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Haleakala neutron monitor redeployment and calibration with AMS data

Cristina Consolandi [1], Veronica Bindi [1], Claudio Corti [1], Nikolay Nikonov [1], James Ryan [2], Jason Legere [2], Waraporn Nuntiyakul [3]

Correspondence

1 Department of Physics and Astronomy, University of Hawaii at Manoa, Honolulu, USA, cconsola@hawaii.edu

2 College of Engineering and Physical Sciences, University of New Hampshire, Durham, USA

3 Department of Physics and Materials Science, Faculty of Science, Chiang Mai University, Thailand

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Abstract

Since the 1950s, neutron monitors (NMs) have successfully measured both the long-term and the short-term variation of Galactic Cosmic Rays (GCRs). NMs are also sensitive to solar energetic particles (SEPs) and solar neutron particles (SNPs), both detected as ground level enhancements. Since SNPs are not affected by the interplanetary magnetic field, they retain direct information about the nuclear reactions happening near the SEP acceleration site. The global NM network has still a huge gap over the equatorial Pacific for measuring high energy GCRs and SNPs which are best measured at low latitudes. We plan to extend the coverage of the world wide NM network for SNP and GCR observations by redeploying the Haleakala NM station (HLEA) on Maui, in time for the upcoming solar maximum (around 2025). Since NMs can only measure the total count rate, it is not trivial to derive the actual particle flux and to compare different station responses. We plan to calibrate the HLEA with the future AMS daily proton fluxes, extended until the ISS decommission date now planned in 2031, and to perform extensive Mote Carlo simulations of the detector and surrounding environment. The initial phase of the project has already started. Status of the upcoming HLEA NM detector is reported.

1. Introduction

Solar energetic particles (SEPs) are particles accelerated by the Sun during explosive events such as solar flares and Coronal Mass Ejections (CMEs). The highest-energy SEPs are primarily accelerated near the Sun; then they follow the complicated structure of the Interplanetary Magnetic Field (IMF) and the Earth's magnetosphere to reach Earth's atmosphere. Thus, their spatial distribution is greatly affected by propagation processes, modifying their arrival time, intensity, duration, and anisotropy. During strong solar flares, the Sun can also emit energetic neutrons, called Solar Neutron Particles (SNPs), created in interactions of SEPs with nuclei in the Sun's atmosphere. Since SNPs are not affected by the IMF, they retain direct information about the nuclear reactions happening near the SEP acceleration site. When an SEP or an SNP event occurs, it may initiate a cascade of secondary particles in the Earth's atmosphere that can be detected on the ground by neutron monitors (NMs), i.e. ground level enhancement (GLE).

NM stations are distributed across the world, working together as a giant spectrometer, known as the global NM network. The global NM network, active since the 1950s, has successfully measured the long-term variation of Galactic Cosmic Rays (GCRs) due to the 11- and the 22-year solar cycle modulation, and the short-term variations of GCRs, e.g. diurnal variations or Forbush decreases (FDs), and the flux of particles accelerated by the Sun: SEPs and SNPs. Nevertheless, the Pacific Ocean represents a large gap in the equatorial coverage of the global NM network for SNP and GCR detection (Mishev & Usoskin 2020). Currently, this gap spans a longitudinal expanse of 162° from the Princess Sirindhorn NM in Thailand to Mexico City. To fill this gap, we will redeploy the Haleakala (HLEA) NM, which is strategically near the middle of this gap at an altitude of 3 km on the island of Maui. The HLEA position is ideal for SNP detection: the high-altitude minimizes SNP absorption in the atmosphere, and the low-latitude maximizes the Sun's elevation, thereby increasing exposure. In addition, space weather (SW) monitoring systems are becoming increasingly important for providing alerts to both the scientific community and private enterprise. For this reason, incorporating novel data from SNPs to advance SW alert systems is highly desirable.

