Accepted for publication in Radiation Protection Dosimetry, April 2005

FORBUSH DECREASE EFFECTS ON RADIATION DOSE RECEIVED ON-BOARD AIRPLANE

P. Lantos, Observatoire de Paris

Abstract

Doses received on-board aeroplane during deep Forbush decreases have been recently measured and published. Using operational model of dose calculation, the effects on aviation dose of the Forbush decreases observed from 1981 to 2003 with neutron monitors are studied and a simplified method to estimate dose variations from galactic cosmic ray variations during Forbush decreases is derived.

1- Introduction

Two sources of particles affect the dose received on-board aeroplane. Solar and galactic primary particles with energies in the GeV range give rise to secondary particle cascades that in turn irradiate at the aviation and at the ground level. Secondary particles are monitored by an international network of ground based neutron monitors (NM). About fifty NMs are in operation around the world. Galactic cosmic ray (GCR) are permanent source of irradiation (Reitz, 1993). Long term modulation of galactic cosmic ray intensity is observed in conjunction with the solar activity cycle. Short term decreases are also observed. They are called “Forbush decreases” (FD) after Dr Scott E. Forbush who discovered them (Forbush, 1937). A detailed analysis of FD has been published, for example, in Hofer and Flueckiger, 2000. Solar particle events are sporadic and those for which particles have sufficiently high energy to affect aviation are quite rare. Indeed only 64 so-called Ground Level Enhancements (GLEs) have been observed with neutron monitors in the last fifty years and most of them were too faint to correspond to significant modification of the doses received on-board aeroplane. Nevertheless some exceptional GLEs could enhance the dose by a large factor (Armstrong et al., 1969, Lantos and Fuller, 2003).

The Forbush decreases are related to the transit of interplanetary shock waves coming from the Sun. The shock wave is travelling in the interplanetary space with a coronal mass ejection, initialised by large scale restructuration of the coronal magnetic field of the Sun (Ondoh and Marubashi, 2001). If the shock wave starts at about the same time as a solar flare, it will be observed one day or two days after the flare because the shock velocity is much slower than the light velocity. The Forbush decreases are typically only 1-5 % in amplitude (Haymes, 1971). Those are quite frequent. The present paper systematically considers deeper Forbush decreases, with GCR decrease larger than 5 %, observed with neutron monitors from 1981 to 2003 to study their effects on dose received on-board aeroplane and to provide an easy first approximation estimation of the variation of effective dose on-board aeroplane during FDs.

Software to calculate doses received on-board aeroplane from galactic cosmic rays in function of the solar cycle is available for operational purpose, like CARI-6 software (Freidberg et al., 1999) developed by the US Federal Aviation Administration or EPCARD (Schraube et al., 1999) developed on behalf of the European Commission. In both cases dose rate is calculated for each location, given by geographic latitude and longitude, and altitude. CARI software is based on particle transport code LUIN (O’Brien, 1976). CARI 6 range in altitude goes from 0 to 18 290 m (60 000 feet). The solar modulation of galactic cosmic ray intensity, owing to interplanetary magnetic field is an important factor, the spectrum of the primary particles varying strongly with solar activity. As a parameter of primary particle spectrum, CARI uses a modulation parameter called heliocentric potential [(10)] and expressed in megavolts. The easiest determination of modulation parameters is with neutron monitor observations. The result of CARI software is in terms of effective dose that is the result of the weighting of the absorbed dose (physical quantity expressed in Gray) by factors to take into account effectiveness of the different types of radiation, as well as radiosensitivity of the organs and tissues [(11)]. Effective doses are expressed in Sievert unit.

EPCARD is based on Monte Carlo calculations and could be applied to any route between 5 and 25 km in altitude. The solar modulation is taken into account thanks to a modulation parameter called solar deceleration potential (Badhwar et al., 1996), which differs from above mentioned heliocentric potential by a few hundreds of megavolts. The solar deceleration potential is deduced from Climax, Colorado, neutron monitor measurements. In addition to effective doses, EPCARD software calculates also ambient dose equivalents (operational quantities of interest to calibrate dosimeters). Dose equivalents and ambient dose equivalents are also expressed in Sievert unit, but they are operational quantities, different in nature from effective doses. So-called "quality factors", different from weighting factors mentioned above, are applied to absorbed dose to take into account the relative effectiveness of the different particle fields (Bartlett, 1999)

2- Assessment of dose calculation during Forbush decreases

Specific events like Forbush decreases could have particle spectra different (Hofer and Flueckiger, 2000) from the spectrum of the undisturbed galactic cosmic rays, whose modulation is characterised by the above mentioned potentials. Indeed time scales are different and the cycle solar modulation is not uniquely owing to successive Forbush decreases. Thus the use of the heliocentric potential together with CARI-6 software must be assessed for Forbush decreases.

