Available online at www.sciencedirect.com
ScienceDirect
Advances in Space Research 43 (2009) 728–734
ADVANCES IN SPACE RESEARCH
(a COSPAR publication)
www.elsevier.com/locate/asr

Real-time GLE alert in the ANMODAP Center for December 13, 2006

G. Souvatzoglou [a], H. Mavromichalaki [a,*], C. Sarlanis [a], G. Mariatos [a],
A. Belov [b], E. Eroshenko [b], V. Yanke [b]

[a] *Nuclear and Particle Physics Section, Physics Department, Athens University Pan/polis-Zografos 15771 Athens, Greece*
[b] *Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN), 42092 Troitsk, Moscow Region, Russia*

Received 29 December 2007; received in revised form 8 July 2008; accepted 26 September 2008

Abstract

Within the last years, a real-time system to monitor high energy cosmic rays for space weather use has been operated at Athens cosmic ray station. Neutron monitors and satellite high resolution data in real time are used, making it possible to observe cosmic rays in dual energy range observations. In large solar energetic particle (SEP) events, ground level enhancement (GLE) can provide the earliest alert for the onset of the SEP event. This system watches for count rate increases recorded in real time by 23 neutron monitors, which triggers an alarm if a ground level enhancement (GLE) of cosmic ray intensity is detected.

Our effort is to determine optimal strategies for detecting the GLE event at a very early stage, while still keeping the false alarm rate at a very low level. We have studied past events to optimize appropriate intensity threshold values and a baseline to determine the intensity increase. We define three levels of alarm (watch, warning and alert) on the basis of the number of stations that record a significant intensity increase. For every station there is a program which every minute calculates in real time the mean value of the last sixty minutely measurements and compares this value with a threshold. If we have five pre-alert points in succession, we define a Station Alert. If we see at least three stations in station alert mode, another program provides a General GLE Alert. A statistical analysis on the last ten GLEs recorded from 2001 till 2006 using 1-min data from our database, produced GLE alarms for nine events in our system. Alarm times for these nine events are compared with satellite data separating if the event is GLE or magnetospheric one. The GLE alert precedes the earliest alert from GOES (100 MeV or 10 MeV protons) by 4–33 min. When the alert is final then an automated e-mail is sent to all the interested users.

An alert signal was established at December 13, 2006 by the ANMODAP Center and for first time an automated e-mail alarm signal was sent out by our system determining the onset of the GLE70 event. A detailed analysis of this alert is discussed.

Keywords: Ground level enhancement; Neutron monitor network; Space Weather; GLE alert system

1. Introduction

Neutron monitors and muon detectors record secondary cosmic rays created by interactions of >1 GeV primary cosmic rays (predominantly protons and heavier nuclei) with Earth's atmosphere. With suitable analysis, ground-based detectors can yield unique information on conditions in the near-Earth interplanetary medium. Neutron monitors can also detect the most energetic solar energetic particle (SEP) events. SEPs that propagate to Earth can cause damage to satellite electronics, and can pose a radiation hazard to astronauts and air crews. In a typical SEP event, the particle flux increases in the 10–100 MeV energy range, but these energies are insufficient to produce an ejecta in ground level detectors. However, in the most extreme SEP events, the particle flux increases at energies >500 MeV, and these can be detected by ground-based neutron monitors as a ground level enhancement (GLE). Because the time propagation of SEPs from Sun to Earth depends on the energy, charged particles the Earth reached

---

[*] Corresponding author.
E-mail addresses: emavromi@phys.uoa.gr (H. Mavromichalaki), abelov@izmiran.rssi.ru (A. Belov).

0273-1177/$34.00 © 2008 COSPAR. Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.asr.2008.09.018

will be recorded by neutron monitors usually earlier than low-energy proton flux on the satellites. Furthermore, at higher energy the time to reach maximum intensity is also shorter. Consequently, GLE observations make it possible to warn of the arrival of SEP event earlier than methods based upon lower energy charged particles (Dorman et al., 2003).

