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RADIATION DOSES POTENTIALLY RECEIVED ON-BOARD AEROPLANE DURING RECENT SOLAR PARTICLE EVENTS

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Abstract

Because the doses received on board aeroplane are now monitored to fulfil legal requirements in some countries, including all the European Community, the models to calculate doses received during solar events have leaved their purely academic status to become also part of operational systems. The present work consider parameters of importance to determine the doses received during solar events: spectral characteristics of the solar particles and anisotropy of primary particles. Precise determination of both, using all information available, being a long process, we test methods to calculate rigidity spectrum exponent and to correct the models for anisotropy. A recent GLE of large intensity, having occurred on 20 January 2005, is used both as an example of important event and because the necessary data were collected within a few days, showing that the above methods, in addition to their own interest, have also an operational potential.

1- Introduction

During the solar particle events, doses received on board aeroplane are sometimes appreciably increased. The secondary particles related to those events are detected at the ground level as so called GLEs (Ground Level Enhancements), thanks to the permanent observations of the neutron monitors. To be detected at the ground level, the primary solar particles must be significant in number, for energies in the GeV range. The neutron monitors (NMs) are operating since 1947 (Simpson, 1985) and have been multiplied in the frame of the International Geophysical Year (in 1957-1958), forming a world-wide network of about fifty stations. Before neutron monitors, a few GLEs have been observed with ionisation chambers. All together 68 GLEs have been recorded since 1942. To estimate doses potentially received on board aeroplane during past GLEs, a semi-empirical model called SiGLE has been proposed (Lantos and Fuller, 2003 and 2004 hereafter called respectively papers 1 and 2). Indeed calculations based on particle transport codes are computer time consuming and they have been applied only to a few GLEs.

The SiGLE model could also be used in the frame of operational applications like the SIEVERT system (Lantos et al., 2003, Bottollier-Depois et al., 2003) which is monitoring doses received by crew members of French air transport companies to fulfil requirements of an European Directive (CEE, 1996). On the one hand, limited time is allowed for operational applications but on the other hand they could tolerate simplifications of the model, as far as the specifications of each operational system are respected. The spectral characteristics and the anisotropy of the GLE particles, which will be considered here are important parameters needed to calculate doses received on board aeroplane. To provide them, detailed data reduction (Miroshnichenko, 2001) of the data of the world-wide neutron monitor network takes months. One of the purposes of the present paper is a test of methods to calculate rapidly the rigidity spectral exponent γ (t) in the course of the GLE. The method has been applied, within a few days, to the recent GLE event of 20 January 2005 (provisionally numbered GLE 68 in the international list of GLEs), which is one of the strongest particle events already observed at the ground level. The method could be useful also outside operational aspect because the above mentioned scientific publications of the GLE parameters are frequently limited to one (frequently the maximum of the GLE) or to a few times in the course of the GLE. A second purpose of the present work is to study, using GLE 68 as an example, how to handle anisotropy effects on the calculated doses received on-board aeroplane thanks to observations of neutron monitors. In addition the study of the anisotropy provides a test of the North-South function used in the model SiGLE.

2- The SiGLE model

The semi-empirical model SiGLE combines few available measurements obtained on board Concorde during GLEs in 1989 and 2000 and on board a subsonic flight during a GLE in 2001, with calculations based on particle transport codes for GLE 42 on 29 September 1989. As the absolute dose scale of the SiGLE model is based on measurements on board Concorde, the resulting doses are expressed in terms of dose equivalent (Davies 1993). The theoretical calculations, not yet validated in absolute scale (see Table III in paper 2, for GLE 42), are only used in relative values in the SiGLE model. Because the measurements on board aeroplane during GLEs are still very limited, the model is thought to assimilate the new information, starting at the beginning with some acceptable simplifications. Thus the precision of the dose calculation will be increased, as new measurements and new calculations will be published.

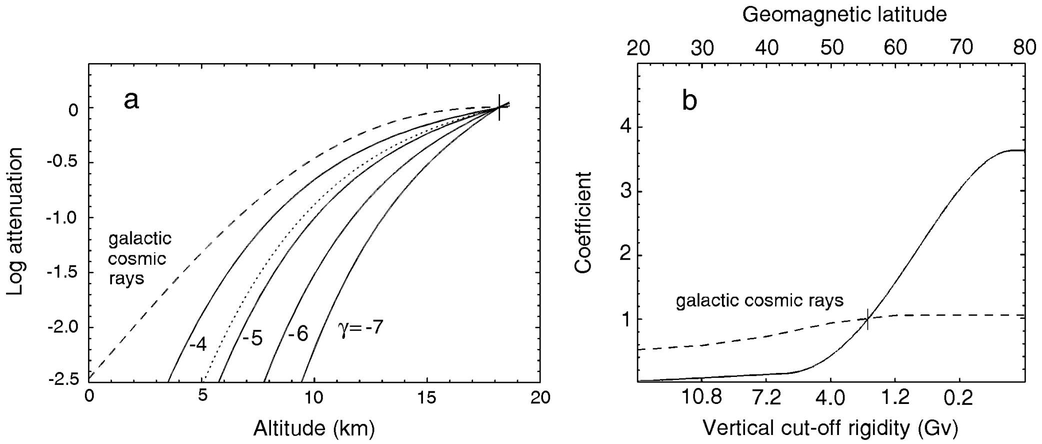

Figure 1a: Logarithm of the attenuation of dose equivalent rate in function of altitude for different values of the rigidity spectrum exponent γ of the primary particles. The reference level is 18,290 m. Attenuation for galactic cosmic rays is indicated with dashed line and attenuation for GLEs with average rigidity spectrum exponent γ = - 4.7 is indicated with a dotted line.

Figure 1b: Dose equivalent rate coefficient L in function of the geomagnetic latitude for subsonic altitude of 10,700 m (35000 feet). The reference latitude corresponds to North Atlantic routes. Lower axis gives corresponding vertical cut-off rigidity for northern hemisphere and European sector (epoch 1995). The same coefficient for galactic cosmic rays is plotted with a dashed line.

