PROCEEDINGS OF SCIENCE

Neutron monitor yield function at several altitudes above sea level: new improved computation

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For an analysis of solar particle events using neutron monitor data it is necessary to model the global neutron monitor network response. This is possible using the corresponding yield function(s). We present new improved computations of standard 6NM64 yield functions for primary protons and alpha particles. The yield functions were computed at several depths, encompassing all the historical and existing neutron monitors. The computations were carried out with the Planetocosmics Monte-Carlo tool for extensive air shower simulations. All the secondary particles, which contribute to the count rate of a NM were considered. An effect of the geometrical correction of the NM effective area was also considered above 5-10 GeV/nucleon. The new NM yield function is compared with previous estimates and with experimental altitude and latitude surveys. The new NM yield function was applied to an analysis of ground level enhancement on the basis of global NM network data. The application of previously used double attenuation length method and the new yield function for ground level enhancement analysis are compared.

36th International Cosmic Ray Conference - ICRC 2019-
24 July–1 August, 2019
Madison, United States

PoS(ICRC2019)1125

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[*] Speaker.

1. Introduction

Systematic study of solar energetic particles (SEPs) provides a reliable basis to understand their acceleration mechanism, propagation in the interplanetary space and quantification [1, 2, 3, 4, 5]. As a result of solar eruption(s) e.g. solar flare(s) and/or coronal mass ejection (CME), SEPs can be accelerated to several tens of MeV/nucleon [6, 7]. In some cases, SEPs are accelerated to energy exceeding 100 MeV/nucleon or even to a GeV range. In such cases the SEP energy is high enough to generate a cascade process in the Earth's atmosphere. Secondary particles of the cascade reach the ground and can be registered by ground based detectors e.g. neutron monitors (NMs). This class of events is called ground-level enhancements (GLEs) [8, 9]. Over the years GLEs have been routinely studied using NM records. NMs data analysis is usually used to derive spectral and angular characteristics of SEPs in the vicinity of Earth by modelling the global NM network response [10, 11]. For this purpose it is necessary to possess precise information of SEP propagation in the Earth's atmosphere and NM efficiency for registration of given secondary particles. The NM specific yield function incorporates the full complexity of the atmospheric cascade development, the secondary particle propagation in the atmosphere and the registration efficiency of the detector itself [12]. At recent, application of Monte Carlo methods allowed one to compute realistically the specific NM yield function [12, 13, 14, 15, 16]. Newly computed by us NM yield function, which considers explicitly a geometrical correction related to the finite lateral extend of the secondary particles, was shown to be consistent with latitude surveys and was recently validated [17, 18, 19].

Nowadays, the global worldwide NM network consists of about 50 stations. An essential part of those NMs is located at moderate and high level altitude (e.g. $>$ 500 m above sea level), therefore they are more sensitive, specifically to SEPs, because the reduced atmospheric particle attenuation compared to sea level ones (Fig.1). Moreover, a large number of high-altitude NMs have been used for continuous recordings of cosmic ray (CR) intensity, whose data about GLEs are accordingly stored in the International GLE database `https://gle.oulu.fi` [20].

During the analysis of GLEs, usually the NM count rate increase are normalized to sea level by employing the two attenuation lengths method [21]. This would include some uncertainty, mostly due to the assumption of SEP spectrum slope and is not suitable for operational space weather purposes [22]. Therefore, computation of NM yield function at several altitudes, which encompass all historical and in operation NMs is rather important. Here, we computed NM yield function for a standard 6NM64 at various altitudes similarly to [15].

