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Key Points:
- A ground level enhancement of cosmic ray intensity, identified as GLE72, was recorded by several stations of neutron monitor network
- This GLE event was successfully detected in real time by the GLE Alert plus System of the Athens Neutron Monitor Station (A.Ne.Mo.S.)
- Seven neutron monitor stations contributed to the GLE Alert plus System due to the functionality of this system and the data availability

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Real-Time Detection of the Ground Level Enhancement on 10 September 2017 by A.Ne.Mo.S.: System Report

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Abstract On 10 September 2017, a ground level enhancement (GLE) of cosmic ray intensity, identified as GLE72, was recorded by several stations of the worldwide neutron monitor network provided by the high-resolution Neutron Monitor Database. The solar proton event that resulted in this GLE was associated with active region AR2673, which produced an X8.2 flare on the solar west limb. Protons were measured by the GOES satellites with energies above 10, 50, and 100 MeV, while particles at higher energies above 500 MeV were registered by ground-based neutron monitors. This GLE event was successfully detected in real time by the GLE Alert plus System of the Athens Neutron Monitor Station (A.Ne.Mo.S.). In this work an overview of the GLE72 event is given, and a detailed analysis of the evolution of the GLE Alert signal issued by the GLE Alert plus System as well as a postevent summary are presented.

1. Introduction

Cosmic rays (CRs) are very energetic particles originating from different sources within and outside our galaxy, such as supernovae, neutron stars, or the Sun (Firoz et al., 2010). Galactic CRs, which comprise most of these primary particles, originate outside our solar system and are modulated by solar activity following the 11-year variation. As CR particles propagate through the interplanetary medium, they enter the Earth's atmosphere, producing cascades of secondary particles by interacting with the atmospheric molecules (Paschalis et al., 2014). On the other hand, solar CRs, also known as solar energetic particles (SEPs), are produced during solar flares and coronal mass ejections (CMEs). Solar proton events with energies at and above 500 MeV can produce secondary particles that are recorded by ground-based detectors, such as neutron monitors (Dorman et al., 2004; Mishev et al., 2014; Núñez et al., 2017; Usoskin et al., 2015). These extreme SEP events, known as ground level enhancements (GLEs), are quite exceptional. They occur about 10 times per solar cycle, mainly during the maximum and descending phase of a solar cycle. Most GLEs are recorded at high geographical latitudes where Earth's magnetic field is more *open* (Andriopoulou et al., 2011).

During the current solar cycle (SC24) two GLEs took place, the GLE71 event on 17 May 2012 near solar maximum (Mishev et al., 2014; Papaioannou et al., 2014; Plainaki et al., 2009; Plainaki et al., 2014) and the GLE72 event on 10 September 2017 near the end of the descending phase of this cycle (Augusto et al., 2018). September 2017 was the most active month in terms of proton flux levels produced by solar eruptions during the last years of SC24. From 6 to 10 September 2017, 19 M-class and 4 X-class solar flares were produced. All X-class flares came from active region AR2673. The first one was a X2.2 flare at 08:57 UT on 6 September 2017, followed by a X9.3 flare at 11:53 UT on the same day. The next day, a X1.3 flare took place at 14:20 UT. After almost 3 days, on 10 September 2017, an unexpected X8.2 flare at coordinates S08W88 started at 15:35 UT. This flare was associated with a high-speed halo-type CME accompanied by high-energy SEPs (Kataoka et al., 2018), resulting in the occurrence of a GLE, the first one recorded since 2012. The CME was produced on 10 September 2017 at 16:00 UT and arrived at Earth on 12 September 2017 at 19:26 UT, causing a minor (G1) geomagnetic storm after the shock arrival. The X8.2 flare was registered by the GOES satellites that are situated in geostationary orbit (NOAA, https://www.swpc.noaa.gov/). Time profiles of the hard and soft X-ray flux and proton fluxes at energies above 10, 50, and 100 MeV observed by GOES on 10 September 2017 are shown in the upper and lower panels of Figure 1, respectively.

