The U.S. and Global Neutron Monitor Network for Heliophysics and Space Weather

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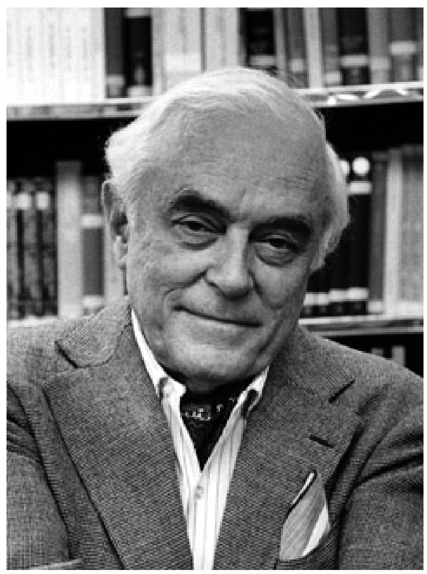

John Simpson

Synopsis

In this white paper, we review the status of the US neutron monitor network, the science activities that utilize the network, the long-standing and permanent need for the network, its key role in the national Space Weather Strategy, future scientific and space weather activities and objectives and, lastly, plans for expanding the public profile and improving the security and scientific function of the network. *Our utmost priority is to maintain, expand and improve the neutron monitor network under US control and to develop the necessary scientific infrastructure to support the network.*

1. INTRODUCTION

For over seventy years, the global neutron monitor (NM) network has been a source of discovery and a data reservoir for numerous science investigations. It has provided an open service for the world-wide space science community, while monitoring the near-Earth radiation environment. In the US its constituents and stake holders are the NSF, NASA, DoD, DoC, FAA, DHS, industry and unrelated science fields, e.g., hydrology. The US part of the global network is entirely funded domestically, but works in seamless collaboration with international monitors and scientists. For decades the international community of monitor operators has been a model of unselfish scientific collaboration. For a similar period of time, the US system has been supported almost entirely by the National Science Foundation with science grants to participating US institutions. This is despite the multitude of stake holders and the instrument operations costs that burden science proposals. We outline the status, outlook, benefits and long-term plans for the network and the network's science, its contributions to Space Weather and plans for improving the system for the benefit of the science community and society.

Ground-based NMs report the cosmic-ray intensity at the top of the atmosphere and sense a wide range of phenomena that we categorize based on time scale. From short to long, we have meteorological effects, direct solar particles (ground level enhancements, GLE), diurnal variations, larger (~1 AU) disturbances, called Forbush Decreases (FD) and their recoveries, solar rotation variations, solar cycle (11 and 22 years) variations and geomagnetic (secular) drifts. Each of these observations informs us of different high-energy activities near Earth and within the entire heliosphere. Different subfields of space, geo and solar physics focus on different subsets of these data, attesting to the wide ranging utility of neutron monitor data.

A neutron monitor is a ground-based omnidirectional detector, designed to record the nucleonic component in overhead cosmic-ray showers in the Earth's atmosphere, typically the ones initiated by Galactic cosmic rays (GCR) and solar energetic particles (SEP) (Simpson 2000). Because of their large volume, neutron monitors, using the atmosphere as the detection medium and stations positioned around the globe, remain the state-of-the-art instrumentation for measuring and monitoring >1 GV cosmic rays globally. The energy threshold (~500 MeV for protons) for producing a ground signal coincides with cosmic-ray energies affected or produced by solar and heliospheric phenomena. Stations are strategically located to provide complementary data based on local rigidity cutoffs and look directions into interplanetary space. The rich data set, spanning multiple decades, provides information on cosmic rays over many solar cycles. A large subset of these data are stored and available at Neutron Monitor Database [https://www.nmdb.eu/station/usa/] in Kiel Germany.

In recent years, much attention and effort has been devoted to space weather that includes both near and far radiation environments, which, in turn, affects society in several ways. These include crew, passenger, avionics and routes of high-altitude aircraft, especially polar routes. See the white paper by Bain *et al.* (2022), *Improved Observations and Modeling for Aviation Radiation,* for more on the topic. Also affected are national space assets, both scientific, military and commercial vehicles and instrumentations; astronaut health and safety in and beyond low Earth orbit; and future lunar and Martian bases and other explorations. The importance of the network is called out in the 2015 National Space Weather Action Plan and the 2020 PROSWIFT bill passed by Congress and signed into law.