Moreover, ground level observations (neutron monitors, neutron telescope and muon telescope) are the only way to identify the occurrence of SEP event on the ground, and would be valuable even if satellite data were not readily available. The University of Delaware provides real-time displays of the cosmic ray intensity of several ground-based neutron monitors with good statistics and 1-min time resolution (Bartol Research Institute at the University of Delaware, http://neutronm.bartol.udel.edu/spaceweather). This article describes the development of a system that watches for count rate increases recorded in real time at neutron monitors and triggers an alarm if a GLE is detected. We determine optimal strategies for detecting the GLE event at a very early stage on the basis of an approach described in Dorman et al. (2004), while still keeping the false alarm rate at a very low level. Using the strategies derived in this work, the GLE alarm system is back tested at recent GLEs. Because the onset of SEPs are regularly monitored by the GOES satellites and alerts are issued by e-mail and on the Web by the NOAA Space Environment Center (http://www.sec.noaa.gov), we compare the issue times of NOAA SEC alerts with the GLE alarm times to determine the usefulness of this system (Kuwabara et al., 2006a,b).

2. Data analysis

On December 13, 2006 the last GLE of the 23rd solar cycle, was occurred. This event, also known as GLE70, started on the neutron monitors at ~2:48 UT and reached its maximum at~3:00–3:10 UT (Plainaki et al., 2008). In northern Europe the event was registered with big amplitudes that in some cases reached ~70–90%, rendering this recent enhancement in one of the greatest GLEs of the 23rd solar cycle.

For a reliable alert signal all the available space data were collected for use. That is why interplanetary and geophysical data from NOAA Space Environment Center (http://www.sec.noaa.gov) are also recorded in real time at the ANMODAP center. The GOES satellites and the Kyoto Center provide all the available data, a part of which for this event is presented in Fig. 1.

Solar activity ranged from very low to high levels through this period. Activity was very low during 11–12 December with numerous B-class flares from active region 930 and increased to high level on 13 December by virtue of an X3/4B flare at 13/0240 UTC from the same region.

The time profiles of the cosmic ray intensity during the event GLE70 recorded at the Neutron Monitors used in the alert system in Athens are illustrated in Fig. 2. The characteristics of these stations are given in Table 1. All these data are directly extracted from the database nested at the ANMODAP Center. A dedicated program for each station in a variable rate downloads data from all the stations of the network. One of the most important capabilities of this database is the real time availability for immediate analysis. This is crucial in order to have as small as possible delay time between the event and the initiation of the alert. From the main database of the ANMODAP Center, a special 1-min database is populated every 1 min in order to provide all the data needed for the alert system.

Data with 1-min resolution and extracted in real time from the online local database are used. The downloaded files construct a simple .txt file with the counting rate and timestamp is used as an input to the system. Because of the variety of problems that appears in real time situations a preliminary scan of the data has been performed in order to put all of them in the same preferred format for the program input. The general alert is initiated if three of them are in the alert phase, in order to prevent data failure in one of them totally seven stations instead of three are monitored.

3. Real-time algorithms

The need for a system that is fast enough for a detection of the GLE without loosing its accuracy guide us to the development of the following algorithm. Firstly the system uses four running states: Quiet, Watch, Warning and Alert on the basis of the number of stations that record an intensity increase with a defined way. These states visualize in real time the status of the stations which provide their data at the ANMODAP center.

The use of 1-min data corrected for pressure from all the available stations is preferred for not to miss an increase at some detectors. The collection of the data is carried out in real time. For every station there is a specific downloader program at the ANMODAP center's database. The program requests the data from the remote station every 1-min, downloads them at the Center's database, checks their validity and makes a common format for all stations. Then for every station a program named [station]_GLE_alert.exe initiates to analyze. This program every minute calculates in real time the mean value of the last 60 minutely measurements and the value of the standard deviation. Using these parameters the moving threshold of each station is defined every minute by using the formula

$$I_{\text{Threshold}} = I_{\text{MEAN}} + \mathrm{n} * \sigma$$

where $\mathrm{I}_{\text{Threshold}}$ 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 has been defined for every station using data for the past seven years of GLE alerts. The n value fulfills the condition of maximum number of true alerts with the minimum number of false.

