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About the necessity to build new polar neutron monitor stations

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Over the years the global neutron monitor network was successfully used to study cosmic ray variations and fluxes of accelerated solar ions, known as energetic solar particles. Recently, it has been used also for space weather purposes, specifically alerts and as a proxy to the related assessment of exposure to radiation (dose). Here, we overview the current status and applications of the global neutron monitor network and discuss its capability to study solar energetic particles, namely assessment of their spectral and angular distribution, during ground-level enhancements, focusing specifically on polar neutron monitors. Here we propose to build several new polar neutron monitor (NM) stations in order to optimize the capability of spaceship Earth to register and provide reliable data for analysis of strong solar energetic particle (SEP) events. We propose to rebuild or open new stations in both North and South hemispheres, e.g. Alert ALRT, Heis Island HEIS, Vostok VSTK, Livingston island LVGI, Barrow BARW, Grise Fiord GSFD, Eureka EUKA, Kotelny island KTLN, Severnaya Zemlya island SEVZ, Summit station SUMT, Wrangel island WRNG.

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1. Introduction

Primary high-energy particles with energies of about GeV/nucleon or greater, originating from space, when entering in the earth's atmosphere produce a large variety of secondaries. The secondaries collide with atmospheric constituents, in turn producing other, that is next generation of high-energy particles. Each collision adds a certain amount of particles, leading to the development of a complicated nuclear-electromagnetic-meson cascade known as an extensive air shower (EAS).

The bulk of those primary particles known as Cosmic rays (CRs) are protons, α-particles and heavier nuclei. Their energy ranges from about 10^6 to 10^{21} eV/nucleon, following roughly a power-law spectrum. The omnipresent component is with galactic origin called galactic cosmic rays (GCRs), produced mostly during and/or following supernova explosions.

Occasionally high-energy protons resulting from solar eruptions, viz. solar flares, and coronal mass ejection (CMEs), where solar ions can be accelerated to high energies, that is solar energetic particles (SEPs) [1] can induce EAS, similarly to the GCRs. Thus, the secondaries would reach the ground and increase the count rates of ground-based detectors, such as neutron monitors (NMs) [2]. This special class of SEP events is called ground-level enhancements (GLEs) [3, 4].

In most cases, SEPs can be studied by space-borne instruments, yet the majority of the space-probes are constrained, because orbiting regions with a high rigidity cut-off, therefore are not very suitable for continuous measurements of GLEs over the whole time-span of the events. On the other hand, GLEs can be studied using the worldwide NM network [5, 6].

Here, we propose an extension of the global NM network with several new detectors, specifically in the polar region, in order to optimize its performance for alerts connected with space weather purposes and non the least to fill the existing gaps. This extension would improve the space weather services and data analysis of NM records related to SEP physics.

2. Alerts, registration and analysis of GLEs using NMs

Registration of a GLE can provide an early alert for the onset of SEP events [7, 8]. Alert systems are based on a reliable coverage of the arrival direction of GLE particles by the global NM network, because selected NMs shall register certain count rate increase(s). In such a way the global NM network can provide reliable space weather services, specifically related to radiation risk [9].

According to a recent adjusted definition [4], a GLE is registered when there are near-time coincident and statistically significant enhancements of the count rates of at least two differently located NMs including at least one station at nearly sea level, whilst for a sub-GLE event, the requirement is two differently located high-elevation NMs. In all cases, it is necessary to have a corresponding enhancement in the proton flux measured by a space-borne instrument(s). We emphasize that the high elevation polar NMs such as DOMC and SOPO are more sensitive and possess lower energy threshold for GLE detection, namely of about 300 MeV/nucleon, because the reduced atmospheric attenuation of the EAS compared to sea level [10].

For reliable analysis of NM records, it is necessary to possess enough NM stations, which allow one to perform a robust unfolding [11]. The methods for analysis of GLEs using NM data are based on modeling of the global NM network response and unfolding n model parameters over the experimental records of m NMs [12, 13].

