AGU PUBLICATIONS

Space Weather

RESEARCH ARTICLE
10.1002/2014SW001102

Key Points:
- It provides valuable added minutes of advance warning for radiation storms
- Is a service of the European Space Agency Space Situational Awareness Programme
- Is an open access service relying on neutron monitor data from NMDB

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Citation:
Souvatzoglou, G., A. Papaioannou, H. Mavromichalaki, J. Dimitroulakos, and C. Sarlanis (2014), Optimizing the real-time ground level enhancement alert system based on neutron monitor measurements: Introducing *GLE Alert Plus*, *Space Weather*, *12*, 633–649, doi:10.1002/2014SW001102.

Received 31 JUL 2014
Accepted 23 OCT 2014
Accepted article online 29 OCT 2014
Published online 19 NOV 2014

Optimizing the real-time ground level enhancement alert system based on neutron monitor measurements: Introducing *GLE Alert Plus*

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Abstract Whenever a significant intensity increase is being recorded by at least three neutron monitor stations in real-time mode, a ground level enhancement (GLE) event is marked and an automated alert is issued. Although, the physical concept of the algorithm is solid and has efficiently worked in a number of cases, the availability of real-time data is still an open issue and makes timely GLE alerts quite challenging. In this work we present the optimization of the GLE alert that has been set into operation since 2006 at the Athens Neutron Monitor Station. This upgrade has led to *GLE Alert Plus*, which is currently based upon the Neutron Monitor Database (NMDB). We have determined the critical values per station allowing us to issue reliable GLE alerts close to the initiation of the event while at the same time we keep the false alert rate at low levels. Furthermore, we have managed to treat the problem of data availability, introducing the Go-Back-N algorithm. A total of 13 GLE events have been marked from January 2000 to December 2012. *GLE Alert Plus* issued an alert for 12 events. These alert times are compared to the alert times of GOES Space Weather Prediction Center and Solar Energetic Particle forecaster of the University of Málaga (UMASEP). In all cases GLE Alert Plus precedes the GOES alert by ≈8–52 min. The comparison with UMASEP demonstrated a remarkably good agreement. Real-time GLE alerts by *GLE Alert Plus* may be retrieved by http://cosray.phys.uoa.gr/gle_alert_plus.html, http://www.nmdb.eu, and http://swe.ssa.esa.int/web/guest/space-radiation. An automated GLE alert email notification system is also available to interested users.

1. Introduction

Ground level enhancements (GLEs) represent a higher-energy end of Solar Energetic Particle (SEP) events in which ions are accelerated to relativistic energies causing a significant sudden increase of cosmic rays at ground-based detectors, mainly at neutron monitors (NMs) [*Forbush*, 1946]. GLEs result from solar eruptive events such as solar flares and coronal mass ejections (CMEs) [*Aschwanden*, 2012]. Both of these phenomena, as well as their interaction, accelerate particles that propagate along the interplanetary magnetic field lines and reach the observer, which in turn is based either on the ground at Earth or, as it was most recently reported at Mars [*Hassler et al.*, 2014]. Particle energies involved in SEP events range from just above solar wind energies up to a few GeV (the GLE limit) [*Posner et al.*, 2006; *Reames*, 2013; *Tan et al.*, 2013]. Middle to higher SEP energies may result in enhanced levels of radiation that in turn pose a significant risk for satellites, systems, and humans [*Núñez*, 2011; *Shea and Smart*, 2012]. For humans, in particular, GLEs are of prime importance since the enhanced radiation levels provide a potential risk either for astronauts exposed out of the protective shielding of the Earth's magnetic field [*Shea and Smart*, 2012] or even for passengers and air crews traveling along high latitude and/or polar routes were the geomagnetic shielding is too thin to provide proper protection [*Kuwabara et al.*, 2006]. Although *Reames* [1999] foresaw that predicting SEPs and their impacts may be very difficult, now several methods that have introduced different physical approaches are in principal in place to provide SEP forecasts. A number of these approaches have led to a quasi-operational, fully available system, such as the SEP forecaster of the University of Málaga (UMASEP) [*Núñez*, 2011], a system with partial availability such as the Relativistic Electron Alert System for Exploration (REleASE) [*Posner*, 2007], and a nonoperational albeit very promising method [*Laurenza et al.*, 2009]. (Current and past UMASEP and REleASE forecasts are available at http://iswa.gsfc.nasa.gov). GLEs have the advantage of involving extremely energetic particles, characterized by large mean free paths which travel almost scatter free; therefore, NM measurements may be used for the prompt notification of an evolving GLE event [*Kuwabara et al.*, 2006]. It should be noted that, all GLEs are accompanied by major SEP events at lower energy; however, a considerable number of SEP events which can lead to a serious radiation risk is not accompanied by a GLE. This highlights the fact that in the future an integration of the available forecasting tools from low-energy SEPs to relativistic GLEs should be made possible. Since the beginning of reliable recordings with NM detectors, 71 GLEs have been identified and confirmed. The mean occurrence rate of GLEs is almost one per year, with a slight dependency on the level of solar activity [*Belov et al.*, 2009; *Papaioannou et al.*, 2011; *Gopalswamy et al.*, 2012]. The most recent event was recorded on 17 May 2012, designated as GLE71 [*Balabin et al.*, 2013; *Gopalswamy et al.*, 2013; *Kudela*, 2013; *Li et al.*, 2013; *Berrilli et al.*, 2014; *Mishev et al.*, 2014; *Papaioannou et al.*, 2014; *Plainaki et al.*, 2014], and it was the first GLE event reported extending at a longitudinal angular distance within the inner heliosphere [*Heber et al.*, 2013].

A variety of direct and indirect effects on geospace, humans, industry, and economy are caused from GLEs. These effects have been reviewed recently by *Shea and Smart* [2012] and include risks and failures at communication and navigation systems, spacecraft electronics and operations, space power systems, manned space missions, and commercial aircraft operations. As noted by *Shea and Smart* [2012] the major effect of GLEs is the enhancement of radiation exposure that may result to the loss of high-frequency communication on commercial aircraft operations and, at extreme polar latitudes, to a considerable increase in the radiation exposure above that experienced from the background galactic cosmic rays. Therefore, it is crucial to establish a real-time operational system that would be in place to issue reliable and timely alerts on GLE events.

2. Concept and Motivation

Neutron Monitors record particles with $\geq$ 433 MeV energy [*Clem and Dorman*, 2000]. Therefore, these near relativistic particles travel almost scatter free and reach the Earth in a few minutes [*Dorman et al.*, 2004]. Hence, the start time of the intensity increase in NMs is much earlier than that of the lower energy proton flux, as this is recorded onboard satellites, for details see Figure 1 of *Kuwabara et al.* [2006]. Therefore, data from the worldwide network of NMs can be utilized in order to establish a GLE alert forecasting system [*Dorman and Zuckerman*, 2003; *Mavromichalaki et al.*, 2004].

Based upon the aforementioned physical concept, three GLE alert systems (that is to our knowledge) have been released in the scientific community, since 2006. The first one was introduced by the Athens Cosmic Ray Group of the National and Kapodistrian University of Athens [*Mariatos et al.*, 2005; *Souvatzoglou et al.*, 2009; *Mavromichalaki et al.*, 2010a], the second one by the Bartol Research Institute of the University of Delaware [*Kuwabara et al.*, 2006], and the third one by the Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation (IZMIRAN) Cosmic Ray Group [*Anashin et al.*, 2009]. The GLE alert operated by the University of Delaware is based mainly on the *Spaceship Earth* concept [*Bieber et al.*, 2004]. The latter utilizes a network of NMs strategically located to provide precise, real-time, three-dimensional measurements of the cosmic ray angular distribution and it comprises 11 neutron monitors on four continents deployed so as to provide good coverage of the equatorial plane. Nonetheless, the online provision of GLE alerts by this system (http://www.bartol.udel.edu/~takao/neutronm/glealarm/index.html) seems to use 10 out of the 11 neutron monitor stations, while *Kuwabara et al.* [2006] refer to the usage of eight out of the 11 stations of *Spaceship Earth*. The GLE alert(s) operated by the Cosmic Ray Group of the University of Athens and the IZMIRAN group that are currently in operation through NMDB take into account all the NMs distributed all over the world that provide 1 min data to the central database of NMDB in real-time mode.

