A SIMPLE MODEL TO ESTIMATE RADIATION DOSES TO AIRCREW DURING AIR FLIGHTS IN BRAZIL AND ABROAD

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Key words: Air flights, cosmic radiation, mathematica, radiation dose, crewmembers.

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Abstract

The objective of this article is to present the results obtained from the development of a simple model used to estimate cosmic radiation doses from crewmembers taking into consideration the variation of the dose rates with the altitude and the latitude, airplane cruise velocity and other important parameters such as, cruise height, takeoff time, landing time, takeoff angle, landing angle. The model was incorporated into a Brazilian computer program developed using the “mathematica” symbolic software.

The data used to calculate the dose rates with altitude and latitude by the authors takes into consideration the mean solar activity from January 1958 to December 2008 (51 years).

Twenty two data including international and national American flights were used to test the program and the results between them compared, showing good agreement. The program also gives excellent results for the doses expected for the crewmembers of three Brazilian national flights (between capitals cities in Brazil) when compared with the doses values measured for these flights using a radiation detector.

According to the results the doses expected for the Brazilian crews of domestic flights can, in some cases, depending on the number of annual flights, overcome the limit of 1 mSv/year established by the Brazilian competent authority in Brazil (Brazilian Nuclear Energy Commission- CNEN) for public annual exposure. In the case of the simulated international flights the results shows a good agreement with the results found in literature especially when considered the different database series used by the authors and by the other references for the solar activity.

INTRODUCTION

Human are exposed to natural radiation from extraterrestrial sources known as cosmic radiation, and from radionuclides present in the earth crust since its appearance on Earth. However, only in the last thirty years, given the use of radioactivity in its multiple applications, increased the interest of scientists in determining the natural radiation exposure levels to which man may face.

The main source of cosmic radiation on earth, known, as galactic cosmic radiation (GCR) is the supernovae explosions but sun activities also contributes to man exposure of radiation.

Occasionally, solar flares, a tremendous explosion that occurs on the sun caused when magnetic energy, that has build up in the solar atmosphere is released, radiation is emitted in the form of electromagnetic waves that could heats and accelerates electrons, protons an even heavy nuclei in the sun atmosphere, sometimes with sufficient energy to cross the earth magnetic field and enter on the atmosphere, increasing the man exposure.

Cosmic radiation consists mainly of subatomic particles such as neutrons and protons incident on earth with enough energy to generate secondary particles when they interact with the earth atmosphere atoms (oxygen, nitrogen and other) generating other subatomic particles such as muons, electrons, etc.

The dose from GCR also depends on the solar activity that varies according to an eleven-year cycle and it is measured by the number of sunspots at the surface of the sun and is related to the neutrons number at the earth surface. The higher the solar activity the lower the number of neutrons and consequently the lower is the dose. In other words, the dose increased in the "solar minimum activity" and decreased in the "solar maximum activity". It should be pointed out that this variation during the sun cycle is small on the equator but higher at the poles (can double the dose). So aircrews are always exposed to cosmic radiation during flights mainly due to the galactic cosmic radiation and in some periods, the solar activities (solar flares) can highly increase their exposure.

An example of the percentage of the dose rate variation curves with the latitude and altitude for a 20 E longitude, as a function of the radiation type, can be seen on FRIEDBERG W. AND COPELAND K., 2011 **[1].** Those curves were obtained based on the CARI-6P computer code developed by FRIEDBERG W, DUKE FE, SNYDER L, ET AL, 2005 **[2]**.

In equator, between 30 kft and 40 kft altitude,neutrons contributed between 40% e 50%, protons usually contributed between 10% and 11%, electromagnetic showers between 41% e 48 % and charged pions and muons between 8% and 1 % of the mean effective dose rate. It´s important to notice that the correct percentage of each type of radiation depends on the latitude, longitude and altitude of the flight and the solar cycle activity.

The calculation of cosmic radiation dose (effective dose) during flights is very difficult because, as shown before, the radiation field involves a mixture of radiation types with different energies not experienced in occupational exposure studies at ground level.