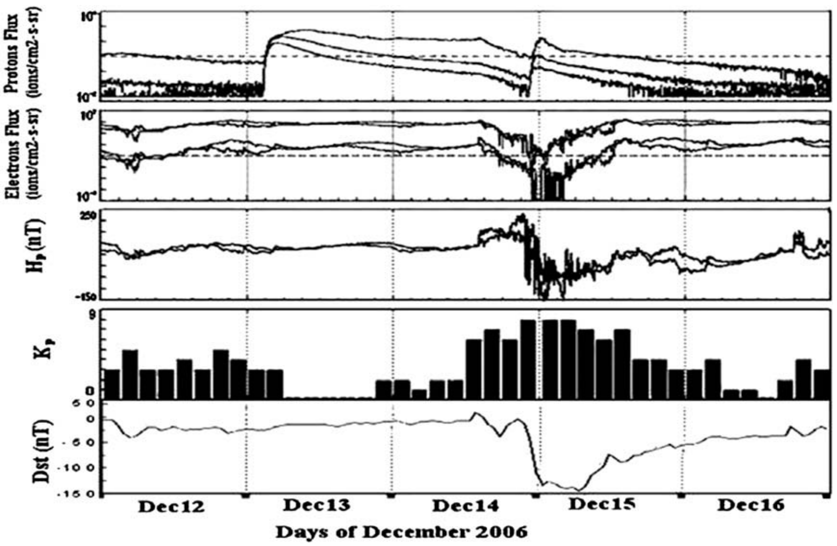


Fig. 1. Interplanetary and geophysical data (NOAA Space Environment Center Web site and Kyoto's on line database).

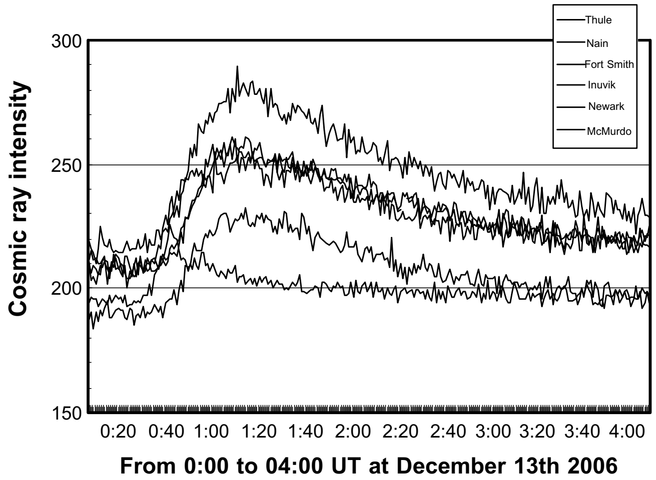


Fig. 2. Time profiles of 1-min cosmic ray data from the NM stations used in the study of the GLE70. From top to bottom: McMurdo, Nain, Fort Smith, Thule, Inuvik, Newark.

Setting the threshold level (n value) for each station, requires a trade off between the generation of the possible earliest station alarm, which favors at lower threshold, avoiding at the same time the false alarms that favor a higher threshold. Stations that record usually lower intensity increases and less sudden rises of intensity, demand smaller threshold multiplier in order to be able to give early alarm signal.

As illustrated in Fig. 3, variable threshold level is set for the cosmic ray intensity increase that can be different for every station. If the last measurement exceeds the moving threshold, the program writes down a pre-alert point. If provided with five pre-alert points in succession a Station Alert is initiated. A program named 'check_for_alert.exe' is supervising the number of station alerts. A General Alarm is generated when the number of station Alerts exceeds three. The most of the time the system is in normal quiet mode. When the first station alert is occurred then the system is in a watch mode, an expiration timer of 15 min is set and the system waits for the next stations to get in station alarm mode. When the second station alert is occurred then the system is in a warning mode. When the third station alert occurs the system produces a general GLE alert. If the timer expires 15 min and there is no second or third station alert mode then the system gets into the normal quiet mode again waiting for the next event (Mariatos et al., 2005).

4. First real-time GLE alert notification in Athens

On 13/12/2006 at 3:05 UT the first real time event was recorded with the use of the ALERT system at the ANMO-

Table 1
Stations from ANMODAP database used for real-time alarm.

