The reliability of GLE analysis based on neutron monitor data – a critical review

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Abstract: Published characteristics of a specific ground level enhancement (GLE), i.e. the solar cosmic ray (SCR) particle spectrum, anisotropy, and main flux arrival direction, derived from ground-based neutron monitor measurements, may vary considerably. As these characteristics are used e.g. as input parameters for the assessment of the radiation dosage at flight altitudes, significant differences in the radiation dose computations along specific flight paths may result.
In this paper we compare published SCR characteristics for the GLEs on 15 April 2001 and 20 January 2005, and we demonstrate the effect of the discrepancies in these characteristics on flight dose calculations for selected flights. We discuss the various GLE analysis procedures and identify possible reasons for the differences in the results obtained.

Keywords: solar cosmic rays, GLE analysis, radiation dose rates at flight altitudes.

1 Introduction

The detection of SCR particles by ground-based detectors occurs on average a few times per solar cycle. Each GLE has its own typical characteristics (amplitude, spectrum, duration, spatial distribution of flux, etc.). The worldwide network of neutron monitors (NMs) using the geomagnetic field as a giant magnetic spectrometer enables to determinate the characteristics of the SCRs near Earth during a GLE in the energy range ∼500 MeV to ∼15 GeV.

The comparison of GLE analysis of individual events shows that the results may vary considerably. From this it follows that e.g. also the radiation dose computations along specific flight paths based on these GLE characteristics may show significant differences. In this paper we investigate the GLE analysis of different groups using GLE60 and GLE69 as examples and discuss possible reasons for the differences in the results.

2 Characterisation of selected GLEs

Both GLEs investigated in this work occurred during the recovery phase of a Forbush decrease and both events show a fast rise after onset. A fast rise indicates a direct access to the field lines connecting the Sun with the Earth and an almost scatter free transport along the interplanetary magnetic field lines. During GLE60 the largest count rate increase was observed by the South Pole NM with more than 200% in the 5-minute data. GLE69 is ranked among the largest in years with gigantic count rate increases of several thousand percent at the south polar NM stations. GLE69 exhibited a strong north-south anisotropy during the early phase of the event and showed a complex intensity-time profile in the data of the NMs of the worldwide network. More detailed information on the characteristics can be found e.g. in [1, 2, 3] for GLE60 and in [4, 5, 6, 7] for GLE69.

3 Description and comparison of GLE analysis procedures

For the determination of the GLE characteristics based on data of the worldwide NM network, the response of the NMs as well as the effect of the geomagnetic field on charged particle transport, i.e. cutoff rigidities and asymptotic directions, must be known.

The response of a NM to relativistic solar protons can be expressed in the following simplified form:

$$\Delta N(t) = \sum_{P_c}^{\infty} S(P) \cdot J_{||}(P,t) \cdot F(\delta(P),t) \cdot \Delta P \qquad (1)$$

where $\Delta N(t)$ is the relative count rate increase due to solar protons as function of time t, P_c the effective vertical geomagnetic cutoff rigidity, P the particle rigidity, $S(P)$ the yield function, $J_{||}(P,t)$ the directional solar particle flux in the presumed source direction, $F(\delta(P),t)$ the pitch angle distribution of solar particles with respect to the source direction, $\delta(P)$ the pitch angle, i.e. angular distance between the arrival direction and direction of the apparent source position outside the geomagnetosphere (asymptotic direction) for particles of vertical incidence at the specific NM location.

The yield functions evaluated for specific detectors and atmospheric depths are determined and published by different authors, for an overview see [8]. The cutoff rigidities and asymptotic directions are obtained by trajectory calculations in geomagnetic field models [9, 10]. The GLE characteristics can then be determined by minimizing the squared differences between $\Delta N_{calc.}$ and $\Delta N_{obs.}$ for the selected set of NM data [11, 12, 13]. Typically ∼10 parameters have to be determined with the data of ∼20-30 NM stations. The determination of the GLE parameters is made either by a trial and error procedure or by a fitting algorithm. The least square fit must be repeated with widely varying

