ULTRA SENSITIVE GEOMAGNETIC MONITORING AT EILAT GEOPHYSICAL OBSERVATORY

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ABSTRACT

Long-term precise magnetic observations are being carried out at the Eilat test site as a part of active tectonic fault multi-sensor geophysical monitoring. The gradiometer system comprises three highly sensitive potassium total field sensors with short bases - up to 50 m. The gradiometer time series contain residuals of external magnetic field variations, which are essentially homogeneous over such short distances. Mutual regression analysis of the gradiometer and the vector magnetometer time series was proved to be an effective tool in reduction of the influence of external homogeneous variation on gradiometer readings. Monitoring results together with time dependence of regression coefficients are analyzed.

Keywords: Magnetic gradiometer, Regression analysis, Geophysical monitoring

1 INTRODUCTION

Long-term precise magnetic observations with the help of a supersensitive potassium magnetometer/gradiometer (SuperGrad) started in the framework of the Canada-Israel project in 2000. The aim of the project was to search for new capabilities of the SuperGrad instrument (GEM Systems) in application to tectonic dynamics. During the first stage of the project, SuperGrad was installed in the geophysical tunnel at the southern part of the Arava Desert. Three total field magnetic sensors of SuperGrad were placed so as to get gradient data both in north-south and east-west directions. Monitoring of the gradiometer differences was carried out together with vector measurements of the Earth's magnetic field by means of a declination-inclination magnetometer (dIdD) (Pankratz, Sauter, Kormendi, & Hegymegi, 1999).

Earlier it was shown (Shirman & Ginzburg, 2004) that gradiometer time series contain residuals of external variations even with a very short gradiometer base of a few meters. This phenomenon was explained by non-parallelism of magnetic field vectors at the measurement points. This misalignment, in turn, is conditioned by magnetization (mainly remnant) of the surrounding rocks. The suggested 'cleaning' procedure based on mutual linear regression analysis of the gradiometer and vector magnetometer data proved to be an effective tool for removal of external homogeneous field variations (Sq, substorms, etc.) from gradiometer time series. Regression coefficients are proportional to differences in magnetic field inclination and declination at the points of sensor location.

In the current work we analyze the temporal behavior of regression coefficients obtained during the monitoring period.

2 ENVIRONMENT AND INSTRUMENTATION

The geophysical tunnel was dug in the Amram Mount composed from Precambrian volcanic granite - diorite rocks. The site is located far from the nearest road and, due to the absence of any industrial activity in the area, features a very low level of man-made electromagnetic and seismic interferences. The site is situated in a tectonically active area of the southern Arava Rift which is a part of the Dead Sea Transform System. The main strike-sleep fault is about 4.5 km from the tunnel. Numerous measurements of rocks susceptibility inside and outside of the tunnel by means of a kappameter gave a value of $(3\text{-}4)\cdot 10^{-4}$ SI. Paleomagnetic measurements show remnant magnetization of rocks having mainly an easterly direction.

Aeromagnetic survey in the Amram Mount region (Rybakov & Goldshmidt, 1996) revealed a large-scale dipole magnetic anomaly. Total field measurements were carried out at the height of 100 m above ground level.

Anomaly intensity made up of about 200 nT in its positive epicenter was located one kilometer to the south-south-east from the tunnel. The tunnel is affected by the negative pole with a gradient magnetic field. Figure 1a shows the map of the aeromagnetic anomaly field in the tunnel vicinity and the tunnel projection. The datum of 42,500 nT has been removed. SuperGrad sensors locations (SG1, SG2, SG3) in the tunnel are shown in Figure 1b.

