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Results of the preliminary geomagnetic field strength measurements in the northern part of middle Croatia

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In autumn 2003 we made a survey of total magnetic field strength in a part of Croatia from river Drava north to river Sava and Pokuplje, between the lines Zagreb – Koprivnica on west, and Hrvatska Kostajnica – Virovitica on east. Thirty positions were surveyed in the net with spacing of 15–20 km. For data reduction, the field variations were recorded at the base station in Pokupsko, acting as provisional geomagnetic observatory. A geomagnetic map was constructed and discussed. The gradient of the field generally points to the north-east, having at minimum 18 nT/10 km, and at maximum 38 nT/10 km. Accounting for the all inaccuracies, we find the positional error of the isodynames to be 1.3 to 3.0 km, depending on the field gradient found in the area.

Using scarce data published for the epoch 1927.5, we found an average change of 2900 nT and obtained an estimate of the secular variation equal to +40 nT/year. By exploiting the data of geomagnetic survey in Hungary for the epoch 1995.0, we have improved a part of the geomagnetic map close to the Hungarian border. Further, we have compared hourly means for the observational periods September 22–29, 2003 and October 14–20, 2003 with the data obtained at the Niemegk Observatory (Germany). As a numerical parameter describing the differences we introduced the average standard deviation of differences between signals Niemegk-Pokupsko; this changed from the first to the second observational period from 5.2 nT to 8.7 nT. We also compared our 1-minute means with the similar recordings of observatories in Tihany and l'Aquila for the most disturbed day.

Keywords: Geomagnetic field, total field strength, secular variation, northern middle Croatia

1. Introduction

Geomagnetic measurements in Croatia are scarce and with long time gaps. For a review see, for example, Skoko (1992) or Vujnović and Marić (2001). We will mention two measurements carried out by Kugler (1916, 1922) and by Goldberg et al. (1952). During 1915 and 1916 Kugler measured declination and horizontal field strength on the northern side of rivers Kupa and Sava (from rivers Kupa – Sava to the northern border of Croatia), from Slovenian border on the west, to Vukovar on the east, on 80 positions; his expedition lasted six months in total. Goldberg et al. measured declination in two summer months of 1949 along the Adriatic coast and on the islands, on 48 positions, and evaluated for the epochs 1949.0. In the meantime, Mokrović (1928) reanalysed the useful data of the previous investigators, and data from the observatories at Potsdam, O-Gyalla (Hurbanovo) and Pula, obtaining values of inclination I, declination D, and horizontal field strength H, for the epochs 1927.5 for 77 positions in previous Kingdom of Serbs, Croats and Slovenians. There were the only data we could use to calculate the total field strength F.

2. Measurements

Nowadays the technique of measurement is greatly improved by lightweight instruments like proton precession and D/I fluxgate magnetometers. We were measuring only total field strength having on disposal two proton precession magnetometers of GEM Systems, Canada: one GSM-18 (Ser.No. 6744) was used as a mobile station, and GSM-19 (vers. 4.0, Ser.No. 51410), the Overhauser proton precession magnetometer, was used for the permanent recording, simulating an observatory. The proton precession magnetometer uses a property of the atomic magnetic moments which precesses in the imposed magnetic field. The gyromagnetic ratio of protons – the ratio of magnetic moment of rotated atomic particle to its angular momentum is accurately known to 8 characteristic digits ($\gamma_p = 2.675\ 152\ 55 \cdot 10^8\ \mathrm{T}^{-1}\ \mathrm{s}^{-1}$).