GLEs can be detected by an array of neutron monitors that can act as a warning tool for the onset of GLE events (Bieber et al., 2004; Kuwabara et al., 2006; Souvatzoglou et al., 2014). This has led to the

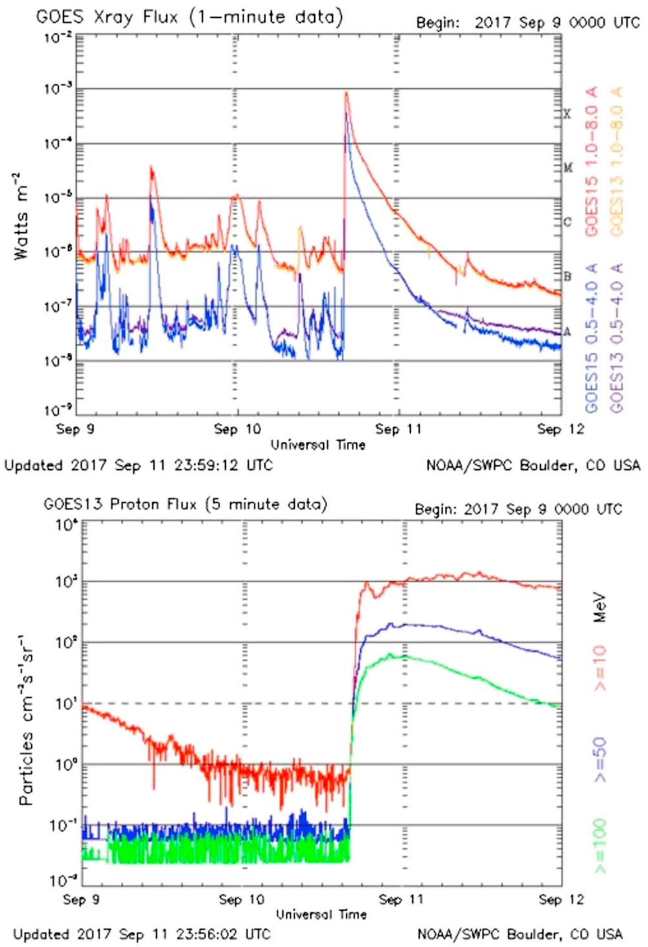

Figure 1. Time profiles of X-ray flux (upper panel) ftp://ftp.swpc.noaa.gov/pub/warehouse/2017/2017_plots/xray/20170912_xray.gif and proton flux at energies above 10, 50, and 100 MeV (lower panel) ftp://ftp.swpc.noaa.gov/pub/warehouse/2017/2017_plots/proton/20170912_proton.gif, respectively, as observed by GOES (NOAA) on 10 September 2017.

establishment of a worldwide network of neutron monitors, placed in locations with different geographical coordinates and various cutoff rigidities. The accurate prognosis and warning of GLEs in real time is very critical, as the high-energy solar particles can cause various problems to technology and biological systems. This can range from damages to the microelectronics of satellites (Mavromichalaki et al., 2007) to the increase of radiation dose received by space crews and air crews (Berger et al., 2018; Lovelace et al., 2018; Paschalis et al., 2016; Sato et al., 2018; Tobiska et al., 2015). Thus, an accurate and timely warning of GLE events is essential from the application side.

This recent GLE event was successfully detected by several neutron monitor stations of the worldwide neutron monitor network. Stations operating in real time provide their data to the high-resolution Neutron Monitor Database (NMDB), which provides 1-min updated data every minute. The Athens Neutron Monitor Station (A.Ne.Mo.S), which contributes to the NMDB, has developed a service named GLE Alert plus System, which produces an accurate and timely warning signal for the arrival of a GLE at Earth. This system uses CR data from a total of 34 real-time neutron monitor stations of the NMDB. The recent GLE72 event was successfully detected in real time by the GLE Alert plus System.

In this work, a detailed description of the evolution of the GLE72 event as recorded by the GLE Alert plus System is given as well as a postevent summary. An evaluation of the results obtained by using this system is also discussed.

2. GLE Alert Signal Issued by A.Ne.Mo.S

The automatic real-time GLE Alert plus System is provided by the A.Ne.Mo.S (http://cosray.phys.uoa.gr) and is available through the European Space Agency (ESA) Space Situational Awareness (SSA) Space Weather Element (SWE) Portal as part of the Space Radiation Expert Service Center (R-ESC, http://swe.ssa.esa.int/space-radiation). Although the GLE Alert plus System has been extensively described in previous works (Souvatzoglou et al., 2014) for the coherence of our analysis, it is essential to present here some key points of its operation.

