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The geomagnetic field in Croatia

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In this study we present the distribution of the geomagnetic field components: declination (*D*), horizontal intensity (*H*), inclination (*I*), total field intensity (*F*), as well as the crustal and anomaly geomagnetic fields over the region of Croatia for the 2003.76 epoch, calculated using the Comprehensive model CM4 (Sabaka et al., 2004).

The smooth change of *D*, *H*, *I* and *F* values over the whole territory is found. The map of the crustal field reveals symmetric north-south and east-west isolines behaviour, with the minimum value in the middle part of the north Croatia. The highest values are found at the Adriatic see, along all the coast and at the very eastern part of the country. The anomalies are everywhere negative, with the smallest values in the north-east of Croatia.

The predicted annual secular variation for the Croatian region is: 0.06 °/year for *D*, 11 nT/year for *H*, 0.02 °/year for *I* and 50 nT/year for *F*.

In order to get an insight in the structure of the local field and determine the best location for the observatory, we made use of a set of intensity data measured over the northern part of middle Croatia in 2003. The obtained detailed anomaly map reveals weak small-scale negative structure (–40 nT in average).

Predicted crustal and anomaly fields suggest that the best place for the observatory would be in the middle northern part of Croatia, what is further constrained with the anomalies obtained on the surveyed area.

With the present study we aim to pave a way for more detail research in the field of geomagnetism in Croatia, which has commenced again after more than 50 years' gap.

Keywords: geomagnetic field, geomagnetic measurements, geomagnetic models, geomagnetic observatory

1. Introduction

(i) Motivation

The geomagnetic measurements in Croatia date back to the year 1806, and continue with the long time gaps to 1949 (Goldberg et al., 1952). Recently, the research of the geomagnetic field in Croatia has commenced after more than 50 years and an effort to establish the geomagnetic observatory was made. In 2003 the first measurements of the total field intensity strength were performed over the northern part of the country (Vujnović et al., 2004).

(ii) Geomagnetic field distribution and importance of geomagnetic observatories

Only at the observatories the geomagnetic field values, liable to continuous changes, are monitored continuously. Continuous observation of the magnetic field elements enables permanent renewal of geomagnetic maps, especially concerning application in air and maritime traffic. The information of the field distribution, together with geological and other geophysical data can be used to create geological and geomagnetic models of the area. Geomagnetic measurements can find also an application in archeology, in identification of minerals, as a helpful tool for directed drilling in oil mining, etc. With permanent measurements it is possible to register sudden changes of magnetic field caused by the processes on Sun, which can produce serious disturbances in telecommunications (Webb and Allen, 2004). The continuous recording of the observatory is used for reduction of data obtained during ground surveys, especially interesting for state geodetic measurements. Combination of the ground based and the satellite data gives the opportunity to fully exploit the geomagnetic field. Due to the different distances from the sources of the field, observatory and satellite data gives different knowledge and the observatories help to better constrain the satellite data which are a mixture of the spatial and temporal signals. Moreover, spatial and temporal distribution of the geomagnetic elements provides the information on the physical processes originating in the deep Earth's interior. Global models are limited by the sparse spatial coverage of ground data in particular on the southern hemisphere. Models from satellite data are limited by the short duration of satellite missions and the limitation to resolution at ground level due to the satellite altitudes of several 100 km. Therefore, modelling the main geomagnetic field as well as its secular variations is not possible without the observatories data. Despite high density of the European network, the network is still not dense enough to detect the small scale phenomena. Past measurements in Croatia indicate the presence of local anomalies especially stressed in the Adriatic coastal region and on the islands. The new Croatian observatory will fill a gap in network of European geomagnetic observatories. The investigation presented in this paper further contributes to the renewal of geomagnetism in Croatia, and to installing the observatory in an area with low field gradient, avoiding magnetic anomalies. This study gives also an idea about the distribution of geomagnetic elements and its recent temporal changes over the whole Croatian territory.