The estimation of the effective dose (related to the stochastic effects) ICRP 60-1991 **[3]** depends first on the estimation of the equivalent absorbed dose (H-Equivalent Dose) in each of the human tissue exposed to the radiation (that depends on the type of radiation and the total amount of energy deposit in the mass of the tissue).

The equivalent dose (H) is obtained by multiplying the absorbed dose (D) (energy absorbed per mass) by a radiation-weighting factor (W_R). These factors are based on the Radiological Biological Effectiveness for stochastic effects known as RBE that in turn are related to the LET (Linear Energy transfer), the average amount of energy per unit track length imparted to a medium by the ionizing radiation of a specified energy, when penetrating a short distance. The energy imparted to the medium includes energy from any secondary radiation. W_R today are based on ICRP 103, 2007 **[4].**

In the past, this W_R factor was called quality factor Q that was direct related with the type of radiation LET value (Linear Energy Transfer) and was based on ICRP 26,1977 **[5]** values. Table 1 shows the variation of this factor with time.

Table 1 – Q and W_R factors for Equivalent Dose (H) calculations

Type and energy of the radiation	Q ICRP 26	W_R ICRP60	
Photons, electrons, muons	1	1	
Protons, charged pions	5	E>2 MeV	2
Neutrons		E<10 keV	5
		10 keV ≤ E ≤ 100 keV	10
		100 keV ≤ E ≤ 2 MeV	20
		2 MeV ≤ E ≤ 20 MeV	10
		E > 20 MeV	5
Alpha particles, fission fragments, heavy ions	20	20	

Effective dose, on the other hand, is defined as a summation of the tissue equivalent dose, each multiplied by the appropriate tissue weighting factor (W_T) that takes into account the different risk of stochastic effects for each tissue irradiated. The W_T factor also changed with time (from ICRP 26 to ICRP 60). Table 2 shows the new values based on ICRP 60.

Table 2- Tissue weighting factors

Where radiation energy deposited	wT	Σ wT
remainder tissues, red bone-marrow, breast, colon, lung, stomach	0.12	0.72
Gonads	0.08	0.08
bladder, esophagus, liver, thyroid	0.04	0.16
bone surface, brain, salivary glands, skin	0.01	0.04
Total	---	1.00

As can be seen before, the estimation of the effective dose during flights is very complex because in principle you need to know the radiation energy spectrum (that varies mainly with the altitude and latitude) in order to apply the correct radiation and weighting factors W_R, that´s the reason why the authors incorporated into the mathematica program, the effective exposure rates curves directly from FRIEDBERG W. AND COPELAND K. 2011, cited before [1].

It should be highlighted that there are many different complexes codes available in literature, such as EPCARD (European Computer Program Package for the Calculation of Aviation) Route H. SCHRAUBE, 1999 **[6],** a code whose concept is based on the idea to collect and combine the large number of calculated and experimentally determined cosmic radiation findings to an uniform data base and then calculate the route doses by integration along great circles.

Another important well known code is PHITS-expacs developed by TATSUHIKO et al **[7],** a very complex Japonese code that includes also the estimation of the atmospheric cosmic-ray spectrum and is capable to calculate not only neutron but also proton, He nucleus, muon, electron, positron and photon spectra for anywhere in the atmosphere at the altitudes below 20 km. This code is enable to estimate the ambient dose equivalent and the effective dose due to the cosmic-ray exposure. It should be highlighted, as stated by the authors of this code that it is extremely time-consuming to perform Monte Carlo simulation of the cosmic-ray propagation for each route-dose calculation even using the latest computers machines.

Comparison between many international cosmic radiation codes can be seen on the EURADO report, 2012 [8] including AVIDOS 1.0, CARI-6M, EPCARD Net 5.4.1, FDOScalc 2.0, IASON-FREE 1.3.0, JISCARD Ex, PANDOCA, PCAIRE, PLANETOCOSMICS 2.0, QRM 1.0 and SIEVERT 1.0, where important parameters such as spectra data, cut off rigidity, dose conversion factors are discussed.