The physical concept of this System is based on the fact that information on interplanetary and solar conditions is brought much earlier by high-energy particles (E $>$ 500 MeV), compared to low- and mid-energy particles. As a result, the high-energy particles (E $>$ 500 MeV) arrive from the Sun in only 8 to 20 min after their acceleration and escape into interplanetary space, while the lower energy particles usually arrive 30 to 60 min later (Dorman et al., 2004). Therefore, the solar proton events registered at the Earth's surface may provide a profile of the SEP event, well before the enhancement evolving the lower energies begins (Dorman et al., 1993).

Real-time technology has made the prognosis of a GLE possible (Kuwabara et al., 2006; Mariatos et al., 2005). Four discrete alert levels are defined for each neutron monitor station (quiet, watch, warning, and alert) based on the increase of the counting rate of each station. The determination of the alert levels is produced by the moving threshold calculation of each station, which is defined as

$$Th_t = M(t) + n\sigma(t), \tag{1}$$

where $M(t)$ is the moving average of the neutron monitor intensity and $\sigma(t)$ is the standard deviation of the moving average. The parameter n is a number depending on every station, taking values between 1.5 and 4. At time $t = \tau$ the term $M(t)$ becomes

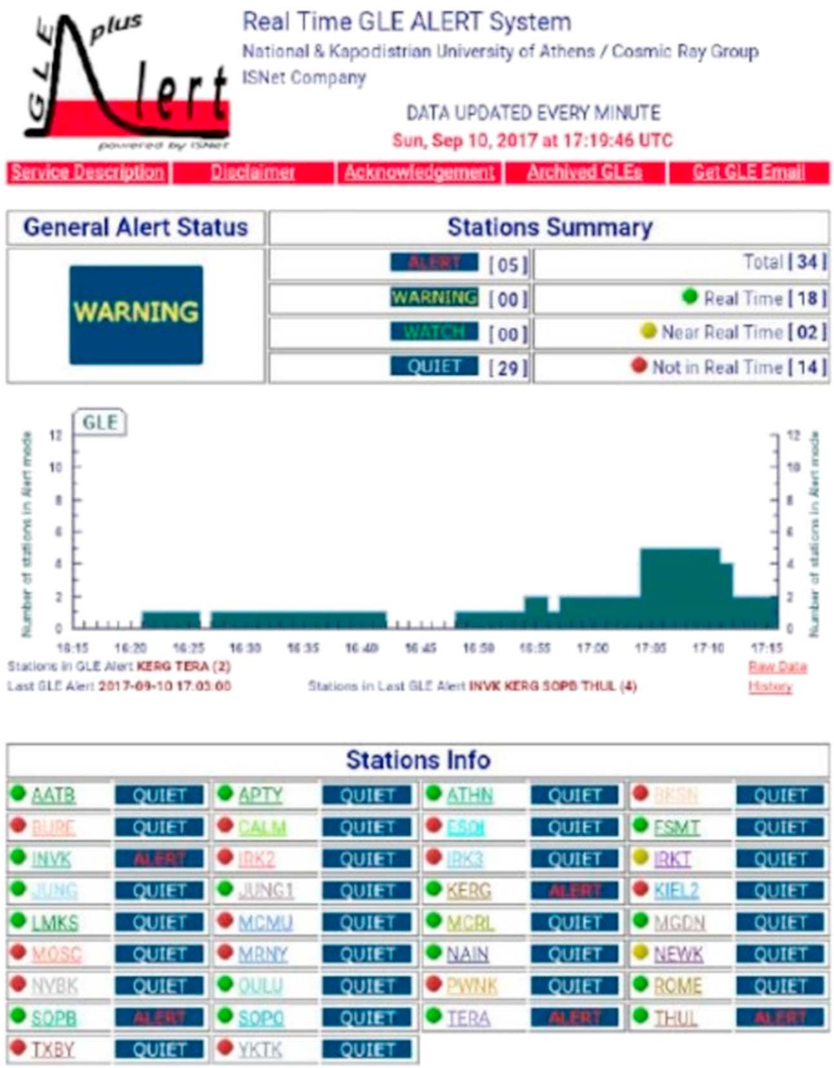

Figure 2. A snapshot of the issued GLE72 event alert signal as it was provided by Athens Neutron Monitor Station and through the ESA Space Situational Awareness Space Weather Element in real-time.

$$M(\tau) = \frac{1}{\tau_m} \Sigma_{t=\tau-\tau_m-\tau_d}^{t=\tau-\tau_d} N(t), \tag{2}$$

where $M(\tau)$ is calculated in each minute from the recorded count rate $N(t)$ averaged over the preceding τ_m minutes (τ_m = 60 min). The value τ_m is the time of the baseline period; τ_d is the time interval between the baseline period and the current time. An analytical description of this system is available at Souvatzoglou et al. (2014).

