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SEMI-EMPIRICAL MODEL TO CALCULATE POTENTIAL RADIATION EXPOSURE ON BOARD AIRPLANE DURING SOLAR PARTICLE EVENTS

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ABSTRACT

Doses received on board airplane are now monitored in Europe in application of a new legislation. The French operational system SIEVERT has been developed to calculate doses due to galactic cosmic rays and to solar particles. Nevertheless very few in-flight measurements have been performed during solar particle events and full calculations of solar cosmic ray effects are also rare. The semi-empirical model SiGLE is used, on the basis of past observations of GLEs, to provide a coherent picture of doses potentially received on board airplane. Potential exposure is calculated for number of routes during three typical GLEs of different amplitudes. It is given for two routes during the past GLEs observed since 1942. Results of SiGLE model are compared to other dose rate estimates available for a few GLEs, showing a reasonnable agreement. The effect of severe geomagnetic storms on dose rate received during solar flares is also studied using SiGLE model.

1. INTRODUCTION

Doses received by European crew members are monitored in application of an European Directive [1], now implemented in the legislation of each country. On the one hand this permits to apply recommended limits to each crew member and on the other hand, monitoring doses will improve precision of future epidemiological studies on possible cancers induced by low level radiation. Calculations have been chosen by many companies instead of costly systematic measurements. The SIEVERT system [2, 3] has been developed on the behalf of the French Aviation Authority to fulfil the new legal requirements. The flight plan of each flight is sent by the companies to the SIEVERT server. The server returns to the companies the effective radiation dose for the flight, computed using a 3-D world map of effective dose rates. The companies then add the calculated dose to each crewmember's file. In addition to galactic cosmic rays, the system treats solar particle events using time-dependent maps based on neutron monitor observations of GLEs (Ground Level Enhancements), which are the highest energy part of the most intense solar particle events.

In terms of dose measurement and calculation, the situation is very different for the two sources of radiation received on board aircraft. Indeed number of in-flight dose measurements are available for the galactic cosmic ray component. At the same time, for this component, dose calculation software is available for operational purposes, like CARI 6 software [4] developed by the US Federal Aviation Administration or EPCARD [5] developed on behalf of the European Commission. The SIEVERT system which is using the first, foresees to adopt the second in the near future. In the contrary, for the solar component, only very few measurements on board airplane have been performed during GLEs. The calculations based on particle transport codes are also quite rare and for the same GLE they are giving dose estimates differing by one order of magnitude. In addition those calculations are computer time consuming. Thus for operational purpose, in the frame of the system SIEVERT, it has

been necessary to develop a semi-empirical model, called SiGLE [6], to estimate doses received from GLEs. Construction of this model has been possible thanks to unpublished measurements on board Concorde during GLEs in 1989 and 2000. As they are only few dose measurements on board airplane during GLEs, both validation of models based on particle transport codes and construction of semi-empirical models are limited. Nevertheless the model SiGLE gives apparently reasonable estimates of the dose received on board a given flight. In addition it could be easily improved when new observations or calculations become available.

2. THE SEMI-EMPIRICAL MODEL SIGLE

The model SiGLE is using high latitude neutron monitor measurements to calculate the dose equivalent rate and its time variations at a chosen reference altitude of 18,290 m (corresponding to 60000 feet) for the North Atlantic routes (vertical cut-off rigidity between 2 and 4 GV). High latitude neutron monitors are defined here as having vertical cut-off rigidity lower than 2 GV. If the neutron monitor output time profiles show important anisotropy of primary particles, an average time profile is taken for operational applications and the output of the closest neutron monitor is taken for a specific flight. The neutron monitor output $\mathbf{I}(t)$, where t is the time, is the GLE intensity (i.e. count) enhancement expressed in percent of the level of the galactic cosmic rays measured before the event. The dose rate at the reference altitude is assumed to be proportional to the neutron monitor output with a conversion coefficient $\mathbf{C}(\gamma)$ function of the primary particle rigidity spectrum exponent, γ. The exponent γ is deduced from the responses of the different neutron monitors of the worldwide network. The coefficient $\mathbf{C}(\gamma)$ is deduced from measurements on board Concorde during GLEs.

In the model SiGLE, calculations with particle transport code are used in relative scale 1) to estimate the attenuation of the dose rate in function of the depth in the atmosphere and 2) to estimate the variation of the dose rate in function of the geomagnetic latitude at subsonic flight level. The attenuation $\mathbf{A}(z,\gamma)$ of the dose equivalent rate in function of the depth in the atmosphere, for North Atlantic routes is deduced from [7] in the case of the GLE 42 ($\gamma_{max} = -4.7$) at the time of its maximum. Note that the attenuation of the dose in function of the depth in the atmosphere is known from number of measurements of galactic cosmic ray, and thus this function could be used in the case of GLE with similar spectrum. During the minimum of the solar cycle, the corresponding rigidity spectrum exponent is $\gamma = -2.5$. The attenuation function will be improved below thanks to measurements on board subsonic flight.

The third function $\mathbf{L}(z,R)$ used in the SiGLE model is the variation of the dose rate in function of vertical cut off rigidity R (which is mainly related to the geomagnetic latitude). $\mathbf{L}(z_o,R)$, at subsonic flight level $z = z_o$, is deduced from calculations with particle transport code applied to GLE 42 [8] at the time of its maximum ($\gamma_{max} = -4.7$). In absence of sufficient numerical calculations or measurements, $\mathbf{A}(z,\gamma)$ is provisionally assumed to be the same for the different geomagnetic latitudes, and $\mathbf{L}(R)$ is assumed, for all GLEs, to be the same as for GLE 42. The dose equivalent rate $\mathbf{D}(t,z,R,\gamma_{max})$ in the course of the GLE is expressed as:

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

This simplified form may be used for any altitude (including supersonic levels) for the North Atlantic routes, and for subsonic altitudes on other routes.

