EXECUTIVE SUMMARY

The global network of ground-based neutron monitors and muon telescopes constitutes a unique "instrument" in an armada of particle detection and measurement facilities now in space and to be deployed in the future. This network has a particle energy detection threshold of order 500 MeV, extending up to 50 GeV, with a full-sky field of view continuously making dozens of pointed measurements in key directions. It is sensitive to the highest energy solar cosmic rays and galactic cosmic rays, whose intensities and anisotropies are produced or heavily influenced by solar activity.

It measures the part of the solar energetic particle (SEP) spectrum that is most influenced by the particle acceleration processes taking place close to the Sun. These processes are affected by coronal turbulence, shock speed and strength and radius, and by turbulence far upstream of the activity. Some particles may be accelerated in flares if the magnetic topology is such that they can escape into interplanetary space to be detected at Earth.

Monitoring of galactic cosmic rays provides information on interplanetary conditions not only at the radius of Earth, but also far out in the heliosphere through variations in the cosmic-ray intensities and anisotropies on time scales from minutes to decades.

Combining these measurements with lower energy measurements from space-based instruments provides a comprehensive data set that can be used to investigate a variety of solar and heliospheric phenomena.

The network is now comprised of some new, but mostly aging, neutron monitors and directional muon detectors. Recently, air Čerenkov telescopes, primarily intended for TeV γ-ray astronomy, have been successfully performed differential measurements of the secondary muon component produced by solar and galactic cosmic rays. The network is not functioning as it once did or as envisioned during the International Geophysical Year, 1957-1958. Several key measurement sites have been closed or turned off, and the perceived lack of interest by the US makes foreign sites vulnerable to cuts and closings. There is little coordination between supporting organizations that are also fighting for their own existence. New and inexpensive technology has had difficulty making its way into the field to modernize and greatly improve the performance of those stations now operating. Key recommendations to bring the network into a condition to support heliospheric physics include:

- A greater scientific priority and appreciation by agencies with a stake in heliospheric physics,
- increased funding (extremely modest by many standards),
- a national (or better still, international) coordination of the network,
- an organized effort to integrate complementary instruments and
- the training of young researchers.

INTRODUCTION

At energies upwards of 500 MeV, the intensity of solar and Galactic energetic particles becomes so low that very large detector masses are necessary to measure them. In this energy regime ground-based instrumentation provides a highly cost-effective method for making measurements with the required statistical accuracy. Generally these instruments acquire information on primary cosmic rays through measurement of the secondary particles created when a primary strikes a molecule in Earth’s atmosphere.

Neutron monitors have been in operation for over fifty years, and provide a vital long-term perspective on solar variations with time scales such as the eleven-year Schwabe cycle or the twenty-two-year Hale cycle. They also make valuable measurements at much shorter time scales, providing
information on relativistic solar particles and on transient, solar-induced variations of Galactic cosmic rays such as Forbush decreases.

The scientific return from neutron monitors is enhanced when they are linked together in coordinated multi-national arrays. Indeed, in most modern applications the “instrument” is the array itself, and not any single detector in it. Analysis of intensities of particles arriving from different directions permits determination of the cosmic ray anisotropy, while combining data from detectors at different geomagnetic cutoffs provides information on the energy spectrum. Coordinated arrays now in operation include the 12-station Spaceship Earth network, which is optimized for measuring the angular distribution of relativistic solar energetic particles (Bieber et al. 2004), and the Neutron Monitor Database (NMDB) recently organized under the auspices of the European Union (Mavromichalaki 2010).

Neutron monitors provide a link between the sub-500 MeV energy regime routinely monitored by spacecraft and the high-energy regime probed by ground-based detectors such as muon detectors and air shower arrays, as well as the new large space-based detectors such as PAMELA and hopefully soon AMS. These higher-energy experiments often have phenomena outside the heliosphere as the primary research objectives, but owing to their extraordinarily high count rates, they also provide important new information on heliospheric phenomena. For example, the Global Muon Detector Network (GMDN) has shed light on the large-scale structure of interplanetary coronal mass ejections (Kuwabara et al. 2009), while Milagro and IceTop have yielded detailed information on the energy spectrum of solar energetic particles (Ryan et al. 2003; Abbasi et al. 2008).