The application of the GLE alert system upon the high-resolution data made available via NMDB demonstrated in the most profound way that both the data flow of the NMs and the resolution of the available measurements was far from ideal [*Souvatzoglou et al.*, 2013]. Random enhancements in the recorded counting rate of NMs due to technical problems of the counting electronics, the sensor tubes, the power supplies, and the temperature conditioning of the sensors are very common, leading to enhanced false *Station Alert* mode (see details in section 4). Furthermore, problems in the data flow due to bad communication links or software disrupt the flow of the data into NMDB, causing the discarding of NM stations and leading to delayed *General GLE alerts* [*Souvatzoglou et al.*, 2013; *Papaioannou et al.*, 2014]. Therefore, the motivation of this work was: (1) to test the GLE alert system and (2) to overcome identified problems. To this end, we have introduced the Go-Back-N algorithm controlling the data flow of the NM stations making the GLE alert system less attached to the availability of the real-time measurements (see section 4) and at the same time we have set up the structure of the GLE alert system in a more efficient and productive foundations based upon the available infrastructure (i.e., NMDB) (see section 4). This optimization has led to the development of

Table 1. Parent Solar Events for the Selected GLE Events From 2000 to 2012 and Comparison of the *General Alert* Issued by GLE Alert Plus to the GLE Onset

GLE No	Event Date	Onset (UT)	Flare Type	Location	Associated CME Type/Onset (UT)	GLE Alert Onset Time (UT)	GLE Alert Plus Time (UT)
GLE59	14 July 2000	10:10	X5/3B	N22W07	Halo/14 10:54	10:34 (APTY)	10:37
GLE60	15 April 2001	13:19	X14.4/2B	S20W85	W/15 14:30	13:57 (APTY)	13:59
GLE61	18 April 2001	02:11	C2	S20WLimb	SW/18 02:30	02:33 (APTY)	02:44
GLE62	4 November 2001	16:03	X1.0/3B	N06W18	Halo/ 04 1635	16:55 (PWNK)	16:58
GLE63	26 December 2001	04:32	M7.1/1B	N08W54	W/26 05:30	05:39 (APTY)	06:06
GLE64	24 August 2002	00:49	X3.1/1F	S02W81	W/24 01:27	01:23 (APTY)	01:38
GLE65	28 October 2003	09:51	X17.2/4B	S16E89	Halo/28 10:54	11:17 (LMKS)	11:17
GLE66	29 October 2003	20:37	X10.0/2B	S15W02	Halo/29 20:39	21:02 (KIEL)	21:17
GLE67	2 November 2003	17:03	X8.3/2B	S14W56	Halo/02 09:54	17:27 (FSMT)	17:42
GLE68	17 January 2005	06:59	X3.8/3B	N15W25	Halo/17 09:30 & 0954	09:52 (APTY)	missed event
GLE69	20 January 2005	06:36	X7.1/2B	N14W61	Halo/20 06:54	06:47 (NRLK)	06:50
GLE70	13 December 2006	02:17	X3/4B	S05W23	Halo/13 02:54	02:42 (KERG)	02:53
GLE71	17 May 2012	01:35	M5/1F	N12W89	NW/17 01:48	01:55 (APTY)	02:00

the new GLE alert, hereafter *GLE Alert Plus*, which is a preoperational service of the European Space Agency (ESA), constituting the European Neutron Monitor Service.

3. Data Used and Event's Selection

This study primarily makes use of neutron monitor data that have been available at NMDB. NMDB was initiated in 2008 [*Steigies and NMDB Team*, 2008; *Mavromichalaki et al.*, 2010b, 2011] and currently is the single easy-to-use point of access for neutron monitor data from ≈ 47 stations distributed around the world. Although significant progress has been marked and most stations provide high-resolution data into NMDB (http://www.nmdb.eu/status/status.php), during the processing of the data subject to this analysis, it became clear that the entries of all stations for all years were not complete. Keeping this in mind and considering the fact that in order to apply a coherent statistical approach we were in need of both a large amount of data and a period within which GLE events have been marked, we downloaded ourselves data for the missing entries for all stations from http://cr0.izmiran.rssi.ru/common/ and have requested data from the Bartol Institute of the University of Delaware (R. Pyle, personal communication, 2008) while—at the same time—using the complete records of NMDB. To this end, we have implemented a test data base with complete records of neutron monitor stations from January 2000 to December 2012.

These stations are located at high, middle, and/or low geomagnetic latitude, covering a wide range of rigidities (energies) from 0 to 11 GV. Although, evidently, high-latitude stations have greater sensitivity to the lower end of the neutron monitor energy range [*Clem and Dorman*, 2000; *Kuwabara et al.*, 2006; *Mishev et al.*, 2013] and thus are considered to be best suited for the rapid and accurate detection of a GLE event occurrence [*Kuwabara et al.*, 2006; *Shea and Smart*, 2012; *Mishev et al.*, 2013; *Papaioannou et al.*, 2014], our intention is to make use of all available neutron monitor stations that contribute data to NMDB and consequently to the *GLE Alert Plus* system. This is because of the fact that there are still major issues concerning the data flow and the availability of the real-time data from several neutron monitors which are especially useful for the detection of GLE events, see the relevant discussion in *Papaioannou et al.* [2014].

Currently, 1 min data from most of the stations are available in real time mode via NMDB [*Souvatzoglou et al.*, 2013]. As explained, further above, we utilize data from January 2000 to December 2012 covering roughly ≈ 13 years. During this period a total of 13 GLE events occurred, and we make use of these events and their characteristics as those are presented in Table 1. We employ the data of neutron monitors to determine the optimal parameters for the *GLE Alert Plus* system, and we further employ the GLE events of Table 1 in order to benchmark and test our system's performance in relation to presently available SEP alert systems such as the one based upon GOES satellites measurements (http://www.swpc.noaa.gov/) at the NOAA/SWPC and the UMASEP forecaster (http://spaceweather.uma.es/performance_results_100mev.html) [*Núñez*, 2011].

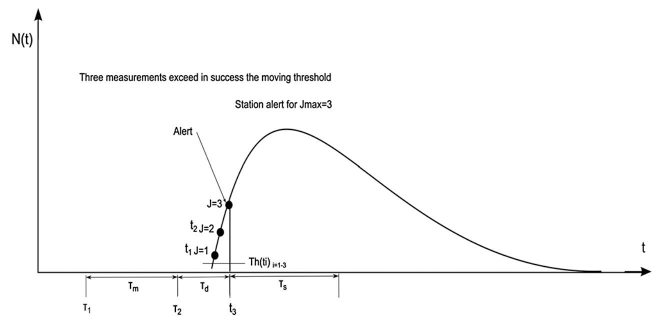

Figure 1. Definition of the *Station Alert* in *GLE Alert Plus*.

4. Algorithm Description

The basis of the GLE alert algorithm is in principle similar to the one that appeared in earlier work [*Kuwabara et al.*, 2006; *Mavromichalaki et al.*, 2010a]. First, we focus on each neutron monitor separately and the objective is to issue a *Station Alert* for this particular neutron monitor. That means that we seek for a persistent increase in the counting rate of the station. We define four levels of alert (quiet, watch, warning, and alert) based on the subsequent number of counts that exceed the Th_t of this neutron monitor station in succession (see Appendix A for details). The establishment of the *Station Alert* mode is illustrated in Figure 1.