2. STATUS: THE SIMPSON NEUTRON MONITOR NETWORK.

Funded by the National Science Foundation in 2021, the US owned and operated neutron monitor network, Figure 1, now called the *Simpson Neutron Monitor Network* in honor of its inventor John Simpson (see frontispiece), is operated and maintained by the Universities of New Hampshire, Delaware and Wisconsin-River Falls. A goal of the project is to place the US stations under one administrative umbrella for a comprehensive and coordinated system of neutron monitors covering the United States, Canada, Antarctica, and Greenland. This arrangement will more effectively and efficiently address science goals and national operations needs. The logistical consolidation of the various US owned sites enhances the mutual security of the various sites and facilitates new activities that enhance and expand the utility of the network. The Simpson network comprises a large fraction of the world-wide set of neutron monitors, but resides entirely in the western and northern hemispheres (except for the South Pole). During periods of inconsistent funding, the US network lost three legacy stations: 1) Climax, but the nearby Leadville CO site is supported as part of the Simpson Network, 2) the station on Haleakala on Maui, but is being redeployed under a different ANSWERS NSF (V. Bindi, PI) grant and will be part of the network (see below) and 3) McMurdo, acquired by South Korea. Global coverage of cosmic-ray activity and asymptotic directions requires participation by a stable and robust US network and similarly for the world, but the set of international stations has been atrophying. NSF has prioritized the network, and we hope this makes a stronger case for our international partners for increased support.

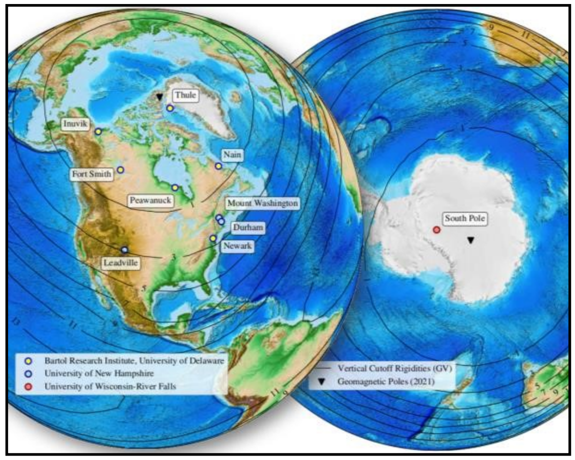

Figure 1: The Simpson NM Network

<u>Priorities and recommendations</u>

i. Maintain the NM network to serve the scientific community, space weather, defense, security and commercial interests.
ii. Decouple operation costs from scientific proposals by shifting operations to agencies.

3. Current Research Activities

a. GLE and FD Measurements with NMs

SEPs are high-energy particles from the Sun accelerated during solar flares and coronal mass ejections (CME). The most intense SEP events produce numerous energetic particles (≲ several GeV). When striking the Earth's atmosphere in large numbers they can produce a significant rise in the radiation levels on the ground, *i.e.*, a GLE. Because the initiation of GLEs takes place close to the Sun, surprisingly little is known about how, when and why of the dynamics of acceleration and transport. With their large effective area, the NM network provides continuous, precise and accurate measurements of the intensity-time profile of an event seen from different asymptotic directions. The coverage of multiple arrival directions of SEPs allows the particles (typically protons and ions) to be propagated back to their source and departure time, providing researchers information on the acceleration and transport of these particles. GLEs and FDs have the same basic origin and can sometimes be seen together at Earth (Fig. 2, Bieber, priv. comm.).

b. Space Weather

See §4.