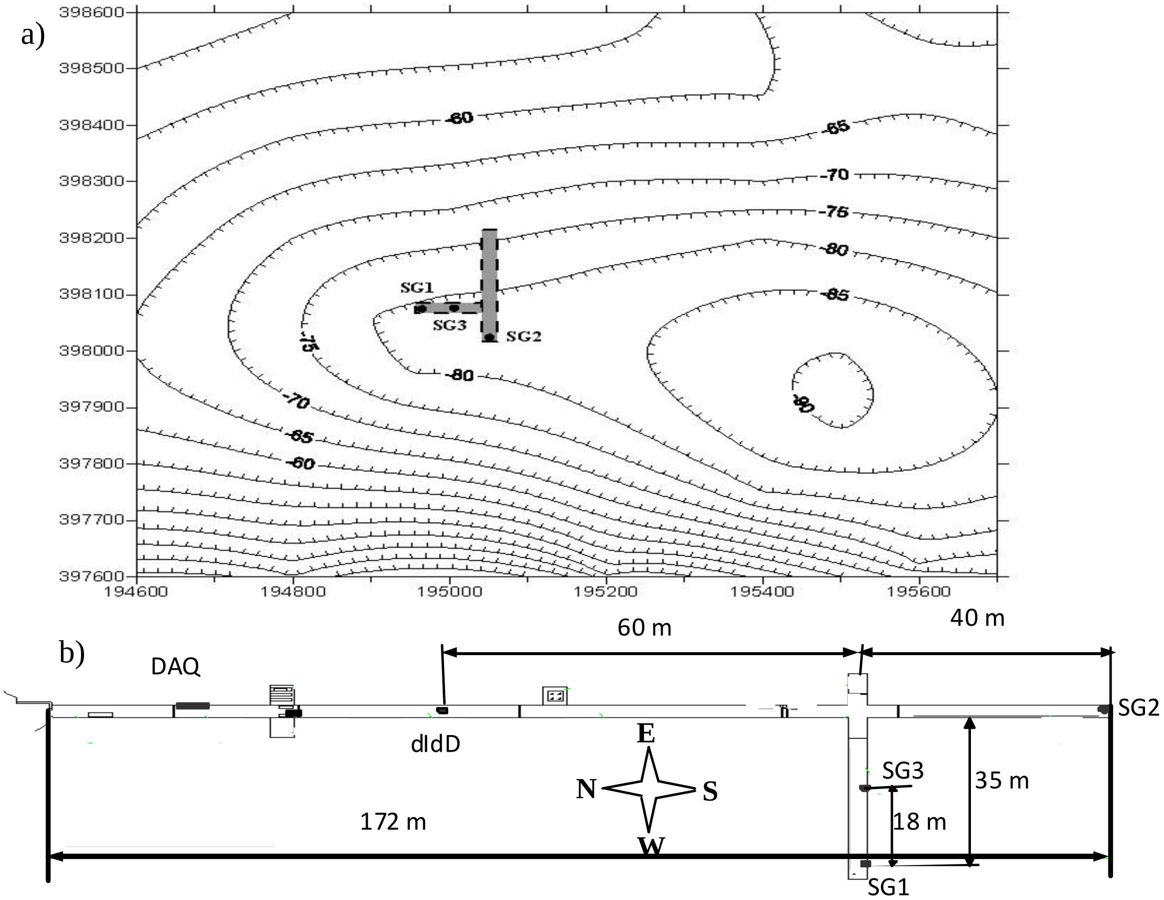

Figure 1. a) The aeromagnetic anomaly map of the tunnel observatory vicinity with the tunnel location: X and Y axes are coordinates in meters (Israel grid), contour levels are in nT; b) Tunnel scheme with equipment layout.

A careful total magnetic field survey inside the tunnel was carried out with the help of a proton Overhauser magnetometer GSM-19 (GEM Systems). Magnetic field profiles along the east-west and north-south dead-end branches of the tunnel were measured on different heights. Total magnetic field gradients of 3 nT/m in an east-west direction and 1 nT/m in a south-north direction are typical for an in-tunnel environment.

At the same time, the gradient of the large-scale magnetic field at a height of 100 m over the tunnel did not exceed 0.05 nT/m (Figure 1a). Moreover, the magnetic field measured outside the tunnel at a distance of about 3 km aside the rock massif is equal to 43,350 nT, which is 250-300 nT more than inside the tunnel.

Based on the aforesaid results, we can conclude that the local inhomogeneity of the magnetic field inside the tunnel is a condition of the magnetization of the surrounding rocks.

For long-term magnetic observations, we made use of a supersensitive magnetometer/gradiometer based on the principle of optical pumping in potassium vapors (Alexandrov, Balabas, Pazgalev, Vershovskii, & Yakobson, 1996), which provides an opportunity for precise short-base gradiometer measurements. This instrument features a 0.001 pT resolution with up to a 20 Hz sampling rate. High absolute accuracy (0.1 nT) and low temporal drifts (less than 1 pT/day) ensure reliable long-term measurement results.

A dIdD Overhauser proton magnetometer (GEM Systems) with a resolution of 0.01 nT was used for the ‘cleaning’ procedure (Shirman & Ginzburg, 2004). GEM’s dIdD employs a mutually orthogonal coil system that measures one unbiased and four biased values of total magnetic fields. The axes of the coil system are arranged so that the axes of the mutually orthogonal coils are themselves perpendicular to the Earth’s magnetic field vector, F, in the horizontal plane and vertical - geomagnetic meridian plane. Our version of the instrument features fixed (unsuspended) sensor installation, which is potentially sensitive to gentle basement tilts. To check the long-term stability of this magnetometer, we performed regular absolute measurements outside the tunnel in accordance with requirements of magnetic observatories (Jankovski & Sucksdorf, 1996).

Figure 2 shows X, Y, Z, and F- base lines in the period 2003-2007. Thanks to temperature stability inside the tunnel, yearly variations in base lines are very low. Mean values of the Earth's magnetic field components for the year 2003 are given in the Table 1.

