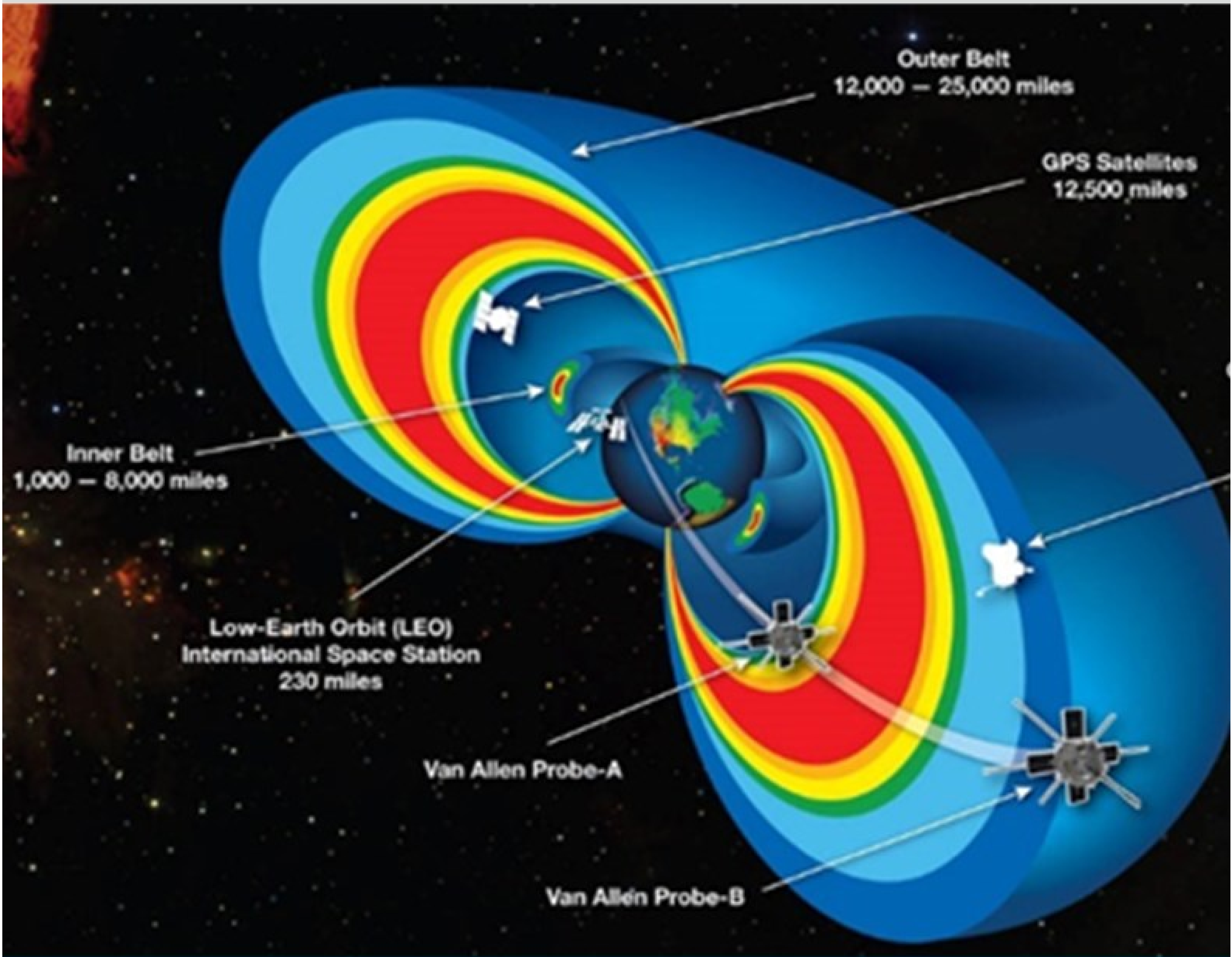
Orbits & Radiation

Teacher guide
Higher secondary



●●●●●● Introduction to satellites and their environment ●●●●●●●
●●●●●●● Space weather and space radiation explained ●●●●●●
●●● Calculate expected doses on different space locations ●●●
●●● Use the online SPENVIS tool in educational exercises ●●●●

OVER ESERO BELGIUM

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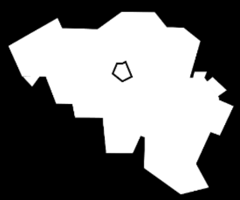

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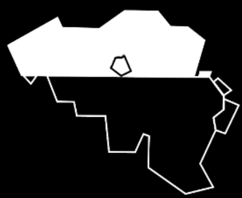

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Orbits & Radiation

Teacher guide

Properties

Target group	Teachers higher secondary education Physics and Geography.
Type	Background learning topics + SPENVIS application for radiation estimations
Teaching time needed	Minimum 2 lessons
Requirements	▪ Computers with internet connection
What students will learn	▪ Satellite techniques and orbits ▪ Space Weather ▪ Space Radiation Environments ▪ Space Radiation Effects ▪ SPENVIS simulation tool

Summary

Travelling to space is exciting, and soon people will go back to the Moon and stay there. The next destination will be Mars. But one of the biggest issues is: what about space radiation?
In this course we will learn to estimate the radiation dose in different space orbits around Earth, including the distance of the Moon. BIRA scientists use the professional online tool SPENVIS to estimate radiation doses for research, but in this course they help us to use it as an educational exercise. The exercise topic is about radiation on electronic devises in our spacecraft. Before starting the SPENVIS exercises, we give a general introduction about radiation in space, and its consequences for spacecraft operation and human activities.

Colofon

First edition	Octobre 2022
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Content

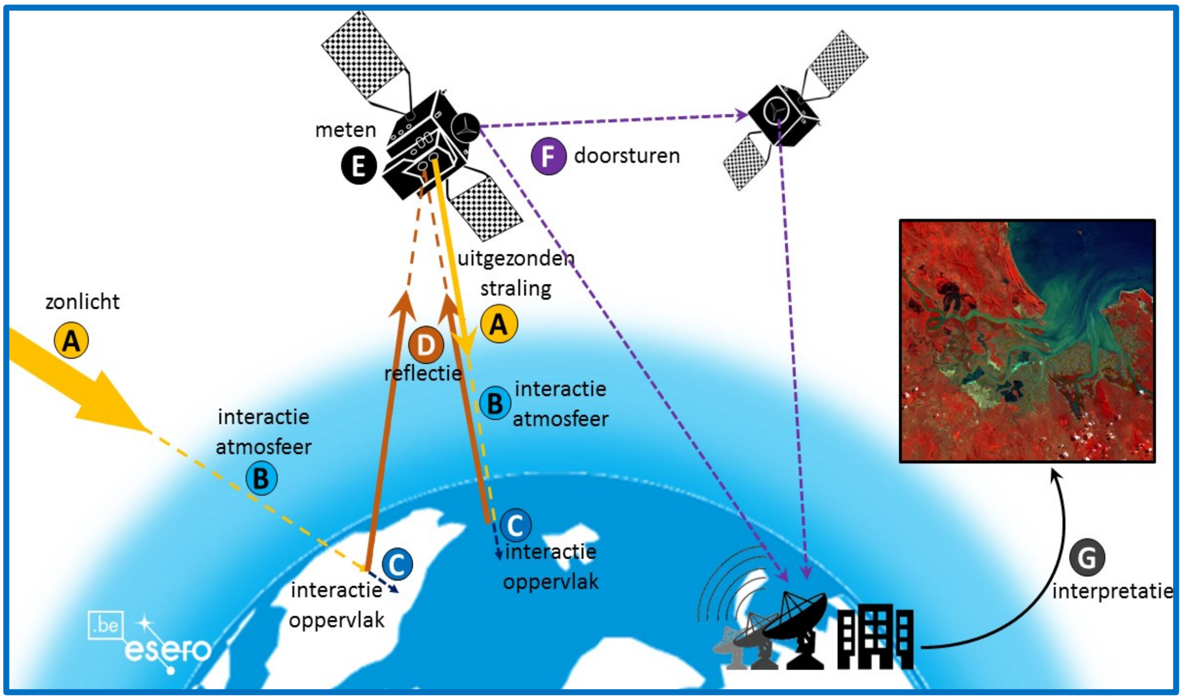
1 Satellites

Satellites today: introduction

Satellite techniques: principles

Earth observation components

Earth observation with satellites is realized not only by the satellite itself, but rather by a chain of components. This chain is pictured below



Chain of Earth observation components. Credits: ESERO BE.

First of all, you need a signal that can be measured or imaged (**A**). This signal might be a natural signal, for example the reflection of sunlight on the surface of the Earth (**D**). Another example is the infrared radiation that the Earth is constantly emitting because of the surface temperature. If the measured signal is indeed a natural one, than the technique is called "passive remote sensing".

However, the satellite can also produce its own signal (**A**), for example by sending a laser beam or radio wave to the ground. When we measure (**E**) the reflected signal that was originally sent out by the satellite, we call the technique "active remote sensing".

In both techniques the information that is to be detected in the signal (**E**) will be influenced by the reflection on the ground and by passing the Earth's atmosphere (**B**). Therefore, scientist must be aware of both sources of information when they try to analyse any satellite image.

The data that are measured by the satellite have to come back to Earth. So any satellite will also have devices that are sending all data to a ground station (**F**). Some satellites are better equipped or are on a better location, and are therefore used as a relais between the ground station and other satellites.
The ground station is used to collect the continuous flow of data and to send back commands to the satellites if any adjustment of position or measuring instruments is needed.

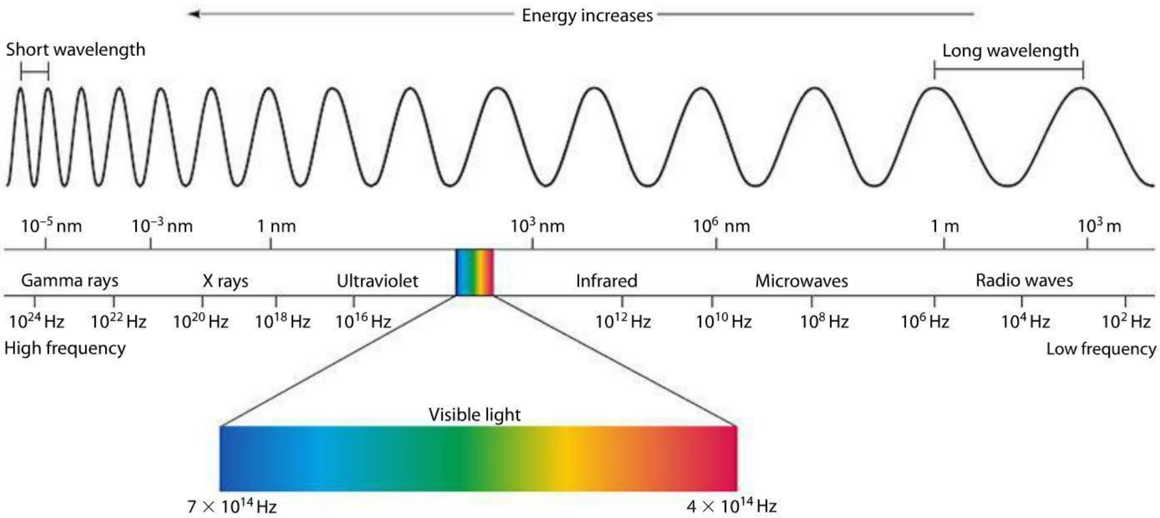
Once the data are collected on the ground, the real work for earth observation scientists gets started. The output of their work are often maps of the surface containing a lot of detailed information that is hard to measure without satellite observations. For picture in visible light, the image can be shown in real colours. But most often, they need to map data that were not visible to the human eye. Then scientists will use colour codes to show the information on a map in ‘false colours’ (**G**). We are familiar with false colour maps in any school atlas, like for example topographic maps showing altitudes. Today anyone can view the Earth in an almost infinitive number of false colour maps showing a very wide range of data and their evolution over time.