The absolute dose rate scale is obtained from measurements of the dose equivalent on board a few Concorde flights during two GLEs on 29 September 1989 (GLE 42) and on 14 July 2000

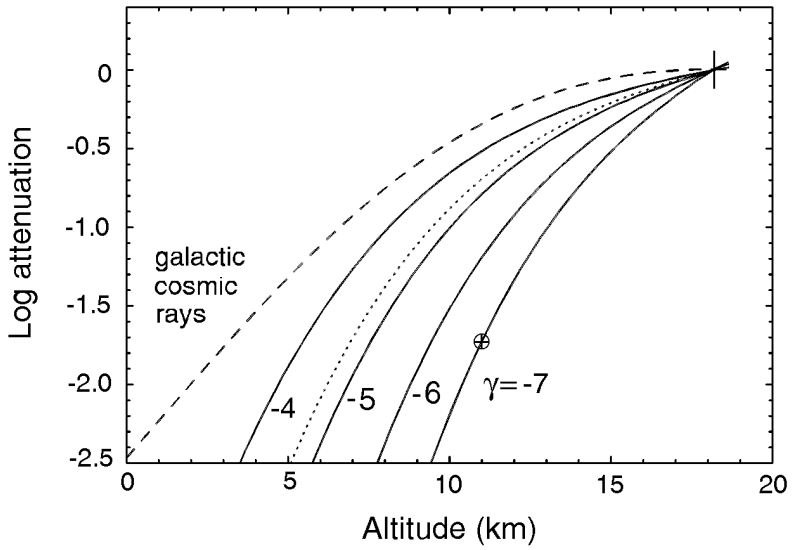

Figure 1: Logarithm of the attenuation of dose equivalent rate in function of altitude for different values of the rigidity spectrum exponent γ of the primary particles. The reference level is 18,290 m. Attenuation for galactic cosmic rays is indicated with dashed line and attenuation for GLEs with average rigidity spectrum exponent γ = - 4.7 is indicated with a dotted line. The point indicated on the curve γ = - 7 is deduced from GLE 60 ambient dose equivalent measurement.

(GLE 59). Parameters and results of the available flights are reported in Table 1 [6]. Dose measurements are converted into ICRP Publication 60 system [9], presently in use: dose equivalents should be increased by 20 % according to current quality factors [10] 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. The two GLEs exhibit quite different solar primary particle spectra. Indeed the rigidity spectrum exponent is γ_{max} = – 4.7 for GLE 42 [11] and γ_{max} = – 7 for GLE 59 [12] at the times of their maximum. The conversion coefficient $\mathbf{C}(\gamma_{max})$ is found to be equal to 0.59 µSv/h/% for γ_{max} = - 4.7 and to 4.06 µSv/h/% for γ_{max} = - 7. The conversion coefficient for other rigidity spectrum exponent is obtained by linear interpolation in logarithmic scale. When applied to γ = - 2.5, the result is found in reasonable agreement with galactic cosmic ray dose as calculated with CARI 6 software.

Table 1: Ambient dose equivalent measurements on board Concorde during the 29 September 1989 and 14 July 2000 GLEs

Date	Route and company	Time of take-off	Time of landing	Measured dose	Conversion into ICRP 60
29/09/1989	Paris-New York (AF)	10:19 UT	13:43 UT	120 µSv	144 µSv
29/09/1989	New York-London (BA)	13:56 UT	17:19 UT	140 µSv	168 µSv
29/09/1989	New York-Paris (AF)	17:07 UT	20:37 UT	70 µSv	84 µSv
14/07/2000	Paris-New York (AF)	09:11 UT	12:40 UT	120 µSv	144 µSv
14/07/2000	New York-Paris (AF)	12:19 UT	15:50 UT	50 µSv	60 µSv

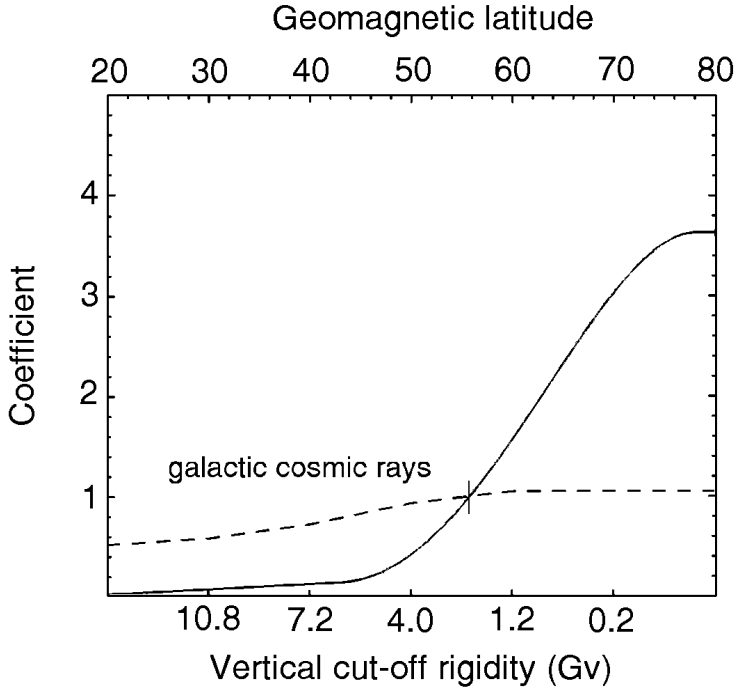

Figure 2: *Dose equivalent rate coefficient L in function of the vertical cut-off rigidity for subsonic altitude of 10,700 m (35000 feet). The reference latitude corresponds to North Atlantic routes. Upper axis gives corresponding geomagnetic latitudes for northern hemisphere and European sector (epoch 1995). The same coefficient for galactic cosmic rays is plotted with a dashed line.*

