Differences in published characteristics of GLE60 and their consequences on computed radiation dose rates along selected flight paths

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Abstract. The radiation dose rates at flight altitudes can increase by orders of magnitude for a short time during energetic solar cosmic ray events, so called ground level enhancements (GLEs). Especially at high latitudes and flight altitudes, solar energetic particles superposed on galactic cosmic rays may cause radiation that exceeds the maximum allowed dosage limit for the general public. Therefore the determination of the radiation dose rate during GLEs should be as reliable as possible. Radiation dose rates along flight paths are typically determined by computer models that are based on cosmic ray flux and anisotropy parameters derived from neutron monitor and/or satellite measurements. The characteristics of the GLE on 15 April 2001 (GLE60) were determined and published by various authors. In this work we compare these results and investigate the consequences on the computed radiation dose rates along selected flight paths. In addition, we compare the computed radiation dose rates with measurements that were made during GLE60 on board two transatlantic flights.

1. Introduction
The effective radiation dose rate at typical aircraft cruising altitudes and at mid-latitudes caused by galactic cosmic rays (GCR) is roughly 5 μSv/h. Therefore, the total effective dose for a transatlantic flight, i.e. between Europe and North America, is generally in the order of 50 μSv.

It is known that the radiation dose rates at flight altitudes and high latitudes can increase by orders of magnitude for a short time during energetic solar cosmic ray (SCR) events that are observed on Earth, so called ground level enhancements (GLEs). Lantos and Fuller [1] estimate in a worst case scenario an additional contribution by SCRs of more than 3 mSv for a subsonic flight from San Francisco to Paris for the largest observed GLE on 23 February 1956 (GLE05). This radiation exposure is above the regulatory limits of 1 mSv per year in addition to the annual natural radiation dose for the general public and for the occupational exposure of pregnant women in Europe [2]. This exposure, however, is strongly dependent on the characteristics of the event. Therefore the determination of the radiation dose rate at flight altitude during GLEs should be as reliable as possible.

Radiation dose rates along flight paths are commonly determined by computer models that are based on cosmic ray flux and anisotropy parameters derived from neutron monitor (NM) and/or satellite measurements. In this study we compare the GLE characteristics as determined by several authors for GLE60 on 15 April 2001, and investigate the consequences of the differences in the results on the computed radiation dose rates along selected flight paths. In addition, our
computed radiation dose rates are compared with the measurements that were carried out on two transatlantic flights during GLE60.

2. Description and comparison of different GLE60 analysis procedures
Detailed analysis results of GLE60 were published by Bombardieri et al. [3], Matthiá [4], and Plainaki et al. [5]. The characteristics of the individual GLE analysis procedures are summarized in Table 1. The determination of the cutoff rigidities and asymptotic directions is made for vertically incident particles into the atmosphere by [4] and [5]. In contrast, [3] consider nine arrival directions. The authors [3] and [5] include the disturbed geomagnetic field in the cosmic ray trajectory computations by using a value of 4 for the geomagnetic $Kp$ index in the Tsyganenko 1989 model [6] during the maximum phase of GLE60. Plainaki et al. [5] state that they used in their analysis only the data of two NM stations in the Southern polar region which may result in an inaccuracy of the main arrival direction of the solar cosmic ray flux.

Table 1. Characteristics of the GLE60 analysis [3, 4, 5]

| CR transport in geomagnetosphere | Bombardieri et al. [3] | Matthiá [4] | Plainaki et al. [5] |
|----------------------------------|------------------------|-------------|---------------------|
| CR transport in atmosphere       | IGRF + Tsy89 model     | only IGRF   | IGRF + Tsy89 model  |
| Yield function                   |                        | PLANETOCOSMICS$^2$ | coupling function [7] |
| NM response                      |                        |               |                     |
| # NM stations                    | 32                     | 27           | 28                  |
| SCR spectrum                     | modified power law in rigidity | power law in rigidity | power law in rigidity |
| Pitch angle distribution         | exponential function   | linear function | exponential function |

1 Debrunner H, Lockwood J A and Flückiger E O, 1982, presented at 8th European Cosmic Ray Symp. in Rome
2 Desorgher L, The PLANETOCOSMICS code, http://cosray.unibe.ch/~laurent/planetocosmics

3. Comparison of the SCR results obtained by the different analysis of GLE60
The SCR rigidity spectrum as derived by the authors [3, 4, 5] around the GLE maximum (1430–1435 UT) is plotted in Figure 1. The flux determined by [3] in the rigidity range 1–2 GV is more than 350% higher than [5]. Figure 2 shows the derived geographic coordinates of the main SCR arrival directions during the first hour of the event. The main arrival direction of [3] and [4] is slightly southward and close to the direction of the interplanetary magnetic field, whereas it was determined at similar longitude but around 60$^\circ$N by [5]. The pitch angle distributions, not shown here, as determined by the authors considered in this work do not show large differences.