Exercise:
Go online to the free Earth observation viewer “Terrascope” and browse a bit through the many satellite layers in your own environment.

Remote sensing

The principle that satellites use are based on ‘teledetection’ or ‘remote sensing’. It means that properties of the Earth are measured or imaged from a distance, without physical touch. There are different signals that can be used for remote sensing: electromagnetic radiation, gravitational fields, magnetic fields, …

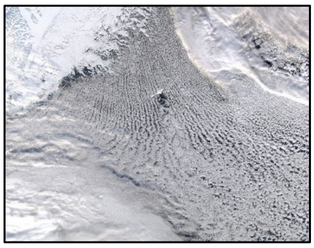
Of course, the electromagnetic spectrum is the most used category of teledetection signal for Earth observation. We often think of visible light (‘normal’ pictures) as a main source of information. But very often, visible light is not enough to examine the structures and properties that we study with Earth observation satellites.



Electromagnetic spectrum. Only the 'visible' light can be detected by human eyes. But all other wavelengths also appear on the Earth, and can be detected by specific sensors on satellites. Credits: https://www.miniphysics.com/electromagnetic-spectrum_25.html

Infrared remote sensing

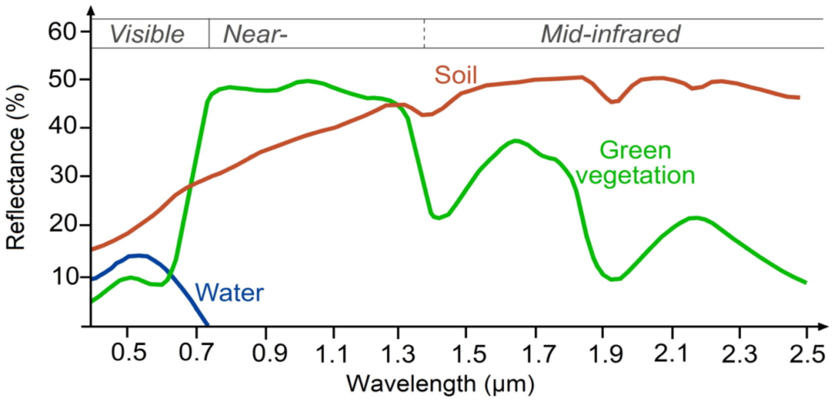
Take the example below.
You see 3 images of the Earth taken from a satellite. They all have white patterns that are not very easy to identify. White colour can represent several elements on Earth. Can you guess the identity of all white elements on the pictures?



Let your students guess what they see on these 3 pictures in visible light.
The answers:

Left: East Greenland: ice at the coast (picture: NASA),
Middle: White Sands National Parc USA (picture: Google maps),
Right: Clouds.

Now, if we add more wavelengths than only visible light, we can much better identify the white colours for what they are. Near infrared for example is absorbed strongly by water, reflected by soil (that also reflects a lot of visible light), and even more strongly reflected by vegetation (chlorophyl, that also absorbs a lot of visible light). This is a good reason to add NIR images on the visible ones. It is the task of Earth observation scientists to combine these layers/bands and make new images of the Earth containing more detailed information.

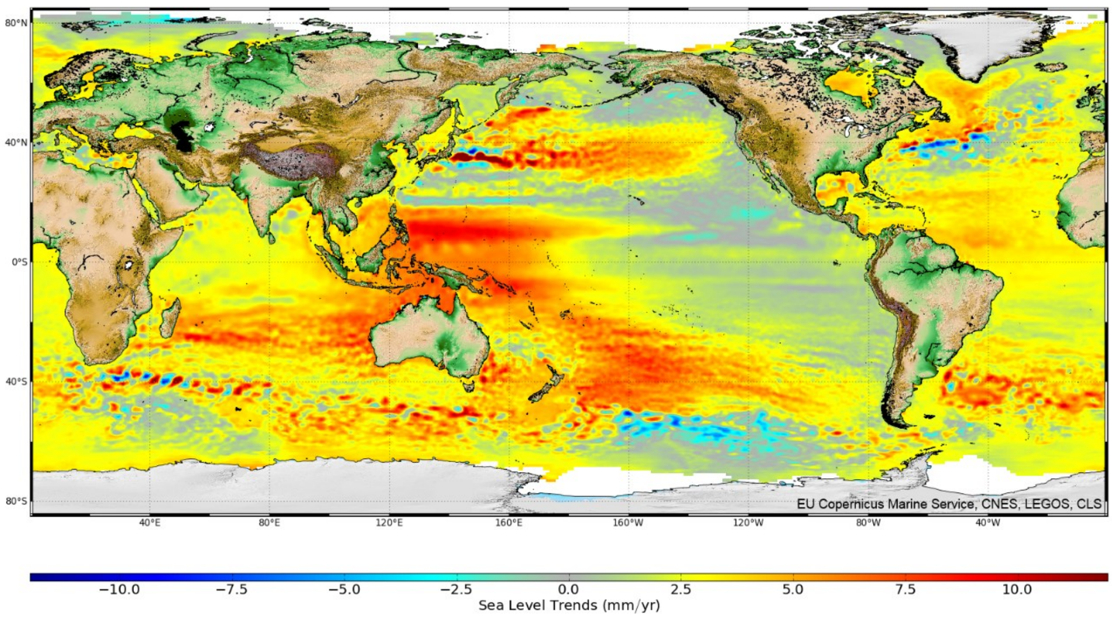


Radar altimetry

Another example of remote sensing is Radar Altimetry. This name is composed of 3 words:

RADAR : Radio Detection And Ranging,
Alti: altitude or height,
Metry: measuring.

So, European satellites like Sentinel-3 have an instrument that send radio waves (Radar) towards the Earth surface. Like all electromagnetic radiation, radio waves travel at light speed. These radio waves are reflected on the surface, and go back to the satellite. When the reflected waves arrives at the sensor of the satellite, we can measure exactly how long the wave was on its way. As the speed is well known, the duration of the wave going down and back is sufficient to calculate the exact distance between the satellite and the point of reflection on the Earth surface. This way, we can make detailed topographic maps of all places on Earth.
Not only the altitude of land is measured this way. There is also a worldwide variation in sea surface level, that is very important to study climate-related sea level rise.



Altitudes measured by Radar altimetry (Sentinel-3, ESA).

Vegetation index

The chlorophyll in plants has the property to reflect near infrared radiation (NIR) almost completely. Otherwise the leaves would get too hot very soon when they receive sunlight. Visible light on the other hand, is largely absorbed by chlorophyll. This light forms an energy source for photosynthesis, and thus for plant growth.

When we combine a photo from space in visible light with a photo in 'near infrared' (NIR), then it is clearly shown in that photo where the largest concentration of chlorophyll is detected. These are the zones where much reflected NIR and little visible light is perceived. A high concentration of chlorophyll represents a well-developed (or healthy) vegetation. With such combined photos (multispectral imaging) we can therefore collect all kinds of data about the presence and vitality of natural vegetation or crops.

Combined picture VIS + NIR of Tenerife as measured by the Belgian Proba-V satellite. The dense red areas have much more vital (productive, green) vegetation.

Orbits

<Under construction>
How can a satellite stay in orbit?
Calculate orbits yourself

- Exercise: compare a LEO and GEO orbit – which one has the highest speed?

Most common orbits

- Inclinations, polar, equatorial
- LEO, MEO, Geostationary
- Lagrange
- Around other objects than Earth

2 Space Weather

Earth and its neighbouring space

Before introducing Space Weather and discuss its impact on Earth it is useful to give a brief description of the space surrounding our planet.

We know that the space environment is harsh and can be harming to humans and life in general. However, Earth's atmosphere provides us with some protection against these dangers.

We are relatively safe when we stay close to the surface of our planet and inside to what is known as the troposphere. This is the lowest layer of the atmosphere and it extends from the surface of the planet up to 9-18 km. It contains 75% of total mass of the atmosphere and it is where most of the weather phenomena occur. The normal cruising attitude of passenger airplanes (11 km) and the peak of Mount Everest (8,848 km) are situated inside the Troposphere.

Moving upwards we encounter the next atmosphere layer that is called the stratosphere. It extends up to 50 km from the surface of the Earth. In contrast with the troposphere there is an increase of the temperature with altitude due to the absorption of the Sun's ultraviolet (UV) radiation by the ozone layer.

Weather balloons can reach altitudes of 40 km and sometimes more before disintegrating due to their expansion. The altitude record for a manned balloon is hold by Alan Eustace who climbed up to 41,425 km on October 24, 2014.

➔ **Action for schools**

In the ASGARD project for secondary schools we offer the opportunity for students to create and run a scientific experiment in the stratosphere (up to 30 km altitude). Go to www.esero.be > projecten > AGARD to learn more.

The next atmosphere layer is called mesosphere and it spreads up to 80-90 km above the surface of Earth. In this layer, temperature decreases as altitude increases.
Some typical phenomena associated with the mesosphere are the noctilucent clouds (the highest clouds in Earth's atmosphere) and meteors. A meteor (known also as shooting star) typically occurs due to aerodynamic heating at altitudes from 76 to 100 km when for example a meteoroid enters Earth's atmosphere at high speed.

Above mesosphere we encounter the thermosphere and it extends up to 800 km. The ionised part of the upper atmosphere due to the incident UV radiation (known as the Ionosphere) lies inside the mesosphere. The orbits of the International Space Station (ISS) and the Chinese Tiangong space station are also situated inside the thermosphere at altitudes of 408-410 and 350-450 km respectively. The aurora (polar lights) phenomenon also occurs in this layer.

The most outer layer of the atmosphere that covers distances where particles are still gravitationally bound to Earth is called the Exosphere and it extends up to 10000 km.

Any satellites with a maximum altitude up to 2000 km is said to travel on a Low Earth Orbits (LEO). LEO satellites with altitudes up to 600 km can experience atmospheric drag from gases in the atmosphere and orbits with altitudes below 300 km can decay fast because of that. Also, the increase of space debris (e.g. due to the frequency of launches) is a growing concern for the safety of spacecraft.