Above dose measurements were obtained with the dosimeters which were flying routinely on board Concorde. Recently two groups have obtained state of the art measurements during GLE 60, on 15 April 2001 and have calculated assessed ambient dose equivalent rate versus time on-board a Prague-New York flight [13] and on-board a Frankfurt-Dallas flight [14]. According to [13], the dose equivalent rate is about 11 μSv/h at 10,970 m, at the time of the maximum of the GLE. At the time of the operational application and of the submission of [6], the spectrum of the GLE 60 was assumed to be standard (i.e. close to $\gamma = -4.7$), in the absence of better information, the rigidity spectrum exponent being not available in the literature. Indeed a recent publication [15] has shown that GLE 60 spectrum, at the time of the maximum, was not close to the standard spectrum, but rather equal to $\gamma = -7$. This leads us to use the measurements performed during GLE 60 to improve significantly the estimate of the attenuation of dose in function of the depth in the atmosphere for the lowest rigidity spectrum exponents. With $\gamma = -4.7$, calculations and measurements were found in agreement apparently by chance: they are now in agreement by construction of the model. Thus calculated dose estimate for GLE 60 is unchanged.

Figure 1 shows the logarithm of the dose rate attenuation in function of altitude. The reference level is 18,290 m. The dotted line corresponds to $\gamma = -4.7$ and dashed line corresponds to galactic cosmic ray spectrum. The point indicated on the curve $\gamma = -7$ is deduced from GLE 60 measurement. Other curves are homothetical to the curve with $\gamma = -4.7$, the coefficient of homothety being obtained with a quadratic interpolation between the curves $\gamma = -2.5$, $\gamma = -4.7$ and $\gamma = -7$. It should be noted that 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 $\gamma = -5.5$. For a subsonic flight from Tokyo to Paris (polar route), the decrease of the GLE related dose is (lower than) about 15 % when γ equals

- 5 (is greater than –5). For γ = - 5.5, the decrease is about 30 %. Thus most of the doses calculated for subsonic Paris-San Francisco flights in [6] remain almost unchanged (for 24 GLEs over 31). Note nevertheless that GLEs 5 and 59, which will be considered in the next section, are concerned with this change. The worse case is GLE 59 because it is the only GLE, except GLE 60, with a rigidity spectral exponent of - 7. The attenuation and dose rate change by a factor 3 for an altitude 12 kilometers (a typical cruising altitude for subsonic flights). Indeed for the flight from Paris to San Francisco, the results of [6] give 77 µSv for the GLE contribution and 130 µSv including GCR contribution. Here we have (see Table 2) 20 µSv for the GLE contribution and 73 µSv including GCR. Thus the error done for this flight is an overestimation by a factor 3.8 of GLE contribution to the dose and by a factor factor 1.8 on the total dose. All estimates of doses on board supersonic flights remain unchanged because of the little effect of the attenuation function at supersonic altitudes which are close to the reference altitude.

Figure 2 gives the variation of the dose rate, **L**(z,R), in function of vertical cut off rigidity R, for subsonic altitude of 10,700 m (35000 feet). The relative coefficient is equal to unity for the average rigidity on the North-Atlantic route.

For operational applications it is useful to simplify the calculations as far as the system specifications are respected. The model SiGLE, as implemented in the SIEVERT system, does not takes into account the changes of the solar particle spectrum in the course of a GLE (considering only the spectrum at the time of the maximum of the event). In the case of the GLE 42, using particle transport code calculations of [7], the effect of neglected spectral variations has been estimated [6] to introduce an underestimation by 6 % (10 µSv) for Flight 1 of Table 1, by 34 % (57 µSv) for Flight 2 and by 53 % (44 µSv) for Flight 3.

Similarly the anisotropy of primary particle is not taken into account for operational applications because, on the one hand, the data (which is the output of the neutron monitors around the world) are not all available in real time. On the other hand it has been shown [6] that taking anisotropy into account would avoid errors with standard deviation of 38 µSv for the Paris-New York flight receiving the maximum dose equivalent (238 µSv) when flying during GLE 42. Such effects could be neglected for operational applications like Sievert, which cumulates, for each crew member, the doses received on a number of flights. Nevertheless SiGLE model calculations could include the corresponding improvements when individual flights are considered.

3. RESULTS OF THE MODEL SIGLE

The calculations of potential exposure presented here are in terms of dose equivalent. They correspond to the time of departure of the flights leading to a maximum dose. A comparison between the doses obtained for numerous flights spread out during the GLE allows to retain the most extensive one in term of dose equivalent. The GLE time profiles from 1957 to now are those observed with the Kerguelen neutron monitor except when its maximum amplitude differs from the average of neutron monitor with low cut off rigidity. In this case a correction factor is applied. The first three GLEs (in 1942 and 1946) were observed only with ion chambers. The effective threshold rigidity of these instruments is larger than 4 or 5 GV, to be compared to high latitudes neutron monitors (with vertical cut off rigidity lower than 2 GV). GLEs 4 (in 1949) and 5 (29 September 1956) were observed with neutron monitors but not at high latitudes. The conversion to virtual high latitude monitor outputs has been taken from

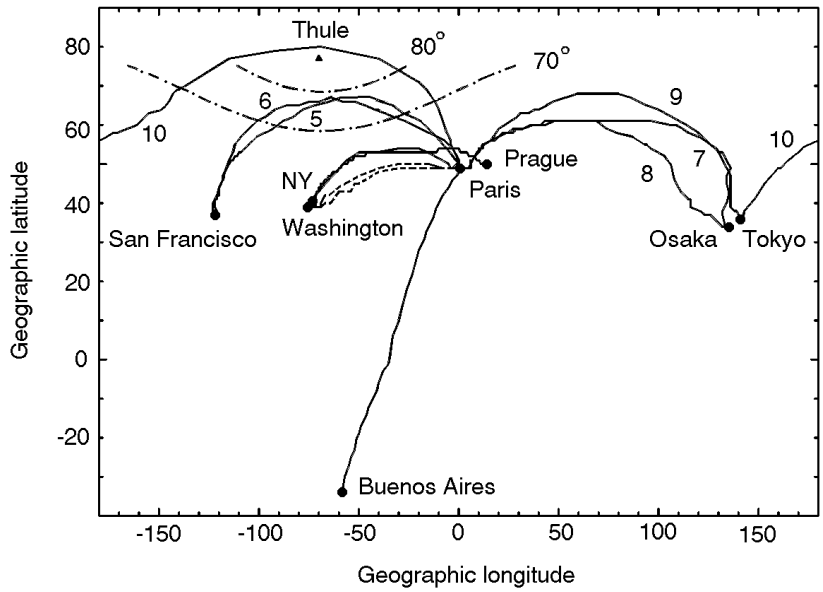

Figure 3: *Routes of the different flights documented Table 3 in geographic coordinates. Geomagnetic latitudes 70° and 80° are indicated. The north geomagnetic pole is close to Thule (Greenland).*