4. Computed and measured radiation dose rates on board two transatlantic flights during GLE60
We computed the radiation dose rates based on the derived SCR characteristics during GLE60 along two flight routes on which the dose rates were actually measured. The computations are made in different steps: 1) transport of cosmic ray particles in the geomagnetosphere (magnetic
Figure 1. SCR flux in the direction of maximal intensity on 15 April 2001, 1430–1435 UT, as derived by [3, 4, 5]), and the GCR flux in April 2001.

Figure 2. Main arrival directions during GLE60 between 1400 UT and 1500 UT as derived by [3, 4, 5], and direction of the interplanetary magnetic field as measured by the Advanced Composition Explorer (ACE).

field is described by Tsyganenko 1989 model [6] superposed on IGRF), 2) determination of secondary flux at different altitude levels in the atmosphere at the grid points of a geographic network with the mesh size $5^\circ \times 5^\circ$ caused by the SCR and GCR flux by using the Geant4 code PLANETOCOSMICS and 3) by applying the flux to radiation dose conversion factors published by Pelliccioni [9].

Figure 3 shows the computed and measured radiation dose rates for the flights Frankfurt to Dallas and Prague to New York during GLE60. In addition, the 5-minute relative count rate increase of the NM station Nain ($56.55^\circ\mathrm{N}, 61.68^\circ\mathrm{W}, 46$ m asl) is plotted. The following facts have to be considered when comparing the computed values with the measurements. For the computation of the radiation dose rate along the flight Prague to New York the real flight route was available. In contrast, only the flight altitudes and the geographic latitudes for selected times could be taken from Figure 3 in [10] for the flight Frankfurt to Dallas. The geographic longitudes were determined by assuming a constant flight speed during the whole flight along the great circle. As an illustration of the incertitude, a displacement in longitude of $2^\circ$ ($\sim140$ km) from $52^\circ\mathrm{N}$, $55.5^\circ\mathrm{W}$ (assumed position of aircraft at 1432.5 UT) results in a change of the computed radiation dose rate of less than 10% at 1430–1435 UT. The computed radiation dose rate during the maximum phase of the GLE on the flight Frankfurt to Dallas according to [3] is more than a factor four higher than according to [5]. The computed total (SCR+GCR) ambient dose equivalent during the first hour of GLE60 on board the flight Prague to New York is 11 $\mu\text{Sv}$ according to the GLE characteristics by [3], 10.5 $\mu\text{Sv}$ by [4] and 6 $\mu\text{Sv}$ by [5]. The measured ambient dose equivalent for this time interval on the flight Prague to New York is 10.5 $\mu\text{Sv}$.

5. Conclusions
This investigation shows that the published characteristics of GLE60 differ considerably. As a consequence also the computed radiation dose rates and radiation doses along flight routes do not have the desired agreement. In the absence of routine measurements in aircrafts, improvements
Figure 3. Ambient dose equivalent rates along the flights from Frankfurt to Dallas (left) and from Prague to New York (right) as computed in this work based on the SCR characteristics determined by [3, 4, 5]. Measured dose equivalent rate (Frankfurt – Dallas [10]) and measured ambient dose equivalent rate (Prague – New York, private communication). Relative count rate increase at the NM station Nain.

and/or adjustments of the different GLE analysis methods or new procedures are needed to realize a more reliable assessment of the radiation dose rates at flight altitudes during GLEs based on neutron monitor data of the worldwide network.

Acknowledgments
This research was supported by the University of Bern and by the International Foundation High Altitude Research Stations Jungfraujoch and Gornergrat. The information about the flight from Prague to New York on 15 April 2001 was kindly provided by Dr. Iva Ambrožová, Department of Radiation Dosimetry, Nuclear Physics Institute, Czech Academy of Science.

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