We use a moving threshold defined as $\mathrm{Th}_t = M(t) + n\sigma(t)$. $M(t)$ is the moving average of the intensity of a neutron monitor at time $t = \tau$, and it is calculated each minute from the recorded count rate $N(t)$ averaged over the preceding τ_m minutes. $M(t) = \frac{1}{\tau_m}\sum_{\tau-\tau_1-\tau_2}^{\tau-\tau_2} N(t)$, where τ_1 is the start time of the baseline period and τ_2 is the end time of the baseline period. Evidently, both are not fixed but develop with time as the real-time measurements enter the database, ideally at every minute (see Figure 1 for details). The standard deviation of the moving average $M(t)$ is $\sigma(t)$. The averaging time is τ_m, τ_s is the duration of the elapsed time window, and τ_d is the time interval between the baseline period and the current time. Every minute the moving average $M(t)$ and the moving standard deviation $\sigma(t)$ for the time interval τ_m that is used as a baseline period is calculated. This baseline period is chosen to be at least an hour (sixty 1 min measurements), and the end of this period is chosen to have a time distance τ_d from the current minute, since, when an actual event takes place we do not want the increase of the count rate to influence the baseline. The values that are being used in *GLE Alert Plus* are $\tau_m = 60$, $\tau_d = 5$ min, and n varies for each neutron monitor station between [1, 4]. The analytic calculations that led to the aforementioned results based on archived data and are presented in detail in Appendix A.

Given the high cadence data that are necessary for the detection of an evolving large SEP/GLE in real time, a large enough time period should be chosen in order to rule out the statistical fluctuations of the counting rate of the neutron monitor stations [*Kuwabara et al.*, 2006]. Moreover, we have set the end of the baseline in some time earlier than the current time in order to ensure that all neutron monitor stations have provided their measurement in time into NMDB and at the same time that the selected baseline does not include the period when SEPs/GLEs are present (see Figure 1 for details).

The second step is the establishment of the *General Alert* which is subject to the number of neutron monitor stations that enter the *Station Alert* mode independently of each other but within a fixed time window of $\tau_s = 15$ min. If three (3) neutron monitor stations enter the *Station Alert* mode, within this given time window a *General Alert* is marked (see Figure 2) and an alarm is issued. It is noteworthy that each neutron monitor station that contributes to the establishment of the *General Alert* follows an independent climax since it exceeded its very own threshold Th_t as this is demonstrated in Figure 2. The red line (vector) in Figure 2 marks the timestamp at which the three NM stations are all in *Station Alert* mode so that the *General Alert* is produced. Similar to the *Station Alert* mode, we also introduce into the *General Alert* four distinct levels of alert (quiet, watch, warning, and alert). If all neutron monitors are in quiet mode (that is, zero stations are in an excitation phase), we have quiet conditions; in case one station is in *Station Alert* mode, we are in a watch condition; in case two stations are in *Station Alert* mode, we are in a warning stage; and finally in case three stations are in *Station Alert* mode, we mark a GLE event and issue a *General Alert*.

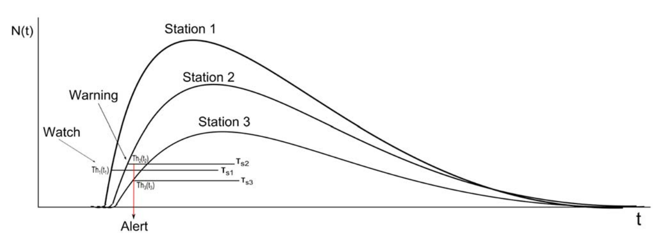

Figure 2. Definition of the *General Alert* in *GLE Alert Plus*.

4.1. Toward *GLE Alert Plus*

The real-time technology has been applied to neutron monitors since 1997 by the IZMIRAN Cosmic Ray Group. Therefore, most stations today record high cadence data (with 1 min resolution) in every minute of time (1 min time resolution) and save these measurements in their local registration systems. However, the flow of the data from the local system to the central database (in our case NMDB) is far from ideal. Taking into account the limitations of GLE Alert—as those were recently noted in *Papaioannou et al.* [2014]—the software of GLE Alert has been rebuilt leading to *GLE Alert Plus*.

4.1.1. Improvements

The new software sets a wealth of discrete differences compared to the previously operating GLE Alert. One of the most important upgrades is that *GLE Alert Plus* is now fully parametric. That means that all the variants of the algorithms are parameters in the new software design. Thus the administrator: (i) can set the parameters of the *Station Alert* independently for every station; (ii) is in place to design a running scenario, trimming all the parameters of the *GLE Alert* system; (iii) can decide which stations will be involved in the scenario; and (iv) can choose how many stations will trigger a *General Alert*.

Multiple scenarios may also run in parallel, in real-time mode and their results will be stored in the local GLE database. One of the scenarios will be selected as the main one. For this scenario the corresponding graphs will be created and posted at the web interface (see section 6). Furthermore, as mentioned above *GLE Alert Plus* stores in a local GLE database important information such as the Universal Time (UT) of the *GLE Alert Plus* server, the value of the measurement including the station's day and time, as well as the time that the value is recorded from the NMDB database. Therefore, currently we are able to recreate a historical run (for the forthcoming GLE events) with the actual data conditions that we had in real time and not with the historical archived data. This is a feature that it was impossible to support in the older version of GLE Alert, and it is very helpful when one needs to explain the time lag between the *General Alert* produced based on historical data from NMDB and the *General Alert* issued based on the actual real time data (for some details on this subject see section 3 of *Papaioannou et al.* [2014]). It should also be noted that *GLE Alert Plus* is based on SQL database and PHP.

4.1.2. The Machine's Logic

The underlying machine of *GLE Alert Plus* has the same core as the GLE Alert and thus has been presented in section 4. High cadence data (1 min resolution) in real or near real time are used (that is ideally with 1 min time resolution). *GLE Alert Plus* watches for excesses in the counting rate recorded in real time by a neutron monitor. The first part of the algorithm leads to the establishment of the *Station Alert*, provided that the conditions of the algorithm are fulfilled. The second part of the algorithm leads to the *General Alert* mode, based on the number of the stations that enter the *Station Alert* mode within a narrow time window.

4.1.3. The Go-Back-N Algorithm

GLE Alert, that is the older version of the system that had been set in operation from the Athens Neutron Monitor Data Processing (ANMODAP) Center [*Mavromichalaki et al.*, 2005] and NMDB [*Mavromichalaki et al.*, 2010b], used strictly the last real-time measurement for every station participating as a seeder of the algorithm. One significant pitfall that was recognized within these 6 years of operation was that some stations provide high cadence data with 1 min resolution every 5 min of time, while other stations provide 1 min resolution data as often as possible since those rely on satellite links or the communication network is problematic. Finally, there are stations with asynchronous clocks (time lag of several minutes) compared to UT [see *Souvatzoglou et al.*, 2013].

One major improvement of the *GLE Alert Plus* algorithm is the implementation of a Go-Back-N procedure. In the new software, every minute, the algorithm is able to go back in time for a number of *N* minutes in order to evaluate the delayed data. The number of *N* minutes is programmable and depends on the uploading behavior of each NM station. In this way, *GLE Alert Plus* increases the amount of usable data from all NM stations, seeding the algorithm. It is noteworthy that the procedure is being implemented in such a way that does not affect the effectiveness of the real-time functionality of the older version of GLE Alert. Additionally, near-real-time measurements that the algorithm can make use of in the new version have only positive results in the process of the establishment of a *General Alert* from *GLE Alert Plus*: more NM stations are being used for the establishment of the *General Alert* and more data of a single NM station are being used in the establishment of the *Station Alert*. Both are crucial parameters when one seeks to issue an alert closer to the initiation of a GLE event.

In order to illustrate the effectiveness of the Go-Back-N algorithm in Table 2, we present the example of the Oulu NM station during the latest GLE event, GLE71, that took place on 17 May 2012. Column 1 provides the date, column 2 the time (UT) of the GLE Alert server clock, column 3 provides the *Station Alert* level without the Go-Back-N, column 4 provides the *Station Alert* level with the Go-Back-N, column 5 provides the timestamp of the Oulu NM, and column 6 displays the measurement at that specific timestamp. As it has been presented in *Papaioannou et al.* [2014], Oulu NM achieved the *Station Alert* mode at 2:10 UT (with respect to the GLE Alert server clock). This is also marked in Table 2, in column 3, when the *Station Alert* level is 3, meaning that for 3 successive measurements Oulu NM exceeded its threshold. The application of the Go-Back-N algorithm shows that Oulu NM would have been set to a *Station Alert* mode at 2:07 UT (based on the GLE Alert server clock), as this is noted in column 4 of Table 2. Therefore, for one station during a small GLE event as GLE71 was the Go-Back-N procedure would have saved at least 3 min of valuable time for mitigation actions.