Beyond the atmosphere of Earth one can encounter the satellite constellations supporting the various global navigation satellite systems (GNSS). For example, the EU Galileo spacecrafts are situated at 23.222 km and the US Global Positioning System (GPS) satellites at 20.180 km.

Farther out, the geosynchronous satellites are orbiting Earth at a constant altitude of 35.786 km. Finally, our natural satellite the Moon has an orbit that brings it at its closest to Earth (Perigee) at 362.600 km.

The cartoon below gives a visual overview of Earth's neighbouring space from the planet surface to the Moon (Note that the picture is not to scale).

➔

Exercise
Look up how noctilucent clouds are formed and when/where they can be observed.
Answer
Noctilucent clouds are extremely rare collections of ice crystals, occasionally appearing in late clear summer evenings after sunset, but before it gets completely dark. They become visible about the same time as the brightest stars appear and often stay visible after dark because they are still reflecting sunlight due to their great height. They are higher up than any other clouds, occupying the layer of atmosphere known as the Mesosphere, and are only seen at latitudes between 45°N and 80°N in the Northern Hemisphere, and equivalent latitudes in the southern hemisphere. They are seen less often in the southern hemisphere as there is very little land and very few people there. Only the southern tip of Argentina and Chile, and the Antarctic are at the correct latitude. Like many clouds, noctilucent clouds need water vapour, dust, and very low temperatures to form. The dust may well come from tiny meteors from space, although dust from volcanoes or man-made pollutants may add to these. (source: https://www.metoffice.gov.uk/weather/learn-about/weather/types-of-weather/clouds/other-clouds/noctilucent)

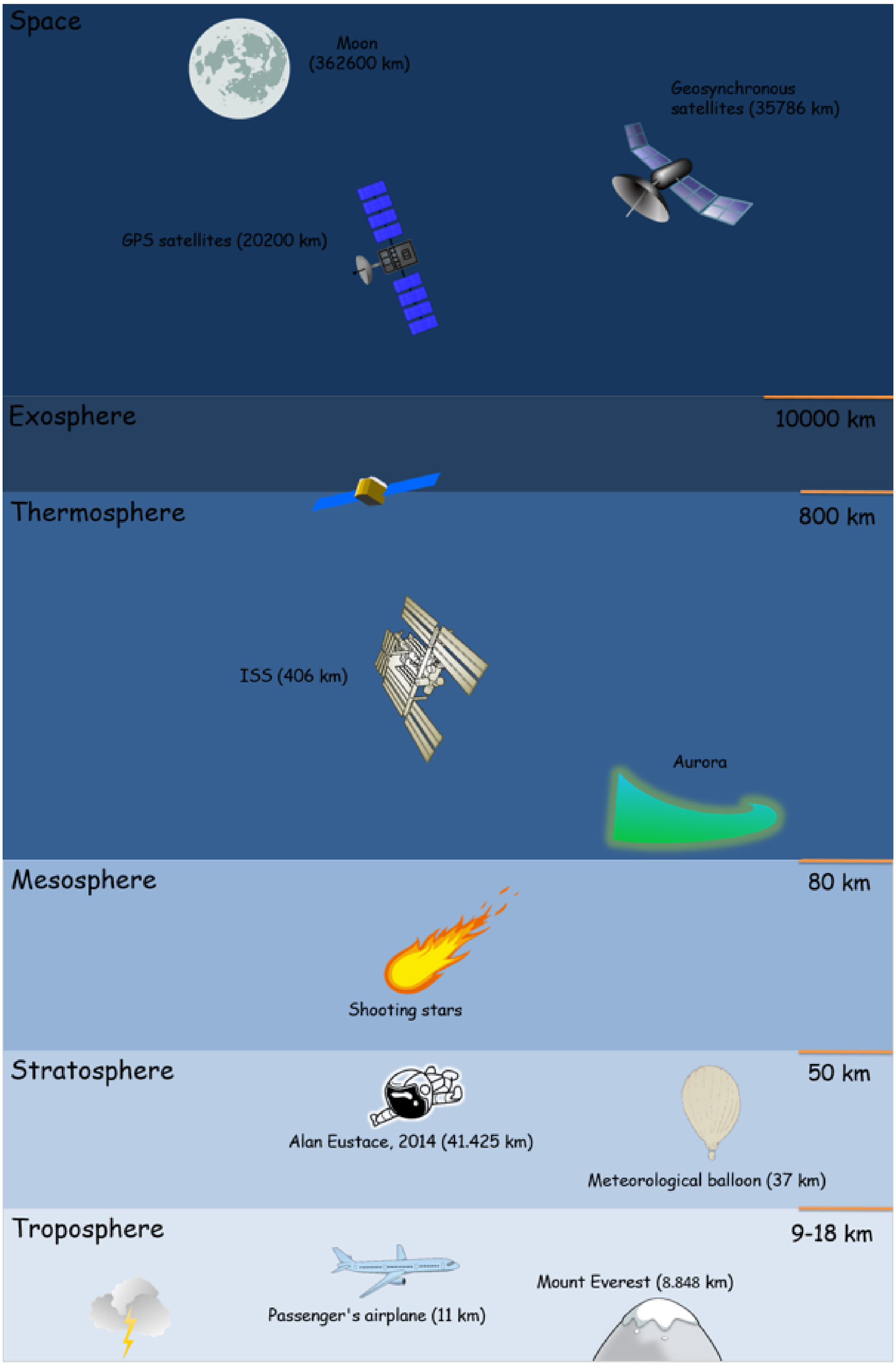


Figure 1 Earth's neighbouring space

The Sun as the driver of Space Weather in the heliosphere

Our local star, the Sun provides a steady source of energy to Earth in the form of electromagnetic radiation (including visible light and UV radiation) and a stream of charged particles released from the upper atmosphere of the Sun known as the solar wind.

Nevertheless, the Sun is also an active star responsible for periodically stormy outbursts that can potentially cause disturbances in our space environment and on Earth. Some energy outbursts go with the release of immense clouds of solar material (Coronal Mass Ejections). When directed towards Earth, they can cause large storms in the magnetosphere and the upper atmosphere.

When we talk about Space Weather we actually refer to the varying conditions on the Sun, the escaping solar wind and the surrounding space of a planet for example Earth's magnetosphere, ionosphere, and thermosphere. Space Weather can influence the performance and reliability of space-borne assets (artificial satellites) but also ground-based technological systems. Moreover, it can endanger the health of astronauts and in general can potentially disrupt out daily life here on Earth.

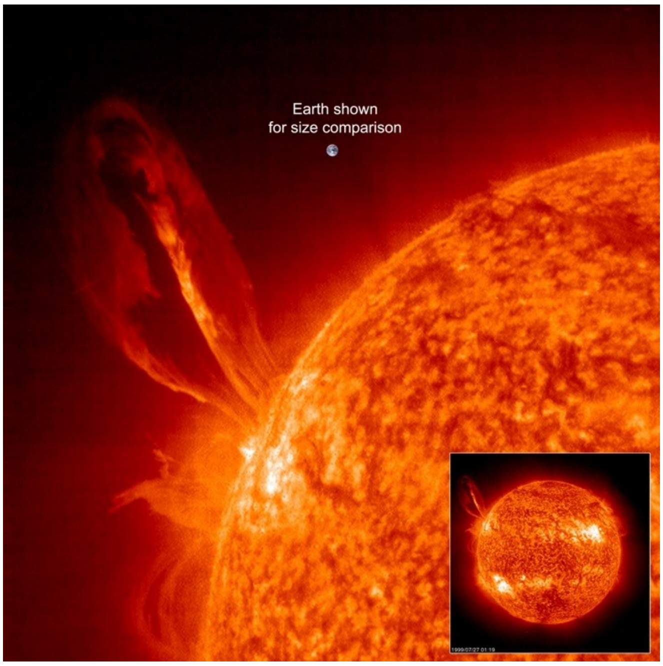


Figure 2 A picture of a Coronal Mass Ejection (CME) above the Sun's surface. A CME can release of large amount of matter and electromagnetic radiation into space.

It should be pointed out that the solar activity varies with a period of about 11 years commonly known as the solar cycle. The solar activity is typically measured in terms of the number of observed sunspots on the surface of the Sun. Hence, solar maximum and solar minimum refer to the periods of maximum and minimum sunspot counts respectively. Each cycle span from one minimum to the next. In general, a solar cycle reflects the magnetic activity of the Sun and its magnetic field flips during each solar cycle when it is near its maximum.

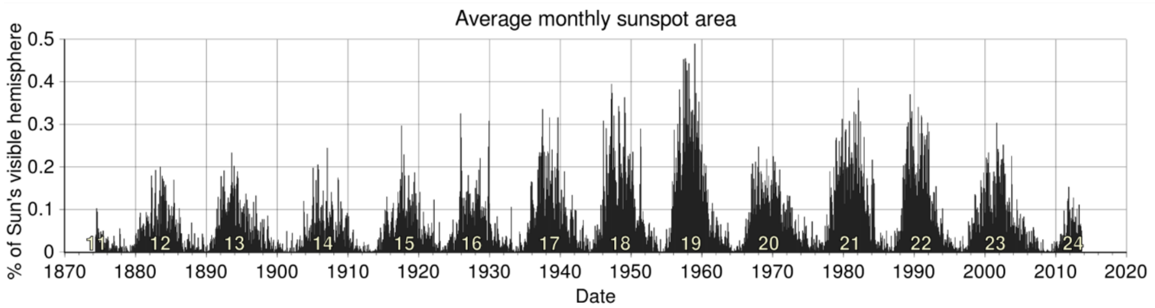


Figure 3 Average monthly sunspot area for different solar cycles.

If we look at the recorded sunspot activity over the last four hundred years, we can see that the amplitude of the sunspot cycle is not constant but varies between different cycles. An average cycle has a peak sunspot number of about 150. However, there are also times when the solar activity becomes so weak so that no sunspots can be observed for an extended period of time (for example the period from 1645 to 1700 known as the Maunder Minimum).

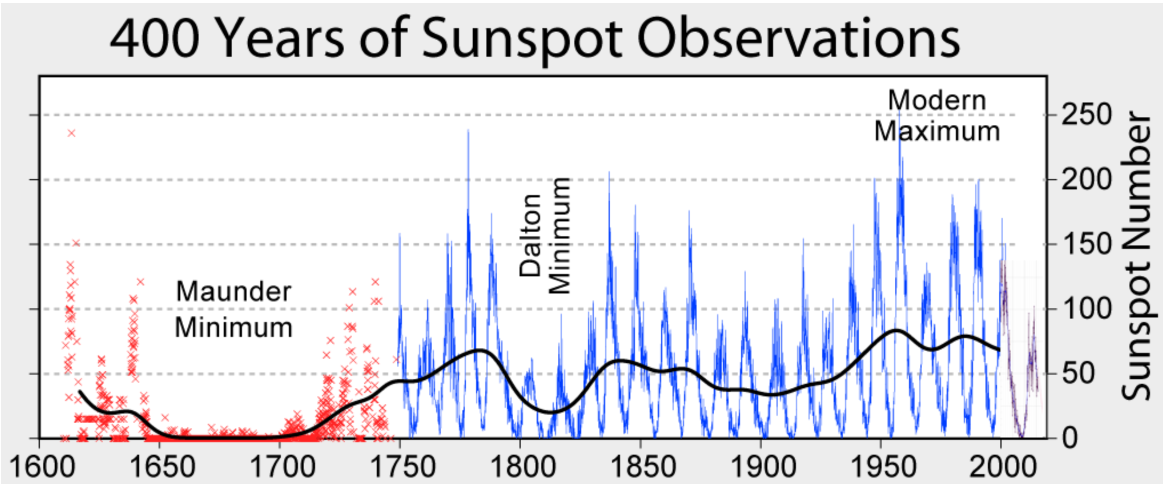


Figure 4 Sunspot observations over a period of 400 years.

