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HISTORY OF THE SOLAR PARTICLE EVENT RADIATION DOSES ON-BOARD AEROPLANES USING SEMI-EMPIRICAL MODEL AND CONCORDE MEASUREMENTS

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ABSTRACT
Measurements during solar particle events with dosemeters flying permanently on-board Concorde are used to develop a semi-empirical model, called SiGLE. The model is intended to calculate for a given flight plan, the dose equivalent received during a solar particle event observed with ground-based neutron monitors. It is successfully in operation in the SIEVERT computerised system intended to improve monitoring of radiation dose received by aircrews, in application to a European Directive. The semi-empirical model is applied to evaluate, for most exposed routes, the radiation doses corresponding to the GLEs observed since 1942 with ion chambers or neutron monitors. The results for the largest GLEs observed in the past are discussed in terms of radiation risk, and guidelines are suggested concerning possible alerts to the aeroplanes in case of events of exceptional magnitude.

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INTRODUCTION

Radiation doses received on-board aeroplanes are due to two sources: the galactic cosmic rays (GCR) and the solar particle event subclass called GLE (Ground Level Enhancement) occurring when primary particle energies are sufficient to produce secondary particles detected at the ground level by neutron monitors. Particles in excess of 1 GeV are of most significance in producing secondaries at aircraft altitudes, as pointed out by Dyer and Lei(1), and thus high geomagnetic latitude neutron monitors are well adapted instrument to study and monitor particles having effects at aircraft altitudes. Those monitors are defined here as having vertical cut-off rigidity lower than 2 GV because proton kinetic energy of 1 GeV corresponds to rigidity of about 2 GV(2).

The galactic cosmic ray component is constant in intensity and isotropic outside the heliosphere. Nevertheless because of the variations of the solar wind magnetic field topology, the intensity and the spectrum of the primary particles at the Earth are varying with the 11 year solar activity cycle as well as with interplanetary shock waves of solar origin giving rise to the Forbush Decreases(3). Radiation doses received from galactic cosmic rays have been the subject of number of state of the art measurements on-board subsonic aeroplanes as well as on-board Concorde(4,5,6). Calculations using transport particle codes like LUIN(7) or FLUKA(8) are numerous for galactic cosmic rays and software is available for operational purposes, like CARI 6 software(9) developed by the US Federal Aviation Administration and EPCARD(10) developed on behalf of the European Commission. Both are limited to galactic cosmic ray component.

The solar high energy particle events(11,12) have an irregular frequency of occurrence and some of them are highly anisotropic. GLEs are rare (in average about one per year) but the intensity can be much higher than galactic cosmic ray intensity. The GLE spectrum varies from one event to another and varies in the course of the GLE. The international neutron monitor network (about fifty monitors around the world) is used to calculate spectrum and anisotropy of the solar particles(13). Indeed each monitor records the GLE differently depending upon the monitor latitude, longitude and altitude, due to the filtering effect of the geomagnetic field and to solar particle anisotropy.

Because the GLE spectrum and anisotropy calculations, as well as the particle transport codes necessary to compute the dose equivalent, are too time consuming, it was necessary to develop a much simpler approach for operational applications. The semi-empirical model SiGLE presented here has been developed in the frame of the so-called SIEVERT system(14,15,16)(Système d'Information et d'Evaluation par Vol de l'Exposition au Rayonnement cosmique dans les Transports aériens). This system is operated by DGAC (French Civil Aviation Authority). The system has been set up to fulfil the new requirements of the EU Directive 96/29/Euratom(17), which reinforce the control of the radiation doses received by air crew. Some of the European countries, including France, have implemented in their national legislation the same recommended limits as for radiation workers: the effective dose should not be higher than 100 millisievert over 5 years with a maximum of

50 millisievert for a given year. Specific rule is applied to pregnant air crew members: the foetus should not receive more than 1 mSv up to the end of the pregnancy[17].

When a GLE occurs, the present semi-empirical model provides, in the frame of the SIEVERT system, dose received during a flight for a given flight plan, on the basis of time dependent world 3-D cartography. Dependencies of the dose equivalent rate, as a function of altitude and of vertical geomagnetic cut-off rigidity, are taken from particle transport code results in relative scale. The absolute scale of dose equivalent rates is deduced from measurements on-board Concorde during two GLEs. The model construction assumes that the solar particle anisotropy could be neglected at least to the extend that it affects the North Atlantic corridor. The primary particle spectrum is simplified and the parameter used is the power law exponent γ of the rigidity spectrum in GeV range of energy, observed with ground level neutron monitors, neglecting lower energy characteristics observed with satellite detectors.

The simplifications of the model are justified in these cases as the available data describing these events do not permits a more detailed approach. The model is also useful for the GLEs having not been studied with validated particle transport codes. There is presently no estimate available for the doses potentially received from the set of GLEs observed with neutron monitors: currently only a few GLEs (in particular in February 1956 and September-October 1989) have been studied with particle transport codes[18,19]. Thus in addition to its operational use, the semi-empirical model is applied to past data. One considers here the complete history of the GLEs, giving some information on the overall risk to have significant dose enhancement during solar GLEs on-board aeroplanes.

IN-FLIGHT MEASUREMENTS

No dose equivalent measurement during GLE has been published in the open literature until very recently. Indeed during the 15 April 2001 GLE two scientific groups have calculated assessed ambient dose equivalent rate versus time, from LUILIN dosemeter measurements on-board a Prague-New York flight[20] and from ACREM measurements on-board a Frankfurt-Dallas flight[21]. Both experiments are giving dose equivalent rates of about 11 µSv/h at 10,970 m, at the time of the maximum of the GLE.

In the past, Concorde dose monitoring system was the only source of dose equivalent measurements during GLEs. The system consists of a boron trifluoride proportional counter (the same device as in neutron monitors) with a moderator in polyethylene for neutron detection, and three Geiger-Muller tubes for charged particle and gamma ray detection[22]. Detailed analysis of Concorde In-Flight Radiation Warning Meter signal and comparison with state of the art measurements have been recently published by Bartlett et al.[6]. Instrument calibration is verified in laboratory on a yearly basis for Air France Concorde aeroplanes. At the end of each flight, the cumulated dose equivalent is written by the pilots on their report. The Q-L relationship presently in use is that recommended by ICRP Publication 60[23]. Dose equivalents should be increased by 20 % according to current quality factors[5] outside GLE. It is used as a conservative factor, assuming that the spectra of secondary particles during GLEs are the same as for galactic cosmic rays. Also noted on the pilot's log is the eventual occurrence of radiation alerts. Let us recall that Concorde sectors are[22]: the green sector covers instantaneous dose rate of 1-100 µSv per hour, the amber sector 100-500 µSv per hour, and the red light at 500 µSv per hour. In ICRP 60 system the amber warning lower limit becomes 120 µSv per hour and the red alarm lower limit becomes 600 µSv per hour.