(iii) Sources of the geomagnetic field

The magnetic field enclosing the Earth is a very complex system. As observed on the surface, there are contributions of internal (core and crustal fields) and external origins (ionospheric and magnetospheric fields). The core field is the dominant component which is belived to be caused by the electrical currents in the outer fluid core (Jacobs, 1987). The maximum intensity is around 60 000 nT near the magnetic poles and around 25 000 nT near the magnetic equator. Its variation over time scales of decades to centuries is referred to as secular variation (henceforth SV). The crustal field is related to the remanent and induced magnetisation. Its magnitude varies from fractions to hundreds of nT, but can reach values as high as several thousands of nT. The external fields are produced by ionospheric current systems (equatorial and polar electrojets) and magnetospheric currents (in magnetopause in the direction of the Sun; tail currents; ring currents surrounding equatorial region at a distance of several Earth radii). The values of those fields at the Earth's surface are of few tens of nT, even few hundred to thousand nT during magnetic storms.

Thus, we consider that the geomagnetic field **B** at a given location can be represented as the vector sum:

$$\mathbf{B} = \mathbf{B}_m + \mathbf{B}_c + \mathbf{B}_e \qquad (1)$$

where $\mathbf{B}_m$ is the main (core) field, $\mathbf{B}_c$ is the crustal field and $\mathbf{B}_e$ is the external field. In this study, we consider only the internal field, which simplifies Eq. 1 to the following one:

$$\mathbf{B} = \mathbf{B}_m + \mathbf{B}_c \qquad (2)$$

(iv) Geomagnetic models

Different models try to fit and explain the observed geomagnetic field and its time variations on global as well as on regional scales. Among global models, the most widely used are the International Geomagnetic Reference Field (http://www.ngdc.noaa.gov/IAGA/vmod/igrf.html; see e.g. Macmillan et al., 2003) and the Comprehensive Model (Sabaka et al., 2004; The CM4 model spans the time domain from 1960 to mid-2002 and has been derived from quiet-time MAGSAT, POGO, Ørsted and CHAMP satellite data in combination with observatory hourly means. Various field contributions (core and lithospheric field, external field generated by magnetospheric and ionospheric currents, together with the field-aligned currents, the currents induced in the conducting Earth) are coestimated in a comprehensive approach. Moreover, the secular variation of the core field is described as a continuous function, in contrast to the IGRF, which provides values only every five years. The purpose of regional modelling is to describe the geomagnetic field over a small region of the Earth's surface, providing a better spatial resolution of the local field. The CM4 model can only describe regional long-wavelength, but not local, short-wavelength crustal field. First, we discuss these long-wavelenth features of the geomagnetic field in Croatia. In order to get an insight in the structure of the local field and determine the best location for the geomagnetic observatory we model the local anomaly field in the region between the directions Zagreb–Koprivnica on the west and Hrvatska Kostajnica–Virovitica on the eastern part of Croatia, based on dedicated measurements carried out in 2003.

2. General field distribution in Croatia

To investigate the core and crustal field, we used the internal field description of the CM4 model, which among the global models in use is the most suitable for our purpose. A detailed study of how well the CM4 predictions and observatory data agree over Europe was performed by Verbanac et al., 2006. They found good fits at most observatories with often constant offsets between data and model predictions, which are considered to be a signature of the local crustal field. All modelled values are given for the epoch 2003.76, which is the middle of the interval of the field measurements used in the next section. Since the CM4 model is valid to mid-2002 and we aimed to make the extrapolation to epoch 2003.76, we first checked how well the extrapolated model fits the measured total field intensity at two nearby observatories, Hurbanovo and L'Aquila, at the epochs bracketing the 2003 epoch. At both observatories, the residuals between measured and modelled values are smallest in 2001 and arose in 2003, as expected. The residuals in 2001 differed from those in 2003 for

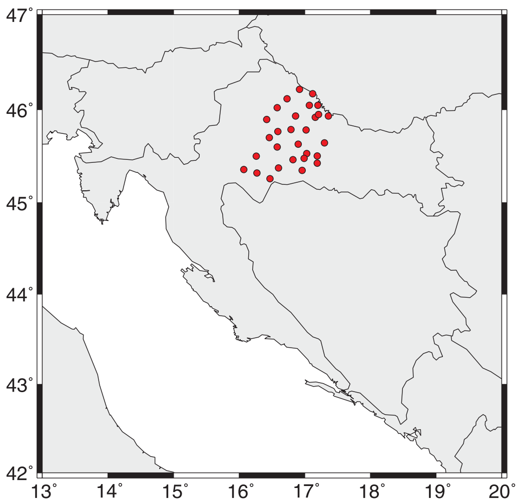


Figure 1. The studied region. Positions of sites surveyed in 2003 are shown as circles.

about 10 nT. The comparison of data and modelled time series, clearly shows that the extrapolation of the secular variation is causing this difference. The same effect can be expected everywhere in Croatia and is not important for this study.

