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AN ANALYSIS OF VARIATION OF GEOMAGNETIC FIELD PARAMETERS UPON APPLYING THE THEORY OF COVARIANCE FUNCTIONS

Jonas Skeivalas, Romuald Obuchovski

Vilnius Gediminas Technical University, Department of Geodesy and Cartography, Saulėtekis 11, LT-10223 Vilnius, Lithuania (✉ *romuald.obuchovski@vgtu.lt*, +370 52 744 705, *jonas.skeivalas@vgtu.lt*)

Abstract

In the paper, the variation of the intensity of the geomagnetic field force is analysed in time and space. For the research, the data from measurements of the intensity of the geomagnetic field force at four airports (Kaunas, Klaipėda, Palanga and Vilnius) and 6 geomagnetic field repeat stations as well as the data from Belsk Magnetometric Observatory (Poland) were used. For the data analysis, the theory of covariance functions was applied. The estimates of the cross-covariance functions of the measured intensity of the geomagnetic field force or the estimates of auto-covariance functions of single data were calculated according to the random functions created from the force intensity measurement data arrays. The estimates of covariance functions were calculated upon varying the quantization interval on the time scale and applying the software created using Matlab package of procedures. The impact of radars of airports on the intensity of geomagnetic field variation and on changes of their covariance functions was established.

Keywords: geomagnetic field parameters, covariance function, quantization interval.

1. Introduction

Earth's magnetic field is a constantly and irregularly changing physical field [1]. The frequency of geomagnetic field parameter alterations is not stable – from fractions of a second to year-long or even longer periods, called secular variations [2–4]. Information about changes of geomagnetic field, which took place between corresponding measurement epochs, are required to process the data of magnetic measurements [5–7]. Such information is gathered in geomagnetic observatories.

In this paper the covariation of geomagnetic field intensity components and its influence on field intensity covariations changes is analysed. The correlation between changes of geomagnetic field intensity in time and space was determined by employing the variation of covariation of field intensity components in time. Equations were formed to calculate estimates of covariation matrices and covariance functions of field intensity components using the data from magnetic measurements. Accuracy of respective calculated parameters was assessed.

The measurements of the intensity φ of geomagnetic field force were carried out at 4 airports of Lithuania (Kaunas, Klaipėda, Palanga, and Vilnius) and 6 geomagnetic field repeat stations, as well as at Belsk Magnetometric Observatory (Poland). The variation of auto-covariance and

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cross-covariance functions of vectors of the intensity φ of geomagnetic field force in various locations in the territory of Lithuania in different times was analysed as well.

The theoretical model is based on the concept of a stationary random function upon taking into account that errors of measuring the geomagnetic field parameters are random and possibly of the same accuracy, *i.e.* the average error $M\Delta = \text{const} \to 0$, their dispersion $D\Delta = \text{const}$, and the covariance function of digital signals depends only on the difference between the arguments, *i.e.* on the quantization interval in the time scale.

The estimates of the covariance functions of two digital arrays of geomagnetic field intensity signals obtained from a proton magnetometer or the estimates of the auto-covariance function of a single array were calculated upon transformation of the digital data arrays into random functions. To process the digital signals, the discrete Fourier transform [8, 9] and the theory of wavelet functions [10–12] were applied.

2. Covariance model of parameters of intensity of geomagnetic field force

To create a theoretical model, we assumed that errors in measuring the vector of intensity φ of digital signals of geomagnetic field are random and possibly systematic.

In each vector of the array of measurement data on the intensity φ of the geomagnetic field, the trend of the measurement data of that vector is eliminated. As one of parameters, the time interval of spread of signals of the magnetometer is used.

We consider a random function (created according to the arrays of the measured vectors of intensity φ of the geomagnetic field) to be a stationary function (in a broad sense), *i.e.* its average value $M\{\varphi(t)\} \to \text{const}$, and the covariance function $K_\phi(\tau)$ depends only on the difference of arguments τ. The auto-covariance function of a single data array or the cross-covariance function of two data arrays $K_\phi(\tau)$ can written as follows:

$$K_\phi(\tau) = \frac{1}{T-\tau}\int_0^{T-\tau} \delta\phi_1(u)\delta\phi_2(u+\tau)du, \tag{1}$$

where $\delta\phi_1(u)$, $\delta\phi_1(u+\tau)$ – the centered values of geomagnetic field intensity measurements, u – a vibration parameter, $\tau = k \cdot \Delta$ – a variable quantization interval, k – the number of units of measurement, Δ – the value of a unit of measurement, T – time.

According to the available data from measurements of the geomagnetic field intensity parameters, the estimate $K'_\phi(\tau)$ of covariance function is calculated as follows [13, 14]:

$$K'_\phi(\tau) = K'_\phi(k) = \frac{1}{n-k}\sum_{i=1}^{n-k} \delta\phi_1(u_i)\delta\phi_2(u_{i+k}), \tag{2}$$

where n – the total number of discrete intervals.

Equation (2) may be applied in the form of an auto-covariance function or a cross-covariance function. When the function is an auto-covariance function, the arrays $\phi_1(u)$ and $\phi_2(u+\tau)$ are parts of single arrays, whereas when the function is a cross-covariance function, they are two different arrays.

The estimate of a normalized covariance function is:

$$R'_\phi(k) = \frac{K'_\phi(k)}{K'_\phi(0)} = \frac{K'_\phi(k)}{\sigma'^2_\phi}, \tag{3}$$

where σ'_ϕ – the estimate of standard deviation of the random function.