Air France and British Airways have collected in-flight doses for years since the beginning of the Concorde flights. Nevertheless because the prime goal of this monitoring was for radioprotection purpose, only data summed by month, for each aeroplane, were archived in most cases by Air France. This prevents systematic use of the past Concorde data for study of a specific GLE. Nevertheless measurements during a few GLEs have been saved. Strady[24] mentions dose equivalent measured from 1976 to 1978 on the days of solar particle events (not necessarily associated with GLE relativistic particles). Only one, on the 22 November 1977, gives a significant enhancement on-board Concorde. During the flight across North Atlantic Ocean, the average dose equivalent rate is found to be 22.9 µSv/h. For the very large GLE of 29 September 1989 Air France pilot's logs have been saved for two flights, as well as the total dose equivalent recorded on the same day on-board a British Airways flight. During the same flight a campaign of measurement with the CREAM detector was under way[1]. The CREAM detector is designed to study single event effect (SEE) environment of concern for electronics: its measures charge-deposition spectra, linear energy transfer spectra and total dose. An estimate of biological doses has be derived from these measurements.

Air France is still continuing the dose monitoring on-board Concorde and since a few years total ambient dose equivalents are available for each flight. On 14 July 2000, two flights were operated during a large GLE and the results will be used here. No significant enhancement of the ambient dose equivalent has been recorded during the GLE of 6 November 1997 (intensity 11 % above galactic cosmic rays at the ground level). Concorde was not flying during the two GLEs of April 2001, as a consequence of the accident of July 2000. The measurements on-board Concorde on 29 September 1989 and on 14 July 2000 are basic data used to develop the present semi-empirical model. They are published with the kind authorisations of Air France and British Airways and they are summarised respectively in Tables 1 and 2. Results of the model will be compared (section 4) to measurements[1,20,24] mentioned above.

SEMI-EMPIRICAL MODEL

The calculation of the dose equivalent received on-board a given flight requires the knowledge of the dose equivalent rate **D**(t) during the GLE in function of altitude, latitude and longitude. The dose equivalent rate is also function of the GLE spectrum. Two main assumptions are made to derive a semi-empirical model as simple as possible. On the one

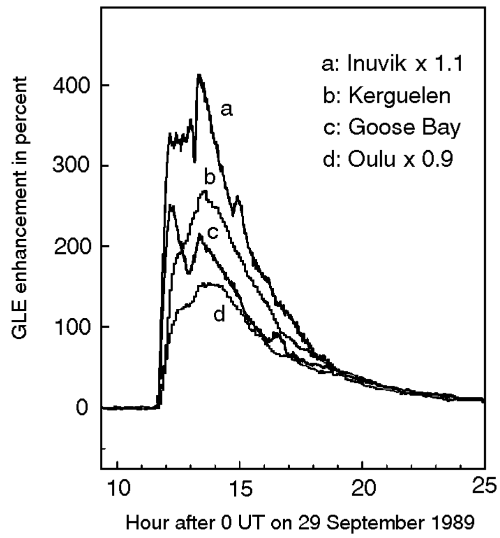


Figure 1: Temporal profiles of the GLE on 29 September 1989, observed with Inuvik, Canada (R = 0.14 GV), Kerguelen, South Indian Ocean (R = 1.14 GV), Goose Bay , Canada (R = 0.74 GV) and Oulu, Finland (R = 0.77 GV) neutron monitors.

hand the anisotropy of the solar particles is neglected. On the other hand in the course of the GLE, the variations of the spectrum are neglected and $\gamma_{max,}$ the rigidity spectrum power law exponent of a given GLE at the time of its maximum, is taken instead of γ(t) varying in the course of the GLE. In the case where different maxima are observed with different neutron monitors, the time of the chosen maximum will be given. The errors induced by these assumptions will be discussed in section 6 for the GLE 42.

When the anisotropy is neglected, local vertical cut-off rigidities[(2)] R replace the longitude and latitude dependencies, in absence of geomagnetic storm (which was the case during GLE 42). In these conditions **D**(t,z,l,λ,γ(t)) where t is time, z is altitude, l is longitude, λ is latitude and γ(t) is rigidity spectrum power law exponent, becomes **D**(t,z,R,γ_{max}). The function **A**(z,R,γ_{max}) is the attenuation of the dose equivalent rate in function of the depth of the atmosphere, compared to the dose equivalent rate at a chosen reference altitude of 18,290 m (which corresponds to Flight Level 600), and **L**(z,R,γ_{max}) which is the dose equivalent rate variation in function of vertical cut-off rigidity, compared to the dose equivalent rate along North Atlantic route (vertical cut-off rigidities between 2 and 4 GV, where Concorde dose measurements are available). Then **D**(t,z,R,γ_{max}) can be expressed as:

$$\mathbf{D}(t,z,R,\gamma_{max}) = \mathbf{A}(z,R,\gamma_{max}) \times \mathbf{L}(z,R,\gamma_{max}) \times \mathbf{C}(\gamma_{max}) \times \mathbf{I}(t) \qquad (1)$$

where **C**(γ_{max}) is a conversion coefficient from a given neutron monitor output, **I**(t), to the dose equivalent rate at altitude 18,290 m along North Atlantic route. Indeed in absence of anisotropy and of variation of the particle spectrum, both time profiles are assumed to be proportional.

