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Alert Service for Extreme Radiation Storms

A. Chilingarian, V. Babayan, N. Bostanjyan, N. Gevorgyan, A. Hovanissyan, G. Hovsepyan, G. Gharagyozyan, S.Kazaryan, L. Melkumyan, S. Sokhoyan, and S. Tserunyan

Cosmic Ray Division of Yerevan Physics Institute, Yerevan 375036, Armenia

Abstract. The Aragats Solar Environment Center (**ASEC**) located on Mt. Aragats in the Republic of Armenia, is providing real time monitoring of extreme radiation storms. Two neutron monitors (NM) and a Solar Neutron Telescope (SNT) operating on Aragats research stations are continuously measuring fluxes of Solar and Galactic Cosmic Rays. Currently, detectors are monitoring for possible abrupt variations of count rate. A prototype *Strong Radiation Hazard Alert* is issued if 2 out of 3 monitoring detectors demonstrate more than a 3σ increase in particle count compared to the predetermined variation allowed in each detector.

1 Introduction

Violent explosions on the sun, called Solar Energetic Phenomena (SEP), including Solar Flares (SF) and Coronal Mass Ejections (CME), dominate space weather conditions and occur frequently during the years of maximum solar activity. Some of them are powerful enough to disrupt space-borne electronics, damage power grids on the ground, and harm space station crews. The sun's activity has an eleven-year cycle during which its activity peaks then slowly subsides and starts to rise again.

In 1982, during the solar cycle 21, the GOES-4 satellite visible and infrared spin-scan radiometer was disabled for 45 minutes after the arrival of high-energy protons from a solar flare. Marecs-B, a marine navigational satellite was disabled [1]. The GOES-7 weather satellite lost half of its solar cells and its life span was cut in half during a large proton release by the sun during the powerful March 13, 1989 radiation storm. The SMM (Solar Maximum Mission) satellite dropped 3 miles from its normal orbit due to increased drag. Local radio transmissions in Minnesota were overpowered by California Highway Patrol messages. Geomagnetically-induced-currents caused a major power failure at the Hydro-Quebec Power Company in Quebec, Canada, causing the loss of 20,000 MW of electricity, leaving 6 million people without electricity for 9 hours, and a $26,000,000 transformer at a New Jersey Public Service Company plant melted down [2]. The cost of repairs at Hydro Quebec were about $10,000,000 . The loss to businesses due to the abrupt electrical outages is estimated to be near $100,000,000 [3]. In 1994 Canadian communications satellites ANIK E1 and E2 were disabled, and in 1997 the AT&T Telstar 401 communications satellite and NASA's GOES-8 weather satellite showed signs of malfunctioning, all a result of severe explosions on the sun resulting in radiation and particle ejections. [1]. The Advanced Satellite for Cosmology and Astrophysics (ASCA) became dysfunctional beyond repair as a result of the energetic Solar activity on July 15, 2000 [4]. These are but a few examples of very costly (billions of dollars) failures of equipment and systems due to the severe explosions on the Sun.

In 1999 L. I. Dorman suggested the potential of using large-area ground-based detectors to predict severe radiation hazards 30 minute before the main phase by analyzing time-intensity profiles of radiation storms from most violent Solar Flares. [5]. This would allow temporary preventative measures to protect vulnerable systems until the danger is past. Currently available services cannot effectively warn against these dangerous disturbances in advance, nor can they predict their severity, as will be demonstrated below. Space born detectors rely on measuring the larger number of medium energy particles created in mild as well as severe explosions, and have a chance of being damaged or going on stand-by to protect themselves, in either case introducing uncertainty in delivering the alert on time.

There are a number of experiments using space born detectors to observe the sun. These experiments continuously measure radio, optical, X and γ- ray fluxes and the properties of the interplanetary magnetic field [6] as well as solar wind velocity, temperature and density [7] . The information available from the space-borne sensors on the location and properties of the Solar Energetic Phenomenon plus the on-line data from ground-based large area detectors measuring the high energy particle intensities, can be used to characterize the phenomenon.