The status of neutron monitor operations in the past decade is summarized in Fig. 1. There were fourteen neutron monitors operated by U.S. institutions at the beginning of the decade (2001), all but one of which were supported by NSF. Since then, four have closed, including the two longest-operating monitors in the world (Climax and Mt. Washington). Of the ten monitors remaining, only two operate with NSF support. The remainder continue to operate, for the time being, under institutional support.

The present situation with U.S.-operated neutron monitors is not sustainable. The small amount of available federal funding makes it difficult to attract young researchers into the field, and the amount of funding for engineering and data analysis support is too small to sustain the long term health of the instrumentation and the integrity of the data. Further, the amount of federal support currently provided is not commensurate with the high scientific return generated by these instruments.

A cursory search of current literature making reference to neutron monitor measurements is illustrated in Fig. 2. Despite the dwindling support for the network, the importance of the supporting role of neutron measurements in other fields is clear and growing.
SCIENCE OBJECTIVES

The science that can be studied with ground-based instruments is diverse. Some of these objectives are described below.

**Solar Energetic Particles**

Ground-based instruments are ideal for studying the highest energy solar energetic particles in so-called Ground Level Enhancements (GLE). Neutron monitor observations are critical to resolving the debate as to whether the acceleration of high energy particles takes place at the Sun or in CME-driven shocks; see Klecker et al. (2007) and Cliver (2009) for recent reviews. While it is generally conceded that shocks dominate SEP acceleration in large SEP events at low (~10 MeV) energies, McCracken et al. (2008) and others have argued that at least some GLEs have an early flare component. Continued observations at neutron monitor energies are necessary to determine the peak energy and efficiency of the flare acceleration process. Regardless of the acceleration process, the spectral shape and intensity carries information about the nature of the acceleration environment. Physical solar parameters such as the volume and time available for acceleration, diffusion coefficients and pitch angle distributions manifest themselves in (1) a rolloff in the spectrum at ground-based energies, (2) duration or time evolution of the signal and (3) anisotropy of the high-energy particles. In principle the spectral measurements in this energy range of the rollover shed light on this issue. One other issue that these instruments can potentially address is shock obliquity, i.e., the quasi-parallel vs. the quasi-perpendicular issue. Quasi-perpendicular shocks have difficulty picking up seed particles, but can accelerate them rapidly near the Sun, as opposed to a slower acceleration process in quasi-parallel shocks. Recent impulsive GLEs, such as that of 2005 January 20, press shock acceleration theory, bringing to the fore the shock geometry issue.

The development of GLEs also tells us about the generation of turbulence that scatter the particles in interplanetary space or the presence of large magnetic particle-scattering structures. No one station or spacecraft instrument is capable of estimating all of these parameters or investigating these processes associated with GLEs. Shown in Fig. 3, for example, are the time-resolved spectra from the 2005 January 20 GLE measured with the Milagro instrument and several NMs, where the initial intensity spike is harder than the longer duration and isotropic component of the GLE.

**Solar Flare Neutrons**

Neutrons produced in solar flares by GeV protons and ions can reach the Earth and be detected with ground-based instruments. The measurement of the first solar neutron event was in 1982; the largest solar neutron event was measured in 1990. These relatively rare events, coupled with time-associated spacecraft and ground-based measurements of solar phenomena provide a unique opportunity for coordinated study of the solar flare/acceleration processes.

