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Vectorial magnetometers for noise reduction in volcanomagnetic monitoring at Mt Etna

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Abstract

The volcanomagnetic monitoring is critically dependent on the ability to detect and isolate magnetic variations related to volcanic activity. Accurate detection of volcanomagnetic anomalies attributable to the volcano's dynamics requires removing from measurements of the earth's magnetic field, fluctuations of external origin which may be up to hundreds of nanotesla during geomagnetic storms. The commonly used method of taking simple differences of the total intensity with respect to the simultaneous value at a remote reference is partially successful. Variations in the difference fields arise principally from contrasting electromagnetic properties at magnetometer sites. To improve the noise reduction of geomagnetic data from magnetic network of Mt Etna we developed an adaptive filtering. Magnetic vector data are included as input to the filter, to account for the orientation of the disturbance field. The filter is able to estimate and rectify the model parameters continuously by means of new observations, so that predictions match the observed data. The error of state estimation has been decreased and the filtering accuracy improved. Experimental data collected on Mt Etna during 2010 are analyzed to relate the field variation at a given station to the field at other sites filtering out undesired noise and enhancing signal-to-noise ratio.

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1 Introduction

Over the last decades volcanomagnetic monitoring has been playing an increasing role for improving the knowledge of the geophysical processes preceding and accompanying volcanic unrest (Zlotnicki and Bof, 1998; Del Negro and Currenti 2003; Napoli et al., 2008). Volcano monitoring is concerned with detection of local magnetic field changes attributable to the dynamics of the volcano's plumbing system and removal of the geomagnetic field variations with no geophysical significance. The rapid changes associated with volcanomagnetic events are usually very small, within 1~10 nT, and must be detected in the presence of considerable noise produced by natural geomagnetic fluctuations of external origin, which make the detection of volcanic source effects more difficult and may lead to misinterpret data. Main sources for natural geomagnetic fluctuations are electric current systems of ionospheric and magnetospheric origin related to the solar activity. Time variations of the external current systems produce time-varying magnetic fields (external primary transitory field, $\mathbf{B_{te}}$) that induce electric currents inside the earth by electromagnetic induction. These induced currents in turn produce time-varying magnetic fields (internal secondary transitory field, $\mathbf{B_{ti}}$).

Although the external primary field may undergo rapid changes both in time and space, the space variation of time changes is smooth and of long wavelength. In general, the spatial distribution of the primary field can be considered uniform compared to the scale of a volcano, and therefore the classical differential technique, based on simultaneous simple differences among the magnetic field amplitudes recorded at several points on a volcano, is the most frequently used and reliable method to reduce this effect. Even if data reduction processes are properly employed, however, we often see geomagnetic variations regardless of the state of the volcanic activity. Spatial changes in both magnetic and electromagnetic

properties of the local crustal rocks make the temporal fluctuations, with periods from minutes to years, of the induced fields different at each station (Parkinson, 1983). At different positions this disturbance appears with different properties and characters because of its interaction with the local environment (Zhou and Wei, 1998), but it should be predictable, because fluctuations at a number of stations will be interrelated by their electromagnetic impedances (Steppe, 1979).

Over the last few decades, a variety of methodologies have been proposed to improve the reduction process of geomagnetic time series aimed at enhancing the detectability of volcanomagnetic effects. A notable approach, relative to predictive methods based on classical Wiener filters theory, was in particular devised by Davis et al. (1981). Predictive methods are flexible enough to allow easy changes in the filter design, varying in terms of the number and choice of input channels and complexity of the filters used. However, predictive filter technique starts out from the assumption that underlying physical mechanism is dominated by a stationary process. Practical findings have evidenced that the assumption to consider the signal to be stationary is restrictive. If we assume the phenomenology of the process to be time-variant, a non-stationary approach is required to better filter out the natural geomagnetic fluctuations. In this regard, we have been testing an approach of adaptive type and we have been investigating its accuracy by applying it to geomagnetic time series acquired on Mt Etna by the continuously recording magnetic stations .