Duggal [16], except for GLE 5. It should be noted that large uncertainties affect the calculations of the five earliest GLEs, even at the basic level of the amplitude of the GLE. In addition when the spectrum is unknown, the average γ_{max} = - 4.7 is assumed. These GLEs being the most intense, they are of high interest to discuss GLE occurrence in terms of radioprotection.
The potential exposures are calculated with the attenuation function modified as described above and taking into account local vertical cut-off rigidity and spectral exponent at the time of the maximum of the GLE, but not taking into account effects of anisotropy nor effects of variation of spectral exponent during the GLE.

3.1 Potential exposures during GLEs 5, 42 and 59 on different routes

The GLE 5 (on 23 February 1956) is the strongest of the GLE events observed since 1942 with neutron monitors or ionization chambers. Thus, despite the high uncertainties on amplitude and spectrum, it is of interest as the worse case concerning doses received on board airplanes. In terms of neutron monitor output, its maximum amplitude at high latitude is assumed here to be an increase of 4554 % of the galactic cosmic ray level, as actually observed with the Leeds neutron monitor. This is, in terms of dose calculation a conservative value compared with the extrapolation to high latitudes by Duggal [16] leading to 9000 %. The time profile of the GLE is taken from Ottawa neutron monitor observations [17]. The rigidity spectrum exponent is taken to be γ_{max} = - 5.6 [18].

The GLE 42 (on 29 September 1989) and 59 (on 14 July 2000) are those measured on board Concorde. The GLE 42 is the strongest event observed since GLE 5. Its maximum amplitude, as observed with Kerguelen neutron monitor, was an increase of 270 % of the galactic cosmic ray level. The GLE 59 was much lower (29 %) on neutron monitor outputs, but as attested by measurements on board Concorde the doses received at high altitudes were similar to those received during GLE 42 (Table 1). This is related to the different spectra of primary solar particles. Indeed, as mentioned above, γ_{max} = - 4.7 for GLE 42 and γ_{max} = - 7 for GLE 59.

Table 2 gives the doses received during the three GLEs on board supersonic and subsonic flights. The first column gives the route and the airplane. Column 2-4 give some parameters of the flight : geomagnetic latitude maximum, flight duration and altitude maximum. For each of the three GLEs, a first column provides the calculated dose due to solar particles only, the second column being the total dose after addition of the galactic cosmic ray contribution, calculated with CARI 6 software [4] and heliocentric potential deduced from Kerguelen outputs, for the month of each GLE.

Table 2 Potential exposures on board airplane on different route during GLEs 5, 42 and 59

	Geomag. latit. maximum	Flight durat.	Altit. maximum (km)	GLE 5 23/02/1956 µSv		GLE 42 29/09/1989 µSv		GLE 59 14/07/2000 µSv	
1- New York-Paris (Concorde)	57.8	3h 26m	17.1	5170.	5200.	253.	276.	95.	119.
2- Paris-New York (Concorde)	58.8	3h 37m	17.6	6290.	6322.	261.	286.	104.	129.
3- Prague-New York (A310)	63.4	8h 32m	11.3	1435.	1480.	172.	207.	7.	42.
4- Paris-Washington (B747)	63.8	7h 41m	11.9	1740.	1785.	182.	214.	11.	43.
5- Paris-San Francisco (A340)	78.6	11h 24m	11.9	3180.	3250.	387.	439.	20.	73.
6- San Francisco-Paris (A340)	78.4	10h 52m	11.3	3630.	3690.	386.	432.	21.	67.
7- Paris-Tokyo (B747)	56.0	11h 38m	12.5	480.	530.	67.	113.	2.	48.
8- Paris-Osaka (A340)	55.6	10h 58m	12.1	690.	750.	79.	123.	4.	48.
9- Osaka-Paris (A340)	59.4	12h 54m	12.5	1840.	1915.	196.	253.	13.	72.
10- Tokyo-Paris (B747 polar route)	88.3	14h 56m	11.3	2830.	2890.	379.	430.	15.	66.
11- Buenos Aires-Paris (B747)	51.9	12h 7m	12.5	520.	550.	29.	62.	3.	36.

The calculations are based on actual flight plans from Air France and, for the flight from Prague to New York, from Czech Airlines. Figure 3 gives the paths of the flight plans labeled with the flight numbers of Table 2. On North-Atlantic path, subsonic flights are indicated with full lines and supersonic routes are indicated with dashed lines.

Flights 1 to 4 are on North Atlantic route at geographic latitudes ranging from 40 to 50° North. The difference between Flight 1 and Flight 2 on board Concorde is related to the altitude profiles of the flights. The same explanation holds for the difference between the subsonic Flights 3 and Flight 4. Comparison between the doses for supersonic and the doses for subsonic flights shows, in particular, the sensibility to the spectral index of the GLE.

Flights 5 and 6 are between Europe and US west coast. The comparison between the doses received on both flights is quite unexpected because the flight with the highest dose during GLE 5 (San Francisco to Paris flight) cumulates together lower maximum of geomagnetic latitude, shorter flight time and lower altitude maximum. Detailed comparison of the calculations shows that for the San Francisco-Paris flight maximum altitude and maximum geomagnetic longitude occur at the time of the maximum intensity of the GLE, which is not the case for the flight Paris-San Francisco at least for the geomagnetic latitude. Indeed the detailed time profiles of the flight parameters, like altitude, as well as time profile of the GLE, are to be considered in addition to the three parameters given in column 2-4 of Table 2.

