Radiation environment and effects in human spaceflight: A Lunar Mission

João Sabino
joaotiagosabino@ist.utl.pt

Instituto Superior Técnico, Lisboa, Portugal

November 2012

Abstract

This work contains an overview of the radiation physics quantities and concepts that are of concern in a crewed mission to the Moon. The radiation effects in biological tissue and their consequences for the astronaut health are addressed. The environment scenario of a mission to the Moon is simulated based on data obtained with the software CREME and data from the Lunar Lander neutron measurements. The mission is divided in five phases concerning the different stages of the trajectory of the mission: LEO, VAB traversing, GEO, Moon orbit, and Moon surface. Major details on the development of a software application in Geant 4 are presented. The application is used for the transport of radiation particles through matter, to simulate the physics processes involved, and to obtain the resultant absorbed dose, equivalent dose and spectre of secondary particles. These quantities are evaluated for solar minimum and solar maximum conditions, the possible occurence of solar flares is also considered.
Keywords: space, radiation, moon, geant4, fluence, dose.

1. Introduction

The radiation environment in the solar system presents the main constrain to human spaceflight outside Earth's protecting radiation belts. As the human presence in space tends to increase or the will to reach other planets grows, radiation in space becomes a more compelling obstacle that needs to be dealt with [1, 2]. The risks that radiation exposure present to space missions affect directly the mission planing. For this reason, a good knowlege of the radiation environment in all mission phases is essential. The development of reliable prediction tools is of major importance to assist mission planing and assure minimum levels of safety for the crew. This work aims at analysing the different factors to be taken into account to acurately predict the effects of space radiation in human spaceflight. In order to fulfill this goal a simulation software tool, named Space Radiation Effects Simulator (SRES), was developed. SRES will provide educated guesses of the effects of radiation expected under certain conditions. The SRES development is described in this work and the results for simulations, assuming a real lunar mission scenario, are presented.

The robotic space exploration looks promising in the next years to come but, despite its huge advantages, many scientist acknowledge that it alone is not sufficient and that humans are needed in space to perform more complex research tasks such as field geology or the acquisition and analysis of geological samples [3].

This is a strong incentive towards human spaceflight and, besides, there is also the natural impetus for curiosity and adventure that the human being has shown in this kind of challenges that lead us to go further and further; not to mention the technological and industrial developments that always come associated to them. Nowdays, even the tourism industry has begun to recognize space as an interesting destination for the wealthy and some companies have already flown tourists to the ISS (International Space Station).

Human space exploration beyond LEO (low Earth orbit) is presumably going to reemerge very soon specially if some of the present risks it poses are minimized.

1.1. Structure

This work starts by giving an overview of some quantities and concepts common in radiation physics and a brief description of the types of radiation in space that matter in the ambit of a crewed mission to the Moon. The radiation effects in biological tissue and their consequences for the astronaut health are addressed. Then, the environment scenario of a mission to the moon is simulated based on data obtained with the software CREME. The mission was divided in five phases concerning the different stages of the trajectory of the mission: LEO, VAB (Van Allen belts) traversing, GEO (geosyncrhonous Earth orbit), Moon orbit, and Moon surface. Based on the data obtained with CREME for each phase, a software application was developed in Geant 4 for the transport of radiation particles through matter, to simulate the physics processes involved, and to obtain the resultant absorbed dose, equivalent dose and spectre of secondaries.

2. Radiation Environment in Space

Radiation is the term used for energetic particles or waves traveling in all directions through space or some medium. The particles or waves are produced or liberated by a source, and the source is said to radiate. Because radiation propagates through space and its energy is conserved in vacuum, the power of all types of radiation follows an inverse-square law of power with regard to distance from its source. Before giving a more detailed description on radiation and the types of radiation that are of concern in a lunar mission it is necessary to stablish some basic concepts and quantities commonly used to describe radiation properties. The following definitions are presented in accordance with the International Commission on Radiological Protection (ICRP) and International Commission on Radiation Units and Measurements (ICRU). [4].

2.1. Fluence and fluence rate

Fluence, ψ, is the number of particles incident on a given area. It measures the particle areal density or the focus of a beam of partices. Fluence is expressed by the quotient of dN by da, where dN is the number of particles incident on a sphere of cross-sectional area da, thus

$$\psi = \frac{\mathrm{d}N}{\mathrm{d}a} \tag{1}$$

The IS unit of fluence is m^{-2}.

Fluence rate, $\dot{\psi}$, the number of particles that pass through an area in a given time interval. It is the quocient of dψ by dt, where dψ is the increment of the fluence in the time interval dt, thus

$$\dot{\psi} = \frac{\mathrm{d}\psi}{\mathrm{d}t} \tag{2}$$

Fluence rate comes in units of $\mathrm{m}^{-2}\mathrm{s}^{-1}$.

The term “flux” has been used historically by the nuclear community for fluence rate and also used for particle flux density, but its use has been discouraged by the ICRU convention to eliminate confusion between the terms “particle flux density” and “radiant flux”[5]. However the term “flux” is still common within the space weather and radiation protection communities for the quantity termed “fluence rate”. Whenever the term “flux” appears in this document the units will be presented to avoid confusion (if by any means you find yourself confused just stick to the units shown).