As can be seen before there are many codes available in literature, all very complex, that is the reason why simple and fast programs based directly on the effective dose exposure rates curves with latitude and altitude such as the presented in this article can be very useful, especially for average dose predictions for crew members, for radiological control purposes.

In some countries (USA) some government organizations recommends limits for aircrew exposure due to cosmic radiation which is not the case of Brazil, although our radioprotection regulation, based on the International Atomic Energy Agency recommendations, states that exposure to natural radiation sources must be taking into consideration case by case.

For a non-pregnant air carrier crewmember, the FAA-USA, for example, the recommended limit for exposure to ionizing radiation is a 5-year average of 20 mSv per year, with no more than 50 mSv in a single year. For a pregnant air carrier crewmember, starting when she reports her pregnancy to management, the FAA-recommended ionizing radiation exposure limits for the concepts are 0.5 mSv in any month and 1 mSv during the remainder of the pregnancy FRIEDBERG W. AND COPELAND K. 2011 **[1].**

On the other hand according to a Directive issued by the Commission of the European Communities **[9]** and an associated document regarding its implementation **[10],** assessments of occupational radiation exposure should be made for crewmembers likely to be occupationally exposed to more than 1 mSv in a year and efforts shall be made to keep annual exposures below 6 mSv. For those who exceeded this value medical surveillance and record keeping is recommended. For a pregnant crewmember, starting when she reports her pregnancy to the manager, her work schedule should be such that the equivalent dose to the child to be born must be as low as reasonably achievable and unlikely to exceed 1 mSv, either for the remainder of the pregnancy or for the whole pregnancy.

According to table 31 from UNSCEAR REPORT, 2000 **[11]** the average worldwide exposure to natural radiation sources due to cosmic radiation is 0.38 mSv/year (0.28 mSv/year due to direct ionizing and photon component and 0.10 from neutron component), considering the population distribution in the different cities altitudes. Cosmogenic radionuclides interaction contribute with only 0.01 mSv/year resulting in 0.39 mSv/year total which represents a fraction of approximately 16% of the total contribution of natural human exposure to radiation that is 2.4 mSv/year. According to the same reference for the directly ionizing and photon component, the world average effective dose rate is 0.34 mSv/year at sea level, outdoor (14%). It is clear that radiation level increases with the altitude since the atmosphere shields radiation.

MATERIALS AND METHODS

Galactic cosmic radiation on earth varies with altitude, with the latitude, longitude and the geomagnetic field and produces an absorbed dose rate in air comparable to that produced by the radiation dose from natural radionuclides existing in the earth's crust.

The program developed in MATHEMATICA 2004 **[12]** symbolic languages takes into consideration the Effective dose rate based on ICRP 60-1991 **[3]** concept, from GCR as related to geographic latitude at selected altitudes at 20 ^{o} E, longitudes taken from WALLE FRIEDBERG AND KYLE COPELAND 2011 [1].

The program considered a geodesic flight curve such as shown in figure 1 between the two desired cities (A to B).

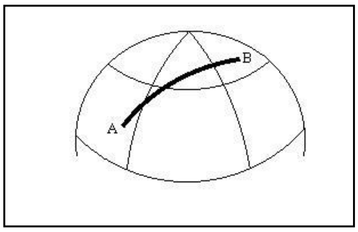

Figure 1- Geodesic model

The latitude and longitude of the two cities are transforming in the program to spherical coordinates in order to calculate the total flight distance and the distance between latitudes since exposure rates vary with the altitude but also with the latitude.

The Mathematica program also took into consideration the takeoff time (angle, and velocity) and the landing time (angle and velocity) as well as the cruise velocity and altitude in order to integrate the dose with the variation of altitude with time. For long flights, the takeoff and landing doses are negligible in comparison with the remaining of the flight.

The second step of the model is to transform the geography latitude and longitude of the departure city and the arrival city in x,y,z coordinates supposing the earth rounded.

