Recent Research applications at the Athens Neutron Monitor Station

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Abstract. The ground based neutron monitor measurements play a key role in the field of space physics, solar-terrestrial relations, and space weather applications. The Athens cosmic ray group has developed several research applications such as an optimized automated Ground Level Enhancement Alert (GLE Alert Plus) and a web interface, providing data from multiple Neutron Monitor stations (Multi-Station tool). These services are actually available via the Space Weather Portal operated by the European Space Agency (http://swe.ssa.esa.int). In addition, two simulation tools, based on Geant4, have also been implemented. The first one is for the simulation of the cosmic ray showers in the atmosphere (DYASTIMA) and the second one is for the simulation of the 6NM-64 neutron monitor. The contribution of the simulation tools to the calculations of the radiation dose received by air crews and passengers within the Earth's atmosphere and to the neutron monitor study is presented as well. Furthermore, the accurate calculation of the barometric coefficient and the primary data processing by filtering algorithms, such as the well known Median Editor and the developed by the Athens group ANN Algorithm and Edge Editor which contribute to the provision of high quality neutron monitor data are also discussed. Finally, a Space Weather Forecasting Center which provides a three day geomagnetic activity report on a daily basis has been set up and has been operating for the last two years at the Athens Neutron Monitor Station.

1. Introduction

The cosmic rays are high energetic particles, mainly protons, alpha particles and heavier nuclei that originate from galactic and stellar sources. The cosmic rays modulated and in some cases enhanced by the solar activity, penetrate the Earth′s magnetic field and reach the atmosphere. The nuclear interactions of these particles with the molecules of the atmosphere produce cascades of secondary particles consisting of muons, neutrinos, electrons, positrons, gamma and the hadronic component which means neutrons, protons, $\pi+$ and $K\pm$. These particles can reach the Earth′s surface and be detected by ground based detectors.

The neutron monitors are the ground based detectors that continuously measure the flow of the cosmic rays that reach the Earth′s surface. The measurements of the neutron monitors are of great importance since they contribute to the study of several scientific fields, such as the solar activity and the prediction of the space weather. Since the beginning of neutron monitor operation about 100 neutron monitors have been installed at different places in the world creating the Worldwide Neutron Monitor Network, in order for their measurements to be easily accessible. A wide research field uses the neutron monitor measurements, which can be divided into three main categories [1, 2]

- Studies of anisotropy, which requires neutron monitors with well-defined and narrow cones of acceptance for charged particles, covering all directions as evenly as possible;
- Solar neutron measurements, which require neutron monitors at high altitude in equatorial regions;
- Spectral measurements, which require an optimal distribution along cut-off rigidities.

The advantage of the neutron monitors in the network is their high statistical accuracy due to their high counting rate, which allows them to observe small events that are not possible to be detected with satellites.

On the other hand, the neutron monitors record galactic and solar relativistic cosmic rays and can play a key-role in space weather forecasting, as a result of their interaction with interplanetary disturbances. Note that space weather is an environmental concept that refers to the dynamic conditions in the space contiguous to Earth, but also at an interplanetary and interstellar space scale. A wide variety of physical phenomena influence space weather including solar events as coronal mass ejections (CMEs) and solar flares (SFs), populations of galactic (GCRs) and solar (SCRs) cosmic rays, geomagnetic storms, ionospheric disturbances and geomagnetically induced currents at the Earth's surface. Cosmic rays also directly affect the terrestrial environment and serve as indicators of solar variability and non-anthropogenic climate changes on Earth at present and in the distant past. Despite decades of tradition, neutron monitors remain the state-of-the-art instrumentation for measuring GeV cosmic rays that cannot be measured in the same simple, inexpensive, and statistically accurate way by space experiments [3]. The continuous monitoring of the cosmic ray intensity near Earth by neutron monitors since the International Geophysical Year 1957/58 represents the longest continuous, high-time resolution series of particle radiation measurements in space science.

In this work the modern Athens Neutron Monitor Station (ANeMoS) operating at the Faculty of Physics of the National and Kapodistrian University of Athens at Greece, as well as its main research applications that have been developed and currently provided to the scientific community is being presented.