5. Validation of the Algorithm

GLE Alert Plus has been tested against historical records from January 2000 to December 2012. In all GLE cases (see Table 1), *GLE Alert Plus* issued alarm signals very close to the initiation of the GLE event (see Table 1). Furthermore, since the core of the algorithm had been set online since 2006, we also report the real-time performance of *GLE Alert* for the last two GLE events, i.e., GLE70 on 13 December 2006 and GLE71 on 17 May 2012 (see section 5.2).

We, then, compare the GLE Alert times to the relevant alarm times based on satellite proton data. Similar to a previous study [*Kuwabara et al.*, 2006], we first examine the alarms issued by the NOAA Space Weather Prediction Center (NOAA/SWPC). These NOAA/SWPC alarm times can be used as an index of how fast a SEP event is detected in low-energy proton data; therefore, we compare *GLE Alert Plus* alert times with these (see details in section 5.1.1). Second, we compare the alarm times of *GLE Alert Plus* to the ones issued by the UMASEP Forecasting system [*Núñez*, 2011]. UMASEP analyzes flare and near-Earth space environment data (soft X-ray and differential and integral proton fluxes), and currently, it has been extended from low ($E > 10$ MeV) to higher energies ($E > 100$ MeV) and thus is also comparable to the alert times issued by *GLE Alert Plus*. UMASEP's results on $E > 100$ MeV forecasts are available at http://spaceweather.uma.es/performance_results_100mev.html, but the exact forecast times presented in this paper are courtesy of Prof. M. Núñez (Núñez, private communication, 2013) (see details in section 5.1.2).

5.1. Historical Events

5.1.1. Comparison With GOES

We compare the times of the *General Alert* issued by *GLE Alert Plus* to the alert times of the NOAA/SWPC. NOAA/SWPC provides real-time monitoring of the proton flux observed by the GOES satellite and issues alarms through http://www.swpc.noaa.gov/. Two energy channels of data (> 10 MeV and > 100 MeV) and two levels of alarm (warning and alert) are issued during SEP events. A warning message is issued when the flux of > 10 MeV protons is predicted to exceed 10 proton flux units (pfu) or when the flux of > 100 MeV protons is predicted to exceed > 1 pfu. An alert message is issued when the flux level at > 10 MeV exceeds up to 5 orders of magnitude starting from 10 to 100,000 pfu, or when at > 100 MeV exceeds > 1 pfu [*Kuwabara et al.*, 2006]. In all cases *GLE Alert Plus* precedes the GOES alert. The time difference of the real-time alerts present a lower limit of 8 min for GLE63 and an upper one of 52 min for GLE71 (see Table 3 and Figure 3). There is also an event (GLE66) where the *GLE Alert Plus* issued an alert while NOAA/SWPC based on GOES data did not.

One GLE event was marked on 17 January 2005 (listed as GLE68) but it was an event lying on an already elevated background due to intense solar activity [*Papaioannou et al.*, 2010], resulting into an increase of only 2% at South Pole neutron monitor [*Kuwabara et al.*, 2006] and thus purely undetectable from the *GLE Alert Plus* system.

In order to illustrate the details of the comparison between these two Alert systems and to discuss their fine structure, we present alarm times from our system for all 12 GLE events compared with alarm issue times from GOES proton data in Figure 3. Colored points on the time axis are coded as follows: black dots give the event's onset at both GOES and NMs, yellow dots the watch stage of NMs, green dots the achieved warning stage for both GOES and NMs, and red dots the Alert stage of both systems.

Table 2. The Go-Back-N Algorithm in Use[a]

Date	Time (UT)	Station Alert Level	Station Alert Level Plus	Time Stamp	Value
17.5.2012	1:49:18	0	0	1:47	6416
17.5.2012	1:50:18	1	1	1:48	6736
17.5.2012	1:51:18	2	2	1:49	6711
17.5.2012	1:52:35	0	0	1:51	6374
17.5.2012	1:53:19	0	0	1:51	6374
17.5.2012	1:54:19	0	0	1:52	6205
17.5.2012	1:55:19	0	0	1:53	6634
17.5.2012	1:56:19	1		1:54	6794
17.5.2012	1:57:35	2		1:56	6858
17.5.2012	1:58:20	2		1:56	6858
17.5.2012	1:59:20	0	0	1:57	6650
17.5.2012	2:00:21	1	1	1:58	7016
17.5.2012	2:01:21	1	0	1:58	7016
17.5.2012	2:02:36	0	0	1:58	7016
17.5.2012	2:03:21	0	0	1:58	7016
17.5.2012	2:04:21	1	2	1:59	6843
17.5.2012	2:05:21	1	0	1:59	6843
17.5.2012	2:06:22	0	0	1:59	6843
17.5.2012	2:07:22	1	3	2:00	7285
17.5.2012	2:08:36	1	0		
17.5.2012	2:09:22	2	4–9(10)	2:07	7357
17.5.2012	2:10:22	3	11	2:08	7497
17.5.2012	2:11:22	4	12	2:09	7431
17.5.2012	2:12:22	5	(13)14	2:11	7409
17.5.2012	2:13:37	5	0	2:11	7409
17.5.2012	2:14:22	6	15	2:12	7351
17.5.2012	2:15:22	7	16	2:13	7283
17.5.2012	2:16:22	0	0	2:15	7136
17.5.2012	2:17:22	1		2:16	7391
17.5.2012	2:18:37	1		2:16	7391
17.5.2012	2:19:24	0		2:17	7254
17.5.2012	2:20:24	0		2:18	7352
17.5.2012	2:21:24	0		2:20	7212
17.5.2012	2:22:24	0		2:21	7365
17.5.2012	2:23:38	0		2:21	7365
17.5.2012	2:24:25	0		2:22	7058
17.5.2012	2:25:26	0		2:23	7023
17.5.2012	2:26:26	0		2:25	6854
17.5.2012	2:27:26	0		2:26	7119
17.5.2012	2:28:31	0		2:27	7035
17.5.2012	2:29:27	0		2:27	7035
17.5.2012	2:30:27	0		2:28	6955
17.5.2012	2:31:27	0		2:29	6975
17.5.2012	2:32:27	0		2:30	6653

[a]Column 4 provides the *Station alert* levels of Oulu NM, as these were derived using the Go-Back-N. Evidently, Oulu NM would have achieved the *Station Alert* mode 3 min earlier. This example illustrates how the Go-Back-N can save valuable minutes in real time for mitigation actions.

Table 3. Comparison of the *General Alert* Issued by GLE Alert Plus to GOES SWPC Alarm Times and to the UMASEP Forecaster

GLE Event	GLE Alert Plus Time (UT)	SWPC Alert Time (UT)	UMASEP Time (UT)	Time Difference # 1 (min)	Time Difference # 2 (min)
GLE59	10:37	10:59	10:35	22	−2
GLE60	13:59	14:21	13:55	22	−4
GLE61	02:44	03:13	missed event	29	
GLE62	16:58	17:07	16:45	9	−13
GLE63	06:06	06:14	05:50	8	−16
GLE64	01:38	01:48	01:25	10	−13
GLE65	11:17	11:51	11:20	34	3
GLE66	21:17	missed event	missed event		
GLE67	17:42	17:56	17:35	14	−2
GLE68	missed event	12:40	10:40		
GLE69	06:50	07:04	06:45	14	−5
GLE70	02:53	03:12	02:50	19	−3
GLE71	02:00	02:52	01:55	52	−5

We see that the GLE alert preceded the earliest alert from GOES (>100 MeV or >10 MeV) by 8–52 min. Also, from Figure 3, it is evident that in nearly half of all events the GLE alert time preceded or was simultaneous with the onset of the GOES proton event at >100 MeV. Furthermore, apart from the X axis that provide the timestamp of the Alert at its several stages from both systems, the Y axis provide also the specific NMs that contributed to the establishment of the GLE alert. Moreover, the gray-shaded areas per NM contributing to the alert represent the start and the end time of the *Station Alert* mode for that specific NM. Also, for three events, namely, GLE66 on 29 October 2003 (at both >10 MeV and >100 MeV), GLE67 on 2 November 2003 (at >10 MeV), and GLE69 on 20 January 2005 (at >10 MeV), it should be noted that there is no well-defined onset, warning, or alert, because the proton flux was already above the threshold value from a prior event at GOES measurements. As a result, no alarm issued by GOES for GLE66. This is also illustrated in Figure 3.

