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Monitoring radiation doses received by air crews

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Abstract : Doses received on board airplanes are monitored in Europe to protect air crews. The French Aviation Authorities have developed a system, called SIEVERT, using effective dose calculation codes. We present here the solution retained in the frame of this system to calculate galactic cosmic ray and solar GLE intensities and corresponding doses using neutron monitor observations.

1. Introduction

Since May 2000, Air Transport Companies in Europe have the legal obligation, according to the EU Directive 96/29/Euratom (CEC, 1996), to monitor radiation doses received by each air crew member. The effective dose should not be higher than 100 millisieverts over 5 years with a maximum of 50 millisieverts for a given year. Specific rules will be applied to pregnant air crew members.

The radiation doses received at aircraft altitudes come from two sources of particles. On one hand the galactic cosmic rays and on the other hand the particles accelerated during solar flares when their energy is sufficient to give secondary particles down to aircraft altitudes. The radiation environment in the stratosphere was described for example by Reitz (1993) and the radiation concepts and quantities were recently reviewed by Barlett (1999). The radiation weighting factors presently in use for the different particle species are those recommended by ICRP Publication 60 (1991).

The SIEVERT system (Système d'Information et d'Evaluation par Vol de l'Exposition au Rayonnement cosmique dans les Transports aériens) is developed on behalf of the French Aviation Administration (DGAC). The flight plan of each flight is sent by the companies and the server, operated on the behalf of DGAC, returns the effective dose for the flight, computed using a world 3-D cartography of effective dose rates. Then the companies attribute to the file of each crew member the calculated dose. Companies submit their files on a monthly basis (large companies operate a few tens of thousands of flights per month). In case of important GLEs, the calculation will be postponed until timedependent cartography becomes available for the GLE interval.

2. Calculation of effective dose from galactic cosmic rays

The dose received on board aircrafts results of interactions between particles and tissues. To compute the dose, it is necessary to know the spectra of the secondary particle species created in the atmosphere at the location of the aircraft. Longitude and latitude must be taken into account, in addition to altitude, because of the filtering of primary cosmic rays due to Earth magnetic field distribution. To take into account the cosmic ray modulation induced by solar activity, a further parameter, the heliospheric potential, is introduced. Such calculations could be done with particle transport codes like LUIN (O'Brien, 1978) or FLUKA (Schraube et al., 1999). Nevertheless transport codes themselves are computer time consuming and for operational purposes they have to be simplified as in CARI 6 software (Friedberg *et al.*, 1998), developed by the US Federal Aviation Administration. Another package, called EPCARD (Schraube et al., 1999) has been recently developed on the behalf of the European Commission. Both are limited to the galactic cosmic ray component.

For the SIEVERT application the heliocentric potential is obtained from measurements of French neutron monitors located at Port-aux-Français (Kerguelen Islands in Indian Ocean) and at Dumont d'Urville (Terre Adélie in Antarctica). Both monitors have a low geomagnetic cut-off rigidity (1.1 GV for Kerguelen and 0.0 GV for Terre Adélie). They are operated by IFRTP (Institut Français pour la Recherche et la Technologie Polaires). Data from the two monitors are received at Paris Observatory on a daily basis via satellite links. For the present application, the Terre Adélie monitor is considered as a back-up of Kerguelen. A quadratic fit of the past heliospheric potential values (from 1964 to 1997) given by the authors of the CARI software versus neutron monitor counts appears to be sufficient, giving correlation coefficient between heliocentric potential estimates and original values of 0.996 for Kerguelen and 0.993 for Terre Adélie, and rms relative errors of 2.5 % for Kerguelen and 3.6 % for Terre Adélie.