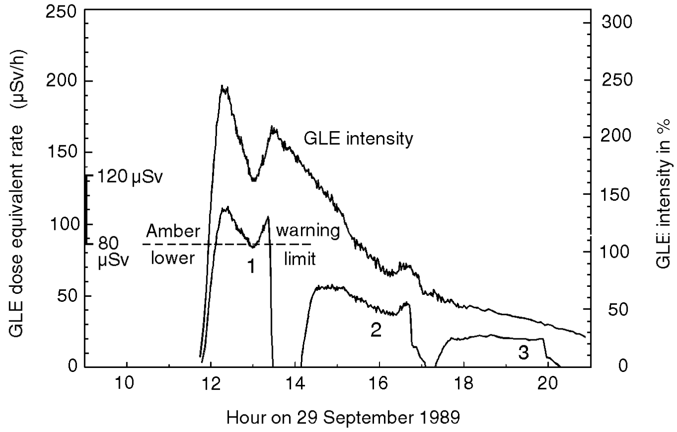


Figure 2: Dose equivalent rate versus time for three Concorde flights on the Atlantic route using the semi-empirical model SiGLE. Galactic cosmic ray contribution is not included. The upper curve is the time profile of GLE 42 observed with Goose Bay N.M.. Lower limit of amber warning dose rate is indicated with a dashed line. Dose rate range (80-120 µSv/h) reported by pilot is indicated along vertical axis, after conversion in ICRP60 and subtraction of galactic cosmic ray contribution.

The GLE of 29 September 1989 plays a central role here because it has been well observed on-board Concorde: cumulated dose equivalent are available for three flights well distributed during the event. This GLE, numbered 42 in the international list of events(25) is the most intense observed since 1956. Its intensity enhanced up to 377 % of the galactic cosmic ray intensity, as measured at 13:26 UT with Inuvik neutron monitor. It has been extensively studied with the observations of the ground-based neutron monitors (see review by Miroshnichenko et al.(26)) and a few authors have made calculations of secondary particles and of doses at the aviation altitudes using particle transport codes(19,27,28,29). In addition, its rigidity spectrum, with a power law exponent γ_{max} = - 4.7 at the time of its maximum at 13:25 UT(13), is close to the average of the documented set of GLEs (γ_{max} = - 4.8), as illustrated on Figure 6 below (section 5). This point is of interest for the reliability of the model SiGLE.

Figure 1 shows that anisotropy of primary solar particles is important: time profiles are very different as well as intensities observed with Goose Bay and Oulu neutron monitors, which have yet the same vertical cut-off rigidity. The neutron monitor chosen for the present computations is located at Goose Bay, Canada (vertical cut-off rigidity 0.7 GV). The intensity recorded with this monitor is close to the average value of the high latitude neutron monitors (rigidity < 2GV) and the monitor is located in the same longitude sector as the transatlantic flights (hence avoiding too important anisotropy effect). Its time profile shows the two maximum recorded during the event (Figure 1).

The attenuation A of the dose equivalent rate with decreasing altitudes may be deduced, at the time of the maximum of the GLE 42 occurring at 13:25 UT from O'Brien et al.(19) calculations. Indeed the authors give, figure 7, the time profiles of GLE 42 in terms of solar energetic particle dose equivalent rates from 24 to 9 km, in steps of about 3,000 m. Only relative values are used. The calculations correspond to high latitudes (i.e.; above the cosmic ray knee located at about 60° of geomagnetic latitude). In absence of calculations at lower geomagnetic latitudes, The attenuation is assumed to be the same in the range of North Atlantic routes, at geomagnetic latitudes between 52° and 60° North (vertical cut-off rigidities between 2 and 4 GV).

With the particle transport code calculations[19,27,28,29] mentioned above, the calculated dose equivalent rates at the time of the maximum of GLE 42 at 18,290 m are quite different (by about one order of magnitude). Thus the dose equivalent at 18,290 m is calculated by applying the coefficient C to the entire GLE 42 time profile observed with the chosen neutron monitor. Then using formula 1 without **L** term (North Altantic route is the only considered), the dose received on-board Concorde during each flight can be computed. A fitting of the measured doses by trial and error gives coefficient C estimate for the GLEs with the same spectrum as GLE 42. If instead of Goose Bay monitor, the observations of the Kerguelen monitor are taken for the trial and error fitting, quite similar parameter C is obtained, despite the important difference of the observed GLE time profile. Only the time profile of the dose rate, calculated for a given flight, will differ in this case.

Table 1
Ambient dose equivalent measurements on board Concorde
during the 29 September 1989 GLE

Route and company	Time of take-off	Time of landing	Measured dose	Conversion into ICRP 60
Paris-New York (AF)	10:19 UT	13:43 UT	120 µSv	144 µSv
New York-London (BA)	13:56 UT	17:19 UT	140 µSv	168 µSv
New York-Paris (AF)	17:07 UT	20:37 UT	70 µSv	84 µSv

Table 2
Ambient dose equivalent measurements on board Concorde
during the 14 July 2000 GLE

Route and company	Time of take-off	Time of landing	Measured dose	Conversion into ICRP 60
Paris-New York (AF)	09:11 UT	12:40 UT	120 µSv	144 µSv
New York-Paris (AF)	12:19 UT	15:50 UT	50 µSv	60 µSv

Figure 2 gives the time profile of the dose equivalent rates calculated for the three flights of Table 1 (left side scale). The upper curve is the time profile of the GLE observed with Goose Bay neutron monitor (right side scale). The dose equivalent rate curves do not include any contribution of galactic cosmic rays, which is about 10 µSv/h during the maximum of the solar cycle[5,22]. The cumulated dose equivalents during each flight are in agreement within 15 % with the dose equivalent measured on-board Concorde.

The second GLE observed on-board Air France Concorde (Table 2) occurred on 14 July 2000. It is numbered GLE 59 in the international list of events. According to Duldig[30] his

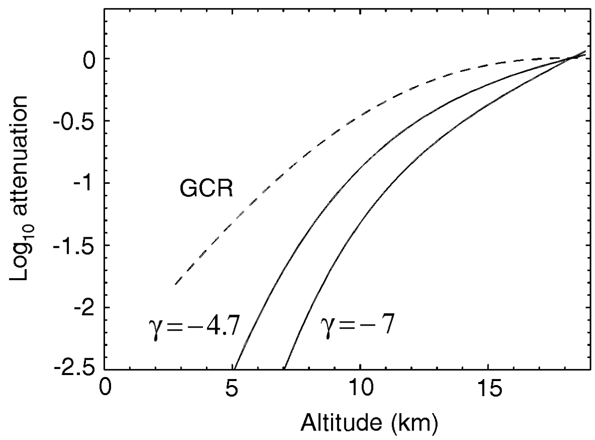


Figure 3 Dose equivalent rate attenuation coefficient normalised to altitude of 18,290 m for North Atlantic routes (R between 2 and 4 GV). The attenuation ***A*** *is given for* γ_{max} *= - 4.7 and for* γ_{max} *= - 7. Attenuation for galactic cosmic rays is given for comparison (dashed line).*