The same explanation holds for a comparison of Flights 7 and 8 between Europe and Japan on Siberian routes. Compared to Flight 9 (Osaka to Paris, northern Siberian route) both previous flights receive much lower radiation dose during GLE 5: about 3 or 4 times less. This important factor is due to conjunction of higher altitudes and higher geomagnetic latitudes for

Osaka-Paris flight compared to Paris-Osaka according to the specific flight plans we have in hands. Flight 10 performs the same journey but passing above Alaska (Fairbanks) and Greenland (Thule), close to the north geomagnetic pole. Due to very high latitude route, and despite a much lower cruising altitude, the dose received during GLE 5 is almost 6 times the dose received on board the flight from Paris to Tokyo (Flight 7). The four flights between France and Japan illustrate the changes of flight plan, due to commercial and operational reasons and because of meteorological conditions.

Finally Table 2 gives the doses received on board a transequatorial flight from Buenos Aires to Paris (Flight 11). Despite a much better geomagnetic shielding against solar particles (see Figure 2), it would be inaccurate to neglect the doses received from GLEs for low latitude routes because the much lower latitude effect could be counterbalanced by an higher altitude.

Dose received during solar particle events are even more sensitive to the detailed characteristics of flight plans (altitude and route) than in the case of galactic cosmic rays. Indeed attenuation with altitude as well as geomagnetic rigidity effects are much more marked for GLEs (see Figures 1 and 2). In addition Table 2 suggests that detailed flight plans and time profile of the GLE are both necessary to compute doses received during a GLE. Obviously the effects differ also in function of GLE duration and of GLE spectral index.

3.2 History of potential exposures during GLEs on specific routes

Dose history for the GLEs observed since 1942 has been discussed in [6] for two transatlantic routes: Paris-New York on board Concorde and Paris-San Francisco on board a subsonic flight. The first is of interest because of the measurements available on board and the second because of its high geomagnetic latitude passage which renders this flight highly exposed to cosmic rays. We consider here two different flights. Figure 4 shows comparison of the doses received from the solar GLEs only, in the worse case, on two specific routes, Prague to New York and Tokyo to Paris (polar route). The first route is typical of North Atlantic subsonic flights, one of the most frequented corridor and the second is one of the most exposed subsonic routes because of its path at very high geomagnetic latitudes.

The calculations have been performed with the SiGLE model taking into account the above described improvement of the attenuation function. The rigidity spectrum exponents of each GLE are the same as in [6], except for GLE 60 for which $\gamma_{max} = -7$ has been taken. Because smaller GLEs give no appreciable dose effect at aircraft altitude, the calculations are limited to the GLEs with intensities at the ground larger than 10 % of the galactic cosmic ray intensity before the solar event. The number of the GLEs in the international consensual list (which comprises, at the end of 2003, 67 GLEs observed since 1942) is indicated along the horizontal axis. The date of the event is given in the upper part of the figure. Bars in white correspond to the route from Prague to New York, and bars in black to the route from Tokyo to Paris. Since 1956, owing to the number of monitors in operation, the GLE history may be considered as exhaustive for GLEs larger than a few percents.

With the same flight plans, CARI 6 software [4] indicates that the galactic cosmic ray contribution varies from 32 to 47 µSv for Prague-New York flight, depending upon the solar cycle phase, and from 46 to 70 µSv for Tokyo-Paris flight (polar route). As reported by Wilson (1998) [19], a US Federal Aviation Administration committee recommended to ensure a limit of 5 mSv on a given flight, in case of a large solar flare. Figure 4 shows that except

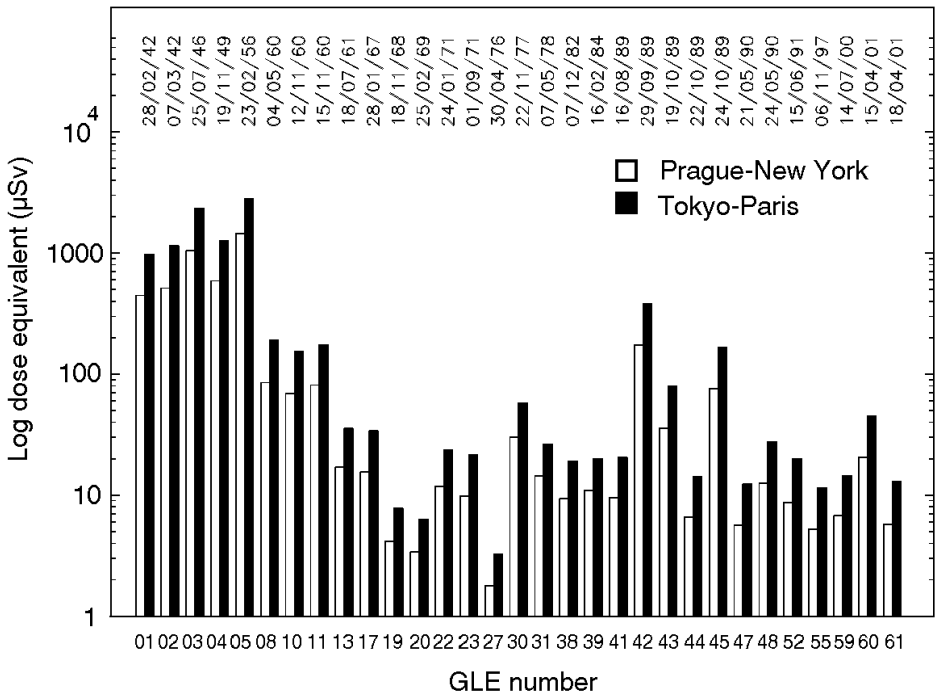

Figure 4: Bar chart of the dose equivalents received in the worse case during GLEs (GLE contribution only), calculated with the model SiGLE. Each group of two bars corresponds to a given GLE (GLE number is indicated along horizontal axis). The first bar shows dose equivalents for Prague-New York flight. The second bar (in black) shows dose equivalents for Tokyo to Paris flight on polar route. The date of the event is given in the upper part of the figure.

during the first five recorded GLEs, the risk has been very limited to reach this level. Indeed the next one, GLE 42 (on 29 September 1989), which is reliable because of the measurement on board Concorde (Table 1) assessing extrapolation to other flights using SiGLE model, remains one order of magnitude below the above limit.