The very few relativistic particles, which can be best observed by large-area detectors on the ground, arrive much earlier than the medium energy particles. Consequently, the magnitude of the expected hazard as well as its time and location of arrival on earth can be predicted some 30 minutes in advance of the arrival of the medium energy "killer" particles, allowing enough time to estimate the peak intensity and profile of the event. Satellite electronics can be temporarily put on stand-by as a protective measure, only if the hazard from a given explosion on the sun is dangerous enough to do harm, but not if the explosion is weak and radiation and particle flux reaching the earth from it pose no danger.

Judging from the recent examination of the nitrate record from the Arctic and Antarctic ice K. G. McCracken et. al. conclude that the danger of severe radiation storms will increase in the near future. A reliable and timely forecasting and alert service is vitally necessary for the safe operation of the fast growing network of satellites. [8,9].

The Aragats Space Environment Center (**ASEC**), under development in the Republic of Armenia, aims at consistently and reliably predicting the most severe explosions on the sun, which can cause damage to satellites so vital to our daily lives.

2 Significant Measurements and Arguments.

During the current and the previous cycles of solar activity (cycles 22 and 23), some very relevant data has been gathered by space-born, and ground-based detectors to cause us to believe that it is possible to predict the most dangerous events arriving at earth from explosions on the sun about 30 minutes in advance. There have been many explosions on the sun during the solar activity cycles, but we use 2 particular ones to build our case. The data from the sun explosion of September 29, 1989 and another one about eleven years later on April 15, 2001 was monitored by 6 different detectors in space and on the ground. The data from these detectors is displayed in Figures 1 and 2 and a description of these detectors follows:

GOES-7 was the Geosynchronous Operational Environmental Satellite, launched by NASA, in orbit from 1987 to 1996. It is about 36,000 km above the earth and at N 0.0° and W 135°. Among other things it measures the proton density rate at different energy ranges covering the spectrum form 0.6 to 500 MeV and the power density for X-rays of two different wavelength ranges: short X-rays 0.5 to 4 Angstrom (Xs), and long X rays 1 to 8 Angstrom (Xl) [6].

GOES-8 is the Geosynchronous Operational Environmental Satellite at 36,000 km above the earth N 0.0° W 75° in orbit from 1995 to 2001. [6]

Apatity Neutron Monitor– is a ground based neutron monitor a few hundred kilometers north of St. Petersburg at the coordinates N67.55° , E33.33° , 177 m above sea level [10]. Because of its close location to the North Pole, where the earth's magnetic field strength is very low, proton fluxes with energies as low as about 0.6 GeV can penetrate the atmosphere in this location and cause count rate enhancement in the detector. This threshold (measured in units of Volts) is called the "rigidity" of the location, because it indicates the rigidity (or lack of it) in the region to allow the penetration of charged particles through the earth's magnetic field at that location. The rigidity is equal to the minimum energy of the ion that can penetrate through the earth's magnetic field at that location divided by its charge. The closer the location is to the poles the lower the rigidity. The rigidity is at a maximum on the equator (15 – 17 GV). The rigidity at the location of Apatiti is about 0.6 GV.

Nor Ambert Neutron Monitor- is a ground based neutron monitor on Mt. Aragats in the Republic of Armenia at the coordinates N44.17° , E40.5° , 2000 m above sea level. Because of its latitude, reasonably far from the North Pole, the rigidity in this location is about 7.2 GV [11].

Aragats Neutron Monitor- is a ground based neutron monitor on Mt. Aragats, at 3200 m above sea level [11].

Aragats Solar Neutron Telescope - is a ground based neutron telescope on Mt. Aragats, at 3200 m above sea level. [12].

The Neutron Monitor and the Neutron Telescope data from the detectors in Armenia are available on line and in real time in 1-minute intervals at http://CRDLX5.yerphi.am [13]

Some explanation of the frames in Figure 1 and 2 follow:

1a and 2a) X ray power Density as measured by GOES. Xl - Long X-rays λ=1 to 8 Ansgrom.
Xs – Short X rays λ=0.5 to 4 Ansgrom [6]

1b and 2b) Proton rate according to different energy ranges as measured by GOES.
P1 – 0.6 to 4.2 MeV, P2 – 4.2 to 8.7 MeV, P3 – 8.7 to 14.5 MeV,
P4 – 15 to 44.0 MeV, P5 – 39 to 82 MeV, P6 – 84 to 200 MeV,
P7 – 110 to 500 MeV. [6]

2c)   The neutron count rate at the Nor Amberd neutron monitor [13].
           It shows the number of the secondary particles produced by the galactic and solar
           cosmic rays (mainly protons with energy greater than 7.2 GeV) reaching the
           Nor Ambert detector at 2000 m above see level. If a very severe radiation storm
           occurs the primary particles coming from the sun can also be detected.