The magnetometer allow readings in time steps, and they can be chosen from 3 s to 1 h. We used cycling times of 10 s and of 20 s. Time resolution of the sensors is given by the cycling time. During that time a cycle of processes is going on: at first, an applied RF current, flowing through the coil within which is situated a proton reach fluid, polarizes protons to a given direction; secondly, another pulse deflects magnetic moments of protons into the plane of precession; third, free precession gives a signal whose frequency in acoustic range is measured and numerically converted into the field strength. Measured magnetic field can be taken to be an average during a part of the cycling time in ordinary proton precession magnetometer, and average value during the cycling time in Overhauser effect proton magnetometer. One subtle atomic process, called Overhauser effect, consists in transfer of the electron

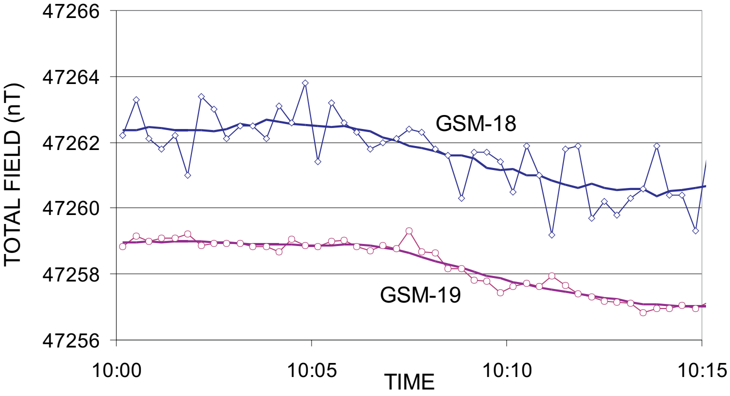

Figure 1. 15-minute recordings of two magnetometers. Two magnetometers were synchronized manually within a few seconds. Mean curves are drawn as moving averages.

spin energy to protons and allows continuous polarization and continuous precession, leading to a better signal-to-noise ratio. This is shown by comparison of traces recorded with available magnetometers (Fig.1). Magnetometer GSM-18 shows scatter of about 1 to 2 nT, while the changes recorded by the GSM-19 are within a minute part of 1 nT and appears genuine.

The base station was situated in the village of Pokupsko, and magnetometer GEM-19 was provisionally placed in a wooden hut. We have not identified eventual metal parts, but sensor recorded values less than values found in the open field, 150 nT to 400 nT less, depending on the position of the sensor in the hut. When constructing the geomagnetic map, the value found in the open field at Pokupsko was used, while observatory data were used for the reduction only. Amplitude of the variations inside and outside the hut were carefully controlled.

Base station in Pokupsko was engaged twice, the first time from 22nd to 29th September, 2003, the second time from 13th to 20th October, 2003.

The survey was conducted on four days in the region of interest, in countryside sufficiently far away from buildings and obvious sources of disturbances, on 22nd, 23rd and 25th September, and on 14th October. We established 30 stations. On each of them we selected an area of 20 m × 20 m; an operator walked along the cross centred in the area, from east to west, and from south to north, activating the magnetometer at every 2 m. Datum was chosen as an average of the individual data. The station position was properly marked. During the expedition, only one station was not adequate, showing differences larger than 10 nT. Differences were usually within a few nanoteslas what leads to the conclusion that the area is geologically homogeneous. It consists mainly of sedimentary layers, left from the Panonian Sea and from river valleys. The scatter of data on an individual station was in range of 1 nT, and averaged standard deviations for the all stations amounted to 1.4 nT.

The vertical gradient was not measured systematically. The magnetic field was measured 2 m above ground. Geographical coordinates of the position of the area centre were registered by a GPS (Garmin chartplotting receiver GPSMAP 76S), indicating uncertainties of 5–10 m. As recommended, measurement position was also secured by making sketch of the surroundings, including directions to some landmarks.

In the reduction procedure of the data used for geomagnetic mapping one has to choose a reference level. Due to the fact that we just started the project of measuring the geomagnetic field, we had no annual mean values available. We were therefore forced to rely on the mean values obtained during a continuous recordings at the base station, *i.e.* the daily mean value, taken from 00:00 to 24:00 UT, of the all 6 days 23nd–28th September, and another mean value for another six days 14th–19th October, 2003. Both runs should be considered to be independent, since the sensor was repositioned. However, difference between two means amounted less than 1 nT.