Experimental data collected during 2010 are analyzed to relate the field variation at a given station to the field at other sites filtering out undesired noise and enhancing signal-to-noise ratio. This filtering technique should improve the ability to detect and isolate magnetic changes related to volcanic activity and consequently to achieve substantial improvements in the evaluation of the volcanic processes

2   Vector Models Analysis

Improvement in noise reduction in geomagnetic field can be achieved if the causes generating the different inductive response at the different magnetic sites are taken into account. The internal transitory field is different at each site because of three main effects (Davis, et al., 1979): i) contrasting conductivity; ii) susceptibility contrast; iii) nonparallel local total fields. Where the electrical conductivity of the crustal rocks of a volcano changes over short distances, time changes can vary correspondingly. Differences in underground conductivity between two close (order of 10 km apart) sites will make the time variable fields different, even if the primary field from ionospheric and magnetospheric origin is the same. Although external geomagnetic disturbances induce currents normal to the geomagnetic variations, the direction of the electric current is deflected by geological local structures. The induced electrical currents depend on geographical relationship between the horizontal magnetic variations and the local geology (Poehls, 1978).

Lateral changes in electrical conductivity cause the directional anomaly of the electrical currents, from which the internal transient field arises. Whereas, the vertical fields usually do not induct significant effects, anomalies of the horizontal component correspond to shallow low resistivity structures, as they attenuate more rapidly than the vertical anomalous component with increasing distance from the structure of interest. In other words, the anomalous horizontal fields are more localized in comparison with the anomalous vertical fields.

Part of the local field is due to induced magnetization and any change in the superimposed field will change the induced part of the local field (Parkinson, 1983). Local geological structures with magnetic susceptibility χ cause a locally induced modification in response to a

magnetic disturbance $\mathbf{\Delta B_{te}}$ of about $\chi \mathbf{\Delta B_{te}}$, relying on the geometry of the magnetic structures and the position of the station.

Usually the local total fields, the external disturbance field, and the induced magnetization have different directions at the magnetic site. Nonparallel local total fields arise principally from local remanence heterogeneity. Even if the external disturbance field is supposed to be uniform over the magnetic network area, when the local total field is added to external field and to locally induced magnetization, different increments appear at each site because of the difference in the orientation of the local total fields.

Therefore geomagnetic disturbances induce large changes in the total field direction, which are evidenced in the total difference field. In order to remove these variations it needs information in the direction of the difference vector. This is the reason why all methods based only on total field information are partially successful (Davis, 1981). In order to improve the prediction error, magnetic vector data should be included as input to the filter, to account for the orientation of the disturbance field. The response to external magnetic fields depends also on latitude of sites. It has been noted that the amplitude of variation in H component at the highest latitude stations is stronger than the one at lower latitudes. Therefore, it is advisable to use data from observatories of geomagnetic latitude close to the monitoring network.

3   Adaptive Filtering

Geomagnetic signal processing over the last few decades have been dominated by the constraint of stationarity (the assumption that the statistics of a process or system do not change with time), a dominance that can be attributed to the simplification of problems arising from such an assumption. Non-stationarity is usually regarded as an undesirable feature, inasmuch as it significantly increases the complexity of the geomagnetic data analysis. Most

currently employed methods that are used in signal processing and time series analysis are based on rather simplistic assumptions about the stationarity of the underlying processes, and are hence suboptimal in many situations. Nevertheless, it has been recognized that non-stationarity can actually be a useful feature to produce superior results, both in existing problems attempted using the stationarity assumption, and in previously intractable problems (Hopgood, 2000).

If we assume the phenomenology of the process to be time-variant, a non-stationary approach is required to describe the natural geomagnetic fluctuations. For this reason we have utilized an approach of adaptive type (Pan, 1991). In the non-stationary analysis all the variables are time varying. Therefore also the weight vector of prediction will depend on time, as well as the cost function (mean squares error). The technique of analysis is based on a set of adaptive mutual predictors trained on a sliding time-window. The objective of an adaptive filter is to estimate and update the model parameters continuously by means of the new observations, so that predictions closely match the observed data. Therefore, the error of estimation can be decreased and the filtering accuracy can be improved.