2.2. Absorbed Dose

The absorbed dose is the measure of the amount of energy a body absorbed. The absorbed dose, D, is the quotient of d$\bar{E}$ by dm, where d$\bar{E}$ is the mean energy imparted by ionizing radiation to matter of mass dm, thus

$$D = \frac{\mathrm{d}\bar{E}}{\mathrm{d}m} \tag{3}$$

The IS unit of absorbed dose is J kg^{-1}. The special name for the unit of absorbed dose is gray (Gy);
1 Gy = 1 J kg^{-1}.

2.3. Equivalent dose

The equivalent dose, H_T, is the dose in a tissue or organ T given by:

$$H_T = \sum_R \omega_R D_{T,R} \tag{4}$$

where $\mathrm{D}_{T,R}$ is the mean absorbed dose from radiation R in tissue or organ T, and ω_R is the radiation weighting factor. This radiation weighting factor is dimensioneless and is used to reflect the higher biological effectiveness of high-LET radiations compared with low-LET radiations.

The IS unit for equivalent dose is the same as for the absorbed dose, J/kg, but with the special name Sievert (Sv).

The recommended numerical values for the ω_R of different radiations are given by ICRP [6] and are presented in table 1.

Radiation Type	Radiation weighting factor, ω_R
Photons	1
Electrons, muons	1
Protons and charged pions	2
Alpha particles, fission fragments, heavy ions	20
Neutrons	A continuous function of neutron energy (see equation 5)

Table 1: Radiation weighting factors [6].

$$\omega_\mathrm{n} = \begin{cases} 2.5 + 18.2e^{-(\ln E_\mathrm{n})^2/6}, & E_\mathrm{n} < 1\,\mathrm{MeV} \\ 5.0 + 17.0e^{-(\ln 2E_\mathrm{n})^2/6}, & 1\,\mathrm{MeV} \le E_\mathrm{n} \le 50\,\mathrm{MeV} \\ 2.5 + 3.25e^{-(\ln 0.04E_\mathrm{n})^2/6}, & E_\mathrm{n} > 50\,\mathrm{MeV} \end{cases} \tag{5}$$

2.4. Galactic Cosmic Radiation (GCR)

Interplanetary space is bathed by a low fluence rate (particles per square meter per second or particles per square meter per steradian per second) of essentially uniformly distributed, highly energetic,

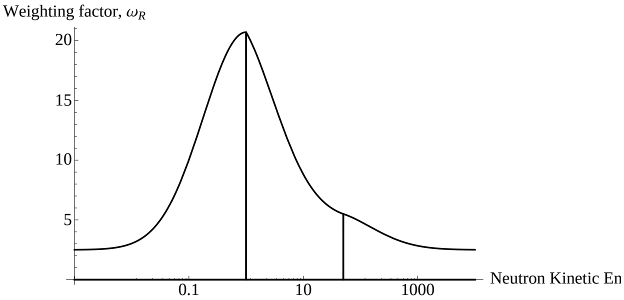

Figure 1: Plot shows the radiation weighting factor for neutrons as a function of their kinetic energy when entering the tissue. The vertical lines are at 1MeV and 50MeV showing the boundaries of the function defined by parts in equation 5.

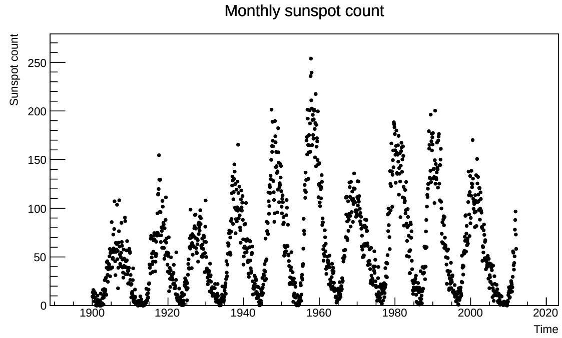

Figure 2: The monthly sunspot numbers for the latest 10 solar cycles.
(Data from `http://sidc.oma.be/sunspot-data/`)

and extremely penetrating ions that are believed to be accelerated by supernova shocks in our Galaxy. These ions make up the GCR.

2.5. Solar Particle Events (SPE)

A solar particle event is an unusually large fluence rate of energetic protons, electrons and heavy ions ejected into space by a solar eruption. Solar particle events are directional. Despite having lower energy than the GCR the SPEs can be particularly dangerous for crews because of their high fluence rates.

The SPEs are in practice unpredictable but it was observed that they are more likely to occur during a solar maximum, often in the sequence of solar flares (SF) with coronal mass ejection (CME). Solar maximum and solar minimum refer respectively to epochs of maximum and minimum sunspot counts in the sun. This epochs occur cyclically and correspond to higher or lower activity in the sun:

- The solar maximum is the time period of maximum solar activity during a solar cycle, usually defined in terms of maximum relative sunspot number or minimum GCR fluence rate. During this period SPEs are more likely to occur.
- The solar minimum is the time period of minimum solar activity during a solar cycle, usually defined in terms of minimum relative sunspot number or maximum GCR fluence rate.

