MATHEMATICAL TOOLS FOR GEOMAGNETIC DATA MONITORING AND INTERMAGNET RUSSIAN SEGMENT

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ABSTRACT

Principally a new approach to detection of anomalies in geophysical records is connected with a fuzzy mathematics application. The theory of discrete mathematical analysis and collection of algorithms for time series processing constructed on its basis represent results of this research direction. These algorithms are the consequence of fuzzy modeling of logic of an interpreter who visually recognizes anomalies in records. They allow analyzing large data sets that are not yielded to manual processing. Efficiency of these algorithms is demonstrated in several important geophysical applications. Plans on extension of Russian INTERMAGNET segment are presented.

Keywords: Magnetic field, Fuzzy sets, Time series, Magnetic observatory

1 INTRODUCTION

Detection of anomalies in geomagnetic records is a fundamental task of data analysis. Significance of the process represented by such records is often concentrated in these anomalies. Principally a new approach for solving this task is based on fuzzy logic and fuzzy mathematics application (Zadeh, 1965). Mathematical theory of Discrete Mathematical Analysis (DMA) (Gvishiani, Agayan, Bogoutdinov & Soloviev, 2010) and collection of algorithms for time series processing (e.g., Gvishiani, Agayan & Bogoutdinov, 2008; Bogoutdinov, Gvishiani, Agayan, Solovyev & Kihn, 2010; Soloviev, Chulliat, Agayan, Bogoutdinov & Gvishiani, 2011) constructed on the basis of DMA represent the results of this research direction. These algorithms are a consequence of fuzzy modelling of interpreter's logic who visually recognizes anomalies in records. The goal is its further application to automated analysis of large data sets that are not yielded to manual processing. A sufficient "flexibility" of the algorithms is provided by a wide range of "rectifications" that arise in interpreter operation modelling. Efficiency of the algorithms was demonstrated in several important geological, geophysical and geodynamic applications, including global real-time monitoring of magnetic storms (I. Veselovsky, S. Agayan, R. Kulchinskiy, A. Gvishiani, S. Bogoutdinov, V. Petrov et al., 2011), recognition of artificial disturbances in geomagnetic records (Soloviev, Bogoutdinov, Agayan, Gvishiani & Kihn, 2009), monitoring of volcanoes (Zlotnicki, LeMouel, Gvishiani, Agayan, Mikhailov & Bogoutdinov, 2005). Herein we present an overview of several of these successful applications dealing with magnetic field studies.

The largest global network of on-ground magnetic observations is International Real-time Magnetic Observatory Network (INTERMAGNET) (Love, 2008). The network consists of more than 110 observatories, however only 5 of them are located on the territory of Russia. Geophysical Center of Russian Academy of Sciences (GC RAS) has elaborated a plan on extension of Russian INTERMAGNET segment (Soloviev, 2011). In particular, five new INTERMAGNET observatories in Russia are being deployed by joint efforts of GC RAS and institutions of regional RAS branches. A regional geomagnetic data node of the Russian INTERMAGNET segment is being created on the basis of Russian WDC for Solar-Terrestrial Physics at GC RAS. A particular feature of this node is an automated system for recognition of artificial disturbances in incoming preliminary magnetograms, which is being introduced.

2 FUZZY MEASURE OF ACTIVITY AND MAGNETIC STORM MONITORING

A geomagnetic field is subjected to fluctuations of different time scales. In order to describe magnetic activity in the planetary scale the following geomagnetic indices were established: 24-hour Ci-index, 3-hour Kp-index, 1-hour indices Dst, AE and others (http://www.ngdc.noaa.gov/IAGA/vdat/). The principal idea of these indices is to give equal estimation of relative strength of disturbances at various observatories. However, more detailed study of the morphology of geomagnetic disturbances and their sources has shown that various indices of geomagnetic activity used nowadays express geomagnetic field activity not on the whole Earth surface but in its separate regions.

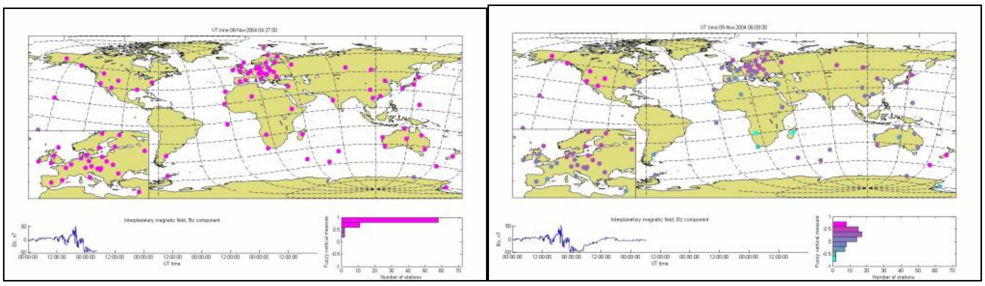
For studying dynamics of geomagnetic disturbances during a storm, it's not enough to use just several standard geomagnetic indices (for example, Cp, AE, Dst, *etc*.). In the process of solar-terrestrial phenomena studies the necessity of simultaneous determination of strength of geomagnetic disturbances at a maximum number of observatories across the Globe has arisen. By now, the largest global network of geomagnetic field observations is INTERMAGNET (Love, 2008). Such a necessity demands an introduction of new parameters independent of geomagnetic latitudes and longitudes.