The following geomagnetic components: D (declination), I (inclination), H (horizontal intensity), as well as the total field intensity F and crustal field were calculated from the model. The spherical harmonic expansion up to degree and order 65 was used, representing the internal core and crustal field.

All values were first calculated on a regular grid of $1° \times 1°$, spanning the longitudinal region from 13° E to 20° E and latitudinal region from 42° N to 47° N (see Figure 1). The maps of D, H, I and F are shown in Figure 2. Declination changes between 1.8° and 3° from west to the east side of the country. Horizontal intensities are in the range 24 200 nT – 21 600 nT, the highest values are found on the south. The map presented in Figure 2c shows gradual increase of the inclination toward the northern part of Croatia. The values are between 59° and 63°. The total field intensity F (Figure 2d) changes from 46 600 nT in the southern part of the country to 47 700 nT in the northern part and its gradient amounts for 83 nT and 308 nT per 1 degree of longitude and latitude, respectivelly.

Then, we estimated the annual change (SV) of these components from the CM4 model. The calculated SV values of D, H, I and F hardly differ over the studied region, as expected, since the country size is comparatively small. Declination changes by 0.06 °/year, horizontal intensity by 11 nT/year and inclination by 0.02 °/year. The SV of the total field intensity is about 50 nT/year.

In Figure 3 the crustal and anomaly field for the same region are presented. The crustal field is the evaluation of the CM4 model for spherical harmonic degree 15 to 65. Its intensity consequently is purely positive. The anomaly field, F_a, describes positive or negative deviations from the main total field intensity, and is given by:

$$F_a = B - B_m \tag{3}$$

where B and B_m are the intensity values of the vectors given in Eq. 2.

The crustal field (Figure 3a) shows somehow symmetric north-south and east-west behaviour, getting the minimal value in the middle of the north Croatia (about 23 nT). Values of about 40 nT are found at the Adriatic see and along all the coast from south to the north. The values decreas to about 20 nT and increase again to 40 nT at the north-eastern part of the country. The anomaly map, presented in Figure 3b reveals negative anomalies over most of Croatia and no deviation over the southern coastal region. The smallest values are found in the nort-eastern part (–5 nT) and the highest values are reached toward the north-western part (around –30 nT).

3. Determining a location for the geomagnetic observatory

In order to determine the detailed anomaly field and find the best location for the geomagnetic observatory, measurements had been taken in the period September 23 – October 19, 2003 (for details see Vujnović, et al., 2004). The geomagnetic total field intensity at 30 sites was measured. The occupied stations are shown as circles in Figure 1. The measurements are concentrated in a specific area, because for practical reasons the ideal case would be to install

