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Implementation of the ground level enhancement alert software at NMDB database

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ABSTRACT

The European Commission is supporting the real-time database for high-resolution neutron monitor measurements (NMDB) as an e-Infrastructures project in the Seventh Framework Programme in the Capacities section. The realization of the NMDB will provide the opportunity for several applications most of which will be implemented in real-time. An important application will be the establishment of an Alert signal when dangerous solar particle events are heading to the Earth, resulting into a ground level enhancement (GLE) registered by neutron monitors (NMs). The cosmic ray community has been occupied with the question of establishing such an Alert for many years and recently several groups succeeded in creating a proper algorithm capable of detecting space weather threats in an off-line mode. A lot of original work has been done to this direction and every group working in this field performed routine runs for all GLE cases, resulting into statistical analyses of GLE events. The next step was to make this algorithm as accurate as possible and most importantly, working in real-time. This was achieved when, during the last GLE observed so far, a real-time GLE Alert signal was produced. In this work, the steps of this procedure as well as the functionality of this algorithm for both the scientific community and users are being discussed. Nevertheless, the transition of the Alert algorithm to the NMDB is also being discussed.

1. Introduction

Solar energetic particles (SEPs) are a manifestation of violent energy release processes occurring at the solar atmosphere, such as powerful solar flares and significant coronal mass ejections having intermediate energies ranging from 10 keV/nucl to GeV. The observations of such events may provide fundamental information on the origin, the acceleration mechanisms and the propagation processes of such particles at the Sun and the corresponding interplanetary space shocks. These dynamic processes reaching the Earth cause geomagnetic storms, heating of the upper atmosphere, changes of the electrodynamic properties of the ionosphere, and creation of the geomagnetically induced currents on the Earth surface. All these conditions of space weather change dramatically with Solar Extreme Events (SEE) development, influenced the reliability of space-born and ground-based technology systems, and endanger human health and life as well. It is of major importance to elaborate reliable methods for monitoring and forecasting dangerous space weather phenomena and to define the mechanisms of various effects. Neutron monitors and muon detectors record secondary cosmic rays created by interactions of >0.5 GeV primary cosmic rays with Earth's atmosphere. During a typical SEP event the particle flux increases up to 10–100 MeV energy range, which is insufficient to produce detection in ground level detectors. On the other hand, the most extreme SEP events provide a significant signature at ground based monitors and are defined as sudden, strong and quick enhancements in the cosmic radiation, the ground level enhancements (Fig. 1). Due to the fact that the time needed for the propagation of such SEPs (extreme and hazardous SEP events) from the Sun to the Earth depends on the energy,

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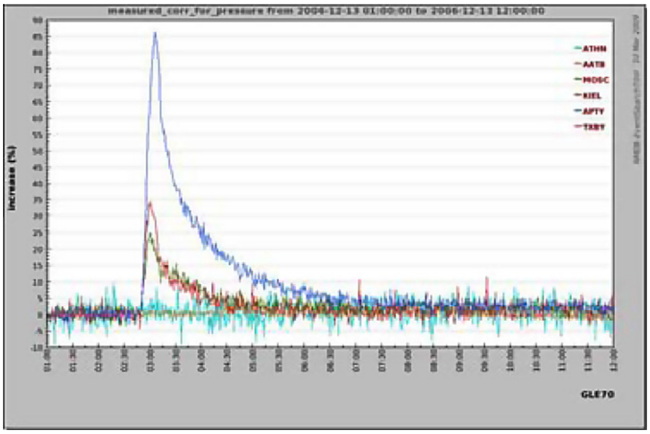

Fig. 1. GLE70 illustrated by the online user tool of NMDB; credit OBSPARIS – N. Fuller.

charged particles reaching the Earth will be recorded by NMs earlier than low-energy protons which are registered on board satellites. In addition, at higher energies the time needed in order to reach the maxima of the flux is also much shorter. Thus, GLE observations from ground based monitors make it possible to establish a warning signal on the arrival of extreme SEP events, earlier than methods based upon lower energy charged particles (Dorman and Zukerman, 2003).