Performing such kind of analysis by an expert manually is very difficult due to large volume of data involved. To solve this task a new geoinformatics approach based on fuzzy logic methods (Zadeh, 1965) is suggested. In particular we apply algorithm FCARS (Fuzzy Comparison Algorithm for Recognition of Signals) (Gvishiani et al., 2008) constructed on the basis of DMA (Gvishiani et al., 2010). Application of DMA enables processing and studying multidimensional arrays and time series.

FCARS algorithm allows the introduction of a measure of geomagnetic activity $\mu(t)$, which estimates geomagnetic activity at each particular time moment at particular geomagnetic record individually. It gives an estimation in a scale [-1, 1], where value -1 corresponds to a calm state and value 1 corresponds to an anomalous state. Testing the measure on magnetograms obtained from several INTERMAGNET observatories showed its high correlation with regional K-index of geomagnetic activity.

By applying measure $\mu(t)$ to the whole set of magnetograms obtained by all observatories (e.g., INTERMAGNET network) we can have a snapshot of a storm distribution over the Earth's surface at each time moment. In the case of INTERMAGNET data, such picture changes with a time step of 1 minute. To visualize measure $\mu(t)$ operation we use GIS technology. Thus, the proposed method for geomagnetic activity monitoring provides a new way of studying dynamics of spreading geomagnetic disturbances. It allows the performance of geomagnetic activity monitoring in real time mode.

The proposed toolkit was tested on two strong geomagnetic storms observed during the 23-rd solar cycle. In the first case a complicated storm on 8-11 November 2004 consisting of two parts was considered. In the second case an isolated storm on 15 May 2005 was considered. Before applying the method the selected storms were studied in details in order to investigate their common and specific features. This study involved INTERMAGNET data, D_{xt}-index values (corrected version of D_{st}) (Mursula, Holappa & Karinen, 2008), parameters of solar wind and interplanetary magnetic field and data on solar events. Figure 1 illustrates the toolkit application to the first storm monitoring at several time moments.



(a) (b)

$-1<\mu(t)\le -0.8$ $-0.1<\mu(t)\le 0.1$ $0.8<\mu(t)\le 1.0$

Figure 1. Global monitoring of the first storm in real time basing on INTERMAGNET data (*H* component). Two screenshots correspond to the toolkit operation at two different UT time moments: 8/11/2004 04:27 (a) and 9/11/2004 06:09 (b).

The toolkit visualizes distribution of anomality parameter μ(t) over the whole set of INTERMAGNET observatories in animation mode on a global map (Figure 1). Below on the right a dynamic histogram, which reflects distribution of INTERMANGET observatories according to different values of μ(t) from -1 (no anomaly) to 1 (strong anomaly) for each time moment, is given. Below on the left there is a dynamic plot of B_z component of interplanetary magnetic field, which evolves correspondingly. A clear conformity between the histogram of observed anomality and B_z behavior can be seen.

The result showed that global, regional and local features of the storms have common and individual particularities depending on external stimulating conditions in heliosphere and on the Sun. Based on the analysis of dynamic distribution of geomagnetic disturbances it was shown that the ring current is not always the main contributor to the equatorial geomagnetic perturbations during the development and the main phase of strong geomagnetic storms. This led to a conclusion that the proposed approach gives a more objective and prompt estimation of geomagnetic activity than a number of classical indices.

3 DE-SPIKING 1-MINUTE AND 1-SECOND MAGNETIC DATA

Each year data experts at observatories and data centers carry out manual processing and filtering of collected preliminary data sets. The aim of such work is to produce definitive data and make it available to the scientific community worldwide. Despite close cooperation between observatories, approaches to data processing may differ and depend on subjectivity of this or that expert's evaluation. In this connection a mathematical formalization of recognition of artificial disturbances could contribute to significant increase of definitive data quality (Soloviev et al., 2009). In turn, an increase of observed data quality contributes significantly to our knowledge about the Earth's magnetic field.