To eliminate the trends of vectors in the i-th digital array of measurements, the following formulas are applied:

$$\delta\phi_i = \phi_i - e \cdot \overline{\phi}_i^T = (\delta\phi_{i1}, \ldots, \delta\phi_{im}), \tag{4}$$

where $\delta\phi_i$ – the i-th digital array of reduced values where a trend of vectors is eliminated; ϕ_i – the i-th array of the geomagnetic field intensity, e – a unit vector with the size $(n \times 1)$; n – the number of lines in the i-th array, $\overline{\varphi}_i$ – the vector of average values of vectors in the i-th array, $\delta\varphi_{ij}$ – the j-th vector of the reduced values in the i-th array; $j = 1, \ldots, m$.

The vector of average values of vectors in the i-th array is calculated according to the following formula:

$$\delta\phi_i = \phi_i - e \cdot \overline{\phi}_i^T = (\delta\phi_{i1}, \ldots, \delta\phi_{im}), \tag{5}$$

The random function of the j-th vector of the i-th array of geomagnetic field force intensity in the form of vectors can be obtained as follows:

$$\delta\phi_{ij} = \left(\delta\phi_{ij,1}, \ldots, \delta\phi_{ij,m}\right), \tag{6}$$

The estimate of the covariance matrix of the i-th array of geomagnetic field force intensity is expressed as follows:

$$K'(\delta\phi_i) = \frac{1}{n-1}\delta\phi_i^T \delta\phi_i \,. \tag{7}$$

The estimate of the covariance matrix of two (i-th and j-th) arrays of geomagnetic field force intensity is expressed as follows:

$$K'(\delta\phi_i, \delta\phi_j) = \frac{1}{n-1}\delta\phi_i^T \delta\phi_j \,, \tag{8}$$

where the arrays $\delta\phi_i$, $\delta\phi_j$ should have the same size.

The estimates of covariance matrices $K'(\delta\phi_i)$ and $K'(\delta\phi_i, \delta\phi_j)$ are reduced into the estimates of matrices of correlation coefficients $R'(\delta\phi_i)$ and $R'(\delta\phi_i, \delta\phi_j)$ [13, 14]:

$$R'(\delta\phi_i) = D_i^{-1/2} K'(\delta\phi_i) D_i^{-1/2}, \tag{9}$$

$$R'(\delta\phi_i, \delta\phi_j) = D_{ij}^{-1/2} K'(\delta\phi_i, \delta\phi_j) D_{ij}^{-1/2}, \tag{10}$$

where D_i, D_{ij} – the diagonal matrices of the principal diagonal members in the estimates of covariance matrices $K'(\delta\phi_i)$ or $K'(\delta\phi_i, \delta\phi_j)$, respectively.

The accuracy of the calculated coefficients of correlation is defined by the standard deviation σ_r, and its value is assessed according to the following formula:

$$\sigma_r = \frac{1}{\sqrt{k}}\left(1 - r^2\right), \tag{11}$$

where $k \to 1400$, r – a coefficient of correlation. The maximum value of standard deviation is obtained when the value of r is close to zero and in this case $\sigma_r' \approx 0.03$; when $r \approx 0.5$, we obtain $\sigma_r' \approx 0.02$.

3. Results of experiment and analysis of results of measurements carried out at airports of Lithuania

The measurements of the intensity φ of geomagnetic field force were carried out at 4 airports of Lithuania (Kaunas, Klaipėda, Palanga, and Vilnius) in 2016 and 4 arrays of the measurement results were obtained. The data were fixed in time intervals $\tau_\Delta = 2{-}3$ s and within a period of 2.5 h–4 h. Each vector of the array includes from $n_1 = 2750$ (Klaipėda) to $n_4 = 5540$ (Vilnius) measurement values. The accuracy of the vectors of geomagnetic field intensity is defined by the estimates of the standard deviation from $\sigma_H \approx 5.0$ nT to $\sigma_H \approx 18$ nT. The arrays of data obtained at the above-mentioned airports were numbered by their sequential numbers: 1, 2, 3, 4. The arrays of measurement data were processed using the software developed upon applying the operators of Matlab 7 package of programs.

The values of the quantization interval of normalized covariance functions vary from 1 to $n/2$, where $n = 2750$ – the number of values of the relevant vector in the array of geomagnetic field force intensity. In such a way, a new array of 4 vectors of force intensity where each vector conforms to the data array of a specific airport was created. For each vector, the estimate $K'_\varphi(\tau)$ of the normalized auto-covariance function $K_\varphi(\tau)$ was calculated and 4 graphical expressions of the normalized auto-covariance functions were obtained. In addition, the estimates $K'_\varphi(\tau)$ of the normalized cross-covariance functions were calculated for 4 vectors, thus the total of 6 graphical expressions of them were found.

The normalized auto-covariance functions achieve the maximum value of the correlation coefficient $r \to 1.0$ when the values of the quantization interval $k \to 0$ ($\tau_k \to 0$ s), and then at relevant airports suddenly fall down to $r \to (0; 0.1; 0.2; 0.6)$ when the values of the quantization interval $k \to 1$ ($\tau_k \to 3$ s). On growing of the values of the quantization interval, the values of auto-covariance functions are "damping" to $r \to 0$ when $k \to (40;\ 700; 1000)$ or $\tau_k \to$ (120 s, 2100 s, 3000 s) The obtained data show that variations of the auto-covariance functions of geomagnetic field force intensity at different airports are different and they equal to zero at different values of the quantization interval. The graphical expressions are provided in Figs. 1 to 4.