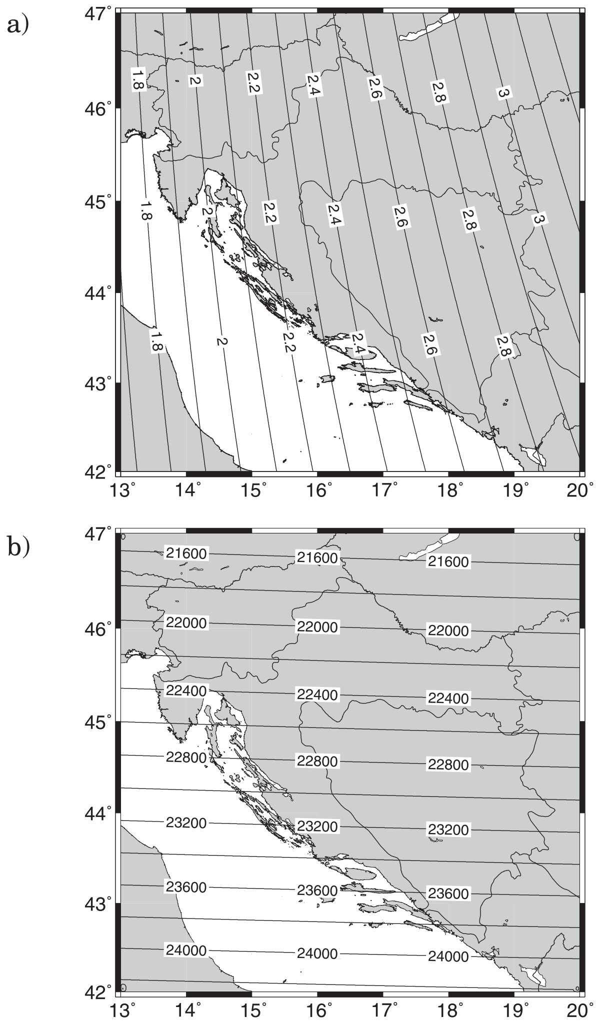


Figure 2. Maps at epoch 2003.76 for a) declination, b) horizontal intensity, c) inclination and d) field intensity, computed from the CM4 model on the regular grid of 1° × 1°.

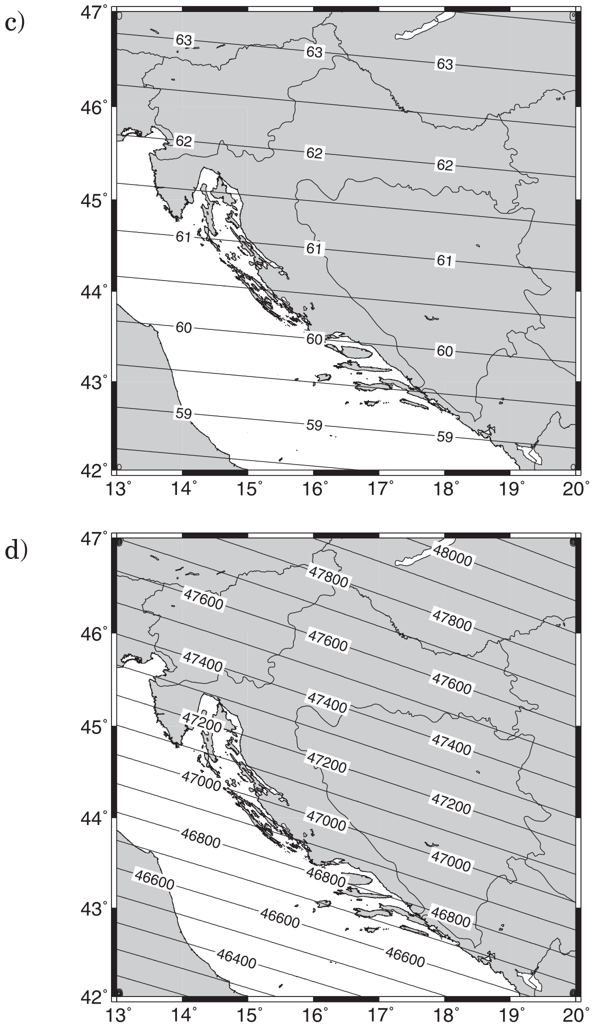


Figure 2. Continued

the observatory in the vicintiy of the University of Zagreb, so firstly the nearby geomagnetic field was investigated. The results from the previous section showed that we do not expect very strong anomalies in this region. The external field is removed from the measurements by the reduction procedure for ground surveys (described in detail by (Vujnović, et al., 2004).

For each measurement location (see Figure 1) we calculated the total field intensity, core and crustal field predictions from CM4. The core field at each location was subtracted from the measurement results in order to obtain the distribution of the anomaly field as in Eq. 3. The interpolation of the unevenly