2. Neutron monitor yield function at different altitudes

The response of a NM to cosmic rays (CRs) is modelled using the expression:

$$N(P_c,h,t) = \sum_i \int_{P_c}^{\infty} S_i(P,h)\, J_i(P,t)\, dP \qquad (2.1)$$

where P_c is the local geomagnetic cut-off rigidity [23], h is the atmospheric depth, $S_i(P,h)$ [m^2 sr] is the specific NM yield function for primaries of particle type i (protons, α-particles, heavy nuclei), $J_i(P,t)$ [GV m^2 sr sec]$^{-1}$ is the rigidity spectrum of primary particle of type i at time t. Accordingly

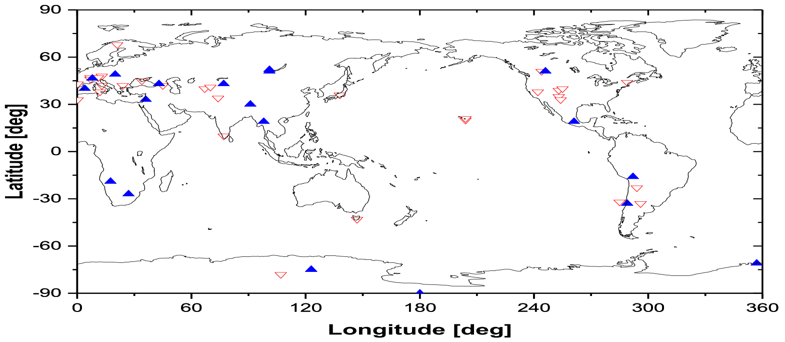

Figure 1: Location map of the non sea level NMs. Up blue triangles correspond to stations in use, while down red triangles to closed stations.

the NM yield function is defined as:

$$S_i(P(E),h) = \sum_j \int \int A_i(E,\theta,C(E)) \cdot F_{i,j}(P,h,E,\theta)\; dE\; d\Omega \qquad (2.2)$$

where $C(E)$ is a geometrical correction factor, which considers the finite lateral expansion of the secondary particles in the cascade, defined according to [15] in the $A_i(E,\theta)$, which is the detector effective area and includes the registration efficiency, $F_{i,j}$ is the flux of secondary particles with energy E and angle of incidence θ. The relative count rate increase of a given NM during GLE is given as:

$$\frac{\Delta N(P)}{N} = \frac{\frac{1}{13}\sum_k \int_{P_{cut}}^{P_{max}} J_{sep}(P,t) S_k(P) G(\alpha(P,t)) dP}{\int_{P_{cut}}^{\infty} J_{GCR}(P,t) Y(P) dP} \qquad (2.3)$$

where J_{sep} is the rigidity spectrum of SEPs, $J_{GCR}(P,t)$ is the rigidity spectrum of GCR at given time t, $G(\alpha(P,t))$ is the pitch angle distribution of SEPs, N is the count rate due to GCR, $\Delta N(P_{cut})$ is the count rate increase due to solar particles, P_{cut} is the minimum rigidity cut-off of the station, accordingly P_{max}=20 GV is the maximum rigidity of SEPs considered in the model, S_k is the specific NM yield function for k=0°, 15°, 30° and 45°, which accounts the contribution of oblique events [24] from 13 weighted by solid angle different segments (Fig. 2), which is particularly important for modelling strong and/or very anisotropic events. Expression (2.3) allows one to model the global NM network response and to derive the spectral and angular characteristics of SEPs using a convenient optimization [25, 26, 27], explicitly considering obliqueness of the events and NM responses at different altitudes [28, 29, 30]. Note, that in case of weak events and/or during isotropic phase of an event, the S_k can be replaced in (2.3) with isotropic NM yield function, which considerably simplifies the computations, but lead to comparable results [28].

For computations of the specific NM yield function we performed Monte Carlo simulations of CR induced atmospheric cascades due to primary protons and α-particles with energy in a wide range. Propagation and interaction of primaries in the Earth's atmosphere was simulated with PLANETOCOSMICS [31] code, employing NRLMSISE 00 atmospheric model [32]. Correction similar to [15] was also considered, which slightly varied as a function of the altitude above sea