From the measurements on-board Air France and British Airways Concorde, a linear relationship between ground based neutron monitor GLE time profiles and dose rates at 18290 m in altitude (60 000 feet) is derived for different particle rigidity spectral exponents γ. The slope is noted $\mathbf{C}(\gamma)$. The reference monitor of the semi-empirical model SiGLE is the monitor of Kerguelen Islands, in South Indian Ocean. The monitor is located at Port-aux-Français (λ_G = 57.5°S and vertical cut-off rigidity of 1.1 GV). The instrument is a NM64 supermonitor (Carmichael, 1968) with 18 counters in 3 independent sections. It is operated without gap since January 1964. Previously a IGY neutron monitor (Simpson, 1985) was operated in Kerguelen Islands, starting in July 1957. The data concerning both GCR and GLEs (from GLE 07 in 1959 to GLE 68 in 2005) are available on Paris Observatory and on WDC Moscow web sites (Ref. 10 and 11). According to the model SiGLE, when the enhancement due to the GLE is expressed in percentage of the intensity of galactic cosmic rays before the event, the conversion coefficient $\mathbf{C}_K(\gamma)$ is equal to 0.59 µSv/h/% for $\gamma = -4.7$ and to 4.06 µSv/h/% for $\gamma = -7$ (paper 2), for Kerguelen NM observations. The conversion coefficient for other rigidity spectrum exponent is obtained by linear interpolation in logarithmic scale. In absence of anisotropy, two Canadian NMs (Deep River and Ottawa) were equivalent to Kerguelen NM because they are almost antipodal, but they are now closed and could be used only for past GLEs. The new NMs implemented in Canada are at higher geomagnetic latitudes. Thus it is of interest to extend the model to another group of monitors.

For this specific purpose, high latitude neutron monitors are not recommended because of North-South anisotropy (see below, section 5) and because of their asymptotic directions (McCracken et al., 1968) which are along meridians, enhance the effects of anisotropy. Indeed Figure 7 shows a comparison of Terre Adélie NM (labelled TAD) asymptotic directions with Kerguelen (KER) asymptotic directions which collect particles over a much larger range in longitude. At lower geomagnetic latitudes, a group of three neutron monitors could be used, namely Moscow, Newark and Kiel NMs (see Table 1 for their characteristics). Their vertical cut-off rigidity is between 2.2 and 2.4 GV. If they measure about the same intensity of the GLE (thus in absence of important anisotropy), they could replace the Kerguelen monitor. In this case, the conversion coefficient $\mathbf{C}_{MNK}(-4.7)$ is equal to 0.91 µSv/h/% and $\mathbf{C}_{MNK}(-7)$ is equal to 10.61 µSv/h/%, as deduced from the Concorde observations of GLE 42 (on 29 September 1989, a GLE with $\gamma_{max} = -4.7$) and GLE 59 (on 14 July 2000, a GLE with $\gamma_{max} = -7$).

The measurement on board a Czech Airlines flight from Prague-to New York (Spurny and Dachev, 2001), during the GLE numbered 60, on 15 April 2001, as well as plots based on particle transport code calculations by O'Brien et al. (1998), are used to derive the attenuation factor $\mathbf{A}(z,\gamma)$ between dose rate at 18290 m in altitude and dose rate at the aeroplane altitude, noted z (Figure 1a). It should be noted that the second version of SiGLE semi-empirical model (paper 2), differs only from the first (paper 1) because of improvement of the attenuation function with atmospheric depth, $\mathbf{A}(z,\gamma)$, following a determination of the spectrum exponent of GLE 60 (on 15 April 2001) by Lockwood et al., 2002. The above improvement of the attenuation function modifies the doses calculated only for subsonic flights and during GLEs with rigidity spectrum exponent lower than about $\gamma = -5.5$.

Because the flights of Concorde available were restricted to routes between New York (geomagnetic latitude λ_G = 50.7°N) and Paris (λ_G = 51.1°N) or London (λ_G = 53.7°N), dose rates at 18290 m, mentioned above, are for the North Atlantic path. Using, for Greenwich meridian, results of dose rate calculation during GLE 42 (see cartography of O'Brien and Sauer, 2000), the function $\mathbf{L}(\lambda_G)$ giving the variation of the dose rate with the geomagnetic latitude, at subsonic altitudes, could be estimated (Figure 1b). Then, from the results on North Atlantic path, the dose rates could be calculated for other geomagnetic latitudes.

When the best precision is required, in addition to the improvements proposed in the present paper, the effect of geomagnetic storms must be taken into account (paper 2) as well as the changes of the galactic cosmic ray background related to Forbush decreases (Lantos, 2005). This is the case, for example, for comparison between model calculations and measurements on board aeroplane.

3- Method to derive rigidity spectrum exponent

Figure 2 shows a diagram published by Palmiera et al. (1970) and based on calculations by Webber and Quenby (1959) and by Lockwood and Webber (1967) of the so-called yield functions (Sandström, 1965) for Kiel and Deep River neutron monitors. On the one hand, as mentioned above, Deep River NM is now closed, but at the rigidity point of view, Deep River NM (R = 1.25 GV) and Kerguelen NM (R = 1.14 GV) are equivalent. On the other hand, Kiel NM (R = 2.36 GV), Moscow (R = 2.30 GV) and Newark (R = 2.21 GV) NM are also equivalent. Thus the curves of Figure 2, which give the rigidity spectrum exponent γ in function of the ratio of the intensity measured with Deep River NM to the intensity measured with Kiel NM, could also be used with Kerguelen and Moscow or Newark NMs.