Stations	Abbrev	Lat (°)	Long (°)	Alt (m)	H_0 (mb)	R_C (GV)
FORTSMITH	FTSM	60.00	−112.00	0	996.10	0.30
INUVIK	INVK	68.35	−133.72	21	1019.10	0.14
McMURDO	MCMD	−77.85	166.72	48	985.10	0.00
NAIN	NAIN	56.50	61.70	46	1000.00	0.40
PEAWANUCK	PWNK	54.98	−85.44	0	1000.00	0.50
THUL	THULE	76.50	−68.70	260	1005.00	0.10
NEWARK	NWRK	39.68	−75.75	50	1013.00	1.97

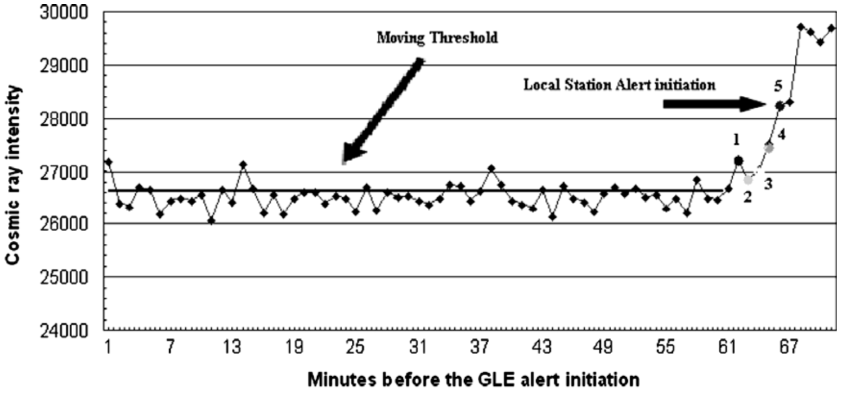


Fig. 3. An example of the visualization of the moving threshold approach in a local station alert for a typical time interval. Numbers show the progress of the Alert.

DAP center (Mavromichalaki et al., 2005b). The stations appeared with bold letters in Table 2 are the ones by which data the alert signal was produced and a graphical representation of the alert from the ANMODAP center web page in real time is also available in Fig. 4. During an unexpected failure on the visualization part of the Alert system it was not possible to produce the exact picture of the event at that day. The typical alert file can not be plotted. This is why the present picture is a reconstruction of the event by all the available data.

As mentioned above, the Alert Time was defined at 03:05 UT, the Onset Time was 02:51. Six stations were in local GLE alert at the system that day: Fort Smith, Inuvik, McMurdo, Newark, Thule, Nain and three of them: Nain, McMurdo and Newark- were the first to fulfill the condition for producing the alert signal. These signals were compared with the ones that NOAA produced that day, as NOAA Space Environment Center (NOAA/SEC) provides real-time monitoring of the proton flux observed by the GOES satellites during solar and geophysical events and issues alarms on the Web and via e-mail (NOAA Web site, http://www.sec.noaa.gov).

The two available energy channels of proton data with energy >10 MeV and >100 MeV and also the two levels of alarm (warning and alert) that are issued during SEP events are evaluated from our system. A warning message is issued when a flux level above 10 particle flux unit (pfu) is predicted at >10 MeV or when greater than 1 pfu is predicted for >100 MeV. It is noted that the SEC's use of the term “warning” is rather different from our usage for the GLE alarm, as it is a prediction rather than an actual detection of SEP. Issue times of the alarms can be used as a barometer of how fast an SEP event is detected in low-energy proton data, therefore we compare our alarm time with these issue times. It is obtained from Fig. 5 that a NOAA SEC alert is typically not issued till some minutes after the relevant threshold is crossed, however we consider the issue time of an alert to be the relevant one for this comparison.

Table 2
The times of the GLE alert signal initiation for each station are given.

Stations	1σ	2σ	3σ
December 13, 2006			
THUL	03:13 UT	03:13 UT	03:15 UT
NAIN	03:02 UT	03:03 UT	03:05 UT
FSMT	03:08 UT	03:08 UT	03:11 UT
INVK	03:15 UT	03:30 UT	NO GLE
NWRK	02:56 UT	03:01 UT	03:01 UT
McMD	03:05 UT	03:08 UT	03:09 UT

Stations in bold are the ones that produced the alert on December 2006.