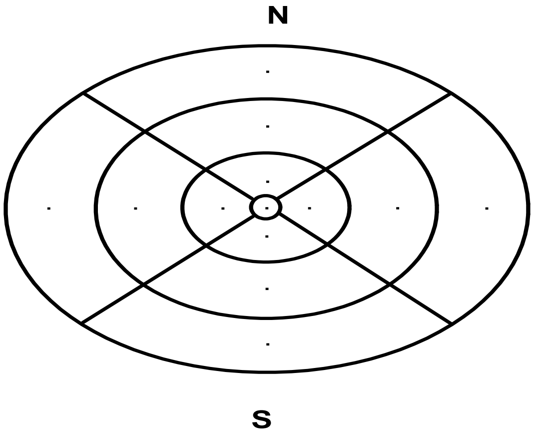

Figure 2: Thirteen segments above a CRs contribute to NM responses. Circles represent zenith angles of 0°, 15°, 30° and 45°. *S*, accordingly NM viewing cones are computed for each direction market with dots (zenith angles 0°, 15°, 30° and 45° and azimuths 0°, 90°, 180° and 270°).

level. Thus, we computed the specific NM yield function at several altitudes and for different angles of incidence, namely for isotropic, vertical, 15°, 30° and 45°.

An example of the computation is given in Fig,3, where isotropic *S* are presented separately for protons and α-particles (panel a) as well as a comparison with other computations (panel b) [14].

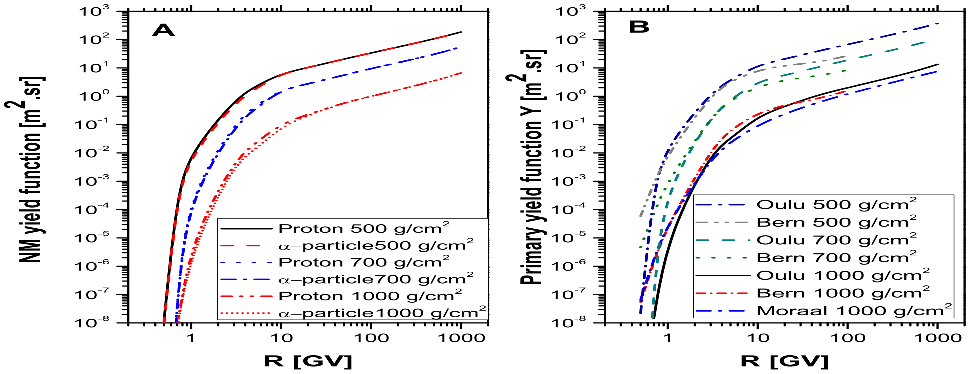

Figure 3: NM yield function for particles with isotropic incidence at different atmospheric depths. Panel a represents NM yield function *S* for protons and α-particles; panel b represents a comparison of *S* for primary protons with other computations [14].

One can see the relatively good agreement of this work specifically with Bern model [14], particularly in the range of maximal NM response (Fig. 4). The computation corresponding to

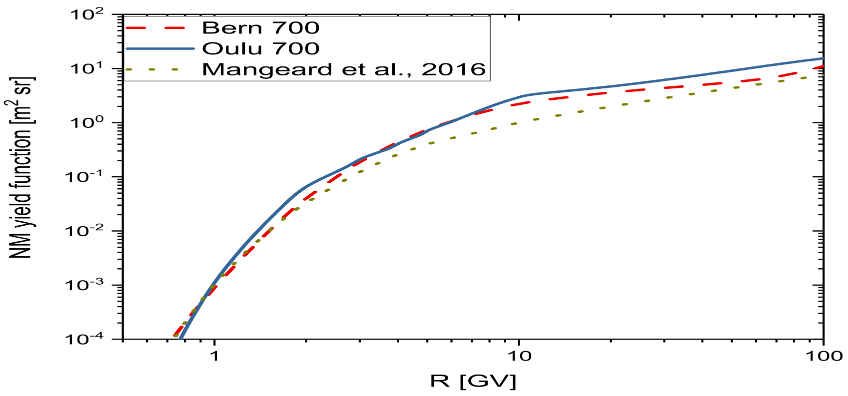

Figure 4: Comparison of several computation of NM yield function *S* at depth of 700 g.m^{-2}. Oulu 700 corresponds to this work, Bern 700 to [14], Mangeard 2016 to [16].