An important step towards such a mathematical formalization was undertaken by Bogoutdinov et al. (2010). The proposed algorithm SP was applied to recognition of artificial spikes (Figure 2) on magnetograms recorded with 1-minute sampling rate. Since the algorithm operation is adjusted by a set of free parameters, it was first learnt based on 1-year preliminary records of the three components and total field intensity obtained in 2008 by seven INTERMAGNET observatories located in different parts of the Northern hemisphere. Then a learnt algorithm was applied to other 1-year preliminary records of the three components and total field intensity obtained in 2009 by the same observatories. Further, it was applied to 2-year preliminary records from the same observatories obtained during increased solar activity period in 2003 and 2005. In all the cases probability of a target miss was between 0% and 1%, whereas probability of a false alarm varied between 5% and 15%. The probabilities were calculated by comparing the algorithm results with definitive data filtered manually for the same time intervals.

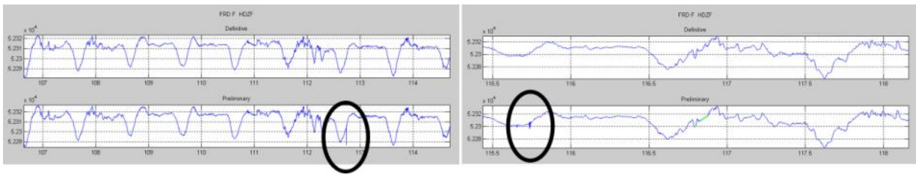


Figure 2. Spikes in 1-minute preliminary data (lower plots) removed manually while producing definitive data (upper plots).

Many observatories now modernize their equipment in order to be able to produce 1-second filtered data. While at many observatories the 1-second data cleaning represents a reasonable amount of work, it becomes a daunting task at some observatories, particularly those installed in remote but important locations where no optimal observatory site could be found. In this case the situation is burdened with increase of data volume (86400 values per record per day comparing to 1440 in 1-minute case) and appearance of short-period geomagnetic pulsations similar to artificial spikes and unseen in 1-minute records. Therefore often automated de-spiking tools are much more demanded in the case of 1-second data acquisition.

For that purpose Soloviev et al. (2011) developed SPs algorithm, which is a modified version of SP algorithm, aimed at recognition of artificial spikes on 1-second magnetograms. As in the case of SP algorithm, the algorithm SPs was first learnt basing on 20-day (1-20/07/2009) preliminary records and then examined basing on 10-day (21-31/07/2009) records obtained by magnetic observatory in Easter Island maintained by IPGP, France. The algorithm efficiency was estimated by comparing the results of automated preliminary data processing with definitive data for the same time spans. After that it was applied to other 30-day (1-31/08/2009) records with no definitive data available. The results of the recognition by the algorithm SPs were subsequently evaluated by eye. After a 20-day learning phase in July 2009 the algorithm was able to recognize more than 94% of the spikes on the three components and the intensity recordings in August 2009, while the percentage of false alarms was less than 6%. At all the stages the algorithm showed worse results in processing vertical component *Z*.

4 INTERMAGNET RUSSIAN SEGMENT

Currently Russian participation in INTERMAGNET program is confined to five observatories, which report preliminary data to geomagnetic information nodes (GINs) in Paris (France) and Edinburgh (UK). A weak development of INTERMAGNET network in Russia and an absence of national GIN induced GC RAS to elaborate a plan on extension of Russian INTERMAGNET segment (Soloviev, 2011). In particular, five sets of geomagnetic equipment compliant with INTERMAGNET standards are ready to be installed in different parts of Russia. Since a network of geomagnetic observations was widely developed in the Soviet Union during the International Geophysical Year in 1957-1958, numerous existing observatories ruled by RAS institutions are considered as possible sites for installing new equipment. These sites include Syktyvkar (Komi Republic), St. Petersburg, Rotkovets (Arkhangelsk region), Novaya Zemlya Islands, Tiksi and others. Apparently, deploying new observatories in auroral zone is of the highest priority in space physics community. However, the major obstacle, which prevents that, is a lack of personnel capable to operate observatories in such locations. In this regard, only those places where the operation of observatories is feasible are considered.

Another goal in the framework of extension of Russian INTERMAGNET segment is creation of a national geomagnetic data node at GC RAS servicing Russian INTERMAGNET observatories. A transmission of magnetograms from functioning and future Russian INTERMAGNET observatories to GC RAS will be performed in a real-time mode. A particular feature of this node is an automated system for data quality control, which involves SP and SPs algorithms, applicable to incoming preliminary magnetograms.

5 CONCLUSION

A new way of study of dynamics of geomagnetic disturbances spreading is presented in the paper. It is based on fuzzy mathematics and GIS technology and involves data of the whole INTERMAGNET network. The measure of geomagnetic activity $\mu(t)$ is computed according to FCARS algorithm and allows magnetic storms too be followed in real time mode. FCARS algorithm also serves as a basis of an automated system for processing electrotelluric and electromagnetic observations in the framework of the Russian-French project of monitoring volcanic activity on Reunion Island and in Kamchatka.