2. The NMDB co-operation

The real-time database for high-resolution neutron monitor measurements (NMDB) project (www.nmdb.eu) stands for the co operation of twelve different countries within the Seventh Framework Programme of the European Commission, with the scope to create a real-time database with high resolution data (Steigies et al., 2007; Steigies, 2008). A European digital repository for cosmic ray data by pooling existing data archives and by developing a real-time database collecting observational results in the highest time resolution from as many NM stations as possible operated by European and some neighbouring countries has been set up. The central database comprises all neutron monitor data acquired in the last 50 years and new continuously updated observations from 23 NMs with 1-min and 1-h resolution, operated by the institutes that constitute the present proposal. The project will also develop some applications of the database to Space Weather tasks (Butikofer and Fluckiger, 2009; Mavromichalaki et al., 2010), e.g. estimation of radiation doses, atmosphere's ionization (Bazilevskaya et al., 2008; Usoskin et al., 2009), monitoring of the predictors of interplanetary disturbances hitting the Earth and so on.

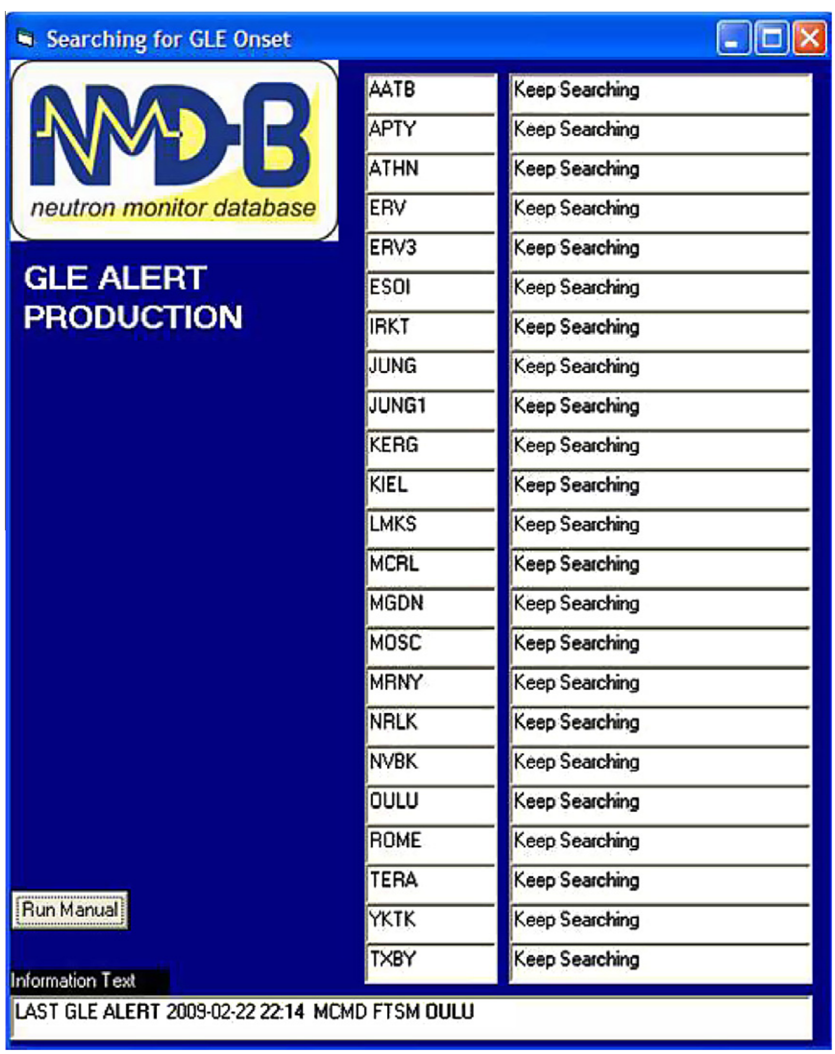

Fig. 2. GLE Alert executable searching for general GLE Alert in order to issue an alarm signal.