rigidity spectrum is fitted with a power law exponent γ_{max} = - 7 at the time of its maximum (11:00 UT). For this very different spectrum, the coefficient C could be calculated as done before for GLE 42. The Kerguelen neutron monitor (vertical cut-off rigidity R = 1.14 GV) has been used for this purpose. Indeed the GLE 59 profiles and amplitudes observed with different low rigidity neutron monitors show almost no anisotropy of solar primary particles, so any of those monitors can be used. The attenuation **A** of the dose equivalent rate with decreasing altitude is modified in consequence. An interpolation between the different γ_{max}, fitting also the dose equivalent rate with atmospheric depth in the case of the galactic cosmic rays calculated with CARI 6, leads to an estimate of **A**(z,R,γ_{max}) for the North Atlantic routes (R between 2 and 4 GV). Figure 3 shows the attenuation **A** for γ_{max} = - 4.7, for γ_{max} = - 7 and for galactic cosmic rays. The coefficient C(γ_{max}) is found to be equal to 0.59 for γ_{max} = - 4.7 and to 4.06 for γ_{max} = - 7.

Using particle transport codes, Beck et al.[28] and O'Brien and Sauer[29] have calculated world maps of effective dose rates at the time of the maximum of GLE 42 (respectively figures 7 and 4). Both figures are used at the Greenwich meridian in northern hemisphere for practical reasons and because the closest monitor (Kiel, Germany) shows regular time profile with maximum at about 13:00 UT and, in terms of anisotropy, is located close to fitted curve of Figure 8 below (section 6). Calculations are for altitudes of 10,700 m. They are used in relative values with respect to the rigidity range 2-4 GV. Both give close results for the function **L**(z_0,R,γ_{max}), where z_0 is for subsonic flight altitudes. This enables us to extend the semi-empirical model to lower and higher latitude in the case of such flights. In fact **L** is also varying with the GLE spectrum (i.e. γ_{max}), but the variation is provisionally neglected here in absence of dose measurement on-board high latitude flights during GLEs.
Figure 4 shows **L**(z_0,R) as a function of the vertical cut-off rigidity. On the upper axis corresponding geomagnetic latitudes are given for northern hemisphere and European sector (epoch 1995)[31].

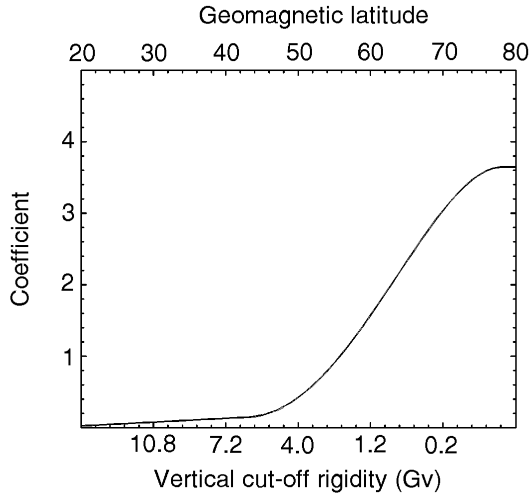


*Figure 4 Dose equivalent rate coefficient **L** in function of the vertical cut-off rigidity. Upper axis gives corresponding geomagnetic latitudes for northern hemisphere and European sector (epoch 1995).*

In this way, using formula 1, the semi-empirical model permits to calculate the dose equivalent received on-board flight with known flight plan, for any GLE, taking into account its rigidity spectrum power law exponent, γ_{max}, at the time of its maximum, and its time profile observed with low vertical cut-off rigidity (R< 2GV) neutron monitors. The model is valid for all altitudes along North Atlantic routes and for subsonic altitudes for all latitudes. This is sufficient for commercial flight presently operated, Concorde flights being limited to North Atlantic. The semi-empirical model could be extended with new particle transport code calculations and with new measurements, if supersonic flights cover the world in the future.

It should be pointed out that the restitution of the effects of particle anisotropy is possible if a sufficient number of neutron monitor time profiles are available. Indeed each instrument gives information on the particles actually received in its region. Nevertheless, high time resolution data are not presently available in near real time for operational purposes.

PRELIMINARY VALIDATION OF THE MODEL

The data used to derive the semi-empirical model are only Concorde cumulated dose equivalent measurements. In addition some information is available concerning the starting time of an amber warning during Flight 1 and concerning the range of dose equivalent rate during the flight. Indeed, the pilot of the aeroplane (registered as BVFF) noted in the Air France report: "BVFF on 29-9 starting at 30 W amber light on, on radiation indicator, with index between 80 and 120 µSv/h up to JFK". The longitude indication given by the pilot sets the beginning of the amber warning on-board Concorde between 11:44 UT and 12:06 UT, according to the different flight plans available.

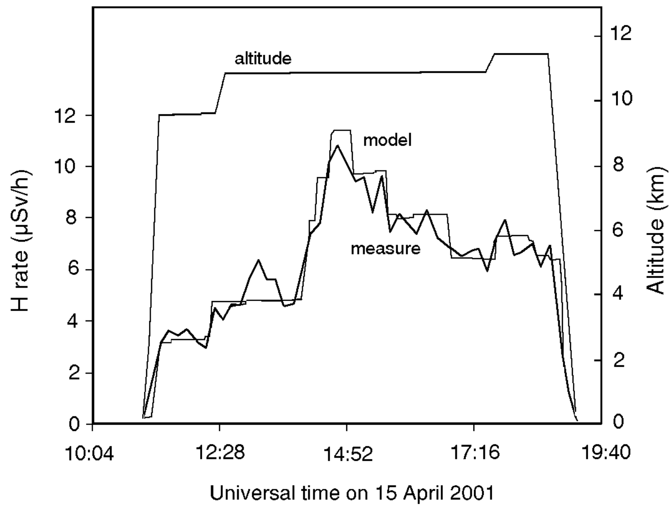


Figure 5: Comparison of dose equivalent profiles observed on a Prague to New-York flight[(19)] *during GLE 59 (heavy line) with corresponding the semi-empirical model SiGLE calculation*[(12)] *as implemented in the SIEVERT system. The upper curve gives altitudes (scale on the right side)*

The horizontal dashed line in Figure 2 is the estimated amber warning lower limit, assuming 20 % uncertainty on the measured dose equivalent rate and subtracting galactic cosmic ray contribution of 10 µSv/h. The calculated amber warning time is found at 12:05 UT and the warning last until 13:27 UT during the descent to Kennedy Airport. In Figure 2 the range of dose equivalent rate given by the index during the amber warning is indicated along the vertical axis after conversion into ICRP60 system and subtraction of the GCR contribution. This shows that the calculation, based on dose equivalent during the entire flight, is also in reasonable agreement with the dose equivalent rates measured during Flight 1. It is to be noted that, according to Figure 2, the British Airways Flight 2 does not encountered amber warning. This is in agreement with a British Airways report[(22)]. As mentioned above an experiment with the CREAM detector was flying on-board this flight. The dose rate deduced from in-flight instrument counts and extrapolated to the time of the GLE maximum by Dyer and Lei[(1)] is in agreement within a factor 2 with the value obtained with the semi-empirical model, for vertical cut-off rigidity of 1 GV and for an altitude of 10 km.