Measurements of doses on-board aeroplane during deep Forbush decreases are presently quite limited. Some dose equivalent measurements during FD have been obtained on-board Virgin Airways flights during the FD of 14-17 July 2000 (Bentley et al., 2002). On 16/07 a London-Los Angeles flight received a dose equivalent of 40 µSv. The day after, a Los-Angeles-London flight received a dose equivalent of 37 µSv and a subsonic London-New York flight a dose equivalent of 26 µSv. The daily average of effective doses calculated with CARI 6 software for similar routes are respectively 45 µSv on 16/07, 41 µSv and 29 µSv on 17/07. Thus our calculations, although based on slightly different flight plans, are in agreement within 10 % with the above measurements. A second comparison is possible with ambient dose equivalent measurements performed, during Forbush decreases, on-board subsonic flights from Prague to New York on 12 April 2001 and from Sofia to Prague on 29 October 2003 (Spurny et al., 2004). Compared to calculations with EPCARD software *not* taking FD into account, the measurements on 12 April 2001 (Prague-New York) show decrease of -16 %, according to Spurny et al.. A calculation using CARI-6 and based on galactic cosmic ray intensity observed at the times of FD gives relative differences with the dose two days before, of -15 % with a Prague to New York flight plan.

More critical is the comparison of the deeper Forbush decrease observed on 29 October 2003. The very low level of cosmic rays during this Forbush decrease is modelled with a high heliocentric potential. Indeed the heliocentric potential is found to be larger, from 13 to 18 UT, than the upper limit specified by authors of the CARI-6 software (potential of 2000 MV). Between 14 and 15 UT on 29 October 2003 the average heliocentric potential is 2240 MV.
Nevertheless the comparison with observation remains quite favourable. On the one hand,

during the hour with the lowest cosmic ray intensity, a calculation still using CARI-6, but with an extrapolation (with a third degree polynome) of the relationship between heliocentric

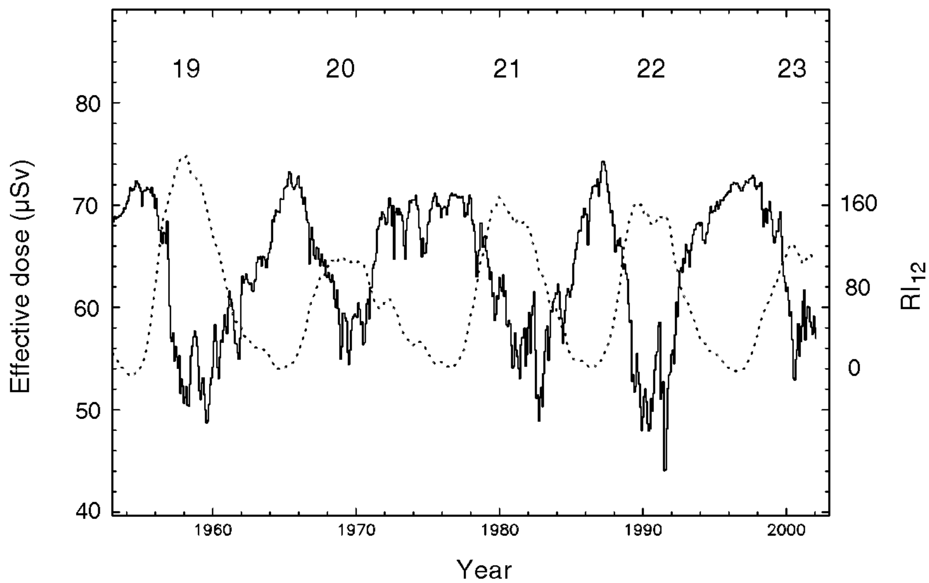

Figure 1: Dose received on-board a ParSF flight from 1957 to 2002 as calculated with CARI-6 software from data obtained with Kerguelen (1958-1961 and 1964-2002) and Climax neutron monitors. Dotted line shows solar cycles with smoothed sunspot numbers RI_{12} (scale on the right side).

potential and corresponding effective dose gives a relative difference with the dose two days before of -30 % with Terre Adélie NM and –27 % with Kerguelen NM (Table 1). On the other hand, as calculated by Spurny et al. (2004) using EPCARD software *not* taking FD into account, the measurements on 29 October 2003 (on-board Sofia-Prague flight) show decreases of -26 %. Thus those preliminary comparisons show that calculation with CARI-6 software gives a reasonable estimate of the effective dose received during a Forbush decrease up to potentials of the order of 2250 MV.