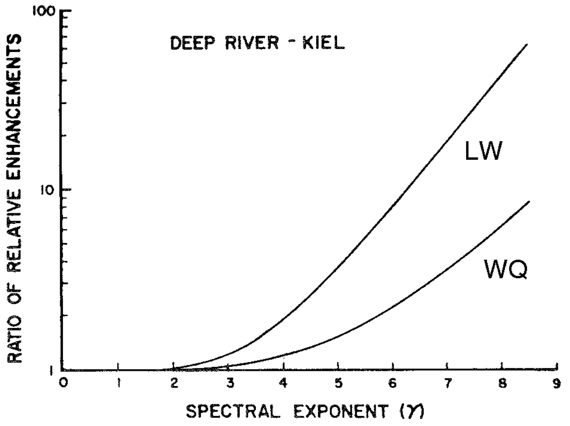

Figure 2: Methods to calculate the spectral exponent from the ratio intensity observed with two neutron monitors : Deep River and Kiel. "LW" is from Lockwood and Webber (1967). "WQ" is for Webber and Quenby (1959).

The rigidity spectrum exponent γ_{max} at the time of the maximum of the GLE, calculated with the two curves could be compared to the rigidity spectrum exponents published for number of GLEs in the literature (see Ref. 8, 13, 22-28), using in general the full global network of the neutron monitors. For the calculations published from 1988 to 2001 (corresponding to 16 GLEs), the curve labelled WQ gives the best results. Indeed the average difference on the spectral exponent is only 0.09 and the standard deviation is 1.01. With the curve labelled LW, the average difference is as large as 1.36 and the standard deviation is 1.09.

The method based on Webber and Quenby (1959) results could be used not only to know the rigidity spectrum exponent γ_{max} at the time of the maximum of the GLE, but also it could be useful to calculate the variable exponent γ (t) in the course of the GLE. If the intensity time profiles measured by more than one of the three monitors (Moscow, Newark and Kiel) are available, the comparison of the exponent γ (t) gives a good indication of the quality of the determination. Figure 3 shows (upper frame) the evolution of the exponent γ (t) in the course of the GLE 42 (29 September 1989). The exponents are calculated from the ratio of GLE 42 intensity observed with Kerguelen NM to intensity observed with Moscow NM (squares) and from the ratio of GLE 42 intensity observed with Kerguelen NM to intensity observed with Kiel NM (points). The determinations by Lovell et al. (1998) at 13:25 and 16:00 UT are indicated for comparison. They are obtained with a conventional and precise method based on measurements of 48 NMs and muon detectors. The determinations by Lockwood et al. (2002) at 12:15, 13:25 and 16:00 are given. They are obtained using two NMs at close geographic locations and having similar vertical cut-off rigidity, but at different altitudes above sea level, namely Mount Washington NM and Durham NM. The comparison shows the good agreement between the different methods. The variation of the spectral exponent with time, obtained by Lockwood et al., 2002 (lower frame) is also in agreement with the results of the present method. Note in particular the same variations at the beginning of the event. The expected precision of the determination is given by error bars.

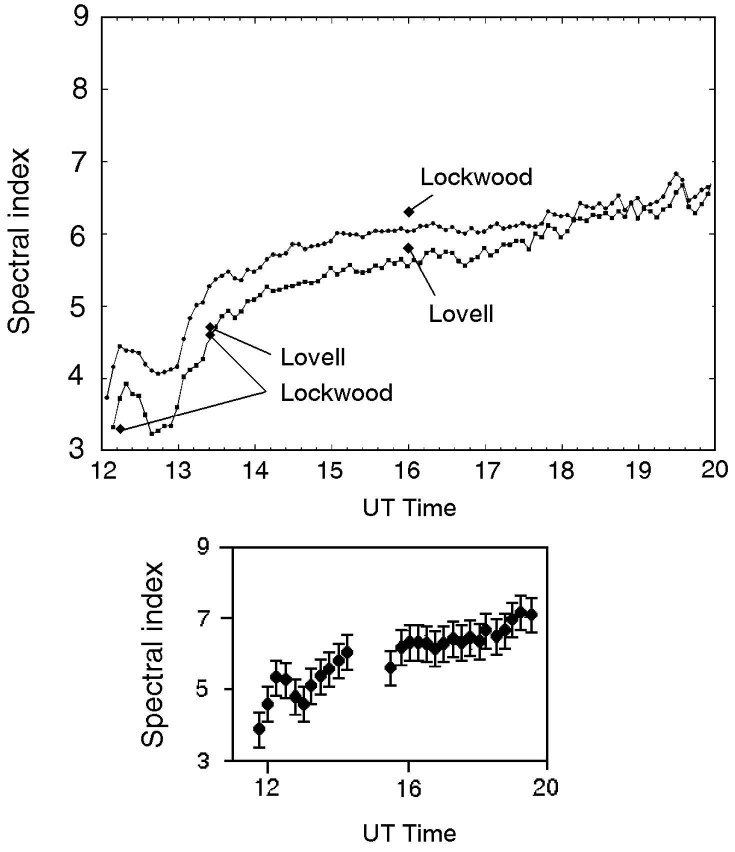

Figure 3 Top: Rigidity spectrum exponent calculated from the ratio of GLE 42 intensity observed with Kerguelen NM to intensity observed with Moscow NM(squares), and from the ratio of GLE 42 intensity observed with Kerguelen NM to intensity observed with Kiel NM (points). Results obtained with other methods are indicated. Bottom: Evolution of the spectral exponent in the course of the GLE 42 as calculated with the method of Lockwood et al., 2002, with the expected precision.

4- Application to recent GLEs

The GLE 59 has been observed on 14 July 2000 (Bastille Day Flare). Its intensity, as measured with Kerguelen neutron monitor, is about 30 % of the galactic cosmic ray intensity. The calculation, at the time of the maximum of the GLE, gives $\gamma = - 6.6$ when Kerguelen is compared to Kiel NM, $\gamma = - 6.2$ when the comparison is with Moscow NM, and $\gamma = - 6.1$

when the comparison is with Newark NM. The average, $\gamma = -6.3$, is compatible with the precise determination, by Duldig et al. (2001), giving $\gamma = -7.0$.