Exercise
Look up the current solar cycle and activity phase (i.e. solar minimum or maximum period).
Answer
Check https://www.sidc.be/SILSO/home

In addition to radiation from the Sun, the heliosphere is also filled with the always present Galactic Cosmic Rays (GCR) consisting of high-energy particles (ranging from hydrogen to uranium) and coming from outside the solar system produced in very energetic events. These atoms have lost most of their electrons (i.e. positively charged), which makes that they are deflected by the magnetic field of the Sun and the Earth. Some reach the top of the Earth's atmosphere, colliding with atmospheric molecules whereby creating showers of secondary particles (see later chapter 3). The particles that reach the ground make up 10 to 12 % of the natural background radiation and can be measured with sensitive instruments like neutron monitors. Because of the Suns changing magnetic field during its 11-year solar cycle, the intensity of the GCR is not constant. This can be seen in the table below that gives the yearly averaged sunspot number (SSN) and neutron flux measured at ground by the neutron monitor station located in Dourbes, Belgium (50.10° N, 50.10° N). The larger the average sunspot number (SSN), the higher the solar activity and the stronger the Sun's magnetic field.

Table 1 Measured neutron flux at ground by the neutron monitor station in Dourbes. Sources: Sunspot Index and Long-term Solar Observations (https://www.sidc.be/silso/) and Neutron Monitor Data Base (https://www.nmdb.eu/nest/).

Year	SSN	Counts/s	Year	SSN	Counts/s
1968	150	100	1994	45	111
1969	149	100	1995	25	111
1970	148	105	1996	12	111
1971	94	107	1997	29	108
1972	98	105	1998	88	106
1973	54	104	1999	136	102
1974	49	107	2000	174	104
1975	23	107	2001	170	103
1976	18	108	2002	164	102
1977	39	105	2003	99	108
1978	131	101	2004	65	108
1979	220	100	2005	46	113
1980	219	98	2006	25	115
1981	199	97	2007	13	115
1982	162	100	2008	4	115
1983	91	101	2009	5	113
1984	61	106	2010	25	110
1985	21	109	2011	81	108
1986	15	109	2012	85	107
1987	34	104	2013	94	103
1988	123	95	2014	113	103
1989	211	94	2015	70	104
1990	192	95	2016	40	105
1991	203	103	2017	22	110
1992	133	108	2018	7	112
1993	76	109	2019	4	114

Exercise
Make one plot with the yearly average sunspot number and the neutron flux as function of time. In MS Excel you can make a combo line plot. What can you say about the relationship between the sunspot numbers and the neutron flux?
Answer
The sunspot numbers and the neutron flux are anticorrelated i.e. maximum SSNs (= maximum solar activity, and therefore maximal magnetic field strength around the Sun) correspond to minimal neutron fluxes. This is because the ever present galactic cosmic rays are more guided away from the Earth following the magnetic field lines during solar maximum. This variation reflects the 11-year solar cycle with ~7 years of solar maximum activity and ~4 years of solar minimum activity.

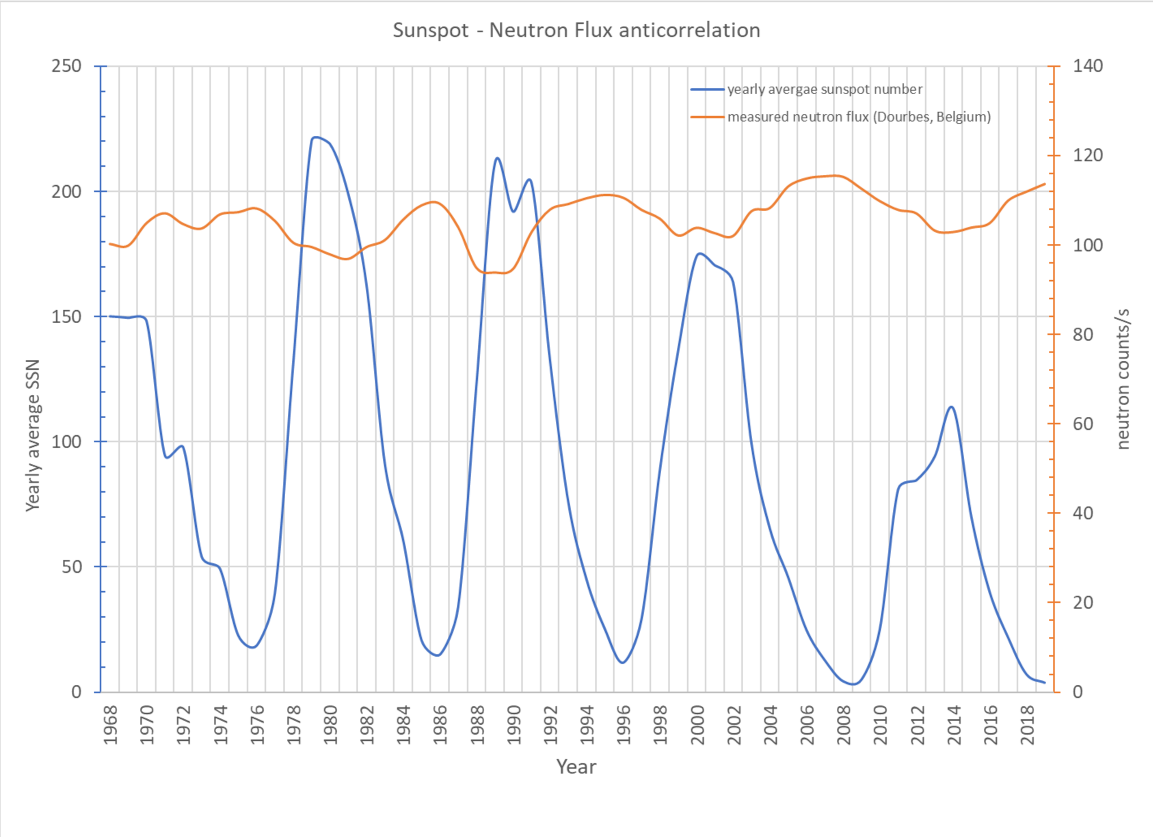


Figure 5 Excel plot of solar activity and neutron counts.

Examples of Space Weather and its impacts on society

Nowadays we are reliant on technology in many aspects of our life. As a result, there are numerous sectors that can be potentially affected by Space Weather. These include sectors depending on space-based technologies (e.g. broadcasting, weather services, navigation) but also other sectors such as electric power distribution and resource exploitation, especially when operated at high latitudes.

The effects of Space Weather can be observed in the degradation of spacecraft performance, reliability and eventually its lifetime. Furthermore, Space Weather can increase the health risks for astronauts especially when participating in extravehicular activities (= EVAs). It also affects operation in the aviation sector and influences the radiation doses received by the crew and passengers. In case of extreme space weather events, the effects on ground can include damage and disruption to power distribution networks, decreased pipeline lifetime and interruption of HF radio communications.

The table below shows different solar activities that can influence Space Weather and the amount of time required to arrive if directed towards Earth.

Table 2 The different solar activities impacting space weather and corresponding arrival time at Earth

Solar activity	Amount of time for Earth arrival
Solar wind	13 hours to up to 4 days
X rays, EUV, radio waves (electromagnetic radiation in general)	8 minutes
Solar Energetic Particles (SEPs)	20 minutes to up to few hours
CME	days

Next, we list some notable historical events that can be referred when discussing the Space Weather impact on our planet and its surrounding environment.

The Carrington Event on 1-2 September 1958

It is currently the most intense geomagnetic storm recorded in history. It caused widespread disruption of telegraph services in Europe and North America and generated global aurora displays. It is named after one of the two British astronomers (Richard Christopher Carrington and Richard Hodgson) who independently observed and recorded the event. Luckily the Carrington occurred before the space age and at a time when our reliance on technology was limited.

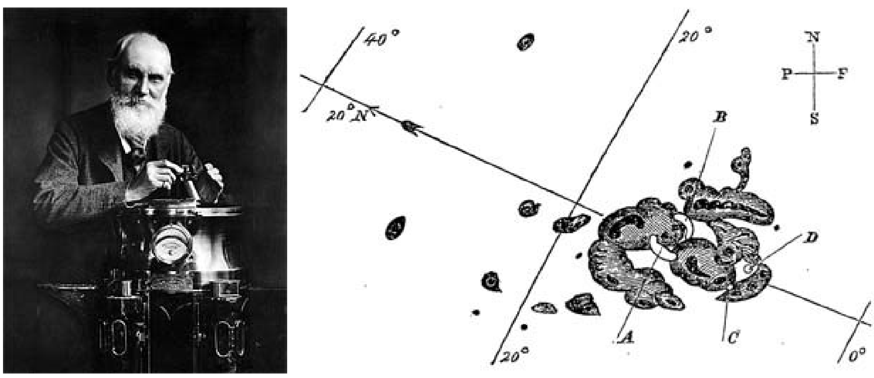
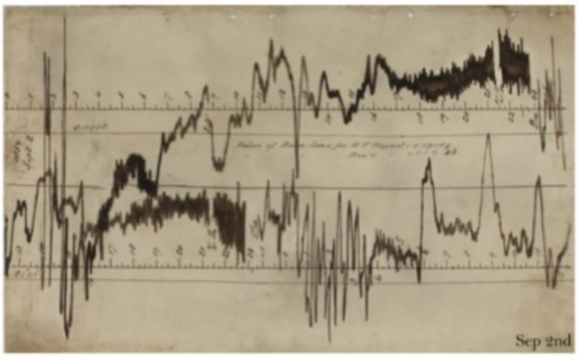
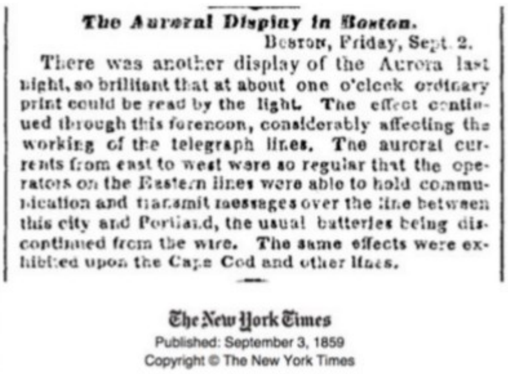


Figure 6 A sketch by Richard Carrington (left) showing the sunspots of 1 September 1859




The Auroral Display in Boston.

