Recent geomagnetic investigations of Palagruža island

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Intention of this work was to examine all available recent geomagnetic survey data, in order to assess Palagruža as a potential location for a permanent variometer station. The most recent data consist of absolute, total intensity vertical gradients and Overhauser effect dIdD vector measurements, carried out in period 2008–2010. Evidences were found in low crustal field estimates, relatively low total field vertical gradient distribution over the island, quite high time series correlation with the near observatories, as well as in low noise level of geomagnetic components. These preliminary results indicate Palagruža as appropriate location for the repeat station as well as for the variometer station. However, additional investigations of the geomagnetic sea and coastal effects by using much longer time series are needed.

Keywords: geomagnetic repeat station, geomagnetic variometer station, crustal field, geomagnetic induction arrow

1. Introduction

The purposes of geomagnetic repeat stations are to provide data for monitoring of secular variation of the geomagnetic field (though not continuously as at geomagnetic observatories), for modelling of the spatial distribution of geomagnetic elements and to update geomagnetic maps (Newitt et al., 1996; Mandea and Purucker, 2005). The Croatian Geomagnetic Repeat Station Network (CGRSN) was established in 2004 and today it consists of ten permanent stations as a part of Basic Geomagnetic Network of the Republic of Croatia (Brkić et al., 2013).

Palagruža is a small isolated archipelago in the middle of the Adriatic Sea (Fig.1); the archipelago forms the main island of Vela Palagruža, smaller Mala Palagruža, and about twenty cliffs and rocks nearby. Vela Palagruža is a ridge from 60 to 320 m wide, extending about 1460 m in EW direction, with the highest point at 103.5 m above sea level, having inaccessible steep banks, except two approachable bays, one on the NW and one on the southern part of the island.

Nonetheless, contemporary geomagnetic investigations of Vela Palagruža (hereinafter: Palagruža) started by setting up the primary repeat station PALA in 2008. This expansion of the CGRSN brought more reliable geomagnetic models and maps (Brkić et al., 2012). Because of Palagruža's specific position, the initial goal of this paper was to examine all the recent data in order to assess Palagruža as a potential location for a permanent variometer station or eventually, geomagnetic observatory.

2. Data and methods

2.1. Data used

The Palagruža data set comprise the vector absolute measurements at PALA in 2008, 2009 and 2010, the total field vertical gradients survey of the island in 2008 and 2009, and one month vector measurements using Overhauser effect dIdD variometer (O-dIdD) in 2010. Observatories mean minute values of the geomagnetic components were also needed, depending on a method of analysis. The following observatories were taken into consideration (Fig. 1): CTS (Castello Tesino), GCK (Grocka), PAG (Panagjurishte) and THY (Tihany). Observatories DUR (Duronia) and LON (Lonjsko Polje) are also shown in Fig. 1. The nearest
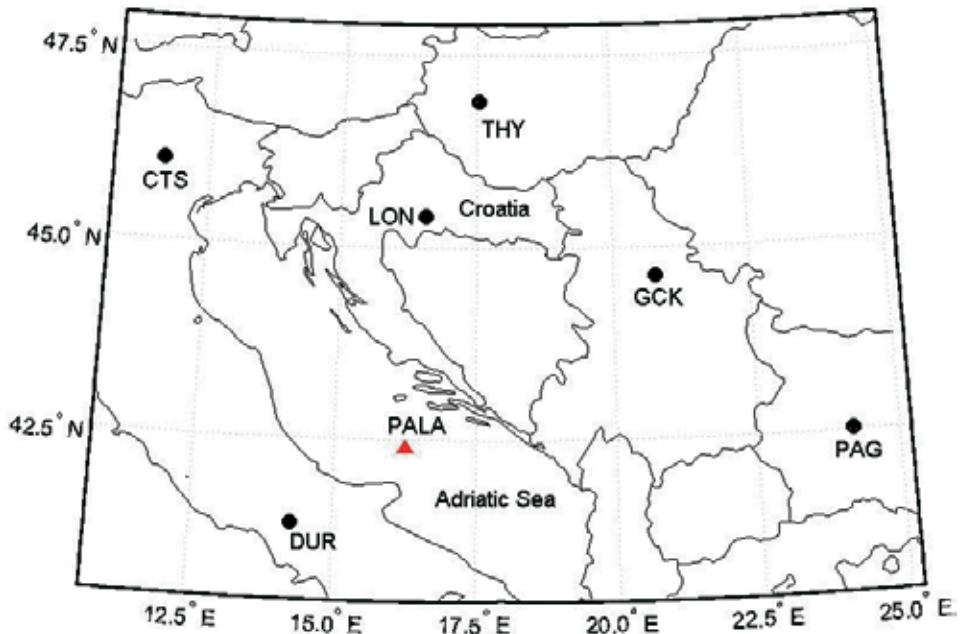