The solar cycle has a period of approximately 11 years but cycles as short as 9 years and as long as 14 years have been observed. In figure 2 is shown a plot of the sunspot counts in the last ten solar cycles.

GCR fluence rate decreases during a solar maximum because the GCR particles lose energy in the more intense solar wind and are also more deflected by the sun magnetic field wich is stronger during that period.

2.6. Van Allen radiation belts (VAB)

The Van Allen radiation belts consist of energetic charged particles held in a torus around the Earth by the Earth magnetosphere. The VARB are split into two distinct belts (figure 3), with energetic electrons forming the outer belt, wich extends from roughly 15000 km to 25000 km altitude, and a combination of protons and electrons forming the inner belt, extending roughly from 1000 km to 6000 km altitude. Most of these protons and electrons come from solar wind thus the solar activity has a great influence on the amounts of radiation trapped in Earth magnetosphere.

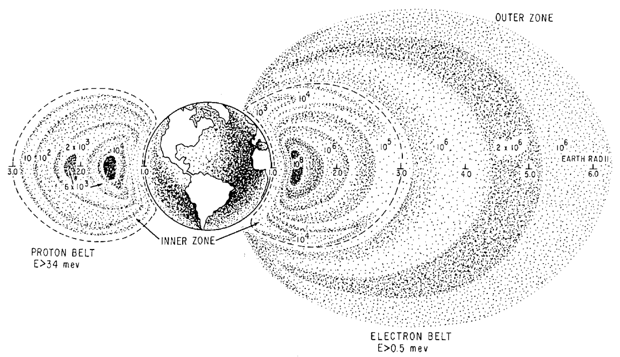

Figure 3: Ilustration of the Van Allen radiation belts evidencing the inner and outer belts. The greyed areas represent areas with approximately the same fluence rates (particles per square centimeter per second).

Radiation belts pose a hazard to satellites, which must protect their sensitive components with adequate shielding if their orbit spends significant time in the radiation belts. For crewed missions these radiation belts are also a significant threat, the areas of greater fluence rates must be avoided and the time spent inside the belts reduced to minimum.

2.7. Lunar albedo neutrons

The albedo is the reflected radiation from a planet. The moon is constantly being irradiated by solar wind and also GCR. Galactic cosmic rays that impact the lunar soil lose energy immediately through a series of intranuclear cascades. These cascades produce many secondary nucleons, mesons, and residual nuclei that will continue to lose energy through new cascades, decay and Coulomb collisions. Ultimately the residual particle population is dominated by neutrons with energies from fractions of eV's to about 100 MeV [7]. Figure 4 shows a measurement of neutron spectra acquired by the Lunar Prospector mission [7]. Albedo neutrons may be produced as deep as 1 meter into the soil and their flux is influenced by the soil composition. The lunar soil is an important consideration in the development of an accurate model for the moon environment, however, in this work, a more straightforward approach was used. Given the availability of reliable measured data from probes such as the Lunar Prospector, real data was used for the lunar albedo instead of simulated one.

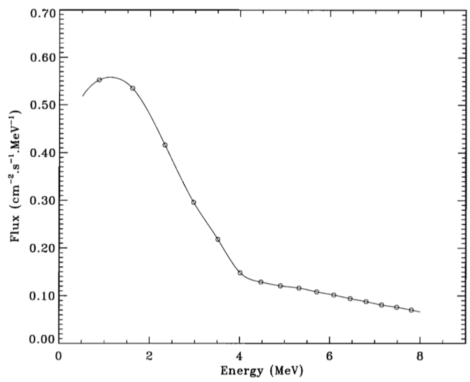

Figure 4: Flux spectrum of albedo neutrons from the moon and its cubic spline interpolation[7].

3. Biological Effects of Radiation

Space is a harsh environment. Nevertheless, engineering technology is capable of protecting astronauts against vacuum, extreme thermal conditions, and micrometeoroid environments. Protection from radiation, however, is much less straightforward. Before addressing the subject of radiation protection lets first understand how radiation exposure causes harm to the human body and what are the short and long term consequences. In order to damage biological tissue radiation must interact physically with the tissue. These interactions occur at the atomic level and may turn out to be harmless or cause nocive effects that propagate to the failure of vital organs (figure 5).

3.1. Cellular damage

Even though all biological effects subsequent to radiation exposure can be traced back to the interaction of the radiation with atoms, there are two mechanisms by which radiation ultimately affects cells. These two mechanisms are commonly called direct and indirect effects [8].

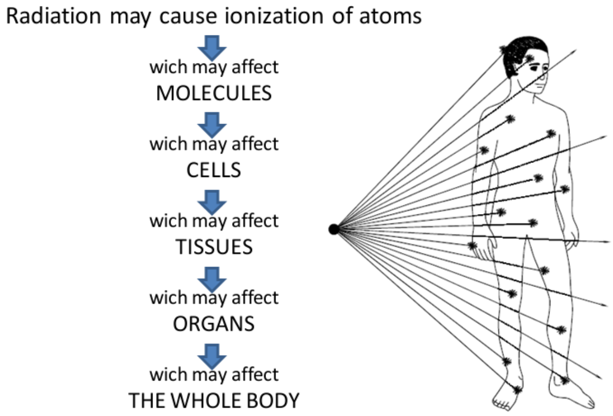

Figure 5: Diagram of the consequences caused by the propagation of the nocive effects from small scale to large scale in human body (adapted from [8]).