Table 1: Characteristics of GLE analysis procedures

Group	CR transport in geomagnetosphere	CR transport in atmosphere	NM response	SCR spectrum	Pitch angle distribution
Apatity	IGRF [14] + Tsy02 model [15]	yield function [16]		two flux model[1] [4, 17]	$\exp\left[\frac{\delta^2}{C(t)}\right]$ [4]
Athens	IGRF [14] + Tsy89 model [18]	coupling function [19]		$J_{\|\|} = K \cdot P^{\gamma}$ [5, 1]	$\exp\left[-n_a^2(t)\cdot\sin^2(\delta/2)\right]$ [5]
Australia	IGRF [14] + Tsy89 model [18]	yield function [16]		$J_{\|\|} = K \cdot P^{\gamma-\delta\gamma(P-1)}$ [2, 6]	[2] [2, 6]
Bern	IGRF [14] + Tsy89 model [18]	yield function [16]		$J_{\|\|} = K \cdot P^{\gamma}$ [20]	piece by piece linear function [20]
Kiel	only IGRF [14]	[3]	NM detect. effic. [8]	$J_{\|\|} = K \cdot P^{\gamma}$ [3, 7]	linear function [3, 7]

[1] $J = J_1(\gamma_1, \delta\gamma_1, C_1, \theta_1, \phi_1, I_1) + J_2(\gamma_2, \delta\gamma_2, C_2, \theta_2, \phi_2, I_2)$ [2] $\exp\left[\frac{-0.5(\delta-\sin\delta\cdot\cos\delta)}{A(t)-0.5(A(t)-B(t))(1-\cos\delta)}\right]$

[3] PLANETOCOSMICS [21]

initial parameter values to ensure finding the absolute minimum in parameter space.

The characteristics of the individual GLE analysis procedures by selected author groups are summarised in Table 1. The Apatity group [4, 17] has introduced a model with two independent solar particle fluxes: a prompt component (PC) and a delayed component (DC). For GLE60 the Apatity group uses only one SCR flux in the form of a modified power law in rigidity, whereas for GLE69 the two flux model is used (PC and DC are represented by a modified power law in rigidity). The Athens, Bern, and Kiel groups consider only vertically incident particles into the atmosphere. In contrast, the Apatity and Australian groups also include off-vertical directions [13]. In addition to NM data the measurements of satellite and balloon based detectors are used for the determination of the solar proton flux in the energy range below the sensitivity of NMs, and data of muon detectors for the adjacent region at the upper energy range of NMs. Figures 1-4 show selected GLE characteristics during the main phase and the time dependence during the initial and main phase for GLE60 and GLE69 as derived by the different groups. The Apatity group gives an accuracy of the SCR spectrum of ± ∼25-30%.

4 Computed radiation dose rates for selected flight paths

The radiation dose rates were computed [22] along selected flight paths based on GLE parameters as illustrated in Figures 1-4. Figure 5 shows the total ambient dose rates caused by GCR+SCR along two actual flights from Frankfurt to Dallas and from Prague to New York during GLE60. In addition, the relative 5-minute data of the station Nain, which is located close to the flight routes during the GLE maximum phase, are plotted. The computed ambient dose equivalents (GCR+SCR) from the onset of GLE69 until 0800 UT based on the GLE parameters of the different groups along three assumed flights are summarised in Table 2. The departure time for each of these flights was adapted so that the dose was maximal (worst case scenario).

5 Discussion

Possible reasons for the differences in the derived GLE parameters are summarised in the following: NM response (yield function/coupling function), altitude correction of NM data (two-attenuation length method [23]), cutoff rigidities and asymptotic directions (geomagnetic field models, variations of the geomagnetic field), incident direction into atmosphere (off-vertical [13]), SCR spectrum (assumed form), pitch angle distribution (assumed form), number and geographic distribution of NM stations used for GLE analysis.

The results of GLE analysis using the data of the worldwide NM network are highly dependent on the accuracy of the used NM response that accounts for the shower of secondary cosmic ray particles in the Earth's atmosphere and the detection of the secondary nucleons by a NM. The discrepancy between different yield functions is in particular present in the energy range where NMs are most sensitive to SCR [8].

For the normalisation of high altitude NM data to sea level as required in some analysis procedures, McCracken [23] proposed a method with two attenuation lengths: λ_g for GCR and λ_s for the SCR component. For high latitude NM stations and for a typical SCR spectrum λ_s is ∼100 g/cm^2 (λ_g ∼140 g/cm^2). Bütikofer et al. [20] have shown that a variation in the attenuation length of ∼10 g/cm^2 can cause changes of some 10% when correcting high latitude NM count rates to sea level.