In order to account for the correlation among the signals recorded from various stations, we propose an algorithm based on mutual signal predictions. If we assume p signals, n and m_i predictors, the finite order linear non-stationary parametric system model that relates the inputs of the system $u_1(t), \ldots, u_p(t)$, to the output of the system $y(t)$ is expressed by:

$$\hat{y}(t) = \sum_{i=1}^{n} a_{0i}(t) y(t-i) + \sum_{i=1}^{p} \sum_{j=0}^{m_i} a_{ij}(t) u_i(t-j) \qquad (1)$$

where, now, the a_{ij} are time-varying parameters.

The above expression (1) in matrix form becomes:

$$\hat{y}(t) = \mathbf{a(t)}U(t) \tag{2}$$

The least mean squares (LMS) solution of the system, obtained by a set of equations such as (1), is achieved by solving:

$$\mathbf{a} = \left(\mathbf{U}\mathbf{U}^T\right)^{-1}\mathbf{U}^T\mathbf{y} \tag{3}$$

where *a* is the vector parameter, U the data matrix, and y the vector of data to be estimated.

In the case of non-stationary approach, the LMS algorithm have to be run continuously and the *a* parameters should be recalculated using new available data. The above expressions are recomputed updating the data-matrix with the new vector of data at time t+1. The LMS algorithm, after performing the updates on the data-matrix **U**, calculates again the solution applying (3). This procedure is not computationally efficient because the evaluations of the matrix inverses may be very expensive and an adaptive algorithm might be preferable (Kuruoglu, 1998).

The classical and the simplest adaptive algorithm adjusts the linear filter parameters with every coming sample by using the gradient descent method. It avoids the re-computation of the inverse of the data-matrix. This minimization method finds a minimum by estimating the gradient. The basic equation for gradient descent method is:

$$\mathbf{a}(t) = \mathbf{a}(t-1) - \beta\nabla\varepsilon \tag{4}$$

where β is the learning rate, $\nabla\varepsilon$ is the gradient of error at time t between the real data value and the predicted value.

The estimate gradient is given by:

$$\nabla\varepsilon = -2\varepsilon U \tag{5}$$

Substituting Eq. (5) in Eq. (4), the equation for updating the filter parameters is expressed by:

$$\mathbf{a}(t) = \mathbf{a}(t-1) + 2\beta\varepsilon U \tag{6}$$

The coefficients are updated in function of: (i) the previous parameters, and (ii) the error between the real value and the estimated value obtained with the previous parameters. The learning rate determines the speed by which the parameters of model are updated. This algorithm has the drawback of being strongly dependent on the β parameter, which largely affects the stability and convergence speed of the algorithm.

An alternative to LMS is represented by Recursive Least Mean Squares (RLMS) algorithm, which does not suffer from these drawbacks. RLMS may be considered as a stochastic Gauss-Newton optimization algorithm. Gauss-Newton algorithms are known to converge onto the minimum of the quadratic cost function from any starting point in one step, with the assumption that the first two order derivatives of the error function with respect to the parameters are continuous, and their values are known at every point. The derivation of the RLMS algorithm is based on the matrix inversion lemma or Woodbury's identity (Kuruoglu, 1998). An adaptive filter estimates the model parameters continuously, so the error of estimation is reduced. This algorithm is performed in a loop so that with each new sample a new coefficient vector, a(t), is computed. In this way, the filter coefficients change and adapt.

In addition to the advantage of conceptual and computational simplicity, this technique is suitable for extracting common changes from geomagnetic signals when a correlated reference signal is available. The filter tends to estimate the variations that are common to different sites and its output is a prediction of the signal based on other sites observations (Fig. 1). The method allows removing the correlating variations in order to emphasize the local changes at the magnetic sites (Rosenberg, 1999). The residual component (the difference between the observed value at the particular site and the value estimated by prediction) contains only the effects that are local to the site (Hattingh, 1988).