For comparison with the dose decreases during FDs, Figure 1 shows the effect of solar cycle modulation on the effective dose received during a Paris-San Francisco flight on-board Airbus A 340. The Paris-San Francisco flight (abbreviation ParSF) is chosen here as the reference flight because its typical highly exposed route, of interest for a comparison with GLE effects. Dose calculations are based on monthly averages of cosmic ray intensity and are performed with CARI-6 software. The well-known anticorrelation of cosmic ray intensity (and thus of doses) with the sunspot number (dotted line) is shown. The relative variation between extreme values of dose since 1953, is 40 %. The variation during the present cycle 23 shows a difference of only 26 % between the minimum and maximum of the received effective doses on-board a Paris-San Francisco flight. Thus short term variations owing to deepest Forbush decreases could be of the same order as the variation owing to modulation by the present cycle.

3- The deepest Forbush decreases

The Forbush decrease of October-November 2003 is one of the deepest FDs observed since the important FD of August 1972 (Lantos et al., 2003). Figure 2a shows the time profile of the cosmic ray intensity observed with the monitor NM-64 of Dumont d'Urville in Terre Adélie. The lowest point is observed on 29 October 2003 at 15 h UT. Compared to undisturbed cosmic ray level measured two days before, the decrease is - 23 % in cosmic ray intensity. The lower part of the frame (Figure 2b) shows the time profile of the total dose received

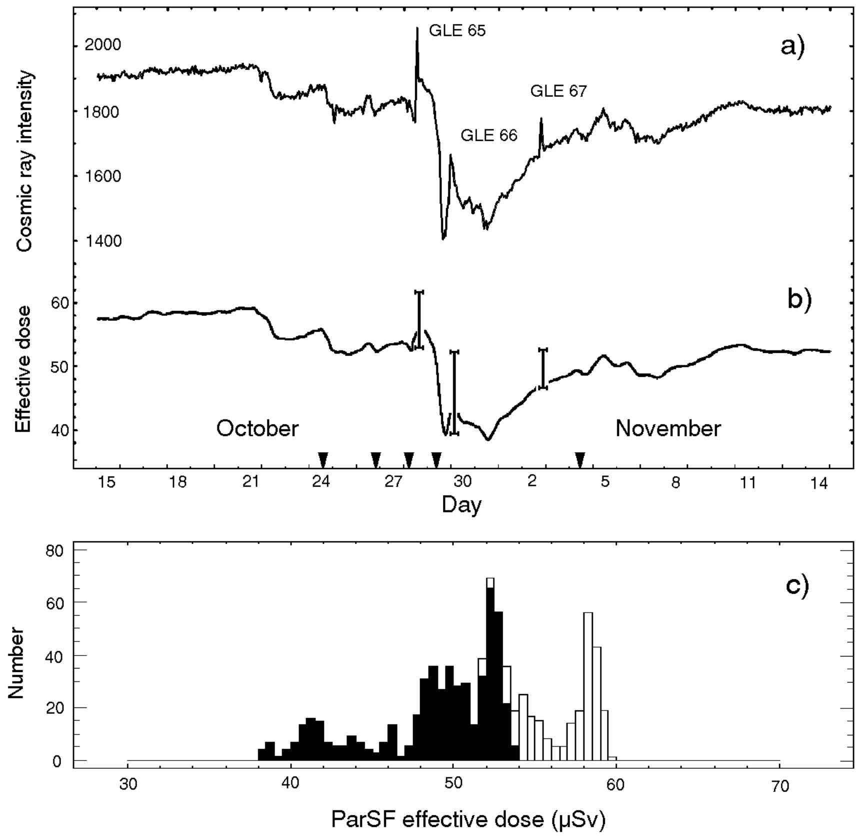

Figure 2a: Time profile of the cosmic ray intensity as measured with Terre Adélie neutron monitor from 15 October to 14 November 2003. Unit is in hourly counts divided by 200.
Figure 2b: Corresponding time profile of the effective dose for a flight from Paris to San Francisco. Unit is in µSv. The SSC are indicated with black triangles (IUGG 2003). For doses received during three GLEs, see text (section 5).
Figure 2c Histogram of the same effective doses. Bars associated to days before the Forbush decrease are left in white.