The NM response function, i.e. the folding of the yield function with the appropriate cosmic ray spectra, has a narrow peak in the range 1-2 GV for a typical SCR spectrum, see e.g. [20]. In this rigidity domain, changes in P_c and in asymptotic directions due to geomagnetic field variations

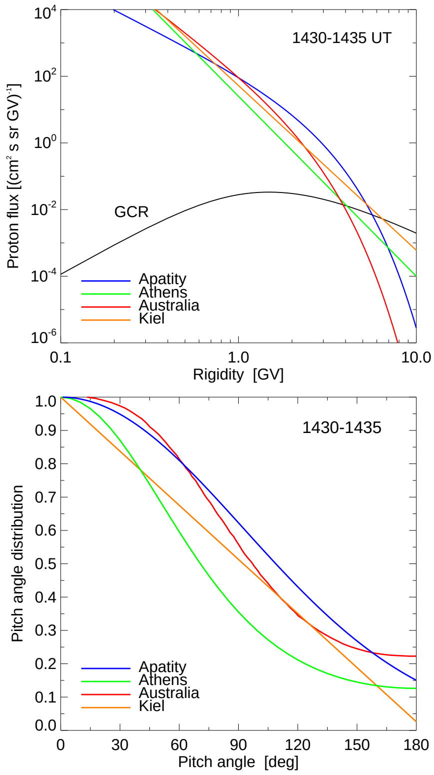

Figure 1: SCR spectra (top) and pitch angle distributions (bottom) during the main phase of GLE60 as derived by different groups.

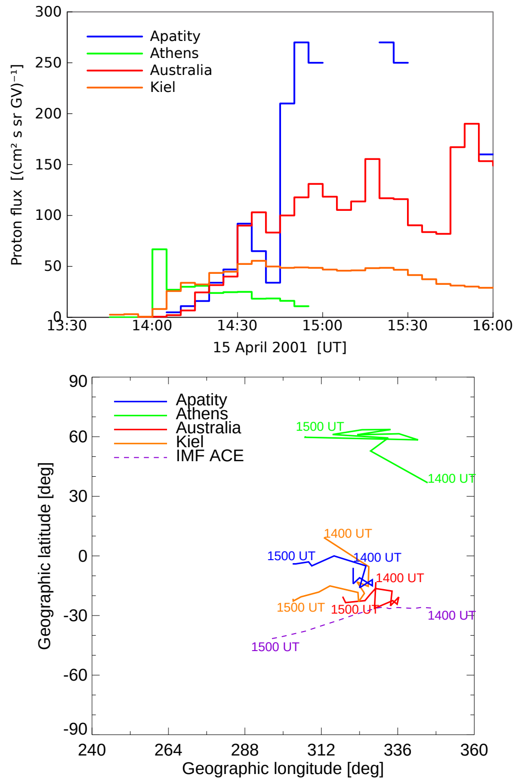

Figure 2: SCR flux at 1 GV in the direction of maximum intensity (top) and apparent arrival directions in GEO coordinates (bottom) during GLE60 as derived by different groups.

can considerably affect the count rate of NMs during a SCR event. Inaccuracies in the determination of P_c and of the asymptotic directions in the rigidity range around 1-2 GV may therefore have a strong influence on the GLE analysis, mainly when the SCR flux is very anisotropic.

The authors [24, 25] showed that the determination of P_c and of the asymptotic directions considerably depends on the used geomagnetic field models during times with a strongly disturbed magnetosphere.

The contribution of off-vertical flux at the top of the atmosphere to the NM count rate can be important during GLEs with a hard SCR spectrum mainly for times with highly anisotropic conditions.

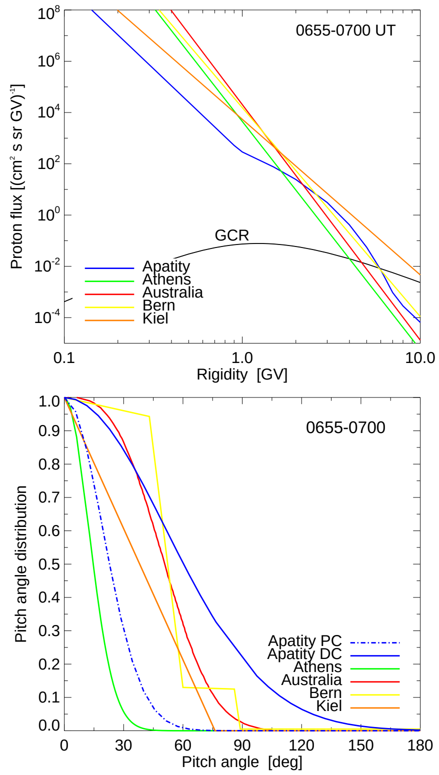

Figure 3: SCR spectra (top) and pitch angle distributions (bottom) during the main phase of GLE69 as derived by different groups.