During GLE 30 (22 November 1977) the measurement of average dose equivalent rate on-board Concorde has been reported by Strady[(24)]. Assuming a typical flight of 3½ hours the Strady's report corresponds to a dose equivalent of 96 µSv (ICRP60). The calculation with our model gives a maximum dose equivalent equals to 97 µSv. Nevertheless because of number of uncertainties in the comparison (e.g. Strady does not give time of departure of the flight), one can only consider that the results are compatible.

A more precise test presently available is with the recent flight[(20)] operated by Czech Airlines between Prague and New-York during the GLE on 15 April 2001, for which the detailed flight plan was made available to us by one of the authors of the experiment. Figure 5[(14)] shows a comparison of the effective dose rate measurements with the

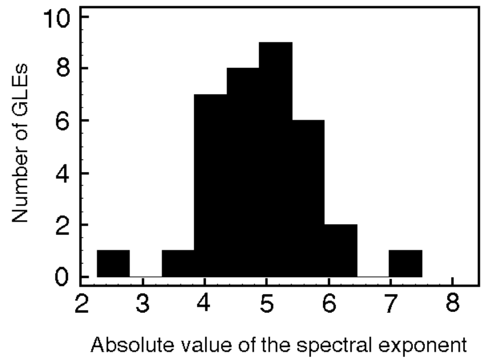


Figure 6: Distribution of absolute value of the rigidity spectrum power law exponent at the time of the maximum for 35 documented GLEs as deduced from neutron monitor worldwide network observations.

calculations of the present semi-empirical model as implemented in the SIEVERT system. It is fair to say that owing to the assumptions done to construct the model, it is unlikely that the agreement will be as good in all cases. It shows that some of the model assumptions as well as the attenuation **A** deduced from O'Brien et al.(1998) are reasonable. Note that the North-South variation is not tested by this comparison because the flight Prague-New-York remains in the rigidity range 2-4 GV.

RESULTS

The most significant parameter, in terms of radioprotection, during a given GLE and for a given flight plan, is the dose equivalent received in the worse case. Except otherwise specified, this is what is considered hereafter. The time of departure of the corresponding flight is obtained by comparison of the doses for number of flights spread out during the GLE. Here one mostly considers routes among the less protected: Paris-New York with Concorde and Paris-San Francisco with an A340 aeroplane. Indeed, according to the flight plans used, the first one reaches 17,530 m and the second one fly at cruising altitude for a rather long time at high geomagnetic latitudes (4h 12 min. above 70° North, with a maximum at 78.6° North).

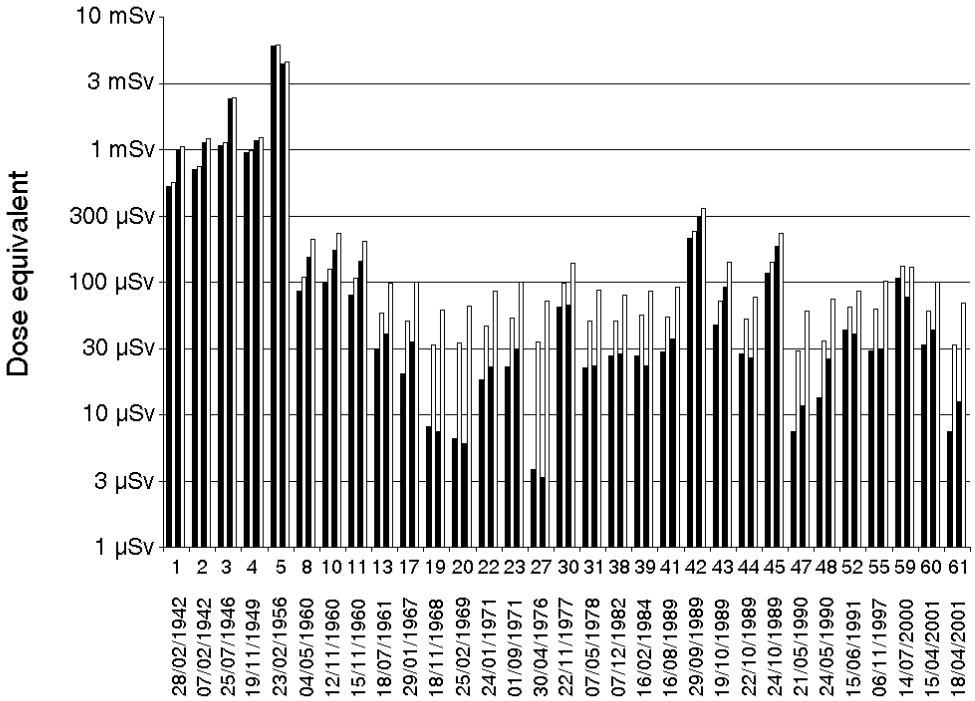
Considering now the whole history of the GLEs, the model has been applied to all the GLEs having magnitude above 10 %. For the GLEs observed since 1959, magnitudes and time profiles observed with the Kerguelen neutron monitor are used, with some exceptions when anisotropy of particles renders its output somewhat lower than with other high latitude neutron monitors. In this case, the magnitude has been taken from Duggal[32] or from Terre Adelie neutron monitor, and the Kerguelen time profile has been normalised to this value. The power law exponents γ, calculated when possible at the time of the maximum of the GLEs, have been taken from number of works [30,32-39]. Figure 6 shows the distribution of absolute value of the spectral exponent γ_{max} for 35 documented GLEs, measured with the neutron monitor world-wide network.

