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On minimizing the external field contributions in annual means of the European geomagnetic observatories

Giuli Verbanac[1], *Monika Korte*[2] *and Mioara Mandea*[2]

[1] Department of Geophysics, Faculty of Science, University of Zagreb, Zagreb, Croatia

[2] GeoForschungsZentrum Potsdam, Telegrafenberg, Potsdam, Germany

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The aim of this study is to provide a method for minimizing the external field contributions in the observatory annual means and try to separate, interpret and explain all the different external field signals present in these data. Investigating the European geomagnetic observatory biases over 42 years, considered as contributions of the crustal field, and generally assumed to be constant in time, we noticed the link to the solar cycle, with short period variations in the order of ±10 nT. Developing an empirical method for minimizing the external fields presented in the observatory annual means, we were able to reduce them better than the used of the external field description included in the global Comprehensive Model, CM4 (Sabaka et al., 2004) was. The external field module provided by the POtsdam Magnetic model of the Earth, POMME-2.5, (Maus et al., 2005) was considered for investigating the sources and characteristics of various external field contributions. We have been able to separate magnetospheric and ionospheric fields, as well as to remove a still significant variation with a function properly scaled by Ap and Dst indices. With this procedure the external field contributions in the annual means are minimized to an uncertainty level of ±2 nT. Our study shows a way to obtain corrected observatory annual means, in order to be used for different studies of the internal geomagnetic field.

Keywords: observatory annual means, external field, ring current, magnetospheric field, ionospheric currents, magnetic field models

1. Introduction

Observatory annual means defined as the average of all days of a year and all times of a day have been widely used in different studies of the internal geomagnetic field (e.g. modelling the core field (Verbanac, 2007), the global secular variation (Wardinski and Holme, 2003), the regional SV (Korte and Holme, 2003)). Moreover, magnetic observatories play a crucial role in reduction of repeat station measurements. For these reasons the annual means should reflect as much as possible the core field contribution, only.

It was already recognized that observatory annual means are affected by the external fields (Yukutake and Cain, 1987; Alldredge, 1976; Courtillot and Le Mouël, 1976), but a suitable model to reduce these influences has not been developed. Our aim is then to study and explain the different geomagnetic field contributions from sources external to the Earth, which are contained in the observatory annual means and provide a method for minimizing these effects.

Since Europe is an area of highest spatio-temporal coverage with ground data, we focused on that region, investigating data (X-northward, Y-eastward and Z-vertically downward component) from 36 geomagnetic observatories, data collected over 42 years (1960–2001). At most European geomagnetic observatories near-continuous time-series exist for that time interval and the considered time span is long enough to allow studying and separating of different external field influences.

Firstly, we subtracted the core field, as predicted by the Comprehensive Model CM4 (Sabaka et al., 2004) which covers the same time period of our interest. After removing the core field, the link to the solar cycle was noticed, with small amplitude variations in the order of ±10 nT.

To minimize these variations we used the external field description included in the CM4 model, but with this approach the level in reducing the external field contributions was minimal. Consequently, we developed an empirical procedure for estimating the external field variations in the annual means. Taking the advantage of the homogeneity of the external influences in the European region, we constructed templates by median averaging of the data in each year, separately for each field component. After subtracting the templates, the temporal variations were successfully reduced.

Further, we investigated the sources and characteristics of various external field contributions and seeked for physical explanations of these signals. For that purpose, the module for external field contributions provided by the POtsdam Magnetic model of the Earth, POMME-2.5 (Maus et al., 2005) was considered. We first focused on the X component, since this component is mostly influenced by the external field. The magnetospheric contributions were successfully removed by parametrize the POMME model with the Dst index. The remaining signal was regarded as caused by ionospheric currents. The daily solar quiet (Sq) geomagnetic variation, which arise from the dynamo-current process in the ionospheric E region were estimated from the CM4 model. The still significant variation, that remains after subtracting the estimated Sq effects, was finally removed with a function properly scaled by Ap and Dst indices. With this procedure we were able to minimize the external field contributions in the annual means to the uncertainty level of ±2 nT.