The reduction was made by the following algorithm:

$$F = F(t) - F_0(t) + F_0$$

where F is the characteristic value of the field strength at location x, $F(t)$ is the value measured at the same location x at time t; $F_0(t)$ is the measured value at the base station (auxiliary observatory) at time t, and F_0 is the reference level, that means, value obtained as an average during some prescribed time interval.

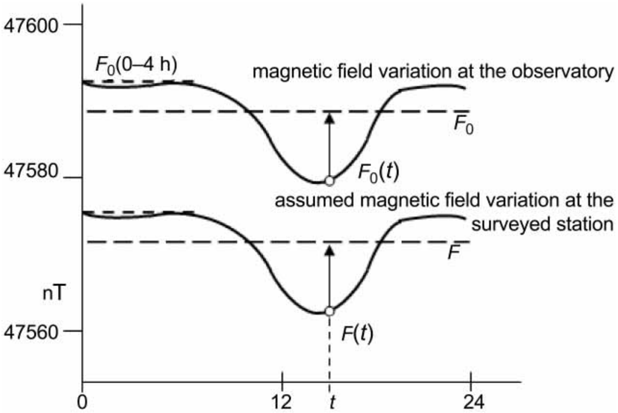

Figure 2. Sketch of the reduction procedure. The field strength measured at the observatory and at the surveyed station at time t are subsequently $F_0(t)$ and $F(t)$. The average value at the observatory is F_0 (long time average) and corresponding value at the surveyed station is F. For the average value one can use also the values measured at the quite night time, here F_0(0–4 h).

The reduction procedure relies on the assumption that daily variations imposed by the outer geomagnetic field are of the same absolute values at the base station as they are on any position in the surveyed area: difference between values $F_0 - F_0(t)$ at the base station is equal to the difference $F - F(t)$ anywhere over the land, regardless the main field strength. The equality is expected to decrease with increasing spacing between base station and surveyed station. It is therefore interesting to compare our recordings with the data obtained at the other observatories. We used, first, the data obtained in the Observatory Niemegk, available on the Internet. It is done by using the hourly mean values, as shown in Figure 3. Observed daily variations are characteristic of the days with moderately perturbed geomagnetic field.

There is a significant similarity between the recordings. Niemegk is 820 km away from Pokupsko. Pokupsko has latitude 45.480° N, longitude 15.989° E, while Niemegk has longitude 52.072° N, latitude 12.675° E. In the week October 13–20, 2003, differences increased. As a measure of differences in daily behaviour observed in Niemegk and Pokupsko, we calculated the