**Short-term GCR modulation**

Coronal Mass Ejections sweep away galactic cosmic rays (GCR) as they propagate outward from the Sun. The GCR depletion within a CME can be sensed early in the form of a local deficit in the pitch angle distribution of GeV GCRs, providing an indication of an advancing CME. The pitch angle distribution can be sensed in neutron monitors, but most graphically in the anisotropy of the muon intensity at ground level (see Munakata et al. 2000). So-called Halo CMEs are coronal mass ejections directed at the Earth. With no oblique perspective, they are the most difficult to detect optically. However, if the CME is large, the signal of its presence reaches us quickly in the form of the GCR anisotropy. The magnitude of the signal directly reflects the depth of GCR depletion within the CME and, thus, the potential impact of the CME on terrestrial phenomena or spacecraft near Earth.
the CME strikes the Earth’s environment, all ground-based stations register the GCR depletion with a magnitude that depends on the local geomagnetic cutoff. These events are called Forbush Decreases (FD). The recovery from an FD is the backfilling of the GCR population in the Earth’s environment. Its time scale depends on the conditions, not only at Earth, but at large heliospheric distances. When joined with measurements by cosmic-ray instruments in the outer heliosphere, the evolution of the FD recovery (measured, for example, as a function of particle rigidity) can be understood in terms of particle drifts and particle density gradients that are determined by, and hence provide information on GCR diffusion coefficients or the intensity of MHD turbulence. With the recovery measured as a function of rigidity (momentum per unit charge) this can constrain the wave spectrum in k-space at large distances from Earth.

Long-term GCR modulation

Galactic cosmic rays at Earth have been monitored and measured over more than five 11-year solar activity cycles and their intensity is inversely related to solar activity. Solar activity is commonly characterized by sunspot number (Fig. 4). It is now understood that conditions in the outer heliosphere have a direct influence on the GCR intensity at Earth. Thus, NM observations provide an estimate of the accumulated activity beyond Earth’s orbit. An early and reasonably accurate description of this was modeled by Gleeson and Axford (1968), who quantified the effect of diffusion in the outer heliosphere as a repulsive electrostatic potential. Models have been refined in the intervening years, but are still based on the assumption that conditions in the outer heliosphere determine the GCR intensity near the Earth. Furthermore, an exciting area now is the extent and nature of modulation in the heliosheath including the heliotail. Ground-level detectors can, in principle, provide information on this, including the associated hysteresis and solar-cycle dependence.

Fig. 4 shows alternating flat top vs. spike shaped GCR maxima in successive solar minima. The shape is determined by the 22-year cycle in the polarity of the solar global magnetic field, which affects the direction of GCR drifts in the heliosphere. During periods of high solar activity when the GCR intensity is depressed. Fig. 4 also shows peaks in the neutron monitor rate due to GLEs.

Another interesting feature illustrated in Fig. 4 is the fact that the greatest GCR rate in the last six cycles was observed both on the ground and by spacecraft during the recent deep and prolonged solar minimum (Mewaldt et al. 2010). The long term record in the galactic cosmic flux, combined with ongoing measurements will enable significant improvements in our understanding of the physical processes underlying the modulation parameters. The recent unusual sunspot minimum and its recovery will make possible important new tests of the modulation process in parameter ranges not seen before. A full recovery to more-normal conditions may take years, and proper measurements will enable a more-precise determination of the interplay of different parameters in modulation.

NM measurements of the GCR intensity are also influenced by secular variations in the geomagnetic field. These gradual changes in the local magnetic field are immediately reflected in the GCR count rate.

Historical reconstructions of heliospheric parameters

Long-term reconstruction of the solar wind magnetic field is a key application of the neutron monitor observations that highlights the need for a continuous long-term record of galactic cosmic rays. Neutron monitor observations cover a relatively short interval (1953-present). However, combined with contemporaneous interplanetary magnetic field data, they can be used to calibrate the much longer term (10³-10⁵ years) records of galactic cosmic ray intensity inferred from concentrations of cosmogenic nuclei obtained from tree rings (¹⁴C) and ice cores (¹⁰Be) (e.g., Steinhilber et al., 2010) which can then be

![Fig. 4. NM count rate (Kiel) and sunspot number.](image-url)
used in turn to infer the variation of the solar wind magnetic field over the millennia. Such information allows one to probe the behavior of the solar dynamo and to better understand sunspot droughts such as the Maunder Minima and the role of the Sun in climate change. However, the 50-year overlap of the neutron monitor and $^{10}\text{Be}$ records is too short to capture the complexity of the factors involved in transforming the measured concentrations of cosmogenic nuclei into reliable $B$ measurements. Recently, geomagnetic measurements extending into the mid-19th century have been used for this purpose, but the magnetic field intensities obtained from geomagnetic and ice core measurements diverge for the last decades of the 19th century, underscoring the need for extending the period of neutron monitor observations.