Figure 1. The positions of repeat station PALA (42.4° N, 16.3° E, 34 m above sea level) on Palagruža island and of selected surrounding geomagnetic observatories: CTS, DUR, GCK, LON, PAG and THY.

observatory DUR is approximately 198 km, while the LON is 337 km away. The data from CTS were provided by Dr. G. Dominici from INGV, while the data from GCK, PAG and THY were obtained from the Intermagnet website (http://www.intermagnet.org).

Prior to the PALA repeat station setup in 2008, the gradiometry using GEM Systems GSM-19G Overhauser PPM confirmed acceptable total field gradients (less then a few nT/m), required at the repeat as well as at auxiliary station (Newitt et al., 1996). The PALA repeat station was situated at the Palagruža's heliport, in the foot of the lighthouse, along with one auxiliary station and four azimuth orientation marks. Those marks have been built for the survey and were permanently marked with a steel spike. The geodetic coordinates of repeat station, auxiliary station and azimuth orientation marks were determined with GPS Real Time Kinematics (RTK) measuring method using Topcon HiPer Pro GPS/GLONASS RTK instrument; all points' positional accuracies were close to or better than 2 cm. After the data processing, the adjusted coordinates were transformed into the local geodetic datum where the north grid azimuths were calculated. The final true north azimuths were obtained by adding the meridian convergence values (Brkić et al., 2012).

The instruments used for absolute measurements in 2008, 2009 and 2010 were: Bartington D/I MAG01H Fluxgate with MAG Probe A and Zeiss 010B theodolite on a nonmagnetic tripod, for the geomagnetic declination D and inclination I, and GEMSys GSM-19G Overhauser PPM with 1/3 Hz sampling rate, for the total field intensity F (Šugar, 2014). The minute mean values of F were obtained by applying the Gauss filter on measured time series (St-Louis, 2011). The values of north (X), east (Y) and vertical (Z) components of the geomagnetic field were then calculated from corresponding D, I and F values. The X, Y and Z components were reduced to 2008.5, 2009.5 and 2010.5 epochs by comparison to the L'Aquila, Fürstenfeldbruck, Grocka, Hurbanovo, Nagycenk and Tihany observatories, as explained in Vujić and Brkić (2015). The Spherical Elementary Current System method was used for separation of the geomagnetic field variations into internal and external parts.

A bigger picture of anomalies of the island was obtained from the dense geomagnetic mapping in 2008 and 2009, which make up the second data group. The total field vertical gradients were recorded in 588 points, using GEM Systems GSM-19G Overhauser PPM, while positions were determined using Topcon HiPer Pro GPS/GLONASS RTK (Vušković, 2010).

The third data group were the vector measurements with O-dIdD in 2010. The instrument was operated with 0.2 Hz sampling rate near PALA repeat station from 27 to 31 July 2010 (Csontos et al., 2012). At the same time, total of 29 sets of absolute measurements at PALA were performed, mostly in the morning and evening hours (Šugar, 2014).