5.1.2. Comparison With UMASEP

UMASEP system make real-time predictions of the time interval within which the integral proton flux is expected to meet or surpass the SWPC SEP threshold of $J(E > 10\text{MeV}) = 10$ pfu and the intensity of the first hours of SEP events [*Núñez*, 2011].

As it is presented in Table 3, UMASEP and *GLE Alert Plus* provide results very close to each other and in a sense those are complementary. UMASEP precedes the alerts issued by *GLE Alert Plus* in almost half of the events with a varying time window of 2 to 16 min (see Table 3). On the other hand, *GLE Alert Plus* precedes UMASEP forecasts in the case of GLE65 by 3 min. UMASEP issues a prediction for GLE68, as opposite to *GLE Alert Plus* that does not issue an alert. Furthermore, UMASEP misses GLE61 and GLE66, but *GLE Alert Plus* issues alerts in both cases (see Table 3).

5.2. Real-Time Events

Although, GLE Alert was set into operation in 2006 at ANMODAP Center and consequently in 2008 at NMDB, prior to the implementation of *GLE Alert Plus*, there was no capability of storing the actual real-time data including all relevant information concerning the performance of a neutron monitor station that had been used as a seeder of the algorithm, in terms of its data availability and data flow. Nevertheless, since 2006 there have been only two GLE events marked and remarkably for both of them a real-time alert was issued, leading to zero false alarms for these 6 years of continuous operation.

GLE70 on 13 December 2006 was successfully recorded in real-time by the GLE Alert software that was set into operation at the ANMODAP Center [*Souvatzoglou et al.*, 2009]. According to the authors, the alert was issued at 03:05 UT. Recently, *Papaioannou et al.* [2014] reported the real-time alert of GLE71 that was marked on 17 May 2012, at 02:13 UT, while the onset of the event fell into ≈ 01:55 UT. The delay was thoroughly commented, and as a result, the limitations of GLE Alert were presented.

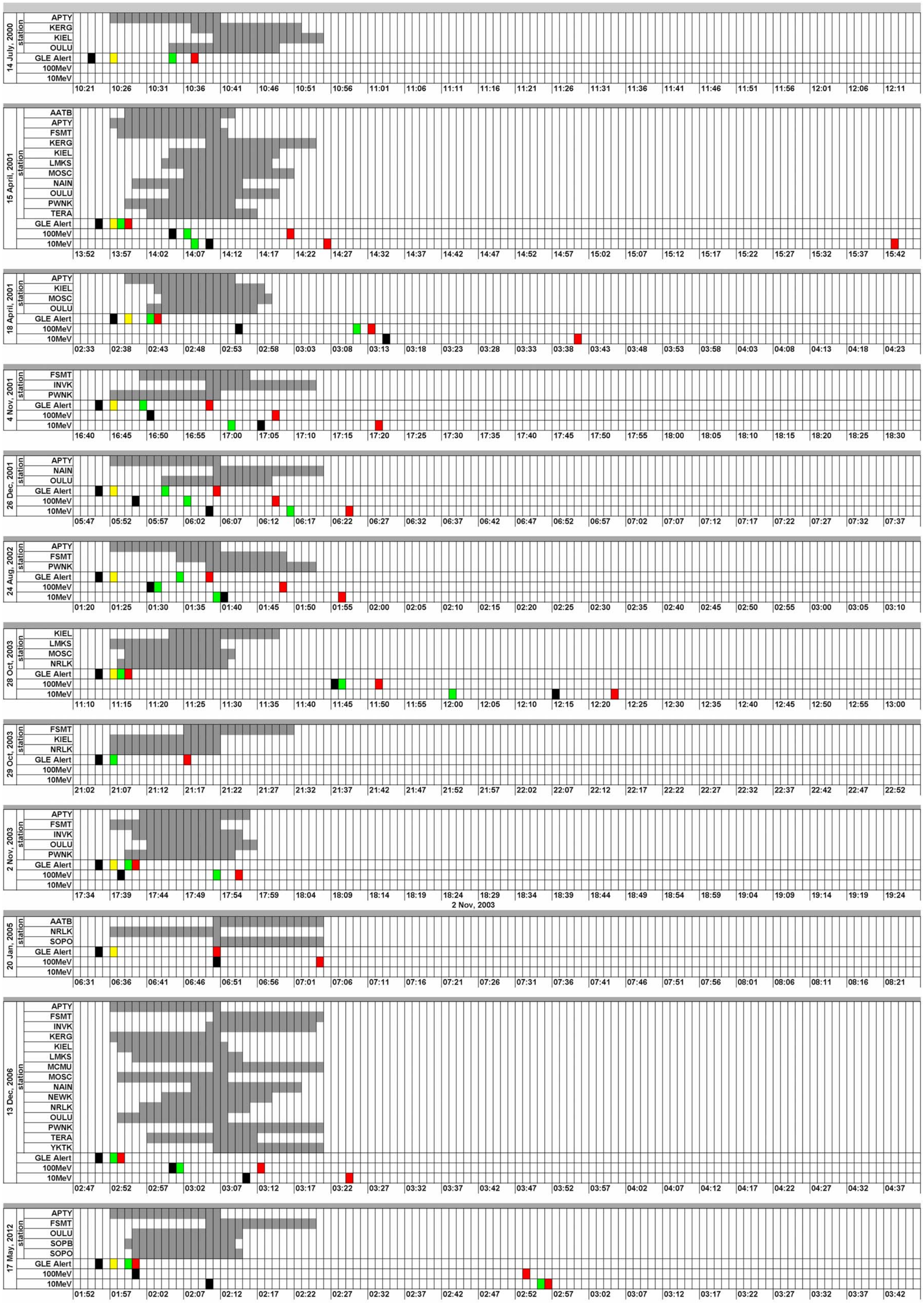

Figure 3. Comparison of the *GLE Alert Plus* alert times to alarms issued by GOES NOAA SWPC. The color code refers to the onset time (black square), watch mode (yellow), warning (green square), and alert (red square). The shaded areas represent the time of the *Station Alert* mode for each NM station. NM stations contributing to the alert are also included on the left side of the figure for each event.

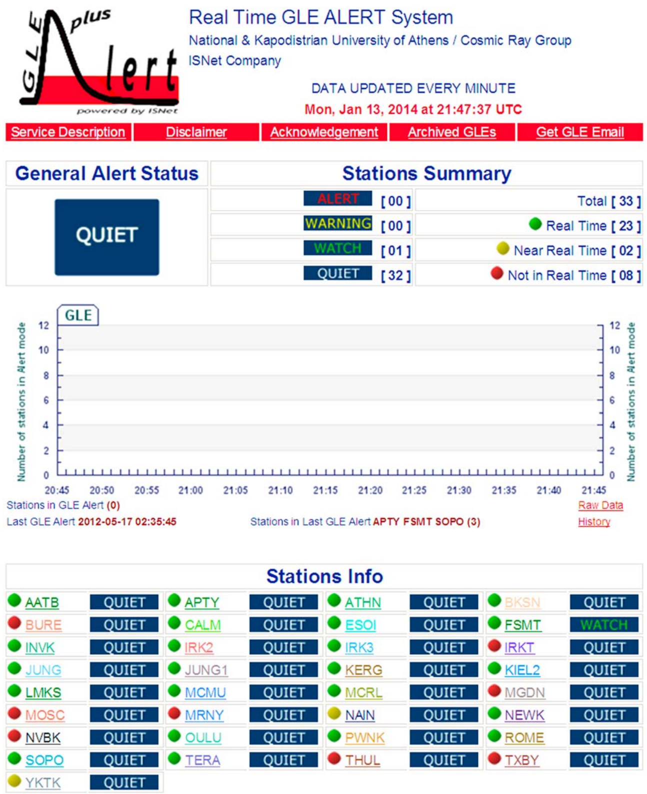

Figure 4. The web interface of the *GLE Alert Plus*.