Table 1. Yearly mean values of the Earth's magnetic field components at the Eilat magnetic observatory

D		H	I		X	Y	Z	F
deg	min	nT	deg	min	nT	nT	nT	nT
3	09.6	31133	43	53.0	31085	1716	29941	43194

As for the observed multiyear trend, it was caused presumably by a slight drift of the magnetometer basement over the years. It is evident from a comparison of the X and Z base lines: their near equality in absolute but opposition in sign changes could be explained by the tilt of the basement around the horizontal EW axis.

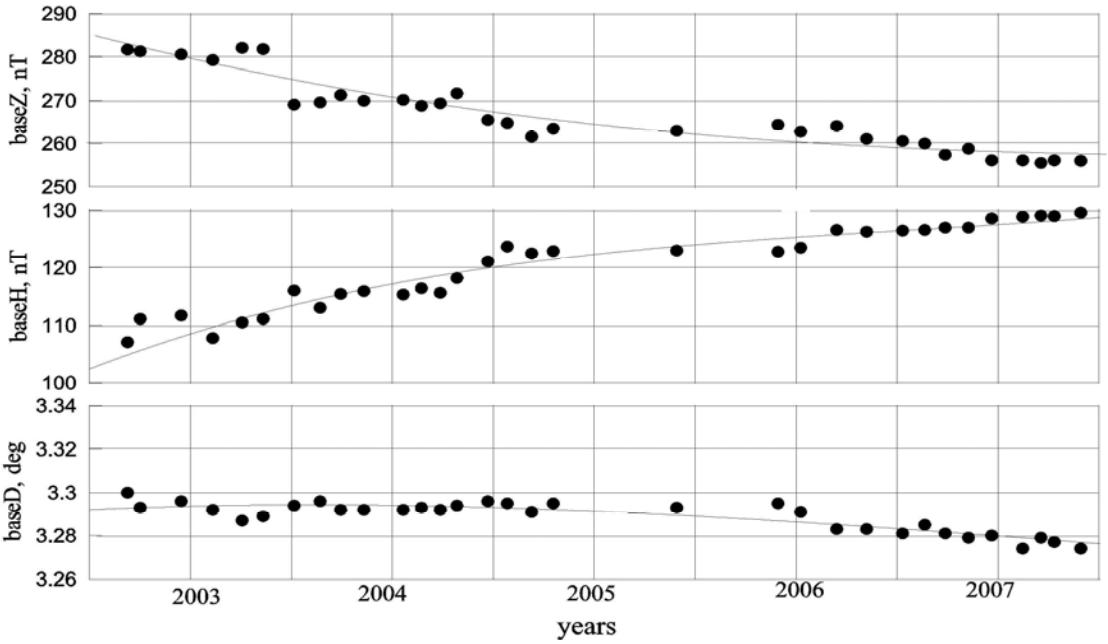

Figure 2. H, D, Z, and F- base lines of the dIdD magnetometer during 2003-2007 (according to Survey of Israel)

3 MAGNETIC FIELD MONITORING AND DATA PROCESSING

The point of the short-based magnetic gradiometer with highly sensitive magnetic sensors is to cancel signals of remote sources like diurnal variations and micro-pulsations but to sense the sources of local/regional origin that could be governed by geodynamic activity. In our case, the separation between magnetic sensors – gradiometer base – is about dozens of meters (see Figure 1b). Over such short distances, both diurnal variations and micro-pulsations are essentially homogeneous. It turned out, however, that the gradiometer time series contain residuals of external variations.

Synchronous monitoring of supersensitive total field and vector magnetometers allowed us to understand the influence of the external magnetic field on gradiometer readings. A comparison between the gradiometer and the external field components time series showed their obvious correlation. The closest correlation was observed with declination changes. In this case, the correlation coefficient was estimated as being more than 0.95. As it was shown (Shirman & Ginzburg, 2004), the main reason for such phenomenon is the non-parallelism of the Earth's magnetic field vectors at the points of the sensors' location. The 'cleaning' procedure based on a mutual regression analysis of the gradiometer and vector magnetometer time series was found to be an effective tool for reduction of the influence of the external homogeneous variation. Figure 3 illustrates the result of such reduction.

Presented here are typical 10-day records at the summer period. High correlation between the Y-component of the external magnetic field (Figure 3a) and the gradiometer readings (Figure 3b, c) is clearly seen. Various methods of the 'cleaning' procedure are discussed below.

The dIdD vector magnetometer measures X (north), Y (east), and Z (downward) components of the Earth's magnetic field. SuperGrad sensors measure the total magnetic field F_k (in our case k=1, 2, 3 for a three-sensor system). Within the bounds of the test site, the magnetic field vector may deviate slightly from the field direction at the dIdD point. Declination D_k and inclination I_k angles specify the field direction at the SuperGrad sensor locations.