Boston, Friday, Sept. 2.

There was another display of the Aurora last night, so brilliant that at about one o'clock ordinary print could be read by the light. The effect continued through this forenoon, considerably affecting the working of the telegraph lines. The auroral currents from east to west were so regular that the operators on the Eastern lines were able to hold communication and transmit messages over the line between this city and Portland, the usual batteries being discontinued from the wire. The same effects were exhibited upon the Cape Cod and other lines.

The New York Times

Published: September 3, 1859

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Figure 7 *Left: A magnetogram of one magnetic storm of 1859, known as the Carrington Event, the same event recorded at Greenwich Observatory in London. Right: New York Times report on the same event*

The solar storm on 23 May 1967

This solar storm nearly caused a nuclear war. Blackout of polar surveillance radars during Cold War led US military to scramble for nuclear war. On-duty officers at the US Strategic Air Command had less than 30 minutes to determine if this was a natural phenomenon or the beginning of a Soviet attack. Fortunately, they confirmed that the radar jamming was a natural occurrence caused by the solar storm and the crisis was averted.

National Geographic article about the solar storm on 23 May 1967:
https://www.nationalgeographic.com/science/article/solar-storm-1967-space-weather-cold-war-science

The solar storm on 9-13 March 1989

This geomagnetic storm (triggered by two separated CMEs) caused a nine-hour outage of the Hydro-Québec's electricity transmission system. These resulted blackouts in Quebec and North America affected millions of people.

Figure 8 Damage done to a transformer at the Salem Nuclear Power Plant in New Jersey US during the 1989 solar storm

The 2003 Halloween solar storms

These were a series of solar storms (involving solar flares and CMEs) that occurred from mid-October to early November 2003. The peak of the event was around 28 – 29 October.

These storms affected satellite-based systems and communications. As a result, airplanes were advised to change their flight path and avoid high altitudes near the polar regions. Moreover, there was a power outage in Sweden that lasted for an hour and twelve transformers in South Africa were damaged and had to be replaced. Aurorae were observed at latitudes as far south as Texas and the Mediterranean European countries.

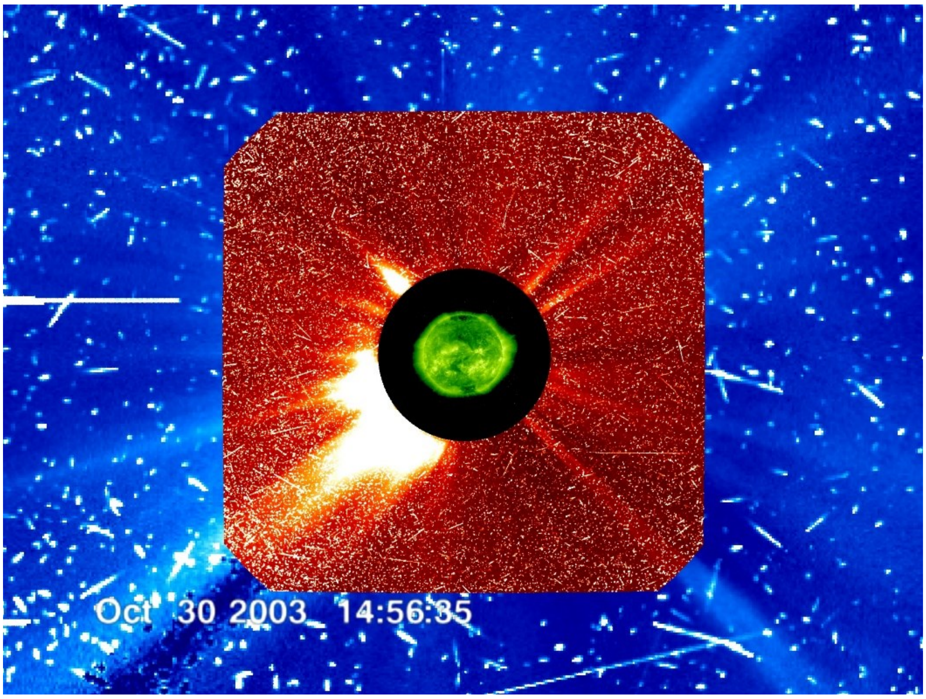


Figure 9 Solar protons from the Earth-directed coronal mass ejection (CME) generate speckles in the CCD (Charged Coupled Devices) detectors of the SOHO spacecraft cameras

The battle of Takur Ghar, Afghanistan 4 March 2002

During operation ANACONDA (1-18 March 2002) a Navy SEAL team was pinned down on a ridge by Taliban forces. When a MH-47 Chinook helicopter was deployed to support them, they tried to inform their command that the landing zone was “hot” and that they should look for an alternative landing place.

However, this vital message was never received. As a result, the incoming Chinook helicopter came under heavy enemy fire and crashed landed. The subsequent firefight led to three reported US fatalities.

It has been shown that Space Weather affecting the ionosphere has been the cause for these radio communications disruptions.

Solar-Terrestrial Centre of Excellence News article about The battle of Takur Ghar:
https://www.stce.be/news/420/welcome.html

The Starlink satellites destruction event on 4 February 2022

Starlink satellites are small satellites that form a constellation and are used for providing satellite internet service. They are operated by SpaceX that started launching them in 2019.

These particular Starlink satellites were initially placed at an orbit of 210 km so that any malfunctioning satellites could be quickly burned in the upper atmosphere instead of becoming space debris. Normally the remaining functioning satellites would have been then raised up to their operational altitude 500 km using their ion thruster.

Two successive geomagnetic storms triggered by two separate CMEs in the direction of Earth warmed the upper atmosphere and increased the atmospheric drag. As a result, 38 of the working Starlink satellites were destroyed before they were lifted to their higher orbit. The estimated economic loss was significant.

News articles about the Starlink satellites destruction event (to show the clear link with general news from media):

- https://nos.nl/artikel/2416511-spacex-verliest-40-van-49-satellieten-vervelend-maar-niet-onoverkomelijk
- https://www.hln.be/wetenschap-en-planeet/spacex-verliest-wellicht-40-starlink-satellieten-door-geomagnetische-storm~ab371d86/

3 Space Radiation Effects

Space radiation intensities and energies

Radiation is energy spread through space or matter in the form of waves or particles, either created by humans (e.g. microwaves, nuclear reactors, ...) or naturally occurring (e.g. stars, radiation from rocks, ...). Apart from the less energetic UV, IR and other electromagnetic waves emitted by the Sun, space radiation is mainly composed of atoms that have lost some or all of their electrons and have been accelerated during energetic processes (e.g. solar flares) in space up to speeds that can approach the speed of light (Figure 10). There are three sources of space radiation:

- Galactic Cosmic Rays (GCR), mainly high energy protons and heavy ions originating from outside the solar system largely produced in exploding heavy stars (aka supernovae);
- Solar Energetic Particles (SEPs) emitted by the sun in erupting solar flares or accelerated in shock waves produced when parts of the solar corona are ejected (aka SEP events);
- Particles trapped in the magnetic field of planets, like the Earth's Van Allen Radiation Belts (RBs) as illustrated in *Figure 11*.

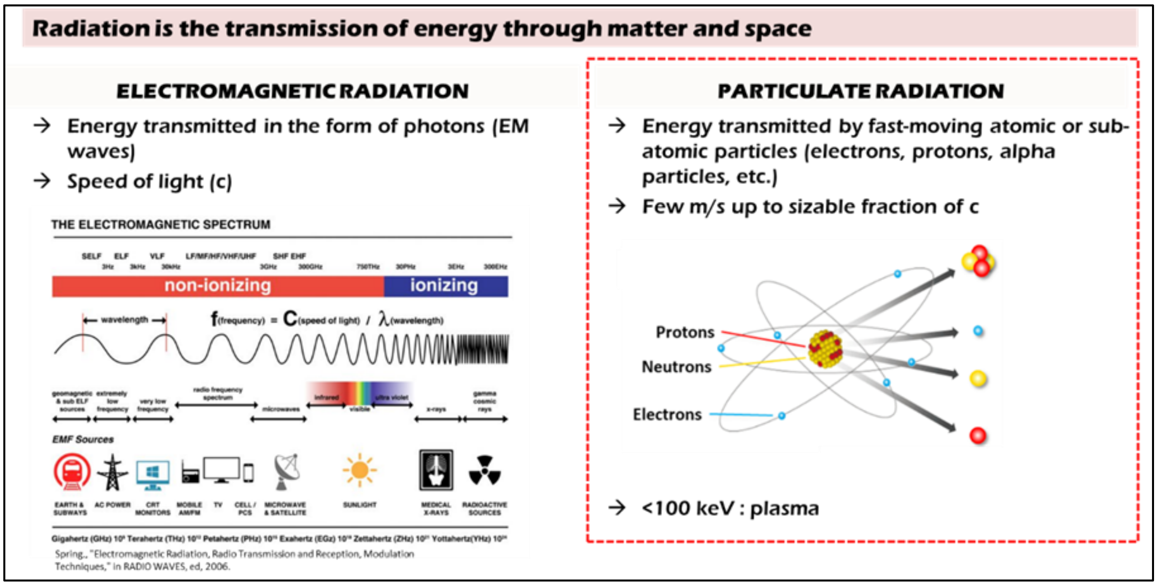


Figure 10 Two forms of radiation exist: EM and particulate radiation. Particles with energies smaller than 100 keV are considered as space plasma

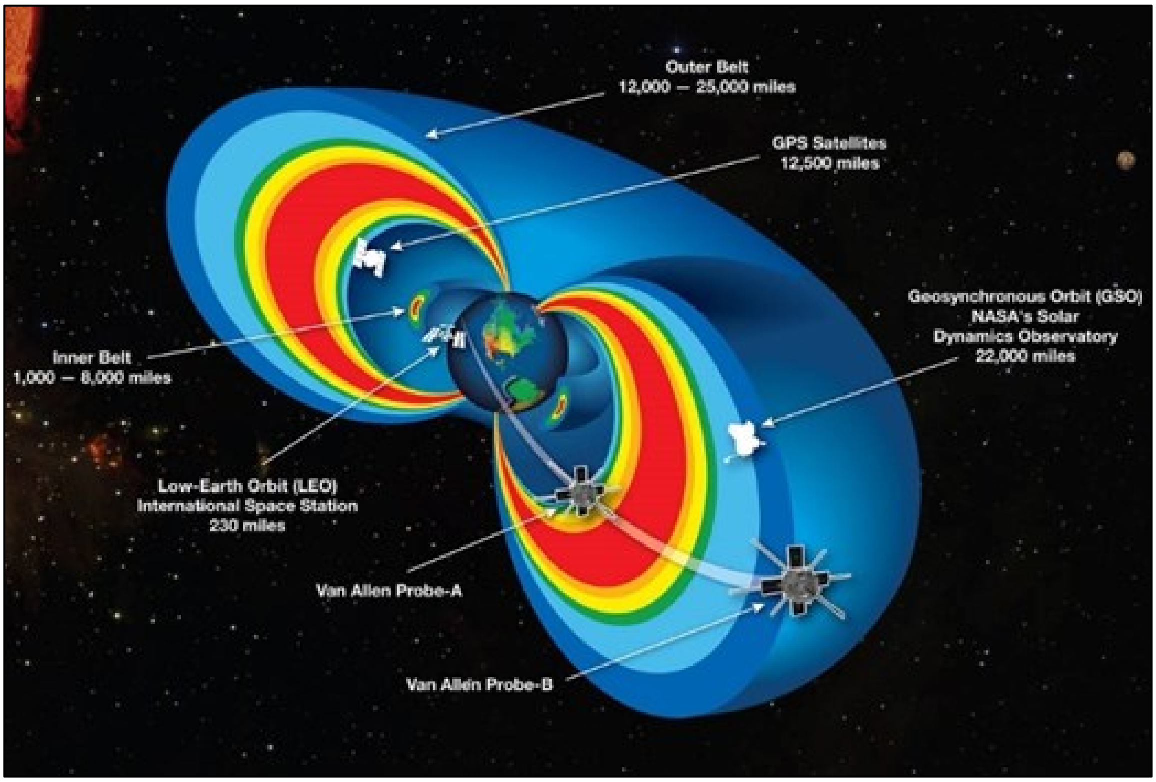


Figure 11 A schematic view of the donut shaped Van Allen inner and outer radiation belts that have been explored (2012 – 2019) by the NASA's twin Van Allen Probes. The red colour marks the region where the radiation intensity is highest. The inner belt is mainly composed of protons, the outer of electrons. (source: NASA)