3. GLE Alert production

Several groups (National and Kapodistrian University of Athens-NKUA, Russian Institute of Terrestrial-Magnetism Ionosphere and Radiowave Propagation after Pushkov-IZMIRAN, Tel-Aviv University – TAU, Kazakhstan's Institute of Ionosphere – ALMATY) participating in the NMDB project run various GLE Alert functions, which does not vary in principle (Bostanyan et al., 2001; Dorman, 2004, 2005a,b; Gevorgyan et al., 2005; Belov et al., 2009; Vashenyuk et al., 2007; Souvatzoglou et al., 2009). Within the cooperation of NMDB, these groups work together to provide the best possible Alert system. The basic idea of the Alert software stands upon the fact that early detection of an Earth-directed cosmic ray event by NMs provides a good chance of preventive monitoring SEP-flux rise leading to an Alert with very low probability of false alarm (Dorman and Zukerman, 2003; Belov et al., 2009; Souvatzoglou et al., 2009). The cosmic ray-flux in the energy range above 500 MeV/nucleon cannot be recorded by satellites with enough accuracy because of their small detecting area. However, it can be measured by ground-based NMs with high statistical accuracy (on average 0.5% for 5 min). In this work the description of the NKUA GLE Alert algorithm will be provided (Mariatos et al., 2005; Souvatzoglou et al., 2009). Together with the transition of this particular code to the NMDB project. The algorithm is being divided into a three steps procedure.

4. Steps of the GLE Alert

In order to monitor GLE evolution and to generate an Alert it is necessary to have NM data with 1-min resolution updated every 1-min in real-time. The algorithm includes three sub-steps.

4.1. The down loaders

One minute NM data, corrected for pressure, from all the available stations are being gathered in real time. For every station there is a unique downloader algorithm nested at the central database. This program requests data from the remote station every 1 min, downloads those at the database and checks their validity.

4.2. Station GLE Alert

The analysis of the GLE Alert is being performed by software called: [*station*] – *GLE* – *alert.exe*. This program, calculates, every minute, in real time the mean value of the previous 60 minutely measurements and the value of the standard deviation. Using these two parameters a moving threshold for every single station is being defined, every minute. The formula that is being used is:

$$I_{\text{threshold}} = I_{\text{mean}} + n * \sigma,$$

where $I_{\text{threshold}}$ is the final value of the threshold for the next minute, I_{mean} is the mean value of the counting rate, σ is the standard deviation of the counting rate and n is a value of the threshold multiplier varying from 1 to 3. This number is unique for every single station and stands as the condition of maximum number of true alerts to the minimum number of false. It has been defined by treatment on every station's data for the past seven years of GLE alerts (for details see Mavromichalaki, 2009 and references within).

Variable threshold level is set for the cosmic ray intensity increase and can be different among NM stations. If the last measurement exceeds the moving threshold the program ([*station*] – *GLE* – *alert.exe*) marks a so called *pre-alertpoint*. If three *pre-alertpoints* are being registered in succession a **Station Alert** is stated. This means that the specific station is recording a sudden increase at cosmic ray intensity.

4.3. General GLE Alert

Another program, called: *check* – *for* – *alert.exe* (Fig. 2), supervises the **Station Alerts**. If the number of indicated **Station Alerts** exceeds the value of three, a **General GLE Alert** is being generated. The GLE Alert algorithm is actually a system that uses four running states: Quiet, Watch, Warning and Alert. Most of the time, the system is running at the Quiet mode. When the first Station Alert appears the system switches to Watch mode. A timer, set to 15 min, is automatically set in the initiation of this mode. The system awaits at this point another Station Alert from a different station. When the second Station Alert is recorded, the system enters the Warning mode. Finally if a third station enters a Station Alert mode, then the system generates an Alert signal (for details see Souvatzoglou et al., 2009 and references within).