Recently, the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) and the Alpha Magnetic Spectrometer (AMS) have provided precise GCR measurements of different nuclei on various time scales (Galper et al. 2017; Aguilar et al. 2021a). AMS is a detector measuring charged particles in the energy range from 300 MeV to a few TeV on the International Space Station (ISS) since May 2011. As a space-borne experiment, AMS detects charged primary particles before their interaction with the atmosphere, enabling direct measurements of their spectra and chemical composition. The simultaneity of space-borne and ground-based detectors give us the possibility to compare and cross-calibrate the two kind of instruments and to understand the effects of the Earth's magnetosphere and atmosphere on charged particles propagation. In our past publication (Koldobskiy et al. 2019) we tested the stability versus time of some of the widely used NM yield functions (YFs) with the AMS monthly Proton and Helium fluxes (Aguilar et al. 2018). The new AMS publications on daily Proton and Helium fluxes (Aguilar et al. 2021b; Aguilar et al. 2022) give us the possibility to extend the same work on a shorter time scale and to set up a procedure for calibrating the forthcoming HLEA data with the future AMS fluxes extended until the ISS decommission date now planned in 2031.

2. Solar Neutron Particles with HLEA NM

J. A. Simpson, of the University of Chicago, deployed the first NMs in the early 1950s. Others followed with many at high altitude. The old HLEA NM, constructed in 1991, was part of the University of Chicago, then later the University of New Hampshire (UNH) system and continuously took data until its decommissioning (due to lack of funds) in 2006. This NM station is located on Haleakala mountain in the middle of the Pacific Ocean. SNPs are best observed by NM stations located at high altitude, to reduce atmospheric ab-

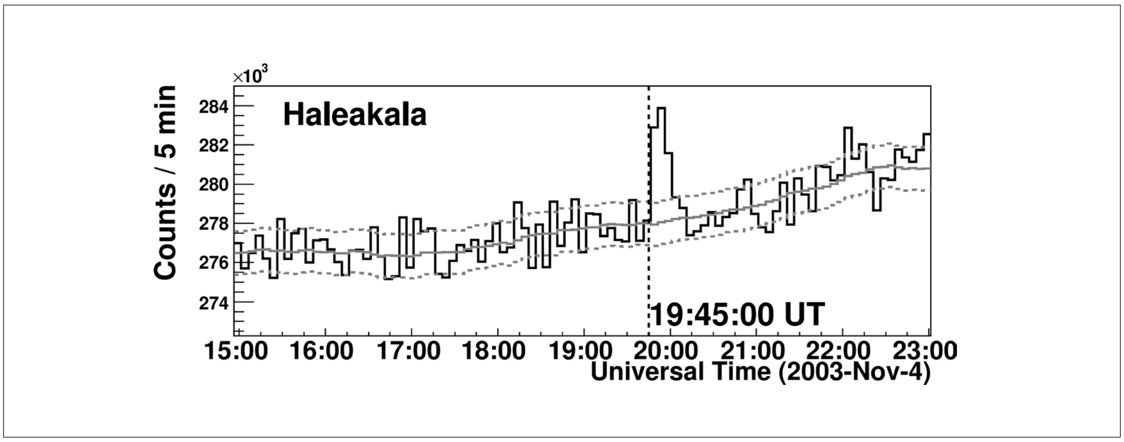

Fig. 1: Most recent SNP event observed by the old Haleakala NM station in 2003, November 4.
Picture taken from (Watanabe et al. 2006): *Five minute averages of the counting rate observed by the Haleakala. The smooth solid line is the averaged background, and the dashed lines are ±1σ from the background.*