The output of this system is the graphical representation of the status of each neutron monitor separately as well as a general GLE Alert graph presenting the overall status, updated every minute. At least three neutron monitors are required to be in alert mode independently of each other within a specific time window in order to issue a general alert. In this case, an automated GLE alert email notification is sent to all subscribed users.

In the case of the 10 September 2017 GLE72 event, several ground-based neutron monitor detectors recorded a GLE. This event was the first one to be successfully identified in real time by the GLE Alert plus System. A snapshot of the issued GLE Alert signal is given in Figure 2. In the upper panel the general status of the alert is given as well as information about the distribution of stations at each alert level. A graphical representation of the evolution of the GLE Alert plus System in the different stations is shown in the

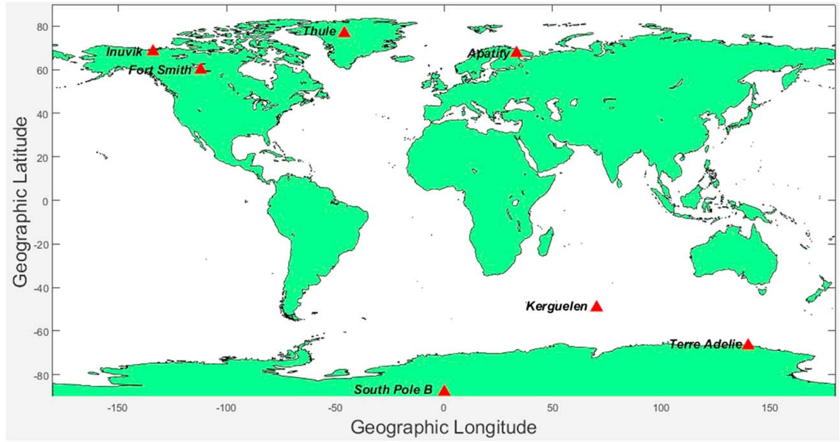

Figure 3. Worldwide distribution of the neutron monitor stations contributing to the GLE72 alert signal.

middle panel of the figure. This figure was updated automatically every minute and presented the status of the stations during the last hour. In this way useful information about the time of each neutron monitor station that is entering in each alert level, as well as the station alert elapsed time, is provided. In the lower panel of this figure an automatically updated summary of the stations, indicating the status regarding their alert level such as quiet, watch, or alert, is given.

Before analyzing the development of the GLE Alert, we should distinguish the two types of timestamps that are related with each station measurement. The first timestamp is the time allotted by the station to the measurement and is called *station time*, while the second timestamp is the time when the measurement becomes available to the GLE Alert plus System and is called *server time*. The server time is delayed by a few minutes compared to the station time in some cases. This happens either because the station has not yet sent the measurements to the NMDB, or due to the time required for the synchronization of the GLE Alert plus System with the NMDB.

In the above-mentioned GLE event seven neutron monitor stations entered in Alert mode during the evolution of the GLE72 event. These stations were Apatity (APTY), Thule (THUL), Inuvik (INVK), South Pole Bare (SOPB), Kerguelen (KERG), Fort Smith (FSMT), and Terre Adelie (TERA). Their worldwide distribution is illustrated in Figure 3. The various characteristics (geographical coordinates, altitude, and cutoff rigidity) for each of the above stations and the onset times of each station of the GLE event is given in Table 1. The normalized CR intensity values recorded by the above stations during GLE72 are presented in Figure 4. These values are obtained from the high-resolution NMDB (www.nmdb.eu). The database shows that this GLE event was moderate in comparison to previous GLE events (see, e.g., http://www.nmdb.eu/nest/search.php and https://gle.oulu.fi/). The SOPB neutron monitor recorded this event with the greatest amplitude reaching values of about 8% due to its location and the asymptotic direction of the solar CR beam, while smaller amplitudes were recorded by the other six neutron monitors.