3.3 Effect of severe geomagnetic storms

During geomagnetic storms, the auroral oval is extended and the modification of the geomagnetic field induces decrease of vertical cut-off rigidity at a given geographic location. Calculations by Smart et al. [20] and [21] have shown that for a proton cut-off energy of 1 GeV, at 450 km, the change from geomagnetically quiet condition ($K_p = 0$) to strongest geomagnetic storm ($K_p^* = 10$ as noted by the above authors) corresponds to an increase of about eight degrees in geomagnetic latitude. As a first approximation, this could be extended to lower altitudes (see vertical cut-off rigidity maps at 450 km [22] and at 20 km [23]). This latitudinal increase could be applied to the dose rate variation in function of the vertical cut off rigidity (Figure 2) for high geomagnetic latitudes, in the SiGLE model. It provides for each GLE an estimate of the relative increase of the dose in case of very high geomagnetic activity.

For a flight from Paris to San Francisco, Figure 5 shows the relative increases of the dose for severe geomagnetic storms, compared to the dose received in absence of geomagnetic activity. Open bars correspond to GLE contribution. The relative increase could be important, up to 45 % for GLE 59. Black bars show relative increases on total dose received during a flight : when galactic cosmic ray contribution is added to that of the GLE itself, the relative

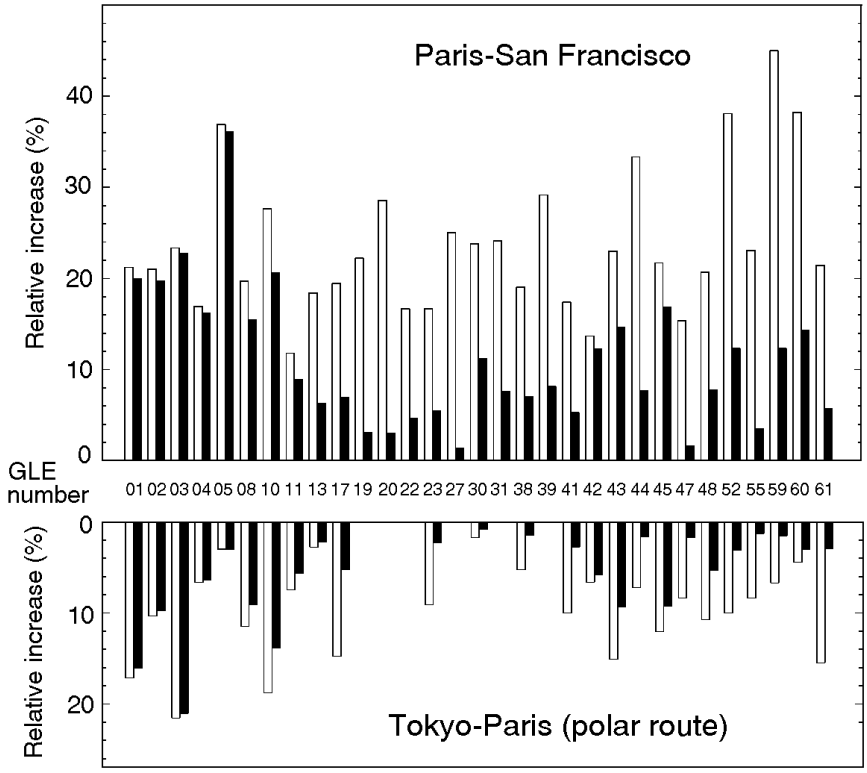

Figure 5:Relative increases of the dose for severe geomagnetic storms, compared to the dose equivalent received in absence of geomagnetic activity. Open bars are for GLE contribution only. Black bars are relative increases on total dose received during a flight. The upper frame is for Paris-San Francisco flight (on board Airbus A 340), the lower frame for Tokyo to Paris flight (polar route on board Boeing 747).

increase is reduced to less than 20 %, for most of the GLEs. One exception is with GLE 5, with a total dose increased by 36 %. Actually GLE 5 was not accompanied with a geomagnetic storm : the planetary geomagnetic index, Ap, was equal only to 7 at that time [24].

The lower part of Figure 5, which gives the same information for a flight from Tokyo to Paris along polar route, shows that the variation with geomagnetic activity is much lower than for the previous flight. The point is that the flight from Tokyo to Paris is passing at very high geomagnetic latitudes even in absence of geomagnetic activity. Indeed its maximum geomagnetic latitude is 87.5 ° in this case and the latitudes higher are than 78 ° during about four hours. As the dose rate in function of the geomagnetic latitude becomes a plateau above this geomagnetic latitude (Figure 2), part of the dose exposure is unchanged even with high geomagnetic activity. The situation is different for the flight from Paris to San Francisco which has a maximum geomagnetic latitude of 78 ° and thus will receive higher dose rate when the vertical cut-off rigidity is decreasing.

Because the North-South coefficient **L**(R) is much less variable in function of the rigidity for galactic cosmic rays than for solar particles with rigidity spectral exponent of $\gamma = -4.7$ (see curves on Figure 2), the effect of geomagnetic activity on the dose calculations is much lower for galactic cosmic rays than for solar particles.