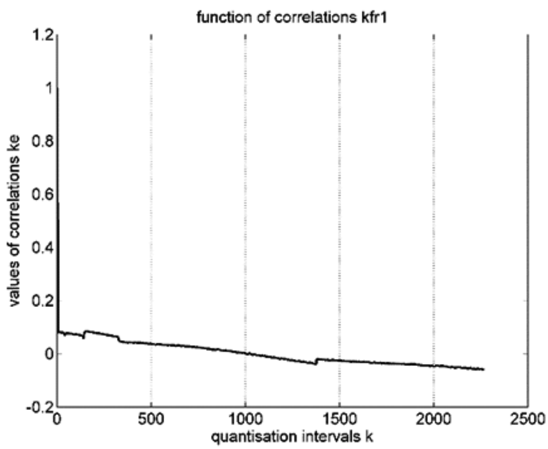

Fig. 1. The normalized auto-covariance function of vector 1 of geomagnetic field intensity (Kaunas airport).

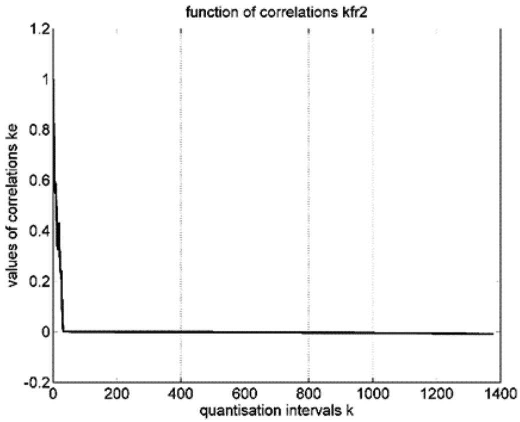

Fig. 2. The normalized auto-covariance function of vector 2 of geomagnetic field intensity (Klaipėda airport).

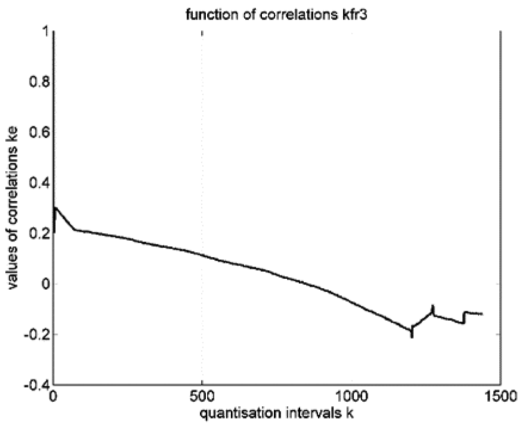

Fig. 3. The normalized auto-covariance function of vector 1 of geomagnetic field intensity (Kaunas airport).

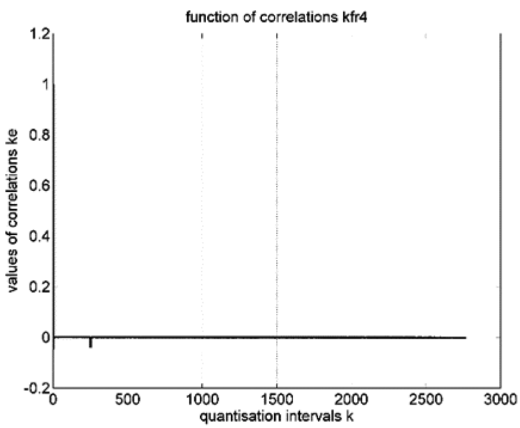

Fig. 4. The normalized auto-covariance function of vector 4 of geomagnetic field intensity (Vilnius airport).

The graphical expressions of the cross-covariance functions of 4 vectors of geomagnetic field force intensity are quite different. The values of the functions vary in a range from 0.8 to 0.35 when the values of the quantization interval $k \to (0; 30)$ or $\tau_k \to (0\ \text{s}, 90\ \text{s})$. The values of the normalized covariance functions of the geomagnetic field intensity vectors of relevant airports "damp" to $r \to 0$ at $k \to (0; 40; 900; 1200)$ or $\tau_k \to (0\ \text{s}, 120\ \text{s}, 2700\ \text{s}, 3600\ \text{s})$. The "peak" values of two normalized cross-covariance functions were obtained at $k \to 1200$ ($\tau \to 3600\ s$), – they are related to the geomagnetic field intensity vectors of Kaunas and Palanga airports ($r \to -0.25$) and the geomagnetic field intensity vectors of Klaipėda and Palanga airports ($r \to -0.30$). The graphical expressions of the normalized cross-covariance functions are presented in Figs. 5 to 10.

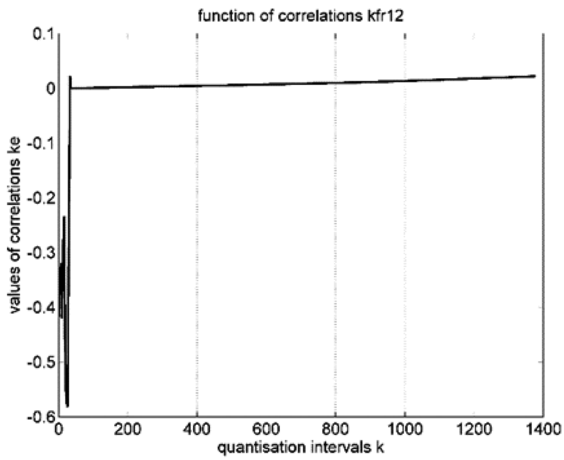

Fig. 5. The normalized cross-covariance function of vectors 1 and 2 of geomagnetic field intensity (Kaunas and Klaipėda).