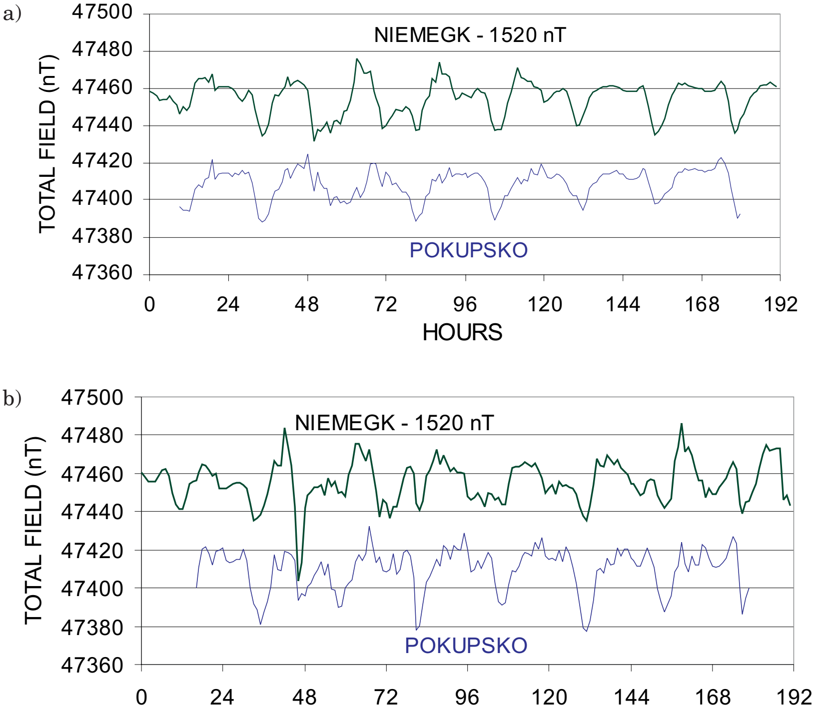

Figure 3. Comparison of the total field measured in Niemegk and Pokupsko: a) from September 22 to 29, 2003, and b) from October 13 to 20, 2003. For comparison, Niemegk data were decreased by 1520 nT.

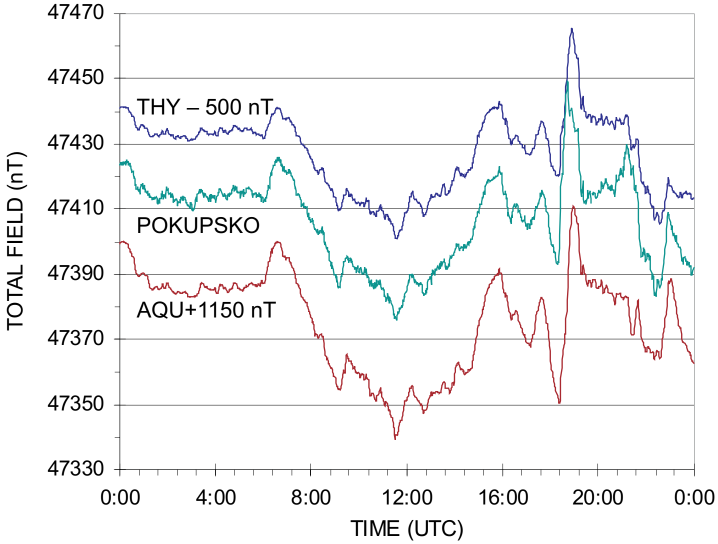

Figure 4. Comparison of the 1-min means of recordings in Tihany, Pokupsko and l'Aquila.

standard deviation of the differences between signals, equal to 5.2 for the 6 days September 23–28, and 8.7 for the second period of 6 days, October 14–19. These values can be regarded as uncertainties when one tries to reduce own measurements with the data from an observatory as distant as Niemegk. (The use of distant recordings is more justified on geomagnetically quiet days.) The maximum distance of our base station in Pokupsko from the positions where we measured was 120 km. Assuming that differences in signals are proportional to distance, we estimate that the distance accounts for the uncertainty in our measurements to about 1 nT.

An useful insight we get by comparing our daily recordings at Pokupsko with the recordings of the geomagnetic observatories in Tihany and l'Aquila (Fig.4). Standard deviation of the absolute differences for 1-minute means between Pokupsko and Tihany, between Pokupsko and l'Aquila, and between Tichany and l'Aquila, were for the most disturbed day, 14$^{\text{th}}$ October, equal to 3.6 nT, 6.5 nT and 7.0 nT respectively. The distance between Pokupsko and Tihany is 260 km, and between Pokupsko and l'Aquila 450 km.

3. Results

Results for the reduced total field strength are shown in Table 1. The reference level was the daily mean value, averaged over six days of continuous recordings. From the geographic coordinates and the data from Table 1, a geomagnetic map (Fig. 5) was constructed by using softwer of the GPS and

Table 1. Reduced total field strength.