sorption, and low latitude, to maximize the elevation of the Sun. During its history, the old HLEA detector measured three SNP events (a list can be found in Yu et al. 2015). For demonstration purposes, Fig. 1 shows the five-minute average count rate for 2003, November 4, measured by the old HLEA station. At 19:45 UT, the detector measured a 2% increase over the background due to SNPs (Watanabe et al. 2006). The significance of this SNP event was 7.5 σ. We now have funds to setup six-tubes which corresponds to one third of the old NM station and the new uncertainty on signal would scale roughly as, resulting in a significance of 4.3σ. Thanks to our collaboration with Chiang Mai University, we will have the possibility to expand HLEA NM with other three-tubes (see Sec. 3). In this case the significance would increase to 5.3σ. Therefore, a scaled-down version of HLEA would still be highly sensitive to SNP events with amplitude of 2% or more over the background. There are only a few NMs in the global NM network in a favorable location for detecting SNPs. The restoration of HLEA would fill a large gap between the Thailand and Mexico stations and will also provide information about FDs for GCRs with rigidity above 13 GV (Mangeard et al. 2017). The new HLEA NM will extend the ground coverage of GCR and SNP detection.

3. Redeployment of the Haleakala NM

Two standard sea containers will host the new HLEA NM and will be placed on Haleakala summit. Fig. 2 shows the facility location for the new HLEA NM. The area will cover a maximum of 50m^2. It is located on the Haleakala summit in island of Maui, near the building that previously hosted the old HLEA NM. The new HLEA NM will be also near to the Daniel K. Inouye Solar Telescope (DKIST). DKIST telescope is imaging the Sun in several wavelengths. The direct observation of solar flares that produce SNPs will provide context for interpreting the new HLEA data.

Complementing HLEA will be a portable NM, Thimon provided by Chiang Mai University in Thailand. Fig. 3 shows a picture of the exterior of Thimon sea container hosting an NM instrument. This sea container was prepared and equipped in Thailand. Thimon NM will be one of the two sea containers that will constitute and expand HLEA NM instrument.

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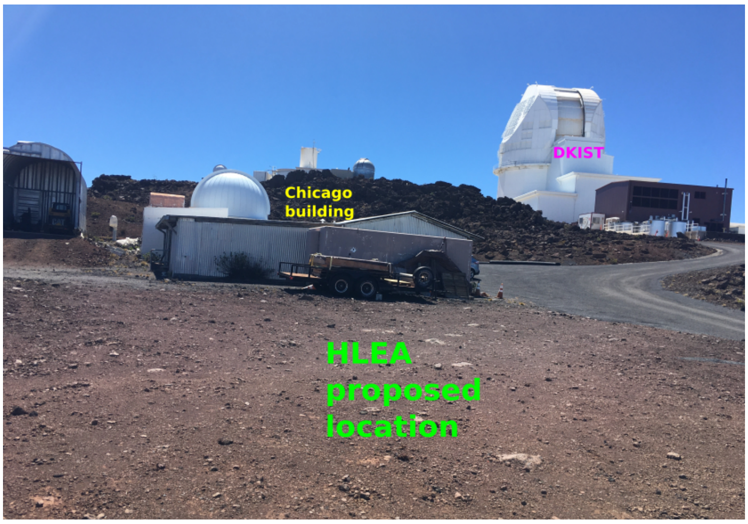

Fig. 2: Picture of new HLEA NM facility close to the Chicago building that previously hosted the old HLEA NM, on the Haleakala summit. The new HLEA will be also near to the DKIST telescope.

Fig. 3: Side view of Thimon shipping container. Logos of different institutes of the collaboration are well visible.

Fig. 4 shows a picture of the interior of Thimon shipping container. This container is already furnished with a 3-inch thick polyethylene (reflector) box and three pure lead rings that will host three Boron Tri-Fluoride (BF_3) NM tubes. We will reuse the original proportional counter tubes, with moderator, that were part of the previous HLEA NM. The Thimon container will be equipped with power cables, computers, temperature sensors, barometers, and lights. New electronic boards will be fabricated and tested at Bartol Research Institue. At the moment Thimon is located on the campus of the University of Hawaii (UH) on O’ahu. It will be shipped to Maui where it will be equipped with three BF_3 tubes and electronics.

