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Test alert service against very large SEP Events

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Abstract

The Aragats Solar Environment Center provides real time monitoring of different components of secondary cosmic ray fluxes. We plan to use this information to establish an early warning alert system against *extreme, very large solar particle events with hard spectra*, dangerous for satellite electronics and for the crew of the Space Station. Neutron monitors operating at altitude 2000 and 3200 m are continuously gathering data to detect possible abrupt variations of the particle count rates. Additional high precision detectors measuring muon and electron fluxes, along with directional information are under construction on Mt. Aragats. Registered ground level enhancements, in neutron and muon fluxes along with correlations between different species of secondary cosmic rays are analyzed to reveal possible correlations with expected times of arrival of dangerous solar energetic particles.

Keywords: Space weather; Alert service; Very large SEP events; Neutron monitors; Solar proton events

1. Introduction

Unpredictable bursts of solar energetic particles (SEP) peaking in 11 year cycles are one of the major constraints on the operation of space systems and further technological utilization of near-Earth space (Tylka, 2001). Some of these bursts produce fluxes of high energy particles which can be harmful to satellite electronics, the Space Station, its crew and to aircraft flights over the poles. In the 1999 report on space weather, the US National Security Space Architect finds that during the preceding 20 years about one or two satellites per year have suffered either total or partial mission loss due to space weather (Space Studies Board, 1999). Since our lives depend heavily on satellite based technologies, not to mention the value of protecting humans in space and in aircraft, it is becoming increasingly important to have an accurate and reliable forewarning of the arrival of these dangerous particles, so that mitigating action can be taken if necessary.

The use of large-area detectors which can only be accommodated at ground based stations is vital for measuring the low fluxes of high energy particles accelerated during solar flares and in shock waves driven by the Coronal Mass Ejections (CME). The highest energy particles from the most severe events, arrive at the Earth about half an hour earlier than the abundant "killer" medium energy particles, thus providing an opportunity to establish an early warning system to alert the client to potential damage to satellites, space personnel, and flights scheduled over the poles (Dorman, 1999). Since few of the large number of SEP events produce dangerous ion fluxes, it is not only important to alert clients of the arrival of the most severe radiation storms, but also to minimize the number of false alarms of events which are not severe enough to cause damage. We can accomplish both goals by detecting secondary fluxes generated by the high-energy ions in the Earth's atmosphere by surface detectors located at mountain altitudes and low latitudes.

Because high energy ions are so few in number and because secondary particles are scattered and attenuated in the Earth's atmosphere, large-area detectors, located

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at high mountain altitudes are necessary to measure them. The information about a primary ion type and energy is mostly smeared during its successive interactions with atmospheric nuclei. Therefore, only coherent measurements of all secondary fluxes (neutrons, muons and electrons) can help to make unambiguous forecasts and estimates of the energy spectra of upcoming, potentially dangerous, flux. Lev Dorman (Dorman and Venkatesan, 1993; Dorman et al., 1993) demonstrated in numerous papers that detecting at least two cosmic ray flux components at one or, preferably, two stations at different altitudes will make it possible not only to reconstruct the solar ion flux outside the Earth's atmosphere, but also to estimate the energy spectra of upcoming solar particle fluxes. Multidimensional statistical methods of analysis of the multivariate data and time series, as well as timely delivery of the alert are also of utmost importance.

2. The structure of the aragats space environment center

The Aragats Space Environmental Center (ASEC, Chilingarian et al., 1999a, 2002) consists of two high altitude stations on Mt. Aragats in Armenia (geographic coordinates: 40°30′N, 44°10′E; cutoff rigidity: ~7.6 GV, altitude 3200 and 2000 m.). At these stations, several monitors are continuously measuring the intensity of the secondary cosmic ray fluxes and sending data to the Internet in real time (see Table 1).