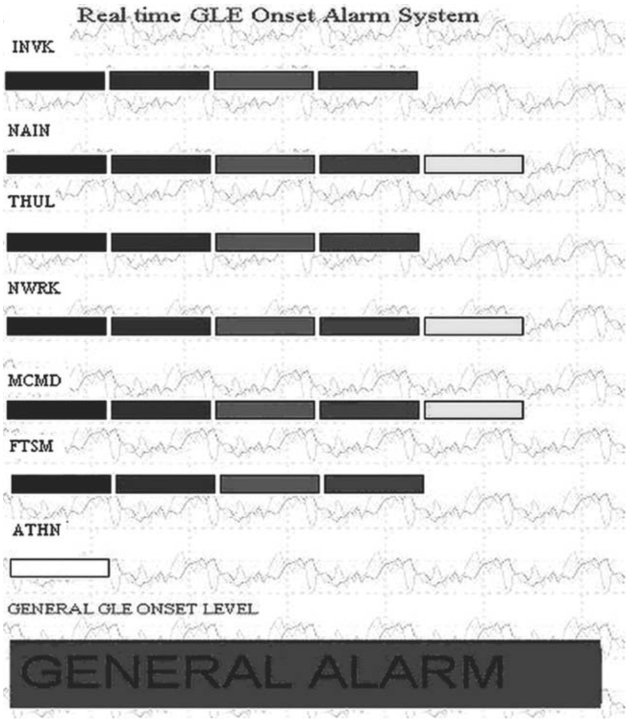
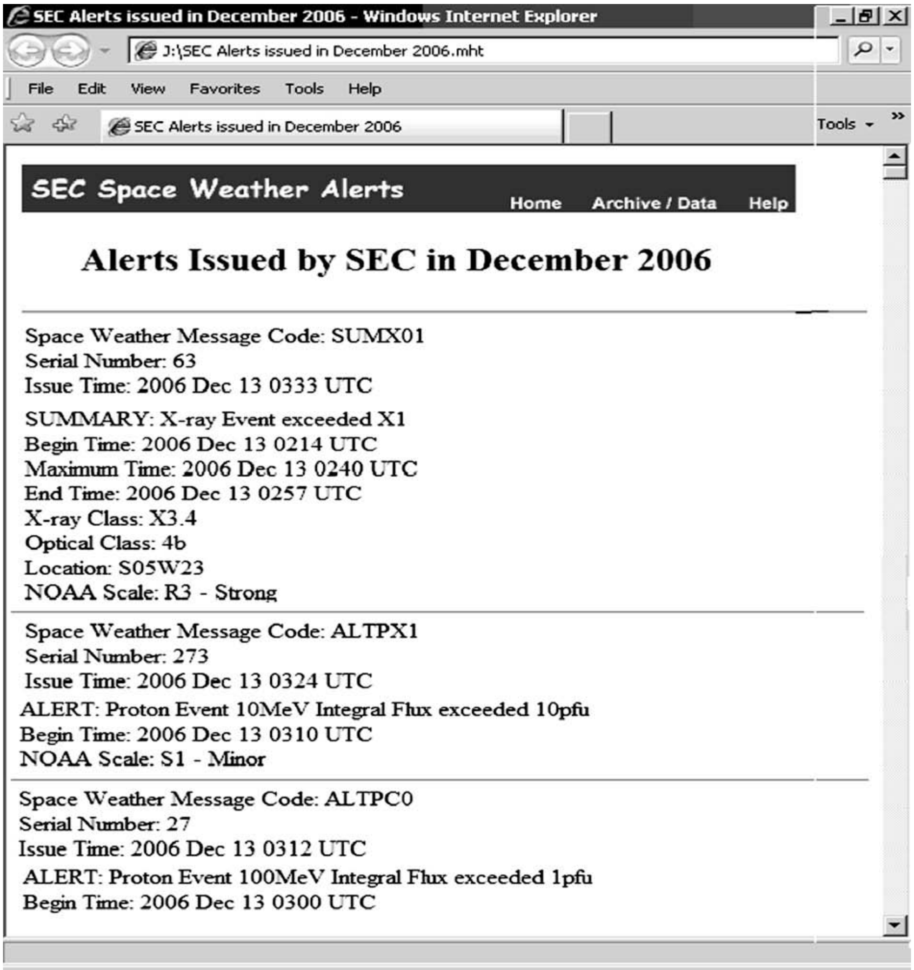


Fig. 4. Real-time evolution of the GLE alert situation. Picture extracted from the ANMODAP's server.