Figure 12 below shows the energy and intensity range of the three radiation populations in the orbital region of the ISS. The GCRs cover a wide energy range peaking around 1000 MeV, the solar energetic protons produced during a strong solar particle event dominate the 200 – 700 MeV range, while the particles trapped in the Earth radiation belts mainly represent the radiation population between 0,1 and 200 MeV.

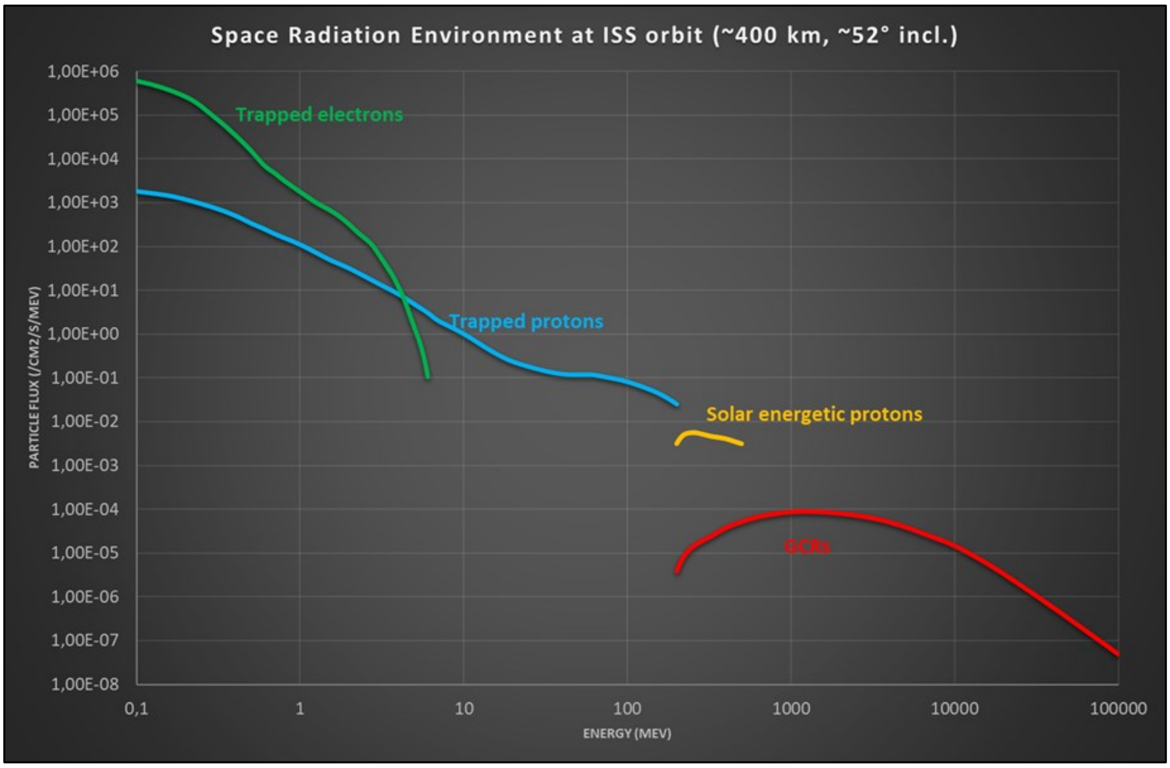


Figure 12 The particle flux (expressed in particle number/cm2/s/MeV) of the different space radiation populations as function of energy at a low Earth orbit comparable to the ISS. Simulations are done with the SPENVIS software tool. Remark that the calculated radiation environment is outside the ISS.

All these particles have enough energy to completely remove electrons from their orbit in an atom and therefore damage material. They can also create secondary particles in the material with enough energy to cause further damage.

Remark that the Sun is also continuously blowing a solar wind mainly composed of protons and electrons. They are of lower energy (0,5 – 10 keV) and classified as space plasma. They get their energy from the high temperature in the solar corona, sufficient to escape from the Sun's gravity. A space plasma is a gas that is so hot that some or all atoms in it are split up in electrons and ions.

➔ **Exercise**

Convert the energy range 0,5 – 10 keV into a speed range for a proton and an electron (use the formula Ek = mv2/2). How do the speeds compare to the speed of light?

Answer

			E = 0,5 keV	E = 10 keV
1 eV	= $1{,}602176565 \cdot 10^{-19}$ J	$v(e^-)$ (m/s) =	$1{,}33 \cdot 10^{7}$	$5{,}93 \cdot 10^{7}$
$m(e^-)$	= $9{,}10938291 \cdot 10^{-31}$ kg	$v(e^-)/c$ =	$4{,}42 \cdot 10^{-2}$	$1{,}98 \cdot 10^{-1}$
$m(p^+)$	= $1{,}672621777 \cdot 10^{-27}$ kg	$v(p^+)$ (m/s) =	$3{,}09 \cdot 10^{5}$	$1{,}38 \cdot 10^{6}$

c = 299792458 m/s	$v(p^+)/c$ =	$1{,}03 \cdot 10^{-3}$	$4{,}62 \cdot 10^{-3}$

On the surface of the Earth, we are protected by the Earth's atmosphere and the magnetic field from most of these particles. The most energetic ones can reach the atmosphere, create showers of secondary particles (see *Figure 13*) which may reach the ground, contributing to the so-called background radiation. At aircraft altitude (9 – 15 km) the radiation exposure may increase significantly during solar storms, especially in the polar regions where the magnetic field lines are more open (see *Figure 13*) and particles can more easily enter the atmosphere. Astronauts in low Earth orbit still receive some protection from the Earth's atmosphere and magnetic field, but radiation becomes a much bigger problem when they travel to places like the moon or Mars that have almost no atmosphere and magnetosphere.

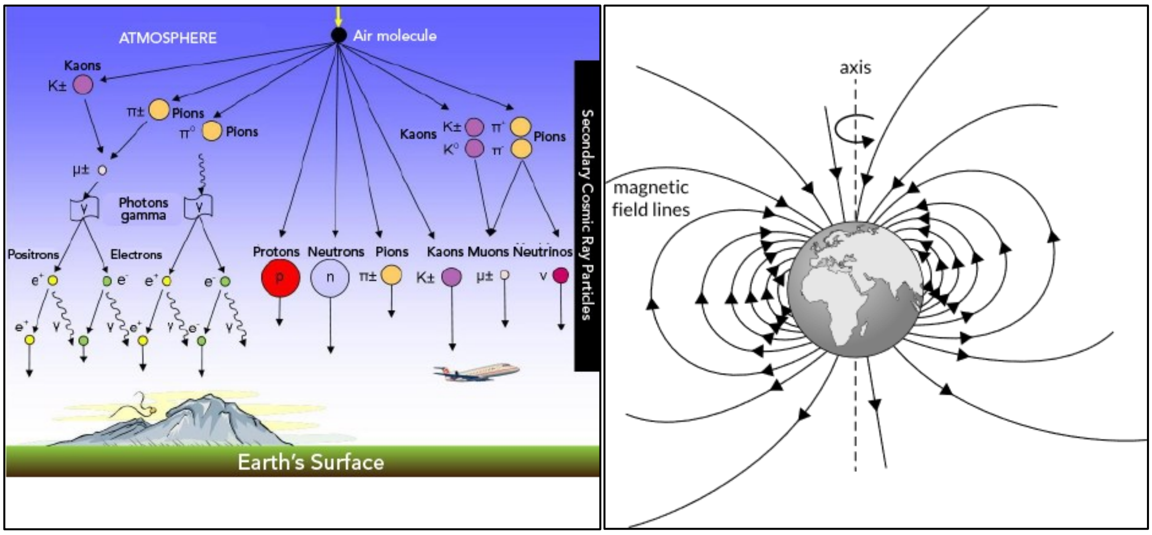


Figure 13 On the left the cosmic air shower produced by an incoming energetic particle (primary cosmic ray) on top of the atmosphere (source: © 2019 Let's Talk Science). A zoo of secondary particles (neutrons, electrons, pions, muons, ...) is created when the primary particle collides with the atoms in the atmosphere. On the right the Earth magnetic field lines which open up in the polar regions (source: Khan Academy).

➔ **Homework**

The magnetic field axis of the Earth is not aligned with the rotation axis and does not go through the center of the Earth (= eccentric). This creates a region above the Earth where the intensity of the magnetic field is particularly low. Look up where this region is located, how it is called and what the effect is on satellites with in particular the ISS. The figure below gives the magnetic field intensity of the Earth as measured by the European Space Agency's Swarm satellites.

Answer

The region is called the South Atlantic Anomaly, is located above the Brazilian coast and reaches down to ~190 km above the surface of the Earth. Because of the weaker magnetic field, the trapped particles of the radiation belts can reach deeper into the upper atmosphere. Satellites going through this region are exposed to higher levels of particle radiation causing glitches in computers and sensitive instruments. ISS spacewalks are planned so that they do not take place during transits across the SAA. The shape of the SAA changes over time (increasing in size) and the center of the region of highest particle intensity drifts to the west at a speed of about 0,3° per year.