In general, the relative count rate increase of a given NM during GLE can be modelled using:

$$\frac{\Delta N(P_{\text{cut}})}{N(t)} = \frac{\sum_i \sum_k \int_{P_{\text{cut}}}^{P_{\text{max}}} J_{\text{sep}_\text{i}}(P,t) S_{i,k}(P) G_i(\alpha(P,t)) A_i(P) dP}{\sum_i \int_{P_{\text{cut}}}^{\infty} J_{\text{GCR}_\text{i}}(P,t) S_i(P) dP} \tag{1}$$

where $N(t)$ is the count rate due to GCR, $\Delta N(P_{\text{cut}})$ is the count rate increase due to solar particles. J_{sep} is the rigidity spectrum of SEPs i (proton or α-particle), $J_{\text{GCR}_\text{i}}(P,t)$ is the rigidity spectrum of the i component (proton or α-particle, etc...) of GCR at given time t, $G(\alpha(P,t))$ is the pitch angle distribution, note for GCRs the angular distribution is assumed to be isotropic, A(P) is a discrete function with $A(P)$=1 for allowed trajectories and $A(P)$=0 for forbidden trajectories. Function A is derived during the asymptotic cone computations. P_{cut} is the minimum rigidity cut-off of the station, accordingly, P_{cut} is the maximum rigidity of SEPs considered in the model, whilst for GCR $P_{\text{max}}= \infty$. S_k is the NM yield function for vertical and for oblique incidence SEPs, k is the number of segments of the sky considered in the analysis. The contribution of oblique SEPs to NM response is particularly important for modeling strong and/or very anisotropic events, while for weak and/or moderately strong events it is possible to consider only vertical ones and using S_k for an isotropic case, which considerably simplifies the computations [14].

An improved model employing validated NM yield function, [15, 16] and robust optimization [17, 18] was successfully used for analysis of a number of GLEs [19–22]. We emphasize that a reliable solution can be derived if an information of about 2(n-1) data (NM stations) is available, where n is the number of the unknowns in the model. Therefore, it is sufficient to retrieve information from about 15–20 NMs, specifically those in a polar region in the simplest case and about 30 NMs for more complicated models, whilst the mid-latitude stations provide the necessary boundary conditions for the inverse problem.

The current global NM network gives a good basis to register and study GLEs, yet a notable gap in coverage, that is asymptotic directions in the Arctic region is seen (Fig.1). While the South polar NMs provide relatively good coverage of the sky, those at North exhibit gaps such that if a GLE with narrow PAD occurs with anisotropy axis located in the polar region of the northern hemisphere, more precisely nearly to international date line of about 180° longitude and at about 55–60° latitude, it would not be registered by the existing NMs (the black solid lines in Fig.1). Moreover, several polar stations e.g. Cape Schmidt (CAPS) and LARC are not operational and/or not providing data, leading to increase of the gap.

3. Extension of the global NM network

The observed gap can be filled, by an extension of the NM network with several new stations, as well as stations replacement of CAPS and LARC. In addition, in order to optimize the sensitivity of the global NM network for registration of solar neutrons [23], we propose to rebuild the Haleakala NM as well as several new low-latitude (high rigidity cut-off), preferably high-altitude stations. We emphasize that several stations are under construction or are on a final stage of planning [24].

The gap in the polar region can be filled with the following stations: Severnaya Zemlya (SEVZ), Summit station in Greenland (SUMT) (for details see Fig. 2 and Table 1) and by reopening of the presently non-operational, but previously existing NMs: Alert (ALRT), Heis Island (HEIS)