2. Athens Neutron Monitor Station

ANeMoS was established in November 2000 with a standard Super 6NM-64 at an altitude of 260 m above sea level located at 37.58° N, 23.47° E and with a vertical cut-off rigidity of 8.53 GV (figure 1). The Athens station operates continuously 24h per day and provides in real time high resolution data (1-hour, 1-min) in graphical and digital format to the internet. It was the fourth station worldwide which operated in real time. This station is important for the estimation of the maximum particle energy during great proton events due to the fact that frequently the maximum energy of these particles ranges within 5–10 GeV, i.e. very close to the minimal energy of particles recorded in Athens [4]. The measurements of the station are being processed automatically in order to be compatible with data from other stations. This is significant because in order to study in detail CR variations and space weather conditions, it is necessary to compare a number of high rigidity stations with good quality data. The resolution of the measurements reaches values as low as one second –with a mean counting rate ~55 counts/s.

Figure 1. Infrastructure of registration system of ANeMoS consisting of 6NM-64 counters.

Figure 2. The webpage of the High Resolution Neutron Monitor Database Project -NMDB.

In 2003 the Athens cosmic ray station has developed a data collection system capable of gathering data from remote stations and able to present their data to the Internet via FTP or HTTP servers, named Athens Neutron Monitor data Processing Center (ANMODAP). It is created with the aim to make feasible the use of the neutron monitor network data in real time for the space weather tasks. The modern methods applied to these data and the obtained results gave a way for a possible forecasting of the arrival at Earth of the powerful disturbances from the Sun. This center was collecting and processing ground based data from twenty-five real time NM stations as well as satellite data [5]. At the same time with some other Centers (IZMIRAN, BARTOL University) was gathering data to detect possible abrupt changes in the cosmic rays associated with the real-time solar wind and geomagnetic disturbances. This center put the basis of a world wide data collection system in real time from the neutron monitor network, adjusted software capable of the real time data processing and worked on the elaboration of forecasting models.

Once in 2008 a wide European collaboration for the implementation of the first real time database of Neutron Monitors with the participation of 12 countries and more than 50 Neutron Monitor Stations has begun. Twelve different countries have cooperated within the Seventh Framework Programme of the European Commission, in order to create a real-time database with high resolution neutron monitor data [6, 7]. The central database comprises all neutron monitor data acquired in about the last 50 years and new continuously updated observations from 17 NMs with 1-min and 1-h resolution, operated by the institutes that constitute the Neutron Monitor Database (NMDB) consortium (figure 2). The key point of this project is the development of a flexible database with important easy to use applications (http://www.nmdb.eu). ANeMoS is one of the fundamental partners of the network of the NMDB database sending data in real time to this database and it furthermore maintains and manages one mirror server of this project.It is important to note that the NMDB had to overcome four important challenges:

(a) To design a database capable of hosting data of 1-min and 1-h resolution, in real-time, together with historical ones and meta-data.

(b) To provide an access point for all NM data providers.

(c) To develop user tools with which NM data will be uploaded to the database and by which users will get access to the NMDB for downloading data.

(d) To compute comprehensive parameters from the NM data in near real-time as CR distribution function in space; ionization rates in the atmosphere *vs*. altitude and cut-off rigidity; radiation dose rates in space, magnetosphere and in atmosphere; possible changes of cut-off rigidities.

Therefore, the need for high quality real time data is imperative. The quality of the data is handled by different correction algorithms that filter the real time measurements for undesired instrumental variations. In order to achieve this essential aim, a number of different correction algorithms has been developed and used in ANeMoS data, the output of which is provided in real time by the corresponding web form (figure 3): a) the established Median Editor and the Median Editor Plus that constitutes an improvement version of Median Editor, b) the ANN algorithm based on neural networks and the improved ANN Plus, c) the Edge Editor that is currently used for the announcement of the data to the NMDB [8]. Moreover, a new online tool is developed for the barometric coefficient calculation by using a reference station, the output of which reflects the data quality of the stations [9] (figure 4).