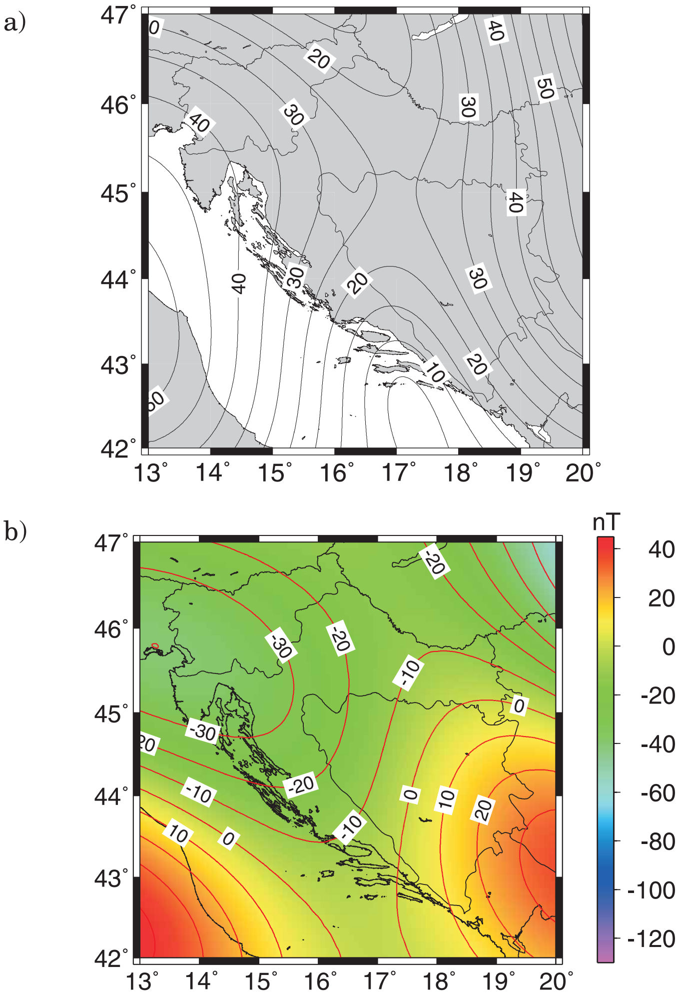
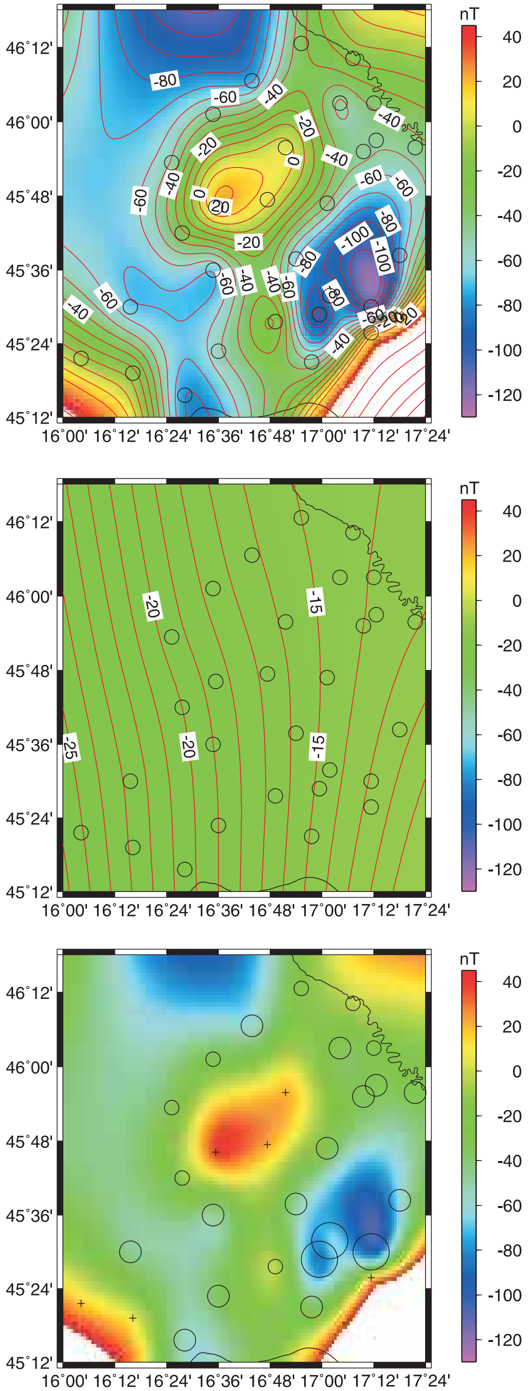


Figure 3. Maps at epoch 2003.76 for the a) crustal and b) anomaly geomagnetic field, computed from the CM4 model on the regular grid of 1° × 1°.

spaced data was done as follows. First, a median position and value for every non-empty block in a defined grid region of 0.001° × 0.001° was calculated to avoid spatial aliasing and eliminate redundant data. Then, the interpolation of the data was done by applying the adjustable tension continuous curvature