1c and 2d) The same as in 2c) except at the Aragats neutron monitor at altitude 3200 m. [13]
           Due to very strong attenuation of the solar protons and neutrons in the atmosphere,
           the probability of detecting primary solar particles is much greater at the Aragats
           station than at similar installations located at 2000 m. and at sea level.

2e)   The same as 2c) but detected by the Aragats Neutron Telescope, a new type of
           monitoring device with the ability to roughly measure incident particle energy as
           well as count them [12].

1d and 2f) The same as 2c) but detected by the Apatiti Neutron Monitor near sea level and high
           latitude where the rigidity is 0.6GV [10] . This monitor will register
           secondary particles from primary solar particles as well as low energy cosmic rays
           because of its low rigidity location.

During Solar flares large number of particles, namely electrons, protons and heavier ions are
accelerated and ejected into the interstellar medium. While the GOES and ACE satellites
measure medium energy particles (<500 MeV) which are in abundance, the large-area ground
based monitors measure the secondary particles which are created by the very high energy
(> 7.2 GeV on Mt. Aragats) particles which are very few in number.   Figures 1 and 2 show the
variety of particles and X-rays reaching the detectors in space and on the ground as a function
of the time of day with respect to the Coordinated Universal Time (UTC), also known as the
Greenwich Mean Time (GMT). Even from the very course time scale on the plots it can be
seen from Figure 1 that the X ray signals at the GOES satellite (Fig.1a) and the particle signals
on the ground based monitors (Apatity, Nor Ambert, and Aragats – Fig. 1c, d, e) arrive earlier
than the proton signal at GOES (Fig. 1b). By extracting the information from the data tables, it
can be seen that the high energy particles arriving at the ground-based monitors at the same
time (11:46 UTC) as the X-rays to GOES are triggering a very fast and very sharp increase in
the count rate at both Apatity and Aragats monitors. While the data for Figure 1b shows that
the higher intensity flux of low and medium energy protons detectable by the GOES satellite
arrive half hour later (12:15 UTC), the GOES satellite completely misses the earlier arriving
but much fewer high energy protons.

Another observation worth mentioning from Figure 1 is the difference in the time-profile of the
Aragats (1c) and Apatity (1d) Neutron Monitor signals. The signal from Aragats is much
narrower than from Apatity due to the large difference in the rigidity of the two locations on
earth. The lower energy particles arriving as much as 10 hours later than high-energy particles
are continuously registered by the Apatity monitor, but not by the Aragats monitors. These
particle have enough energy to penetrate the earth's magnetic field at the Apatiti location
(rigidity 0.6 GeV) but not high enough to penetrate at the Aragats location (rigidity 7.2GV) .
Thus with the Aragats monitors register only the high energy particles, which are directed
toward earth from the severe solar explosions only; these explosions, when directed toward
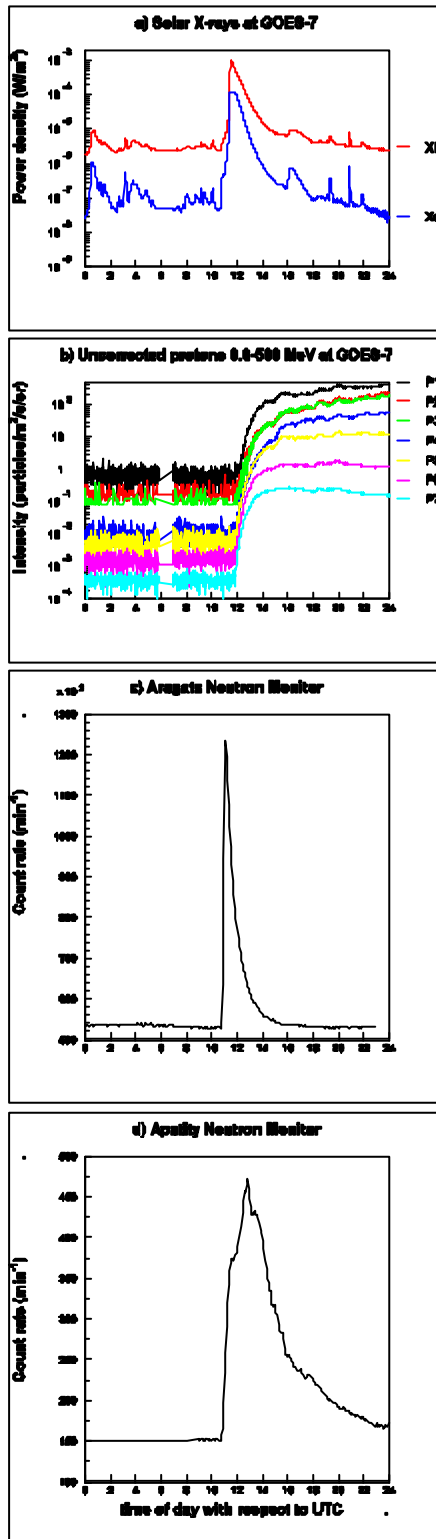earth, can fatally or partially damage near-earth systems.