After 50 years of operational experience, neutron monitors continue to be the best instrumentation for measuring intensity variations of cosmic rays starting from threshold values (determined by the rigidity cutoff and attenuation in the atmosphere) of ~1 GV (in polar regions) to ~15 GV (in equatorial regions) (Moraal et al., 2000). In the 1960s, Carmichael developed a neutron monitor with statistical accuracy of 0.1% for hourly data in preparation for the Year of Quiet Sun (IQSY) (Carmichael, 1964). This type of neutron monitor is usually designated by the name X-NM-64, where X denotes the number of counters operating in the entire monitor. For more details and for a list of world-wide monitors see Shea and Smart (2000).

Two 18NM-64 neutron monitors are in operation at the Nor-Amberd (2000 m elevation, NANM) and Aragats (3200 m elevation, ANM) research stations. The monitors are equipped with interface cards, providing time integration of counts from 1 s up to 1 min. Real-time data from these monitors is available at URL http://crdlx5.yerphi.am/DVIN.

One of the improvements to the Aragats monitoring facilities includes registration of the variations of the muon flux under different angles of incidence. The Nor-Amberd muon multidirectional monitor (NAMMM) consists of two layers of plastic scintillators above and below the NM installation. The lead filter of the NM will absorb electrons and low energy muons. The threshold energy of the detected muons is estimated to be 350 MeV. NAMMM consists of two parallel layers of scintillators, of total area of ~5 m^2, for details see the figure on page 944 in (Chilingarian et al., 2003). The data acquisition system of the NAMMM can register all coincidences of detector signals from the upper and lower layers, thus allowing measurement of the arrival of the muons from different directions. Changes in the relative count rates from different directions will indicate the direction of an approaching magnetized cloud, allowing the forecasting of geomagnetic storms. Changes in count rate with respect to the Sun direction will show any solar origin of ground level enhancements (GLE).

The solar neutron telescope (SNT-1) at the Aragats station is part of a world-wide network coordinated by the Solar-Terrestrial Laboratory of the Nagoya University (Matsubara et al., 1999; Tsuchiya et al., 2001). It consists of four 1 m^2, 60-cm thick scintillation blocks with anti-coincidence shielding (consisting of four 5-cm thick plastic scintillators, each of area 1 m^2) vetoing particles arriving from near vertical directions. An important advantage of the SNT over the NM is its ability to measure the energy of detected neutrons. The amplitude of the SNT output signal is discriminated according to four threshold values. The data from the solar neutron telescope is available online at URL http://crdlx5.yerphi.am/DVIN.

Table 1
Characteristics of the ASEC monitors

Detector	Altitude (m)	Surface (m^2)	Threshold(s) (MeV)	In operation since	Mean count rate (min^{-1})
NANM (18NM64)	2000	18		1996	2.5×10^4
ANM (18NM64)	3200	18		2000	6.2×10^4
SNT-1	3200	4; 4	130; 240; 420; 700	1998	6×10^4[a]; 1.5×10^5[b]
NAMMM	2000	5; 5	350; 10[d]	2002	2.3×10^5[c]; 2.9×10^5
AMMM, EMM	3200	48; 15	5000; 10[d]	2002	1.3×10^5[c]; 4×10^5

[a] Count rate for the first threshold; near vertical charged particles are excluded.
[b] Count rate of all particles registered in 60-cm scintillators.
[c] Expected total coincidences rate for the near vertical muon flux.
[d] First number – energy threshold for the bottom (muon) detector, second number – upper (electron and muon) detector.

At the Aragats high altitude station two surface arrays (MAKET and GAMMA) operate with the main purpose of detecting extensive air showers (EAS) initiated by very high energy primaries $>5\times10^{14}$ eV. The EAS installations are triggered 3–5 times per minute by high energy particles incident on the array. Plastic scintillators of 1 m^2, viewed by photomultipliers, are used for measuring charged particle densities and arrival times (for the determination of the angles of incidence). The total area of the surface detectors of GAMMA and MAKET installations is about 150 m^2. The spacing between detectors varies from several meters to tens of meters.