**INSTRUMENTS**

**Muon Telescopes**

Cosmic rays at the top of the atmosphere produce muons as well as neutrons. Muons are registered with ground-based or underground hodoscopes. Two types of muon detectors are functioning, the scintillation detector (SD) and the proportional counter tube detector (PCTD). The SD consists of horizontal layers of plastic scintillators, viewed by photomultiplier tubes. By counting pulses of the coincidences between a pair of detectors in different layers, one has the rate of muons from the corresponding incident direction. A typical field of view (FOV) of the instrument is $30^\circ$. A PCTD instrument instead uses long proportional counter tubes with an overlying Pb layer to absorb the soft component radiation. Muon recording is triggered by the coincidence of pulses from different layers with the incident direction identified by the $x$-$y$ locations of the interactions. A typical FOV in this detector is $7^\circ$ half angle.

**Neutron Monitors**

The neutron monitor was invented by University of Chicago Professor John Simpson in 1948 (Simpson 2000). There have been various types of neutron monitors, notably the “IGY-type” monitors (Fig. 5) deployed around the world during the 1957-1958 International Geophysical Year (IGY) and the much larger “NM64” monitors, “supermonitors.” All monitors, however, employ the same measurement strategy: There is an outer superstructure of polyethylene and lead ingeniously designed to suppress local neutrons, while amplifying the signal from cosmic secondary neutrons. At the heart of a neutron monitor is a proportional counter. The early Simpson monitors detected neutrons through $^{10}\text{Be}$ gas enriched in the isotope $^{10}\text{B}$, which produces a signal via the reaction $n + ^{10}\text{B} \to \alpha + ^7\text{Li}$. Recent proportional counters use $^3\text{He}$ which produces a signal via the reaction $n + ^3\text{He} \to ^3\text{H} + p$.

**Solar Neutron Telescopes**

Over the past ten years, an array of Solar Neutron Telescopes has been deployed near existing NMs to augment the observations performed with those NMs (Valdes-Galicia et al. 2008).

**TeV Čerenkov Detectors**

The IceTop air shower array is now nearing completion at the South Pole as the surface component of the IceCube neutrino telescope (Achterberg et al. 2006). IceTop will have approximately 500 m² of ice Čerenkov collecting area arranged in an array of 80 stations on a 125 m triangular grid with the primary objective of studying air showers from 1 PeV to 1 EeV. Each station consists of two, 2-m $\odot$ tanks containing ice to a depth of 90 cm. Light from fast particles is measured with photomultiplier tubes. Due to the high altitude (2835m) and the nearly zero geomagnetic cutoff at the South Pole, secondary particle spectra at the detector retain a significant amount of information on the spectra of the primary particles. The signal amplitude carries information about the composition and spectra of the incident particles, albeit integrated over broad regions of the spectrum. IceTop can measure the energy spectrum of these particles in the multi-GeV regime from a single detector with a well-defined viewing (asymptotic) direction (Abbasi et al. 2008). IceTop has a counting rate approximately $10^4$ times that of a neutron monitor. With its inherent energy resolution this permits study of Forbush Decreases,
Corotating Interaction Regions (CIR), and other transients in the cosmic-ray flux with unprecedented resolution (Kuwabara et al. 2007). Ice Top, with other instruments at the South Pole, will permit the first ground-based detection of a possible component of nuclei heavier than protons in solar particles in the multi-GeV regime.