c. Solar Physics

A different type of GLE is caused by solar-flare neutrons arising from ~GeV protons and ions striking the Sun (Bieber et al. 2005). NM data can be used with high-energy γ-ray data to tease out the production and behavior of the progenitor particles in the near-Sun environment and whether these neutrons (and γ rays) are produced within the flare itself or by the rapidly receding coronal shock. The phenomenon of Long Duration Gamma Ray Flares (Ryan 2000) has been frequently observed in the 100-MeV γ-ray data from the Large Area Telescope on the Fermi mission. The high-end spectrum of the protons and ions producing these photons and their evolution is difficult to determine solely from the γ-ray data. However, ground-level neutron measurements can constrain the upper bound of the progenitor proton spectrum, such as seen in the Haleakala NM before its decommissioning (Fig. 3). Valuable observation such as this require global coverage with low latitude NMs, such as what the new Haleakala NM will provide. In contrast with charged particle GLEs, a single NM observation without the rest of the network can be adequate.

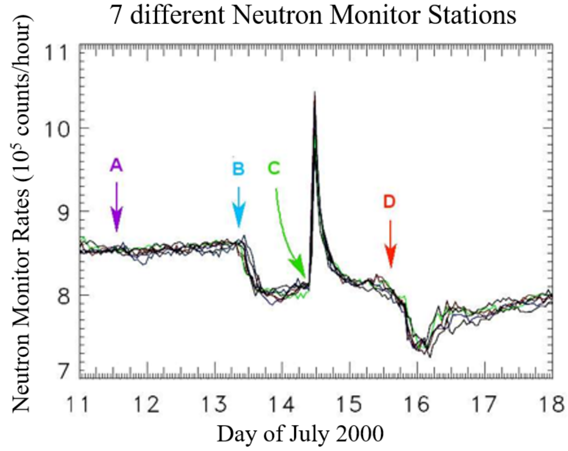

Fig. 2. Cosmic-ray activity during the Bastille Day solar storm. A: First CME departs the Sun. B: First CME arrives at Earth resulting an FD. C: Second CME departs the Sun and accelerates SEPs that arrive Earth in minutes, as recorded by several NMs as a GLE. D: Second CME arrives at Earth for another FD, producing a great geomagnetic storm.

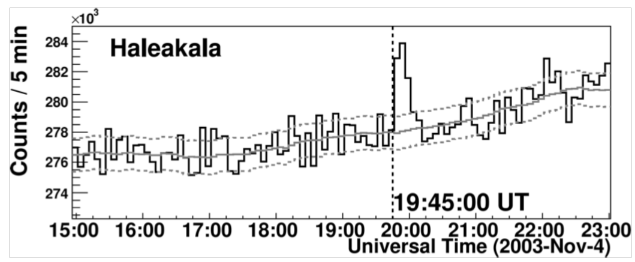

Fig. 3. Solar neutron signal in Maui (Watanabe et al. 2006)

To better measure charged-particle or neutron GLEs, multiple stations in proximity to one another can provide spectral information without relying on the rest of the network. This is critical in the early stages of these events when few stations register the event. There are considerable advantages to have co-located neutron monitors with different yield functions. Because each monitor is a single-channel integral counter, two instruments can provide a measure of the spectrum shape. One pair, operating since 1966 is in New Hampshire, the other at the South Pole. The South-Pole pair is comprised of a standard 3NM64 (Hatton et al. 1964) and an unleaded array of twelve proportional counter tubes with very different yield functions. The difference in the New Hampshire pair is due to the altitude difference, while the difference in the South Pole pair is from the different designs. The ratio of the count rates in these pairs can be used to estimate the spectral shape of the SEPs (Bieber et al 1991). In addition, as described later, Čerenkov tank muon detectors, such as IceTop (IceCube Collaboration 2013) or Milagro (Morgan 2010) are sensitive to the most energetic components of the SEPs, bringing additional spectral information.

c. Spectroscopic Measurements

Despite the fact that NMs are simple omnidirectional integral counters, when used as part of a network distributed over rigidity and "look angle," they can together constitute a powerful cosmic-ray tool. Few results come from an individual NM, i.e., the network is essential. The physical characteristics of the detector and its environment determine the energy response, while the particle anisotropy is measured with similar detectors located at different parts of the globe. Furthermore, this can be amplified when NMs join forces with directional muon telescopes.