In an underground hall originally constructed for the ANI cosmic ray experiment (Danilova et al., 1992), another 150 detectors of the same type are located to measure the muon content of the EAS. The absorption in the 6-m thick concrete blocks and 7 m of soil filters electrons and low energy muons, so that only muons with energies >5 GeV reach the detector location. The high count rates of the charged component (mostly electrons and muons) at mountain altitudes (~450 counts/m/s for electrons and ~50 counts/m^2/s for 5 GeV muons) and the large area of the electron and muon detectors on Mt. Aragats are very attractive for establishing a monitoring facility for the investigations of the correlations between short term variations of electron and muon count rates which result from the enhancement of the flux of solar ions incident on the Earth's atmosphere or from additional galactic cosmic rays reflected by an approaching magnetized cloud of solar plasma.

As with the NAMMM, we will use the coincidence technique to estimate the arrival direction of high-energy muons. Scattering of high-energy muons is negligible in the atmosphere. Therefore, by measuring the incident muon direction, we can determine the arrival direction of the solar or galactic ions. This will give us additional evidence for the detection of solar particles. The count enhancements of the present ASEC monitors are integrated over all directions. The signal enhancements can be due either to solar particles or to disturbances of the Earth's magnetic field, leading to decrease of the local rigidity threshold (see for example Kudela and Storini, 2001). The *mean* count rate of muons in the Aragats Multidirectional Muon Monitor (AMMM) registered by the 48 m^2 scintillators is approximately 200,000 per minute. Thus, the sensitivity of this new monitor, calculated by simple Poisson statistics, reaches a record value of ~0.3% for 1min count rates, three times better than the Aragats N M. Using 27 m^2 scintillation detectors located on the top of the ANI concrete calorimeter, 24 m above the 48 m^2 underground array, we can monitor count rates from several different directions with respect to the Sun. Detectors on the top are grouped in 3, while those in the underground hall are grouped in 8 to provide a significant number of coincidences. We expect 300–500 coincidences in a 5-min interval. The geometry of the detector arrangement allows us to detect on directions from the vertical to 60° declination, with an accuracy of ~5°. Together with the Moscow TEMP muon telescope (Borog et al., 2001), the AMMM could fill the gap in the world-wide network of muon telescopes intended for forecasting severe geomagnetic storms (Munakata et al., 2000).

3. GLE correlations with solar energetic ion arrivals at 1 AU

The arrival times of ions at 1 AU are estimated by the technique proposed by Lockwood et al. (1990) and Fluckiger (1991). In those papers, it was proposed to use the arrival times and energies of the first ions detected by space-borne ion spectrometers to deduce the spatial-temporal history of the accelerated ions. Extrapolating the obtained dependences to relativistic particles, we can obtain the expected arrival time of ions that are energetic enough to enter the atmosphere at the Aragats geographical location, and produce the secondary fluxes reaching the Aragats altitudes. Relativistic ions arriving at 1 AU, and generating secondary fluxes through interactions with atmospheric nuclei, are detected by the ASEC monitors as peaks in the time series of 1 or 5 min count rates.

Here, we compare the times of detection of the first ions of GLEs by the ASEC detectors with the times of arrival of the bulk of so-called "hard" particles with energies greater than 50 MeV. The energies of the "hard" particles are sufficient for them to penetrate the walls of manned spacecraft and to result in a harmful or even fatal radiation dose to astronauts. Such intense events also degrade electronic components on unmanned spacecraft. Solar energetic ions can also penetrate deep into the atmosphere over the Earth's magnetic polar regions and produce increased ionization, lowering the ionosphere and disrupting radio communication (HESSI, 1997). In Fig. 1, the count rates of the ASEC neutron monitors (left *Y* axes) are superimposed on the solar "hard" (greater than 50 MeV) proton fluxes detected by the GOES satellites spectrometers (right *Y* axes) (GOES Integral Proton Flux, internet address www.sec.noaa.gov/Data/goes.html), for four different SEP events.