Total field gradiometer time series

$$G_{k1k2}^{i} = F_{k1}^{i} - F_{k2}^{i}$$

are calculated from the total magnetic field F^{i}_{k} measured by any of the SuperGrad sensors k where i is the sample number.

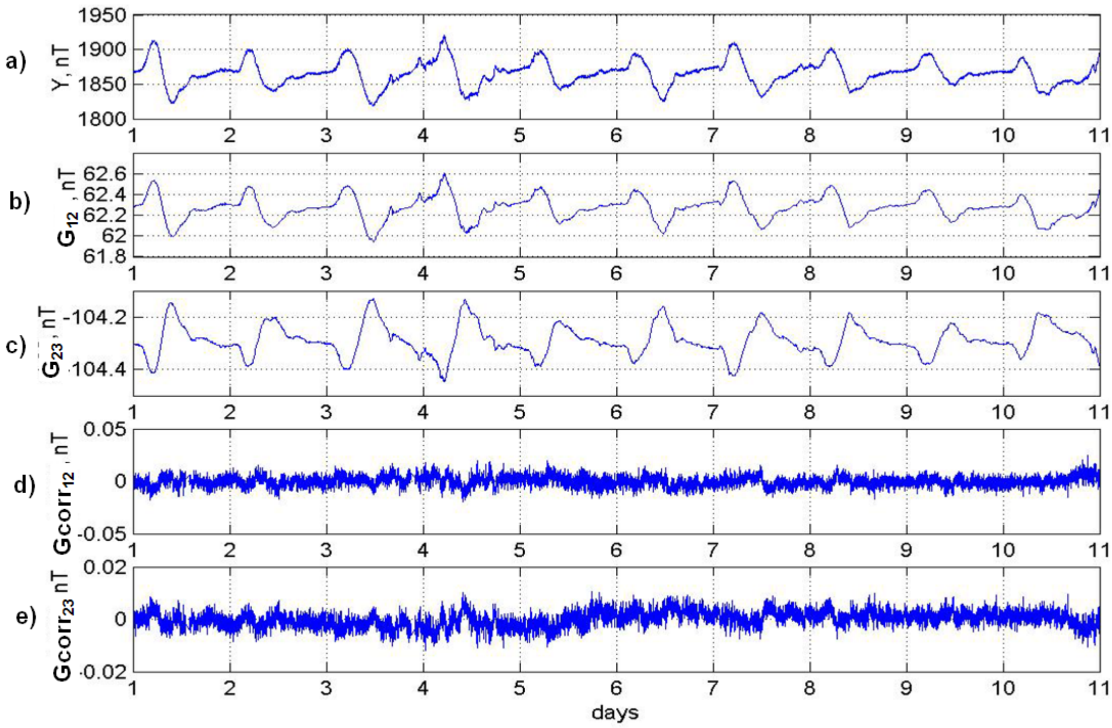

Figure 3. Example of the 10-day record (01-10/07/2007): a) Y-component of the Earth's magnetic field; b), c) raw gradient time series; d), e) corrected readings.

According to Shirman and Ginzburg (2004), misalignment of magnetic field vectors in the points of the SuperGrad sensor locations results in the dependence of gradiometer readings on the homogeneous component variations of the Earth's magnetic field:

$$\boldsymbol{dG_{k1k2}} = b1_{k1k2} \cdot \boldsymbol{dX} + b2_{k1k2} \cdot \boldsymbol{dY} + b3_{k1k2} \cdot \boldsymbol{dZ} + \boldsymbol{\varepsilon}_{k1k2} \quad (1)$$

where d***X***, ***dY***, ***dZ*** are the centered vectors of magnetic field component data, $\boldsymbol{dG_{k1k2}}$ is the centered vector of gradiometer readings, $\boldsymbol{\varepsilon}$ is a vector of residuals, and coefficients b are as follows:

$$\begin{aligned} b1_{k1k2} &= -\sin(I_0) \cdot (I_{k1} - I_{k2}) \\ b2_{k1k2} &= \cos(I_0) \cdot (D_{k1} - D_{k2}) \\ b3_{k1k2} &= \cos(I_0) \cdot (I_{k1} - I_{k2}) \end{aligned} \quad (2)$$

where I_0 is the mean inclination angle at the reference point.

Angles of misalignment in Eq. (2) are not known a priori and in many instances could not be measured with satisfactory accuracy. In this case linear model (1) may be treated as a linear regression of $\boldsymbol{dG_{k1k2}}$ onto ***dX, dY, dZ*** (predictors). In matrix notation, Eq. (1) takes the form:

$$dG = \beta \cdot P + \varepsilon$$

$$P = \begin{pmatrix} dX_1 & dY_1 & dZ_1 \\ dX_2 & dY_2 & dZ_2 \\ - & - & - \\ dX_n & dY_n & dZ_n \end{pmatrix} \quad (3)$$

where β is a vector of the true coefficient and n is the number of readings in the data set series.