during flight from Paris to San Francisco. Compared to level two days before, the maximum variation in terms of effective dose is about - 30 %. Note that ten days are necessary to recover the level before the FD. According to Air France flight plan, the flight duration is about 11 ½ hours. Thus the dose time profile is smoothed compared to the cosmic ray time profile. At the same time as the Forbush decrease, the shock wave induces an abrupt variation of the Earth magnetic field called geomagnetic storm sudden commencement (SSC). The occurrences of SSC are indicated with black triangles along time axis of Figure 2b. The three GLEs occurring during this period will be discussed later (section 5). Note nevertheless that the additional dose owing to GLE 66 is amply counterbalanced by the simultaneous Forbush decrease. Figure 2c gives histogram of effective dose received from 15 October to 14 November 2003. The bars are open for the days before the Forbush decrease (i.e. before 29 October 2003). The rest of the month is shown in black. The bars in black below 46 µSv correspond to the deepest part of the FD, while the part in black but above 46 µSv is mostly owing to the recovery phase of the Forbush decrease.

When effective dose decreases on different routes are compared for the same FD, the relative variation is found to be similar. Thus using ten flight plans representative of the North hemisphere traffic, it is possible to deduce an average decrease which may be used with a good precision even if the detailed flight plan is not known. Flights used here are mainly flights between Paris, New York, San Francisco, Tokyo or Osaka. Bars in Figure 4, which are rms values deduced from statistics over the different flights, show that the dispersion is small.

Table I Characteristics of the deep Forbush decreases observed from 1981 to 2003

	Date of FD minimum	CR decrease Terre Ad. in %	Average decrease of dose in %	CR decrease Kergu. in %	Average decrease of dose in %	Tri hourly indices k_p	Hα flare index	X ray flare intens.
1	14 July 1982 *	-19.9	-25.6	-15.1	-20.0	9o	3B	X9
2	09 February 1986	- 9.6	-14.8	- 8.1	-12.7	9-	3B	X1
3	13 March 1989	-12.9	-17.5	-15.0	-20.8	9o	3B	X15
4	21 October 1989	-14.5	-17.8	-13.0	-17.0	8+	4B	X13
5	29 November 1989	-15.3	-18.9	- 9.4	-12.8	4o	2N	X1
6	24 March 1991 *	-19.0	-24.1	-16.2	-21.6	9-	3B	X9
7	28 October 1991	-15.1	-19.0	-17.7	-23.8	8+	3B	X6
8	15 July 2000	-12.5	-15.9	-13.2	-18.0	9o	3B	X6
9	12 April 2001	no data	no data	-10.1	-14.2	6+	3B	X2
10	06 November 2001	- 9.6	-14.0	- 9.4	-14.5	9-	3B	X1
11	29 October 2003 *	-23.1	-30.1	-20.1	-27.4	9o	4B	X17

Note * : Forbush decreases with corresponding heliocentric potential partly above 2000 MV (see text).

Table I gives the characteristics of the deep Forbush decreases observed from 1981 to 2003 as deduced from Terre Adélie NM and Kerguelen NM measurements. The maximum decreases are defined with hourly values with respect to the daily average level of cosmic rays two days before (except for FDs numbered 2, 4 and 8 for which the reference is 3 days before). Cosmic ray (CR) decreases in % and corresponding average decreases for the different routes mentioned above are given columns 3 and 4 for Terre Adélie NM and columns 5 and 6 for Kerguelen NM. As we are considering decreases, the denominator is the higher intensity or dose. As mentioned in section 2 the effective dose minimum of the FDs with corresponding heliocentric potential above 2000 MV (indicated with an asterisk) is presumably less precise because of extrapolation needed. The comparison of the effective dose decrease obtained independently with Terre Adélie and with Kerguelen neutron monitors gives information on the expected uncertainties owing to the use of different low rigidity neutron monitors. Terre Adélie and Kerguelen NMs have a vertical cut-off rigidity of 0.0 GV and 1.14 GV respectively, according to Shea and Smart (2001) calculations for year 1995. When both sets of results are considered globally, they are found in agreement: the mean difference on the average decreases is 0.70 % and the distribution rms is 3.4 %.

During Forbush decreases, intense geomagnetic storms with sudden commencement (SSC), also associated to interplanetary shock waves, can occur. The maximum logarithmic planetary index k_p on the day of the FD minimum is reported (Table I column 7). In the case of the deep FDs, the geomagnetic storm can be extremely severe. Indeed the maximum possible k_p index of 9 is reached during more than half of the events given here. Geomagnetic data are taken from IAGA Bulletin (1990, 1992, 1996, 1998) and IUGG-ISGI Bulletin (2000-2003). In the contrary to the case of solar particle during GLEs (Lantos and Fuller, 2004), the high geomagnetic activity is not expected to affect the dose received during FD. Indeed the rigidities are changed, but the North-South coefficient on dose rate is much less dependent upon latitudes for galactic cosmic rays than for solar particles (see Figure 2 in Lantos and Fuller, 2004).