The spectrum of GLE 60 (15 April 2001) has been studied by Lockwood et al. (2002), using a method involving two monitors with different altitudes (see above). At the time of the maximum, the rigidity spectrum exponent is found to be $\gamma = -7$. The results obtained with the present method are $\gamma = -5.4$ when Kerguelen is compared to Kiel NM, $\gamma = -5.2$ when the comparison is with Moscow NM, and $\gamma = -4.6$ when the comparison is with Newark NM. The results are coherent, showing that the anisotropy is not sufficient to dismiss the method, but the average, $\gamma = -5.2$, differs significantly from the value given by Lockwood et al. (2002). In absence of precise determination based on the NM world-wide network, it is difficult presently to know the reasons of the difference.

During a period in October and November 2003, important solar flares have occurred, but their counterpart in the GeV range of particle energy has been very limited. Indeed the measurements give for GLE 65, on 28 October 2003, intensity of about 3 % with Kerguelen NM, for GLE 66, on 29 October 2003, intensity of about 7.7 % with Kerguelen NM and for GLE 67, on 2 November 2003, intensity of about 8.6 % with Kerguelen NM. Such GLEs are negligible for most applications. Nevertheless the determination of the spectrum exponent is important, at least for the GLE 66 (29 October 2003), because a measurement on-board aeroplane has been performed (Getley, 2004).

For GLE 66, because of anisotropy of the primary particles, the intensity measured with Kiel NM and with Newark NM are equal or even larger than the intensity measured with Kerguelen NM. Thus the calculation of the rigidity spectrum exponent γ_{max}, at the time of the GLE maximum, must use the ratio of Kerguelen and Moscow intensities. Owing to the noise on the ratio of the couples of monitors, the method is not precise enough when 1 minute or 5 minute data are used. The data are first integrated over one hour around the time of the maximum and the deduced $\gamma_{max} = -6.4$. The measurement mentioned above is for a flight from Los Angeles to New York on board a Qantas B747 aeroplane. The detailed flight plan is given by the author (the time of departure is 17:50 UT) and the equivalent dose received from GLE alone can be calculated, by integration of the dose rate plotted on Figure 3 of Getley's paper (2004). The measured dose contribution of GLE 66 is 0.5 µSv only. The total dose, including galactic cosmic rays is 12 µSv. The GLE dose calculated with SiGLE and with the given flight plan, for a departure from Los Angeles at 18:00 UT is 0.34 µSv, in good agreement with the measure. Note that the flight with departure at 21:00 UT, the worse case, receives only 1.1 µSv from GLE 66.

For comparison, a flight from Paris to San Francisco during the same GLE would have received 13.2 µSv from the GLE and a total dose of 70.9 µSv for the worse departure time. If the rigidity spectrum exponent is assumed to be average value ($\gamma_{max} = -4.7$, see paper 1), the other GLEs of the end of 2003 would have given a maximum contribution of 9.5 µSv for GLE 65 (28 October 2003) and 6.8 µSv for GLE 67 (2 November 2003), for the same flight plan from Paris to San Francisco. Theses values are indeed negligible for passengers as well as for crew. Nevertheless it should be noted that, according to collection of information about October-November flare effects, number of US aeroplanes were rerouted or delayed (Jansen et al., 2004). Some routes were even closed during the events. Because the dose calculations at the origin of such costly actions are not documented in the open literature, it is difficult to know what are the measurements and the criteria in use.

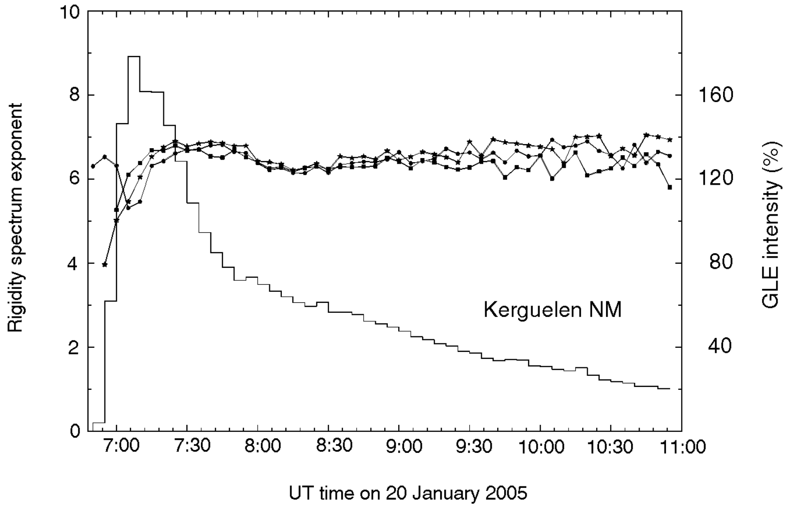

Figure 4 : Full line : time profile of GLE 68 as observed with Kerguelen neutron monitor (scale on the right side). Lines with symbols are rigidity spectrum exponents calculated in function of time with the method described above. Line with points is obtained from ratio of Kerguelen and Moscow NMs, line with squares is obtained from ratio of Kerguelen and Newark NMs, and line with stars is obtained from ratio of Kerguelen and Kiel NMs.

Figure 4 shows the results of the method to calculate rigidity spectrum exponent γ in the course of the GLE 68 (on 20 January 2005). After a period with some anisotropy at the beginning of the event, the three stations of Moscow, Newark and Kiel give very similar results when they are combined with Kerguelen neutron monitor measurements. At the time of the maximum of the event (07:05 UT) the rigidity spectrum exponent is found to be γ_{max} = - 6.0 and to stay between 6 and 7 until the end of the event. To show the rapid increase, the time of the maximum and the subsequent evolution of the intensity, the time profile of the GLE observed with Kerguelen NM is plotted in terms of 5 minute data.