In the simplest case of the ordinary least squares (OLS) method, an estimation $b = (b1, b2, b3)$ of coefficients β in Eq. (3) is obtained as follows (Draper & Smith, 1998):

$$b = (P^T \cdot P)^{-1} \cdot P^T \cdot dG \quad (4)$$

where P^T is the transpose of the matrix P.

Residuals ε in the linear regression model (3) represent gradiometer data corrected for non-parallelism of magnetic vectors at measurement points. Figures 3d and e present these 'cleaned' or corrected gradiometer series $Gcorr^i_{k1k2} = \varepsilon^i_{k1k2}$

$$\varepsilon = dG - b \cdot P \quad (5)$$

Misalignment angles and therefore regression coefficients in (4) are expected to be time independent since they are influenced only by the rocks' magnetization. Processing of monitoring data for the period of 2003-2010 indeed shows an absence of a long term trend in coefficient values.

With the help of Eq. (2) we can calculate the non-parallelism angles of the Earth's magnetic field in the points of sensor locations based on the mean values of regression coefficients.

Table 2. Non-parallelism angles of the Earth's magnetic field in the points of sensor locations

	Misalignment in D	Misalignment in I
Sensors 1 & 2	28'	3'26"
Sensors 1 & 3	14'	2'45"

We see that declination differences are substantially larger than inclination ones. This result is a direct consequence of the fact that local magnetic field inhomogeneity is governed mainly by the rocks' remnant magnetization oriented almost in an E-W direction as mentioned above. Note that declination differences (D_2-D_1) and (D_3-D_1) differ by a factor 2, which is also a ratio of spatial separation between these sensors in an E-W direction (see Figure 1b). This means a presence of a constant D-gradient along the Y-axes within the bounds of the tunnel.

Though the annual mean values of regression coefficients are highly stable over a monitoring period of about 8 years, their current values feature small but distinct season changes. We show these by the example of the coefficient $b2_{12}$ since it has the maximum value of all the coefficients. Figure 4a shows the graph of the coefficient $b2_{12}$ temporal changes during one year of monitoring – from 2003, May to 2004, June. Each point in the plot is obtained by calculation of regression coefficients according to Eq. (4) for ten-day data series. We see that seasonal changes of about+/- 1.5% take place in the course of the year. Similar changes are observed during the whole monitoring period. Below we shall try to analyze possible reasons for this variability.

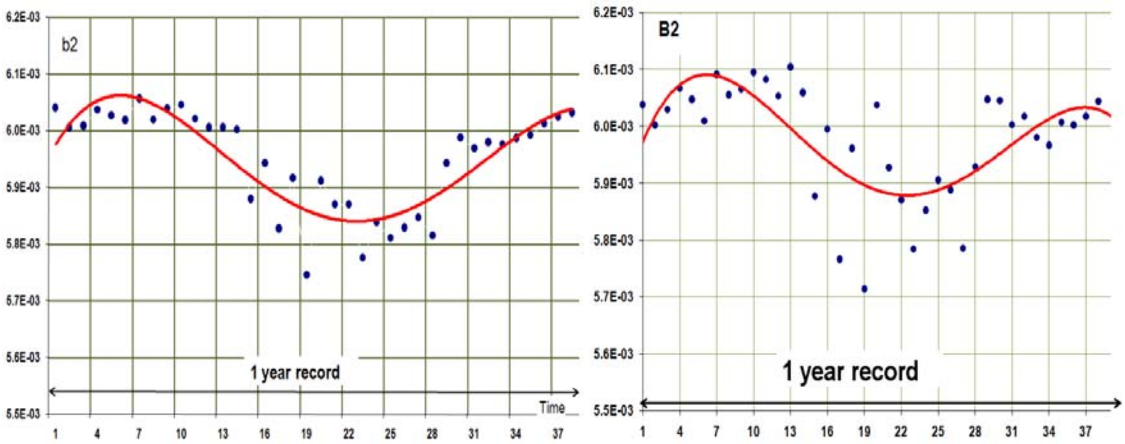

Figure 4. Seasonal changes of regression coefficient $b2_{12}$. Each point is calculated over a 10-day data set. a) Three predictor model; b) two predictor model – see explanation in Section 4.4.1.

4 ANALYSIS OF SEASONAL VARIABILITY IN REGRESSION COEFFICIENTS

4 .1 Temperature stability

The temperature inside inner tunnel compartments is very stable. According to our measurements, yearly temperature variation in the vicinity of the DIDD location (see Figure 1b) does not exceed +/- 0.3 C. The compartment of the SuperGrad sensors location is even deeper into the rock massif and has an additional thermal baffle separating it from the entrance. As noted above, the magnetic SuperGrad system has very high temperature and long-term stability. Stability of the dIdD magnetometer is lower, mainly due to the temperature sensitivity of its coil system. However, such low yearly temperature variations do not seem to exert direct influence on magnetometer readings.