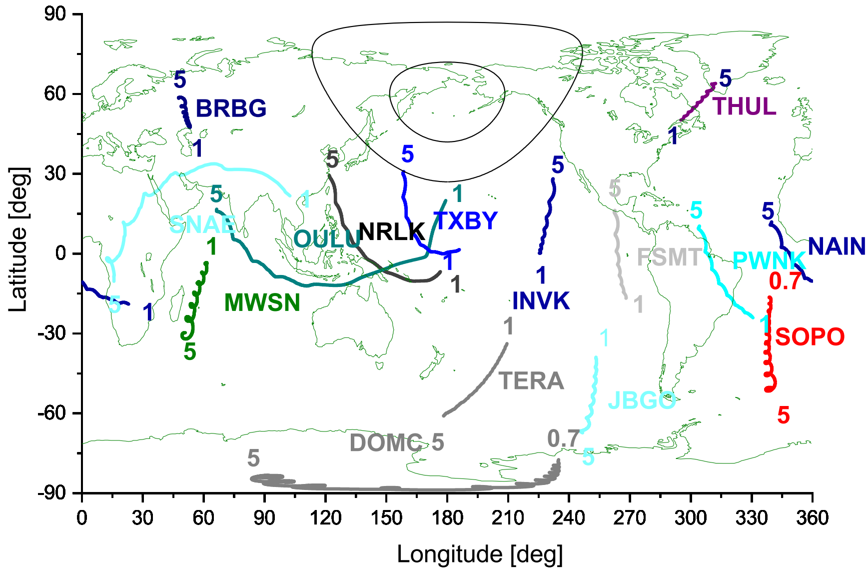

Figure 1: Asymptotic directions of polar NMs with the standard acronyms. The color lines depict asymptotic directions plotted in the rigidity range 1–5 GV, for DOMC, SOPO from 0.7 to 5 GV respectively. The contour plot (black solid lines) for 15° and 30°, reveal the gap in the coverage.

and Vostok (VSTK), the latter for optimization the performance of the unfolding procedure. In addition, we propose several NMs alternative of CAPS: Eureka, Grise Fiord, Barrow located in Nunavut country and Alaska, as well as the islands Kotelny and Wrangel in the Russian Arctic region. Note, that for all possible locations we choose place with existing meteo-station(s) or other facilities, which can provide power supply and data transmission. We emphasize that a new station at Livingston island, with asymptotic direction virtually the same as LARC was recently constructed [25]. Hence, the extended network of polar stations will provide almost global coverage in the maximal NM response rigidity range, namely 1–5 GV (for details see Fig.2).

The sensitivity of the global NM network for registration of solar neutrons can be improved with new stations located in low latitudes and high altitudes, namely at the Canary islands and New Zealand. At recent new station in Adis Abeba was opened, which can also contribute to the improved sensitivity of NM network to solar neutrons (see Table 1). Summary of the extension of the global network is given in Table 1 and Fig.3.

4. Conclusions

Here we discussed the instrumental bases, that is coverage of the global NM network to register and provide reliable information for study of relativistic SEPs and GLEs. The existing gap in the current network can be filled with the proposed by us extension of the network with several new stations. We propose to reopen four previously operational NMs: ALRT, HEIS, HLEA and VSTK and to build several new polar stations: CANI, MTJO and BARW, EUKA, GSFD, KTLY, SEVZ, SUMT.

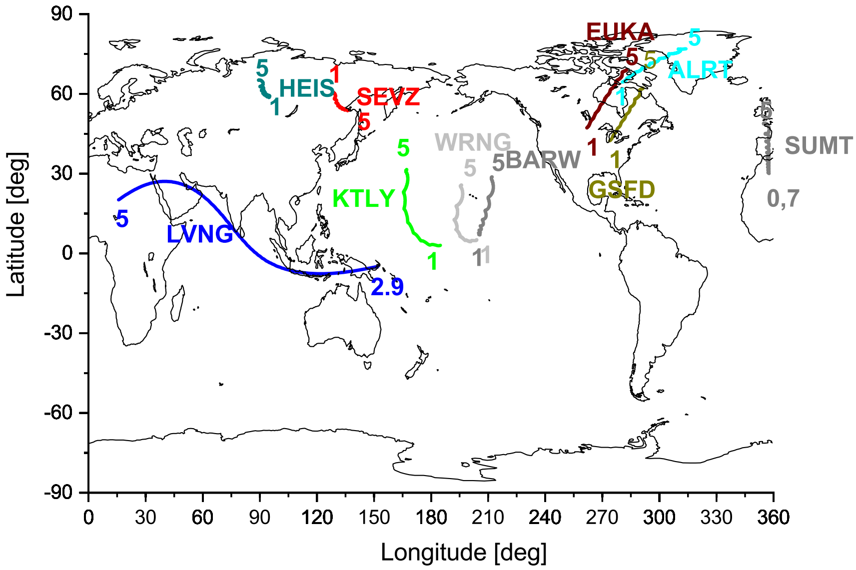

Figure 2: The same as Fig.1. The color lines correspond to new or under construction NMs proposed for extension of the network.