2.2. Methods of analysis

The reduced absolute measurements (assumed to be the annual mean values at PALA) were further used for the crustal field estimation at PALA. From the annual mean values of X, Y and Z at PALA, corresponding main field values and the long-term external contributions were subtracted, as follows. The main field at PALA was estimated by using the global Enhanced Magnetic Model (EMM) up to degree and order 15. This geomagnetic model up to degree of 720 is derived from ground, satellite, marine and aeromagnetic data (Maus, 2010), and the lithospheric field in this model is described by degrees and orders of 16–720.

Secondly, the long-term external contributions, even present in the annual mean values at the observatories, can be estimated by a procedure explained in Korte and Thébault (2007). This procedure is applied to the observatory data. First, the values computed by EMM of degree up to 720 were subtracted from the annual mean values in some interval. After that, the linear trends (due to the global model secular variation misfit) and the constant offsets (due to a part of the crustal field not estimated by the global model) were removed. The remainders are the estimations of the external contributions at observatory. Finally, the mean values of external contributions from the selected observatories were used as the estimations for PALA station.

It was assumed that it is not likely that magnetic fields produced by a DC load railway in town Peschici (in Italy, some 53 km away from PALA) interfere significantly with the measurements. However, a simple measure of a noise level was the standard deviation ($σ$) of the fourth derivatives of the one-minute total field time series, which can be calculated from (Reeves, 2005): $[F(t{-}2) - 4\,F\,(t{-}1) + 6\,F(t) - 4F(t+1) + F(t+2)]\,/\,16$, where $F(t-2)$, $F(t-1)$, $F(t)$, $F(t+1)$ and $F(t+2)$ are five consecutive values centred on the current value $F(t)$. The values of $σ$ were calculated for PALA time series (durations in the range 1–5 h), as well as for the simultaneous time series from GCK and THY, respectively, while the geomagnetic activity K_p index was obtained from the website of WDC Kyoto (http://wdc.kugi.kyoto-u.ac.jp).

Considering O-dIdD data, mean minute values of geomagnetic components were obtained by applying the Gauss filter on measured time series (St-Louis, 2011). Estimation of a noise level was examined with the standard deviations of the fourth derivative applied to X, Y, Z and F minute time series, as explained above. Further, linear correlation coefficients between the O-dIdD and selected observatories minute time series were calculated.

The next analysis uses geomagnetic transfer function for detection of the anomalous inductive effects, such as geomagnetic coastal effect (Viljanen et al., 1995), and was performed on O-dIdD and corresponding observatory data. In geomagnetic deep sounding, at mid-latitudes under certain assumptions follows the relation in the frequency domain (Gough et al., 1973; Viljanen et al., 1995):

$$Z(f)=A(f)X(f)+B(f)Y(f) \tag{1}$$

where $X(f)$, $Y(f)$ and $Z(f)$ are the Fourier transforms of geomagnetic components, while $A(f)$ and $B(f)$ are the complex geomagnetic transfer functions. Further, $Z(f)$ is obtained from the time series from points whose transfer function is to be determined, and $X(f)$ and $Y(f)$ of the time series from the normal (reference) point, usually the geomagnetic observatory. A normal point is regarded to be the location where magnetometer measure variations of the geomagnetic field and there is no influence of anomalous induced electric currents; on the contrary, anomaly point is near the conductivity anomaly. Geomagnetic transfer functions at anomaly point can be calculated from following expressions:

$$A(f) = \frac{S_{ZX}S_{YY} - S_{ZY}S_{YX}}{S_{XX}S_{YY} - |S_{YX}|^2} \tag{2a}$$

$$B(f) = \frac{S_{ZY}S_{XX} - S_{ZX}S_{XY}}{S_{XX}S_{YY} - |S_{YX}|^2} \tag{2b}$$

where S are cross-spectra of the geomagnetic series (Gough et al., 1973). There must be enough power at the frequency of interest, in order to spectral estimates had significance. Eq. (1) determines the preferred plane where the geomagnetic field changes occur at frequency f. The length of the real induction arrow and its azimuth are given by: $Amp_r(f) = ([\mathrm{Re}(A(f))]^2 + [\mathrm{Re}(B(f))]^2)^{0.5}$ and $Az_r(f) = \arctan[\mathrm{Re}(B(f))/\mathrm{Re}(A(f))]$, respectively. Thus defined real induction arrow lies in the preferred plane, and rotated by 180° is directed towards the area of anomalous concentration of induced currents. Imaginary induction arrow is defined analogously, and is directed from the conductor in which the current leads the phase in respect to the normal external field (Gough et al., 1973; Viljanen et al., 1995).