4.2 dIdD stability

The stability of the dIdD Overhauser vector magnetometer was controlled by absolute measurements according to the requirements (Jankovski & Sucksdorf, 1996). As shown in Figure 2, yearly variations were negligible in dIdD baselines.

Our dIdD instrument is an early version of a GEM vector magnetometer with an unsuspended Overhauser sensor. Therefore, the seasonal tilt of the dIdD pillar may, in principal, be a plausible reason for seasonal changes in regression coefficients in Eq. (2). To get a quantitative estimation of this effect, we performed computer simulation of the influence of the dIdD frame angular position on regression coefficients. Our results showed that in order to get an observed seasonal variability in regression coefficients of +/-1.5%, we need to assume an approximate 10° tilt of the pillar which is, of course, unfeasible.

4.3 Ground tilt

Ground tilt may cause changes in regression coefficients only when it differs at the gradiometer sensor locations. For the case of the $b2_{12}$ coefficient vertical component of the anomaly magnetic field, a difference in ground tilt in the east-west direction may be responsible for the change in declination differences. Simple estimation shows that impossible tilts of about 1° are needed to explain the observed variability in the appropriate regression coefficient.

4.4 Possible bias in the estimation of regression coefficients

4.4.1 Two-predictor model

First, let us note that the non-parallelism of magnetic vectors at every pair of measurement points is governed by only two parameters - $(I_{k1}-I_{k2})$ and $(D_{k1}-D_{k2})$. In fact, this means that the three-predictor regression equation (3) contains redundancy which could, in principle, cause errors in estimation of our physical model (1-2) parameters. We need, therefore, to rewrite Eqs. (1) and (2) as follows:

$$\mathbf{dG}_{k1k2}=(I_{k1}-I_{k2})\cdot[-\sin I_0\cdot\mathbf{dX}+\cos I_0\cdot\mathbf{dZ}]+\cos I_0\cdot(D_{k1}-D_{k2})\cdot\mathbf{dY}+\varepsilon_{k1k2} \qquad (6)$$

This means that the three-predictor regression equation (Eq. (3)) can be replaced by a two-predictor model in the following manner:

$$\mathbf{dG} = \mathbf{B}\cdot\mathbf{R} + \varepsilon$$

$$\mathbf{R} = \begin{pmatrix} dC_1 & dY_1 \\ dC_2 & dY_2 \\ . & . \\ dC_n & dY_n \end{pmatrix} \qquad (7)$$

Here $\mathbf{dC}=-\sin I_0\cdot\mathbf{dX}+\cos I_0\cdot\mathbf{dZ}$ is a centered projection of the Earth's magnetic field variation onto a direction orthogonal to the mean total magnetic field vector in the plane of magnetic meridian.

Similar to Eq. (4), the OLS estimation of $\mathbf{B}=(B1,B2)$ is given by

$$\mathbf{B} = (\mathbf{R}^T\cdot\mathbf{R})^{-1}\cdot\mathbf{R}^T\cdot\mathbf{dG} \qquad (8)$$

It is interesting to compare gradiometer data corrected by the three-predictor model (3) with two-predictor (7). An example is given in Figure 5. We see that some useful signals can be erroneously depressed by the three-predictor model due to its superfluous degree of freedom. However, periodical season changes of regression coefficients around their annual average values remain for the two-predictor model as well, see Figure 4b.

4.4.2 Other possible reasons for the bias in the estimation of regression coefficients

There are several reasons that could lead to bias in the estimation of regression coefficients.

a) Dependence between predictors: If predictors $\mathbf{C}$ and $\mathbf{Y}$ in Eq. (7) are nearly linearly dependent, then matrix $\mathbf{R}^T\mathbf{R}$ in Eq. (8) is close to singular, giving rise to unstable estimates of regression coefficients. $\mathbf{C}$ and $\mathbf{Y}$ are projections of the Earth's magnetic field variation onto directions orthogonal to the mean total magnetic field vector – one in the plane of the magnetic meridian and the other in an easterly direction. For our case, $\mathbf{dC}$ and $\mathbf{dY}$ are not linearly dependent but correlated. The correlation coefficient calculated on our obtained data set features a mean annual value of about 0.5. However, there is a considerable spread in the course of the year so that the correlation coefficient can take values from 0.2 to 0.8. Modifications of the OLS regression, such as ridge regression (Draper & Smith, 1998), exist to evaluate and remove possible bias in parameters estimation due to the dependence between predictors.