Currently, the method for minimizing the external field contributions works and for all three field components. With this approach, our study shows

Table 1. Geomagnetic observatories considered present study.

Nr.	IAGA code	Station	Geographic Long	Coordinates Lat	Geomagnetic Long	Coordinates Lat
1	PEG	Penteli	23.87	38.05	103.05	36.32
2	PAG	Panagjuriste	24.18	42.52	104.76	40.59
3	AQU	L'Aquila	13.32	42.38	94.37	42.53
4	SPT	San Pablo	355.65	39.55	104.22	43.20
5	GCK	Grocka	20.77	44.63	102.29	43.27
6	ODE	Odessa-Stepanovka	30.88	46.78	112.44	43.48
7	EBR	Ebro	0.50	40.82	98.85	43.51
8	CTS	Castello Tesino	11.65	46.05	94.14	46.39
9	NCK	Nagycenk	16.72	47.63	99.64	46.93
10	KIV	Kiev-Dymer	30.30	50.72	113.44	47.37
11	WIK	Wien-Cobenzl	16.32	48.27	99.53	47.62
12	FUR	Fuerstenfeldbruck	11.28	48.17	94.68	48.49
13	BDV	Budkov	14.02	49.07	97.70	48.83
14	CLF	Chambon-la-Foret	2.27	48.02	94.22	50.10
15	BEL	Belsk	20.80	51.83	105.31	50.17
16	MNK	Minsk-Pleshchenitzi	27.88	54.50	112.99	51.42
17	MAB	Manhay	5.68	50.30	90.22	51.61
18	DOU	Dourbes	4.60	50.10	90.93	51.63
19	NGK	Niemegk	12.68	52.07	97.85	51.94
20	BOX	Borok	38.97	58.03	124.30	52.89
21	HLP	Hel	18.82	54.60	104.89	53.17
22	WIT	Witteveen	6.67	52.82	92.49	53.82
23	WNG	Wingst	9.07	53.75	95.31	54.23
24	HAD	Hartland	355.52	51.0	99.60	54.24
25	BFE	Brorfelde	11.67	55.63	98.86	55.50
26	LNN	Leningrad-Voiekovo	30.70	59.95	118.42	56.08
27	VAL	Valentia	349.75	51.93	105.11	56.22
28	NUR	Nurmijarvi	24.65	60.52	113.65	57.67
29	LOV	Lovo	17.83	59.35	106.89	57.82
30	ESK	Eskdalemuir	356.80	55.32	95.80	58.09
31	OUL	Oulujarvi	27.23	64.52	118.77	60.92
32	DOB	Dombas	9.12	62.07	101.14	61.97
33	LER	Lerwick	358.82	60.13	90.26	62.18
34	SOD	Sodankyla	26.63	67.37	120.83	63.62
35	KIR	Kiruna	20.40	67.80	116.37	65.06
36	LRV	Leirvogur	338.30	64.16	107.76	69.77

a way to obtain corrected observatory annual means, in order to be used for different studies of the internal geomagnetic field.

This paper is organized as follows. In the next section we briefly introduce the used data sets. Then, we describe the approaches for reducing the external fields contributions to the observatory annual means. We continue with a section describing the sources and characteristics of various external field contributions and finish with conclusions.

2. Data

Our analysis was based on annual means and synthetic data obtained from the Comprehensive Model CM4 (Sabaka et al., 2004) and POtsdam Magnetic model of the Earth, POMME-2.5 (Maus et al., 2005) for the European observatory locations.

Althought European observatories provide high quality data, the time series at some locations reveal peculiarities as unreported jumps, long-term trends, scattering (Verbanac et al., 2007). These sites were not considered in this study. We analysed the X, Y and Z components from 36 geomagnetic observatories over time-span 1960–2001. The list of observatories with their corresponding IAGA codes and both geographical and geomagnetic coordinates is given in Table 1.