For all events, the intensity of the dangerous "hard" particles reaches significant values later than the arrival of the first relativistic ions that generate GLEs. Thus, the detection of the early arrival of relativistic ions by measuring GLEs forewarns us of the arrival of harmful fluxes of solar particles. Continuously comparing the well synchronized data streams from the ASEC solar monitors and estimating the correlations between differ-

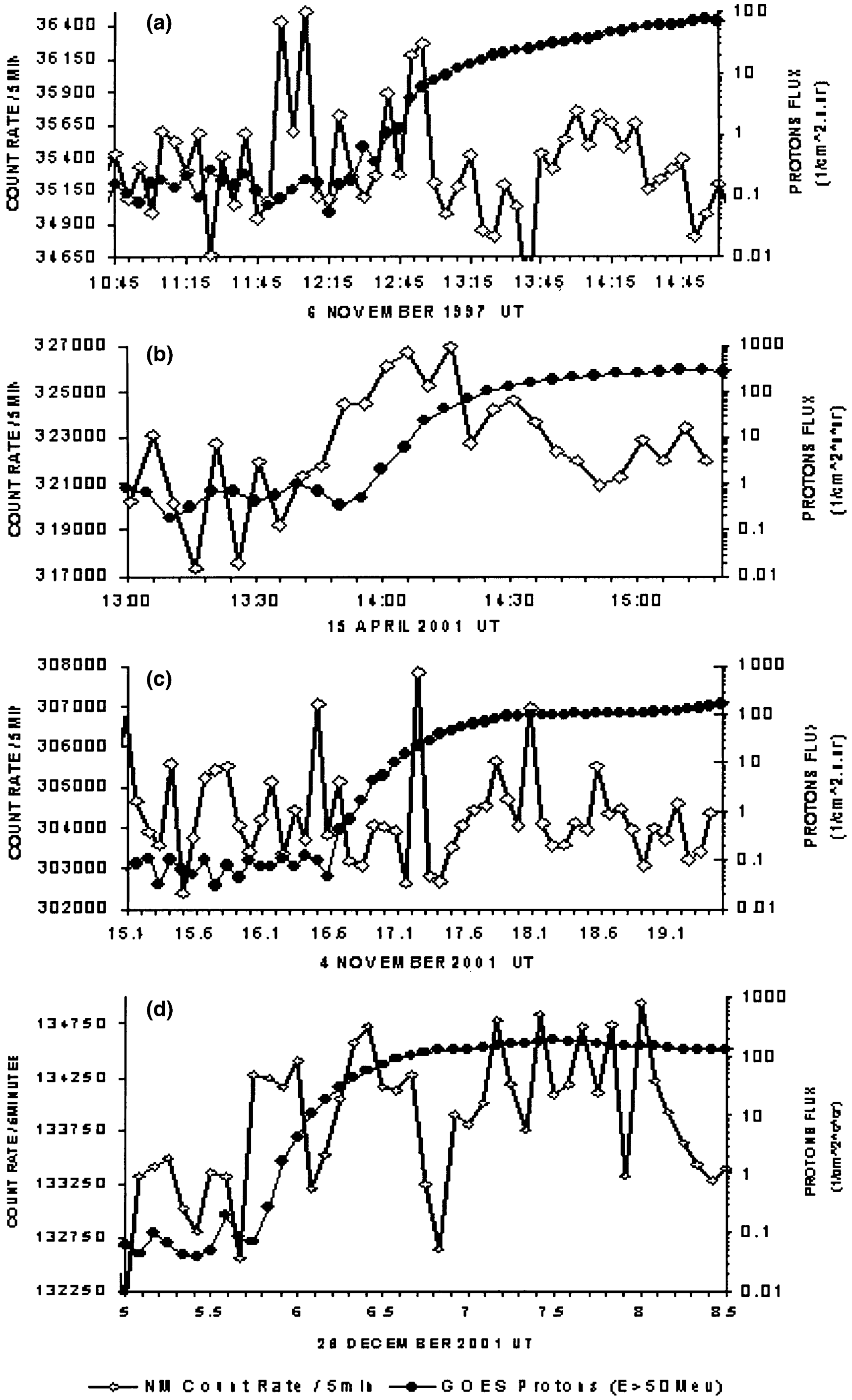

Fig. 1. Comparison of neutron count rates and GOES proton fluxes.