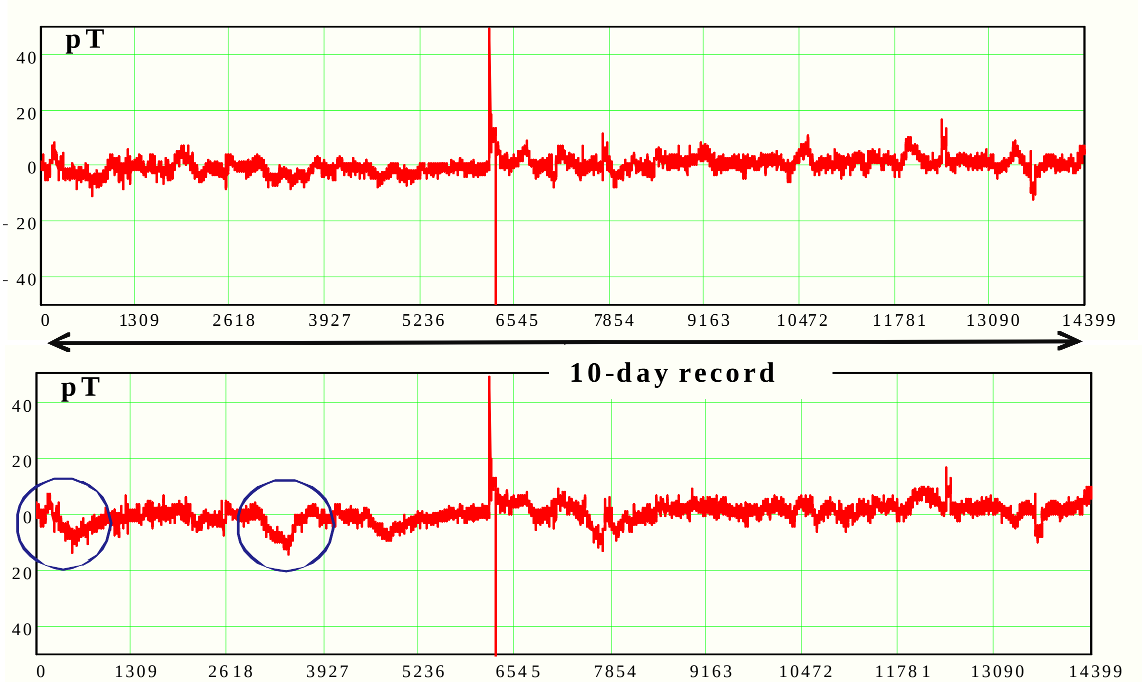

Figure 5. 10-day gradiometer record $Gcorr_{12}$ after correction - top: three predictor and bottom: two predictor methods. Signals erroneously surpressed by three-predictor model are clearly seen.

b) Influence of outliers: The standard method of OLS regression assumes a normal distribution of the residual ε in Eqs. (3) and (7). In practice, departures from this assumption occur. In fact, these departures are just the ‘useful’ signals we are searching for to correlate with the regional geodynamic activity. Except for these ‘useful’ signals, there are different kinds of instrumental spikes, local interferences, and disturbances unavoidable in any magnetic observatory. A least square analysis weights each observation equally in getting parameter estimates. However, observations containing different kinds of ‘signals’, which are not conditioned by the linear model in Eq. (7), should be down-weighted for estimation of regression coefficients. There are several, so called, robust methods of linear regression that enable the observations to be weighted unequally.

c) Non-linearity of the model: If the linear model in Eq. (7) is not exactly true and there are other unaccounted terms, for instance, higher orders of predictors ***dC, dY***, then estimations of regression coefficients could be somewhat biased.

d) Influence of dIdD noise: In the OLS regression method, it is assumed that predictors (***R*** in Eq. (7)) are measured exactly while output variable (***dG*** in Eq. (7)) is subject to the random error ε with normal distribution. If this is not true and random error in measurements of predictors (magnetic field components in our case) should be accounted for, then the OLS estimate of regression coefficients will be biased (Draper & Yang, 1996). In our case, the contribution of dIdD magnetometer noise is significant. Moreover, the variance of *C* and *Y* components features seasonal changes, see Figure 6. This means that the ‘signal/noise’ ratio for estimation of regression coefficients is liable to seasonal variations as well. Various methods of line regression when all the variables are subject to error have been suggested. Among these are the geometric mean functional relationship (GMFR), maximum likelihood estimation (MLE), method of moments, and others. Further details can be found in Draper & Smith (1998).

Detailed analysis of possible reasons for the bias in the estimation of regression coefficients as described in this section is a subject of separate research. These results will be published later.

5 CONCLUSION

In this work, we analyzed details of the data processing of precise total-field short-based magnetic gradiometer monitoring aimed at searching for the magnetic manifestation of regional geodynamics. The intention of the method is to cancel signals of remote sources like diurnal variations and micro-pulsations while sensing the sources of local/regional origin that could be governed by geodynamic activity.