No.	NAME	φ (degree)	λ (degree)	h (m)	F (nT)
1	Babina Rijeka	45,26131	16,47342	166	47327,35
2	Bijela	45,50447	17,18847	148	47429,50
3	Bjelovar	45,93264	16,86111	132	47641,01
4	Čazma	45,76706	16,59156	97	47586,71
5	Derežani	45,70078	16,46389	108	47506,45
6	Drnje	46,21378	16,91972	131	47690,52
7	Đurđevac	46,04622	17,06728	116	47633,43
8	Ferdinandovac	46,04519	17,19822	112	47656,78
9	G. Uljanik	45,53136	17,02583	130	47452,37
10	Ivanska	45,78619	16,78742	111	47590,66
11	Križevci	46,01911	16,58394	121	47597,35
12	Kutina	45,46450	16,82342	118	47472,41
13	M. Črešnjevica	45,91778	17,16336	151	47607,29
14	M. Pašijan	45,63200	16,89839	124	47480,45
15	M. Pisanica	45,78194	17,02228	148	47554,21
16	Maslenjača	45,64392	17,29944	146	47514,50
17	Novska	45,34839	16,95978	119	47422,29
18	Okrugljača	45,93147	17,35519	107	47627,85
19	Pakrac	45,42669	17,18836	165	47519,87
20	Petrovec	45,50172	16,26189	107	47396,71
21	Pitomača	45,94861	17,20889	123	47618,86
22	Pokupsko	45,47969	15,98861	120	47409,00
23	Sunja	45,37561	16,59911	94	47398,69
24	V. Ludina	45,60081	16,57886	103	47448,44
25	V. Mučna	46,11478	16,72603	200	47609,99
26	V. Šušnjar	45,32058	16,26622	216	47394,50
27	Viduševac	45,35939	16,06556	125	47400,88
28	Vrbovec	45,89358	16,41806	128	47545,18
29	Ždala	46,16850	17,11886	120	47707,96

Surfer Programme. For the extrapolation we used *natural neighbour* extrapolation.

From the available data sets we can estimate secular variation for the last 75 years. In the list of Mokrović (1928), several stations are found close to some of our positions, and from comparison we find that field strength in-

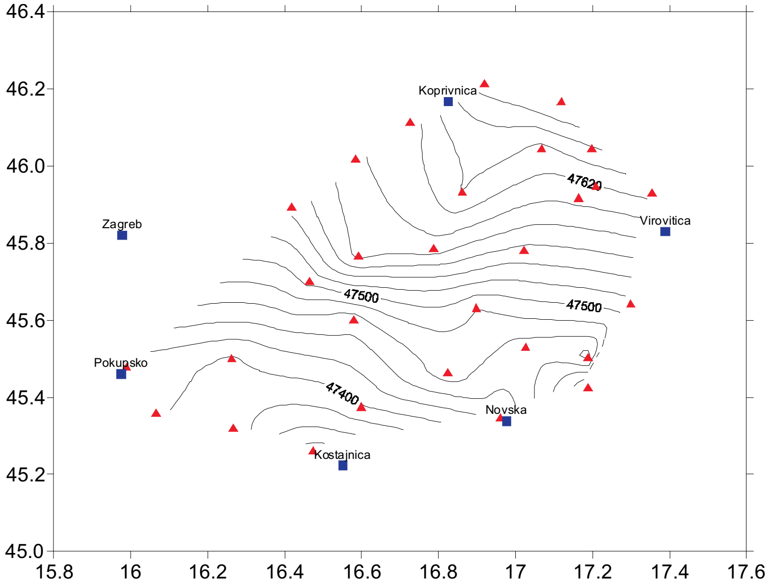

Figure 5. Isodynames of the total field strength in steps of 20 nT, with the stations (triangles – waypoints).

creased for about 2900 nT ± 100 nT, what means that the mean secular variation is about +40 nT/year. The figure serves only for rough estimate, since there is influence of the spatial gradients, and possible influence of local anomalies. However, not very different estimate can be obtained from the curves published in the Fig. 7. of Kóvacs and Körmendi (1999) for the Observatory Tihany, Hungary, which is 260 km away from Pokupsko. It is obvious that secular variation is not constant through time; approximate rates of +41 nT/year for the period 1955 to 1960, and +26 nT/year for 1960 to 1995 can be estimated from that figure. Assuming the same rates of secular variation for our region from 1928 to 1955, and from 1955 to 2003, we obtain a total increase of 2350 nT (in average, about 30 nT/year). Perhaps secular variation was even stronger earlier, in order to span the total difference of previously mentioned figure.