The direct effects consist in radiation interacting directly with a DNA molecule or other cellular component of critical to the survival of the cell. This interaction may affect the cells ability to reproduce and subsequently survive. If a sufficient amount of atoms in the DNA becomes affected in such a way that the cromossome cannot replicate itself or the information it contains is significantly changed then the cell suffers consequences that directly affect is chances of survival. The direct effects are predominant for radiation with higher LET such as neutrons, protons, alpha particles and heavier nucleus.

When the DNA of a cell is damaged by radiation there are 4 possible outcomes for that cell (figure 6):

- The cell manages to completely repair the damage inflicted by the incident radiation and continues its functions normally.
- The cell dies due to the provoked damage.
- The cell manages to continue its vital functions but dies when it comes to replication.
- The cell is affected in a way that it does not die but suffers mutation. The mutated cell is still able to replicate and thus survive but the daughter cells are still mutations presenting non-repared damages and/or DNA aberrations.

3.2. Sensitivity to radiation

Not all tissues are equally sensitive to radiation. The sensitivity of the various organs of the human body correlate with the relative sensitivity of the

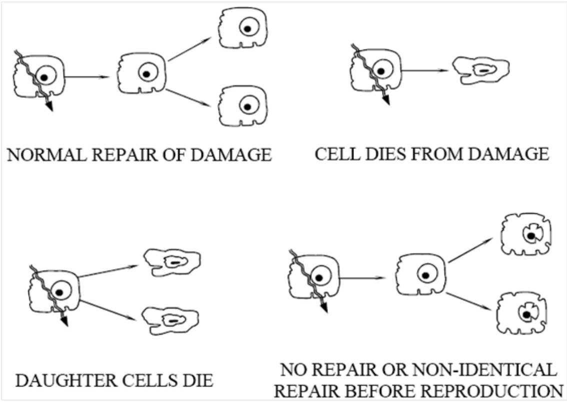

Figure 6: Possible outcomes for the evolution of an irradiated living cell [8].

cells from which they are composed. In general tissues containig cells that are more actively regenerating are more sensitive to radiation. This is because cells that replicate more frequently have a greater need for its DNA information to be correct, and if the DNA is incorrect large amounts of cells with erroneous DNA would be reproduced causing the organ they belong to to fail earlier. The rate of reproduction of the cells forming an organ system is not the only criterion determining the overall sensitivity. The relative importance of the organ system to the well being of the body is also important [8]. This measure of the overall sensitivity of an organ is expressed by the tissue weighting factor. The organs that are more sensitive to radiation present higher tissue weighting factors, and according to ICRP [6] those are (from the most sensitive to least sensitive):

-Blood forming organs;
-Gastrointestinal tract organs;
-Reproductive organs;
-Eyes;
-Skin;
-Muscles and brain.

3.3. Recommended dose limits

Permissible exposure limits (PEL) for radiation exposure of astronauts have the primary functions of preventing in-flight risks that would jeopardize mission success and limiting chronic risks to acceptable levels based on legal, ethical or moral, and financial considerations. The European Space Agency uses limit values for the maximum dose in tissue largely based on the recommendations of the National Council for Radiological Protection (NCRP) for ground-based works with some modifications for 30-day and annual limits for non-cancer effects [**?**, **?**]. The values of PEL used by ESA are presented in table 2 grouped by organ sensitivity and exposure interval - where they differ from the NCRP limits the NCRP limits are presented in parentheses.

Exposure Interval	Equivalent Dose [Sv]		
	Skin	Ocular Lens	BFO
30 Days	1.5	0.5	0.25
Annual	3	1	0.5
Career	6	4	1-4[1]

[1] Varies with gender and age at initial exposure.

Table 2: Limits, at ESA, for the exposure to radiation in equivalent dose per tissue.

4. Simulation framework

The radiation exposure scenario in a space missions can be very heterogeneous depending on whether the mission is within the magnetosphere (missions to the ISS for example) or in the interplanetary (as missions to the Moon and Mars). Here we will be considering the case of a crewed mission to the Moon. The mission will be divided in five phases and the environment for each phase will be simulated separately.

The division in phases was chosen according to five locations where the spacecraft passes that present similar patterns of radiation environment. A summary of all mission phases can be seen in table 3.

Mission phase	Radiation types considered	Altitude [km]	Duration
LEO	GCR + trapped protons (+SEP)	200 – 2000	180 + 30 min
VAB traversing	GCR + trapped protons (+SEP)	1000 – 25000	90 + 90 min
GEO & Interplanetary	GCR (+SEP)	35786	3 + 3 days
Moon Orbit (LLO)	GCR + albedo neutrons (+SEP)	100	3 days
Moon Surface (SRF)	GCR + albedo neutrons(+SEP)	0	3 days

Table 3: Characteristics of each mission phase. The altitudes in LLO and SRF phases are relative to the Moon. The duration depicts the approximate time spent in each phase considering as example the case of an astronaut onboard the Apollo 17 mission.