4   Noise reduction in Etna volcanomagnetic series

On Mt Etna, detection of clear magnetic signals (Del Negro and Currenti, 2003; Napoli et al., 2008) associated with the renewal of the volcanic activity led to improve during recent years the permanent magnetic network set up on the volcano in 1998 (Del Negro et al. 2002). At present, the network consists of 5 scalar magnetometers (BVD, BCN, PTL, PDN, DGL) and 2 magnetic gradiometers (CST, PDG), which simultaneously sample the Earth's magnetic field at 5 s. The magnetic gradiometer stations consist of two sensors (namely CSTsouth, CSTnorth, PDGsouth and PDGnorth) horizontally spaced by about 50 m. Stations are located at elevations ranging between 1700 and 3000 m a.s.l. along a North-South profile crossing the summit craters. The magnetic reference station (CSR) is installed further west (about 27 km) on the Nebrodi Mountains (Fig. 2). During 2009 a new magnetic station (CSRV) equipped with a vectorial magnetometer (resolution 0.1 nT) was installed 30 meter away from the scalar magnetometer of CSR. The vectorial magnetometer, devised at INGV-Roma 2 Section, guarantees uninterrupted working under harsh environmental conditions with a high long term stability and restrained thermal drift (Palangio et al., 2004). Magnetic field measurements are usually differentiated with respect to the reference station (CSR) to isolate local magnetic field changes and cancel out common noise from ionospheric and magnetospheric sources.

External primary transitory field is approximately identical for the reference stations and those located on Mt Etna given their small spatial separation, so it can be assumed that, by subtracting the total intensities at two sites, this contribution to transient magnetic field is removed. In Fig. 3 the daily means of total intensity variations from 21 January to 13 May 2010 observed at magnetic stations relative to CSR are shown. We ignored the DGL and CST stations which are running for a shorter time interval. Although, the magnetic disturbances are reduced by about 95% strong variations are observed in the differenced data in

correspondence of strong external activity (geomagnetic K index values more than 5; Fig. 3),

when high geomagnetic components clearly appear. This effects can seriously hinder the

accurate detection of volcanomagnetic signals. When we expect only a small

volcanomagnetic signal either due to a weak volcanic activity or due to the large distance

between the source zone and the observation sites, the presence of non-volcanic changes can

make the detection of volcanic source effects more difficult.

4.1 Nonstationary Analysis

To improve the reduction process of geomagnetic time series gathered on Mt Etna we

implement a nonstationary filter by means the vector field components of CSRV and total

field from Etna magnetic array as reported below:

$$\hat{y}(t) = \sum_{i=0}^{m_1} a_{1i}(t) CSR(t-i) + \sum_{i=0}^{m_2} a_{2i}(t) X(t-i) + \sum_{i=0}^{m_3} a_{3i}(t) Y(t-i) + \sum_{i=0}^{m_4} a_{4i}(t) Z(t-i) \qquad (7)$$

where now the filter parameters a_{ij} are time-varying.

The accuracy of the filter was investigated by applying it to geomagnetic time series recorded

from the magnetic network on Mt Etna from 21 January to 13 May 2010 when significant

geomagnetic storms (Fig.3) due to high solar activity occurred. So this period is particularly

indicated to assess the performance of filtering technique to reduce the geomagnetic

disturbances affecting the magnetic fields at stations.

During the whole period significant correlation exists between total field at Cesarò and the

ones recorded from Etna stations (Tab. 1). In fact the external primary fields are enough

uniform over the studied area to assure that vector field data from CSRV are sufficient

consistent to be used for this processing.

The 10-minutes average of X, Y, and Z components are analyzed (Fig.4). The residual components of Etna magnetic stations are computed (Fig.5) and their associated standard deviations is compared to the one obtained for the differential method (Tab. 2).

The results show that the nonstationary filtering process is successfully carried out, especially if we look at the low residual components obtained during the most disturbed days. More importantly, no explicit choice of the period of the filter definition has to be made to accommodate non-stationary behavior of the data as, due to the adaptive structure, the filter weights (coefficients) are update continuously on a sample to sample basis.