In any two-dimensional representation there is a question of validity of data treatment at the area borders. When there are no measurements done outside the outlined area, extension of the isodynames at the area borders should be taken with precaution. We investigated different methods of interpolation and chose the *natural neighbour* interpolation which gave the smallest residuals and extrapolated little out of the stations laying on the skirt of the investigated area.

Our measurements were performed close to Hungary what gave us the possibility to use the data published by Kóvacs and Körmendi (1999) for the

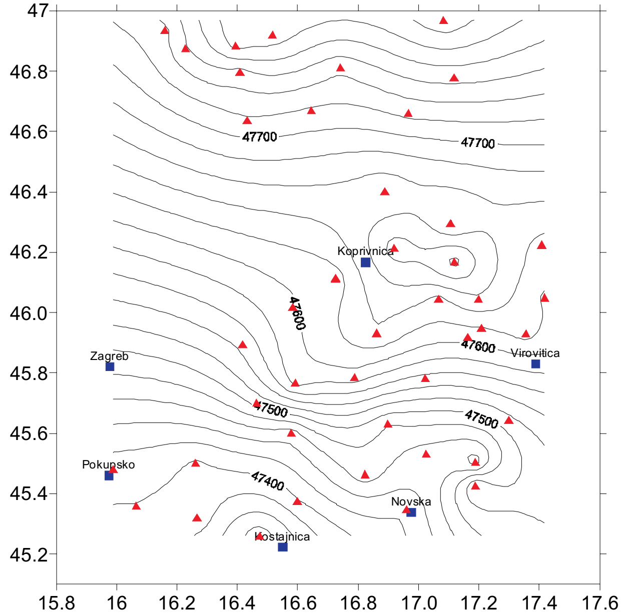

Figure 6. Isodynames obtained from the values of Table 1. and of 14 point data from Hungarian survey (Kóvacs and Körmendi, 1999)

epochs 1995.0 and to extrapolate them linearly to the year 2003. Using the data for 14 Hungarian repeat stations situated close to the state border, we constructed another map of isodynames (Fig. 6).

4. Discussion

Resulting position and shape of the isodynames depend on the number of data found outside the investigated area. Comparison of the Fig. 5. and Fig. 6. clearly shows difference within the investigated area about 20 km from the borders. When the data from Hungary are included into analysis, shapes of isodynames 47660 nT and 47680 nT were changed and extended. Isodynames generally flow paralelly between rivers Sava and Drava, with total strength increasing in the north-east direction. In the western part of the investigated area, between V. Gorica and Drnje (Koprivnica), the field gradient amounts to 18 nT/10 km. The gradient is even less in the vicinity of Pokupsko, but it points to the north-west direction. The maximal gradient is found in the region of Lonjsko polje, from river Sava towards Čazma, increasing to 37 nT/10 km. The configuration is the most complex in the south-east corner of the area, from Moslavačka gora to Zrinska gora.

We evaluated the nocturnal means (00–04 h UT) and compared them with daily means (00–24 h UT) for each day (Fig.s 7.a and 7.b). In the September observational period of six days, the average nocturnal mean is 5 nT higher than the average daily mean level, while in October period the difference diminishes to 3.2 nT. The change could be understood by pointing to different magnetic activities in September and October 2003.

While nocturnal and daily means in September run almost paralelly, the next month there is a perturbation from 14th to 15th October, and nocturnal level drops bellow the daily level – quite opposite to the normal situation. The variation of the magnetic field in the evening on 13th and in the morning of 14th October (Fig. 8) is striking. After a sudden increase with the maximum at 18:43, field drops during the night and recovers the next morning at about 05:00.