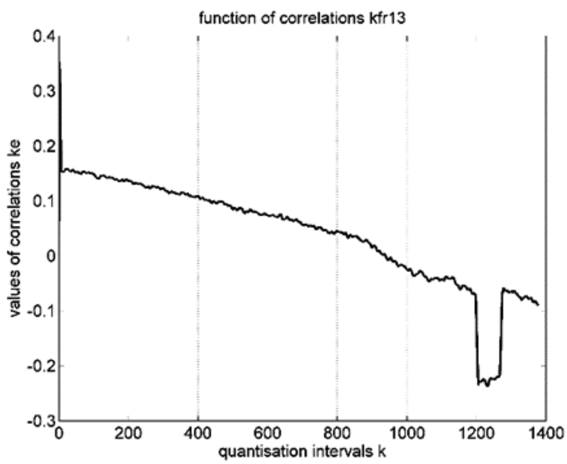

Fig. 6. The normalized cross-covariance function of vectors 1 and 3 of geomagnetic field intensity (Kaunas and Palanga).

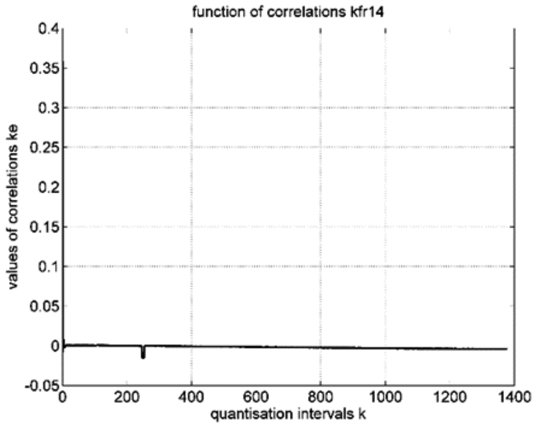

Fig. 7. The normalized cross-covariance function of vectors 1 and 4 of geomagnetic field intensity (Kaunas and Vilnius).

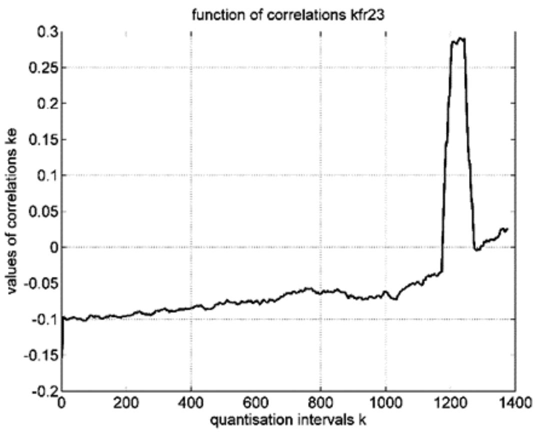

Fig. 8. The normalized cross-covariance function of vectors 2 and 3 of geomagnetic field intensity (Klaipėda and Palanga).

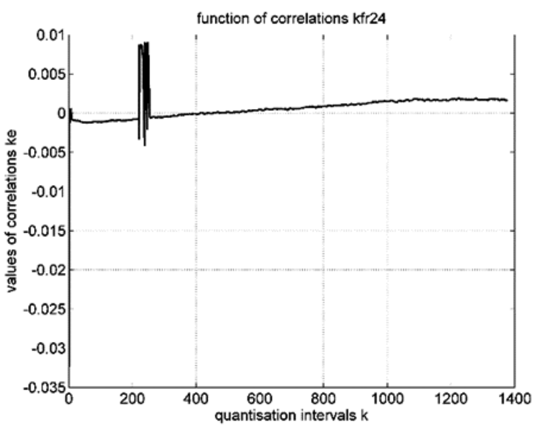

Fig. 9. The normalized cross-covariance function of vectors 2 and 4 of geomagnetic field intensity (Klaipėda and Vilnius).

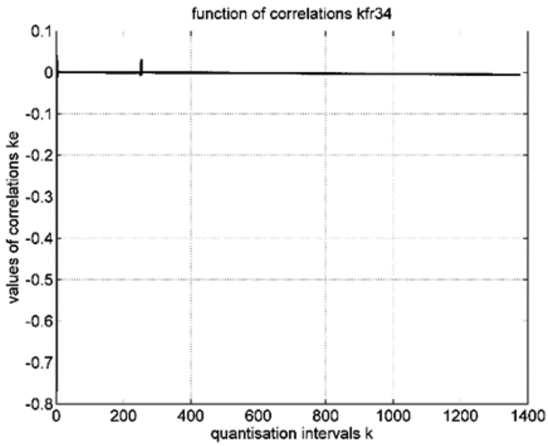

Fig. 10. The normalized cross-covariance function of vectors 3 and 4 of geomagnetic field intensity (Palanga and Vilnius).