With the CM4 code we calculated the core field at each observatory location for all 42 epochs up to degree and order 14 and subtracted it from the annual means to eliminate the core field and secular variation contribution. We also used the module within the CM4 to estimate the Sq currents and related induced magnetic fields.

The POMME-2.5 model was used to estimate the large-scale external fields caused by ring, magneto-tail and magnetopause currents. Althought the model is centered on 2002.0, it may be used for epochs outside its validity because the external field contributions can be estimated independently from the core field. This allowed us to correct the European time series over 42 years.

3. Method

After removing the core field, as predicted by the CM4 model, we obtained the crustal biases which are generally assumed to be constant in time. However they show the link to the solar cycle, with variations in the order of ±10 nT. Figure 1 (first three panels) shows the pictograms of X, Y and Z crustal biases in nT. The observatories (y-axes) are ordered by geomagnetic coordinates with North at the top (see Table 1). A variation pattern is most prominent in the X component with vertical stripes of maxima and minima clearly correlated with the solar cycle (see last panel in Figure 1). For the Y component a similar, but weaker sign-changed pattern is observed (i.e. in the years after solar maxima the residuals increase). The Z component is more influenced by ef-

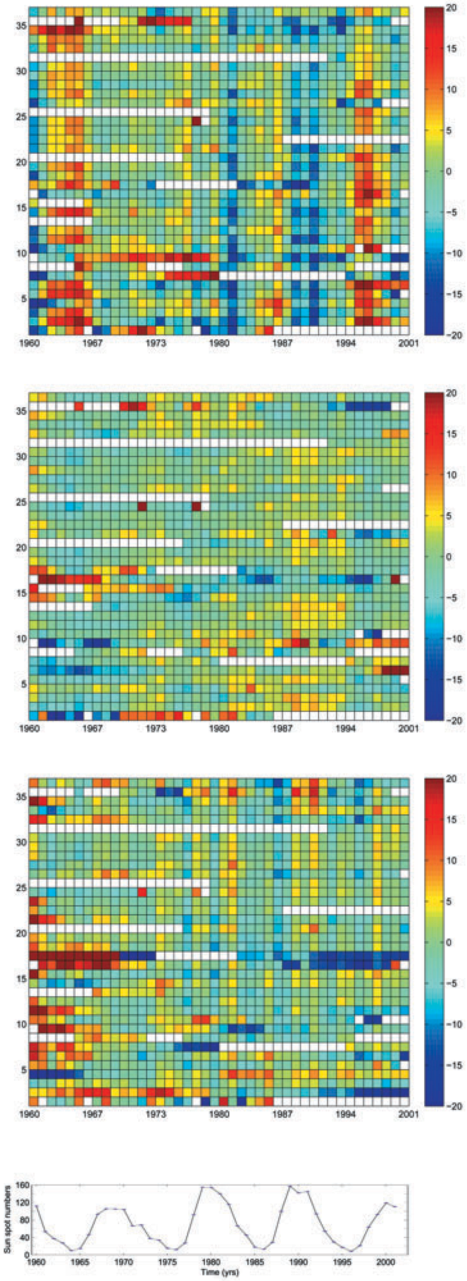

Figure 1. Pictograms of X (top), Y (middle) and Z (second from bottom) crustal biases in nT. The observatories (y-axes) are ordered by geomagnetic coordinates with North at the top, see Table 1. Annually averaged Sun spot numbers (bottom).

fects of shorter time scale and observed maxima and minima in time seem not to be linked to the solar cycle. For *Y* component and *Z* component, no dependence of the variations with geomagnetic latitude was found. In *X* omponent, however, the maxima and minima amplitudes are mostly observed in the Southern European observatories.

Reduction of the external field – Approach 1

In order to estimate and reduce the remaining external influence in the observatory annual means, our first approach was to remove the external and induced contributions provided by CM4, modulated by storm-time-disturbance (Dst) and Solar flux (F10.7) indices.