Table 1
Characteristics and Onset Times of the Neutron Monitor Stations Contributing to the GLE72 Alert Signal

NM stations	Geogr. Coord.	Altitude (m asl)	Rc (GV)	Onset time (UT)
Fort Smith (FSMT)	60.02°N, 111.93°W	180	0.30	16:18
Apatity (APTY)	67.57°N, 33.40°E	181	0.65	16:47
Kerguelen (KERG)	49.35°S, 70.25°E	33	1.14	16:53
Inuvik (INVK)	68.36°N, 133.72°W	21	0.30	16:58
Thule (THUL)	76.5°N, 68.70°W	26	0.30	16:58
South Pole Bare (SOPB)	90.00°S, N/A	2,820	0.10	16:58
Terre Adelie (TERA)	66.65°S, 140.00°E	32	0.00	17:01

Several neutron monitors present a clear, rapid increase in their relative count rates between 16:00 and 17:00 UT. The increase ranged from 2% to 15% and was recorded by about 21 neutron monitor stations of the NMDB, with cutoff rigidity up to 5.6 GV (corresponding to proton energy of about 5 GeV). However, only seven neutron monitor stations contributed to the GLE Alert plus System due to the functionality of this system and the data availability. These stations are polar or near polar stations at both the northern and southern hemispheres.

According to Kurt et al. (2018) there was no north-south asymmetry during this event in the CR intensity data. The very beginning of the event was only observed at the FSMT station, indicating an anisotropic behavior of

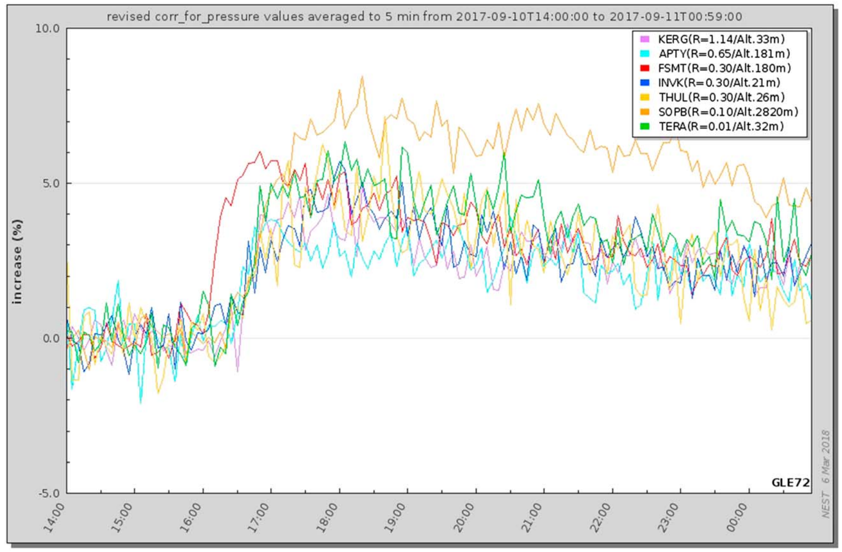

Figure 4. Intensity-time profiles in relative scale of the GLE72 event as it was recorded by the neutron monitor stations of FSMT, SOPB, APTY, KERG, INVK, TERA, and THUL on 10 September 2017.

a narrow stream of accelerated particles (see red curve in Figure 4). This station became the first one to record the arrival of the high-energy relativistic particles and therefore the first station to enter alert mode at 16:18 UT till 16:39 UT. The stations APTY and KERG entered also into alert mode after several minutes at 16:47 UT and 16:53 UT, respectively, and were followed by the INVK, SOPB, and THUL stations at 16:58 UT. Consequently, the stations KERG, INVK, SOPB, and THUL were the first ones to initiate the general GLE alert signal from A.Ne.Mo.S. The last station to enter into Alert mode was the TERA station at 17:01 UT.

The first station that contributed to the General GLE Alert was the KERG station, followed by INVK, SOPB, and THUL. It is important to note that while the FSMT station was the first one to record this event, it did not actually contribute to the establishment of the GLE Alert, as it entered in Alert mode 35 min earlier in comparison to the first station contributing to the General GLE Alert signal. Despite the fact that APTY also entered into alert mode 6 min earlier than KERG, it did not contribute to the General GLE Alert either. This is because the event in APTY was nearing its end and therefore the APTY alert level was marginally low at the time the other four stations entered alert mode. The GLE Alert algorithm works in such a way that the APTY alert level would have had to be at alert level 3 to have contributed to the General GLE Alert. As noted above, the onset time observed in the FSMT station was much earlier in comparison with the other stations. In Figure 5 the evolution of the alert situation of each station entering in Alert mode independently of each other, is illustrated. The first automated e-mail notification was sent to all subscribed users at 17:03 UT. In total nine such e-mails were sent every minute from 17:04 to 17:11 UT. The time range of the general alert was about 10 min.