The adaptation of filter parameters allows enhancing the filtering process since their updating is addressed to minimize the cost function continually. Even if the geomagnetic signals change their dynamical behaviors because of variations of the geomagnetic activity, the filter is able to adapt itself to the new conditions. Adaptive approach is found to be superior over the whole period at each station. After filtering the data sets, residuals have a very low STD in comparison with the one obtained by differential method. The STD is reduced of about one order of magnitude in comparison with simple differences. The improvements are gainful during periods of strong magnetic storms.

To evaluate and appreciate the efficiency of filtering procedure, the residuals were analyzed not only in time domain but also in frequency domain. Checking the frequency residual components, it is possible to verify whether or not the model has adequately captured the frequency domain characteristics. The analysis of their power spectrum provides insight about their statistical properties. The power spectra of residuals are shown in Fig. 6. The residuals calculated by taking differences between stations are dominated by large power at diurnal periods. Instead, after adaptive filtering, the residual power spectra are reduced also in the shorter frequency interval. Analyzing them, it is evident that this technique is more able to describe whole frequency range of the geomagnetic signals.

5. Discussion and Conclusions

Up to now filtering of geomagnetic noise is a very complex problem that involves the development of different algorithms based on experiences and physical knowledge. In this paper we propose an adaptive algorithm, based on the use of magnetic vectorial data, to properly process geomagnetic time series acquired in volcanic area.

When simultaneous magnetic field differences are calculated between total fields at two stations, non-homogenous variations are not removed and local transient components remain. Several methods were used to eliminate the transient fields, which are of the same order of the volcano-magnetic signal to be detected (Zlotnicki, 1995).

The reduction of residual components is the first objective in detection of magnetic anomalies because of their small magnitude. If very rapid changes in field are indeed characteristic of volcanomagnetic events, then filtering techniques for removing short-period geomagnetic noise due to induction effect may be very helpful in increasing the detectability of volcano-related magnetic field changes. The low residuals obtained demonstrate that assumption of a linear regression relationship, between magnetic sites, is reasonable. Data from vector component magnetometer permit to better estimate the ground currents induced from external transitory magnetic field. The algorithm doesn't require a complex implementation and it is extremely easy to design. The magnetic vector data acquired at CSRV, that is only 30 km away from the magnetic network of Etna, were used as input to the filter. This allowed accounting for the orientation of the disturbance field and therefore guarantee a good performance of the filtering process. The adaptive vectorial filtering developed works well both during quite days and strong magnetic storms. The diurnal solar variation, which is the main component of the transient field, is completely removed.

The non-stationary analysis shows how the filter parameters change dynamically when strong variations occur. This characteristic might be useful to detect time-dependent variations between stations correlated with volcanomagnetic signals. If signal exhibits abrupt changes respect with reference station, it is possible to evidence the time instants when the changes occur. So not only the residuals could give information about magnetic anomalies but also the filter parameter variations would enhance the ability to detect the occurrence of local phenomena. Any local effect to the site should be evidenced as an increasing of residual and a rapid variation of filter parameters connected with fluctuations related to internal dynamics of the sites. The vectorial non-stationary technique is particularly suitable in a real time monitoring system, given the low computational cost. Further, since the filter parameter are update at each step, as new data are available, it does not require a previous data set over which the filter parameters have to be estimated. This method was especially effective in reducing the residuals associated with diurnal variations, thus advancing the detecting volcanomagnetic events that may be indicators of ongoing dynamic processes also during times of apparent rest.

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Table 1 Correlation coefficients between total magnetic field from Mt. Etna array and total magnetic

field at Cesarò during 2010

	BCN	BVD	PDGnord	PDGsud	PDN	CSR
BCN	1,000	0,983	0,988	0,982	0,992	0,981
BVD	0,983	1,000	0,996	0,995	0,994	0,993
PDGnord	0,988	0,996	1,000	0,997	0,996	0,990
PDGsud	0,982	0,995	0,997	1,000	0,997	0,995
PDN	0,992	0,994	0,996	0,997	1,000	0,996
CSR	0,981	0,993	0,990	0,995	0,996	1,000

Table 2 Standard deviations of magnetic stations obtained for differential technique and adaptive

filter.