What is noteworthy is that in both cases (i.e., GLE70 and GLE71) a real-time alert was actually issued by the GLE Alert software, which means that in two out of two verified GLE events the algorithm was in place to issue a real-time alarm. On top of that, the issued alerts preceded the ones presented by the SWPC of NOAA by 7 and 39 min, respectively.

One should note that for the prompt identification of an event, *GLE Alert Plus* needs the input of low cutoff rigidity stations. However, these stations are established in remote locations and often transmit their data via unreliable internet connections making such stations, partially usable by the system or even completely unusable—in real-time mode. Real-time NM data are being processed automatically by our system for the time period that the communication link is active whereas historical runs of *GLE Alert Plus* can take into account the data from NM stations that had periods of no real-time data, provided that these stations have send their data into NMDB. In order to overcome this problem, we have introduced the Go-Back-N algorithm into our system (see section 4.1.3). If the data link is down for a maximum of 15 min and after that break the link is up again and the station sends the delayed data, the use of the Go-Back-N algorithm can help to evaluate the delayed data end to extract the *Station Alert* lever from that data. A highlighted example of a very useful station for the identification of evolving GLE events is the South Pole (SOPO) NM, which is a high-latitude station with a vertical cutoff rigidity of 0.10 GV, also located at a high altitude (≈2820 m), providing the advantage of detecting a small event with a clear profile; see for example the work of *Kuwabara et al.* [2006]. If the data of such stations are made available with continuous data flow at NMDB, *GLE Alert Plus*, as presented here, will be implemented in full.

6. Web Interface

The web interface that provides access to the user of the *GLE Alert Plus* has been designed in such a way so that the information provided is condensed and simple to follow. As it can be seen in Figure 4 there are three levels of information. The top part of the interface provides access to the description of the service; archived GLE events and to the email notification engine were interested users may be registered. The middle part of the interface provides a graph that demonstrates the evolution of the *General Alert*—as this was described further above in section 4. Finally, the bottom part of the interface gives a summary of the neutron monitor stations contributing to *GLE Alert Plus* including a notification of their data flow (red = not in real-time, yellow = near real-time, and green = real time). Then a graph for each neutron monitor station which acts as the seeder of the algorithm is included. This latter graph demonstrates the behavior of a particular neutron monitor and reflects its independent climax toward the *Station Alert* mode. As it can be derived from Figure 1 when three successive measurements of that particular station exceed its own Th_t, the station enters at a *Station Alert* mode and the elapsed time window (presented as a red triangle) is triggered. The user may also get the evolution of the *Station Alert* of that neutron monitor as an ASCII file under the *History* option as well as its ingested data under the option *Raw data*. Finally, in Figure 5 the establishment of the *General Alert* is being presented for GLE61 on 18 April 2001 based upon archived data. These plots are available to the user of *GLE Alert Plus* at the *Archived GLEs* option, mentioned further above. One can note the independent climax of each station and the accomplishment of the *Station Alert* mode for Apatity (APTY)

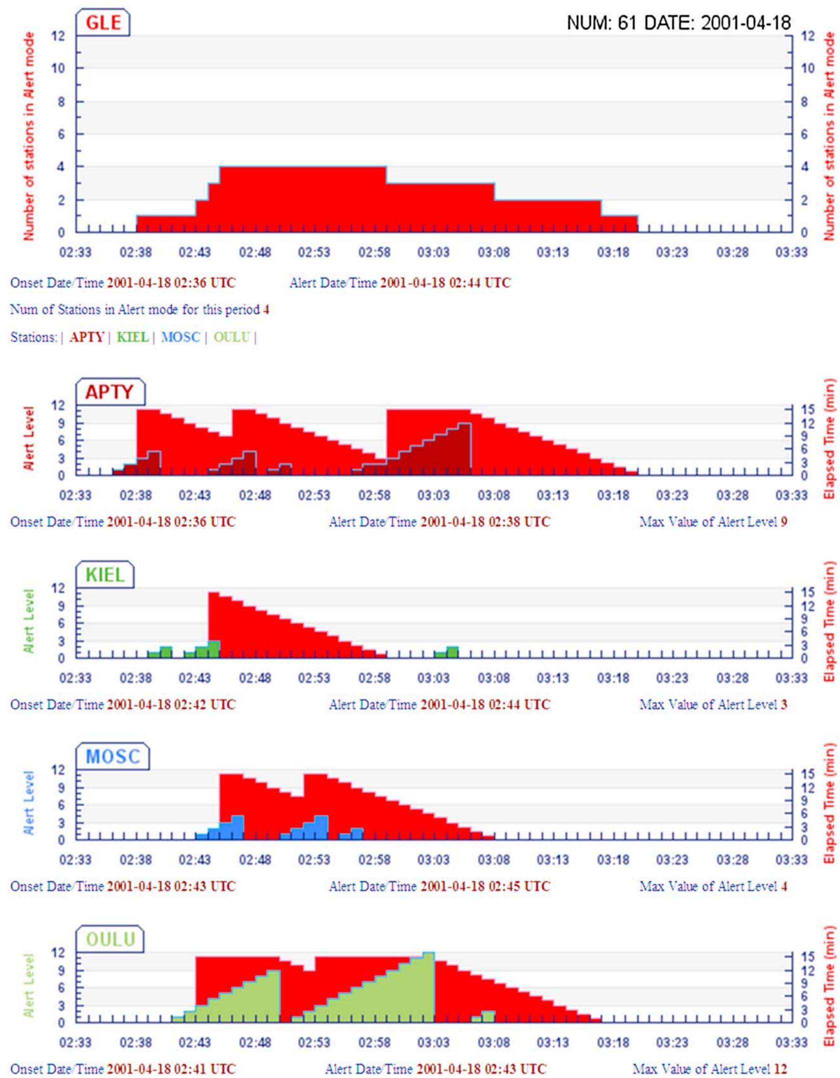

Figure 5. The evolution of the *GLE Alert Plus* for GLE61. The user of *GLE Alert Plus* may derive such plots for every GLE from 2000 to 2012.

NM at 02:38 UT, followed by Oulu (OULU) NM at 02:43 UT and Moscow (MOSC) NM at 02:45 UT. This latter timestamp represents also the time stamp for which the *General Alert* was issued.

7. Contribution of GLE Events to the Radiation Risk

An attempt to quantify the contribution of GLE events to the radiation risk has been performed by monitoring the occurrence rate of GLEs versus SEP events from 2000 to 2012. A total of 60 SEP events that exceeded the threshold of 100 pfu at > 10 MeV channel onboard GOES satellites have been reported in this period. Apparently not all SEP events present clear signatures at Earth, resulting into a GLE. All SEP events are tabulated in Table 4 and are classified by maximum proton flux as S2 (moderate storm, > 100 pfu), S3 (strong storm, > 1000 pfu), and S4 (severe storm, > 10, 000 pfu). Twelve of the 13 GLE events accompanied SEP events and are marked in the right column. An event that occurred on 20 January 2005 was originally not an individual SEP event, because a former event on 16 January was continuing when this event occurred. However, we consider this as a separate SEP event (see also the comment at *Kuwabara et al.* [2006]).