3. Results and discussions

Repeat station PALA is located close to the southern edge of the Adriatic anomaly, according to Vujić et al. (2016). However, to gain more precise picture about the local crustal field distribution, preferably aeromagnetic or marine data are needed. The estimated X, Y and Z components of the crustal field at PALA are (-12 ± 4) nT, (33 ± 4) nT and (-13 ± 4) nT. These values were derived as the averages in the interval 2008.5–2010.5. The estimated accuracies comprise the reduction errors and the long-term external contributions uncertainties. The external contributions were derived by GCK, PAG and THY data in time interval 2005.5–2013.5, by a procedure given above.

The results of the noise level estimate for intensity measured by the PPM are presented in Tab. 1, for all three years of the repeat station surveys. Based on this simple estimation, one can assume that the noise at PALA was in the range of a corresponding noise at GCK and THY. The table also demonstrates relatively

Table 1. The mean values of the standard deviations (σ) in nT of the fourth derivatives of the one-minute total field time series at PALA, GCK and THY, respectively, for years of the repeat station surveys. The mean values of the linear correlation coefficients (CC) of one-minute total field time series from PALA and GCK, and PALA and THY, are also given.

F	σ (PALA)	σ (GCK)	σ (THY)	CC (PALA–GCK)	CC (PALA–THY)
2008	0.02	0.05	0.05	0.974	0.964
2009	0.02	0.04	0.06	0.924	0.870
2010	0.03	0.05	0.07	0.858	0.820

high values of linear correlation coefficients of PALA and GCK, and PALA and THY total field time series.

Next, although geomagnetic mapping tracks may look sparse, they refer to places at the island that are feasible to get to, thus they are informative (Fig. 2). The largest vertical gradient of total intensity found was 97.6 nT/m, and the lowest –317.8 nT/m. However, large gradients are rare and dispersed (and could be linked to artificial sources), while 90% of all the measurements fell in the range from –5 to 5 nT/m. From Fig. 2, as well as geologic reconnaissance (Korbar et al., 2009), follows that the accessible central and northern parts of the island, close to the heliport, were the appropriate choice for the location of a repeat station as well as a variometer station. On the other hand, a systematic aeromagnetic survey is a solution to get more complete picture of the anomalies. The anomalies were found around a big cove on NW part of the island (Fig. 2). There is a ship wreck close to the cove, and the visual inspection of the inlet area showed that it contains discarded cables, barrels, cables, etc. Moving away from
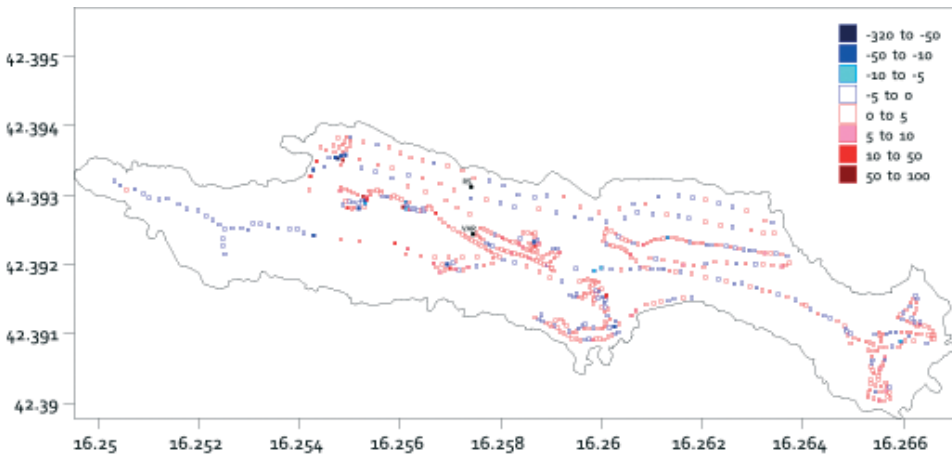