5- Dose received during the GLE of 20 January 2005

The five first GLEs ever observed (from 1942 to 1956) have been potentially the most important in terms of doses received on-board aeroplane (paper 1). Next GLEs in intensity are GLE 42 (29 September 1989), which has been measured at 270 % with Kerguelen NM, and GLE 31 (7 May 1978) with an intensity of 214 %. The GLE 68 of the 20 January 2005 is following immediately, with an intensity of 178.4 % measured with Kerguelen NM. Thus GLE 68 appears as one of the strongest GLEs observed during the last fifty years.

During GLE 68, very important North-South anisotropy has been observed for neutron monitors above 65 ° in geomagnetic latitude. Indeed the increase has been 3308 % with Terre Adélie NM and 2091 % with McMurdo NM (with 5 minute counts). In the North hemisphere, at about the same geomagnetic latitudes, the intensity is only 277% for Inuvik (Canada) NM, 114 % for Thule (Greenland) NM and 112 % for Barentsburg (Spitzberg) NM. Note that an increase of 3350 % of the galactic cosmic ray level before the event has been measured with South Pole neutron monitor, but it is located at 2820 m in altitude, whereas we consider here uniquely neutron monitors at the see level, or at least at low altitude.

Applying the SiGLE semi-empirical model to the time profile observed with the Kerguelen NM, it is possible to deduced the dose rate at 18290 m in altitude (60 000 feet), which is proportional to intensity measured with monitors, expressed in percent of the galactic cosmic ray intensity before the event. As discussed above, the conversion coefficient is **C**(γ). The attenuation **A**(z,γ) of the dose rate with atmospheric depth, in function of the rigidity spectrum exponent is given in Figure 1a. The dose rates, in the course of the GLE 68, for altitudes of 9150 m (30 000 feet) and 12200 m (40 000 feet) are given Figure 5. The dose rates correspond to routes between western Europe and New York, which are reference routes for the SiGLE model. At other latitudes, because GLE occurred during a period without geomagnetic activity, it is not necessary to take into account potential modifications of cut-off rigidity studied in paper 2, and thus the function **L**(λ_G) could be applied without modification, except because of anisotropy.

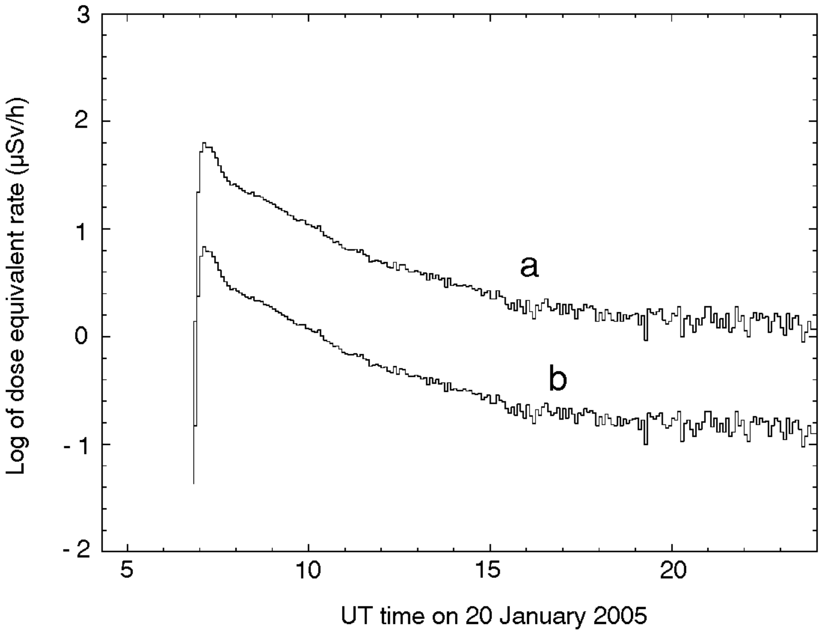

Figure 5: Time profile of the dose rate received from GLE 68 at 12200 m (40 000 feet, labelled a) and 9150 m (30 000 feet, labelled b), over North Atlantic path. The time profile of the GLE, with 1 minute time resolution, is measured with Kerguelen NM.

Above the region of Kerguelen Islands (λ_G = 57.2°S), according to the function **L**(λ_G), the dose rate is higher by a factor 1.34, than above North Atlantic path. If the time profile is measured (in percent of galactic cosmic ray intensity) with another neutron monitor, the same factor gives the dose rate above the region of the given neutron monitor. For GLE 68, total doses received, from 07:00 UT to 14:00 UT at 12200 m (40000 feet) above number of sea level neutron monitors have been calculated. An integration over time is useful because the differences between the time profiles observed with the different monitors could be important. An integration over 7 hours has been chosen because this is a minimum duration of a long-haul flight (corresponding to a North Atlantic flight) and because at 14:00 the level of the GLE is down to only 1/20 of its maximum value. Thus the corresponding dose is representative of each region as seen by a long haul flight during GLE 68.

Table 1 gives, for the North hemisphere, co-ordinates of the NM stations, geomagnetic latitude, vertical cut-off rigidity in GV, measure of the maximum of the GLE intensity in percents, based on 5 minute data and dose calculated above the region. Because they are easier to identify on Figure 6, the few neutron monitors available in the South hemisphere are not reported in Table 1.

Table 1: GLE 68 doses at 12200 m, in the region over each of the NMs

Station	Latitude	East Longitude	Geomag Latitude	Cut-off rigidity in GV	Maximum intensity in %	Dose over 7 hours in µSv
Bern	46.95	7.98	47.85	4.42	10	7.
Kiel	54.33	10.13	54.51	2.36	95	32.
Rome	41.86	12.47	42.10	6.27	2	1.
Barentsburg	78.12	14.42	74.65	0.00	133	112.
Oulu	65.05	25.47	61.83	0.77	269	142.
Apatity	67.55	33.33	62.89	0.55	186	129.
Moscow	55.47	37.32	50.87	2.30	100	32.
Novosibirsk	54.80	83.00	44.94	2.69	55	22.
Norilsk	69.26	88.05	59.02	0.53	128	92.
Tixie Bay	71.58	128.92	60.31	0.43	199	91.
Yakutsk	62.02	129.72	51.86	1.63	145	51.
Magadan	60.07	151.01	51.55	1.99	98	62.
Cape Schmidt	68.92	-179.47	63.66	0.52	282	116.
Inuvik	68.35	-133.72	70.93	0.14	277	119.
Fort Smith	60.02	-111.93	67.17	0.30	242	138.
Newark	39.70	-75.70	50.36	2.21	88	38.
Thule	76.50	-68.70	87.14	0.00	114	93.
Nain	56.55	-61.68	67.03	0.45	270	154.