5. Historical GLE results

In order to examine the accuracy of the algorithm the last eight GLE events starting from 2001 have been tested (Bieber



Alerts Issued by SEC in December 2006

Space Weather Message Code: SUMX01
Serial Number: 63
Issue Time: 2006 Dec 13 0333 UTC
SUMMARY: X-ray Event exceeded X1
Begin Time: 2006 Dec 13 0214 UTC
Maximum Time: 2006 Dec 13 0240 UTC
End Time: 2006 Dec 13 0257 UTC
X-ray Class: X3.4
Optical Class: 4b
Location: S05W23
NOAA Scale: R3 - Strong

Space Weather Message Code: ALTPX1
Serial Number: 273
Issue Time: 2006 Dec 13 0324 UTC
ALERT: Proton Event 10MeV Integral Flux exceeded 10pfu
Begin Time: 2006 Dec 13 0310 UTC
NOAA Scale: S1 - Minor

Space Weather Message Code: ALTPC0
Serial Number: 27
Issue Time: 2006 Dec 13 0312 UTC
ALERT: Proton Event 100MeV Integral Flux exceeded 1pfu
Begin Time: 2006 Dec 13 0300 UTC

Fig. 5. GOES alert signal for December 13, 2006.

et al., 2004). The evaluation of the system is performed by the comparison of the time of alert signals established from the application with the announced time of the real events by NOAA (2006). Data from the following stations are used for the offline analysis: CAPE SCHMIDT, FORT SMITH, INUVIK, KIEL, LOMNICKY STIT, McMURDO, MOSCOW, NORILSK, NEWARK, OULU, THULE, NAIN and INUVIK. Depending on the kind of the event a selection of a number of them is made in order to have the best results. The results of this analysis of the GLE events and the comparison with NOAA SEC alerts are presented in Fig. 5.

One event that occurred on 17 January 2005 is excluded from this analysis, because the intensity increase was only 2% at South Pole station. We considered these eight events to determine optimal parameters for use in a GLE alarm system, and we also employed these events for back testing the system and determining its performance in relation to presently available SEP alarms (Table 3).

6. Discussion and conclusions

One of the main problems in real-time operation of the GLE Alarm system is the validity of the collected data. The system uses one minute data updated every minute in real time. In order to have a continuous operation of the system it is necessary to use as many stations as possible from the world wide Neutron Monitor Network provided their data. In this way three stations can be selected in order to provide continuous analysis for the alarm signal. Depending on the way that every station gives out its own 1-min data we have the following problematic situations.

1. The stations provide different data formats and different technologies in data sharing. Using different types of downloader programs (ASP, FTP, SSH and http technologies) the data are formatted at the same type.

2. Although data are with 1-min resolution, they are not updated every 1-min but periodically every 5 min or every hour. A problem of this type can be overcome only with direct upgrade of the remote station. For these stations our data collection program works with a time window in the past (1 h or 5 min) but it runs every minute in order to be ready for 1-min updating of these stations.

3. Minutely data update stops for some reasons, no data at all, unexpected messages in data files or not valid flags, network of remote station not reachable. In all these situations the downloader program automatically sends the

message "Not valid input file" to the higher level programs and the station gets out from the team of stations that participate the alarm system without affecting the running of the others.

4. Data from different stations do not have the same UT timestamp for the same minute. A several minute differences between station clocks have been noticed. GLE system gives at real time collected measurements from the different stations additional timestamp from the local time server. In this way we record the data that all station give in the same minute with common time so we can reproduce the revolution of a historic event based in common time for all stations that give one minute data updated every minute with one minute good synchronization (Mavromichalaki et al., 2005a).

The bad synchronization of the stations is a problem when running historic non real-time data in the past. The alert time that is produced for the past GLEs is based in the assumption that the stations were well synchronized. In nowadays we can mark several minutes' time differences between stations for the same moment. This means that the results for the runs of the historic events are worse (more delayed GLE alarms) than those that would be produced if the system is running then in real time. It means that at real time the system will give even earlier GLE alarms than that exacted from the analysis of historical data.

According to the above analysis the designed system proves to be able to produce real time alert signals earlier than those that NOAA system produces. Time difference between the two systems varies depending on the event. The ANMODAP Center, using its experience and tested methods, works on elaborating of more modern methods, in order to carry out a timely and feasible prognosis of the GLEs using all the available data from the worldwide NM network. It is clear that the joint complex analysis of the relevant information from space-borne and ground-based detectors will minimize the number of false alarms and will maximize the reliability and the timely forecasting of the arrival of dangerous fluxes and disturbances from space.

Table 3
Comparison of the GLE alarm times from our system to the alarm times on the basis of satellite proton data.