Various techniques have been used to derive cosmic ray spectrum variations using NMs. The oldest and most commonly applied technique relies on the geomagnetic cutoff. At any location on earth the magnetic field prevents cosmic rays below a specific cutoff rigidity from reaching the atmosphere. Cutoffs range from near zero to 17 GV. The difference in count rates between two monitors is proportional to the integral of the cosmic ray spectrum between the two rigidities. Fixed monitors are typically used, but they generally do not have identical inherent responses and nearly always have secular variations in the cutoff as the magnetic field changes.

Other methods use the memory of the energy of the primary particle retained in the structure of the cascade, even down to sea level. Monitors located close together but at different altitudes have count rate differences related to the spectrum, i.e., solar vs. galactic. Differences in the internal structure of monitors, typically the ratio of lead to polyethylene, at the same location are similarly used.

Advanced electronics have been developed to enable spectral sensitivity in NMs by recording the fraction of multiple neutrons per particle detection—a modified old idea that shows renewed promise. This class of techniques exploits the detailed detection method in the NM. Incident neutrons over approximately 100 MeV penetrate interact with lead surrounding each NM tube to generate many 1-2 MeV neutrons, some of which are captured in the detector. The number of these neutrons and the time structure of their detection are sensitive to the energy of the incoming neutron (Mangeard et al. 2018). Some secondary neutrons also diffuse into neighboring NM tubes and are detected. Collection times range from a few μs to ten ms, so identifying and characterizing these interactions requires existing specialize electronics.

This behavior can be used to study SEP storms. These events exhibit dramatic variability from event to event in the time-resolved spectrum at Earth. This was clearly demonstrated with joint measurements of SEPs with the PAMELA spacecraft and NMs. Some were GLEs, while others not, with the set of events showing a continuous distribution of spectral hardness, i.e., events with the hardest spectrum are detected by the NM network (Bruno et al. 2018). However, such measurements require a fortuitous location of the spacecraft to complement the NM signal. Such occurrences are not frequent. We have been fortunate to have PAMELA and AMS make such measurements in space to combine with NM data, but this has been infrequent. In the not too distant future, ground based observations will again be the only option to detect GeV protons and ions. Thus, it is important to use this period of simultaneous observations to better understand ground based measurements and to develop new techniques for the future and to secure the continued operation of the detectors.

The analysis of multiple co-located NMs, or NMs with greatly different yield functions, or a NM paired with a surface muon detector has been used for this purpose, but often these instrument pairs are inconveniently located for a given ground signal. This calls for more doubly instrumented sites.

Even the GCR spectrum at Earth can vary. This occurs for FDs and also during quiet periods due to the transport of GCRs through the heliosphere. Effects like sign-dependent drifts and magnetic field helicity can yield a spectral variation over time scales of the solar cycle. Thus, having NMs with some degree of spectral differentiation can help understand these transport-induced spectrum changes (Bieber et al. 1991). Specially equipped monitors that measure multiplicity (see above) can be employed for this purpose. This can be coupled with global sea-based surveys that examine the GCR rigidity dependence over a solar cycle (Nuntiyakul et al. 2014).

Priorities and recommendations

i. Continue research of GLEs using archival and new data.
ii. Investigate other potential low-latitude, high-altitude sites for solar neutron coverage.
iii. Continue research into single instrument spectroscopic sensitivity.
iv. Pursue definitive cross calibration with space instruments.

d. Cross Calibration of AMS-02 and NMs

The stations of the Simpson NM network are currently located in a rigidity cutoff range from 0 to 3 GV. The GLEs of cycle 25 will provide a unique opportunity to perform a precise cross calibration between the NMs and the differential energy spectrum from AMS-02 below a few GeV. It will greatly enhance the spectral measurements of SEPs when spacecraft data are not available. Such a cross calibration is planned in the awarded Hawaii NSF ANSWERS grant.

4. Remote Sensing of Conditions in the Inner Heliosphere and Space Weather

Neutron monitors detect primary cosmic rays via their showers in Earth's atmosphere. They are sensitive to primaries that exceed an atmospheric cutoff (~1 GeV) and a local geomagnetic rigidity cutoff (~zero - ~17 GV, from pole to equator). Atmospheric showers provide a much larger effective area than is available for space instruments, enabling continuous high-precision cosmic-ray measurements from a stable platform for years.