Filtering Technique	BCN	BVD	PDGnord	PDGsud	PDN
10-minutes means difference	1,770	0,962	1,128	0,784	0,736
Nonstationary Analysis	0,605	0,630	0,666	0,621	0,342
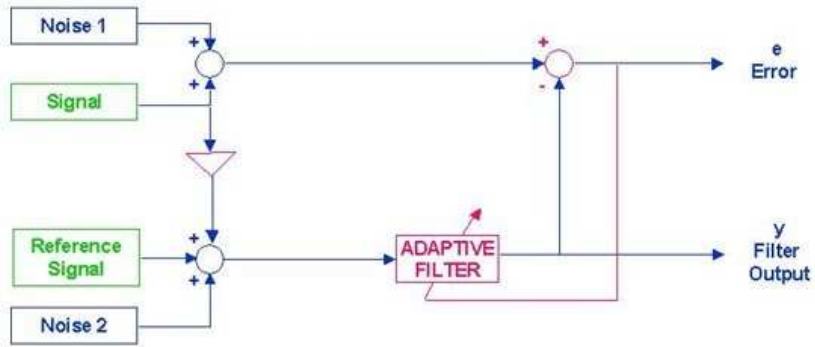
Fig.1 - Adaptive filter structure.

175x102mm (96 x 96 DPI)

Fig.2 - Schematic map of the Etna summit area and locations of magnetic stations. Inset shows the position of the reference stations.