In order to get insight into the global geomagnetic conditions during the measurements, one uses K-index. During measurements, we consulted K-index given by the observatory in Niemegk. Index is a 3-hourly quasi-logarith-

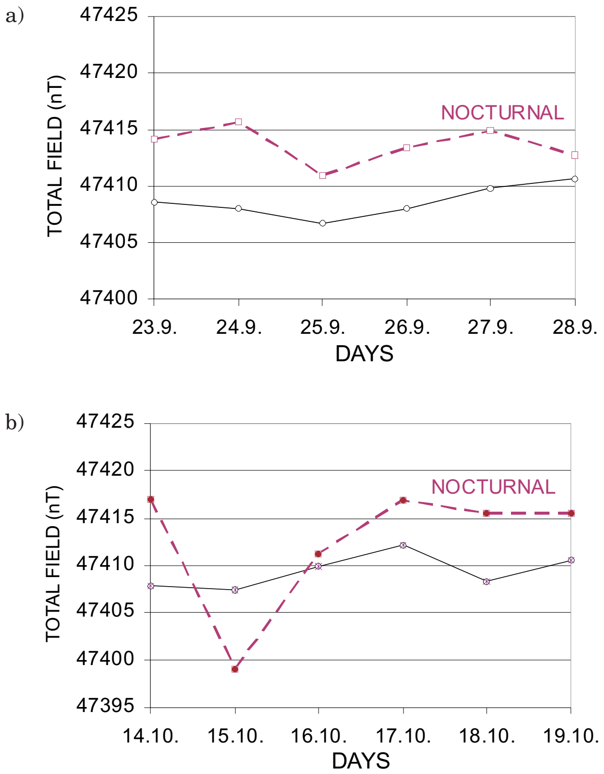

Figure 7. Daily and nocturnal means for the two observational periods: a) 23–29 September 2003 and b) 14–19 October 2003.

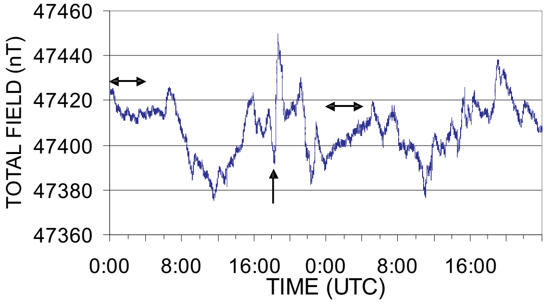

Figure 8. The variation of the magnetic field on 14th and 15th October. Nocturnal reference line had 47417 nT on 14th, and droped to 47399 nT on 15th October.

mic local index of geomagnetic activity relative to an assumed quiet-day curve for the recording site and it ranges from 0 to 9. Its values we can now compare with the final value of the planetary index, called Kp-index, which is based on the recordings of 13 world stations. For some days in September and October 2003 we show K and Kp-index (Fig. 9).

For proper survey measurements, the index during the quiet night time according to Linthe (2002) should not exceed 1. However, those days, as it was generally during the autumn of the year, solar and geomagnetic activity were by no means moderate. In the night from 14th to 15th October, index raised to 7. Although the solar activity cycle is in its declining phase, autumnal solar flares were frequent, and eventually auroras were seen even in our latitudes. The larger disturbance in October in comparison with the September observational period is probable reason for also noted deviations between our recordings and the recordings in Niemegk.

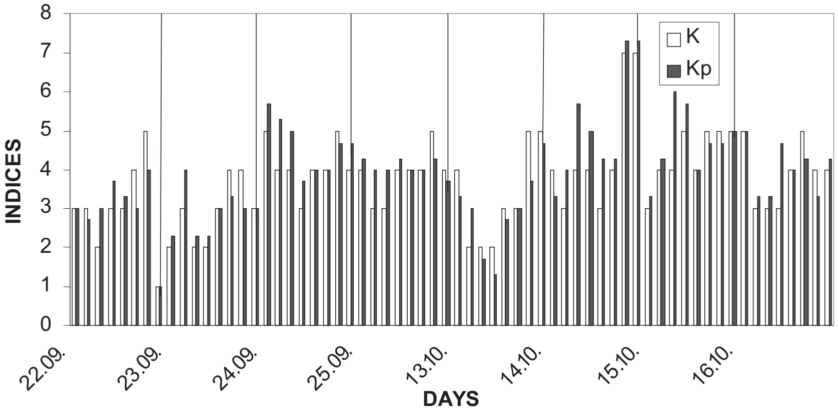

Figure 9. K and Kp indices, according to Observatory Niemegk, for a part of September and October 2003.