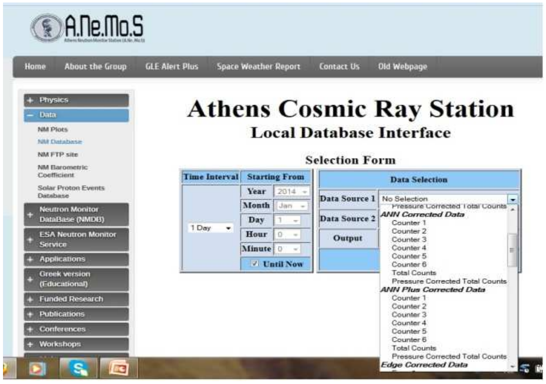

Figure 3. Athens NM station provides cosmic ray corrected data with five different algorithms in graphical and digital form.

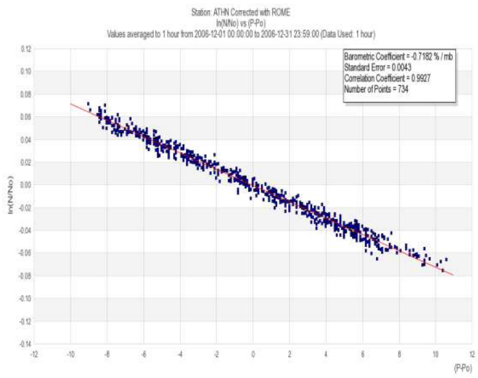

Figure 4. The barometric coefficient, necessary for the pressure correction of data, can be calculated for every NMDB station via the new online tool. The accuracy of the calculation, expressed via the correlation coefficient of the linear regression, reflects the data quality of the stations.

3. Research Applications

During the past years ANeMoS has developed and implemented several research applications that can play a key role in space and solar terrestrial studies as well as for space weather tasks. The most important applications provided at this time are presented below:

3.1 ESA Services

The Cosmic Ray group of ANeMoS has developed and implemented the establishment of the European Neutron Monitor Service available via the ESA SSA SWE portal (http://swe.ssa.esa.int) in the frame of the Space Situational Awareness (SSA) Program of the European Space Agency (ESA). The Athens Cosmic ray group is considered as an expert group of the Space Radiation Center and provides to ESA two products: [a] Access to the Neutron Monitor Data of Multiple Stations and [b] Reliable and timely GLE Alerts (http://swe.ssa.esa.int/web/guest/space-radiation).

3.1.1 GLE Alert Plus

Ground level enhancements (GLEs) are observed as significant cosmic ray intensity increases at neutron monitor measurements, caused by an intense solar flare and/or a very energetic coronal mass ejection. Due to their space weather impact it is crucial to establish a real-time operational system that would be in place to issue reliable and timely GLE Alerts. Such Neutron Monitor Service named GLE Alert Plus has been developed. The core of this Neutron Monitor Service is the GLE Alert software that is an upgrade of the existing GLE Alert software [10, 11] and aims to minimize the probability of false alarms.

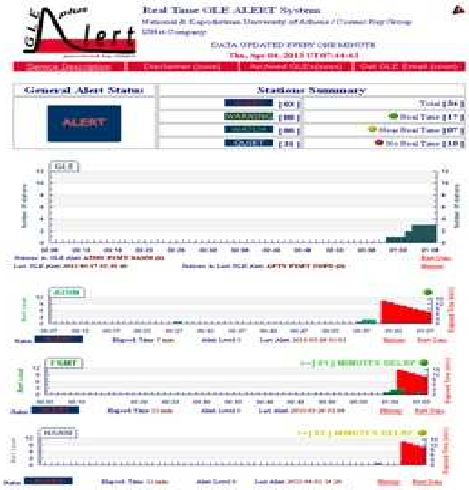

Figure 5. An artificial example of the evolution of the GLE Alert Plus issuing an Alert signal.

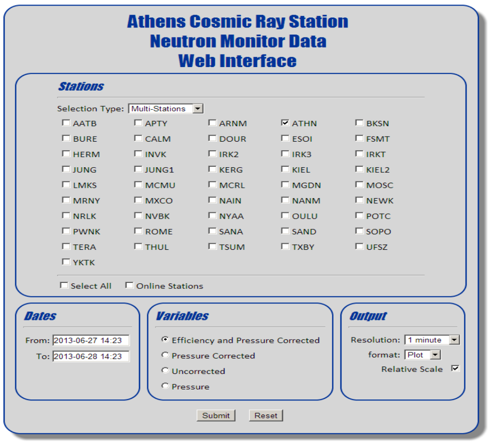

Figure 6. Multi-station NM Data Service.