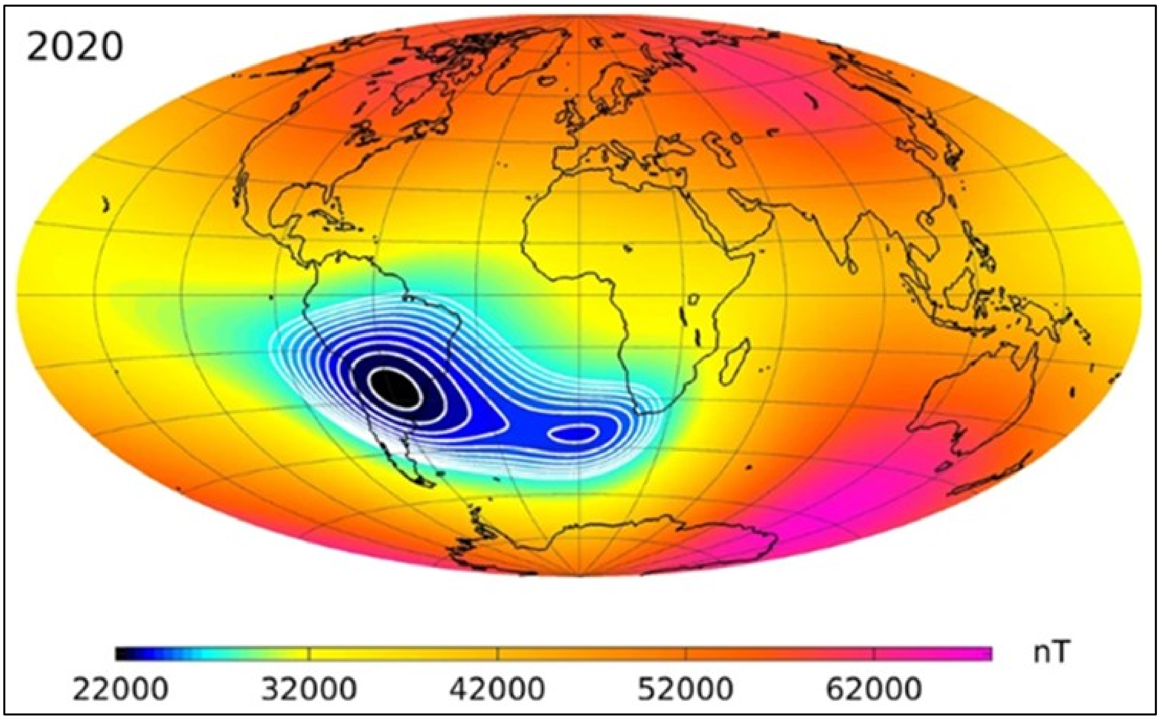


Figure 14 Strength of the Earth's magnetic field (expressed in n(ano)T(esla)) as measured by the Swarm satellites (source: Finlay et al., Earth, Planets and Space volume 72, 156 (2020)).

Effects on spacecraft components

Radiation damage effects limit the lifetime of a spacecraft and increase the risk of failure. Therefore, satellite materials and electronic components are tested for the effects of radiation on both short-term and long-term. Radiation can change the properties of material and devices through ionisation and displacement of atoms in a cristal lattice (non-ionising effect).

Long-term exposure to space radiation has a negative impact on a component, device or system. Due to the accumulation of absorbed energy the performance or material degrades. The effect is defined in terms of the total radiation dose expressed in Gy (Gray) or rad (where 1 Gy = 100 rad). For Si material, it is customary to use Gy(Si) because different materials have different abilities to absorb energy from an ionizing radiation field.

In some cases, a brief, high-energy exposure can damage or destroy an electrical component in a spacecraft. It may also happen that the effect is transient and anneals when back to the normal environmental conditions.

Figure 15 and Figure *16* give an overview of the main types of radiation induced effects and observed effects on a spacecraft.

Total Ionising Dose
The ionizing dose affects a wide class of materials and devices, by changing their mechanical and electrical properties. For example, after a long exposure to radiation insulating materials become less insulating.

Displacement Damage
Displacement of atoms in a crystalline lattice mainly affects the properties of optical material like detectors and solar cells. After long-term irradiation solar panels lose efficiency in producing electric power.

Spacecraft Charging
Exposure to low energy electrons in plasmas and high energy (>100 keV) electrons can lead to the accumulation of charges on the surface of the spacecraft and on dielectric material inside the spacecraft. Large electric fields (potential differences of several kilovolt) can build up causing electrostatic discharges (sparks) that result in background interference on instruments and detectors, physical damage to materials and electronics, etc.

Single Event Effects
They occur when a single high energy particle crosses a micro-electronic device and deposits sufficient energy to cause errors in memory cells or even totally disrupts the device. An example of a frequently occurring (soft) error is a memory bit flip (aka single event upset) whereby a zero becomes a one or vice versa. High energy particles that reach the ground can induce bit flips in computer chips.

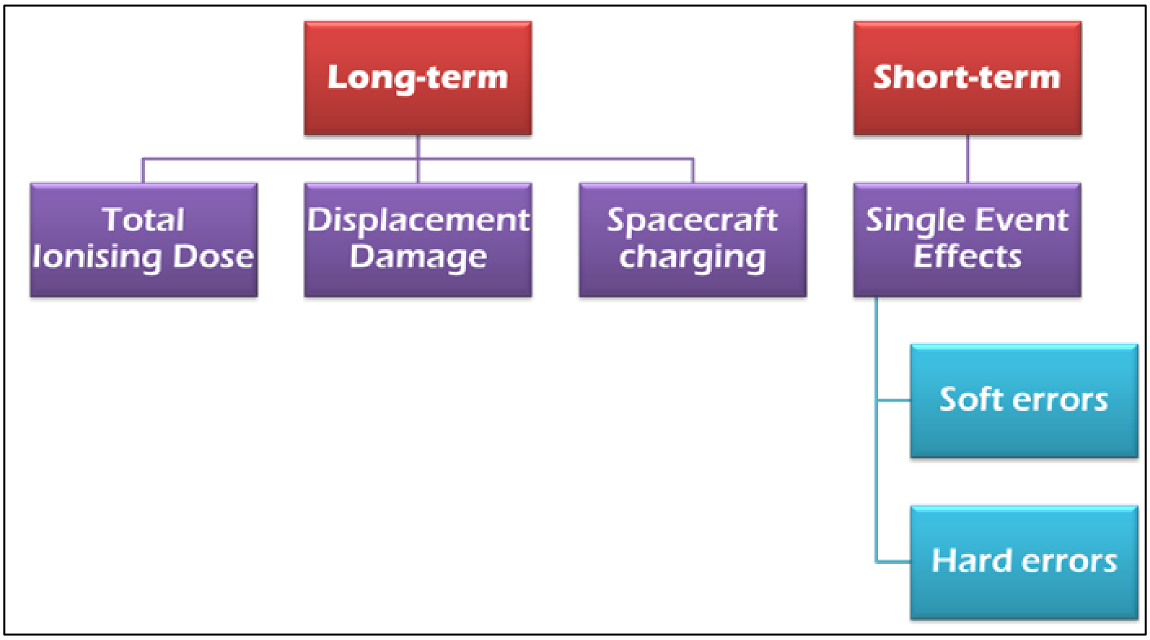


Figure 15 Main types of radiation induced effects.

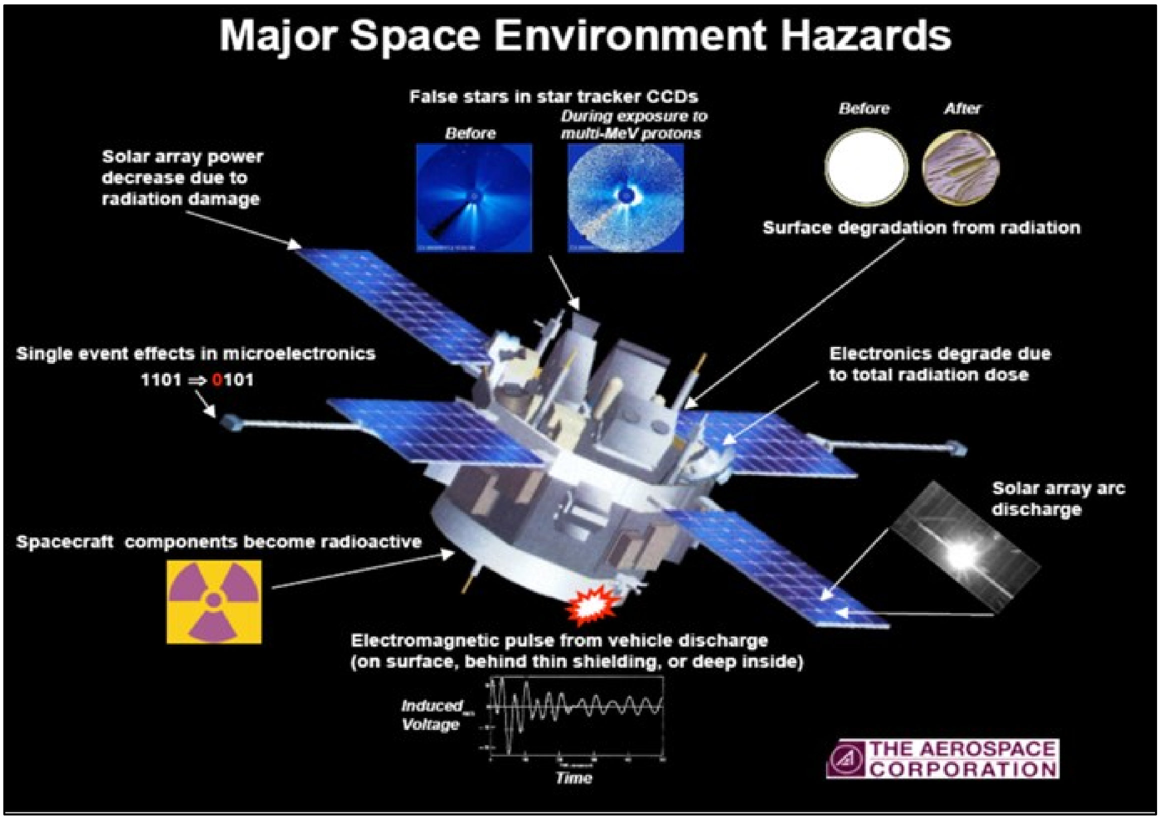


Figure 16 Main radiation effects observed on a satellite.

To minimize the effects of radiation on the spacecraft components appropriate testing is done to help the spacecraft manufacturer identify areas where changes in design, materials or both are needed. In addition, most components are surrounded with some shielding material.

➔ **Exercise**

Correcting bad data using parity bits (source: taken from Space Math http://spacemath.gsfc.nasa.gov).

Data is sent as a string of ‘1’s and ‘0’s which are then converted into useful numbers by computer programs. A common application is in digital imaging whereby each pixel is represented as a ‘data word’ and the image is recovered by relating the value of the data word to an intensity or a particular color. In the sample image below, red is represented by the data word ‘10110011’, green by ‘11100101’ and yellow by the word ‘00111000’. This means that the first three pixels would be transmitted as the ‘three word’ string ‘101100111110010100111000’.