Because charged cosmic rays with enormous Larmor radii are deflected by magnetic fields and scattered by magnetic fluctuations in the solar wind, those detected at a given time and location have collectively traveled or diffused across great distances in the heliosphere. Plasma conditions in the heliosphere vary on several time scales: the 11 and 22-year solar cycle, 27-day solar rotation, and solar storms, including coronal mass ejections (CMEs) and the shocks they drive. All these variations are reflected in the local cosmic-ray intensity, spectrum, and anisotropy, providing unique remote sensing of plasma conditions elsewhere in the heliosphere.

Fitting Solar Energetic Particle Profiles and Ground Level Enhancement Alarm System

During each sunspot cycle there are some solar storms that accelerate ions to relativistic energies at an intensity above the GCR background for hours or days, i.e., GLEs. By precision modeling of the interplanetary transport of relativistic solar particles, we can infer special upstream magnetic configurations, such as magnetic bottlenecks [Bieber et al., 2002] and magnetic loops [Ruffolo et al. 2006]. We can also determine the scattering mean free path of relativistic ions, which relates to magnetic turbulence between the Sun and the Earth.

SEPs propagate to Earth and cause damage to satellite electronics, and pose a radiation hazard to astronauts and aircraft crews. If energetic and numerous enough, these SEPs can produce a GLE. The University of Delaware team has developed a system that continuously watches for count rate increases in multiple neutron monitors. This triggers an alarm if a GLE is detected [Kuwabara et al., 2006]. We are evaluating different strategies for detecting the GLE event at an early stage, while still keeping the false alarm rate low. Although this work is under development, this system has provided GLE alerts that proceed the earliest alert by GOES by 10-30 minutes.

Solar Modulation of Galactic Cosmic Rays

GCRs undergo significant solar modulation. Data from numerous neutron monitors over several solar cycles [Moraal 1976] indicate an intensity variation of ±15% over a solar cycle. In parallel, there have been advances in 1) models of solar wind turbulence and its transport through the heliosphere, as informed by spacecraft measurements and 2) theories of cosmic ray transport [Engelbrecht in preparation]. While many challenges remain, neutron monitors provide important constraints on modeling of solar wind turbulence and transport. Without ongoing data from stable neutron monitors the instantaneous solar modulation cannot be determined accurately, and all the practical calculations and measurements that depend on knowing the atmospheric neutron flux will be severely impaired.

Anisotropy during Forbush Decreases in Galactic Cosmic Rays

As a shock and/or CME pass Earth, neutron monitors can register an FD in the GCR intensity. While Earth is inside the magnetic flux rope of a CME, plasma turbulence can be weak and relativistic particles may have a mean free path of ~1 AU [Ruffolo et al. 2006, Bieber et al., 2005]. Therefore, the GCR anisotropy inside a flux rope can provide direct information about distant plasma processes. In particular, there was a prediction that cosmic rays drift into a CME flux rope along one leg and out the other, that would generate a unidirectional anisotropy [Krittinatham et al. 2009]. Such anisotropy has been confirmed with neutron monitor data [Tortermpun et al. 2018].

CR-intensity variability begins before the arrival of the CME at Earth. The observed effect is a combination of pre-increases and pre-decreases of the CR intensity. Generally, particles with large pitch angles, with respect to the Interplanetary Magnetic Field, approaching the shock are reflected and are observed as pre-increases, while particles with small pitch angles experience a "loss cone" effect and are observed as pre-decreases. The resulting anisotropy in cosmic rays can be observed by the network of NMs and muon telescope/detector (MD).

With the NM and MD network, observing multiple directions simultaneously, it is possible to extract the anisotropy with time resolution of roughly 1 hour or better [Bieber et al. 1995]. Thus, it becomes possible to study transient anisotropies in the pre-existing GCR population produced by CMEs. Precursor "loss-cone" anisotropies can potentially provide up to ~4-12 hours advance warning of geomagnetic storms [Leerungnavarat et al, 2003, Mavromichalaki et al. 2011, Kuwabara, et al. 2006, Tortermpun et al. 2018, Rockenbach et al. 2011, Rockenbach et al. 2014], important for Space Weather watches or warnings. A near real- time (~10-minute delay) anisotropy loss-cone chart was implemented on the Bartol Neutron Monitor webpage (http://neutronm.bartol.udel.edu/spaceweather/welcome.html). We anticipate future improvements such as options to increase the number of stations, to scan archival data and to implement a B_z prediction algorithm.