The recordings of each NM station providing data to the NMDB are the input data for the GLE Alert Plus [12]. For every 1 minute it calculates the moving average of the previous hour (i.e. 60 1-min measurements) and the threshold that represents the upper limit for which each NM station is considered to be at 'Quiet' mode. If three consecutive 1-min measurements exceed this threshold, the particular NM station is considered to be at a ***'Station Alert'*** mode and an elapsed time window of 15 min is being triggered. In case three NM stations, independently of each other, enter the ***'Station Alert'*** mode within the aforementioned time window a General ***'GLE Alert'*** is being marked and an Alert is issued (figure 5). The operational real-time Alert Code of the ANeMoS via NMDB issued an Alert signal at 17.05.2012 at 02:13UT. The relevant Alert from GOES 100MeV protons issued by NOAA at 02:52UT (http:// www.swpc.noaaa.gov/alerts/warnings_timeline.html) [13].

3.1.2 Multi Station Data

The multi-station interface provides an easy way to access the data that are stored in the NMDB database. The interface connects to the NMDB mirror server located at the Athens station. The user has to select the stations, the variables, the time interval and the resolution of the exported data. The output can be obtained in both plot and ascii format (figure 6). Moreover, a feature that allows the retrieval of data in csv file has been implemented, allowing further processing of the data by the user.

3.2 Simulations

A simulation model, named Dynamic Atmospheric Shower Tracking Interactive Model Application (DYASTIMA), based on the well known Geant4 toolkit has been developed in ANeMoS [14]. The model allows the study of the cosmic ray showers that are developed when primary cosmic ray particles enter the atmosphere. DYASTIMA supports the definition of a beam consisting of particles that vary in type, energy and direction. The output data are exported in a detailed or in a synoptic form, ready to be used for plots, histograms or contour figures. The spatial distribution of neutrons in several heights when a vertical proton beam of 10 GeV enters the atmosphere is shown in figure 7. The neutron monitor response to the several cosmic ray particles that reach the Earth's surface can be determined by using the simulation application of the 6NM-64 providing information concerning the detection efficiency [15].

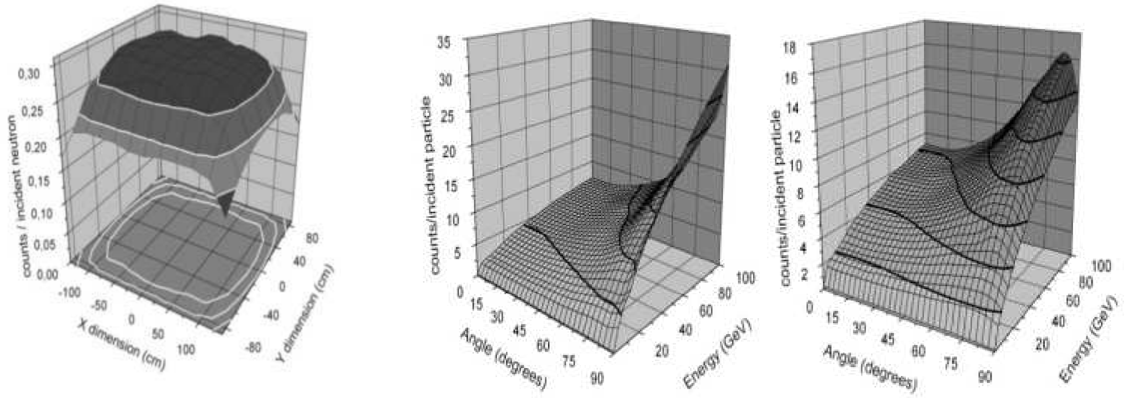

Figure 7. These diagrams illustrate the detection efficiency in case of neutron beam for the different regions of the neutron monitor surface (left) and for the different energies and incoming angles when the azimuth of the beam is perpendicular (middle) or parallel (right) with the counters [15].