September 29, 1989

April 15, 2001

Figure 1. Large Solar Flare event recorded by various monitors around the world on September 29, 1989.
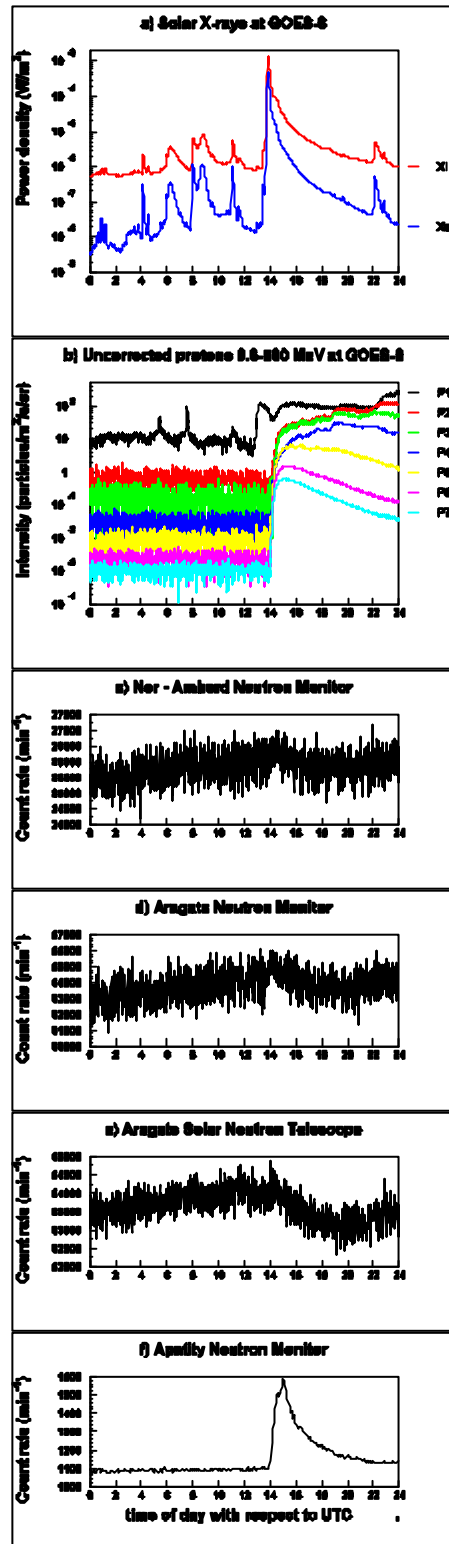

Figure 2. Large Solar Flare event recorded by various monitors around the world on April 15, 2001

Since 1989, when the data in Figure 1 was taken, we have reactivated a neutron telescope on Mt. Aragats and the Nor Ambert Neutron Monitor also on Mt. Aragats but 1200 m lower than the Aragats Neutron Monitor and Telescope. Signals from these additional detectors are displayed in Figure 2 as well, which shows the data from a flare accompanied by a radiation storm on April 15, 2001. The source of this explosion was near the Sun's western limb, directed mostly away from Earth. Thus, this flare, nearly as powerful as others which have caused damage to near-earth systems, caused no such effects.