From Table 4, we can confirm that all GLEs except for the one occurred on 29 October 2003 (GLE66) were accompanied by an S2 or greater storms. The occurrence rate of GLEs is 24% at S2, 25% at S3, and 50% at S4 storms. Therefore, GLE events tend to occur more frequently in higher-level storms and thus have a

Table 4. Information on the Solar Energetic Particle Events From 2000 to 2012 Ranked Based on the NOAA Radiation Risk Scale

Year	Start Time (Date/UT)	Maximum Time (Date/UT)	Flux (pfu) @ > 10 MeV	GLE
		S4 Severe Radiation Storm		
2001	04 Nov/17:05	06 Nov/02:15	31700	Yes (GLE62)
2003	28 Oct/12:15	29 Oct/06:15	29500	Yes (GLE65)
2000	14 Jul/10:45	15 Jul/12:30	24000	Yes (GLE59)
2001	22 Nov/23:20	24 Nov/05:55	18900	No
2000	08 Nov/23:50	09 Nov/1555	14800	No
2001	24 Sep/12:15	25 Sep/22:35	12900	No
		S3 Strong Radiation Storm		
2012	07 Mar/05:10	08 Mar/11:15	6530	No
2012	23 Jan/05:30	24 Jan/15:30	6310	No
2005	16 Jan/02:10	17 Jan/17:50	5040	Yes (GLE68)
2005	14 May/05:25	15 May/02:40	3140	No
2002	21 Apr/02:25	21 Apr/23:20	2520	No
2001	01 Oct/11:45	02 Oct/08:10	2360	No
2004	25 Jul/18:55	26 Jul/08:10	2086	No
2006	06 Dec/15:55	07 Dec/19:30	1980	No
2005	08 Sep/02:15	11 Sep/04:25	1880	No
2005	-	20 Jan/08:10	1860	Yes (GLE69)
2003	02 Nov/02:15	03 Nov/08:15	1570	Yes(GLE67)
2001	02 Apr/23:40	03 Apr/07:45	1110	No
		S2 Moderate Radiation Storm		
2001	15 Apr/14:10	15 Apr/19:20	951	Yes (GLE60)
2000	24 Nov/15:20	26 Nov/20:30	940	No
2002	22 May/17:75	23 May/10:55	820	No
2001	26 Dec/06:05	26 Dec/11:15	779	Yes (GLE63)
2006	13 Dec/03:10	13 Dec/09:25	698	Yes (GLE70)
2004	07 Nov/19:10	08 Nov/01:15	495	No
2001	16 Aug/01:35	16 Aug/03:55	493	No
2012	13 Mar/18:10	13 Mar/20:45	469	No
2003	26 Oct/18:25	26 Oct/22:35	466	No
2002	09 Nov/19:20	10 Nov/05:40	404	No
2001	10 Apr/08:50	11 Apr/20:55	355	No
2003	04 Nov/22:25	05 Nov/06:00	353	No
2005	22 Aug/20:40	23 Aug/10:45	330	No
2001	18 Apr/03:15	18 Apr/10:45	321	Yes(GLE61)
2000	12 Sep/15:55	13 Sep/03:40	320	No
2002	24 Aug/01:40	24 Aug/08:35	317	Yes(GLE64)
2004	13 Sep/21:05	14 Sep/00:05	273	No
2012	17 May/02:10	17 May/04:30	255	Yes(GLE71)
2002	16 Jul/17:50	17 Jul/16:00	234	No
2002	07 Sep/04:40	07 Sep/16:50	208	No
2012	17 Jul/17:15	18 Jul/06:00	136	No
2005	14 Jul/02:45	15 Jul/03:45	134	No
2003	28 May/23:35	29 May/15:30	121	No
2013	11 Apr/10:55	11 Apr/16:45	114	No
2001	30 Dec/02:45	31 Dec/1620	108	No

considerable radiation impact. Furthermore, this result is also in line with the results presented at an earlier study [*Kuwabara et al.*, 2006].

8. Conclusions

We have optimized the real-time GLE event detection system using neutron monitors providing their data through NMDB. GLE alarms are produced at four levels (quiet, watch, warning, and alert) corresponding to the number of stations that exceed the intensity threshold of each neutron monitor station. The intensity threshold for each neutron monitor station depends on the statistical behavior of its data. All of the GLE alert parameters were optimized by backtesting against past neutron monitor data.

Thirteen GLE events occurred from 2000 to 2012, and our system produced GLE alarms for 12 of these events while missed one. Alert times deduced from *GLE Alert Plus* were compared with the earliest alert issued by SEC/NOAA on the basis of GOES (> 100 MeV or > 10 MeV protons) data. We find that alert times produced by our system are 8–52 min earlier than alert issue times from SEC/NOAA and are also substantially earlier than the time when dangerous amounts of low-energy particles reach the satellite (S2 storm level). These results suggest that *GLE Alert Plus* can provide valuable added minutes of advance warning for radiation storms of concern for satellites, astronauts, and air crews.

Furthermore, the comparison with the UMASEP forecasting system has shown that *GLE Alert Plus* is a very useful asset that can potentially be used complementary to UMASEP for the forecasting of large SEP events (> 100 MeV) that extend to neutron monitor energies.

Finally, a real-time email notification engine has been built, and it is available via http://cosray.phys.uoa.gr/gle_alert_plus.html, http://www.nmdb.eu, and http://swe.ssa.esa.int/web/guest/space-radiation. At this point it should be noted that *GLE Alert Plus* is currently an preoperational service of the European Space Agency (ESA) Space Situational Awareness (SSA) Programme.

Appendix A: Determination of Parameters

In this section we present the determination of parameters used in the *GLE Alert Plus*.

A1. Definition of the Optimal *n* for Each Neutron Monitor Station

One of the improvements of *GLE Alert Plus* is that each neutron monitor station has its own threshold rather than a common threshold that all stations should meet. In order to identify the optimal parameter n, we first assume that n ranges between 1 and 4 with a step of 0.5. Furthermore, we calculate the percentage (%) of measurements that exceeds one specific threshold for a given n compared to the sum of the measurements that exceeds the resulted thresholds for all n values. For every neutron monitor station and for the whole time period that we make use of its data, we define the total number of measurements that exceed the Th_t for a certain n value, as $A(n)$, similarly the total number of measurements that exceed Th_t for all n values is $Sval = \sum_{n=1}^{4} A(n)$. Moreover, we define and calculate the percentage $P(n) = \frac{A(n)}{\sum_{n=1}^{4} A(n)}\%$ for each neutron monitor station. Our results are presented in Figure A1. For every $P(n)$ there is a value of n that corresponds to each neutron monitor, as denoted by their distributions. For the set of n values we make a run of the

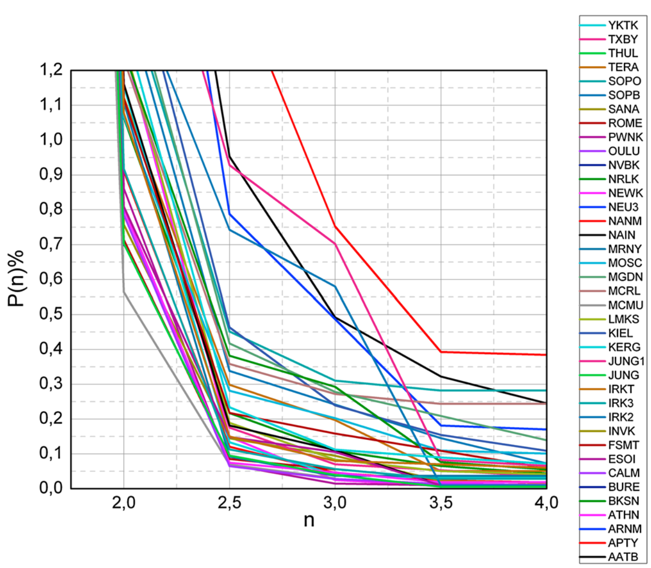

Figure A1. Distribution of $P(n)$ as a function of n for all neutron monitors contributing to *GLE Alert Plus*.

Table A1. Summary of the Results Derived by *GLE Alert Plus* When 0.75% < $P(n)$ < 3%

$P(n)$ (%)	Successful Alert	Missed Event	False Alert	True Warning	False Warning
0.75	10	3	0	11	18
0.78	10	3	0	12	20
0.80	10	3	0	12	23
0.81	12	1	0	12	14
0.82	12	1	0	12	14
0.83	12	1	0	12	14
0.84	12	1	0	12	14
0.85	12	1	0	12	14
0.87	12	1	0	12	15
0.90	12	1	0	12	15
0.95	12	1	0	12	19
1.00	12	1	0	12	24
1.50	12	1	3	12	82
2.00	12	1	5	12	91
2.50	12	1	5	12	106
3.00	12	1	5	12	176

algorithm on the historical data in order to identify the optimal $P(n)$ and correspondingly the optimal set of n values.

Evidently, a larger n value favors a smaller $P(n)$ but this also includes the possibility of issuing delayed alarms. In order to pinpoint the optimal set of n parameters, we impose the following condition: the set of n parameters should lead to a successful GLE Alert issued at all GLE events with the minimum number of false alerts and the minimum number of false warnings. The best results have been achieved for $P(n)$ values ranging within 0.75% < $P(n)$ < 3%. The results of the algorithm in this range are summarized in Table A1.