Important Forbush decreases and corresponding geomagnetic storms are not isolated. The deepest FDs occur frequently one or two days after very bright solar flares as reported in Table I. Columns 8 and 9 give information on the importance of the electromagnetic emissions of the flares, in the H_α optical line and in the X-ray (see note and Space Environment Center web site). Those flares are among the most important ever observed. High energy particles are also frequently present, as observed from satellites. In the proton GeV range, GLEs have been observed with neutron monitors in conjunction with Forbush decreases number 4, 8, 10 and 11 of Table 1. Some will be discussed in terms of dose enhancement in section 5.

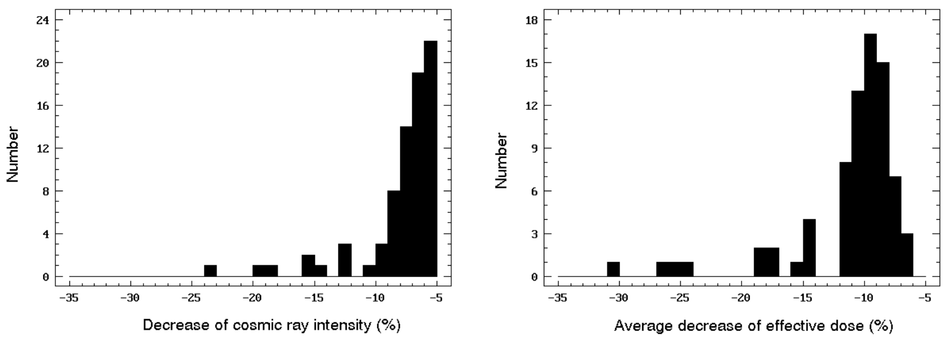

Figure 3: Histogram of FD decreases in cosmic ray intensity (left side) and histogram of average decrease in effective dose (right side). Both decreases are expressed in percent.

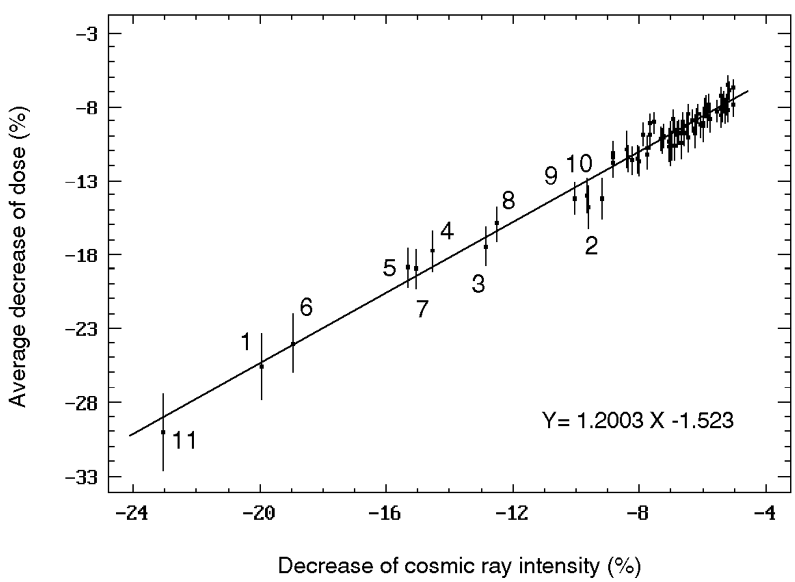

Figure 4: Effective dose decrease averaged on different flights in function of the cosmic ray intensity decrease for Forbush decreases deeper than 5 %. The data from 1981 to 2003 included are obtained with Terre Adélie neutron monitor. Numbers refer to the Forbush decrease numbers given Table I. Bars are rms differences between ten routes.

4- Systematic analysis of Forbush decrease occurrence

A search for Forbush decreases with cosmic ray intensity decrease larger than 5% has been performed, using observations obtained with the Terre Adélie neutron monitor, in order to analyse systematically the effect of FDs on the effective dose. From 1981 to 2003 included, 76 FDs comply with this criterion. The effective dose received on each of the ten routes mentioned above has been calculated and we consider here the relative variation averaged over the different flights. Figure 3 shows the histogram of the decrease in terms of galactic cosmic ray intensity, compared to the histogram of the corresponding dose average decrease.