159x135mm (600 x 600 DPI)
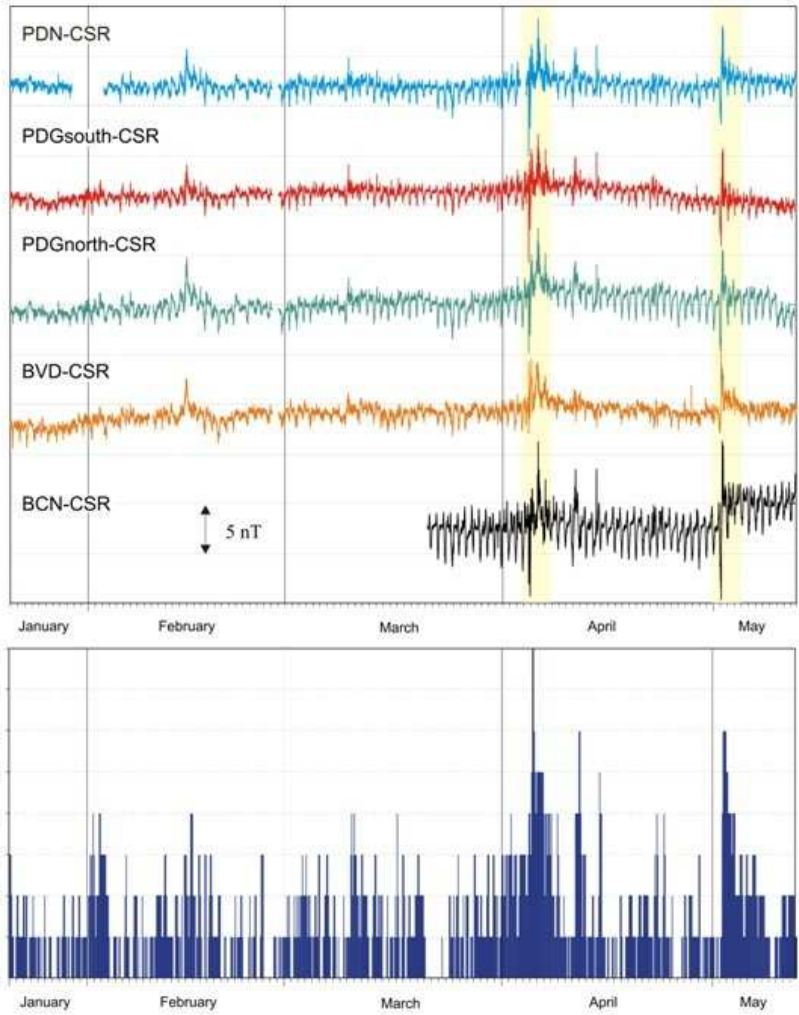
Fig. 3 - 10-minutes mean differences of total magnetic intensity with respect to CSR station from 21 January to 13 May 2010. Geomagnetic storms occurred in April and May are highlighted (top). The local K index values are shown as well (bottom).
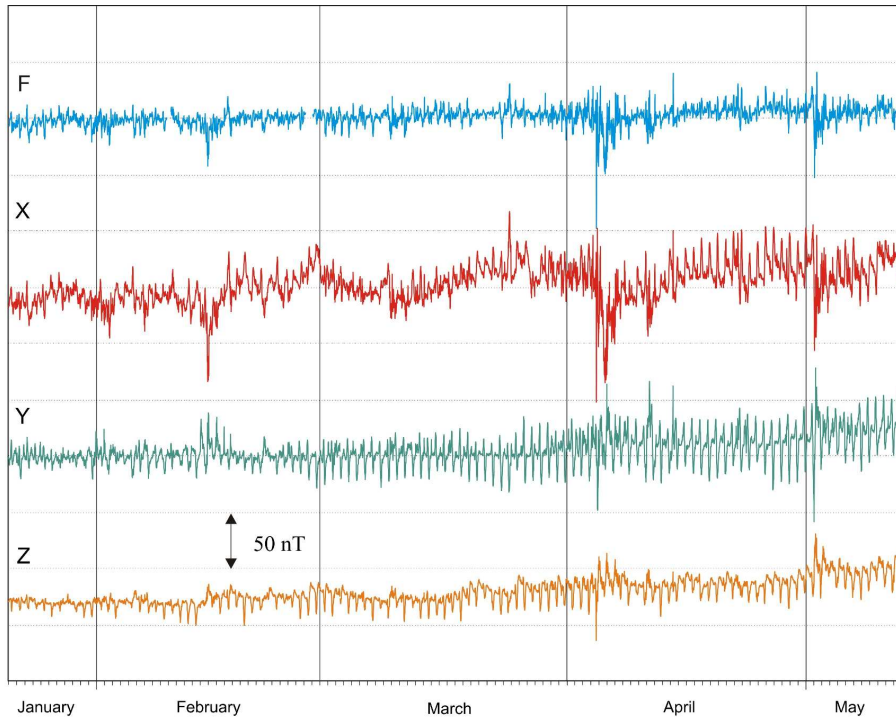
173x210mm (96 x 96 DPI)