In Fig. 11, a graphical expression of the generalized (spatial) correlation matrix of the array of 4 vectors of the intensity of geomagnetic field force (Kaunas, Klaipėda, Palanga, Vilnius) is presented. The expression of the correlation matrix turns into a block of 4 pyramids where the values of correlation coefficients are represented by tints of the colour spectrum. The chromatic projection of the pyramids is shown in the horizontal plane.

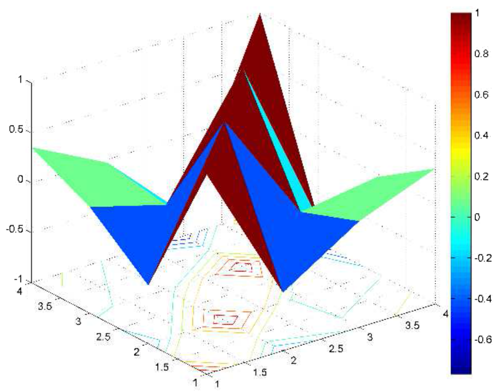

Fig. 11. A graphical expression of the generalized (spatial) correlation matrix of the array of 4 vectors of the intensity of geomagnetic field force.

4. Results of experiment and analysis of results of measurements carried out at geomagnetic field repeat stations of Lithuania

The measurements of the intensity φ of the geomagnetic field force were carried out at 6 geomagnetic field repeat stations of Lithuania: Dusetos, Parovėja, Šaukotas, Šyliai, Tryškiai and Žiežmariai. For the experiments, there were used the results of measurements carried out at the above centres on the following days (of the year 2016): 08th August; 11th August; 12th August; 16th August; 17th August; 19th August; 22nd August; and 23rd August. In addition, the results of measurements carried out at Belsk Magnetometric Observatory (Poland) in the same period were used. The data were fixed in time interval $\tau_{\Delta} = 1$ s and within a period of 0.8–3 h. Each vector of the relevant array includes from $n_1 = 2830$ to $n_8 = 11438$ measurement values. The accuracy of the vectors of geomagnetic field intensity is defined by the estimates of the standard deviation σ_φ: at geomagnetic field repeat stations of Lithuania [3.0; 0.7; 0.9; 0.6; 1.1; 1.1; 0.6; 1.2] nT and at Belsk Magnetometric Observatory [0.8; 0.9; 2.3; 1.3; 2.0; 1.9; 0.6; 1.0] nT. The expression of each measurement vector is a random function when – on approaching to the stationary form – the function of constant and periodic trend was eliminated.

The measurement data arrays were processed using the software developed upon applying the operators of Matlab 7 package of programs.

The values of the quantization interval of normalized covariance functions vary from 1 to $n/2$, where $n = 2830$ – the number of values of the vector in the array of geomagnetic field force intensity φ. Thus, an array of 8 vectors of geomagnetic field force intensity φ was created for the data from geomagnetic field repeat stations of Lithuania and an array of 8 vectors of geomagnetic field force intensity φ was created for the data from Belsk Magnetometric Observatory.

For each vector of geomagnetic field force intensity φ, the estimate $K'_\varphi(\tau)$ of the normalized auto-covariance function $K_\varphi(\tau)$ was calculated and 16 graphical expressions of normalized auto-covariance functions were obtained. In addition, the estimates $K'_\varphi(\tau)$ of the normalized cross-covariance functions were calculated for all 16 vectors, thus the total of 88 graphical expressions of them according to relevant combinations of vectors were found.

The normalized auto-covariance functions for the measurements carried out at geomagnetic field repeat stations and at Belsk Magnetometric Observatory achieve the maximum value of the correlation coefficient $r \to 1.0$ when the values of the quantization interval $k \to 0$ ($\tau_k \to 0$ s) and then fall down to $r \to 0$ at $k \to$ (300 s : 1000 s). On growing the values of the quantization interval, the values of auto-covariance functions become negative down to $r \to (-0.2 : -0.7)$ The obtained data show that the random functions created according to the measurement data are not purely stationary functions. Because the rates of "damping" of the values of the normalized auto-covariance functions for the measurements carried out at different geomagnetic field repeat stations aiming to zero are different at different values of the quantization interval, this shows the variation of the intensity φ of the geomagnetic field force to be different as well and dependent on the fluctuations of geomagnetic field parameters. The graphical expressions of the auto-covariance functions are presented in Figs. 12 to 15.

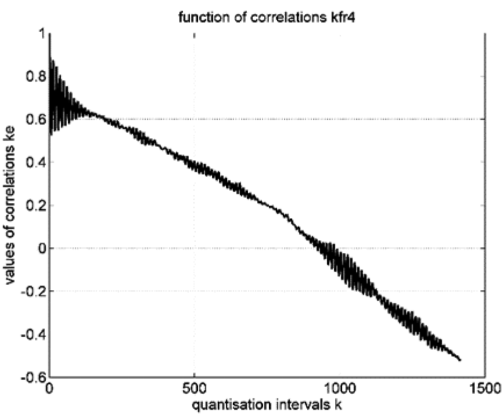

Fig. 12. The normalized auto-covariance function of the intensity vector F at Žiežmariai geomagnetic field repeat station.