In Table 1 the geomagnetic latitudes are calculated with centred dipole and with IGRF North Pole co-ordinates for 1995 (latitude = 79.30°, longitude = 288.59°, according to the web site of Space Environment Information System (Ref.31). The vertical cut-off rigidities are also calculated for 1995 (Shea and Smart, 2001). Figure 6 shows, in function of geomagnetic latitude, the doses given in Table 1 and the same doses calculated for southern hemisphere.

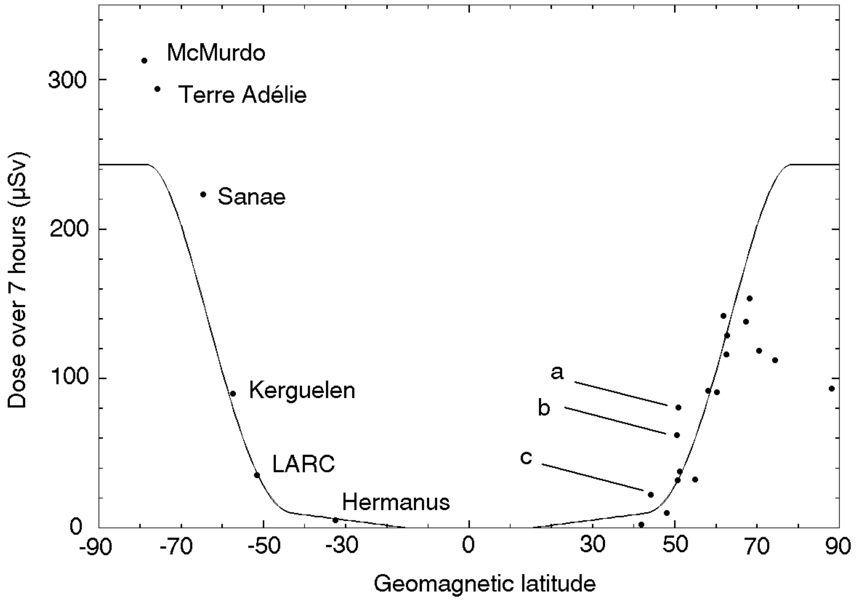

Figure 6: Doses received from GLE 68, over 7 hours, at 12200 m in regions above NMs. The curve is the same dose, calculated with the SiGLE model assuming no anisotropy of the primary particles. Label a is for Yakutsk NM, label b for Magadan NM and label c for Novosibirsk NM.

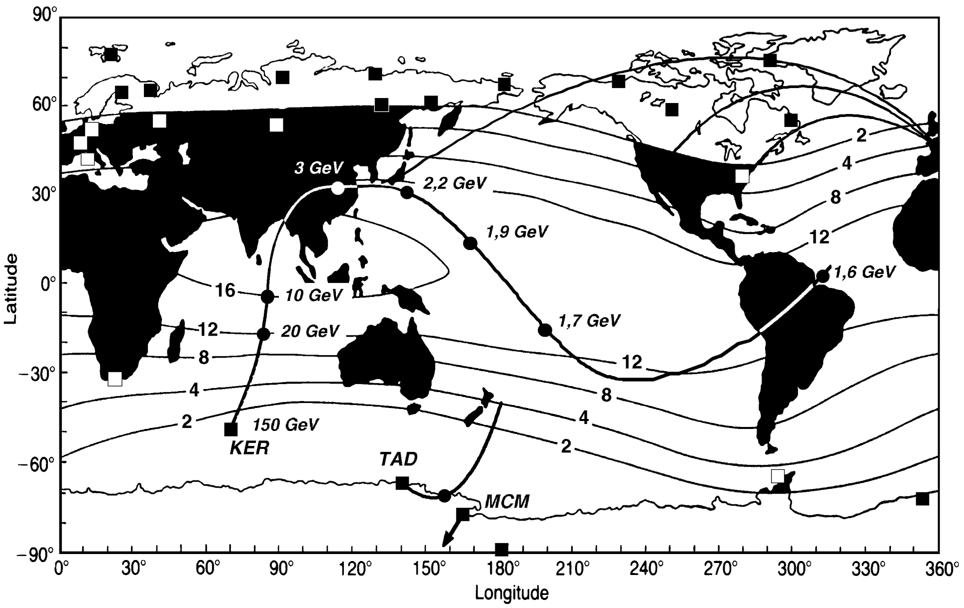

Figure 7: Locations (squares) of the NMs available for GLE 68. Vertical cut-off iso rigidity curves are from Smart and Shea (1987). Regions with vertical cut-off rigidity larger than 2 GV are drawn in black. On the upper right part of the figure three flight plans are plotted: Paris-Washington, Paris-San Francisco and Tokyo-Paris (polar route). The asymptotic directions of the French neutron monitors in the southern hemisphere : Kerguelen (KER) and Terre Adélie (TAD) are plotted and labelled with the energy of the particles coming from the corresponding direction (Flueckiger,1997).

The monitors mentioned Table 1 and Figure 6 are located on Figure 7. The vertical cut-off iso-rigidity curves are labelled from 2 to 16 in GV (Smart and Shea, 1987).