The X-ray signal from the April 15 2001 explosion was registered by GOES-8 to have arrived at 13:35 UTC (Fig. 2a). The Apatity monitor and GOES-8 satellite registered an abrupt enhancement in the arrival of particles at both the Satellite and the ground at 14:00 UTC (Fig. 2a an 2f), some 25 minutes later than the X-rays. These are primary X-rays coming from the solar flare itself. Since the X-rays travel at the speed of light the arrival of the primary X-rays would coincide with the arrival of the high-energy particles, because the high-energy particles are traveling at nearly the speed of light. For example at the Rigidity threshold of 7.2 GV at the **ASEC** detectors the speed of the protons registering on these detectors is equal to or greater than 0.993 times the speed of light, that is the speed of the protons is almost equal to the speed of the X-rays. And indeed comparing the time of arrival of the X-rays on GOES-7 (Fig 1a) and the time of arrival of the high energy particles at **ASEC** (Fig 1c) one can see that the X-rays and the particles arrived at the same time, an added confirmation that the particles registered by the **ASEC** monitors are high energy particles traveling at almost the speed of light.

On the other hand at the location of Apatity (rigidity = 0.6GV) protons traveling with speeds as low as 0.8 times the speed of light can penetrate the earth's magnetic field and register a signal on the detector. One should also consider that the lower energy particles travel a longer path length due to more spiraling in the magnetic fields through which they travel. Thus their arrival time is delayed by even more than just the ratio of their speed as compared to the speed of the high-energy particles or X-rays originating from the same explosion at the same time and in the same direction. Thus the arrival of the particles at Apatity (Fig 2f) and GOES-8 (Fig. 2b) some 25 minutes after the arrival of the X-rays at GOES-8 (Fig 2a) in the April 15, 2001 data indicates that the arriving particles were the low energy (< 0.6 GeV) particles.

On April 15, 2000, the monitors at the Aragats Space Environmental Center (**ASEC**) registered less than one percent particle enhancement shown in Figures 2c, 2d, 2e. These signals are so low that they are practically in the noise, thus in the Figure 2 c, d, and e we don't subtract the background noise as we did for Fig. 1c. The lack of signal on the **ASEC** monitors demonstrates that there was no significant flux of high energy particles reaching the earth, thus the flux of lower energy particles directed toward earth would not be large enough to cause damage. The coincidence of the time of arrival of particles at the GOES-8 (Fig. 2b) and Apatity (Fig. 2f), the anticoincidence of the time of arrival of the particles at Apatity (Fig. 2f) and the X-rays at GOES-8 (Fig. 2a), and the lack of significant count rate on the Aragats Space Environment Center monitors (Fig. 2c,d,e) shows that the particles registered by Apatity are those of only medium to low energy unaccompanied by particles of high energy, thus the radiation storm from this explosion does not pose danger to satellites on earth. While GOES-8 (Fig. 2b) continues to register particles of less than 0.6 GeV energy (the Apatity threshold) for a long, time, the Apatitiy signal has subsided in about 4 hours.

The data in Figures 1 and 2 illustrate that weak solar storms which cause no harm, can trigger signals at satellite sensors and high latitude detectors on earth while only severe storms directed

toward earth can trigger signals on large-area, ground-based detectors at lower latitudes, such as at **ASEC**. Thus the rate of false alarms when using lower latitude, large-area ground based detectors would be very rare, and much lower than with other methods. This phenomenon presents a compelling reason for why the Aragats Space Environmental Center (**ASEC**) in the Republic of Armenia is ideally located for the extreme radiation and particle storm alert service.

3 The Alert Service

One of the most important features of the alert service must be it's reliability, its timeliness, and ease of access to the customer. Thus as soon as the high energy particles from severe solar storms arrive at earth, the data must be analyzed very quickly, processed and sent to the customer alert watch control centers, allowing the customer most of the time until the arrival of the more abundant medium energy killer particles to take damage control action. Naturally this alert has to come via fast computer communication between the alert service and the customer.