A second shipping container with double doors will host the other six BF_3 tubes arranged such as three tubes will be reached at each side of the container independently. Fig. 5 shows a model of this second

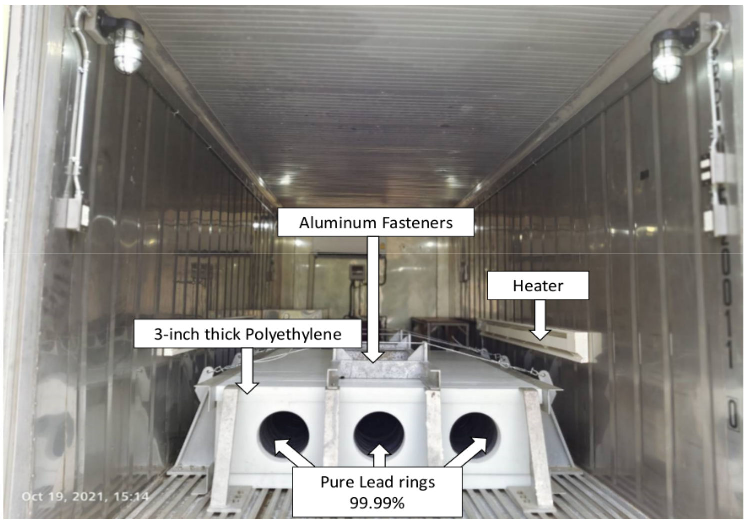

Fig. 4: Interior of Thimon, one of the two HLEA shipping containers minus the BF3 tubes. This container is equipped with a 3-inch thick polyethylene box and three pure lead rings. Aluminum fasteners and heaters are also marked.

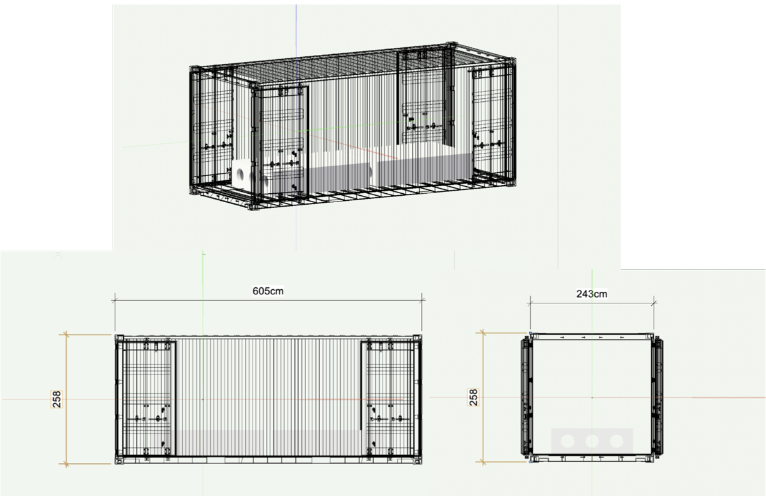

Fig. 5: Model of the second HLEA shipping container with double doors and two banks of 3-tubes at each side.

container seen from different angles. To minimize the operations at the summit, the second container will be assembled, equipped and tested at UNH. Also this second shipping container will be sent to Maui.

After the setup procedure is done, tests will be performed on Haleakala summit to check that the new HLEA NMs are running properly. We will take data and perform end-to-end tests. After these tests, normal operation will begin and the new HLEA NM will be remotely monitored. A monitoring system program will be developed and displayed at UH campus. Finally, HLEA data will be publicly available through the online NM database (NMDB) (https://www.nmdb.eu, last accessed July 4, 2023).