Figure 2. The distribution of total field vertical gradients (nT/m) at the Palagruža island. The positions of the PALA repeat station (RS) and the vector variometer (O-dIdD) station (VAR) are designated.

apparent contaminations, the anomalies were also found. It is unknown that any possible underground structure or cables leading from that cove. The anomalies could also origin from the island's geology (e.g. see Fig. 2 in Korbar et al., 2009). However, for a confirmation that anomalies are linked to possible fault zone, a more detailed survey is needed.

Further, based on the mean values and the uncertainties of the O-dIdD calibration parameters, as well as on the mean minute values of measured field components (in a dIdD reference frame), it was estimated that the accuracies of X, Y, Z and F mean minute values were ± 0.9 nT, ± 1.3 nT, ± 0.5 nT and ± 0.04 nT, respectively. The minute time series of geomagnetic components and of total field are displayed in Fig. 3. Some unexpected data gaps occurred during the instrument operation, but there are four uninterrupted intervals with durations in the range 391–1540 minutes (Tab. 2), which were used for further analysis.

The tests of a noise level in geomagnetic components are given in Tab. 3. The smallest mean values of σ in X and Y components are for PALA, while in Z component are the highest for CTS (the smallest for PAG and THY), and in F the smallest values are for PALA. In Tab. 4 are the mean linear correlation coefficients between the O-dIdD and selected observatories minute time series. The values are relatively high, and they are highest for Y component, and for 3rd interval from Tab. 2. Again, exactly this is one more important reason to think of Palagruža worth being at least permanent variometer station, or even observatory. Some lower values for Z component could be prescribed to the different induction effects at station PALA with respect to the continental observatories.
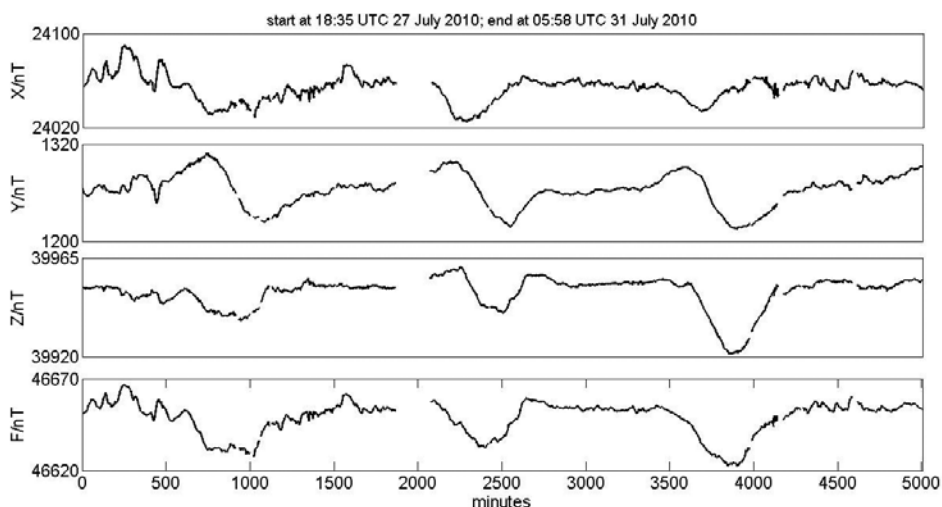

Figure 3. The mean minute time series of X, Y, Z and F from O-dIdD near station PALA in July 2010.

Table 2. The durations of four time series and corresponding activity K_p index, which were recorded by O-dIdD near PALA station during July 2010 (Fig. 3).