The alert service can be comprised of a distributed network of detectors, readout computers and servers issuing the alert to the customer via e-mail as shown in Figure 3. To meet the requirements of the alert service, network bottlenecks associated with failures related to data acquisition, data transfer, and alert delivery to the end users should be eliminated.

The alert process can be accomplished through 4 phases:
  – Data readout from the detector;
  – Transfer of the latest data to the server;
  – Data analysis and alert triggering;
  – Alert delivery to the end user.

We have created a small, prototype alert service to demonstrate its feasibility.

3.1 Data Readout
The data from each detector at **ASEC** is collected using local computers and stored on their hard disks in 1-minute intervals. After being stored the data is available for transfer. The execution of this part of the task takes less than 3 seconds.

3.2 Data Transfer to On Line Computers
The data is transferred to the server in 1-minute intervals, as soon as it is available from the local computers. To make the data available to the server, the readout computer should support data exchange services, such as NFS (Network File System), FTP (File Transfer Protocol), HTTP (Hyper Text Transfer Protocol) or File Sharing (Windows). FTP is the best choice since it is secure and robust against connection failures and the most efficient in terms of computer resource usage. Every minute the server initiates parallel downloading processes for each of the 3 detectors (Nor Ambert Neutron Monitor, Aragats Neutron Monitor, and Aragats Neutron Telescope) at **ASEC**. The use of a multitasking operating system is mandatory in such schemes for simultaneous access to the same data file. We use Linux OS [14]. This stage takes less than 25 seconds.
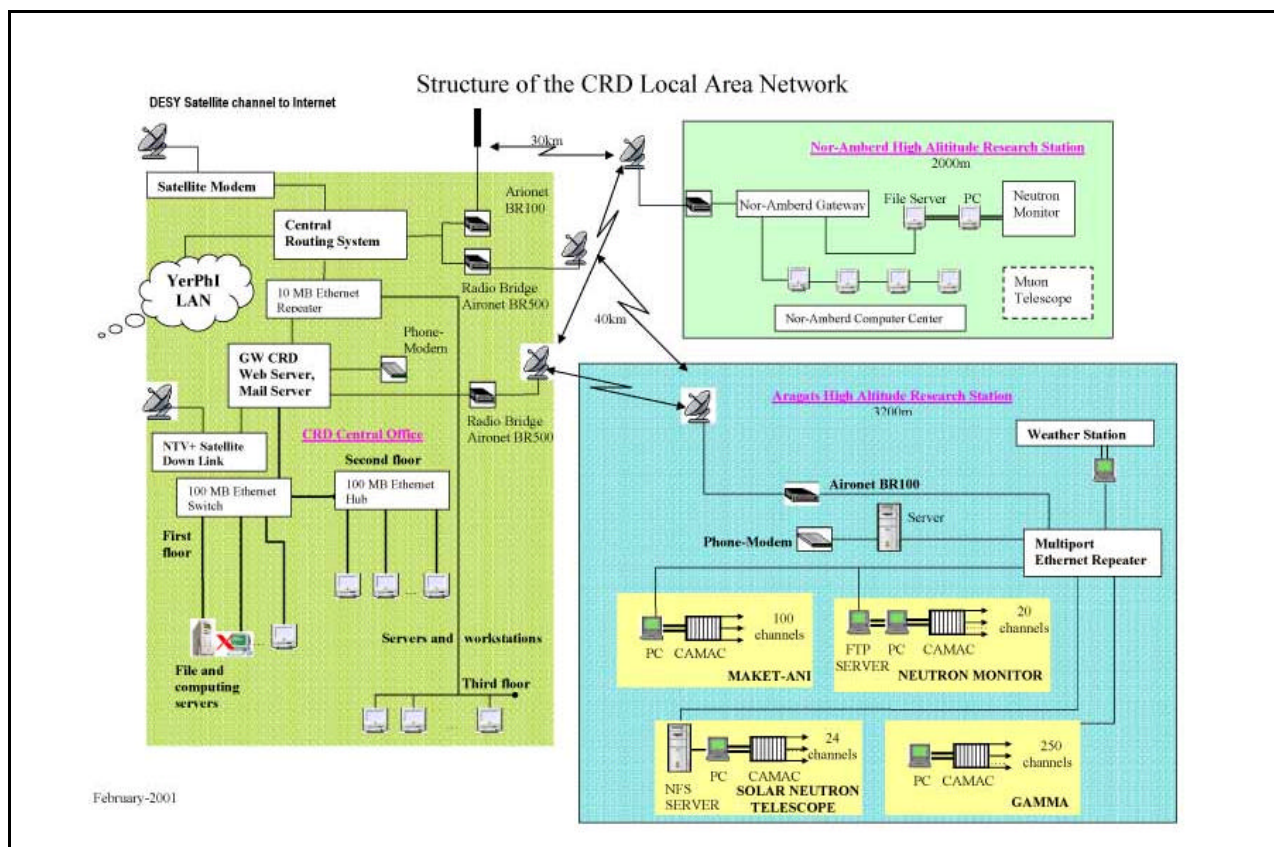
Fig. 3. Local Area Network and monitoring facilities of ASEC