3.2 Space Weather Forecasting Centre

Space Weather is the term applied to disturbances that occur in the Earth's magnetosphere and ionosphere as a consequence of interaction of solar wind with the Earth's main field.
From the beginning of the year 2012, a new service named "*Athens Space Weather Forecasting Centre*" is operating at the ANeMoS [16]. This service provides a 3-day geomagnetic activity forecast report on a daily basis at the website of the station *(http://cosray.phys.uoa.gr).* Due to the fact that the space environment and the conditions that are prevalent in it, result into disturbances at the Earth's magnetosphere and ionosphere, which are the direct consequences of the interaction of solar wind and transient magnetic fields of coronal mass ejections (CMEs) with the Earth's magnetic field, an estimation of the disturbances of the Earth's magnetic field is usually being quantified with indices. The Ap index is a measure of the magnetic activity and is the only global planetary magnetic index [17]. The forecasting process is based on a set of rules that include a number of known parameters/properties of the Ap index, as well as current observations of the Sun and near-Earth space [16]. The first item to note in the forecasting agenda is the yesterday's Ap index. If a trend is being marked in Ap's behavior, i.e. if the Ap has been decreasing or in contrast if it has been increasing for several days, this trend may continue, as it may be due to a recurrent behavior of the Sun or the passage of a transient magnetic field.

The next item is the recurrent behavior of the Sun, which is dominant within the heliosphere and acts as the ruler of the near-Earth environment conditions. The magnetic activity 27-days before, when due to the solar rotation the same active region was facing the Earth is also considered. Moreover, the phase of the solar cycle is taken into account.

3.3 Galactic Cosmic Ray Spectrum

According to the coupling coefficient method [18], secondary cosmic ray measurements can be linked to the primary incident cosmic ray particles via specific mathematical functions that take into account the acceptance vectors for each detector (neutron monitor), based on its local characteristics [19]. In order to study analytically the temporal changes of the rigidity spectrum of the GCR intensity during Forbush decreases, daily averaged data of neutron monitor stations obtained from the High-resolution Neutron Monitor Database–NMDB are used. In order to pinpoint the spectral index γ, the difference between the mean amplitude and the amplitude of the specific detector, is considered [20]. Moreover, the Galactic cosmic ray spectrum during the ground level enhancements (GLEs) is modeled using the PPOLA NMBANGLE model [21]

3.4 Forbush Decreases Precursors

It is suggested in many studies that the pre-increases or pre-decreases of the cosmic ray intensity (known as precursors) which usually precede a Forbush decrease could serve as a useful tool for studying space weather effects. A number of Forbush decreases, which were associated with western solar flares and followed by geomagnetic activity, were studied. It was concluded that before geomagnetic storms and Forbush effects, caused by CMEs with a source in the western portion of the solar disk, precursors can be seen in galactic cosmic rays as pre-increases and/or pre-decreases in certain longitudes [22]. Growing amplitude of the first harmonic of cosmic ray anisotropy by neutron monitor network data is connected, as a rule, with the appearance of the precursor. Sometimes the size of the precursor is so big and the cosmic ray intensity distribution is so unusual and specific, that this precursor may serve as a basis for prognosis of a significant interplanetary disturbance arriving to Earth, even in the absence of other data.

3.5 Galactic Cosmic Ray Modulation

Cosmic ray modulation is a complex phenomenon which occurs all over the heliosphere and depends on many factors. No single solar or heliospheric index, however sophisticated, can account for cosmic ray variations. Different scientists have proposed empirical relations describing the long-term cosmic ray variations based on the joint use of solar and/or heliospheric indices (see [23] and its references). Athens Cosmic Ray group developed a model taking into account monthly values of the sunspot number, the CME index based on the characteristics of CMEs [24], the interplanetary magnetic field (IMF) and the heliospheric current sheet tilt (HCS). This model is applied in the 10 GV data of cosmic ray intensity obtained from all neutron monitors worldwide with very good results giving a standard deviation <10% between the observed and the calculated by the model values [25].