The obtained residuals at one German observatory (Niemegk, NGK), after removing different combinations in field contributions (*i)* core field, *ii)* core and external fields, *iii)* core, external and induced fields) are shown in Figure 2. The remaining variability after subtraction the signal described by CM4 is still of order of 8 nT in *X* and *Z*, and some 4 nT in *Y*. Similar orders of magnitudes are obtained at other observatory locations.

Reduction of the external field – Approach 2

The remaining signal, observed after applying the first approach, indicates that the external and induced fields still exist in the observatory annual means, so we developed an empirical method for estimating these remaining variations. The procedure is based on the homogeneity of the external field influences over the European region. We first constructed templates by a median averaging of the observatory residuals in each year, for each component separately. These templates (shown as solid lines in Figure 2) were then subtracted from all observatory residuals.

Comparison of the pictograms after removing the templates (Figure 3) with those in Figure 1, reveals largest changes in the *X* component (expected, since this component is the most influenced by the external field). Here, the prominent stripes linked to the solar cycle are not present any more with the exception of a few Southern observatories, where still some influence of the external field remains. The matrix related to *Y* component changed slightly because the pattern in the original matrix was already smoother. In the *Z* component pictogram, the previously observed annual and bi-annual stripes have disappeared.

4. Sources and characteristics of various external field contributions

In the attempt to separate and explain different external field signals present in the observatory annual means, we focused on the *X* component.

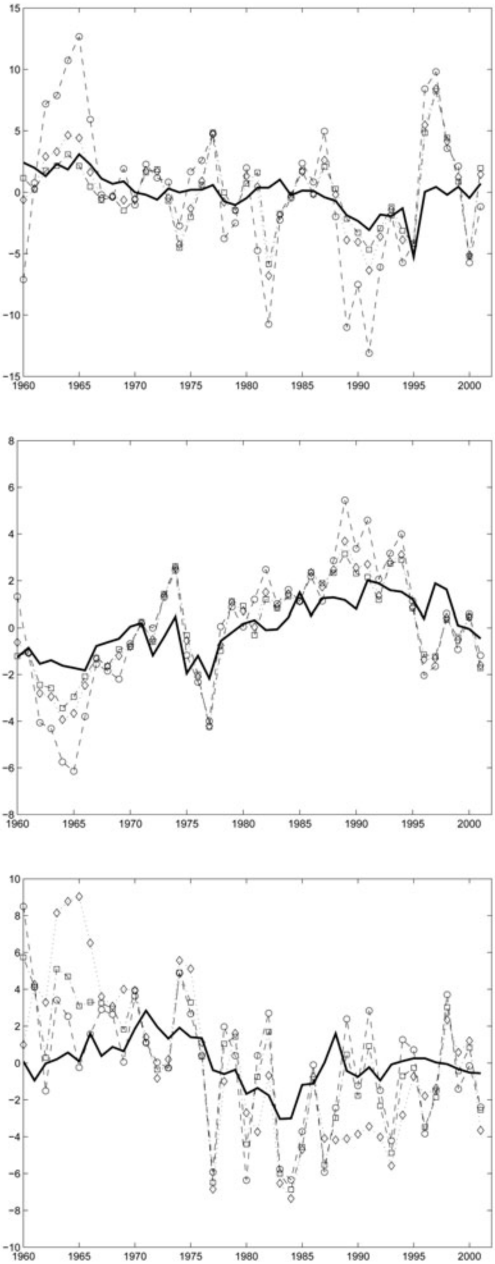

Figure 2. The *X*, *Y* and *Z* residuals (in nT) at NGK observatory after subtracting: core field (dashed line-circle); core and external fields (dotted line-diamonds); core, external and induced fields (dash-dot line-square) as given by the CM4 model. The empirical template is overplotted as tick solid line.