3. Discussion and Conclusions

In this work the real-time detection of the GLE72 that occurred on 10 September 2017 by the GLE Alert plus System is presented. The first version of this alert system was installed and has been in operation since 2006 at the A.Ne.Mo.S (ANMODAP CENTER) with continuous improvements (Mavromichalaki et al., 2006; Souvatzoglou et al., 2009). The creation of the high-resolution NMDB providing 1-min updated every 1-min data ensures that an accurate GLE Alert signal can be issued (Mavromichalaki et al., 2010; Mavromichalaki et al., 2011). The latest version *GLE Alert plus System* was established in the frame of the ESA SSA SNIV-3 project and is receiving continued support for operation as part of the ESA SSA R-ESC activities. The system is working on a continuous basis 24 hr/7 days with the support of the Athens Cosmic Ray Expert Group (Mavromichalaki et al., 2017).

The GLE72 event that occurred on 10 September 2017 was a moderate event and was recorded successfully by the GLE Alert plus System of A.Ne.Mo.S. In this case seven neutron monitors contributed to the

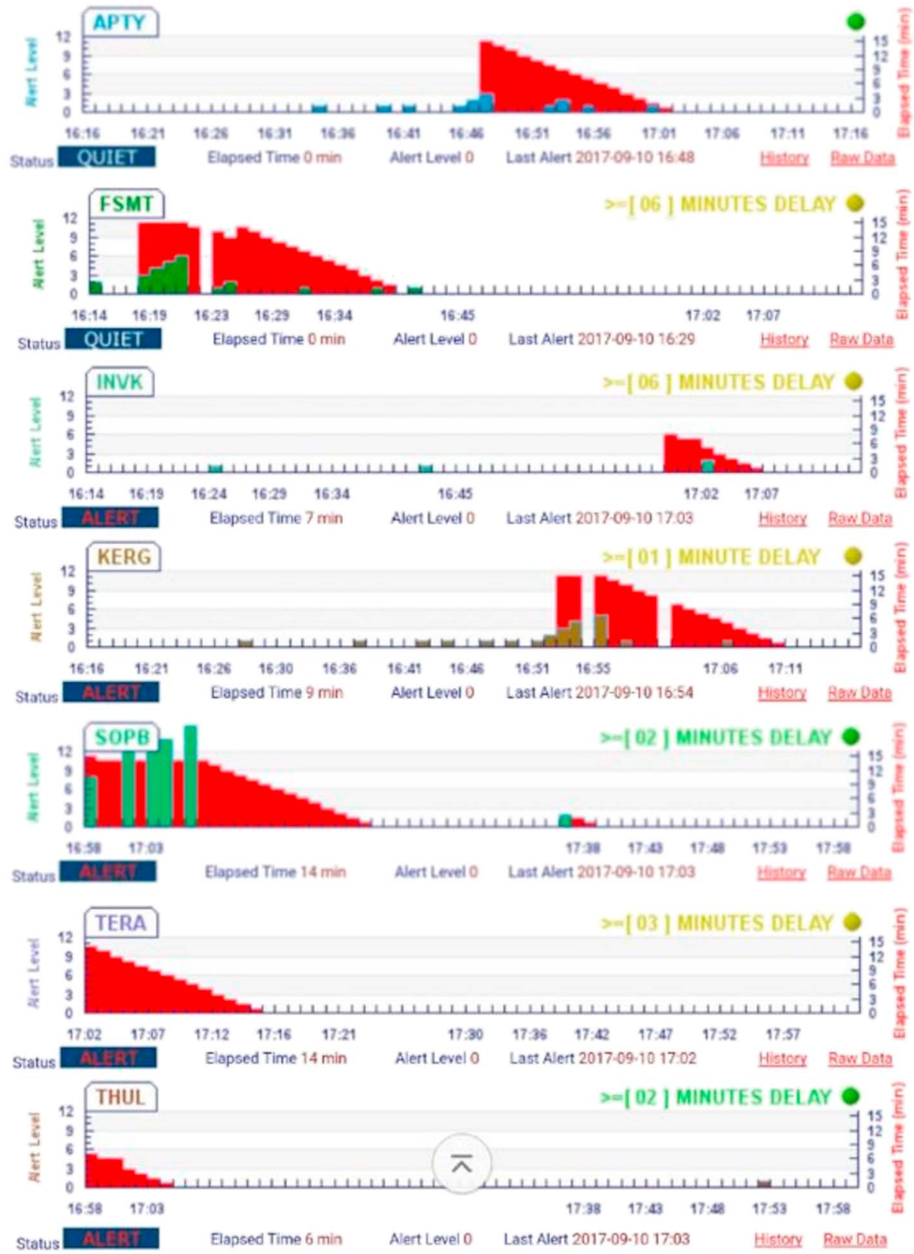

Figure 5. Snapshots of the seven neutron monitor stations of A.Ne.Mo.S. entering in alert mode on 10 September 2017 from about 16.00 to 18.00 UT (red color indicates alert mode and other colors indicate warning mode according to each station color).

establishment of the alert issued by A.Ne.Mo.S. in real time. The first time that at least three neutron monitors (KERG, INVK, SOPB, and THUL) entered in alert state individually during the same time window and a general alert was issued was at 16:58 UT. However, the first automated e-mail notification was not sent until 17:03 UT. The delay of 5 min was due to some internal processes of the system software.

A postevent analysis of the GLE72 event was also performed. The results are easily accessible through the A. Ne.Mo.S. and ESA SSA SWE portals under the option *Archived GLEs*. The evolution of the alert status for each station contributing to the GLE Alert is presented in Figure 6. The postanalysis of GLE72 gave the possibility to observe the evolution of this event in each neutron monitor station offline. There is a time difference between the timestamp of the stations, as presented in Figure 5, and the corresponding timestamps