3.3 Analysis and Alert Triggering

Each minute the server initiates a routine which performs checks for abrupt increases on the latest available data from the three **ASEC** detectors located at the same latitude but two different altitudes. Independent data from the three independently operating monitors ensure robust operation against possible outliers (false signals due to technical or human error). If 2 out of 3 detectors demonstrate more than 3σ increase in the count rate, the alert is issued by sending e-mail to the mail list, running on the same server. This operation requires less than 3 seconds.

3.4 Alert Delivery

Prompt alert delivery reaching to the end user is of highest priority. To ensure fast delivery of the alert, the best solution is to keep the messages short and fit them into one TCP/IP (Transmission Control Protocol/Internet Protocol) massage.

Message length = 1500 byte - TCP header - mail headers = 1000 bytes

Therefore, the message body should contain around 1000 characters. In such a situation we expect that 1 - 3 minutes will be spent on e-mail delivery. For reliable operation a reserve internet link should be established. Thus, from the time of the arrival of the most energetic particles at the detectors to the delivery of the alert at the customer's server 4 minutes will have

elapsed, allowing almost all of the available time until the arrival of the "killer" particles for protective action.

3.5 Synchronization of the Readout and Server Computers
The key factor for reliable operation of the alert system is the synchronization of the server and readout computers at scales less than 1 second. The synchronization is achieved by using the GPS (Global Positioning System) as the reference clock and the Network Time Protocol (NTP)

4 Some Considerations.

The coincidence of the data from 3 independent detectors on Mt. Aragats will make **ASEC** alert service robust against false alarms. In the future we plan to add a forth check on the detection of the severe solar explosions with the use of additional data from the multi-directional muon telescope, now under construction. Our flexible scheme of data integration makes it possible to use data from other detectors worldwide. At the onset strong radiation storms are very anisotropic, and only after about an hour do they become quasi isotropic. Thus, to improve our alert service we plan to analyze on-line data available from worldwide network of cosmic ray stations [15] as well. To make our protocol alert service efficient, we routinely check for possible failures of detectors, on-line computers, Local Area Networks and satellite antennas.

5. Conclusion

The use of large-area detectors which can only be accommodated at ground based stations is vital to measurement of very-few the very few high energy particles released only in severe solar explosions. The high energy particles arrive about a half hour earlier than the abundant "killer" medium energy particles, thus providing an opportunity to establish an early warning system to alert the client of the potential damage to satellites, space personnel, and flights scheduled over the poles. The controlled preventative measures to protect these systems can be quite disruptive to our daily lives, but not as disruptive and certainly not as costly as the damage caused if the measures are not taken. Thus it is not only critical to alert clients about the arrival of the most severe radiation storms directed toward earth, but also to minimize the number of false alarms. We can accomplish both goals by detecting the few high-energy particles released only by severe explosions on the sun. Because these particles are so few in number, large-area, ground-based detectors are necessary to measure them. Because lower energy particles can penetrate the earth's magnetic field at latitudes closer to the poles, detectors located at lower latitudes, far away from the poles such as at **ASEC** are necessary. Reliable analysis of the data and delivery of the alert is of utmost importance. All of the requirements to deliver timely, accurate, and reliable alerts to the end user against severe solar explosions directed toward the earth which can cause damage to satellite electronics can be accomplished from the Aragats Space Environmental Center (**ASEC**) in the Republic of Armenia.

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