The environment in each mission phase is basically characterised by the particle fluence rates that are obtained with CREME [9] for that particular region. CREME provides the particle fluence rates (in [m^2-s-sr-MeV/nuc]$^{-1}$) vs. the kinetic energy (in MeV/nuc) at the external surface of the spacecraft, before transport through shielding, given the orbit of the spacecraft and the environment conditions (sun activity and magnetosphere weather). Near the Moon fluence rates from the Lunar Prospector mission data were used [10, 7]. Three different solar conditions were used: solar minimum, solar maximum, and solar flare. Once obtained the differential fluence rates, this are then integrated to obtain the fluence rates independent of the energy. The generated integral fluence rate files contain *per se* the energy distribution for each species. These files are needed by the Geant4 macro so that the simulation knows how to distribute any given number of particles by species and energy. A C++ script was written to automate the process of reading the differential fluence rate files, generate the integral fluence rates and write the respective Geant4 macro.

Having the particle fluence rates in each phase, the transport and all subsequent calculations, such as deposited energy, doses and spectre of secondaries, is done using GEANT4[11]. In figure 7 is a flowchart that elucidates how the different software modules are assembled and what are the inputs and outputs of the simulation.

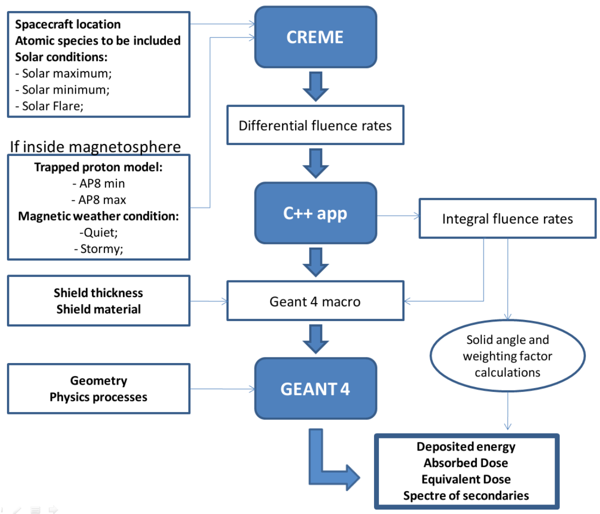

Figure 7: Flowchart evidencing the inputs on the left side and how the different software modules are integrated.

4.1. GEANT 4

Geant4 is a C++ toolkit for the simulation of the passage of particles through matter, using Monte Carlo methods. In Geant4 a generic geometry was built to test the effects of the exposure to radiation. The geometry is a simple sphere and the user as the option to set an spherical shielding shell around it with the desired thickness, ranging from 0 to 200 mm (figure 8). The materials used for the shield or sphere can be chosen from a set of already defined materials. The material used for the sphere by default is the *TissueEquivalent* and the sphere radius is 15 cm, these values are chosen in order to reproduce the dimensions and constitution of the ICRU sphere used as a reference phantom in defining dose equivalent quantities [12]. The shielding material is by default an alluminium alloy widely used in aerospace industry for the construction of the spacecraft fuselage [13], its composition information was taken from [14]. In order to simulate the isotropic incidence of radiation all the geometry is placed inside a larger spherical dome, with radius of 0.6 meters, from where the particles are fired inwards as can be seen in figure 8. The direction of the fired particles is uniformly distributed over a solid angle of 2π and the point from where they are fired is also uniformly distributed over the surface of the dome.

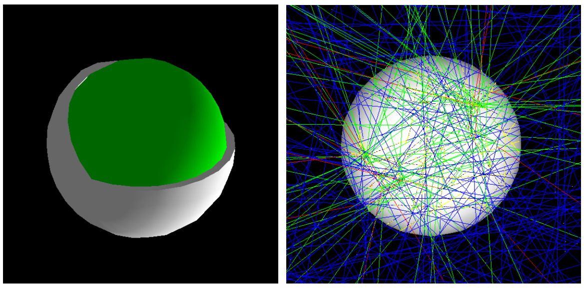

Figure 8: Geometry of the sphere with a cut in shield for better visualization (left). Sphere being irradiated (right). (Images obtained with Geant4)

The way the initial particles are fired into the geometry as well as their species, quantity and energies are defined externally through a macro that is read by the simulation just before the start of the Geant4 run.