Time interval in UTC	K_p
18:35 July 27–09:18 July 28	2–4
13:23 July 28–01:38 July 29	2–3
11:06 July 29–12:48 July 30	1–2
23:28 July 30–05:58 July 31	1–2

Table 3. The mean values of the standard deviations of the fourth derivatives of the one-minute time series of geomagnetic components and of total field, at CTS, GCK, PAG, THY observatories and at O-dIdD near PALA repeat station, during July 2010 (intervals from Tab. 2).

2010	X	Y	Z	F
σ(PALA)/nT	0.08	0.06	0.04	0.02
σ(CTS)/nT	0.09	0.08	0.05	0.07
σ(GCK)/nT	0.13	0.10	0.03	0.05
σ(PAG)/nT	0.09	0.07	0.02	0.05
σ(THY)/nT	0.16	0.11	0.02	0.07

Table 4. The mean values of the linear correlation coefficients between (CC) the mean minute time series of geomagnetic components at CTS, GCK, PAG, THY observatories, and at O-dIdD near PALA repeat station, during July 2010 (intervals from Tab. 2).

CC	X	Y	Z	F
PALA-CTS	0.917	0.977	0.868	0.936
PALA-GCK	0.968	0.985	0.811	0.929
PALA-PAG	0.917	0.969	0.718	0.902
PALA-THY	0.919	0.990	0.817	0.926

Finally, for finding geomagnetic transfer functions it is common to use geomagnetic substorms or storms records (Gough et al., 1973). During the time span of 2010 campaign, only one such disturbance connected with geomagnetic pulsations occurred, with duration of 128 min that begun in 20:32 UTC July 27 (Gjerloev, 2012). However, after finding the so-called plane wave events (Viljanen et al., 1995) out of records given in Fig. 3, when correlation coefficients of X and Y components between PALA and GCK were above 0.9 in this case, it was possible to use such events for calculations (eight events with duration of 128 min). In total, nine events were taken for the transfer functions computation. In computation of induction arrows, GCK observatory was taken as a reference station; it is about 441 km away from PALA, but there was no closer observatory at the time.

The resulting induction arrows at PALA, for periods in the range 2–128 min, are depicted in Fig. 4. It can be noticed that there is no large and systematic anomalous induction effect at PALA. The mean values of real and imaginary arrows were 0.12, respectively. Six real arrows in the range of periods
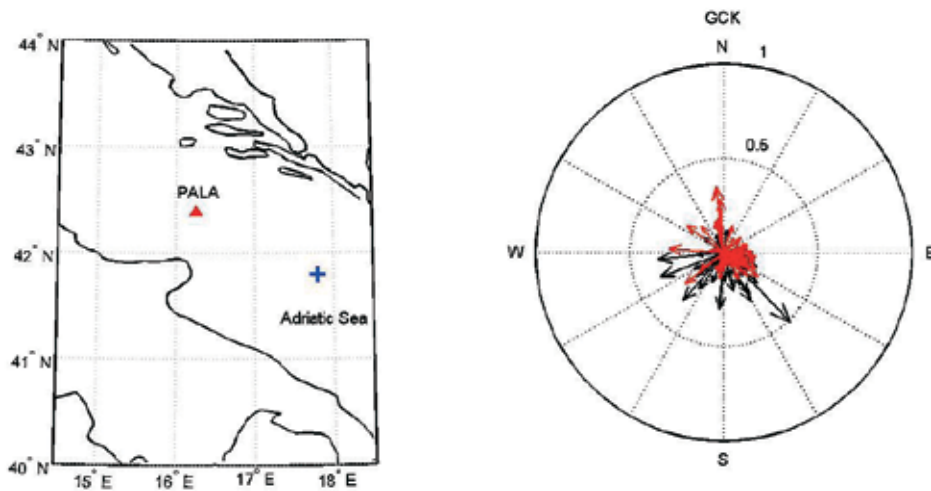
Figure 4. *Left*: geographic position of PALA station inside Adriatic Sea, and of the deepest point in Adriatic Sea (*blue cross*). *Right*: Real (black) and imaginary (*red*) induction arrows for periods in the range 2–128 min at PALA, with GCK as a reference station.