Figure 4. Maps at epoch 2003.76 for the a) local anomaly geomagnetic field, b) CM4 anomaly field and c) differences between the local and anomaly geomagnetic fields shown in panels a) and b). The symbol sizes are according to the amount of differences. The symbol (+) belongs to the positive differences and the circles to the negative ones. →


nT
40
20
0
-20
-40
-60
-80
-100
-120
46˚12'
46˚00'
45˚48'
45˚36'
45˚24'
45˚12'
16˚00' 16˚12' 16˚24' 16˚36' 16˚48' 17˚00' 17˚12' 17˚24'
-80
-60
-40
-20
0
20
-100
-15
-25

surface gridding algorithm (on a chosen $0.01° \times 0.01°$ grid) which results in the minimum curvature solution. The interpolated values fits very well the measured data. At most locations, the differences are not significant, only at one location the values differ by 2 nT. The rms between the interpolation model and the data is 0.88 nT.

The map of the anomaly field (Figure 4a), reveals two strong anomalies (–100 nT, –80 nT) and a localised area of zero anomaly, centered approximately at 16.61 E longitude and 45.8 N latitude. Comparing with Figure 4b, which represents the CM4 anomaly field (note that the same color scale is used in both maps), this map reveals more structure, what was espected since CM4 model is the global model. With the spherical harmonic expansion used in the CM4 predictions (degree/order 15 – 65), the resolution is limited to 620 km. On the other hand, the biggest distance between the measured points is 155 km. Differences between the local anomalies and those predicted by CM4 can be further noticed from the results presented in Table 1 which for each site gives measured total field intensity value, anomaly field based on measurements (local anomaly field) and modelled anomaly field. At some locations, the two anomaly fields differ significantly from each other, althought both anomalies are negative over the whole region (at only one location the anomaly is small and positive). The constructed map of differences between the measured values and the model predictions is shown in Figure 4c. The overall range of discrepances is from –95 nT to 45 nT and was splited into four categories: (–95, –60), (–60, –30), (–30, 0) and (0, 45). The symbol sizes are according to the amount of differences (the smallest the differences, the smallest symbol is denoted). The symbol shape (+) belongs to the positive differences and the circles to the negative ones. The map reveals domination of the negative intermediate differences.

4. Conclusion

In this study we presented the distribution of the declination (D), horizontal intensity (H), inclination (I), total field intensity (F), as well as the crustal and anomaly geomagnetic fields over the region of Croatia for the 2003.76 epoch, calculated using the Comprehensive CM4, model (Sabaka et al., 2004). The obtained maps of D, H, I and F show smooth change of the values from the western to the eastern (D) or from the southern to the nortern part of the country (H, I and F). The map of the crustal field reveals symmetric north-south and east-west isolines behaviour, with the minimum value in the middle part of the north Croatia (about 23 nT). The highest values (about 40 nT) are found at the Adriatic see, along all the coast and at the very eastern part of the country. The anomalies are everywhere negative, with the smallest value (–5 nT) in the north-east of Croatia. The negative sign of anomalies means that the absolute value of the total field intensity is smaller than the absolute value of the core field.

Table 1. The geomagnetic total field intensity values for the 2003.76 epoch at the measured points.

Epoch	Geografic Long	Coordinates Lat	Measured total field (nT)	Anomaly field (nT)	Modelled Anomaly field (nT)
2003.76	45.26	16.47	47327.3	–79.5	–20.5
2003.76	45.50	17.19	47429.5	–103.0	–12.9
2003.76	45.93	16.86	47641.0	4.5	–15.8
2003.76	45.77	16.59	47586.7	18.9	–18.5
2003.76	45.70	16.46	47506.4	–32.2	–20.0
2003.76	46.21	16.92	47690.5	–33.4	–15.0
2003.76	46.05	17.07	47633.4	–51.8	–14.5
2003.76	46.05	17.20	47656.8	–37.6	–13.9
2003.76	45.53	17.03	47452.4	–76.5	–14.5
2003.76	45.79	16.79	47590.7	2.8	–16.7
2003.76	46.02	16.58	47597.3	–44.8	–17.6
2003.76	45.46	16.82	47472.4	–21.2	–16.6
2003.76	45.92	17.16	47607.3	–46.4	–14.0
2003.76	45.63	16.90	47480.4	–69.3	–15.8
2003.76	45.78	17.02	47554.2	–49.0	–14.8
2003.76	45.64	17.30	47514.5	–67.8	–12.4
2003.76	45.35	16.96	47422.3	–46.4	–14.9
2003.76	45.93	17.36	47627.8	–44.4	–13.1
2003.76	45.43	17.19	47519.9	10.8	–12.7
2003.76	45.50	16.26	47396.7	–67.8	–22.7
2003.76	45.95	17.21	47618.9	–47.6	–13.8
2003.76	45.48	16.99	47409.0	–101.5	–14.8
2003.76	45.38	16.60	47398.7	–52.2	–19.0
2003.76	45.60	16.58	47448.4	–68.9	–19.0
2003.76	46.11	16.73	47610.0	–71.2	–16.2
2003.76	45.32	16.27	47394.5	–15.9	–22.8
2003.76	45.36	16.07	47400.9	–7.0	–25.1
2003.76	45.89	16.42	47545.2	–48.3	–19.5
2003.76	46.17	17.12	47708.0	–17.0	–14.3