4. COMPARISON WITH OTHER ESTIMATES

The measurements of Spurný and Dashev [13], as well as the measurements on board Concorde during GLE 42 and 69 which have been used for the construction of the semi-empirical model, are not considered here. Other measurements are rare and rather indirect. Thus the present section does not intend to be a validation of the model SiGLE. Nevertheless it is of interest to compare SiGLE results to other estimates, based on calculations or measurements, to see to what extent they are compatible or not. The comparison is done in terms of potential dose rate received at the time of the maximum of the GLE. Functions of the SiGLE model (Figures 1 and 2) have been use to give the expected values at 18,290 m (60000 feet) and at high latitudes, close to the geomagnetic pole. Table 3 gives the different sources of information and the corresponding estimates on the dose rate during GLE 5, GLE 21 and GLE 42.

Table 3 comparison of different dose rate estimates

GLE 05 (23 Febr. 1956)			
authors	*dose rate estimate µSv/h*	*Reference*	*comments*
Armstrong et al. (1969)	10000 - 60000	[25]	lower and upper limits
Dyer and Lei (2001)	16720	[28]	
present work	9680		with GLE amplitude of 4400 % (as observed with Leeds NM)
present work	19800		with GLE amplitude of 9000 % (Dugall, 1979)
GLE 21 (30 Mar. 1969)			
authors	*dose rate estimate µSv/h*	*Reference*	*comments*
Wilson (1998)	13	[19]	based on measurement
present work	7		
GLE 42 (29 Sept. 1989)			
authors	*dose rate estimate µSv/h*	*Reference*	*comments*
O'Brien et al (1992)	147	[27]	derived from Figure 12
O'Brien et al (1998)	32	[7]	derived from Figure 7
Beck et al. (1999)	222	[29]	derived from Figure 7
O'Brien and Sauer (2000)	277	[8]	derived from Figure 4
Dyer and Lei (2001)	929	[28]	based on indirect measurement
present work	575		

The dose rates calculated with a Monte Carlo particle transport code by Armstrong et al. (1969) [20] are lower and upper limits for GLE 5 for which the spectrum is not very precisely known. Note that other authors have obtained very similar ranges [19, 26, 27] for GLE 5. More recently another Monte-Carlo calculation has been published by Dyer and Lei (2001) [28]. Table 3 shows that the estimate based on SiGLE model is compatible with the lower limit of the dose rate range given by Armstrong et al. and is, within a factor 2, in agreement with Dyer and Lei estimate.

The measured dose rate at the time of the maximum of the GLE 21 (30 March 1969) has been given by Wilson (1998) for a high latitude flight at supersonic transport altitude [19]. Our

estimate is compatible within a factor 2 with the observed value. For GLE 42, the same holds for a comparison with the most recent of the calculations performed by O'Brien and his colleagues [7, 8, 27, 29]. During the British Airways flight of Table 1, a campaign of measurement with the CREAM detector was under way. The CREAM detector is designed to study single event effect (SEE) environment of concern for electronics: it measures charge-deposition spectra, linear energy transfer spectra and total dose. An estimate of biological doses has been derived from these measurements [28]. The dose rate deduced from in-flight instrument counts and extrapolated to the time of the GLE maximum by Dyer and Lei is in agreement within a factor 2 with the value obtained with the semi-empirical model for regions close to the pole and at 18,290 m.

Thus from Table 3 it appears that, for the very few documented GLEs, different estimates agree within a factor better than 2 with the model SiGLE results, giving some coherence to the different approaches. In absence of a sufficient number of state of the art measurements during GLEs, this could be considered as a favorable indication, but not as a proper validation. As the situation is the same for all models, campaigns of long duration measurements on board airplane with automatic dosimeters (like those of the DOSMAX project [14] supported by the European Commission), appear as most urgent.

In the SIEVERT system, because of the uncertainties of the models, one considers that GLE 42 corresponds to the upper limit of GLE magnitude for which the semi-empirical model can be applied for monitoring aircrew doses. In case of similar or higher GLEs, dose equivalent estimation will be obtained after analysis of passive dosimeters flying routinely on-board number of Air France subsonic airplanes and collected in principle on a monthly basis. In case of a large GLE the dosimeters will be immediately picked up. It should be noted that such a GLE will likely give a signal well over the dose due to galactic cosmic rays during previous days.

5. DISCUSSION

The SiGLE model is based on GLE observations, i.e. on neutron monitor outputs, the enhancement being expressed in percent of the galactic cosmic ray level measured before the solar event. More precisely, the model assumes that dose rates at airplane altitude are proportional to high latitude neutron monitor outputs. High latitude neutron monitor measurements correspond to the GeV range of primary solar particles. On the contrary, some of the particle transport code calculations are limited to proton energy range well observed from satellites, below 400 MeV.

The range of energy responsible for doses received on board airplane is important for two reasons. In a first place its knowledge is needed to assess use of instruments, neutron monitors or different particle detectors on board satellites, to calculate doses received on board airplanes. Comparison of dose measurements time profiles with the time profiles of the outputs of the different instruments gives reliable information on the energy range to be taken into account. Secondly the time profiles are needed to know which flights are concerned by a given particle event. Indeed as shown on Figure 6 the time profile of the lower energies (on the left side) could be very different from the GLE time profile (on the right side), as illustrated with GLE 42 (on 29 September 1989). The time of the maximum of the GLE (13:25 UT) is indicated on both frames with a vertical line. At 24:00 UT the 110-500 MeV channel indicates flux of about the same level as at the time of the GLE maximum, while the GLE 42 itself is already finished.

The CREAM detector experiment [28] on board Concorde during Flight 2 of Table 1 indicates unambiguously a decrease of the counts from 14 UT to 17 UT in agreement with GLE time profiles and not with 110-500 MeV channel time profile. During the same event, total doses measured during Flights 1 to 3 of Table 1 were easily fitted with GLE time profile in the frame of the construction of the SiGLE model [6]. In addition, with particle transport code, O'Brien and Sauer [8] have recently calculated world maps of dose rates at the time of the maximum of the GLE 42 (on 29 September 1989) and 24 hours later. Both calculations are for the same altitude of 10,668 m. At high northern latitudes they obtain a dose rate of 50 µSv/h at the time of the maximum and, 24h after the maximum, a much lower dose rate of 0.4 µSv/h (by a factor 1/125). According to GOES time profiles, the flux measured in the 110-500 MeV channel has only decreased by a factor four during the 24 hour period. For comparison, the GLE intensity measured with precision for example with Kerguelen neutron monitor [30] is 270.2 % at the time of the maximum (at 13:40 UT) and is 2.1 % 24 hours later ($1/128^{th}$ of the previous intensity).