With this two points, the two vectors cities can be calculated since the other point is the center of the earth (0,0,0) coordinates. It should be clear that the program considers the earth rounded as an approximation.

With this two vectors the plane between them can be calculated since we have two vectors and two vectors defines a plane (the vector product gives the a, b and c value of the plane equation (ax+by+cz=0).

The latitude planes from 80 degrees south to 80 degree north regions equations can be easily calculated based on z=R.Sin (latitude)). Table 3 shows the planes z values for north and south hemisphere.

The next program step is to calculate the interception between the Planes formed by the takeoff city and landing city with the planes equations of the 17 latitudes (between 80 N and 80 S) shown before and then estimate the geodesic distance between two latitudes in sequence. As shown before knowing the coordinates of the two latitudes the geodesic distance between them can be easily calculated based on the scalar product concept between two vectors (u and v) that allows calculating the angle between them and consequently the arc length.

Table 3- Z planes for north and south hemispheres

North Coordinate (degrees)	Zn (km)	South Coordinate (degrees)	Zs (km)
80	6274.21	80	-6274.21
70	5986.78	70	-5986.78
60	5517.45	60	-5517.45
50	4880.47	50	-4880.47
40	4095.2	40	-4095.2
30	3185.5	30	-3185.5
20	2179.01	20	-2179.01
10	1106.31	10	-1106.31
0	0	0	0

The interceptions points (x and y) for each plane z, are very easy to calculate since it is the solution of the system between the plane equation obtained before (ax+by+cz=0) and the earth sphere equation $x^2 + y^2 + z^2 = r^2$ (r=earth radius) for each of the seventeen z planes (all z known).

Knowing the vectors between the desired latitudes (that the plan cut) including the departure and arrival city vectors, the angle between them can also be calculated based on the scalar product. Knowing this information, the cruise velocity and the cruise altitude, the arc curved distance between the points can be calculated (radius+cruise high) * angle between vectors.

With all this information, the time spent between latitudes can be calculated and knowing the average effective dose rates between latitudes, on that altitude, the doses can be calculated.

For the takeoff dose calculation it is necessary to know the takeoff angle, take off average velocity and the cruise altitude in order to calculate the height of the flight with time h(t) until it reaches the cruise altitude. For each high h(t) the effective dose rate with time can also be calculated generating an effective dose rate curve with time during takeoff that can be integrated to estimate the dose during takeoff. The same procedure is used for landing. The takeoff and landing aircraft velocity were considered equal to 250 km/h with an angle of 30° degrees.

Table 4 shows the points taken direct from the paper of Friedberg and Copeland cited before used to generate the spline curve necessary for the program. For intermediate highs and a fixed latitude, a linear relation is considered.

With these points, a cubic spline-fitting curve can be calculated using the mathematica software in order to estimate the effective dose rate for each altitude and latitude resulting on figure 2 of the article.

The program also fit curves for each fixed latitude varying the altitude that is important to estimates the doses between takeoff and landing.

Table 4 -Effective dose rates points taken from reference 1. Data given in μSv/h.

	0 ft	10 kft	20 kft	30 kft	40 kft	50 kft
80 S	0.035	0.5	1.0	3.2	7.1	10.6
60 S	0.035	0.4	1.0	3.2	7.0	10.0
50 S	0.035	0.35	0.8	2.6	5.5	7.6
40 S	0.035	0.3	0.6	2.0	4.0	5.2
30 S	0.035	0.25	0.5	1.7	3.3	4.0
20 S	0.035	0.20	0.4	1.4	2.6	3.4
10 S	0.035	-----	-----	-----		
0	0.035	0.20	0.4	1.4	2.4	3.4
10 N	0.035	----	----	---		
20 N	0.035	0.25	0.5	1.8	3.3	4.5
30 N	0.035	0.325	0.65	2.2	4.35	5.9
40 N	0.035	0.4	0.8	2.5	5.4	7.4
50 N	0.035	0.45	0.9	2.8	6.2	8.8
60 N	0.035	0.5	1.0	3.2	7.0	10.2
80 N	0.035	0.55	1.1	3.3	7.1	10.6

Dose rates in table 4 and, consequently, on figure 2 are for the mean solar activity from January 1958 through December 2008. The curves from this reference were included in the program through splines (See figure 1). Negative sign means south latitude.