4.4. The kernel of the GLE algorithm

The kernel of the GLE Alert algorithm is being presented in Fig. 3. Every one minute the program receives as input one new count. According to the algorithm this value is compared with the threshold. A file named *level* – *file.txt* is being created and it is updated according to the result of the comparison. Another variable *J* is being introduced. *J* increases *if* a pre-alert point is registered or *else* it returns to zero. When *J* is equal to three a local **Station Alert** is produced (for details see Section 4.2). This state triggers a 15 min time window and initiates a search at other stations data. This aims at the identification of the conditions of every station. In case the number of stations reaching a **Station Alert**-mode is greater than three a **General GLE Alert** is being produced (for details see Section 4.3). The entire algorithm is being executed every minute from the initiation point.

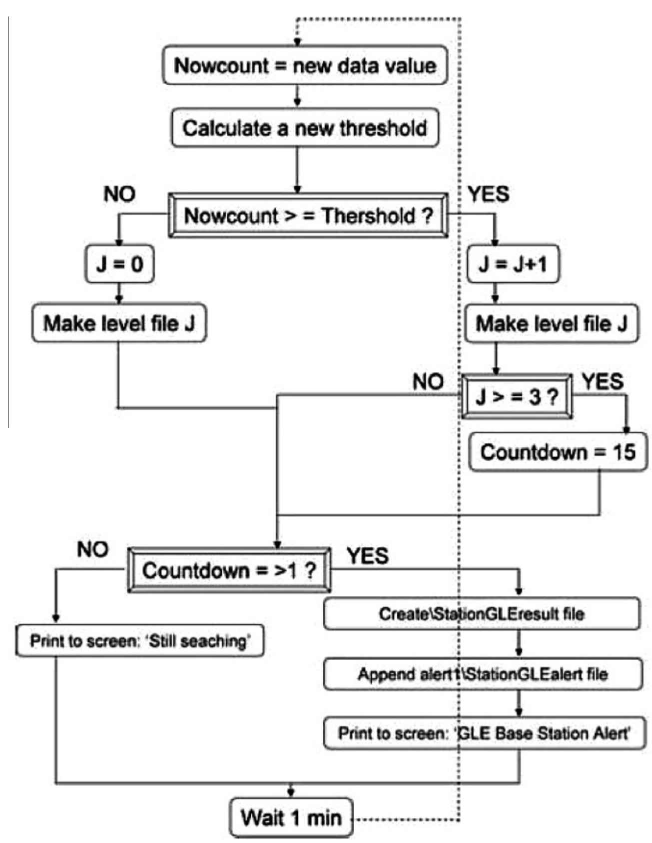

Fig. 3. Flowchart of the Alert algorithm.

Table 1
Comparison of the GLE Alert of ground based measurements to the recorded initiation times by satellite proton data.

GLE no.	Event date	Flare time (UT)	Flare	GOES Alert (100 MeV > 1 pfu)	NM stations Alert
60	15 April 2001	13:19	X14.4	14:21	13:59
61	18 April 2001	02:11	C2	03:11	02:43
62	04 November 2001	16:03	C2	17:07	16:50
63	26 December 2001	04:32	C2	06:14	06:07
64	24 August 2002	00:49	X3.1	01:48	01:35
65	28 October 2003	09:51	X17.2	11:51	11:17
66	29 October 2003	20:37	X10.0	—	21:08
67	2 November 2003	17:03	X8.3	17:56	17:39
68	17 January 2005	–	–	–	NO GLE
69	20 January 2005	06:35	X7.l	07:04	06:52
70	13 December 2006	02:48	X3.4	03:12	02:53

Table 2
NM stations contributing to the statistical analysis of the GLE Alert.