Now one must not forget that the fluence rates given correspond to the ones felt at the external surface of the spacecraft and they come in units of particles per square meter per steradian per second. So, if we want to obtain the total number of particles per second that reach the environment inside the spherical dome in the simulation, we must multiply by the area of the spherical dome ($4\pi \times R^2$) and by the angular acceptance of each point in that area (2π). As an example, if the integration of the fluence rates in a given scenario is X $\mathrm{m^{-2}sr^{-1}s^{-1}}$, then, by multiplying by the area that is being irradiated and by the angular acceptance of that area, we get the total number of incident particles Y $\mathrm{s^{-1}}$. Given the spherical geometry used in this work the equation reads:

$$X\ [\mathrm{m^{-2}sr^{-1}s^{-1}}] \times 2\pi\ [\mathrm{sr}] \times 4\pi \times R^2\ [\mathrm{m^2}] = Y\ [\mathrm{s^{-1}}] \tag{6}$$

Y is the number of particles that actually should enter the dome but since the value used in the simulation is N_{gen}, in the end the results must be corrected by multiplying by the factor α:

$$\alpha = \frac{\text{Real number of particles}}{\text{Number of particles in simulation}} \Leftrightarrow \frac{Y}{N_{gen}} \tag{7}$$

Geant 4 has classes that contain different sets of physics processes to simulate the interaction of the particles with matter. In this work the classes used were "G4EmStandardPhysics" that contain the electromagnetic processes and "HadronPhysicsQGSP_BERT" for the hadronic processes. For the case of lunar albedo "HadronPhysicsQGSP_BERT_HP", which includes a more accurate description of neutron interactions from thermal neutrons up to 200 MeV neutrons, was used.

The conditions for the calculation of the absorbed dose and equivalent dose were defined in the "MySensitiveDetector" class whitin the method "ProcessHits". The version of Geant4 used was the 9.4p02.

5. Results

5.1. Absorbed Dose

The results for absorbed dose, obtained with the SRES for each mission phase and weather scenario, are presented in figure 9. Figure 10 contains the values for a shielding thickness 27,8 g/cm^2. In these figures one can imediatelly notice the high doses in VAB, due to the high fluence rates of particles trapped in the belts, and the differences of exposure to radiation from flares from zones inside the magnetosphere (LEO and VAB) to zones outside the magnetosphere (GEO, LLO and SRF). The values presented in Flare are the variation felt in the environment if a SEP occurs. To evaluate the total dose during a SEP, the Flare value should be added to the respective *SolarMin* or *SolarMax* background value.

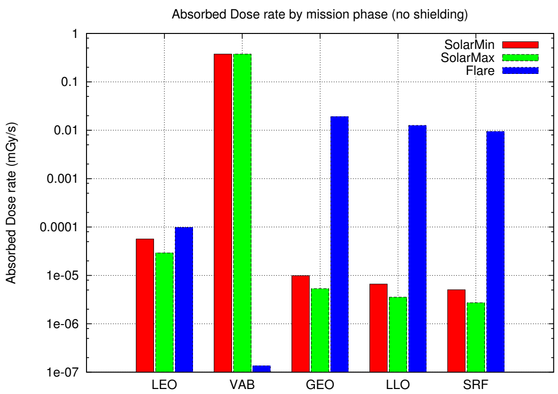

Figure 9: Absorbed dose rates for each weather scenario by mission phase (SRF represents the lunar surface phase). No shielding was considered.

Comparing the two plots it is noticeable the high decrease in the absorbed doses resulting from flares in all mission phases when behind shielding. There is also a huge decrease of the dose coming from trapped protons in VAB. This is easily explained by the cut of the lower energy particles by the shield. The greater fluence rates in cosmic rays come from protons and protons that surpasse a range of 27.8 g/cm^2 in aluminium must have kinetic energies above 180 MeV. So, a huge portion of the protons is being caught by the shield. On the other hand, the dose for *SolarMin* and *SolarMax* scenarios in GEO, LLO and SRF, barely changes because in this phases the dominant particle radiation consists mainly of high energy GCR that can

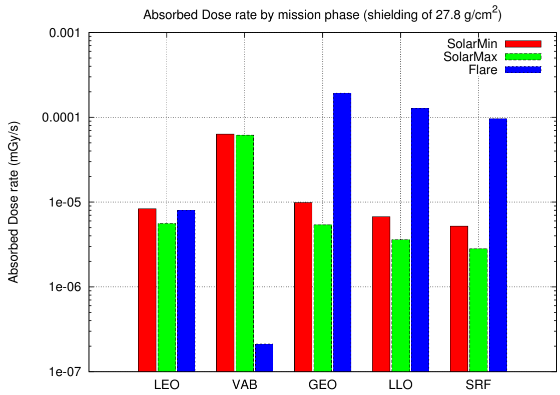

Figure 10: Absorbed dose rates after a shield of 27,8 g/cm^2 of Aluminium (100mm).

easily pass through the shielding.

The values obtained with SRES for absorbed doses are consistent with already published works on space radiation. Doses, without shielding, of 0.9 mGy per day (1.04×10^{-5} mGy/s) are mentioned for the Skylab (435 km altitude) [15] and biodosimetry studies of astronauts who have stayed in the ISS (shielded by the space station) revealed doses of 85 mGy per 6 month (5×10^{-6} mGy/s) [16]. The results obtained for VAB and GEO are also concordant with other works [17].

5.2. Equivalent Dose

The equivalent dose rates in figures 11 and 12 present similar characteristics to the absorbed dose rates. The equivalent dose accounts for the biological sensitiveness to radiation depending on its particle composition. Since the espectre of incident particles is mainly dominated by protons in each phase, the equivalent dose plot for no shielding appears almost just as an increment of the absorbed dose plot. However, when behind shielding secondary particles are generated wich have different weighting factors and the differences between the two quantities become more evident.