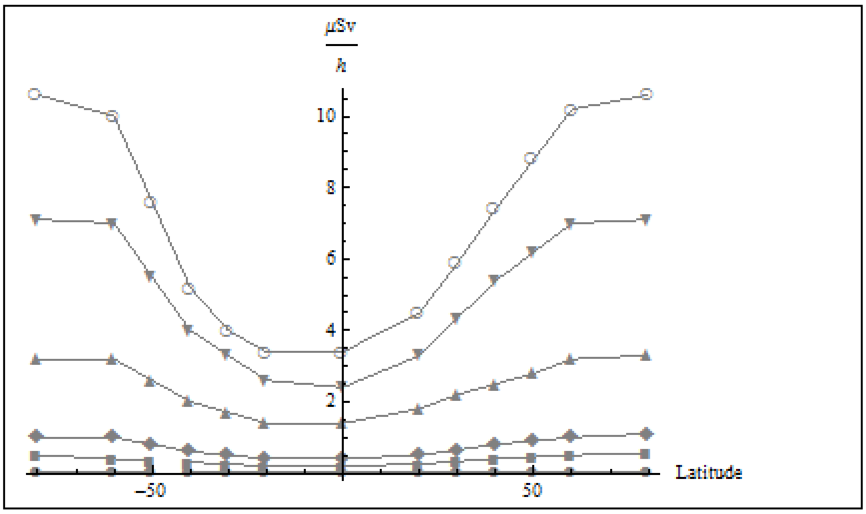

Figure 2- Cubic Splines adjusted by the program (from 0, 10kft, 20kft, 30kft, 40kft and 50kft - From bottom to top).

The heliocentric potential used in estimating these dose rates was based on the average Deep River equivalent count rate for the 51-year period reported by COPELAND K, SAUER HH, DUKE FE, FRIEDBERG W. 2008 **[13].**

RESULTS

Table 5 shows the results obtained by the mathematica program and the measurements made by a Brazilian scientist of the average exposure rate during three Brazilian flights.

Table 5- Comparison between the doses measured in some Brazilian flights and the theoretical model developed

Flight	Altitude Ft	Vc Km/h	Approximately Distance between cities km	Total flight time h	Average dose rate neglecting takeoff and landing time (MATHEMATICA PROGRAM) μSv/h	Average dose rate taking into consideration takeoff and landing time (MATHEMATICA) μSv/h	Average dose rate measured during flight μSv/h Ref Dr Rex Nazaré Alves**[14]**
Rio Brasília	31000	850	935	1.1	1.54	1.41	1.42
Brasília-Manaus	35000	850	1937	2.27	2.01	1.91	1.87
Manaus Rio	37000	650	2856	4.39	2.21	2.13	2.12

In order to estimate the doses for the Brazilian air flight crewmembers one of the longest national flights were chosen (Porto Alegre - Boa Vista) and the data used and obtained for the simulation were: Altitude (37.000 ft ≃ 11,3 km); Cruse velocity (850 km/h); Distance between cities (3795 km) and total flight duration (4.47 h).

Table 6 shows the results obtained for the total cosmic radiation dose, average dose rates between latitudes, time flight between latitudes, for these flights.

Table 7 shows a comparison between the cosmic radiation doses estimated for twenty two international flights obtained using the program developed by the authors (based on the reference curve of figure 1 - effective dose rate from CGR, as related to geographic latitude at selected altitudes at 20 ° E longitude – mean solar activity from January 1958 and December 2008 - 51 years) and the results obtained by FRIEDBERG AND COPELAND (2011) **[1]** using the CARI-6 code from the Federal Aviation Administration based on 45 years average effective flight dose from January 1958 through December 2002 and another work for the same authors reported from BAILEY (2000) [15] with data from January 1958 and December 1997.