Stations	Abbrev.	Lat (°)	Long (°)	Alt (m)	H_0 (mb)	R_C (GV)
Almaty	AATA	43.25	76.92	806	938.00	6.66
Apatity	APTY	67.55	33.33	177	1000.00	0.65
Barentsburg	BRBG	78.12	14.42	0	1013.00	0.20
Erevan	ERVN	40.17	44.25	2000	800.00	7.60
Fort Smith	FTSM	60.00	−112.00	0	996.10	0.30
Inuvik	INVK	68.35	−133.72	21	1019.10	0.14
Irkutsk	IRKT	52.47	10.13	435	965.00	3.65
Kiel	KIEL	54.33	104.03	54	1007.00	2.29
McMurdo	MCMD	−77.85	166.72	48	985.10	0.00
Moscow	MOSC	55.47	37.32	200	1000.00	2.46
Nain	NAIN	56.50	61.70	46	1000.00	0.40
Newark	NWRK	39.68	−75.75	50	1013.00	1.97
Norilsk	NRLK	69.26	88.05	0	1005.00	0.63
Oulu	OULU	65.02	25.50	0	1000.00	0.81
Peawanuck	PWNK	54.98	−85.44	0	1000.00	0.50
South Pole	SOPO	−90.00	0.00	2820	680.00	0.11
Tixie Bay	TXBY	71.61	128.90	0	1000.00	0.53
Thule	THUL	76.50	−68.70	260	1005.00	0.10
Athens	ATHN	37.97	23.72	40	1000	8.53

5. GLE Alert validation

In order to validate the accuracy of the GLE Alert algorithm, which has been described in the above section an off-line statistical analysis was performed. This actually states a number of simulation *runs* over all actual GLE events that has been recorded from 2001 to 2006. A total of 19 NM stations have been used for the analysis (Table 2). The goal was twofold: (a) reliability of the GLE algorithm and (b) comparison of the GLE Alert originating from NM measurements to the Alert originating from satellites measurements. Regarding (a), 10 out of 11 GLEs were recorded by the algorithm (Table 1) and a GLE Alert signal was produced at all these cases. At this point, it is important to note that GLE68 could not be detected either from the GLE algorithm or from GOES satellites. This is the reason why this case constitutes exclusion for the analysis. The evaluation of the GLE Alert system has been performed by comparison of the time alert signals established from the application to the actual initiation times announced by NOAA. The results of this off-line analysis are being presented in Table 1 (Mavromichalaki, 2009). As can be obtained from Table 1 the GLE Alert which depends solely on ground based observations precedes the one triggered by GOES at a time window of 7–34 min. There is also a single case (GLE66) where the NM GLE algorithm issues an Alert while satellite data did not. More details regarding the algorithm can be found at Souvatzoglou et al. (2009).

6. Transition to NMDB

The implementation of the GLE algorithm and the co-operation among several groups, over the years, revealed some of the drawbacks regarding the use of NMs. NMDB project, provided the unique chance to overcome problems of the past. In order to make proper use of the GLE algorithm all NM stations had to provide data of the same format in real-time. When this goal was achieved within NMDB, the next step was to make the transition of the algorithm to the necessities of the new real-time database. This was accomplished later on and an on-line tool was added at the NMDB website (www.nmdb.eu) under the node: http://www.nmdb.eu/?q=node/19. It provides a real-time monitoring of current interplanetary conditions as being registered at 23 NM stations participating at NMDB project (Table 3).

Table 3
NMDB stations contributing to GLE Alert on-line.

Almaaty	Jungfraujoch, NM64	Norilsk
Apatity	Kerguelen	Novosibirsk
Athens	Kiel	Oulu
Aragats	Lomnicky stit	Rome
Nor-Amberd	Mobile Cr lab	Terre Adelie
Irkutsk	Magadan	Tixie Bay
Mt. Hennon	Moscow	Yakutsk
Jungfraujoch IGY	Mirny	

7. Conclusions

Today the impact of space science on every day life is very important. Communication, space satellites, air travels at high altitudes, power supply factories and many other daily activities depend on space conditions. Thus those activities constitute a user community for neutron monitor data. NMDB's prime aim was the construction of one easy to use database. In order to do so, all neutron monitors that take part in this effort were updated with the technological advantages of our days. NMDB promotes the usage of applications such as GLE Alert algorithm which will be of major help for the understanding of space environment and for the protection of people and systems that depend on space technology. The idea and several steps of GLE algorithm have been described in the present work. At this point GLE Alert algorithm stands as an operative user tool operating on-line through NMDB website (www.nmdb.eu).

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