TheMilagro instrument, or more recently HAWC, operated in a similar way to that of Ice Top. These instruments detect the muon-Čerenkov light produced in a water pond or in tanks. Milagro, now de-commissioned, operated near Los Alamos, but HAWC (High Altitude Water Čerenkov detector), in a small version, has begun taking data on Sierra Negra in Mexico. At low-latitude, HAWC, once fully populated, will survey the sky for TeV $\gamma$-ray sources and, in the process be sensitive to secondary muons in GLEs. At low latitude, it will be sensitive to direct solar neutrons $>500$ MeV from solar flares. The utility of this Čerenkov technique was illustrated in Fig. 3, where Milagro data were used with NM data to produce a time-resolved spectrum of the 2005 January 20 GLE (Morgan 2010). The high count rates of Ice Top and HAWC permit studying fast temporal structure in GLEs.

International participation

By its very nature international participation in this system is critical. Faltering US support for the system is interpreted elsewhere as a low US priority, thereby encouraging cuts in support by foreign governments, with the entire system suffering the consequence. One bright point has been European support for an integrated database for the NM system. The European Commission has funded the creation of the real-time database for high resolution neutron monitor measurements (NMDB) during 2008 and 2009 as a scientific data repository in its 7th framework programme (FP7). Currently the Neutron Monitor database NMDB is accumulating data from more than twenty ground-based cosmic ray stations, most of which are operated by European institutions. The NMDB makes the data from all participating stations available in real-time in a common format. In addition to real-time data, NMDB also archives data from all participating stations.

The NMDB data coverage is currently limited to Europe and neighboring countries. Space Weather applications, like GLE and CME alerts, require a global coverage to achieve their full potential. Currently, the NMDB has no data coverage from the American sector, which reduces the reliability of the GLE alert and other applications. The inclusion of neutron monitor data from the Western Hemisphere will significantly improve the value and utility of the database. The implementation of this database is significant in that it demonstrates untapped willingness and enthusiasm for fully integrating a variety of international ground-based instruments into a single system. Until recently, this has been an entirely cooperative, but informal arrangement with minimal coordination of data formats and access to facilitate research.

SUMMARY AND RECOMMENDATIONS

Measurements of the cosmic radiation have been made continuously for over half a century. During this time the community has made significant advances in understanding the nature of galactic cosmic radiation, solar particle events and processes and structure of the interplanetary medium. The advent of space measurements has augmented the ground-based measurements, leading not only to greater knowledge of our Earth’s environment, but also motivating future research. It is not possible to address new questions that are raised without continuous measurements from a set of stable and robust monitors.

The research addressed with this ground-based network is extensive and diverse, affecting research in many fields, as compared to spacecraft experiments that are focused in their objectives by necessity. Compared to space experiments, the scientific return of the ground-based network is a bargain. For example, with modest money for supplies, the entire US network of neutron monitors could be maintained by little more than one full time engineer/technician. Investments for upgrading stations would reap benefits for decades. Although on one scale, the costs for these data are modest, they are large for individual researcher grants, from which one supports students. The de-coupling the network costs from the science-based grants allows researchers to provide both service and data to the community, yet conduct his or her own research, training the next generation of cosmic-ray scientists.

In addition to the many fundamental scientific achievements resulting from basic ground-based cosmic-ray detectors, there is a practical aspect in understanding Space Weather phenomena and its effects on national assets. We realize the important role that the neutron-monitor measurements play in
determining, understanding and predicting the Earth’s space environment with the concomitant implications for climate, e.g., linkages between cosmic-ray intensity and cloud cover. The measurements from neutron monitors and the possibilities for long-term comparisons are a critical component in understanding our whole environment in a broad sense.

To continue this research the community must train young scientists to carry on the work of the cosmic-ray pioneers, many of whom have retired or left us. To achieve this, the present cadre of scientists needs sufficient funding to maintain the present cosmic-ray detectors and analyze the data. We recommend that there should be increased scientific priority on these ground-based measurements and an appreciation by agencies having a stake in various aspects of Earth’s environment. Increased funding and interest from US National Agencies would have a strong and immediate effect on the scientific vitality of this research.

REFERENCES


Selected Publications Using Neutron Monitor Data (includes PI institutions and external institutions)