Table 3
Worse case total dose equivalents received during the largest GLEs

GLE number	Date	Magnitude	Dose equivalent Paris-New York (Concorde)	Dose equivalent Paris-San-Francisco (A340)
1	28 February 1942	600 %	560 µSv	1050 µSv
2	7 March 1942	750 %	750 µSv	1190 µSv
3	25 July 1946	1100 %	1110 µSv	2450 µSv
4	19 November 1949	2000 %	970 µSv	1220 µSv
5	23 February 1956	4554 %	6100 µSv	4550 µSv
42	29 September 1989	252 %	238 µSv	360 µSv

Despite the very limited information available, earliest GLEs observed, numbered 1 to 5, are considered, because of their importance in terms of radioprotection. The GLE 1 (28 February 1942), GLE 2 (7 March 1942) and GLE 3 (25 July 1946) were not observed with neutron monitors but with ion chambers. Those devices have effective threshold rigidity of more than 4 or 5 GV and intensities of the GLE have been normalised by Duggal(32) to correspond to the sensibility of a high-latitude neutron monitor. This leads to magnitudes of 600 % for GLE 1, 750 % for GLE 2 and 1100 % for GLE 3. The same has been done for the GLE 4 (observed with neutron monitors and with ion chambers) and one has taken the Duggal's estimate (2000 %). The intensity time profiles obtained with Godhavn ion chamber for GLEs 1 to 3 and with Climax monitor for GLE 4 are taken from Sandström(40). It should be noted that the time profiles observed with ion chambers are presumably shorter because of the higher rigidity, and dose equivalents deduced for GLE 1-3 are to be understood as lower limits. In absence of spectrum information, the power law exponent γ has been assumed to be - 4.7 for GLEs 1 to 3. The exponent for GLE 4, γ = - 4.5, is taken from reference 33. Table 3 gives the flight dose equivalents calculated with the semi-empirical model.

The case of the GLE 5 (23 February 1956) should be particularly considered because it is the highest observed since 1942, and because particle transport code results are available for this GLE. It was rather well observed with number of neutron monitors, but none at high latitude. One has taken a magnitude of 4554 % (33) actually observed at Leeds (UK). This is, in terms of dose calculation, a conservative value compared with the extrapolation to high latitudes by Duggal(32), giving 9000 %. The time profile taken here was observed with the Ottawa neutron monitor(41). The power law exponent γ = -5.6 is taken from Heristchi et al.(33). As shown in Table 3, our calculation gives dose equivalent of 6.1 millisievert for a Paris-New York flight with Concorde and 4.5 millisievert for a Paris-San Francisco subsonic flight. They represent the historical worse case for three reasons: the GLE of 23 February 1956 is the largest since the beginning of the observations, the routes are among the more exposed and finally the time of departure of the selected flight corresponds to the maximum of the dose equivalent.



Armstrong et al.[18], from particle transport code calculation, gives for the dose equivalent rate, at the time of the maximum of the GLE 5 and at high latitudes, a range from 10 mSv/h to 60 mSv/h at 18,290 m. Taking the time profile of the GLE into account, this leads on-

Figure 7: Bar chart of the dose equivalents received in the worse case during GLEs, calculated with the model SiGLE. Each group of four bars corresponds to a given GLE (number and date are indicated along horizontal axis). The first pair shows dose equivalents for Paris-New York flight on-board Concorde (GLE contribution in black, total dose in white). The second pair shows dose equivalents for Paris-San Francisco flight on-board Airbus A 340.

board Paris-New York flight with Concorde to doses ranging from 7 to 40 mSv (in ICRP60 system) and on-board Paris-San Francisco subsonic flight to doses ranging from 5 mSv to 30 mSv. Thus the result obtained with our semi-empirical model corresponds to the lower limit of Armstrong calculations even if the additional factor 2 suggested by extrapolation of GLE magnitude to higher latitude by Duggal[32], is taken into account.

Dyer and Lei[1] have also calculated, with a particle transport code, the cumulated ambient dose equivalent at conventional (10,060 m) and supersonic altitudes (17,070 m) for GLE 5. They found respectively 1.4 mSv and 9.4 mSv for 1 GV cut-off. For the same cut-off, our model gives compatible results with respectively 0.9 mSv and 8.0 mSv for above altitudes.

Thus the comparison of the results of the semi-empirical model with more sophisticated measurements and theoretical calculations appears as quite satisfactory. The limits of the model and its precision will be discussed in the following section.

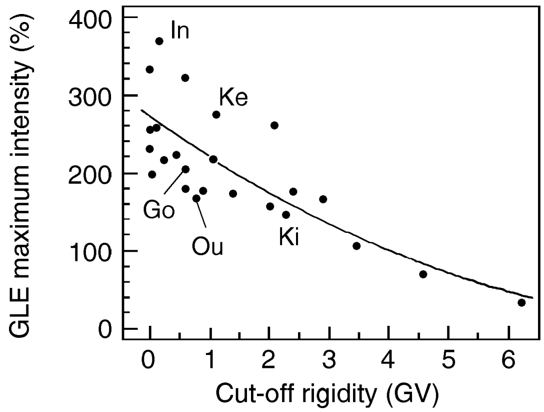
Figure 7 summarises the dose equivalents received for both above routes during 31 GLEs (over 64 observed until August 2002), the others giving negligible radiation effect. To each GLE correspond four bars. The first (in black) is the contribution to dose equivalent of the GLE itself for Paris-New York flight on-board Concorde. The second (in white) is the total dose equivalent taking into account galactic cosmic ray contribution, calculated for the month of the event. The two last bars are the same, for Paris-San Francisco subsonic flight. As previously mentioned all calculations correspond to the worse case in terms of departure time. The number along the horizontal axis is the GLE number. Their dates of occurrence are given at the bottom of the figure.

It should be recalled first that the ambient dose equivalents received from galactic cosmic rays are about 30 µSv for a Paris-New York flight on-board Concorde and about 60 µSv for a subsonic Paris-San Francisco flight[(15)]. Figure 7 shows that the GLE component (black bars) gives rather similar dose equivalents for both routes. This is because the lower atmospheric protection of the supersonic flight is counterbalanced on the one hand by the much longer duration of the subsonic flight (11 h 24 m instead of 3½ h) and on the other hand by the lower protection when the subsonic flight is at high geomagnetic latitudes. In fact the GLE contribution to the dose equivalent is larger during the supersonic flight only for quarter of the GLEs. When the GCR component is added, the subsonic flight receives larger dose equivalents in all the cases but one, the GLE 5 of 23 February 1956. The results of Table 3 and Figure 7 will be discussed in terms of radioprotection in section 7.