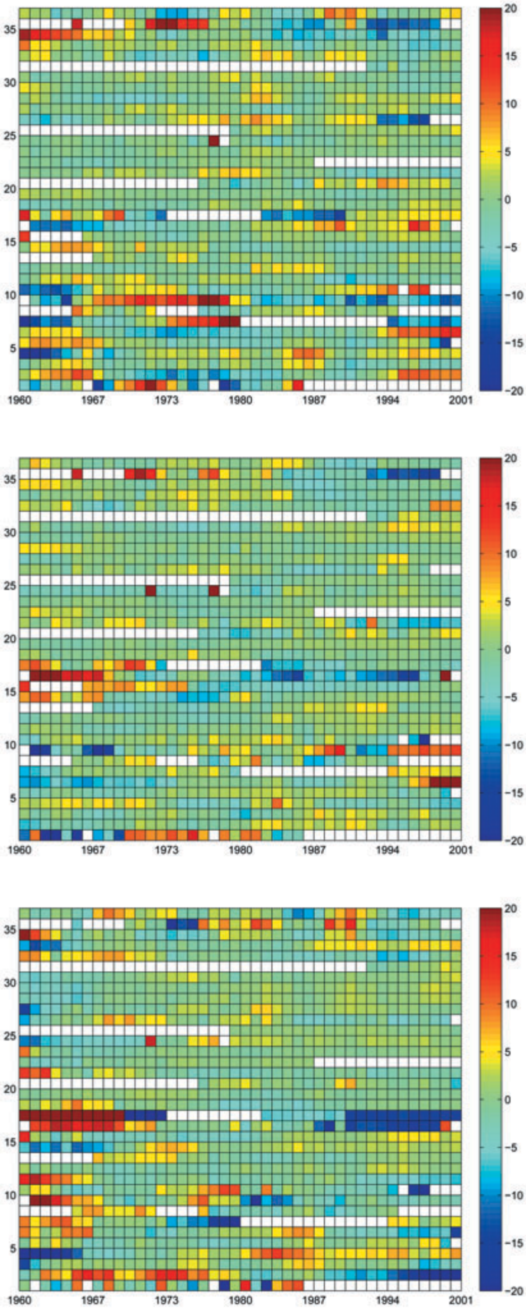

Figure 3. Pictograms of X (top), Y (middle) and Z (bottom) biases in nT after applying the empirical reduction procedure for the external field contributions (see text for details).

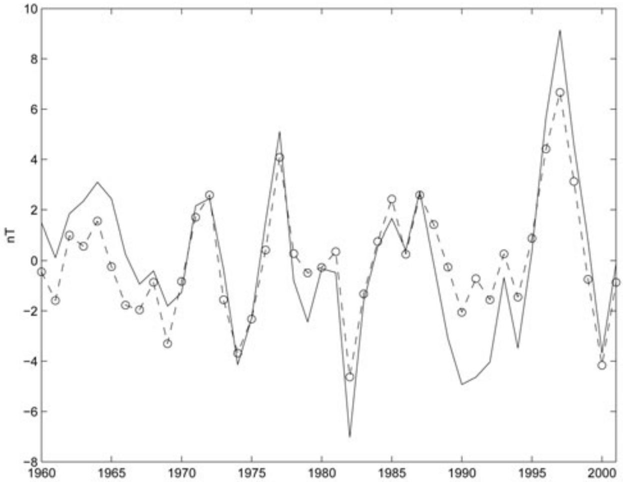

Figure 4: The vertical averaged *X* component over all observatories after subtracting the POMME-2.5 magnetospheric field, Res1 (dashed line-circle), and Res1 at NGK (solid line).

So far we analysed residuals obtained as differences between the observatory annual means and CM4 core model predictions. As a next step, we additionally subtracted the POMME-2.5 magnetospheric field from the annual means. A template for remaining common variations was constructed again by median averaging over all locations for every year. The obtained average variation (hereafter named Res1) along with the variation at NGK, is shown in Figure 4. Both curves track each other quite well allowing us to consider central NGK location to be representative as an average value of the European network. Res1 can be understood as the reflection of the persistent external field signal in the residuals.