Table 2: Computed ambient dose equivalents (GCR+SCR) during GLE69 from the GLE onset until 0800 UT based on the GLE parameters of the different groups for three assumed flights.

	Chicago-Beijing [μSv]	San Francisco-Paris [μSv]	Sydney-Johannesburg [μSv]
Apatity	410	620	690
Athens	50	80	80
Australia	150	220	500
Bern	170	270	320
Kiel	80	100	310

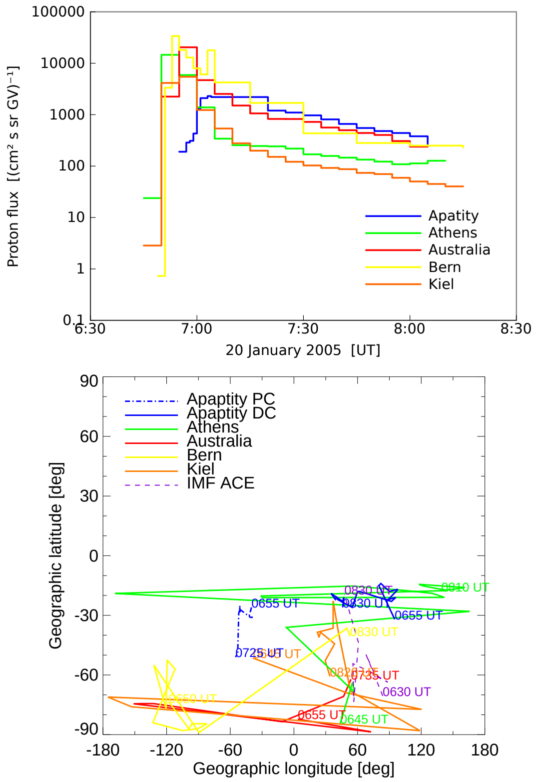

Figure 4: SCR flux at 1 GV in the direction of maximum intensity (top) and apparent arrival directions in GEO coordinates (bottom) during GLE69 as derived by different groups.

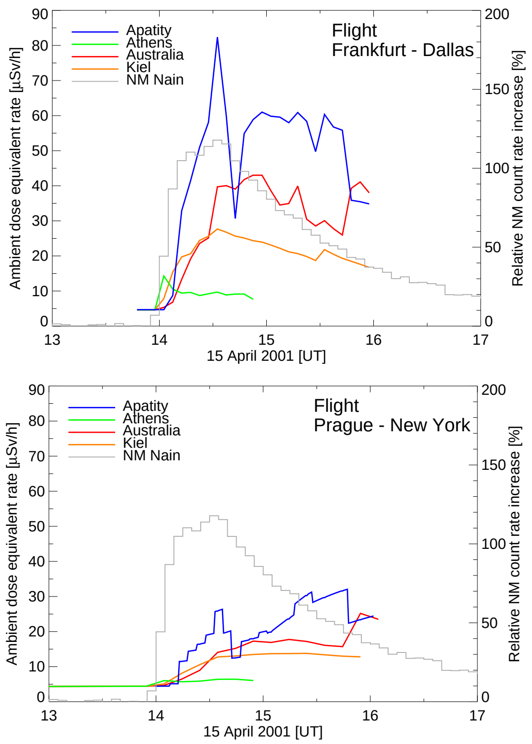

Figure 5: Ambient dose equivalent rates during the main phase of GLE60 along two actual flights computed from the GLE parameters deduced by different groups. Relative 5-minute count rate of NM Nain.

6 Conclusions

This investigation shows that the GLE characteristics for an individual GLE as published in the literature may differ considerably. The comparison of the GLE analysis procedures and the achieved results do not allow to conclusively identify the causes for the differences in the deduced GLE characteristics. Although e.g. the Apatity, Australia, and Bern groups use the same yield function, the derived GLE parameters differ significantly. More detailed information on the GLE analysis procedures is needed to find out the reasons for the large discrepancies in the results of GLE analysis and to improve the reliability of GLE analysis.

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