When the time distribution of the FDs is considered, the events appear much more frequent when the sunspot number is above half cycle amplitude. For cycle 22, 25 Fds deeper than 5 % are found during this period. During cycle 23 the number is 24. This frequency has to be compared with the periods during which sunspot number is below half cycle amplitude: only 4 FDs are found during the solar minimum between cycles 22 and 23. Nevertheless large solar flares and deep FDs also occur exceptionally during solar cycle quietest periods (like FD in 2003, numbered 11) or even during solar cycle minimum (like FD in 1986, numbered 2).

For the same sample of FDs, Figure 4 shows the relationship between decreases in terms of cosmic ray intensity (horizontal axis) and effective dose decreases averaged over ten different routes (vertical axis). The bars give the rms values, confirming the similarity of the relative effective dose decrease on the different routes mentioned section 3. For the deepest FDs, labels give the reference of the FDs in Table 1. The linearity of the relationship leads to a first approximation dose variation estimate. The effective dose decrease is found to be about 1.2 times larger than the cosmic ray decrease. In the contrary to GLEs intensity, which varies strongly with geomagnetic cut-off rigidity of the neutron monitor in use, the decreases related to Forbush decreases and thus linear relation discussed above is expected to be less dependent upon low rigidity monitor characteristics.

5- Comparison of doses received from GLEs with decreases owing to FDs

Let us consider Figure 2 again. In addition to the galactic cosmic ray variations, three GLEs have been observed during the period from 15 October to 14 November 2003. They are numbered 65 to 67 in the international list of GLEs. As measured with Terre Adélie neutron monitor, the amplitude of the three GLEs, compared to level of GCR before the event is respectively 26.8, 13.7 and 14.2 %. Because of the important difference of particle spectrum between solar particle events and galactic cosmic rays, the doses received from the former cannot be calculated with software like CARI-6. In Figure 2b the bars give the maximum dose received from the GLEs during a ParSF flights, as calculated with the semi-empirical model called SiGLE (Lantos and Fuller, 2003). The results are provisional because the characteristics of the primary particle spectrum have not been presently calculated for the three GLEs of 2003. An average spectrum with a rigidity spectrum exponent γ = - 4.7 is assumed. Despite this limitation, Figure 2b shows that when GLEs of about 30 % or less are taken into account, short term variations related to Forbush decreases, if any, must also be considered in the dose calculations.

Another example is with the GLE 59 observed on 14 July 2000 (the so-called Bastille Day Flare). Figure 5 shows the effective dose received on-board ParSF flight calculated during the whole month of July 2000 and based on Kerguelen measurements. The average effective dose during the first ten days of the month, i.e. before the Forbush decreases, is 58 µSv (horizontal line), while the minimum, occurring on 15 July, is 44 µSv. The decrease in terms of dose is thus 24.1 %. The overall decrease is the result of successive FDs. The corresponding SSC are indicated with black triangles along time axis. The amplitude of GLE 59, compared to GCR is 30.8 %. The dose received during GLE, as calculated with the SiGLE semi-empirical model mentioned above. The maximum dose received from the GLE solar particles is 73 µSv, including galactic cosmic ray contribution (Lantos and Fuller, 2004) This corresponds to a maximum enhancement of 54 % of the dose received on-board ParSF flight, compared to effective dose received from GCR component. Here again the variations of dose owing to fine structures of Forbush decreases must be taken into account when precise effective dose determination is requested, for example when calculation is compared to dosimetric

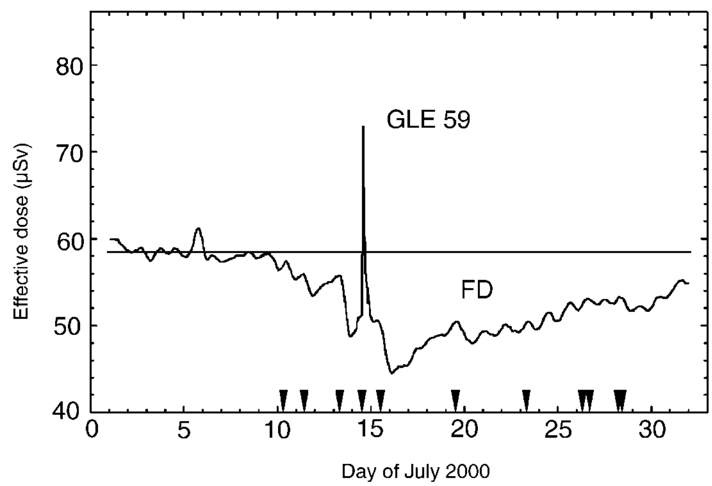

Figure 5: Effective dose received during July 2000 on-board ParSF flight as calculated with CARI-6 software from Kerguelen measurements. The doses corresponding to GLE 59 have been calculated with the SiGLE model. Storm Sudden Commencements (SSCs) are indicated with black triangles (IUGG,2000).

measurements. The situation is obviously different when larger GLEs are considered: FD variations (and even in some cases, GCR contribution to dose) could become negligible.