4. NM Calibration with AMS Data

The simultaneous measurements of AMS and NMs provide us the opportunity to validate and calibrate the NM YFs, i.e., the response of an NM to the particle flux with a given energy. The NM count rate at a time *t*, $N(t)$, can be related to the near-Earth spectrum, $J(R,t)$, as a function of rigidity R and time t,

$$N(t) = \frac{1}{k} \sum_{i=\mathrm{p,He,\ldots}} \int_{R_c}^{\infty} J_i(R,t)\, Y_i(R) \mathrm{d}R, \tag{1}$$

where R_c is the rigidity cutoff of the selected NM, k is a normalization factor that corrects for the realities of the NM (electronic efficiency, environmental effects, etc), $Y_i(R)$ is the YF, and the sum over the index i runs over all cosmic-ray elements. In our previous work (Koldobskiy et al. 2019), we tested the validity of different YFs commonly used in literature, by computing the normalization factor k as the ratio between the modeled and observed count rate. If a YF correctly describes the low-energy response of a NM, then the normalization factor k should be stable in time and uncorrelated to the level of solar activity. As $J_i(R,t)$, we used the monthly proton and helium fluxes measured by AMS from May 2011 to May 2016 (Aguilar et al. 2018). To correctly account for the contribution of Z>2 elements in GCRs, we used the fluxes of lithium, beryllium, boron, carbon, neon, and oxygen measured by AMS between May 2011 and May 2016 (Aguilar et al. 2021a), assuming that their spectrum has the same time dependence as that of helium. Recent AMS results on daily proton and helium fluxes (Aguilar et al. 2021b; Aguilar et al. 2022) give us the possibility to do the same work on a shorter time scale and to extend the YF validity. We will redo the same analysis testing different YFs on a daily basis until November 2019.

This job will serve as a starting point for calibrating the GCR spectra measured by the upcoming HLEA NM with future AMS publications.

5. Simulation of HLEA detector response

The particle environment on Haleakala, and the instrument itself, differs from all other stations in the Simpson network. Consequently, it is essential to understand in some detail how the detector responds to the particle spectrum. We will assess the realistic, energy-dependent effective area of HLEA, the so-called YF, for both GCRs and SNPs. To that end, we will embark on a thorough simulation of the instrument and its surrounding environment, which includes the overlying atmosphere. We will use GEANT-4 and PLANETOCOSMICS (Agostinelli 2023) simulation of the GCR and SNP magnetospheric and atmospheric transport with a realistic atmospheric depth profile. Variables that should be studied are: incident direction, solar cycle dependent cutoff, atmospheric overburden, and water content at the site of the instrument. To completely model the instrument requires an accurate representation of locations of the various components, i.e., the lead, low density polyethylene, other passive material, the sea container housing the instrument, and even the rock or soil lying beneath the monitor. We will characterize how the instrument responds to barometric pressure variations that affect the count rate. The elemental composition of GCRs affects the ground level neutron intensity. An NM responds to the number of hadronic interactions, so a ^{4}He cosmic ray will roughly generate four times the signal of a proton. NMs have typically assumed either pure protons or a mix of protons and helium. With AMS measurements available, we can now properly compute the response from a cosmic-ray spectrum of variable composition. The effect of different species on the NM response will be simulated. As primary particle spectra, we will use the published AMS fluxes of the most abundant GCRs species: proton, helium, carbon, and others from oxygen up to a high-Z component, such as iron. The final simulated response will be compared to data. To check the validity of this YF, we will compare the measured count rate with the one calculated with Eq.1 of Sec.4.

For SNPs, the incident spectrum and composition is markedly different (softer) than that of the GCRs. The response of NMs is consequently different. Therefore, a complete air shower simulation will be performed for incoming neutrons of different energies. As SNP input spectra we will use a power law function with exponential rollover (Ellison & Ramaty 1985) as suggested by γ-ray measurements (Hurford et al. 2003; Ackermann et al. 2021). Because neutrons are not affected by the IMF and magnetosphere, they travel straight from Sun to Earth, and thus their distribution will be modeled as a point-like source coming from the Sun with different incident angles depending on the time of day at the detector and declination of the Sun. Earth's rotation will be taken into account and the particle distribution for seasonal and local time effects will be estimated at Haleakala location.

The entire process will serve as a calibration method for the HLEA detector.

Acknowledgements

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