Table 6 – Geodesic distances and dose rates between successive latitudes from Porto Alegre (*) to Boa Vista(**)

PROGRAM MATHEMATICA	RESULTS	LATITUDES	LATITUDES	LATITUDES	LATITUDES	LATITUDES
		30.03 S AND 30:00 S	30:00 S AND 20:00 S	20:00 S AND 10:00 S	10:00 S AND 0	0 AND 2.82 N
	DISTANCE BETWEEN LATITUDES Km	3.85	1160.34	1154.43	1151.86	324.69
	TIME FLIGTH BETWEEN LATITUDES HOURS	0.00453	1.365	1.358	1.355	0.382
	AVERAGE DOSE RATE BETWEEN LATITUDES µSv/h	2.85	2.56	2.26	2.26	2.26
	DOSE BETWEEN LATITUDES µSv	0.013	3.49	3.06	3.06	0.86
	TOTAL DOSE µSv	10.48				

(*)Porto Alegre Latitude {30,1′,59′′},South and longitude{51,13′,48′′} west
(**) Boa Vista. Latitude {2,49′,11′′} North and Longitude {60,40′,24′′} west

Table 7 – Comparison between the cosmic dose estimated by the program developed on this work and the results obtained from CARI-6.

Flight	Altitude ft	Average velocity km/h	Time flight hours	Dose obtained on this work µSv (*)	Average Dose Obtained by FRIEDBERG FROM REFERENCE BAILEY (min - max) µSv(**)	Percentage difference between this work and BAILEY	Dose obtained from CARI-6 code µSv(***)	Percentage difference between this work and CARI-6
Los Angeles-Honolulu	35000	780	5.2	12.5	12.9 (11.5-13.3)	-3.1%	14.7	-15%
London-New York	37000	820	6.8	30.9	34.0 (23.8-40)	-9.1%	37.4	-17.4%
London-Los Angeles	39000	800	11.0	56.0	55.2 (38.5-64.9)	1.5%	61.6	-9.1%
New York- Seattle	39000	790	4.9	21.8	25.6 (17.7-30.1)	-14.8%	28.0	-22.1%
Dallas-London	37000	885	8.7	37.4	35.3 (24.8-41.4)	6.0%	39.6	-5.6%
Los Angeles-Tokyo	40000	760	11.6	41.8	38.0 (31.8-40.4)	10.0%	43.4	-3.7%
Seattle-Portland	21000	760	0.3	0.21	0.14 (0.11-0.15)	50.0%	0.17	23.5%
London- Dallas	39000	800	9.7	46.7	38.8 (27.6-45.1)	20.4%	39.6	17.9%
Houston- Austin	20000	430	0.5	0.24	0.14 (0.12-0.15)	71.4%	0.17	41.2%
Miami-Tampa	24000	550	0.6	0.44	0.34 (0.28-0.36)	29.4%	0.39	12.8%
St Louis-Tulsa	35000	650	0.9	2.23	1.57 (1.20-1.74)	42..0%	1.71	30.4%
Tampa-St Louis	31000	650	2.0	4.00	4.31 (3.35-4.74)	-7.2%	4.71	-15.1%
New Orleans-San Antonio	39000	660	1.2	3.45	3.11 (2.54-3.31)	10.9%	3.27	5.5%

Washington-Los Angeles	35000	790	4.7	13.0	17.2 (13.2-19.1)	-24.4%	19.1	-31.9%
New York -Chicago	39000	630	1.8	6.8	8.42 (5.93-9.85)	-19.2%	8.92	-23.8%
Seattle -Washington	37000	890	4.1	15.7	20.4 (14.3-23.8)	-23.0%	19.2	-18.9%
Chicago-San Francisco	39000	770	3.8	14.5	17.7 (13.2-19.8)	-18%	19.4	-25.2%
San Francisco-Chicago	41000	770	3.8	15.8	19.5 (14.2-22.1)	-19%	20.7	-23.7%
New York-Tokyo	43000	830	13.0	59.3	67.1 (48.3-77.7)	-11.6%	75.4	-21.4%
Tokyo-New York	41000	880	12.2	51.8	63.5 (44.3-74.8)	-18.4%	69.6	-25.6%
Chicago-London	37000	860	7.3	33.7	38.7 (26.6-45.8)	-12.9%	43,0	-21.6%
London-Chicago	39000	810	7.8	40.4	43.3 (29.6-51.6)	-6.7%	47.5	-14.9%