We then assumed that the remaining signal is caused by ionospheric currents, and calculated the effect of the Sq currents as well as the related induction effect by employing the module within the CM4 model. The annual averages of the Sq variation estimated for a central location (NGK) were subtracted from the residuals and remaining signal (hereafter termed Res2) is shown in Figure 5. This signal is still significant and we attributed it to additional ionospheric currents which are not explained by the CM4 model. Further, we performed the bi-variant correlation considering the Ap index and ring current simultaneously. Since the ring current has a clear latitudinal dependence (Verbanac et al., 2006), for this analyses we considered regional ring current (Rc) and correlated the Ap with Rc for the central region, NGK. This current was parametrized by the new parameter Est for the external part and Ist for the induction part (available at http://www.ngdc.noaa.gov/seg/geomag/est_ist.shtml), both derived from the Dst index (Maus and Lühr, 2005).

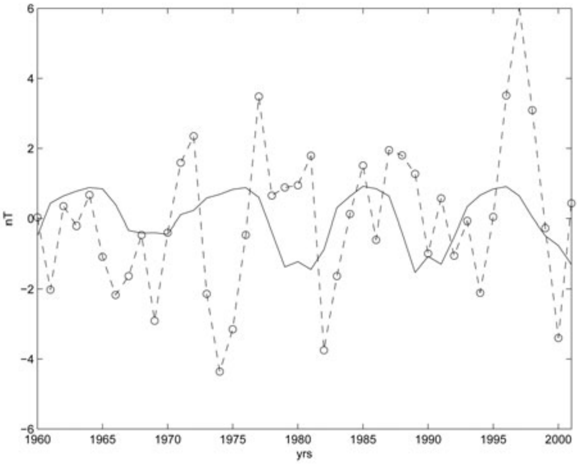

Figure 5: The Res2 variation, defined as the Res1 corrected for the Sq effect (dashed line-circle). The annual average of the Sq signal (solid line), as predicted by the CM4 model for the NGK location.

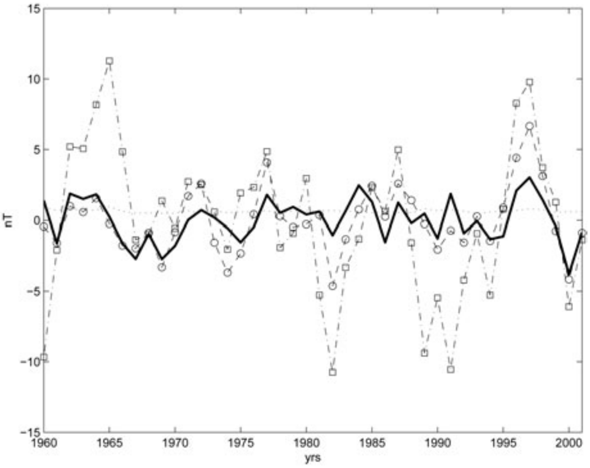

Figure 6: Residual of the annual means X component: prior to any external field correction (dash-dot line-square); Res1 (dashed line-circle); Res3 (tick solid line). The dotted line represents mean uncertainty of averaged annual means derived from the observatory residual.

The results of the bi-variant correlation allow to express the ionospheric signal for component, for the central part of Europe as follows:

$$X_{iono} = Sq - 0.60 \cdot (Ap + 0.82 \cdot Rc) + 3.84. \qquad (1)$$

The Ap-correction was then subtracted from the residuals Res2 and the final residual, Res3 is shown as tick solid line in Figure 6. The obtained signal varies predominantly within ±2nT with no features particularly outstanding. Comparison of different residuals plotted in Figure 6 shows that a significant improvement is already achieved by removing the ring current effect (Res1: dashed line-circle). This is supported by the almost free times less standard deviation of Res1 (which amounts for 2.3 nT) than that of the uncorrected residuals (dash-dot line-square). For the final residual Res3, we computed a standard deviation of 1.54 nT. The remaining dotted line reflects the mean uncertainty of the averaged annual means.

5. Conclusion

Analysing 36 European geomagnetic observatory biases over 42 years, considered as contributions of the crustal field, and generally assumed to be constant in time, we found that this is not true. Namely, we noticed that these data are contaminated by the external field influences. Firstly, the link to the solar cycle was detected.