2.0–2.7 min, with amplitudes and azimuths in the range 0.18–0.36 and 185–264°, respectively, point to the western coast of the Adriatic Sea, and this could be an indicator that at PALA exists a small geomagnetic coast effect, in the given range of periods. The largest real arrow (with amplitude 0.5 at period 2.3 min) points approximately toward the deepest point in Adriatic Sea (coordinates taken from Bensi et al., 2013), *i.e.* it could be prescribed to the geomagnetic sea effect caused by a difference between the integrated electrical conductivities of deeper and shallower sea water (Samrock and Kuvshinov, 2013). However, this result has to be taken with large caution, because *e.g.* in Samrock and Kuvshinov (2013) was obtained that at least approximately 30 days of geomagnetic data are necessary for stabilization of induction arrows. To confirm the results presented here, further examination is needed, by the longer time series and probably by the more robust methods in frequency or time domain.

4. Conclusions

Although the Palagruža geomagnetic data is not abundant, it is one of the longer among Croatian repeat stations. On the other hand, being southernmost Croatian land, situated in the central part of the Adriatic Sea, its location is appreciated in updating of national geomagnetic maps and models, but is also interesting at least as a prospective permanent variometer station. With this intention, the results of various measurements on the island carried out during 2008–2010 were analyzed and presented in this paper. Acceptable crustal field values, below 35 nT in all three components, were estimated at the PALA repeat

station; however, a comprehensive marine and aeromagnetic survey would contribute in depicting more features of the crustal field of the island area. Then, the 2008–2010 total field absolute data indicated that a noise at PALA is comparable to corresponding noise at GCK and THY; quite a high correlation between PALA and the selected observatories was also estimated. In addition to 2008–2010 gradiometry of repeat and auxiliary stations and surroundings, the 2008–2009 total field vertical gradients of the island confirmed its central and northern part as the most appropriate for the location of repeat station as well as variometer station. Next, the O-dIdD variometer mean minute values of X, Y, Z and F in 2010 helped to reveal high correlations between PALA and CTS, GCK, PAG and THY observatories. Then, in regarding to presence of civilization noise, PALA is found comparable to or even better than the selected surrounding observatories.

These are important reasons to think of Palagruža worth holding the repeat station and at least variometer station, eventually geomagnetic observatory. Much longer time series data sets, durations of at least 3–6 months, and eventually additional methods, are needed to confirm the presented results, and to investigate in-depth the features like the geomagnetic coast effect and the induction effects of sea water.

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SAŽETAK

Novija geomagnetska istraživanja na otoku Palagruži

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Cilj ovog rada je bio istražiti sve dostupne suvremene podatke geomagnetskih istraživanja, kako bi se Palagruža procijenila kao potencijalna lokacija za stalnu variometarsku postaju. Najnoviji podaci sadržavaju apsolutna mjerenja, mjerenja vertikalnih gradijenata ukupnog polja i vektorska mjerenja Overhauser-efekt dIdD instrumentom, koja su provedena u razdoblju 2008.–2010. Dokazi su pronađeni u procjenjenim malim poljima kore, raspodjeli relativno niskih vertikalnih gradijenata ukupnog polja preko otoka, prilično visokoj korelaciji vremenskih nizova sa bliskim opservatorijima, kao i u

niskim razinama šuma geomagnetskih komponenata. Ovi početni rezultati nagovještavaju Palagružu kao primjerenu lokaciju za sekularnu postaju, kao i za variometarsku postaju. Međutim, potrebna su dodatna istraživanja geomagnetskih efekata mora i obale, koristeći dulje vremenske nizove.

Ključne riječi: geomagnetska sekularna postaja, geomagnetska variometarska postaja, polje kore, geomagnetska induktivna strelica

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