Remote Sensing the Interplanetary Magnetic Field.

Predicting the interplanetary magnetic field **B** is a crucial parameter for estimating the level of geomagnetic activity from an approaching CME. The *z*-component (north-south component) of the IMF is particularly important, because of the key role it plays in driving magnetic reconnection at the nose of the magnetosphere [Goncharova et al. 2000, Gonzalez et al 2005]. For short-term forecasts, a spacecraft at L1 can provide forecasts of the field ~½ to ~1 hour in advance.

Bieber et al. [2013] demonstrated that B_z can be inferred from NM data by applying quasilinear theory to derive an expression relating fluctuations in the cosmic-ray pitch-angle distribution to fluctuations in **B** integrated along the reverse particle trajectory. In their analysis, they considered 161 events and found that the percentage of events with positive correlation between predictions and measurements of B_z varies from about 85% (60%) for predictions 1 hour (4 hour) into the future. An improved model of predicting Bz using NM and MD network data should support the advancement of Space Weather predictions of geomagnetic storms.

Priorities and recommendations

i. Extend range of remote sensing of CMEs and IMF orientation.
ii. Consult with interested parties about rapid SW watches, alerts and warnings.
iii. Engage with surface muon telescopes to expand remote sensing capabilities.

5. Growth of NM Network

Over the decades, we have witnessed the atrophy of the US and world-wide NM network. Investing resources to restore or replenish the network will yield tangible benefits, especially in light of the fact that NMs after deployment are inexpensive to operate and maintain. With a goal of achieving better latitude (rigidity), longitude (asymptotic direction) and altitude coverage (spectrum studies), future sites can be studied and evaluated. Historically, sitings ofter are often co-located with the institutions where the science is conducted, but this need not be so, as seen with SpaceShip Earth. Unknown is the future participation of Russian stations and may require other stations to partially fill the gap.

The network is already expanding with the redeployment of the station on the summit of Haleakala on Maui. A high-altitude, pseudo equatorial station 12 hours west of the central meridian will begin to plug a wide gap in rigidity and asymptotic direction. Along with a 3NM64 instrument (collaboration between U Hawaii and Thailand), the permitting process has begun as well as the procurement process for materials for a 6NM64 instrument.

Priorities and recommendations

i. Investigate candidate future high- and mid-latitude NM sites as well as low-latitude, high-altitude sites.
ii. Support international community in setting up new stations or resurrecting old ones.
iii. Investigate converting some single NM sites into multiple NM sites for spectral sensitivity.

6. Education and Outreach

An important contribution to the future of high-energy heliospheric physics community is the education and grooming of young scientists. The NSF NM program has trained numerous graduate students, but many are nearing retirement age. More can be done, not only to train new scientists, but more generally, to engage students in science or space weather work, thus education and public outreach will be an important part of the general NM program.

Currently funded outreach efforts will draw upon the expertise of the University of Hawaii (UH) team and at the other educational institutions. Middle school, high school, and undergraduate students, many of whom, in Hawaii, are minorities that are typically underrepresented in STEM fields, will be educated about space weather, solar physics, particle physics, and all science involved in this field. They will have the opportunity to visit the Haleakala instrument, to engage with Haleakala NM and AMS operations at the SW control center located at UH, and to work on dedicated interdisciplinary projects and activities. Teachers will help identify students who have more interest in this field and will closely work with them during these activities. The team in Hawaii will link the NM work to the funded Quarknet program, providing access to muon detectors, the Haleakala instrument, the global NM network, and AMS data.

Priorities and recommendations

i. Recruit students to be groomed as the next generation of high-energy space scientists.
ii. Continue to engage middle school and secondary education students in the excitement around high-energy space physics, space weather and science in general.

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