To estimate and reduce the external fields in the observatory annual means, our first approach was to remove the external and induced contributions provided by the CM4 model, modulated by storm-time-disturbance (Dst) and Solar flux (F10.7) indices. The remaining variability at most observatory locations after subtraction the signal described by CM4 is still of order of 8 nT in X and Z, and 4 nT in Y, which is not satisfying for high-accuracy core field studies.

To decrease these contributions we developed a new approach for estimating the remaining external field variations in the data. By a median averaging of the observatory residuals in each year, independently for each component, we constructed templates which were then subtracted from all observatory residuals. The obtained results are much better than when using the external field description included in the CM4 model.

Further, we systematically studied, interpreted and explained the different geomagnetic field contributions from sources external to the Earth, contained in the X component observatory annual means. We successfully removed the magnetospheric contributions estimated from the POMME-2.5 model external field module parametrized by the Dst index. The remaining signal had an amplitude ±6 nT and was assumed to be caused by the ionospheric currents. We estimated the annual averages of the Sq variation from the CM4 model, subtracted it from the residuals, but still an anti-correlated variation with the Ap index was observed. We attributed it to additional ionospheric currents which are not explained by the CM4 model. With an empirically determined Ap-relation we further reduced the residuals.

The finally remaining residuals of the European observatory annual means over the considered 42 years reach a level of ±2 nT, which is the one of uncertainty with no features particularly outstanding.

The present investigation shows that the external field signal contained in the observatory annual means is significant and their elimination is a prerequisite for obtaining reliable and physically meaningful results when such data are used in studies of the core field and its secular variation. As the method for minimizing the external field contributions that works for all three components we can offer the developed empirical technique. The procedure which takes into account different external field sources has further to be investigating on the Y and Z component.

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SAŽETAK

O smanjenju doprinosa vanjskog polja godišnjim srednjim vrijednostima Europskih geomagnetskih opservatorija

Giuli Verbanac, Monika Korte i Mioara Mandea

Cilj ovog rada bio je nalaženje metode za minimiziranje utjecaja vanjskog magnetskog polja na opservatorijske godišnje vrijednosti, te razlikovanje, interpretacija i objašnjenje različitih signala vanjskog polja sadržanih u tim podacima.Geomagnetski opservatorijski reziduali posljedica su doprinosa polja kore i općenito se pretpostavlja

da su vremenski nepromjenljivi. Proučavajući reziduale s europskih opservatorija kroz 42 godine, uočili smo kratkoperiodične varijacije reda veličine ±10 nT, jasno povezanih s 11-godišnjim sunčevim ciklusom. Razvili smo empirijsku metodu za minimiziranje vanjskih magnetskih polja prisutnih u opservatorijskim godišnjim vrijednostima, koja je omogućila njihovo bolje reduciranje u odnosu na uporabu modula procjene vanjskog polja sadržanog u globalnom, CM4 modelu (Comprehensive Model, CM4). Za proučavanje izvora i karakteristika različitih doprinosa vanjskog polja korišten je POMME-2.5 (POtsdam Magnetic model of the Earth) model kojim smo uspjeli razdvojiti magnetosferska i ionosfersa polja, te eliminirati preostalu, još uvijek značajnu varijaciju, s funkcijom adekvatno skaliranom Ap i Dst indeksima.Tim pristupom, doprinosi vanjskog polja smanjeni su na vrijednosti unutar ±2 nT. Naše istraživanje pokazuje način dobivanja korigiranih opservatorijskih vrijednosti koji se onda mogu koristiti za različita proučavanja unutrašnjeg magnetskog polja.

Ključne riječi: opservatorijske godišnje vrijednosti, vanjsko polje, prstenaste struje, magnetosferska polja, ionosferska polja, modeli magnetskog polja

Corresponding author's adress: Giuli Verbanac, Department of Geophysics, Faculty of Science, University of Zagreb, 10000 Zagreb, Croatia, e-mail: verbanac@irb.hr