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Flight	Calculation (μSv)	Measure (μSv)	Difference
Paris-New York (Concorde)	32.4	34 ± 5	- 5 %
New York-Paris (Concorde)	31.1	30 ± 5	+ 4 %
Paris-San Francisco (A340)	71.9	72 ± 11	- 1 ‰
San Francisco-Paris (A340)	63.1	68 ±10	- 7 %
Paris-Tokyo (B747 Siberian route)	58.8	75 ± 11	- 22 %
Tokyo-Paris (B747 via Fairbanks)	63.3	74 ± 11	- 15 %
Paris-Washington (B747)	43.4	43 ± 7	- 1 %

Table 1.: Comparison of calculated and measured dose equivalents

3. Comparison of dose calculation with measurements

In the absence of solar flares, many measurements of ambient dose-equivalent have been obtained with different techniques by scientific laboratories in collaboration with airlines. We consider here recent measurements by IPSN (Institute for Protection and Nuclear Safety) in collaboration with Air France (see detailed analysis in Bottollier-Depois *et al.*, 2000). The measurement device is a tissue-equivalent proportional counter (TEPC), called NAUSICAA, developed in collaboration with CNES and used on board MIR station. It measures ambient dose-equivalent rate and quality factor with time resolution of a few minutes. The measurements were carried out both on board Concorde and on board subsonic planes (Airbus A340 and Boeing 747) on long haul routes. Table 1 summarizes measurement results and calculations using CARI 6 software and detailed flight plan of each flight. Flights between Paris and San Francisco were carried out in April 1996, Paris-New York and New York-Paris in August 1996, Paris-Tokyo and Tokyo-Paris in January 1997 and Paris-Washington in January 1998. All the flights correspond to a period of the minimum of the solar activity cycle and thus during the maximum of galactic cosmic rays.

Except for the Paris-Tokyo flight with presumably less precise measurements during part of the flight, the difference between calculations and measures remains within ± 15 %, which is close to estimated precision of the best ambient dose-equivalent measurements. The general tendency is an underestimation of the calculation compared with the measure by 4 % in average (not including Paris-Tokyo flight). Note that doses received on board transatlantic subsonic flights are larger than with Concorde, because of longer duration and that even during solar cycle minimum, a daily transatlantic subsonic flight will not be sufficient to reach the recommended limit of 20 mSV per year.

Compared with measurement, the computation allows estimates of the effective dose for past periods, if neutron monitor data are available. Figure 1 shows the estimated effective dose for flights between Paris and New-York on board Concorde from 1958 to 1999, based on Kerguelen monitor measurements. For the period from 1958 to 1962 Kerguelen observations, done with a IGY neutron monitor, have been globally adjusted using Climax monitor data (University of Chicago). The assumed flight plan is the actual plan of the flight Paris-New York of Table 1, in August 1996. Measurements of the 1996 flights are indicated with black points. The flight from Paris to New-York is labelled 1 and the flight from New-York to Paris is labelled 2. The difference between the two flights (of about 13 %) is due to the difference between flight plans, as both flights have been operated on two consecutive days. Calculations for both flights are given with open circles. The flight labelled 3 is a journey from Paris to New-York on 8 June 1992, closer to solar cycle maximum (Bottollier-Depois et al., 2000). The good agreement between measurements and calculations shows that the latter are an effective alternative to inflight monitoring.

4. Requirements of galactic cosmic ray dose calculation

For operational purpose it is important to decide at what rate the neutron monitor data must be refreshed for dose calculations. Daily, monthly or yearly values could be considered. From an operational point of view, yearly values prevent from following the evolution of received doses before the end of the year. In addition, because large companies are operating hundreds of thousands of flights per year, calculations per month appears much easier. The question is thus to know the precision obtained on the calculated effective dose using monthly average of the neutron monitor observations. During solar cycle minimum, for a flight from Paris to San Francisco (for example in January 1997), the relative difference between effective dose computed with monitor monthly average and hourly values remains lower than 5 %. During the solar cycle maximum, the interplanetary magnetic field, and thus the cosmic ray time profile observed at the Earth, are much more disturbed than during solar cycle minimum. As an extreme example, the period labelled A in Figure 1 corresponds to a drop of the effective dose for Paris-New York flight by 27 % within only 4 months (from February to June 1991). This period is known to be exceptionally disturbed (Shea et al., 1993). Extreme differences between monthly average and hourly values of calculated effective doses remain nevertheless lower than 15 %. Finally the same test extended over 12 years (period from January 1980 to December 1991 including two solar cycle maxima) indicates that relative differences on effective doses computed with monitor monthly average and hourly values very rarely exceed 20 %.