As expected, the Van Allen belts is the most risky area, even when behind shielding, but it is also the phase where less mission time is usually spent.

5.3. Lunar Mission Scenarios

By multiplying the equivalent doses in each phase by the time the mission is expected to spend in that phase, we get the total dose for the mission. These doses should now be compared with the PEL for astronauts in order to estimate the risk of radiation exposure. Blood forming organs (BFO) are the most sensitive to radiation, with permissible exposure limits of 0.25 Sv for 30 days exposure and 0.5 Sv for annual exposure. Tables 4, 5 and 6 show the doses already integrated for the lunar mission time and contain below the totals. These are the val-

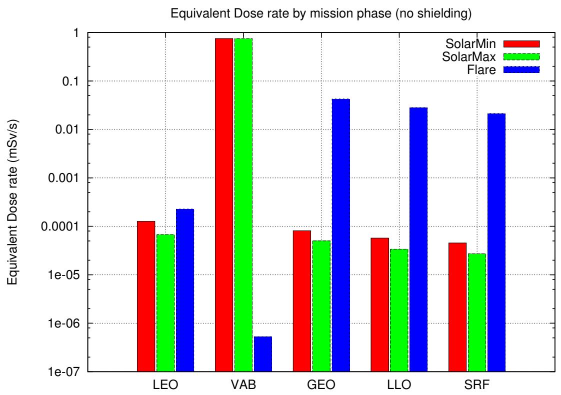

Figure 11: Equivalent dose rates for each weather scenario by mission phase. No shielding was considered.

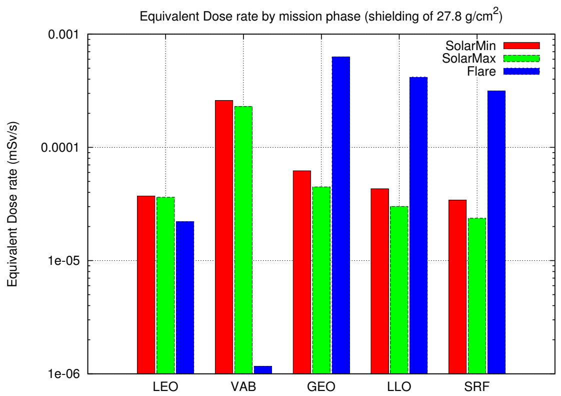

Figure 12: Equivalent dose rates after a shield of 27,8 g/cm^2 of Aluminium (100mm).

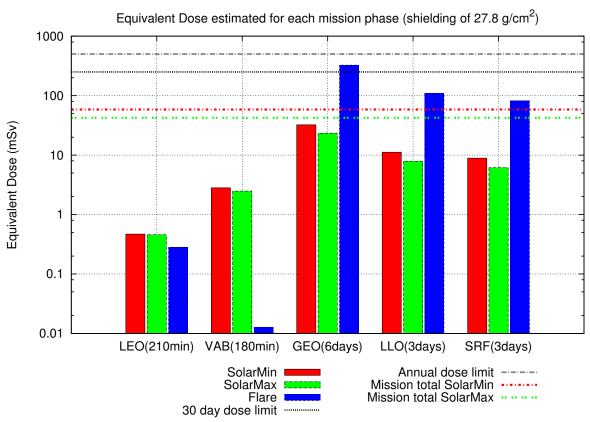

Figure 13: Equivalent dose for each weather scenario considering the total time of the mission under a shielding of 27,8 g/cm^2 of Aluminium (100mm). The horizontal lines indicate the total mission dose and the PEL in BFO.

ues that a dosimeter would supposedly register if it accompanied the astronauts during the trip to the moon. The time for each mission phase was based on the Apollo 17 mission: 210 minutes in LEO, 180 minutes in VAB, 6 days in GEO, 3 days in LLO and 3 days at SRF. Figure 13 shows the equivalent doses for each mission phase integrated in these times (bars) and the sum of the equivalent doses in all phases, for solar minimum and solar maximum scenarios (the two lower horizontal lines), also the dose limits, recommended by ESA, for 30 day and annual exposure in BFO are shown (the two upper horizontal lines). In LEO and VAB phases the equivalent doses are lower than in the other phases, essentially because it is where less time is spent, but also because of the protection of the magnetosphere which cuts a huge part of the particles that come from flares which have the highest contribution to dose in phases outside the magnetic field of the earth.

Mission Phase		Absorbed Dose [mGy] (27,8 g/cm^2)	Equivalent Dose [mSv] (27,8 g/cm^2)
Solar Minimum	LEO	0,11	0,47
	VAB	0,68	2,81
	GEO	5,12	32,21
	LLO	1,74	11,18
	SRF	1,35	8,87
	TOTAL	**9,00**	**55,53**

Table 4: Total absorbed and equivalent doses for a lunar mission during a period of solar minimum.