Fig. 4 - Total Magnetic field (F) and vector components (X, Y, Z) from CSR and CSRV

reference stations.

159x148mm (600 x 600 DPI)

Fig. 5 - Residual components after adaptive filtering.

159x142mm (600 x 600 DPI)

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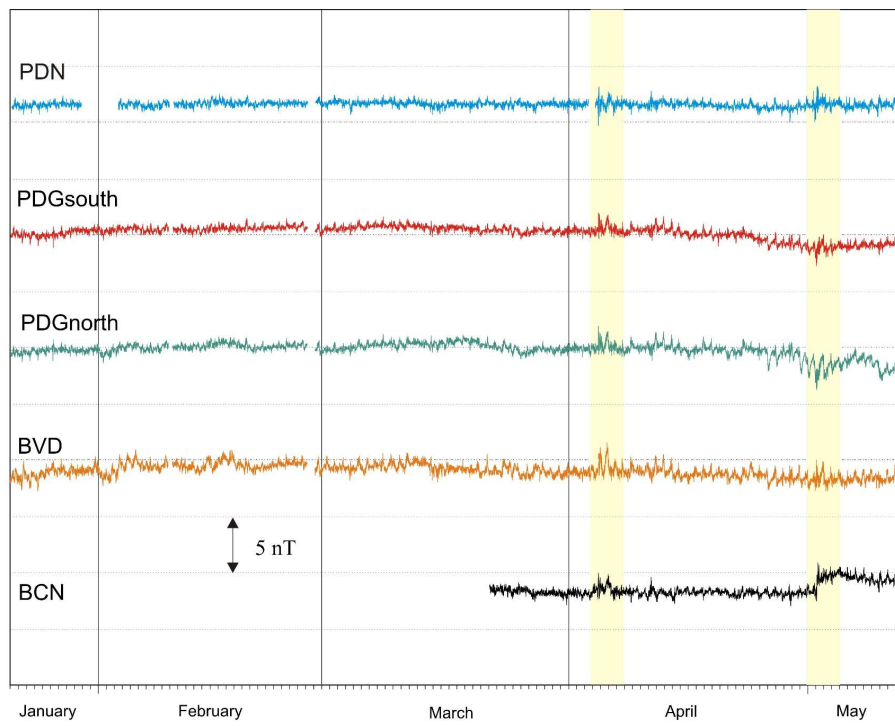49
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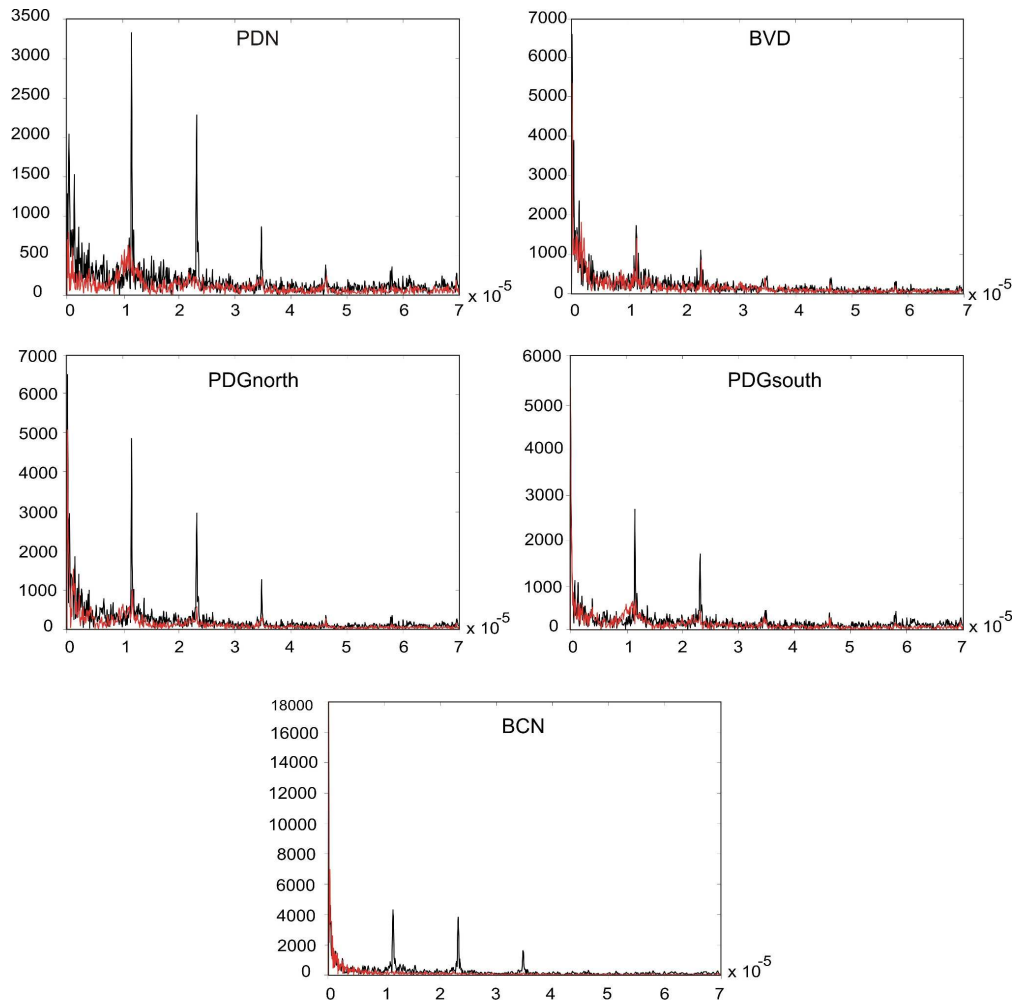51
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Fig. 6 - Power spectrum of the difference field at magnetic stations (black) and the power spectrum of their residual components after filtering (red).

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