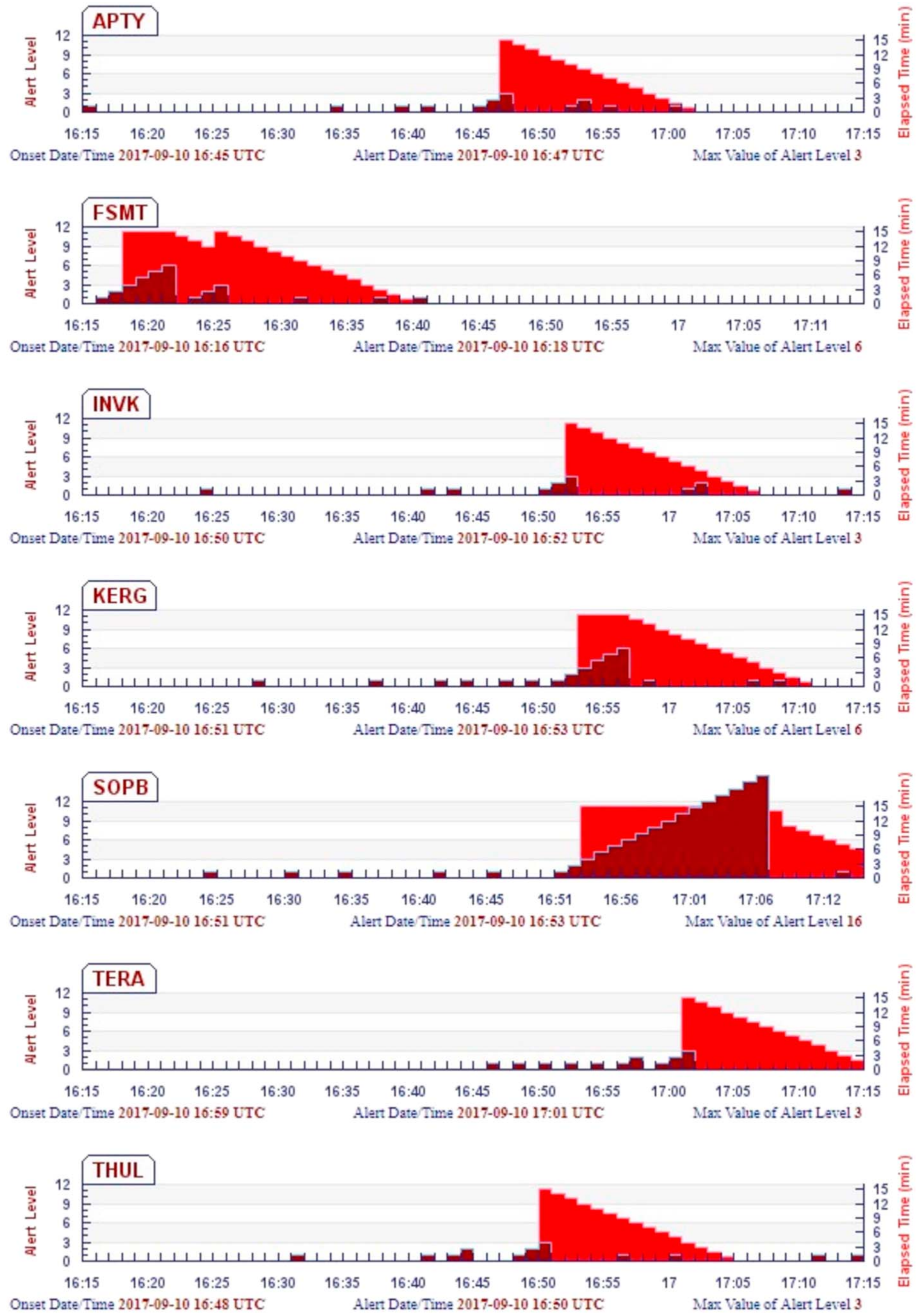

Figure 6. The alert level of the individual neutron monitor stations (in alphabetical order) that participated to the establishment of the GLE alert, namely, APTY, FSMT, INVK, KERG, SOPB, TERA, and THUL. Red color indicates alert mode and brown color indicates warning mode. These results have been reproduced from the GLE Alert plus database, available via the A.Ne.Mo.S. (http://cosray.phys.uoa.gr) and ESA Space Situational Awareness Space Weather Element (http://swe.ssa.esa.int/web/guest/space-radiation) portals under the option Archived GLEs.

obtained from the postevent analysis presented in Figure 6. This difference is due to synchronization issues or/and to small time delay between the timestamp of the neutron monitor station and the time of data provision to the GLE Alert plus System. Due to this fact, the data gaps observed in the real-time data (Figure 5) were filled in later during the postevent analysis, as seen in Figure 6 (see also http://195.134.93.53:8080/Archived_Gles.html). It should be mentioned that the plots in postevent analysis appear with the same time stamp, while the plots in Figure 5 display the real-time evolution of the event.

Table 2
A List of Proton Event Alerts Issued by NOAA SWPC Around the Time of the GLE72 Event (See Table 1)

#	Service Center	Alert	Begin time	Issue time
1	NOAA SWPC, ALTPC0, No44	Proton Event 100 MeV, Integral Flux >1pfu	10 Sep 2017 16:25 UTC	10 Sep 2017 16:40 UTC
2	NOAA SWPC, ALTPX1, No317	Proton Event 10 MeV, Integral Flux >10pfu	10 Sep 2017 16:45 UTC	10 Sep 2017 17:01 UTC