On Figure 6, for geomagnetic latitudes lower than 65°, the doses deduced from neutron monitor measurements (points) are in good agreement with the predictions of the SiGLE function $\mathbf{L}(\lambda_G)$ (curve), which does not take anisotropy of the primary particles into account. Thus the Figure 6 validates the function $\mathbf{L}(\lambda_G)$ used in the SiGLE model, at least for geomagnetic latitudes lower than 65° in absolute value. Points labelled **a, b** and **c** are exceptions. They will be discussed latter. For geomagnetic latitudes larger than 65°, the difference with the curve is important. In the northern hemisphere the dose deduced from NM measurements are about half of the expected values for the three NM, with geomagnetic latitudes equal or higher than 70° N on the right side of the figure. They are Inuvik (NW Territories, Canada), Barentsburg (Spitzberg) and Thule (Greenland). In the southern hemisphere, the three stations located above geomagnetic latitude of 75°, in Antarctica (McMurdo, Sanae and Terre Adélie), show also dose larger than expected, due to North-South anisotropy.

Table 1 and Figure 6 show that the regions of Finland (Oulu), north of European Russia (Apatity), and north of Siberia (Norilsk, Tixie Bay, Cap Schmidt) NMs have geomagnetic latitudes lower than 65°N and are among those well fitted by the function $\mathbf{L}(\lambda_G)$. As pointed out above, monitors labelled **a** and **b** are two exceptions. The point labelled **a** is for Yakutsk NM and the point **b** is for Magadan NM. Both are in the eastern part of Siberia, at geomagnetic latitudes of about 50°N. A plot of vertical cut-off rigidity (Shea and Smart, 2001) in function of geomagnetic latitude shows that their cut-off rigidity is about 2 and 2.5 GV *below* the rigidity of European neutron monitors of the same geomagnetic latitude. Note that for regions, like Novosibirsk (labelled **c**), with vertical cut-off rigidity larger than 2 GV, the absolute error using the function $\mathbf{L}(\lambda_G)$ is small (for example 11 µSv for Novosibirsk) even if the relative error is important (underestimation by a factor 2 for Novosibirsk). The regions with vertical cut-off rigidity larger than 2 GV are indicated in black on the Figure 7. The flights from Europe to Eastern Asia are normally not passing over Yakutsk or Magadan. For those reasons, flights between Europe and Eastern Asia, following Siberian routes, do not need specific correction because of anisotropy.

The situation is different for flights between Europe and North America (or between Europe and Japan when following so-called polar routes over Greenland and Alaska). Three examples of flight plans are plotted on Figure 7: flights from Paris to Washington, from Paris to San Francisco and from Tokyo to Paris, passing over Fairbanks in Alaska (polar route). Indeed the flight from Paris to San Francisco is passing in the region of the Canadian monitors of Nain (Labrador) and Fort Smith (NW Territories). In this region, Figure 6 shows that the dose calculated with the function $\mathbf{L}(\lambda_G)$ must be decreased by about 20 %. The flight from Tokyo to Paris is passing over Inuvik (NW Territories) and Thule (Greenland) NMs for which the dose calculated with the function $\mathbf{L}(\lambda_G)$ is overestimated by a factor 2. Thus applying the corresponding corrections (a factor 0.8 between 65° and 70° in geomagnetic latitude and a factor 0.5 for geomagnetic latitudes above 70°, one can compare the doses calculated with and without tacking anisotropy into account. Note that such a correction is specific to each GLE. In general an interpolation between the locations of the different NMs will be necessary to correct each point of the flight plan for anisotropy, eventually as a time dependent function..

Table 2 gives doses received from GLE 68 and from galactic cosmic rays for a few typical flights. The flights are based on actual flight plans and doses are calculated with the SiGLE model. The doses given are for times of departure corresponding to the highest doses received from the GLE. The doses received from galactic cosmic rays (GCR) are calculated with CARI 6 software (Friedberg *et al.*, 1999). According to the above discussion the flights from Paris to San Francisco and the flight from Tokyo to Paris along polar route are corrected from anisotropy. Without this correction, the contribution of the GLE 68 could be estimated, respectively to 96.9 µSv and to 88.3 µSv. Thus the decrease due to correction is respectively 23.7 % and 43.6 % for the dose received from the GLE and respectively 14.1 % and 25.6 % for the total dose.

Table 2: Doses potentially received during the GLE 68

Route	Dose received from GLE 68 µSv	Dose received from GCR µSv	Total dose µSv
Paris-Washington (B747)	53.1	39.4	92.5
Paris–San Francisco (A340)	73.9	65.8	139.7
Tokyo–Paris (polar route,B747)	49.8	61.8	111.7
Paris-Tokyo (Sib. route,B747)	14.1	44.3	68.4
Paris-Osaka (Sib. route,A340)	21.2	52.2	73.4
Osaka-Paris (Sib. route,A340)	60.8	70.6	131.4
Los Angeles-New York (B747)	15.2	61.8	77.0
Buenos Aires-Paris (B747)	11.7	35.3	47.0

The flights between Paris Tokyo (or Osaka) along Siberian routes illustrate the sensitivity to the detailed flight plans. For GCR, from a flight to another between the same airports, the dose could be quite different (Bottollier et al., 2003). The effect is even larger when GLEs are considered (paper 2). According to Table 2, the GLE 68 contribution is three or four times larger when the flight above northern Siberia, follows the limits of the Arctic Ocean (Osaka-Paris) than when the flight is passing above southern Siberia (as for this specific Paris-Tokyo flight). Finally the flights between Los Angeles and New York and the flight between Buenos Aires and Paris are examples of flights protected because they are almost entirely flying at relatively low geomagnetic latitudes. Even if Concorde is not flying anymore, it is of interest to mention that the dose potentially received, during GLE 68, on-board a supersonic flight between Paris and New York with Concorde is about 190 µSv. This value is to be compared to the dose received during GLE 42 on similar flights which is 260 µSv (paper 2).