GLE number	Event date	Flare time (UT)	Location	Flare's type	GOES alert (100 MeV, >1 pfu)	Stations GLE alert (UT)	Difference of the two alerts (min)
60	15 April, 2001	13:19	S20W85	2B/X14.4	14:21	14:07	14
61	18 April, 2001	02:11	S20WLimbb	C2	3:11	2:51	20
64	24 August, 2002	00:49	S02W81	1F/X3.1	1:48	1:44	4
65	28 October, 2003	09:51	S16E08	4B/X17.2	11:51	11:18	33
66	29 October, 2003	20:37	S15W02	2B/X10.0	–	NO GLE	–
67	2 November, 2003	17:03	S14W56	2B/X8.3	17:56	17:46	10
68	17 January, 2005	–	–	–	–	NO GLE	–
69	20 January, 2005	06:36	N14W61	2B/X7.1	7:04	6:56	8

Acknowledgments

The authors thank the collaborators from the following real-time CR stations who kindly provide us with the data used in this analysis: CAPE SCHMIDT, FORT SMITH, INUVIK, KIEL, LOMNICKY STIT, McMURDO, MOSCOW, NORILSK, NEWARK, OULU, THULE, NAIN (see also in http://cr0.izmiran.rssi.ru/ThankYou/main.htm).

This work is partly supported by the Greek Project 'PYTHAGORAS II" funded by European funds and National resources and by RFBR grants 07-02-13525 and 07-02-00915, and Program BR of the Presidium RAS "Neutrino Physics".

References

Bieber, J.W., Clem, J., Evenson, P., Pyle, R., Ruffolo, D., Saiz, A. Spaceship Earth observations of the Easter 2001 solar particle event. Astrophys. J. 601, L103–L106, 2004.

Dorman, L., Pustil'nik, L., Sternlieb, A., Zukerman, I. Using ground-level cosmic ray observations for automatically generating predictions of hazardous energetic particle levels. Adv. Space Res. 31, 847–852, 2003.

Dorman, L.I., Pustilnik, A., Sternlieb, A., Zukerman, I.G., Belov, A., Eroshenko, E., Yanke, V., Mavromichalaki, H., Sarlanis, C., Souvatzoglou, G., Iucci, N., Villoresi, G., Fedorov, Yu., Shakhov, B.A., Murat, M. Monitoring and forecasting of great solar proton events using the Neutron Monitor Network in real time. IEEE Plasma Sci. 32 (4), 1478–1486, 2004.

Kuwabara, T., Bieber, J.W., Clem, J., Evenson, P., Pyle, R. Development of a ground level enhancement alarm system based upon neutron monitors. Space Weather 4, S10001, doi:10.1029/2006SW000223, 2006a.

Kuwabara, T., Bieber, J.W., Clem, J., Evenson, P., Pyle, R., Munakata, K., Yasue, S., Kato, C., Akahane, S., Koyama, M., Fujii, Z., Duldig, M.L., Humble, J.E., Silva, M.R., Trivedi, N.B., Gonzalez, W.D., Schuch, N.J. Real-time cosmic ray monitoring system for space weather. Space Weather 4, S08001, doi:10.1029/2005SW000204, 2006b.

Mavromichalaki, H., Gerontidou, M., Mariatos, G., Plainaki, C., Papaioannou, A., Sarlanis, C., Souvatzoglou, G., Belov, A., Eroshenko, E., Yanke, V., Tsitomeneas, S. Space Weather forecasting at the New Athens Center: the recent events of January 2005. IEEE NSREC TNS 52, 2307–2312, 2005a.

Mavromichalaki, H., Souvatzoglou, G., Sarlanis, C., Mariatos, G., Gerontidou, M., Papaioannou, A., Plainaki, C., Tatsis, S., Belov, A., Eroshenko, E., Yanke, V. The new Athens center on data processing from the neutron monitor network in real time. Annales Geophys. 23, 1–8, 2005b.

Mariatos, G., Souvatzoglou, G., Sarlanis, C., Mavromichalaki, H. Alert systems for ground level cosmic ray enhancements prediction at the Athens neutron monitor network in real time. J. Mod. Phys. A 20, 6711–6714, 2005.

Plainaki, C., Mavromichalaki, H., Belov, A., Eroshenko, E., Yanke, V. Application of the NM-BANGLE model to GLE70, in: Caballero, R., D'Olivo, J.C., Medina-Tanco, G., et al. (Eds.), Proc. 30th Inter. Cosmic Ray Conference, vol. 1. Universidad Nacional Autónoma de México, México City, pp. 281–284, 2008.