For the same GLE amplitude measured with neutron monitors, the dose received on-board aeroplane could be very different because rigidity spectrum exponent as well as duration of the GLE are important parameters for the dose calculation. Obviously the doses also strongly vary with the time of departure of the flight because the time profiles of the GLEs are frequently quite steep. In addition it has been shown (Lantos and Fuller, 2004) that the dose received from GLE is more variable with the detailed flight plan than the effective dose received from galactic cosmic rays. Indeed variations of dose rate with altitude as well as with geomagnetic latitude are stronger. Calculations of dose decreases during Forbush decreases are much simpler than for GLEs, because standard software like CARI-6 or even linear relation could be used and because relative effective dose decrease is almost the same for the different routes, as illustrated by Figure 4.

6- Conclusion

The few available measurements of dose equivalents operated during important Forbush decreases are found in reasonable agreement with CARI-6 calculations. For the last measure by Spurny et al. in October 2003, which has been performed during the deepest FD observed since 1981, the heliospheric potential is outside the range of the CARI-6 calculation, but the result of an extrapolation is in agreement with observations. Thus possible effects of the deep Forbush decreases on the effective dose received on-board aeroplanes could be easily analysed.

Deep FDs are rare: only eight are found from 1981 to 2003 when the criterion of dose decrease larger than 15 % is applied. They are frequently associated with very high geomagnetic activity and are often following very bright solar flares. The distribution of FDs with decrease larger than 5 % in terms of cosmic ray intensity has been systematically searched from 1981 to 2003. Such FDs are mostly present during periods of solar cycle with sunspot index above half cycle amplitude. Calculation for different flights representative of north hemisphere traffic shows that the variation of effective dose on-board aeroplane is almost the same for a given Forbush decrease. Thus an average variation could be used instead of calculations based on detailed flight plans. A linear relationship is found between variation of cosmic ray intensity and average variation of effective dose on-board aeroplane and this provides an easy first approximation estimate of the later. Nevertheless specific calculation with precise flight plan and detailed cosmic ray time profile remains necessary when the best precision is required.

Compared to GLEs that can exceptionally enhance by hundreds of microsieverts the dose received on-board aeroplane on exposed routes like ParSF (Lantos and Fuller, 2003, 2004), the effect of FDs on the dose is much more limited. For the period from 1981 to 2003, the maximum dose decrease is found to be limited to about 30 %. In the frame of aircrew radiation exposure assessment, like the French system SIEVERT (Bottollier et al., 2000), which considers the doses received on a monthly basis, it is not necessary to calculate effects of individual FD, as it is performed for the largest GLEs. It should be noted, in addition, that because they are lowering the doses, Forbush decreases are playing in a favourable direction for aircrew protection purposes. Nevertheless, for a precise estimate of the effective dose on-board a given flight, Forbush decreases must be taken into account as shown by the few measurements already available and by the calculations presented here. Indeed the variation owing to Forbush decrease could be, within a few hours, of the same amplitude as variation observed during the whole solar cycle 23.

Finally one should note the importance of further dosimetric measurements on-board aeroplane to collect more information on the dose equivalent received during deep Forbush decreases as well as during GLEs. In both cases one can expect from the systematic measurements now in operation or in project, in Europe for example, much more experimental results than the few presently available.

Note : Brightness and area of optical flares observed in Hα hydrogen line are given by the standard classification used by solar physicists: « B » is for bright, importance 3 is for area between 12.5 and 24.7 square degrees and importance 4 is for area above 24.7 square degrees. « N » is for normal brightness and importance 2 is for area below 12.5 square degrees. For X ray flares emission indices: **Xα** means X-ray flux maximum is, as measured in the 0.1-0.8 nm range, of $\boldsymbol{\alpha\ 10^{-4}\ W\cdot m^{-2}}$. For example index X15 means flux maximum of 1.5 10^{-3} $W\cdot m^{-2}$.