As an application of the model, it is interesting to consider the importance of using the actual flight plan to estimate the dose equivalent received during a given flight. This was pointed out for the dose received from galactic cosmic rays[(15)], but this becomes even more critical for GLEs because of the large dose rates potentially considered and because North-South variations and attenuation with atmospheric depth are larger for GLEs than for galactic cosmic rays. Indeed, if one considers flights from Europe to Japan, the estimation during GLE 5, based on a few actual flight plans, goes from 900 µSv for a Paris-Tokyo flight following a southern Siberian route to 2.5 mSv for a flight from Osaka to Paris along a northern Siberian route. As expected, the dose received is much higher (3.8 mSv) for a polar flight from Tokyo to Paris (with a stop at Fairbanks, Alaska), because this flight passes close to the northern geomagnetic pole (maximum geomagnetic latitude of 88.3° North) above Thule, Greenland.

EXPECTED PRECISION AND LIMITS OF THE MODEL SiGLE

The estimate of the precision of the model is limited, in particular, by the absence of in-flight validation, during GLEs, of two parameters: (1) the conversion factor between Concorde measurements and dose equivalents taking into account the quality factors



recommended by ICRP60 and (2) the variations of the received dose rate with geomagnetic latitude, for different spectral power law exponent γ.

Figure 8: GLE 42 (29 September 1989) intensity at the time of the maximum at 13:25 UT (in percent of the galactic cosmic ray level before the event) observed with neutron monitors in function of vertical cut-off rigidity of the monitor. The line is the least square fit with a parabola. The distance to the fitted line gives an estimate of the anisotropy of the primary solar particles. Neutron monitors mentioned in text or in Figure 1: Inuvik (In), Kerguelen (Ke), Goose Bay (Go), Oulu (Ou) and Kiel (Ki) are labelled.

It is possible nevertheless to estimate the error made when accepting two simplifying assumptions of the semi-empirical model: neglecting variations of the power law exponent γ in the course of the GLE and neglecting anisotropy of the solar particles. Indeed the GLE 42 of 29 September 1989 exhibits large variations of the exponent γ and the different neutron monitors have observed important particle anisotropy (Figure 1) related to its complex structure.

From a detailed analysis of the neutron monitor outputs, Lovell et al.[13] have shown that γ is varying from $\gamma = -2.2$ at 12:15 UT to $\gamma = -4.7$ at the time of the maximum at 13:25 UT and to $\gamma = -5.8$ at 16:00 UT. O'Brien et al.[19], see their figure 7, have computed for GLE 42 dose equivalent rates at aeroplane altitudes taking into account spectral variations of the GLE. The maximum effect is a factor of about 2.5 on the dose equivalent rate for the same neutron monitor output. If the O'Brien results are scaled to ours, it appears that flight 1 is underestimated by 6 %, Flight 2 by 34 % and Flight 3 by 53 %, when the spectral variations are neglected.

As a rule the anisotropy, if any, is observed during the rising phase of the GLEs. Nevertheless during GLE 42, the anisotropy remains important at the time of the maximum at 13:25 UT. Figure 8 shows the magnitude of the GLE observed at this time with number of monitors[13], as a function of the vertical cut-off rigidity of the monitors. The line is a least squares fit of the intensities with a 2nd degree polynome. The standard deviation is 18 % of the maximum GLE magnitude and this corresponds, in terms of dose equivalent, to an standard error of 25 µSv for Flight 1 when anisotropy is neglected and to a standard deviation of 38 µSv for the Paris-New York flight receiving the maximum dose.

Because of the approximations done with the semi-empirical model, particularly neglecting variations of the spectrum and neglecting anisotropy, one considers that GLE 42 corresponds to the upper limit of GLE magnitude for which the semi-empirical model can be applied presently to the SIEVERT system. In case of similar or higher GLEs, dose equivalent cartography will be obtained after analysis of passive dosemeters flying routinely on-board number of Air France subsonic aeroplanes and collected in principle on a monthly basis. In case of a large GLE the dosemeters will be immediately picked up. It should be noted that such a GLE will likely give signal well over the dose due to galactic cosmic rays during past days. The delay of analysis of dosemeters will be a few weeks and the calculations of SIEVERT will be postponed, for the interval of the GLE, until time dependent cartography of dose equivalent rate becomes available.

DISCUSSION OF THE RESULTS IN TERMS OF RADIOPROTECTION

A consensual estimate of the annual dose actually received from galactic cosmic rays by air crews on long haul routes is 3 or 4 mSv [9,42,43]. If one considers that the GLEs contributing by less than 20 % of the monthly dose could be neglected, the threshold is 60 µSv. Setting in addition a factor 2 for safety, the SIEVERT system consider only the GLEs having some risk to give dose equivalents above 30 µSv. This threshold is also representative of the lower limit of the dose equivalent received from GCR during a typical intercontinental journey. Indeed it corresponds to the dose equivalent received from galactic cosmic rays during a transatlantic flight on-board Concorde and to 2/3 of the dose received on the same route on-board subsonic flights[15]. According to Figure 7, over 64 GLEs observed since 1942, only 18 are to be included in operational dose calculations. During the last ten years only the two GLEs of 14 July 2000 and 15 April 2001 are concerned. Nevertheless their frequency is subject to large variations: two were observed within one week in November 1960 and more recently four were occurring during the 3 months from August to October 1989.

On the other hand, it is important to discuss dose equivalents received from the largest events with respect to the legal recommended limits. First of all it should be recalled that GLEs 1 to 5, of most importance here, are subject, because of the restricted observations available, to uncertainties of at least a factor 2, even in terms of their magnitude only. According to our calculations (Table 3) for exposed routes between Paris and New York with Concorde and between Paris and San Francisco with subsonic aeroplane, none of the GLEs gives dose equivalent larger than 20 mSv, the average yearly limit fixed by national implementations of the European Directive. If one considers the upper limit of Armstrong and al.[18] (section 5) dose equivalent rate as input of our calculations for the two above flights, the GLE 5 on 23 February 1956 seems the only approaching or even exceeding the upper yearly recommended limit of 50 mSv. It should be noted that the recommended limits are expressed in terms of effective dose which is larger than dose equivalent. In the case of galactic cosmic rays, according to Bartlett [44] and to Ferrari et al. [45], a factor 1.2-1.3 must be applied to dose equivalent on-board subsonic flights and a factor 1.3-1.6 must be applied to dose equivalent on-board Concorde to estimate effective dose.

