 0.01 nT) and *Bartington DI magnetometer Mag-01H* (accuracy 0.1 nT). The measurements showed that the geomagnetic field is homogenous in the surroundings of the microlocation where the 3-axis magnetometer was installed and in the broader surroundings of the location where the measurements of the absolute values of geomagnetic field elements were carried out. From the results of the measurements of the '*F*' gradient of the magnetic field, it may be deduced that the site is not magnetically contaminated by man-made electromagnetic noise or by noise which might occur because of the heterogeneity of electrical conductivity in the Earth's upper mantle. Only the remains of an iron wire in the stone wall on the boundary between two plots induced some distinctive change in the vertical component of the magnetic field's '*F*' gradient. The recorded magnetic anomaly had peak-to-peak magnitude values of up to ± 20 nT (Fig. 3).

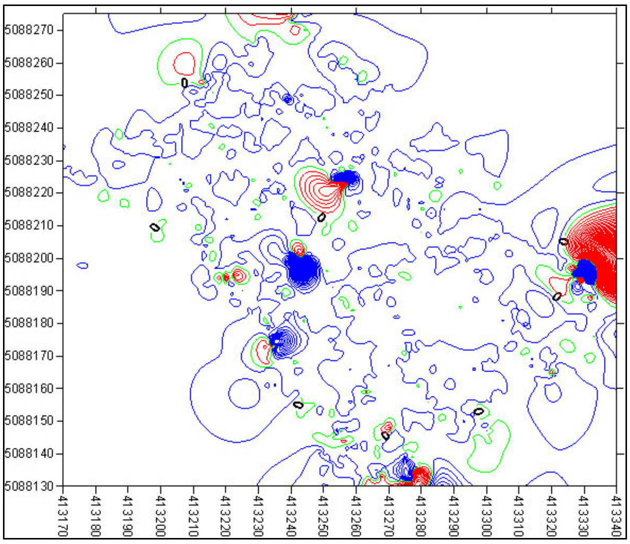


***Fig. 3: The vertical homogeneity of the magnetic field's 'F' gradient; d=100 cm, e=10nT (the visible anomalous signature at the right edge were induced by the wire remains).***
***Sl. 3: Vertikalna homogenost gradienta 'F' geomagnetnega polja; d=100 cm, e=10nT (vidne anomalije na desnem robu so posledica ostankov žice).***

The measurements of the geomagnetic field's diurnal variations were observed by the *MAGSON 11 Flux-gate Magnetometer* and *Proton Magnetometer GSM-19*. The components *dX/dt, dY/dt, dZ/dt, dF/dt* are shown as relative values measured with the *MAGSON 11 Flux-gate Magnetometer*. The total intensity of the magnetic field *Fp* was measured by *Proton Magnetometer GSM-19*, while the change in total intensity of the magnetic field *Fm* was calculated from the recorded measurements made by the *MAGSON 11 3-axis Magnetometer*. *Te* and *Ts* stand for the temperatures in the housing of the *MAGSON 11 3-axis Magnetometer* (Fig. 4).

The results of measurements at the selected site showed that the geomagnetic field's *Y-axis variation* has a harmonious sinusoidal form. The amplitude in the *Y-axis* was approximately 50 nT. The signature of the geomagnetic field's diurnal variation in the *X-axis* was harmonious with the amplitude of 30 nT, but the signal had visible short-term changes that show the presence of magnetic noise. A similar record for the geomagnetic field could be seen in the *Z-axis*. This noise could be attributed to the morphological and geological characteristics of the Karst region.

A comparison of the geomagnetic field elements' diurnal variations recorded during the measurements at Predmeja station with those recorded at the Geomagnetic Observatory in Grocka (GCK) showed that the level of short-term noise was higher at Predmeja station. This is especially visible from the geomagnetic field's signature in the *X-axis* and the *Z-axis* (Fig. 5). The time of observation of the geomagnetic field elements' diurnal variations at the Geomagnetic Observatory in Grocka (GCK) was indicated as '*q*' (quiet days), while the changes in the geomagnetic field elements' diurnal variations at Predmeja station were indicated as *local characteristics signal*.