Acknowledgements

The author would like to thank Pr. E. Flueckiger, University of Bern, Switzerland, for friendly discussions on the physics of Forbush decreases.

The Kerguelen and Terre Adélie neutron monitors are operated by French Polar Institut (IPEV), Brest, under scientific responsibility of LESIA department of Paris Observatory.

References

Armstrong T.W., Alsmiller R.G., Barish J. Calculation of the radiation hazard at supersonic aircraft altitudes produced by an energetic solar flare. Nucl. Sci. Eng. 1969; 37:337-342.

Badhwar G.D.and O'Neill P.M.: ,1996, Galactic cosmic radiation model and its applications, *Adv. Space Research*, **17**, (2)7-(2)17.

Bartlett D.T. Radiation protection concepts and quantities for the occupational exposure to cosmic radiation. Radiat. Prot. Dosim. 1999; 86:263-268.

Bentley R.D. et al., *Monitoring Cosmic Radiation On Aircraft*, in Proc. SOLSPA 2001, September 2001, ESA-SP477, pp 535-538, (2002).

Bottollier-Depois, J.-F. *et al.* Assessing exposure to cosmic radiation during long-haul flights. *Radiat. Res.*, 153 , pp.526-532, 2000.

Forbush, S.E. *On the Effects in Cosmic Ray Intensity Observed During the Recent Magnetic Storm*. Phys. Rev., **51,** 1108-1109, 1937.

Freidberg W. et al., *Guidelines and Technical Information Provided by the US FAA to Promote Radiation Safety for Air Carrier Crew Members*, Radiat. Prot. Dosim., **86**, pp. 323-327, 1999.

Haymes R.C., *Introduction to Space Science*, John Wiley and Sons, Inc., p. 393, 1971.

Hofer M.Y. and Flueckiger E.O., *Cosmic ray spectral variations and anisotropy near Earth during March 24, 1991, Forbush decrease*, J. Geophys. Res., **105**, 23,085-23,097, 2000.

IAGA Bulletin, 1990, *Geomagnetic Data 1985* (and SSC 1982-1985), N°32 p, ISGI Publication Office, St Maur des Fossés, France, p. 136.

IAGA Bulletin, 1992, *Geomagnetic Data 1986*, N°32 q, ISGI Publication Office, St Maur des Fossés, France, p 143.

IAGA Bulletin, 1996, *Geomagnetic Data 1989*, N°32 t, ISGI Publication Office, St Maur des Fossés, France, p. 123.

IAGA Bulletin, 1998, *Geomagnetic Data 1991*, N°32 v, ISGI Publication Office, St Maur des Fossés, France, p; 143.

IUGG-ISGI Bulletin from GeoForschungsZentrum Potsdam, Germany, monthly, 2000-2003.

Lantos P., Fuller N. and Bottollier-Depois J.-F., *Methods for Estimation of Radiation Doses Received by Crews of Commercial Aircraft*, Aviation, Space and Environmental Medecine, **74**, n°7, 746-752, 2003.

Lantos P. and Fuller N., *History of the solar flare radiation doses on-board aeroplanes using semi-empirical model and Concorde measurements*, Radiat. Prot. Dosim., **104**, n°3, pp. 199-210, 2003.

Lantos P. and Fuller N.,*Semi-empirical model to calculate potential radiation exposure on board airplane during solar particle events*, IEEE Proceedings on Plasma Science, vol **32,** issue 4, 1468-1477, 2004.

O'Brien K., *Cosmic ray propagation in the atmosphere*, Nuovo Cimento, **A3**, 52-78, 1971

Ondoh T. and Marubashi K.,edts, Science of Space Environment. (Tokyo: Ohmsha Ltd) (2001) ISBN 4-274-90384-2.

Reitz G. *Radiation environment in the stratosphere*. Radiat. Prot. Dosim; **48**, 5-20, 1993.

Schraube H. *et al.*, *Experimental Verification and Calculation of Aviation Route Doses* Radiat. Prot. Dosim., **86**, 309-315, 1999.

Shea M.A. and Smart, D.F., *Vertical cutoff rigidities for cosmic ray stations since 1995.* Proc. 27th Int. Cosmic Ray Conf, Hamburg SH 4063-4066, 2001.

Spurny F., Kudela K. and Dachev T., *Airplane radiation dose decrease during a strong Forbush decrease*, Space Weather, **2**, S05001, 2004.

Space Environment Center site : *Solar Proton Events Affecting the Earth Environment.* http://www.sec.noaa.gov/alerts/SPE.html.