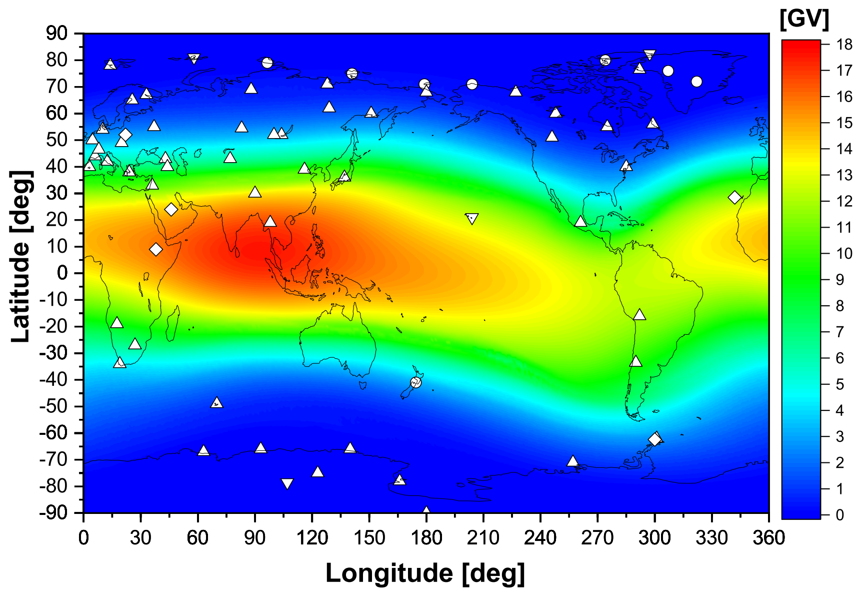

Figure 3: Present and extended global NM network. The upper triangles depict the existing stations, lower triangles correspond the previously existing stations to be reopened, circles to the new stations, rhombus to planned, under construction stations or recently established stations.

The proposed extension of the NM network is a natural continuation of the previous proposition for optimization [26]. The extended NM network will provide the necessary experimental basis to

Table 1: Extension of the NM network. Columns represent station name, location, geomagnetic cut-off rigidity and altitude above sea level. The upper part corresponds to the closed but previously existing stations to be reopened (low triangles in Fig. 3), the middle part corresponds to the planned or under construction stations (rhombus in Fig. 3) and the lower part corresponds to the new stations proposed for extension of the network (circles in Fig. 3).

Station	latitude [deg]	Longitude [deg]	P_c [GV]	Altitude [m]
Alert (ALRT)	82.5	297.67	0.0	57
Heiss island (HEIS)	80.62	58.05	0.1	20
Haleakala (HLEA)	20.71	203.74	12.91	3052
Vostok (VSTK)	-78.47	106.87	0.0	3488
Canary Islands (CANI)	28.45	342.47	11.76	2376
Entoto Observatory (ENTO)	9.1	38.5	16.0	3175
Livingston Island (LVNG)	-62.36	299.40	2.75	10
Riyadh (KANM)	24.38	46.43	14.4	600
Siedlce (SDLC)	52.95	22.16	2.5	155
Barrow (BARW)	71.17	203.5	0.05	3
Eureka (EUKA)	79.59	273.4	0.0	83
Grise Fiord (GSFD)	76.25	306.5	0.0	41
Kotelny Island (KTLY)	75.2	141.0	0.17	10
Mount John Observatory (MTJO)	-43.59	170.27	3.28	1029
Severnaya Zemlya (SEVZ)	79.29	96.5	0.11	10
Summit (SUMT)	72.34	321.73	0.01	3126
Wrangel Island (WRNG)	71.14	179.25	0.09	15

register and study GLEs [27–30].

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