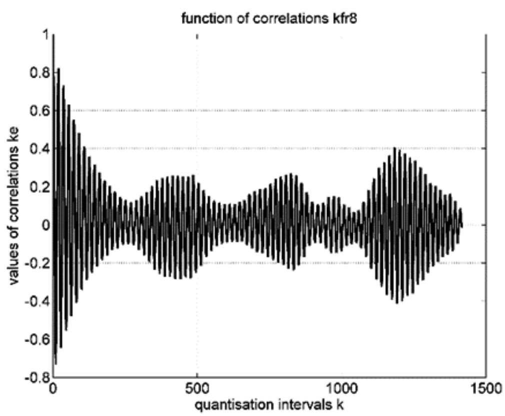

Fig. 13. The normalized auto-covariance function of the intensity vector F at Šyliai geomagnetic field repeat station.

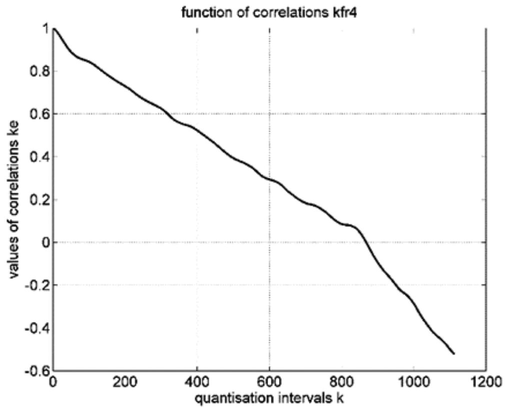

Fig. 14. The normalized auto-covariance function of the intensity vector F at Belsk Magnetometric Observatory on the 08th August.

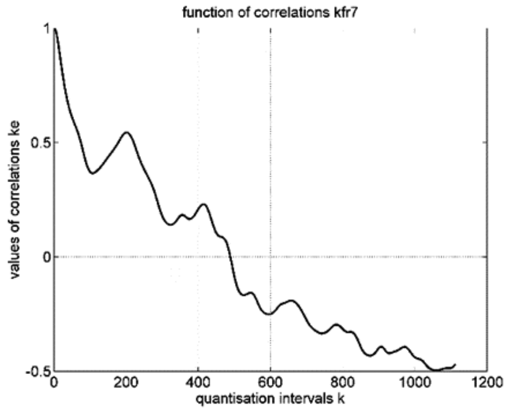

Fig. 15. The normalized auto-covariance function of the intensity vector F at Belsk Magnetometric Observatory on the 22nd August.

The expressions of the normalized cross-covariance functions of geomagnetic field force intensity φ vectors at geomagnetic field repeat stations of Lithuania and Belsk Magnetometric Observatory are various: they are either increasing or decreasing. The values of decreasing cross-covariance functions varied in a range $r \rightarrow$ from 0.9 to -0.7 when the values of the quantization interval $k \rightarrow (0\text{ s} : 1400\text{ s})$. The values of increasing cross-covariance functions varied in a range $r \rightarrow$ from -0.9 to 0.6 when the values of the quantization interval $k \rightarrow (0\text{ s} : 1400\text{ s})$. They are shown in Figs. 16 to 23.

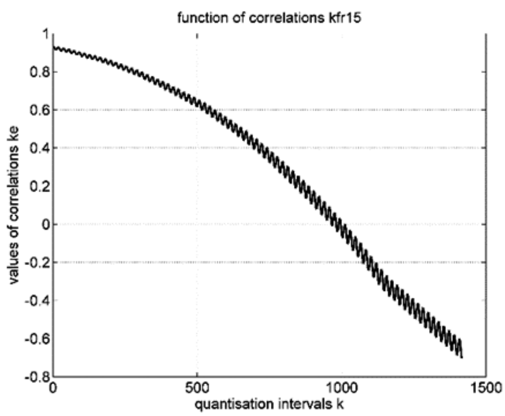

Fig. 16. The normalized cross-covariance function of the intensity vector F at Žiežmariai and Šaukotas geomagnetic field repeat stations.

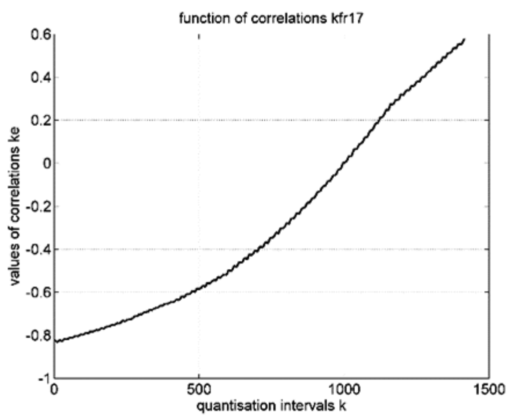

Fig. 17. The normalized cross-covariance function of the intensity vector F at Žiežmariai and Šyliai geomagnetic field repeat stations.

In Figs. 24 and 25, the graphical expressions of the generalized (spatial) correlation matrices of the arrays of 16 vectors of the intensity φ of geomagnetic field forces obtained according to the data from geomagnetic field repeat stations and Belsk Magnetometric Observatory are shown. The expressions of the correlation matrices turn into a block of 8 pyramids where the values of

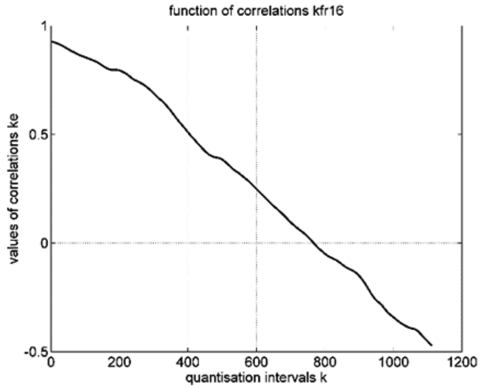

Fig. 18. The normalized auto-covariance function of the intensity vector F at Belsk Magnetometric Observatory on the 08th and 19th August.