## DISCUSSION

The multi-stage, multi-criteria decision process for selecting a feasible location for setting up a geomagnetic observatory in the Republic of Slovenia required a lot of work. Initially the efforts were mostly focused on acquiring necessary digital data, and a comprehensive field work on site was carried out after that. GIS was

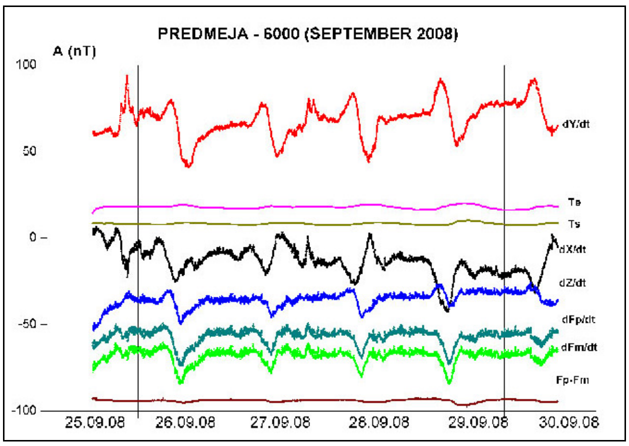


***Fig. 4: Magnetograph of the geomagnetic field elements' diurnal variations.***
***Sl. 4: Magnetogram dnevnih variacij komponent geomagnetnega polja.***

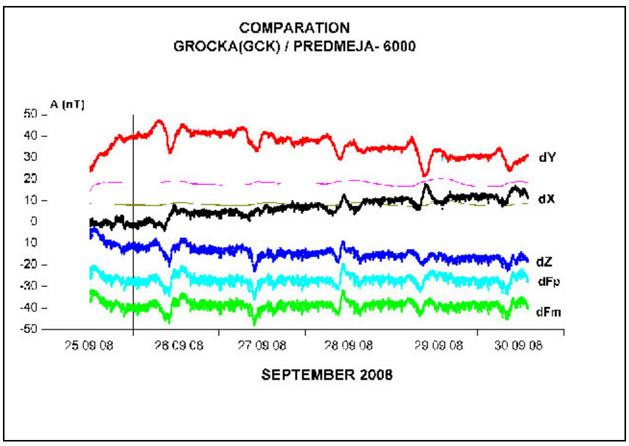


***Fig. 5: Magnetograph of the differences between the geomagnetic field elements' diurnal variations.***
***Sl. 5: Magnetogram razlike v dnevnih variacijah komponent geomagnetnega polja.***

used as a platform enabling the management of the criterion data, spatial analysis, cartographic modelling and production of map layers.

The major advantage of the method presented in the article is the possibility of predicting suitability indices for large areas within a reasonable period of time. The most important objective in the decision process was to find a location with low level man-made electromagnetic noise. Therefore potentially inappropriate sites were excluded from the evaluation process using cartographic modelling including Boolean logic. The criteria and given threshold values were carefully selected with prior consultation with known experts from the *INTERMAGNET Association* and on the basis of literature on this matter.

Extensive on-site measurements were made, including measurements of all geomagnetic field elements, and the results showed that the location is in magnetically calm and homogenous surroundings. The intensity vector of the geomagnetic field did not show any presence of magnetic noise that might be induced by the non-homogeneity of the geophysical parameters of geological formations or artificial electromagnetic radiation. The results of the measurements of change in the 'F' gradient of the magnetic field showed smaller changes with values within the prescribed limits for setting up a reference station.

If in the continuation of the process – installation and safeguarding of the base-point – this location appears inappropriate, the reasonable solution would be to search for an alternative location within the proposed site.

# IZBIRA LOKACIJE ZA POSTAVITEV NOVEGA GEOMAGNETNEGA OBSERVATORIJA Z UPORABO MULTIKRITERIALNE ANALIZE V GIS OKOLJU

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*POVZETEK*

*Raziskave na področju geomagnetizma lahko označimo kot prve raziskave na področju geofizike. Opazovanje geomagnetnega polja je bistvenega pomena za razumevanje fundamentalnih procesov v središču Zemlje, njeni skorji in bližnji okolici planeta Zemlja. V prispevku je predstavljena metodologija izbire lokacije za postavitev geomagnetnega observatorija na ozemlju Republike Slovenije. Izbira temelji na večstopenjskem multi-kriterialnem modelu odločitve. Prvi del je zasnovan v GIS okolju kot postopek analize in vrednotenja prostora ter opredelitve lokacije glede na predhodno postavljena merila. Nadaljnja analiza temelji na metodi utežne vsote, saj moramo upoštevati različne skupine parametrov, ki v končni oceni primernosti lokacije nimajo enake teže. Pri zasnovi modela je bil poseben poudarek na izločitvi območij, kjer je mogoče pričakovati višje ravni elekromagnetnega šuma. Na potencialno primernih območjih so bili opravljeni terenski ogledi in preliminarne meritve homogenosti gradienta totalne intenzitete magnetnega polja, absolutne, bazne in trokomponentne meritve geomagnetnega polja.*

**Ključne besede:** geofizika, geomagnetizem, geografski informacijski sistemi (GIS), observatorij, izbira lokacije, multi-kriterialni model odločitve

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