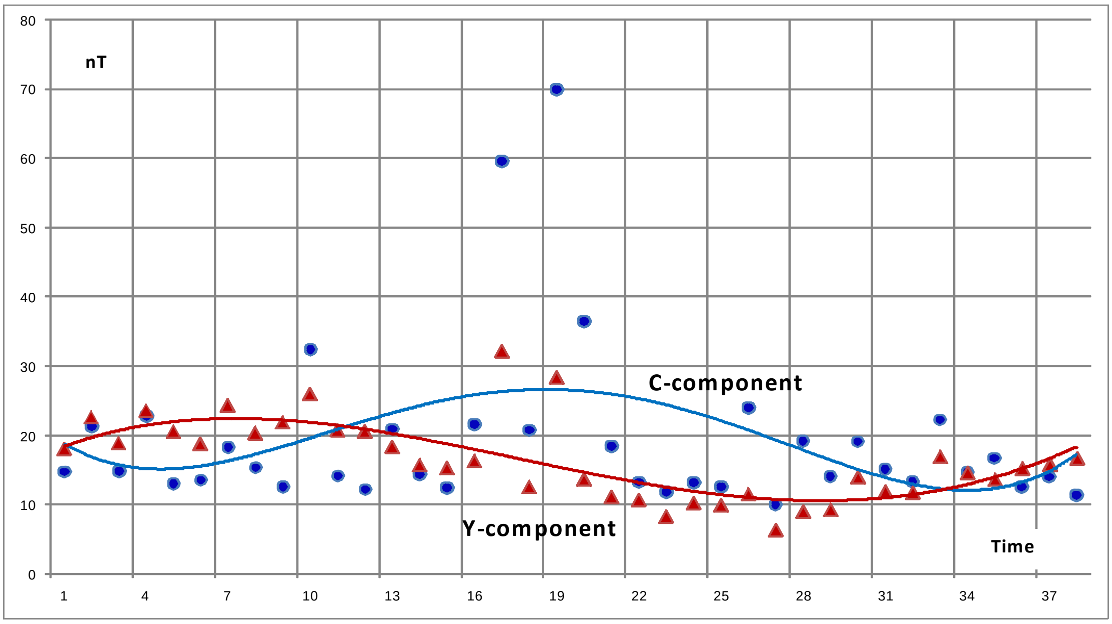

Figure 6. Root-mean-square deviation values of the Earth's magnetic field components during 1 year of monitoring. Each point is calculated over a 10-day data set.

It was shown that gradiometer time series contain residuals of external variations even with a very short gradiometer base of dozens of meters. Over such short distances both diurnal variations and micro-pulsations are essentially homogeneous. This phenomenon can be explained by the non-parallelism of magnetic field vectors at the points of magnetic sensor locations. This misalignment is, in turn, caused by magnetization (for the most part, remnant) of the surrounding rocks.

A 'cleaning' procedure based on mutual regression analysis of the gradiometer and vector magnetometer time series was found to be an effective tool for reducing the influence of an external homogeneous variation.

According to our model, regression coefficients depend on misalignment angles only and therefore are expected to be highly stable in time. As our results show, indeed, there is no long term trend in regression coefficient values, which also verifies instrumentation stability.

Though annual mean values of regression coefficients are highly stable over the monitoring period of about 8 years, their current values feature small but distinct season changes.

Our estimations show that either geophysical phenomena or instrumental errors are unlikely responsible for these changes. We believe that possible bias in estimation of regression coefficients may cause their small periodical seasonal changes. Further research of the subject will be a target of our future work.

6 REFERENCES

Alexandrov, E., Balabas, M., Pazgalev, A., Vershovskii, A., & Yakobson, N. (1996) Double-resonance atomic magnetometers: from gas discharge to laser pumping. *Laser Physics* 6, 244 – 251.

Draper, N., & Yang, Y. (1997) Generalization of the geometric mean functional relationship. *Computational Statistics & Data Analysis*, 23, 355-372.

Draper, N. R. & Smith, H (1998) *Applied Regression Analysis, 3rd ed*, NY., Wiley & Sons.

GEM Systems. Retrieved from the World Wide Web, April 29, 2011: www.gemsys.ca.

Jankovski, J. & Sucksdorff, C. (1996) *IAGA Guide for Magnetic Measurements and Observatory Practice*, Warsaw.

Pankratz, L. W., Sauter, E. A., Kormendi, A., & Hegymegi, L. (1999) The US–Hungarian delta I delta D quasi-absolute spherical coil system. *Geophys. Trans*. *42*, 195–202.

Rybakov, M. & Goldshmidt, V. (1996) *Gravity and magnetic investigations in the Har Amram area (Southern Israel).* Report. 844/486/96 The Geophysical Institute of Israel, Lod, Israel.

Shirman, B. & Ginzburg, B. (2004) Influence of local field inhomogeneity on the accuracy of precise total magnetic field monitoring. *Meas. Sci. Technol. 15*, 2370-2374.

Survey of Israel. Retrieved from the World Wide Web, April 28, 2011: www.mapi.gov.il