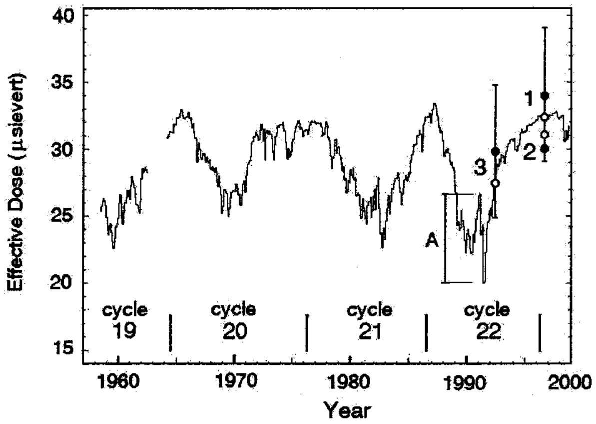

Figure 1.: Calculated effective dose for Paris-New York flight on board Concorde from 1958 to 1999. Solar cycle number is indicated at the bottom of the figure. For comparison measures during flights of Table 1 (Paris-New York labelled 1 and New York-Paris labelled 2) and during a Paris-New York flight in 1992, labelled 3, are indicated with black dots. Estimated errors for Flights 1 and 3 are given. Calculations for the three flights are indicated with open circles. A period, in 1991, during which important variations of cosmic ray intensity were observed, is labelled A.

Extreme variations are due to two different kinds of events. On one hand they could originate from the Forbush Decreases, which are related to interplanetary shock waves. On the other hand large variations could be related to GLE's (Ground Level Enhancements), when accelerated protons are energetic enough to give secondary particles detectable by ground based neutron monitors. Discussion of such exceptional events will be the subject of section 5.

To fulfil their legal requirements, some companies have proposed to use a database with airport-to-airport average doses, updated for example each year to take solar cycle into account. Nevertheless, routes and altitude profiles may differ appreciably for the same journey because of meteorological conditions and/or commercial and operational reasons. As an example calculation of effective doses for two flights between Paris and Osaka could be compared. We used actual flight plans of Air France Airbus A-340 on October 2000. The first flight from Paris to Osaka followed the south siberian route via Bejing and Seoul. The upper latitude of the flight is 61.7 ° North (at 57° East). The calculated effective dose with CARI 6 software is 47 μSv. The second flight from Osaka to Paris followed the northern siberian route with an upper latitude of 68.5° North (at 68° East). The calculated effective dose in this case is 62 μSv. Thus, as mentioned above, the SIEVERT system is using the reported flight plans, in order to obtain calculated doses as close as possible to the actual values.

It is also of interest to analyze possible effect of variation of atmospheric pressure on dose calculations. As an atmospheric pressure variation is equivalent to a change of altitude, it is possible to use CARI 6 (assuming standard pressure) for the calculation. For an altitude of 9.5 km (31,000 feet) at geographic co-ordinates 49° N and 3° E, low pressures (975 hPa) correspond to effective dose rate of 3.41 μSv/h and high pressures (1035 hPa) to 3.14 μSv/h. The dose rate is 8.8 % higher than for standard pressure (1013.25 hPa) for low pressures and 4.4 % lower for high pressures. For higher flight altitude (11.6 km; 38,000 feet) the effect decreases respectively to +5.2 % and -2.5 %. Nevertheless as a plane encounters both high and low pressures during a long-haul flight, the total difference is negligible. For example a calculation based on the actual meteorological map for the flight Paris-Washington of Table 1, shows that the difference on the effective dose, compared with calculation assuming standard pressure, is only 0.3 %. Thus it is not necessary to take into account the meteorological situation to compute effective doses.