ent species of secondary cosmic rays, it is possible to issue alerts and warnings of when the abrupt increase in count rates will be detected at all muon and neutron monitors listed in Table 1. An e-mail alert is sent to users within 5 min of the start of the abrupt enhancement of the count rate (see Babayan et al., 2001), allowing time for satellite operators to take mitigating actions.

All the events in Fig. 1 are consequences of very strong flares which occurred in the 23rd solar cycle and were registered by the Aragats monitors. The GLE depicted in Fig. 1(a) was caused by the X9.4 X-ray flare of 11:41–12:01 UT, November 6, 1997; in Fig. 1(b), due to the X14.4 X-ray flare of 13:11–14:47 UT, April 15, 2001; in Fig. 1(c), due to the X1.O X-ray flare of 15:55–16:49 UT, November 4, 2001; and in

Fig. 1(d), due to the M7.14 X-ray flare of 04:24–06:39 UT, December 26, 2001.

4. Conclusion

The influence of solar radiation on humans and orbiting technological systems was summarized in the public documents of the ESA Space Weather Programme Studies as follows (Horne, 2001).

Energetic ions from SEP arriving to 1 AU can produce single event effects (SEEs) in satellite electronics (single hard errors, single event upsets, latchups, burnouts, gate and dielectric ruptures). These effects are normally due to heavy ions, but particles as light as protons or neutrons can produce the same effects as heavy ions through nuclear reactions with silicon inside the electronics (in the future, due to increasing miniaturization, protons may be able to directly induce SEEs);

The radiation effects on human beings are similar to the effects on electronics. Dose effects affect all cells, especially those, which are not renewed or at least not rapidly renewed. Single energetic particles can also break the DNA chain in the cell nucleus, producing chromosome aberrations, translocations and tumor induction. They can induce also cell mutation that can have effects on the genetics.

Tylka (2001) made the following conclusion based on his analysis of the observations by sensors on the WIND and ACE satellites: “at present SEP events are not predictable in any meaningful sense”. “We cannot give a reliable prediction of when such event will occur, nor can say, once an event has started, what its characteristics will be, even a few hours in advance.”

However, the SEP events discussed in this paper unambiguously indicate solar ions well above NM cutoff rigidities, arriving before 50 MeV protons are registered by GOES. Combining neutron monitor data with precise monitoring of the secondary muon flux by means of large directionally sensitive ground-based muon detectors provides good prospects to overcome partly the difficulties mentioned by Tylka (2001).

Simultaneous monitoring of the different secondary particle fluxes at two different altitudes and in different energy bandwidths, along with measurements of the anisotropy of particle fluxes will allow forecasting of forthcoming severe radiation storms. The advantage of the ASEC alerts as compared with NOAA services (SEC Space Weather Alerts – internet address www.sec.noaa.gov) is in the possibility of detecting ions of the highest energies, thus improving both the timing and the information content. However, for 24-h coverage, similar detectors must be located at two or three more locations around the circumference of the Earth. The information from ASEC will compliment the information from the space-borne sensors. The joint multidimensional multidetector analysis (Chilingarian et al., 1999b) of all relevant information will minimize the number of false alarms and will maximize the reliability and timeliness of forecasting the arrival of dangerous SEPs. The operating facilities at ASEC provide a test Space Weather Early Warning service using solar monitors equipped with all the necessary components to collect, store, analyze and send data to the Internet.

5. Uncited references

GOES Integral Proton Flux, Martirosyan et al. (2002), SEC Space Weather Alerts.

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