If one now considers the recommended limit for pregnant crew members, to ensure that the foetus does not receive more than 1 mSv, it can be claimed (Table 3) that apart from the 5 first GLEs, none has presented some risk to attain the limit of 1 mSv. Indeed the next one in magnitude, GLE 42 on 29 September 1989 remains below this recommended limit, as precisely attested, on-board Concorde, by the measurements presented here. It represents about one month of galactic cosmic ray exposure only.

In case of very large GLEs, it is highly desirable to envisage actions able to limit the received dose below 1 millisievert both with regard to crew's carrier and because one millisievert per year is the limit recommended for the general public[23]. Two kinds of actions have been envisaged. In the case of red alert on-board Concorde, the procedure provides a change of its flight level. To our knowledge this has never been necessary, and indeed according to present calculations none of the GLEs have reached the level of 600 µSv/h (ICRP60) on Concorde routes since the inaugural flights in 1976. Additional calculations have been done with a simulated descent within the few minutes following the red alert. For GLE 5 and with a descent to the foreseen safeguard altitude of 9,140 m [24] where Concorde is flying at Mach 0.93, the model indicates that the dose is lowered from 6.1 mSv (see Table 3) to 630 µSv, confirming the adequacy of the present Concorde procedure. The second kind of action is the change of the flight plans in case of large GLE to avoid high geomagnetic latitude regions. Rerouting has been operated by United Airlines in October-November 2000, Continental Airlines in April 2001 and Northwest Airlines[46]. Reported costs are $100,000 and delays up to 5 ½ hours. The present results suggest that those costly actions were needless, in terms of radiation doses, because of the total inadequacy of the solar particle event alert criterion taken into account.

As warnings and alarms, dosemeters on-board the aeroplane have some advantages. On the one hand the information transmission is not subject to radio propagation disturbances which may prevent contact with the ground stations during large solar flares. On the other hand the alert corresponds exactly to the airline location. Indeed the anisotropy of GLEs may protect or penalise some large geographic regions. Nevertheless the cost to implement and to maintain dosemeters on-board all subsonic long-haul aeroplanes is quite important, for alarms expected to occur a few times per century.

From the ground, alert to the aeroplanes could be launched on the basis of two kinds of observations: either satellite data or neutron monitor observations. Particles accelerated during large solar particle events are permanently observed on-board the geostationnary satellites GOES of the US National Oceanic and Atmospheric Agency (NOAA). The experiment called HEPAD has a channel recording proton flux for nominal kinetic energy range E > 700 MeV[47]. As already pointed out[1] this is a right range for monitoring dose on-board aeroplanes. The second solution, based on the international network of neutron monitors has the advantage, because of their distribution around the world, to modulate the alert in function of the geographical regions where the aeroplanes are localised, avoiding costly false alerts to aeroplanes not concerned. Indeed in presence of GLE anisotropy, each monitor is relevant for the aeroplanes flying over its region. To protect crews and passenger from doses larger than 1 millisievert, the alerts must be considered when HEPAD highest energy channel measures about 0.1 proton/$cm^{-2}/s^{-1}/sr^{-1}$ above 850 MeV (provisional estimation based on reference 20) and/or when GLEs are in the range 1000 % on high latitude neutron monitors, a magnitude which corresponds also to the red alerts on-board Concorde. As already pointed out by Lantos et al.(15), the prediction of solar particle events, although useful for other purposes, is unable to predict the flux of GeV-range relativistic particles. Thus the best that can be done for the moment remains effectively to monitor the solar particles from on-board dosemeters, satellite or neutron monitors.

As an optimistic concluding remark, it is interesting to consider the future evolution of solar cycles. Indeed the frequency of the solar particle events is closely related to the amplitude of the sunspot numbers(48). Because of a 100-year noisy modulation of the amplitude of the solar cycles(48), well attested by three centuries of solar observations, it is likely that the number of large solar particle events will be lower during the coming half-century than during the past sixty years studied here. This means that even if a larger GLE can never been excluded, the “climatology” presented here gives an upper limit of the future radiation risk on-board aeroplanes.

CONCLUSIONS

The presently available calculations of dose equivalent received at aeroplane altitudes from solar particles were obtained from particle transport code calculations. They are restricted to a few GLEs and for the same GLE give quite divergent results. In addition they are too computer time consuming to be used for operational purpose. A semi-empirical model, called SiGLE, has thus been developed in the frame of the French operational system SIEVERT intended to improve monitoring of radiation dose received by aircrews. The model is mostly based on Concorde dosemeter measurements, presented here, obtained during the GLEs of 29 September 1989 and of 14 July 2000. It gives reasonable agreement with independent measurements.

The semi-empirical model SiGLE has been applied to evaluate, for exposed routes, the radiation doses corresponding to the whole GLEs observed since 1942. Over 64 GLEs observed up to now, only 18 have presented some risk to give dose equivalents above 30 µSv, a value selected for the SIEVERT system, which corresponds to the dose equivalent received from galactic cosmic rays during a transatlantic flight on-board Concorde and to 2/3 of the dose received on the same route on-board subsonic flights. Only the first observed GLEs have presented some risk to give dose equivalents above 1 millisievert on exposed routes. The estimates of the doses potentially received during GLEs 1 to 5 are nevertheless subject to large errors, in particular because of the restricted observations available and because of the uncertainties concerning the actual solar particle spectrum. To avoid doses over 1 millisievert during subsonic flights the presence of dosemeter on-board is obviously technically the best solution. Nevertheless because of the cost and of the expected extreme rareness of needed alerts, neutron monitor network appears to be the best solution, because it will give alerts to the aeroplanes in the regions actually concerned and not to all aeroplanes, as with satellite observations.

The present semi-empirical model will be more precisely and more exhaustively validated, and presumably improved, as further in-flight measurements during GLEs become available. In particular this is likely to become possible in the frame of the SIEVERT validation program and of the European Commission Research Program, as well as with the similar effort undertaken in other countries. Indeed state of the art dosemeters have been developed for automatic in-flight operation during long periods, increase considerably the chance to catch a GLE, as already done by two flights in April 2001. The new data, including those presented here, will certainly also facilitate, in the case of the GLEs, the validation of particle transport code calculations which remain the only method to understand the physics involved .

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