Inspection of Table A1 shows that when selecting a set of n values for $P(n)$ < 0.8% leads into losing GLE events and thus the missed event rate of the algorithm is being increased. On the other hand, when selecting a set of n values for $P(n)$ > 1% leads to enhanced false *GLE Alerts*. Therefore, the optimal choice for $P(n)$, which also by definition determines the set of n parameters, is in the range 0.8% < $P(n)$ < 1%. Nonetheless, for 0.85% < $P(n)$ < 1% the false warnings of the algorithm are also increased; therefore, an even closer optimal range for $P(n)$ is 0.8% < $P(n)$ < 0.85%. Finally, out of this latter set of $P(n)$ values we selected $P(n)$ = 0.85% and by a vertical cut in Figure A1, one can see the range of the optimal n parameters used in *GLE Alert Plus*. Furthermore, in Table A2 we present the specific n value for every neutron monitor that is being used as a seeder of the *GLE Alert Plus* algorithm.

A2. Definition of τ_m and τ_d

For the NM stations that participate in *GLE Alert Plus*, we choose the discrete values of τ_m: 60, 65, 70, 75, 80 and correspondingly for τ_d: 5, 10, 15 (both in minutes). We then set the n value to range between [1,4] with a step of 0.5. For all n values the Sval quantity (see above) is being calculated. Our goal is to test the performance of the algorithm when τ_m is being increased and τ_d is fixed and vice versa. From all possible combinations of τ_m and τ_d, *GLE Alert Plus* provides 100% successful results in all historic GLE events, without false alarms, using the n values of Table A2, $\tau_m = 60$ and $\tau_d = 5$ (both in minutes).

A3. Definition of the Number of Successive Steps in Order to Define the *Station Alert* Mode

If we set the number of successive steps that are needed in order to establish the *Station Alert* mode from 3 to 2, the number of the identified GLE events, i.e., that is, the number of issued GLE Alerts remains 12 (which represents 100% success of the system), but the number of false alarms increases dramatically from 0 to 353 (see Table A3). Furthermore, if we set the number of successive steps from 3 to 4, the number of successful GLE Alerts that are being issued drops from 12 to 9, and at the same time the missed GLE events increase from 1 to 4 (see Table A3). Therefore, the number of the successive steps that are necessary to define the *Station Alert* mode is 3.

A4. Definition of the Number of Neutron Monitor Stations Needed to Define the *General Alert* Mode

The number of neutron monitor stations that are being used in order to define the *General Alert* mode within *GLE Alert Plus* is 3. If we increase the number of neutron monitor stations from 3 to 4, only eight successful GLE Alerts are issued and five GLE events are missed. In case we decrease the number of neutron monitor stations from 3 to 2, the number of successful GLE Alerts remain 12 (which represents 100% success of the system), but the number of false GLE Alerts increases dramatically from 0 to 42 (see Table A3).

Table A2. Optimal *n* Value for Each NM Station Contributing to *GLE Alert Plus*

NM Station	$P(n)$ $n = 1.5$	$P(n)$ $n = 2.0$	$P(n)$ $n = 2.5$	$P(n)$ $n = 3.0$	$P(n)$ $n = 4.0$	Optimal n
Almaty (AATB)	13.78%	2.78%	0.95%	0.49%	0.25%	3
Apatity (APTY)	10.35%	0.91%	0.12%	0.05%	0.02%	2.5
Aragats (ARNM)	11.91%	2.74%	0.79%	0.49%	0.17%	2.5
Athens (ATHN)	11.73%	1.27%	0.15%	0.02%		2.5
Baksan (BKSN)	11.41%	1.06%	0.22%	0.11%	0.04%	2.5
Plateau de Bure (BURE)	11.17%	0.70%				2
Castilla-La Mancha (CaLMa)	5.88%					2
ESOI-TAU (ESOI)	10.92%	0.86%	0.07%	0.01%	0.01%	2.5
Fort Smith (FSMT)	8.94%	0.71%	0.09%	0.06%		2
Inuvik (INVK)	9.56%	0.76%	0.14%	0.09%	0.02%	2
Irkutsk (IRK2)	12.73%	1.42%	0.34%	0.24%	0.07%	2.5
Irkutsk (IRK3)	11.40%	1.47%	0.45%	0.31%	0.28%	2.5
Irkutsk (IRKT)	10.35%	1.12%	0.30%	0.20%	0.05%	2.5
Jungfraujoch (JUNG)	13.83%	4.59%	2.98%	2.36%	1.46%	4.5
Jungfraujoch (JUNG1)	11.61%	1.16%	0.18%	0.07%	0.04%	2.5
Kerguelen (KERG)	11.94%	1.16%	0.13%	0.04%	0.03%	2.5
Kiel (KIEL)	11.69%	1.63%	0.46%	0.24%	0.11%	2.5
Kiel (KIEL2)	11.79%	1.76%	0.50%	0.20%	0.10%	2.5
Lomnicky stit (LMKS)	11.96%	1.28%	0.19%	0.08%	0.04%	2.5
McMurdo (MCMU)	8.84%	0.56%	0.07%	0.03%		2
Mobile CR Laboratory (MCRL)	10.70%	1.23%	0.36%	0.27%	0.24%	2.5
Magadan (MGDN)	11.76%	1.52%	0.42%	0.28%	0.14%	2.5
Moscow (MOSC)	10.82%	1.07%	0.28%	0.20%	0.10%	2.5
Mirny (MRNY)	10.51%	1.11%	0.09%	0.04%	0.04%	2.5
Nain (NAIN)	9.55%	1.16%	0.18%	0.11%	0.01%	2.5
Nor-Amberd (NANM)	13.08%	4.38%	1.50%	0.75%	0.38%	3
Neumayer III (NEU3)	12.54%	2.19%				2.5
Newark (NEWK)	9.67%	0.80%	0.07%	0.05%	0.02%	2
Norilsk (NRLK)	10.22%	1.25%	0.38%	0.29%	0.06%	2.5
Novosibirsk (NVBK)	11.54%					2
Oulu (OULU)	10.04%	0.79%	0.06%	0.03%	0.01%	2
Peawanuck (PWNK)	9.71%	0.81%	0.15%	0.11%	0.01%	2
Rome (ROME)	11.12%	1.12%	0.22%	0.16%	0.06%	2.5
Sanae (SANA)	8.09%	1.47%				2.5
South Pole Bare (SOPB)	10.08%	1.51%	0.74%	0.58%	0.01%	2.5
South Pole (SOPO)	9.83%	0.92%	0.11%	0.06%	0.03%	2.5
Terre Adelie (TERA)	10.56%	1.08%	0.15%	0.08%	0.06%	2.5
Thule (THUL)	9.22%	0.70%	0.09%	0.04%	0.01%	2
Tixie (TXBY)	11.34%	1.99%	0.93%	0.70%	0.07%	3
Yakutsk (YKTK)	11.46%	1.34%	0.23%	0.11%	0.07%	2.5

Table A3. Successive Steps of the *Station Alert* Mode and Number of NM Stations of the *General Alert* Mode

	Run ID	No. of Stations to Confirm	No. of Steps to Confirm	Successful Alerts	Missed Events	False Alerts
	15	3	3	12	1	0
Station	19	3	2	12	1	353
Alert	20	3	4	9	4	0
	15	3	3	12	1	0
General	21	2	3	12	1	42
Alert	26	4	3	8	5	0

Acknowledgments
The research leading to these results has utilized the Neutron Monitor Database (NMDB) which has received funding from the European Community Seventh Framework Programme (FP7/20072013) NMDB under grant agreement 213007. Moreover, the authors would like to thank both referees, R. Pyle and A. Posner, for the careful evaluation of the manuscript that has significantly improved the original text. Furthermore, the authors wish to acknowledge funding from the European Space Agency (ESA), Space Situational Awareness (SSA), contract SN-IV 3, 4000106756/12/MRP. A.P. is indebted to Marlon Núñez for his valuable contribution to this paper. Moreover, the NOAA Space Environment Center and the GOES team in particular are gratefully acknowledged for the provision of useful space weather information and their open source policy.

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