* Data from December 1958 to January 2008 - 51 year period.
** Data from December 1958 to January 1997-40 year period.
*** Data from December 1958 to January 2002 - 45 year period.

DISCUSSIONS

It can be seen from table 5 that the three doses simulated by the program for the three national flights shows excellent agreement with the three doses measured for these flights using a radiation detector by the professor of the Military Institute of Engineering for the three simulated flights.

The workload of Brazilian crews is regulated by an old Law N° 7.183 (1984) **[16]**, which has nearly 30 years. Legislation says that, on domestic routes, "the limits of flight time may not exceed 85 hours per month, 230 hours per quarter and 850 hours a year." The law establish that "the limit of flight and landings allowed for a day (daily) is 9 hours and 30 minutes of flight and five landings."

In the case of national flights (within the national territory) the doses expected are not so low for the crew (the limit establish by the Brazilian Nuclear Energy Commission for public is 1 mSv/year-average in 5 years -CNEN-NE-3.01)(2005) **[17].** For example the dose expected for each Brasília - Manaus flight is the order of 1.91 μSv/h*2.27 h =4.3 μSv which means that the maximum number of flights allowed per year to respect the dose limit is 1000 μSv/4.3μSv ≈232 but taken into consideration the maximum 850 h per year allowed by the law could lead to an annual dose to the crew of 1.91 μSv/h*850 h/year= 1.6 mSv/year above the limit established by the Brazilian Nuclear Energy Commission for public.

In the case of the longest possible national flight in Brazil, Porto Alegre to Boa Vista the dose expected can be the order of 10.5 μSv that means a maximum number of flights for the crew of 95 per year considering the limit of 1 mSv/year in order to respect the regulation or a maximum dose of 2.35 μSv/h*850 ≈2 mSv/year taken into consideration the 850 h per year limitation.

It can be seen from the results shown on table 6, that in the case of national flights within USA and international flights between USA and Europe the program developed by the authors gives values very near those cited in BAILEY [3**]** and most of the time a lit bit lower than those found using the CARI-6 program based on Friedberg results with the highest difference appearing in the case of the New York-Seattle and New York–

Tokyo simulation flights that occurs on higher north latitudes which in the authors opinion is not too high since the dose rate series date used by the authors and cited in the two references for the dose rates with altitude and latitude were certainly different. For example, data from Friedberg cited by Bailey (2000) shows exposure rate levels based on a data series from 1960 to 1995 on equator (0° , 20° E latitude) at 40000 ft between 2.55 μSv/h and 2.78 μSv/h (while in the program, for the same high, the value used was 2.5 μSv/h). In the case of a high latitude (70° N , 20° E latitude) the same series gives values between 4.89 μSv/h and 8.87 μSv/h (while in the program the value used was 6.5 μSv/h). The same occur for 20000 ft in equator between 0.4 μSv/h and 0.44 μSv/h (in the program 0.4 μSv/h) and for the same high latitude cited before values between 0.63 μSv/h and 0.98 μSv/h (while in the program 1.05 μSv/h).

ACKNOWLEDGMENTS

The authors would like to thank professor Rex Nazaré Alves, from the Nuclear Department of the Military Institute of Engineering, for allowing the use of his flights radiation measurements used to verify/validate the model. The authors would also like to thank the two students (Rafael Heilbron and Mario Luth) involved in the development of a version of the mathematica program in the maple language for training engineer's students on this field, co-authors of this article especially for their dedication and enthusiasm.

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