Mission Phase		Absorbed Dose [mGy] (27,8 g/cm^2)	Equivalent Dose [mSv] (27,8 g/cm^2)
Solar Maximum	LEO	0,07	0,46
	VAB	0,67	2,48
	GEO	2,79	23,23
	LLO	0,94	7,80
	SRF	0,73	6,14
	TOTAL	**5,20**	**40,11**

Table 5: Total absorbed and equivalent doses for a lunar mission during a period of solar maximum.

Mission Phase		Absorbed Dose [mGy] (27,8 g/cm^2)	Equivalent Dose [mSv] (27,8 g/cm^2)
Flare	LEO	0,10	0,28
	VAB	0,002	0,013
	GEO	100,0	326,9
	LLO	33,1	108,3
	SRF	25,0	81,7
	TOTAL	**158,19**	**517,21**

Table 6: Total increment in solar minimum or solar maximum doses if a large solar flare occurs during a lunar mission.

Notice that a single flare event when in GEO, LLO or in the Moon surface (outside the Earth magnetosphere) may exposure the crew to more dose than the total of the mission without any flare, this could be fatal. Remember that the flare doses presented here are from the October 1989 which is one of the most intense SEPs and, in this example, it even reaches the 30 day dose limit. Flares present a serious threat to missions outside the magnetosphere and as space missions tend to last longer it is possible that more than one large flare occurs during a mission.

In order to prevent excessive risks of radiation exposure a good planning of the mission timings could prove to be more efficient than increasing the depth of shielding in the spacecraft. Missions should be planned for periods of solar minimum activity, when flares are less likely to occur. Solar Flares however are not that predictable. Continuous observations of solar activity allow for the existence of flare alarms that give astronauts the possibility to refuge in areas of the spacecraft that provide more shielding. For future longer missions specially shielded areas in the spacecraft are being architected.

6. Conclusions

The work presented in this thesis was mainly focused on the study of the radiation environment in space, its effects in astronaut crews and the development of a software tool (SRES) to systematize a way to simulate that environment taking as an example the case of a lunar mission. The SRES was entirely based on Geant4 and a set of control scripts in C++. The major details on its development were presented and a glimpse of its capabilities revealed in the assessment of dosimetric quantities. The simple spherical model used in the geometry of the simulation environment, as well as the methods of implementing the radiation incidence on the sphere, produced rather good results, in agreement with already existing values for dose in space. Equivalent doses of 55,5 mSv and 40,1 mSv were obtained for astronauts that embark in a lunar mission, during periods of solar minimum and solar maximum activity, respectively, considering a mission duration of 12 days. This values may vary up to 517 mSv if a large flare occurs during the mission.

It is important to note that all results obtained with SRES were based in fluence rates from CREME wich is not specifically designed for dose calculations and is more focused in the effects of radiation in micro-electronics. The approach used was to get from CREME only the fluence tables for the different locations and weather scenarios, all subsequent simulation an dosimetric calculations were entirely based in Geant4. SRES is still far from being a user friendly tool. Some improvements should be considered specially in what concerns to interface and data management. Also, as future work, it should be considered the use of fluence data from different sources such as Spenvis and ApexRad and the results compared to the ones obtained from CREME.

References

[1] Marc Heppener. Spaceward ho! *EMBO Reports*, 9:S4–S12, 2008. doi:10.1038/embor.2008.98.

[2] Review of U.S. Human Spaceflight Plans Committee. Seeking a human spaceflight program worthy of a great nation. Technical report, NASA, 2009.

[3] European Science Foundation. Science-driven scenario for space exploration. 2008.

[4] Journal of the ICRU Vol 10 No 2 (2010) Report 84. Oxford University Press. doi:10.1093/jicru/ndq019.

[5] Journal of the ICRU Vol 11 No 1 (2011) Report 85. Oxford University Press. doi:10.1093/jicru/ndr011.

[6] ICRP, 2007. The 2007 Recommendations of the ICRP. ICRP Publication 103. Ann. ICRP 37 (2-4).

[7] S. Maurice et al. High-energy neutrons from the moon. *Journal of Geophysical Research*, 105:20365–20375, 2000.

[8] Technical Training Center US Nuclear Regulatory Commission. *Reactor Concepts Manual*.

[9] CREME site. `https://creme.isde.vanderbilt.edu/`.

[10] William C. Feldman, Alan B. Binder, and Sylvestre Maurice. Lunar prospector reduced spectrometer data - special products. `http://geo.pds.nasa.gov/missions/lunarp/reduced_special.html`.

[11] Geant4 website. `https://geant4.web.cern.ch/geant4/`.

[12] Journal of the ICRU (1980) Report 33. Oxford University Press.

[13] NASA Human Spaceflight. `http://spaceflight.nasa.gov/shuttle/reference/shutref/structure/structure.html`.

[14] Metal Suppliers Online: Material Property Data. `http://www.suppliersonline.com/propertypages/2024.asp`.

[15] Benton EV, Henke RP, "Radiation exposures during space flight and their measurement" , Adv. Space Res. 1983; 3(8):171-85.

[16] Cucinotta FA, "Physical and biological organ dosimetry analysis for international space station astronauts". Radiat Res. 2008 Jul;170(1):127-38.

[17] Foelsche T. "Estimates of radiation doses in space on the basis of current data". Life Sci Space Res. 1963;1:48-94.