Application of the measure $\mu(t)$ to selected INTERMAGNET records has shown its high correlation with regional K-index of geomagnetic activity. The proposed method for geomagnetic activity monitoring was tested on two strong geomagnetic storms. Based on the analysis performed it was shown that the ring current is not always the main contributor to the equatorial geomagnetic perturbations during the development and the main phase of strong geomagnetic storms. This led to a conclusion that the proposed approach gives a more objective and prompt estimation of geomagnetic activity than a number of classical indices. Basing on the analysis it can be concluded that geomagnetic proxies could also serve as an important source of indirect information about solar and heliospheric activity in the past, when direct observations were not available.

The algorithms SP and SPs based on DMA are specifically aimed at recognition of singular artificial spikes with a simple morphology on 1-minute and 1-second magnetograms. The algorithms rely on fuzzy mathematics principles. It was shown that after a learning phase these algorithms are able to recognize artificial disturbances efficiently and distinguish them from natural ones, such as short-period geomagnetic pulsations in the 1s-1min period range. This capability is critical and opens the possibility to use the algorithms in an operational environment. The algorithms were tested on real magnetic data. Small probability values for target miss and false alarm were obtained.
Knowledge of experts who carry out geomagnetic data analysis manually is effectively incorporated into all the developed algorithms at the stage of their learning.

Five new INTERMAGNET observatories in Russia are being deployed by joint efforts of GC RAS and institutions of regional RAS branches. A regional geomagnetic data node of the Russian INTERMAGNET segment is being created on the basis of Russian WDC for Solar-Terrestrial Physics at GC RAS. An automated quality control system for on-the-fly processing of incoming magnetograms can significantly facilitate and hasten transformation of geomagnetic preliminary data into definitive data.

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7 REFERENCES

Bogoutdinov, S.R., Gvishiani, A.D., Agayan, S.M., Solovyev, A.A. & Kihn, E. (2010) Recognition of Disturbances with Specified Morphology in Time Series. Part 1: Spikes on Magnetograms of the Worldwide INTERMAGNET Network, *Izvestiya, Physics of the Solid Earth*, Vol. 46, 11, 1004–1016.

Gvishiani, A.D., Agayan, S.M. & Bogoutdinov Sh.R. (2008) Fuzzy recognition of anomalies in time series, *Dokl. Earth Sci.*, 421(5), 838-842.

Gvishiani, A.D., Agayan, S.M., Bogoutdinov, S.R. & Soloviev, A.A. (2010) Discrete mathematical analysis and geological and geophysical applications, *Vestnik KRAUNZ. Earth Sciences*, 2, Vol. 16, 109-125 (in Russian).

Love, J.J. (2008) Magnetic monitoring of Earth and space, *Physics Today*, 61, 31-37.

Mursula, K., Holappa, L. & Karinen, A. (2008) Correct normalization of the Dst index, *Astrophys. Space Sci. Trans*., 4, 41–45.

Soloviev, A.A., Bogoutdinov, Sh.R., Agayan, S.M., Gvishiani, A.D. & Kihn, E. (2009) Detection of hardware failures at INTERMAGNET observatories: application of artificial intelligence techniques to geomagnetic records study, *Russ. J. Earth Sci.*, 11, ES2006, doi:10.2205/2009ES000387.

Soloviev, A. (2011), Artificial intelligence in the Earth’s magnetic field study and INTERMAGNET Russian Segment, *ICSU CODATA Newsletter*, 100, p. 4.

Soloviev, A., Chulliat, A., Agayan, S., Bogoutdinov, S. & Gvishiani, A. (2011) Automated system for recognition of artificial spikes on 1-minute and 1-second magnetograms (#1170), *XXV IUGG General Assembly “Earth on the Edge: Science for a Sustainable Planet” (28 June - 7 July 2011, Melbourne, Australia), Program Book and Abstracts*.

Veselovsky, I., Agayan, S., Kulchinskiy, R., Gvishiani, A., Bogoutdinov, S., Petrov V. & Yakovchouk, O. (2011) Global, regional and local dynamics of strong geomagnetic storms (#5313), *XXV IUGG General Assembly “Earth on the Edge: Science for a Sustainable Planet” (28 June - 7 July 2011, Melbourne, Australia), Program Book and Abstracts*.

Zadeh, L.A. (1965), Fuzzy sets, *Inf. Control.*, 8, 338-353.

Zlotnicki, J., LeMouel, J.-L., Gvishiani, A., Agayan, S., Mikhailov, V. & Bogoutdinov, Sh. (2005) Automatic fuzzy-logic recognition of anomalous activity on long geophysical records. Application to electric signals associated with the volcanic activity of la Fournaise volcano (Réunion Island), *Earth and Planetary Science Letters*, 234, 261-278.