Let us consider the scale which was in use on board Concorde to decide change in altitude in order to limit the dose received during solar events. The green sector covered 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. Applying the same scale to subsonic flights for GLE 68, above calculations show that in the worse case the dose rate has been 80 µSv/h on board the flight from Paris to San Francisco and about 50 µSv/h on board the flight from Tokyo to Paris. Although an amber warning could not be excluded on some subsonic flights, a red alarm is certainly excluded. Thus no specific actions were necessary during the GLE 68 on subsonic flights. For comparison, on board Concorde on a virtual Paris-New York flight the calculated dose rate maximum is 244 µSv/h during the GLE 68, corresponding to an amber warning and not to a red alert.

As pointed out before, very important North-South anisotropy has been observed during GLE 68. For high latitude neutron monitors differences could be also important in function of the longitude of the NM, because of the specific shape of the asymptotic directions of the high latitude neutron monitors. Asymptotic directions of Terre Adélie NM (located at Dumont d'Urville and labelled TAD) is compared, on Figure 7 to the asymptotic directions of Kerguelen, labelled KER (Flueckiger, 1997). The asymptotic directions of Terre Adélie are almost aligned with a meridian, while those of Kerguelen are collecting particles over a large range of longitudes. On Figure 7, the asymptotic directions of the neutron monitor of McMurdo (labelled MCM) is also indicated. Both stations are rather close from each other, but their fields of view are in opposite directions. Thus high latitude monitors, like Terre Adélie or McMurdo are much more sensitive to the anisotropy of particles than middle latitude neutron monitors like Kerguelen. In terms of dose received from the GLE 68 during 7 hours of flight at 12200 m (40000 feet), a dose of 89.6 µSv is calculated for Kerguelen NM, 313 µSv for McMurdo and 294 µSv for Terre Adélie. Except over Antarctica, the neutron monitors are not numerous enough in the southern hemisphere, to apply the same approach as in the northern hemisphere. Nevertheless in the southern hemisphere, most of the flights starting from South Africa, Australia, Chile or Argentina, are expected to fly toward equator rather than to pass at high latitudes.

When the same study as for Figure 6 and Table 1 is done for GLE 42 (29 September 1989) it shows that for 13 of the 19 NMs available for geomagnetic latitudes lower than 65°, the doses deduced from NM observations agree with the doses expected from the function $\mathbf{L}(\lambda_G)$. For higher latitudes, the GLE doses are overestimated in the North hemisphere, as for GLE 68. For the southern hemisphere, in the contrary to GLE 68, the doses deduced from the function $\mathbf{L}(\lambda_G)$ are also *overestimated* by the model for GLE 42 (this is true for neutron monitors which are located in Antarctica: McMurdo, Terre Adélie, Mirny, Sanae and Mawson). In the northern hemisphere, as for GLE 68, a few monitors, located at geomagnetic latitudes lower than 65° are not in agreement with the doses expected from the function $\mathbf{L}(\lambda_G)$. For GLE 42, the exceptions are NMs located at Oulu (Finland), Apatity (Russia) and Goose Bay (Canada) and Magadan, Novosibirsk and Irkutsk in central and eastern Siberia. As pointed out before, the absolute error on the doses remains low for regions like Novosibirsk and Irkutsk, because of the relatively high vertical cut off rigidity.

6- Discussion and conclusion

Because of its amplitude, the GLE 68 (on 20 January 2005) is of particular interest to test improvements of the semi-empirical model SiGLE. It has been observed with precision by most of the neutron monitors of the world-wide network. An important parameter, the rigidity spectrum exponent, could be deduced from couples of neutron monitors, either for the maximum of the event, γ_{max}, or in the course of the GLE, γ (t). Indeed the method, proposed by Palmiera et al., 1970 and based on Webber and Quenby (1959) results, has been extended to neutron monitors presently operating, and tested. The method has been also used to compare a measurement performed on board aeroplane during the GLE 66 (on 29 October 2003) with the prediction of the model SiGLE. The method is obviously not as precise as the classical methods involving a large number of monitors, but it is most easy to applied. It is nevertheless limited to the GLEs for which the anisotropy is not too important.

The observations of number of neutron monitors located at the see level have been collected to study the distribution of the GLE intensity over the globe. Below 65° in geomagnetic latitude, the North-South function of the model SiGLE is found in agreement with the neutron monitor results, both for GLE 68 and for GLE 42 (on 29 September 1989). For each GLE the method leads to a specific correction of the predictions of the SiGLE model when anisotropy modifies the dose rate distribution. The correction along the path of the flights could be obtained by interpolation between the different NM regions.

In addition to the Kerguelen NM, the neutron monitors of Moscow, Newark and Kiel could also been used to applied the SiGLE semi-empirical model. The corresponding conversion parameter is given in the present work. The calculation of the rigidity spectrum exponent in the course of the GLE, γ (t) and the correction for anisotropy are improving the calculation, with the SiGLE model, of the dose received on board aeroplane. If necessary the calculation could also take into account geomagnetic storm and Forbush decrease effects on the dose. Both effects have been discussed in previous papers (paper 2 and Lantos, 2005).

The GLE being the largest observed since 1989, the GLE 68 is also important at the operational point of view. Thanks to an efficient international co-operation, the observations of 25 neutron monitors have been collected within a few days after the event. Thus the rigidity spectrum exponent in function of time as well as the anisotropy observed by the different neutron monitors were available for operational purposes (like the SIEVERT system). The calculations presented here show that the doses received from this GLE were not negligible. They were much larger than the doses due to the GLEs having occurred at the end of 2003. Nevertheless they do not justify delay or re-routing of subsonic flights, even among the most exposed, on the basis of the regulations applied, in the past, to the Concorde flights.

As far we know, the GLE 66 of 20 January 2005 has not be measured on board aeroplane, despite number of programmes to measure automatically doses on board aeroplane. It is a shame because of the exceptional amplitude of this GLE which permits more reliable measurements. Whatever the efforts to improve models, the measurements on board aeroplane remain the corner stone for the knowledge of the doses received during solar events.

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