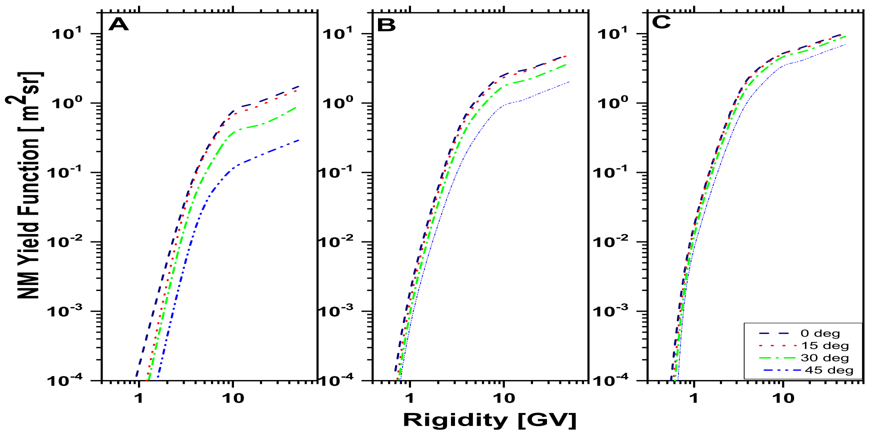

Figure 5: NM yield function *S* for protons with various incidence. Panel a corresponds to sea level, panel b to 700 g.m^{-2} and panel c to 500 g.m^{-2}, respectively.

oblique events are shown in Fig. 5. Note, that those computations were carried out up to 20 GeV/n, because they aimed particularly SEPs.

3. Applications

Reliable analysis of several GLE have been performed using the newly computed specific NM yield functions, explicitly considering the altitude above sea level of the station, i.e., the response of each NM is modelled with a yield function corresponding to it's exact altitude [28, 30]. Moreover, due to the reduced uncertainties and robust procedure, the application of specific high-altitude NM yield function(s) for GLE analysis, allowed us to derive spectra and angular distribution of new sub-class SEPs events, namely sub-GLEs [9], the details are given elsewhere [29] and to derive more precise GLE spectra.

In addition, we compared the derived SEP spectral and angular characteristics of GLE 71 using two attenuation lengths method [27] and employing NM yield function at several altitudes. During the new analysis the responses of all high-mountain NMs, namely South Pole, which recorded a notable NM count rate increase, accordingly Alma Ata, Baksan, Jungfrau Joch with marginal or null NM count rate increases, were modelled using yield functions corresponding to their exact altitude above sea level. The derived on the basis of the new analysis SEP spectra are with reduced uncertainties compared to rescaling method, the details are given elsewhere. Moreover, we expanded considerably the time span of derived SEP spectra, specifically in the late phase of the event, where an isotropisation of SEPs was observed.

4. Conclusion

Here, we presented new improved computations of standard NM 64 yield function at several altitudes. The newly yield function was computed for primary protons and α-particles. Note, that α-particles effectively consider all heavy species of primary CRs [33, 34]. The computations were performed using a realistic atmospheric model employing Monte Carlo simulations. Similarly to sea level NM yield function, a geometrical correction of the detector effective area was explicitly considered, which was found slightly to vary as a function of altitude above sea level. This correction explicitly takes into account the finite lateral extend of the CR-induced atmospheric cascade. It becomes important at energies greater of about 5–10 GeV/nucleon. Hence, we computed NM yield functions at various altitudes, which appeared consistent with the experimental NM count rates for several NM stations. In addition, we computed NM yield function for events with different incidence, namely 0°, 15°, 30° and 45°, which allowed us to consider several important effects and to model more precisely, specifically very strong and highly isotropic, events. The newly improved computation of the NM yield function at several altitudes, improved the developed by us procedure for GLE analysis using NM data, leading to a faster convergence of the optimization and more robust results in contrast to procedure based on rescaling NM responses to sea level.

Acknowledgements

This work was supported by the Academy of Finland (project 307411, Center of Excellence ReSoLVE, HEAIM project 314982 and 316223) and by the International Space Science Institute support to International Team 441: High EneRgy sOlar partICle Events Analysis (HEROIC).

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