We also calculated the annual secular variation of all field components. The following values are found: 0.06 °/year for D, 11 nT/year for H, 0.02 °/year for I and 50 nT/year for F.

Based on a set of intensity data measured over the northern part of middle Croatia in 2003, we carried out a detailed investigation of local anomalies in order to determine the most suitable location for a new geomagnetic observatory. The obtained anomaly map reveals small-scale negative structure.

Generally, the anomalies are not very high, amounting for –40 nT in average. Two very localised areas of higer anomalies (–100 nT and –80 nT) are noticed, and one location with zero anomalies. Even though the CM4 model is a global model, it gave us an idea about the field behaviour over the whole Croatian territory. However, the measurements are crucial to obtain the small-scale information not included in the global models. The later is important not only to obtain knowledge about the anomalies, but also to find the most suitable place for the observatory location. From predicted crustal and anomaly fields, we concluded that the best place would be somewhere in the middle northern part of Croatia. The anomalies obtained on the surveyed area, further constrain this suggestion, recommending the area around 16.61 E in longitude and 45.8 N in latitude as optimal location for the geomagnetic observatory.

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SAŽETAK

Geomagnetsko polje u Hrvatskoj

Giuli Verbanac i Monika Korte

U ovom radu predstavljamo raspodjelu slijedećih komponenata geomagnetskog polja: deklinacije (*D*), inklinacije (*I*), horizontalnog intenziteta (*H*), intenziteta totalnog polja (*F*), kao i polja kore, te anomalnog polja na području Hrvatske. Navedene veličine modelirane su za epohu 2003.76 pomoću CM4 modela (Sabaka et al., 2004).

Svi se elementi sporo mijenjaju duž cijelog područja. Polje kore pokazuje simetrično sjever–jug i istok–zapad ponašanje, sa minimalnom vrijednosti u srednjem dijelu sjeverne Hrvatske. Najveće vrijednosti zapažene su u Jadranu, duž cijele obale i u vrlo istočnom dijelu zemlje. Anomalije su svuda negativne, sa najmanjim vrijednostima u sjeveroistočnoj Hrvatskoj.

Izračunate sekularne promjene su pozitivne i iznose: 0.06 °/god za *D*, 11 nT/god za *H*, 0.02 °/god za *I* i 50 nT/god za *F*.

Na osnovi izmjerenih vrijednosti intenziteta ukupnog polja u sjevernom dijelu srednje Hrvatske, sprovedena je detaljna analiza lokalnih anomalija u cilju procjene najpogodnije lokacije za instaliranje geomagnetskog opservatorija. Dobivena mapa anomalija pokazuje negativne strukture malih dimenzija. Općenito, anomalije nisu velike, te u prosjeku iznose 40 nT.

Procijena polja kore i anomalija sugeriraju da je središnji dio sjeverne Hrvatske najadekvatnije za lociranje geomagnetskog opservatorija, a što je također potvrđeno anomalijama dobivenim na području premjera.

Rezultatima ovog istraživanja nadamo se doprinijeti postupcima novog početka geomagnetizma u Hrvatskoj.

Ključne riječi: geomagnetsko polje, geomagnetska mjerenja, geomagnetski modeli, geomagnetski opservatorij

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