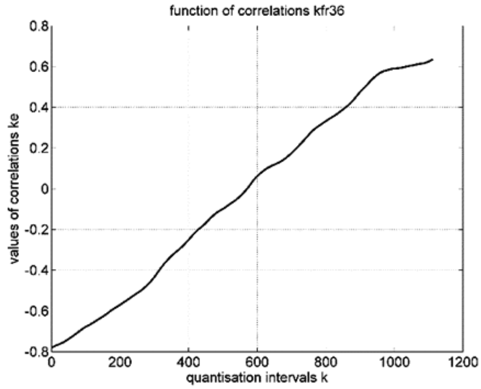

Fig. 19. The normalized auto-covariance function of the intensity vector at Belsk Magnetometric Observatory on the 12th and 23rd August.

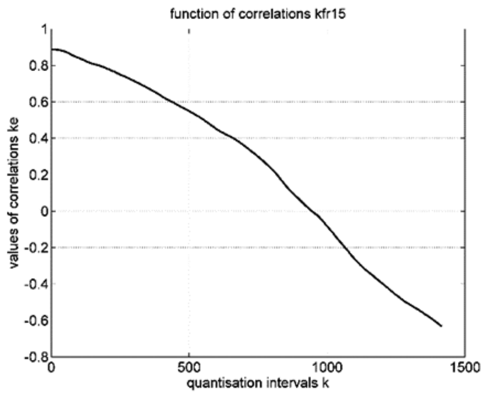

Fig. 20. The normalized cross-covariance function of the intensity vector at Žiežmariai geomagnetic field repeat station and Belsk Magnetometric Observatory on the 08th August.

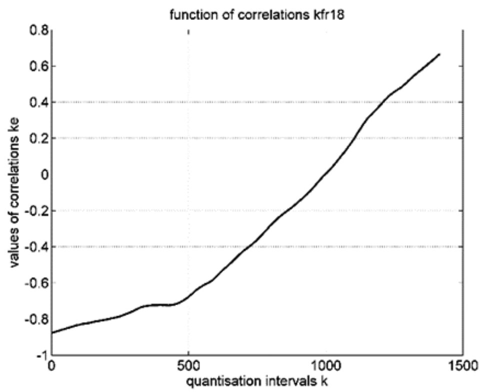

Fig. 21. The normalized cross-covariance function of the intensity vector at Žiežmariai geomagnetic field repeat station and Belsk Magnetometric Observatory on the 23rd August.

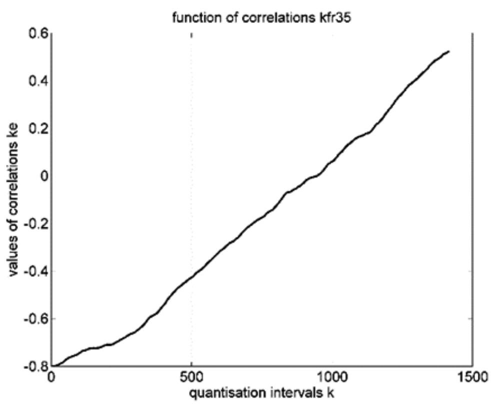

Fig. 22. The normalized cross-covariance function of the intensity vector at Šyliai geomagnetic field repeat station and Belsk Magnetometric Observatory on the 08th August.

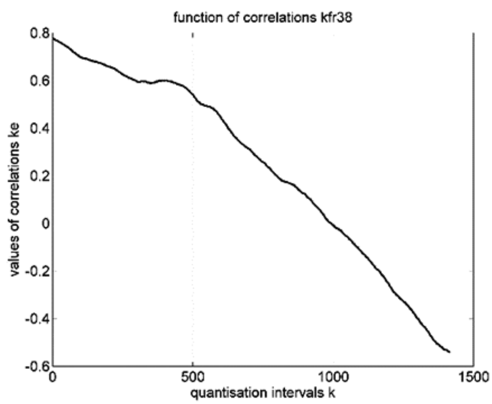

Fig. 23. The normalized cross-covariance function of the intensity vector at Šyliai geomagnetic field repeat station and Belsk Magnetometric Observatory on the 23rd August.

correlation coefficients are represented by tints of the colour spectrum. The chromatic projection of the pyramids is shown in the horizontal plane.

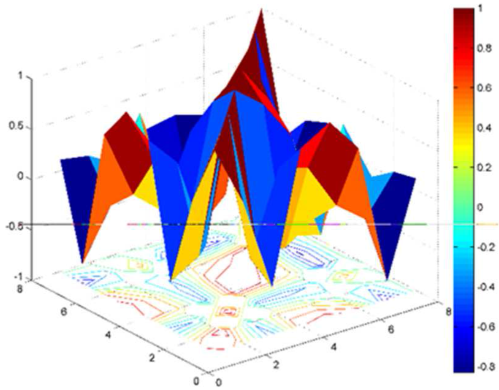

Fig. 24. A graphical expression of the generalized (spatial) correlation matrix of the array of the data from geomagnetic field repeat station for 8 epochs.