During the GLE 59 (on 14 July 2000) the two dose measurements on board Air France Concorde (reported Table 1) are well fitted with the GLE time profile [6]. During GLE 60 (on 15 April 2001), on board the Czech Airline flight mentioned above, a comparison of dose rate time profile measurements with the intensity of cosmic rays measured with Oulu neutron monitor shows [13] a good agreement between both time profiles as well as with the time profile of HEPAD detector [31] on board GOES-8 satellite for protons with energy larger than 850 MeV. Compare to the simultaneous maximum at 14:30 UT, the dose rate to silicon time profile due to solar particles is divided by 2 at about 16:00 UT while the neutron monitor and the HEPAD time profiles are divided by 2 at about 15:45, i.e. only a quarter before. On the contrary, according to GOES time profiles [32], the integral flux of the solar protons with E > 100 MeV was divided by a factor of about 2 at about 18:00, i.e. 2 hours later.

For the same GLE, Iles et al. [33] reported an attempt to detect dose enhancement on board a Virgin Airways flight from London to Hong Kong. As the flight started at 21:00 UT on 14^{th} July, at a time were the GLE was already finished, above considerations explain the absence of detected dose enhancement. Indeed, according to [13] the dose rate due to solar particles becomes negligible, compared to galactic cosmic ray contribution, probably at about 18:00 UT, and certainly before 19:00 UT. Instead the authors suggest an explanation in terms of nightside/dayside difference. It should be clearly pointed out that owing to the complicated trajectory of charged particles in the terrestrial magnetic field (and eventually anisotropy of the particles), the solar particles are not arriving preferentially on the dayside. Figure 6 (right frame) gives a demonstration. Indeed at the time of the maximum of the GLE 42, 13:25 UT, Inuvik neutron monitor, located on the night side, measures GLE amplitude of 370 % of the galactic cosmic rays before the event, while Oulu neutron monitor, located on the dayside, measures only 167 % [11].

Previous discussion shows that GLE characteristics are most relevant for dose calculations during GLE. Thus neutron monitors are, like the high energy channels of satellite instruments a tool to calculate doses received on board airplane during a GLE. In addition the worldwide network of neutron monitors, unlike satellites, also give a clue on the distribution of particles (and corresponding doses) around the Earth. Indeed anisotropy of solar particles is responsible for large differences from place to place as illustrated for GLE 42 with the four neutron monitor output time profiles on the right frame of Figure 6.

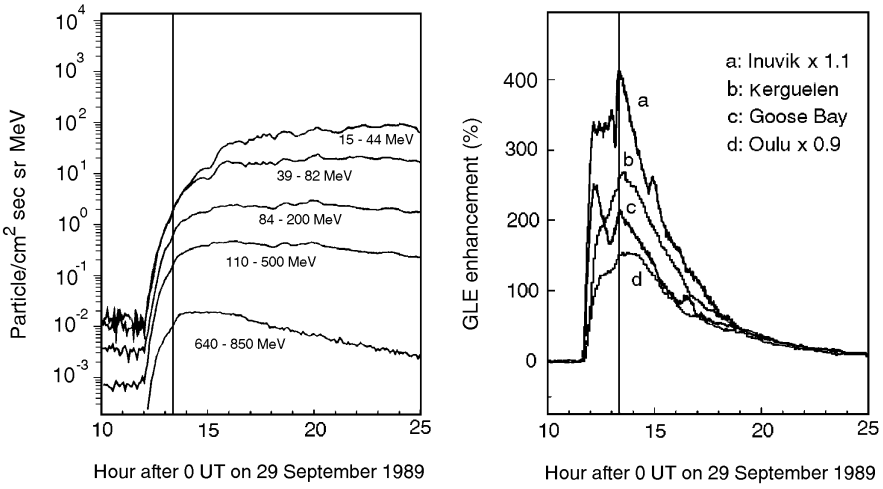

Figure 6 : Left frame: time profiles of different energy channels on board GOES satellite during SPE on 29 September 1989 (logarithmic scale). Right frame: time profiles of the GLE 42 observed with Inuvik, Kerguelen, Goose Bay and Oulu neutron monitors (linear scale) [6]. The vertical line corresponds to the maximum of the GLE intensity at 13:25 UT.

6. CONCLUSION

Because particle transport codes are too computer time consuming, a semi-empirical model, called SiGLE, has been developed to fulfil the requirements of the operational system SIEVERT. In absence of study of doses received on board airplane during the past solar flares with validated particle transport software, the semi-empirical model has also been used, on the basis of past observations of GLEs, to provide a coherent picture of doses potentially received on board airplane. Validation of particle transport codes as well as construction of semi-empirical models are difficult because of the very few measurements on board airplane presently available during solar flares. Nevertheless comparison between dose estimates during GLEs 05 (on 23 February 1956), 21 (on 30 March 1969) and 42 (on 29 September 1989) shows that the model SiGLE results agree, within a factor better than 2, with estimates deduced from measurements and with most estimates derived from particle transport code calculations. The study of effect of severe geomagnetic storms on dose rate received during solar flares shows that the increase is limited to 20 % on an exposed Paris-San Francisco flight during most GLEs, but it may be much larger for GLEs like the GLE 05. Owing to the rareness of GLEs (about one per year in average) and impossibility to predict them, campaigns of long duration measurements on board airplane with automatic dosimeters must be strongly encouraged, as the sole possibility to validate particle transport codes and to improve semi-empirical models.

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