3	NOAA SWPC, ALTPX2, No61	Proton Event 10 MeV, Integral Flux >100pfu	10 Sep 2017 17:05 UTC	10 Sep 2017 17:11 UTC
4	NOAA SWPC, ALTPX3, No29	Proton Event 10 MeV, Integral Flux >1,000pfu	10 Sep 2017 18:40 UTC	10 Sep 2017 18:46 UTC

Therefore, some differences between the two figures are observed, highlighting the importance of the postevent analysis.

On the other hand, proton event (>10 and >100 MeV) alert signals are provided by the wide-known Space Weather Prediction Centre of NOAA (SWPC NOAA) based on measurements provided by the GOES satellites. A list of the alerts issued by this center concerning the GLE72 event is given in Table 2. A comparison of the GLE Alert issued by A.Ne.Mo.S. (last column of Table 1) with the >100 MeV alert by GOES is of great interest, since additional information about the radiation effect of the solar proton event can be obtained by having also observed the event at higher energies inside the Earth's atmosphere using ground-based observations provided by neutron monitors (e.g., Meier & Matthiae, 2014).

Thus, real-time provision of high-resolution CR data by neutron monitor stations, indicating primary protons with energy greater than 500 MeV, is very useful for the forecasting of large Earth-bound SEP events. In conclusion, the GLE Alert plus System, which relies on neutron monitor measurements obtained via the NMDB, provides the community a significant space weather asset. Currently, an updated version of the GLE Alert plus System is under construction, taking into account information obtained from the successful GLE72 event detection described in this paper.

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