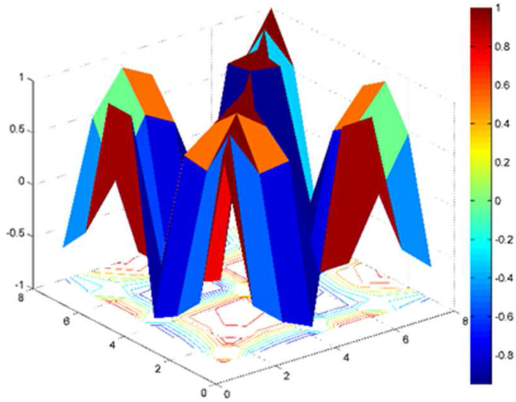

Fig. 25. A graphical expression of the generalized (spatial) correlation matrix of the array of intensity vectors from Belsk Magnetometric Observatory for 8 measurement periods.

When analysing the expressions of the normalized auto-covariance functions and the normalized cross-covariance functions, no dependence of their variation on the coordinates of the involved repeat station and on the date of measurement was found. It is evident that the variation of the values of covariance functions depends on the fluctuations of the parameters of the geomagnetic field intensity only.

The expressions of the normalized covariance functions of the vector of intensity φ of geomagnetic field force at Lithuanian airports differ considerably from the expressions of the normalized covariance functions of the vector of intensity φ of geomagnetic field force at geomagnetic field repeat stations and Belsk Magnetometric Observatory.

5. Conclusions

1. The normalized auto-covariance and cross-covariance functions of the vectors of the intensity of geomagnetic field force enable to establish the variation of the correlation between data vectors according to the quantization intervals of signals. The results of magnetic field parameter measurement in single epochs are strongly correlated due to turbulence of magnetic field and measurement errors, therefore the covariation matrix should be used when processing them. The vectors of field forces were used in a time scale with eliminated trends.
2. The probabilistic dependence of the values of vectors on the intensity of geomagnetic field force measured at the airports (auto-covariance) is very strong ($r \to 1.0$) when the quantization interval is short enough only, *i.e.* when $k \to 0$ ($\tau_k \to 0$ s) It falls down very quickly to $r \to (0.1; 0.6)$ at $k \to (1; 5)$ and $\tau_k \to (3$ s; 15 s) and then suddenly "damps" to $r \to 0$ (Klaipėda and Vilnius airports) and "damps" slowly to $r_{1,3} \to 0$, when $k_{1,3} \to (1000, 700)$. The above-mentioned results show that fluctuations of geomagnetic field parameters at different airports differ considerably.
   The expressions of normalized auto-covariance functions have a greater deviation from zero at Klaipėda and Palanga airports compared with those from Vilnius and Kaunas airports.

This indicates that radars in smaller airports have a less impact on the geomagnetic field parameters than radars of large airports.

The fluctuations of the geomagnetic field parameters of different airports vary considerably, though this may depend on the power of the airport radars.

3. The normalized cross-covariance functions of the intensity φ of geomagnetic field force at the airports are different when the values of covariance may be either positive or negative. The values of the coefficients of correlation vary within the limits $r \to (-0.8; 0.35)$ when the quantization interval $k \to 0$ and correlation suddenly falls down to $r \to 0$. Such results are obtained for the vectors related to airport 1 and airport 2 (Kaunas and Klaipėda airports), airport 1 and airport 4 (Kaunas and Vilnius airports) as well as airport 3 and airport 4 (Palanga and Vilnius airports). Some normalized cross-covariance functions become equal to zero at a considerably high value of the quantization interval only. It may be seen from the values of cross-variance function of vectors 1 and 3 (Kaunas and Palanga airports), vectors 2 and 3 (Klaipėda and Palanga airports), when $r \to 0$ at $k_{13} \to 900(\tau_{k_{13}} \to 2700$ s) and $k_{23} \to 1200(\tau_{k_{23}} \to 3600$ s), respectively.

   The values of covariance function between vector 2 and vector 4 (Klaipėda and Vilnius airports) are practically equal to zero, when $r_{24} \to (-0.03; 0.01)$ in the total range of variation of the quantization interval.

   The values of covariance functions between 2nd and 4th vectors (Klaipėda and Vilnius), 1st and 4th (Kaunas and Vilnius), 3rd and 4th (Palanga and Vilnius) are practically equal to zero throughout the quantization interval range of change. This may indicate that the cumulative values of the geomagnetic field parameters of large airports are close to zero.
4. According to the data from Lithuanian geomagnetic field repeat stations and Belsk Magnetometric Observatory, the probabilistic dependence (auto-covariance) of the values of vectors on the intensity φ of geomagnetic field force is strong ($r \to 1.0$) only at short quantization intervals, *i.e.* when $k \to 0\,s$. This dependence remains for a sufficiently long time – from 300 to 1000 s. The trends of variations of this dependence on the intensity parameters found at the geomagnetic field repeat stations and Belsk Magnetometric Observatory are approximately the same.
5. At both Lithuanian geomagnetic field repeat stations and Belsk Magnetometric Observatory, the character of variation of the normalized covariance function of the vectors of intensity φ of geomagnetic field is similar. The normalized covariance functions are of two characters: some of the functions are increasing when $r \to -0.9 : 0.6$ and some of them are decreasing when the values of coefficients of correlation vary in a range $r \to 0.9 : -0.7$.

   The obtained results show variations of both the value and the direction of the fluctuations of the intensity φ of geomagnetic field. A strong dependence of the expressions of normalized covariance functions on the influence of geomagnetic field intensity vectors of radars of airports was found.

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