Conclusions

As the recordings of the ground based neutron monitors constitute a useful tool for space weather studies, the ANeMoS has developed a lot of research applications based on these data. This kind of applications is important at first for fundamental studies of Cosmic Ray and Solar-terrestrial Physics as well as for applied research. For example, the applications of the Galactic Cosmic Ray Spectrum and the simulation model DYASTIMA can be used for the calculation of the ionization rate and the radiation dose in the atmosphere that affects the crew and passengers during flights. Moreover, the services of GLE Alert Plus and Multi-Station provided at the ESA Space Radiation Centre portal (http://swe.ssa.esa.int), as well as the Athens Forecasting Centre and Forbush decreases Precursors provided by the ANeMoS (http://cosray.phys.uoa.gr) serve for a trustworthy and timely alert of a great solar particle event and as a basis for prognosis of a significant interplanetary disturbance or/and arriving to the Earth.

The Galactic Cosmic Ray Spectrum as well as the Forbush Decreases Precursors are described in detail in a number of published works [20, 21, 22] and are useful for space weather effects monitoring. The influence of the magnetic fields of the CMEs in the galactic cosmic ray modulation can be an important factor in order to improve the forecasting models of the geomagnetic conditions near Earth. This will be the upcoming new service of the Athens Forecasting Centre. All of the above applications are currently provided to the scientific community.

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References

[1] Mavromichalaki H, Papaioannou A, Plainaki C et al. 2011 *Adv. Space Res.* **47** 2210
[2] Dorman L 1974 Cosmic ray variations and Space Explorations *North-Holland Publishing Company*-Amsterdam
[3] Simpson J 2000 *Space Sci. Rev*. **93** 11
[4] Mavromichalaki H, Sarlanis C Souvatzoglou G, Tatsis S, Belov A et al. 2001 Proc. 27th ICRC 4099
[5] Mavromichalaki H., Souvatzoglou, G., Sarlanis, C., Mariatos G, Gerontidou M *et al.* 2005 *Ann Geophys.* **23** 3103
[6] Steigies C 2008 *Geophys. Res. Abstr.* 10 EGU2008-A
[7] Mavromichalaki H 2010, *EOS AGU* 305
[8] Paschalis P, Mavromichalaki H 2013 *NIM A* **714** 38
[9] Paschalis P, Mavromichalaki H, Yanke V, Belov A, Eroshenko E et al. 2013 *New Astron.* **19** 10
[10] Mavromichalaki H, Souvatzoglou G, Sarlanis C et al for the NMDB team 2010 *New Astron***. 15** 744
[11] Mavromichalaki H, Papaioannou A, Plainaki C et al for the NMDB team 2011 *Adv Space Res*. **47** 2210
[12] Souvatzoglou G, Papaioannou A, Mavromichalaki H, Dimitroulakos J, Sarlanis C 2014 *Space Weather* **12** 633
[13] Papaioannou A, Souvatzoglou G, Paschalis P, Gerontidou M, Mavromichalaki H 2014 *Solar Phys.* **289** 423
[14] Paschalis P, Mavromichalaki H, Dorman L, Plainaki C, Tsirigkas D 2014 *New Astron*. **33** 26.
[15] Paschalis P, Mavromichalaki H, Dorman L 2013 *NIM A* **729** 877
[16] Abunina M, Papaioannou A, Gerontidou M, Paschalis P, Abunin A *et al.* 2013 *Jour. Phys.: Conf. Ser.* **409** 012197
[17] McPherron R 1999 *Physics and Chemistry of the Earth* Part C **24** 45
[18] Dorman LI 2004 *Astrophys. Space Sci. Libr.* **303**
[19] Wawrzynczak A and Alania M V 2008 Adv. Space Res. **41** 325
[20] Livada M, Papaiannou A, Mavromichalaki H 2013 Proc. Helas Conf. S_1
[21] Plainaki C, Mavromichalaki H, Laurenza M, Gerontidou M, Kanellakopoulos A and Storini M 2014 *Astrophys. J.* **785** 160
[22] Papailiou M, Mavromichalaki H, Belov A, Eroshenko E, Abunina M, *et al.* 2013 *Solar Phys***. 283** 557
[23] Mavromichalaki H, Paouris E, Karalidi T 2007 *Solar Phys.* **245** 369
[24] Paouris E 2013 *Solar Phys.* **284** 589
[25] Paouris E, Mavromichalaki H, Belov A, Gushchina R, Yanke V 2012 *Solar Phys.* **280** 255