5. Exceptional events

Let us recall that the Forbush Decrease of 4-5 August 1972 has been one of the deepest ever observed, showing a rapid decrease of the galactic cosmic ray intensity by 20-25 %, followed by a slow recovery phase of about a week duration. With Terre Adélie neutron monitor data, calculations with CARI6 software for a Paris-New York flight with Concorde, show that the dose during this Forbush Decrease has been lowered, compared with the monthly mean, by as much as about 27 % (a deficit of 8.3 μSv) for a specific time of flight. For a Paris to San Francisco flight, the dose is lowered by 28.6 % (a deficit of 17.4 μSv). Nevertheless because such Forbush Decreases are exceptional and because the dose deficit remains smaller than 20 μSV, it appears that a specific operational procedure to take into account FDs is not necessary.

The situation is different for solar flares which could represents much higher dose changes. To take into account the effective dose received for a given flight, time dependent cartographies will be used. A semi-empirical model based on particle transport calculations for GLE 42 (Sauer and O'Brien, 1991, O'Brien et al., 1996, Beck et al., 1999) and measurements on board Concorde has been developed for this purpose (Lantos and Fuller, 2001). This model shows that GLE with intensity lower than 20 % of the cosmic ray level before the event have not to be taken into account, owing to the precision required on dose calculations. Over the sixty GLEs observed since 1942 (see for example Shea and Smart, 1993), only sixteen are above the limit. A limitation of this model is the assumption of a standard particle spectrum and the neglected anisotropy of solar particles. Those approximations are sufficient for most of the GLEs, but for events larger than GLE 42 (29 September 1989), with a relative enhancement of 300%, they could not been used anymore. Let us recalled that the worse case, observed on 23 February 1956 with an increase of about 9000 %

(Duggal, 1979) above the galactic cosmic ray level, could have given, within one hour, a significant fraction of the recommended yearly dose at the supersonic level according to Armstrong and Alsmiller (1969) calculations. In the SIEVERT system, in case of a very large GLE the dosimeters analysed in principle each month, will be immediately picked up. The delay of analysis of dosimeters will be a few weeks. Such large GLE will give signal well over the dose due to galactic cosmic rays during past days.

6. Discussion

Three methods are available to monitor radiations aboard aircraft routinely. The first requires dosimeters, as done on board Concorde planes (Davies, 1993), where the data are collected after each flight. Nevertheless subsonic planes are not presently equiped with such devices and their cost would be important. Individual dosimeters could also be used, but this method is not fully reliable because badges could be forgotten or, inversely, left in the luggage receiving X-ray detector radiations. In addition this method implies using an expensive logistic for the large companies having tens of thousands of crew members. Thus a third method, based on calculation of dose has been retained by European working groups to fulfil the new legal requirement. As shown above the accuracy of calculation is sufficient for the present purpose. In addition models have the advantage to permit evaluations of doses received in the past as well as dose prediction for a given route. Calculations provided by the SIEVERT system for dose evaluation will be also open to public thanks to a Web site. This would have been impossible with individual dosimeters. Compare with other solutions, the system offers lower cost which is an important criterion for operational applications as well as full tractability, which is important for the legal aspect of the dose evaluation. Calculations provided by Air Transport Authorities have in addition the advantage to place all companies as equals.

7. Conclusion

The SIEVERT system appears to be a good example of Space Weather application. Starting with particle transport code and simplified operational software, it could take into account all the situations actually encountered in present and predictable future (i.e. frequent supersonic) flights. It could evolve with improvements of effective dose software, ICRP recommendations and legal requirements. Computations could be redone for past flights in those cases. Continuous validation with state-of-the-art measurements is part of the system. In addition to routine measurements aboard Concorde, more precise measurement campaigns with active devices will be operated on a regular basis to validate the SIEVERT system so that corrections could be done. Passive dosimeters are also routinely transported on board number of planes and are analyzed, on a monthly basis. For calculations, necessary inputs are space environment data from well-established, ubiquitous and stable devices, the ground-based neutron monitors. Finaly let us remark that involvement of neutron monitors in operational applications will facilitate long term operation of neutron monitors for the benefit of the international network community.

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