We consider our results as preliminary ones. We plan to renew the measurements and to extend them to a larger area. The scatter of daily means equal to 2 nT can be considered as maximum error of reduced data. There is an important question about the precision of positions of isodynames. When the field gradient is stronger, inaccuracies in reduction have smaller influence. For instance, if we in Croatia use the curves from Niemegk with scatter of differences amounting 5 nT, it might lead to the positional inaccuracy of 1.4 km in average for strong gradient, and twice as large, 2.9 km, for the weakest gradient found.

Taking into account the scatter of recorded traces of the magnetometers GSM-18 and GSM-19 of 1 nT, the average scatter of signals on stations of about 1 nT, 1 nT uncertainty because of the distance to the base station, and 2 nT because of the difference in the daily averages, we come to the overall uncertainty of 5 nT which results in the positional uncertainty from 1.3 km to 3.0 km, depending on the real field gradients.

5. Conclusion

We made a survey of the geomagnetic field in a part of Croatia during autumn 2003, measuring the total field strength. Twenty nine positions in the area between Pokupsko, Koprivnica, Virovitica and Hrvatska Kostajnica had the spacing of 15–20 km. Results are shown in the maps (Fig.s 5. and 6); for the second map data from survey in Hungary (Kóvacs and Körmendi, 1999) were used in order to improve values of the field strength at the northern border of the investigated area. Accuracy of the data was discussed, field activity, and an estimate of the secular variation was given.

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SAŽETAK

Rezultati preliminarnog mjerenja jakosti geomagnetskog polja u sjevernom dijelu srednje Hrvatske

V. Vujnović, G. Verbanac, J. Orešković, A. Marki, K. Marić, I. Lisac i M. Ivandić

U jesen 2003. godine izveli smo premjer jakosti magnetskog polja u dijelu Hrvatske, od rijeke Drave na sjeveru do Save i Pokuplja, između smjera Zagreb – Koprivnica na zapadnoj strani, do smjera Hrvatska Kostajnica – Virovitica na istočnoj strani. Mjerili smo na 30 položaja, razmaknutih po 15–20 km. Dnevni hod jakosti, mjeren u provizornoj geomagnetskoj postaji u Pokupskom, poslužio je za redukciju podataka za izradu geomagnetske mape. Nađeno je da je gradijent polja općenito usmjeren prema sjevero-istoku, s najmanjom vrijednosti od 18 nT/10 km, te najvećom vrijednosti od 37 nT/10 km. Uzimajući u obzir ustanovljene mjerne netočnosti, procijenjena je pogreška u položaju izodinama od 1,3 do 3,0 km, u ovisnosti o gradijentu polja.

Upotrebom malobrojnih podataka za epohu 1927,5, ustanovljena je promjena jakosti polja od 2900 nT, te je time učinjena procjena sekularne varijacije od +40 nT/god. Iskoristivši podatke premjera u Mađarskoj za epohu 1995,0, poboljšali smo položaj izodinama na dijelu područja uz državnu granicu. Usporedili smo naše dnevne zapise sa zapisima opservatorija u Niemegku, Njemačka, za opažački period 22–29.IX.2003. i 13–20.X.2003. te analizirali razlike. Kao numerički parametar koji razlike opisuje, uveli smo standardnu devijaciju razlika signala; za prvi opažački period iznosila je 5,2 nT, za drugi 8,7 nT, što tumačimo promjenom geomagnetske aktivnosti. Usporedili smo i naše minutne srednjake sa zapisima opservatorija Tihany i l'Aquila za dan najvećeg poremećenja.

Ključne riječi: Zemljino magnetsko polje, ukupna jakost polja, sekularna varijacija, sjeverni dio srednje Hrvatske

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