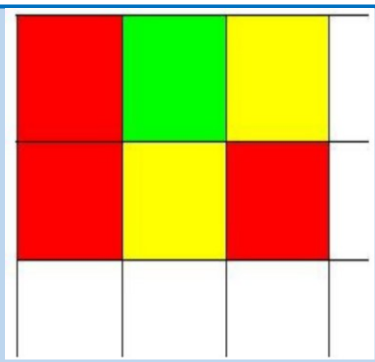


Figure 17 Digital imaging: pixels in a large image

What happens if one of those 1-s or 0-s is accidentally reversed? You would get an error in the color used in a particular pixel. Since the beginning of the Computer Era, engineers have anticipated this problem by adding a 'parity bit' (last digit) to each data word. The bit is '1' if there are an even number of 1's in the word, and' 0' if there is an odd number. For example, in the data word for red '10110011' the last '1' to the right is the parity bit.

When data is produced in space, it is protected by parity bits, which alert the scientists that a particular data word may have been corrupted by a cosmic ray accidentally altering one of the data bits in the word. For example, the data word A '11100011' is valid but the data word B '11110011' is not as there are five '1's which is odd and so the parity bit should be '0'. This mean that somewhere a '0' flipped into a '1'. One way to recover the good data is to simply re-transmit data words several times and fill-in the bad data words with the good words from one of the other transmissions.

Below are two data strings that have been corrupted by cosmic ray glitches. Look through the data (a process called parsing) and use the right-most parity bit to identify all the bad data. Create a valid data string that has been 'de-glitched'.

String 1	10111010	11110101	10111100	11001011	00101101
	01010000	01111010	10001100	00110111	00100110
	01111000	11001101	10110111	11011010	11100001
	10001010	10001111	01110011	10010011	11001011
String 2	10111010	01110101	10111100	11011011	10101101
	01011010	01111010	10001000	10110111	00100110
	11011000	11001101	10110101	11011010	11110001
	10001010	10011111	01110011	10010001	11001011

Answer

The corrupted data are marked in red:

String 1	10111010	11110101	10111100	11001011	00101101
	01010000	01111010	10001100	00110111	00100110
	01111000	11001101	10110111	11011010	11100001
	10001010	10001111	01110011	10010011	11001011
String 2	10111010	01110101	10111100	11011011	10101101
	01011010	01111010	10001000	10110111	00100110

	11011000	11001101	10110101	11011010	11110001
	10001010	10011111	01110011	10010001	11001011

In the first string first row, 11110101 has a parity bit of '1' but it has an odd number of '1' so its parity should have been '0' if it were a valid word. Looking at the second string first row, we see that the word that appears at this location in the grid is '01110101' which has the correct parity bit. We can see that a glitch has changed the first '1' in String 2 to a '0' in the incorrect String 1.
By replacing the red-marked corrupted data words with the uncorrupted values in the other string, we get the following de-glitched data words:

String 1	10111010	01110101	10111100	11001011	10101101
	01010000	01111010	10001100	00110111	00100110
	11011000	11001101	10110101	11011010	11100001
	10001010	10001111	01110011	10010001	11001011

The odd word is the first word in the third row (marked in blue). The first transmission says that it is '01111000' and the second transmission says it is '11011000'. Both wrong words have a parity of '1' which means there is an even number of '1's in the first seven places in the data word. But the received parity bit says '0' which means there was supposed to be an odd number of '1's in the correct word. Examining these two words, we see that the first three digits are '011' and '110' so it looks like the first and third digits have been altered. Unfortunately, we can't tell what the correct string should have been. Because the rest of the word '11000' has an even parity, all we can say about the first three digits is that they had an odd number of '1's so that the total parity of the complete word is '0'. This means the correct digits could have been '100', '010', '001', or '111', but we can't tell which of the three is the right one. That means that this data word remains damaged and can't be de-glitched even after the second transmission of the data strings.

→ **Homework**

"Super Mario 64: a cosmic ray responsible for the mysterious glitch for speedrun"? Watch the video https://www.youtube.com/watch?v=o3Cx2wmFyQQ

Effects on astronauts

Space radiation is a serious health hazard in human spaceflight. As we saw earlier space radiation has sufficient energy to damage DNA molecules and even destroy human cells. This can induce health problems ranging from acute effects (diarrhea, nausea, … or even death) to long-term effects (cataracts, increased risk of cancer and sterility, …).

→ **Homework**

Look up some specific effects of space radiation on the human body (link with biology)

In general, the effect of radiation depends on the:

- Altitude of the spacecraft
- Amount of shielding from the spacecraft or spacesuit
- Length of the spaceflight
- Duration and intensity of radiation exposure
- Type of radiation
- Individual sensitivity to radiation
- Differences in age, sex and health status

Apart from radiation, there are also other factors in space like weightlessness and body temperature which can weaken the immune system and affect how body tissues and organs respond to radiation.

Like for airline pilots and crew, there are space radiation exposure limits for astronauts that follow the recommendations given by the International Commission on Radiological Protection (ICRP) and the National Council on Radiation Protection and Measurement (NCRP). In Belgium advisories come from the Federal Agency of Nuclear Control (FANC). When the career limit has been exceeded, there is an increased risk for developing harmful health effects, and astronauts are no longer allowed to participate in spaceflight missions. For ESA astronauts the career limit is currently set at 1Sv.

Sievert (Sv): The sievert is a physical unit that measures the amount of radiation absorbed by a person, accounting for the type of radiation and sensitivity of the particular organs and tissues in the body. It is equivalent to one joule of energy per kilogram of mass.

To have an idea of what 1 Sv means we compare with bananas which are slightly radioactive because they are rich in potassium. One of its natural isotopes (variants) is potassium-40, which is radioactive. One banana contains about 0.07 mg of potassium-40, our body on average 16 mg.

1 banana	0.1 microSv	0.0000001 Sv
50 bananas	5 microSv	1 dental x-ray
100 bananas	10 microSv	100 g Brazilian nuts
800 bananas	80 microSv	1 transatlantic flight[1]
12000 bananas	1200 microSv	1 day at ISS

Shielding

Apart from shielding by the magnetosphere and the atmosphere, there are three ways to reduce the radiation dose from an external source:

- Increasing the distance from the source

[1] During a solar storm the radiation dose may increase more than 10-25%.

- Minimizing the time of exposure
- Using shielding

Most spacecraft components are inside the spacecraft and therefore protected by the spacecraft structure itself, usually made of Aluminium which is light and strong. Often Aluminium composite materials are used to better reduce the radiation. The solar cells that are outside the spacecraft are protected by a layer of cover glass.

To protect humans during space travel, studies are ongoing to use several layers of different materials and to create artificial magnetic fields surrounding the spacecraft like the Enterprise in Star Trek.

High energy particles may produce highly penetrating secondary particles inside the shielding material that can further create damage. When calculating the required shielding, one must account for this effect in combination with the mass constraints on the spacecraft.

➔ **Exercise**

1) A hollow cubic shaped satellite with 1-meter sides is made of Aluminium (density = 2.7 g/cm3). Calculate the mass of the satellite when the walls have a thickness of (a) 4 mm and (b) 12 mm. 2) If the launch cost is 15 keuro per kilogram, how much extra will it cost to launch the heavier better shielded satellite?
3) The satellite will fly at a 200 km polar orbit above Earth and operate for 1 year. Figure 17 gives the received radiation dose as function of wall thickness. To keep the inside sensitive electronic instruments working normally, the radiation should not exceed 200 rad/yr. Is the 4 mm thick Al shielding sufficient?
(source: Space Math http://spacemath.gsfc.nasa.gov)

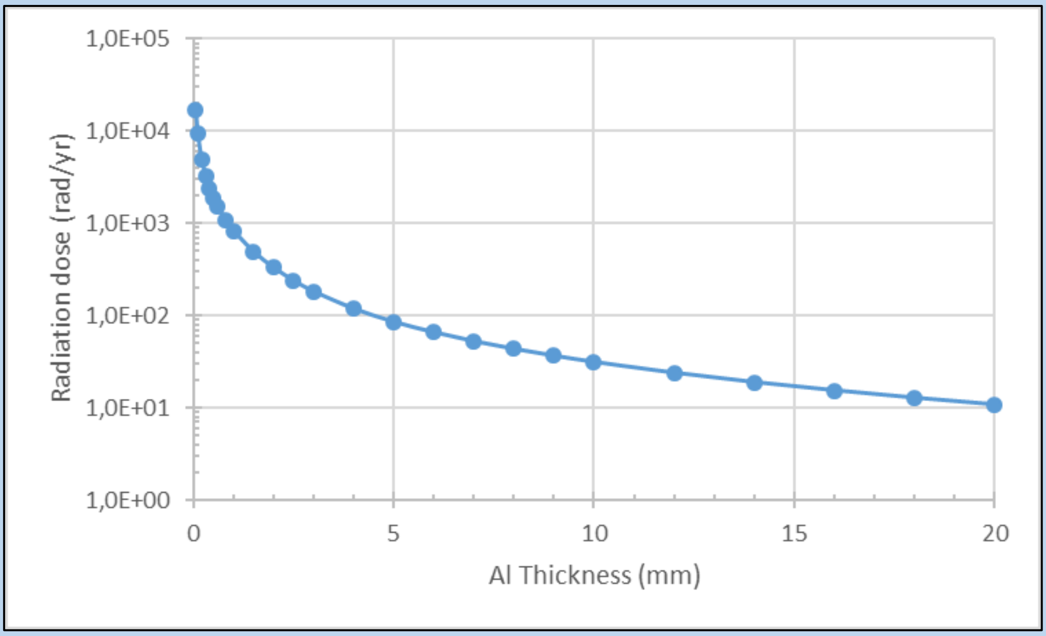


Figure 18 Radiation dose (expressed in rad/yr) as function of depth in Al (expressed in mm) for a 200 km high polar Earth orbit. Simulation done with SPENVIS.

Answer

Answer:

1) Mass = density x volume = 2,7 (g/cm^3) x 6 x size x size x thickness wall
   a) Mass = 2,7 x 6 x 100 (cm) x 100 (cm) x 0,4 (cm) = 65 kg
   b) Mass = 2,7 x 6 x 100 (cm) x 100 (cm) x 1,2 (cm) = 194 kg
2) Extra cost = 15 (keuro/kg) x (194 – 65) (kg) = 1935 keuro
3) With a 4 mm wall thickness the yearly radiation dose is about 100 rad (=1 Gy) and so sufficient to guarantee 1-year nominal operation.

❹ SPENVIS Workshop

Goals of the workshop

This workshop is intended for students looking for additional challenges in physical sciences and mathematics. It will expose them to a tool used mainly by professionals (working in the private space sector or for various space agencies including ESA and NASA) to perform rapid radiation analysis on spacecraft components for different types of space missions.

Teachers can use the workshop as an opportunity to discuss further orbital mechanics while students can experience first-hand how this knowledge can be put in use for defining realistic spacecraft orbits using the SPENVIS orbit generator.

Furthermore, the workshop can provide a practical way to introduce students to various concepts related to space weather and space radiation. In particular, students will use the SPENVIS system to simulate the space radiation environment experienced by a spacecraft on a particular orbit. In turn, they can use the information regarding the radiation environment to calculate one of its effects on a spacecraft, namely the total ionisation dose (TID). This accumulated radiation can cause undesired aging of satellite systems and electronics.

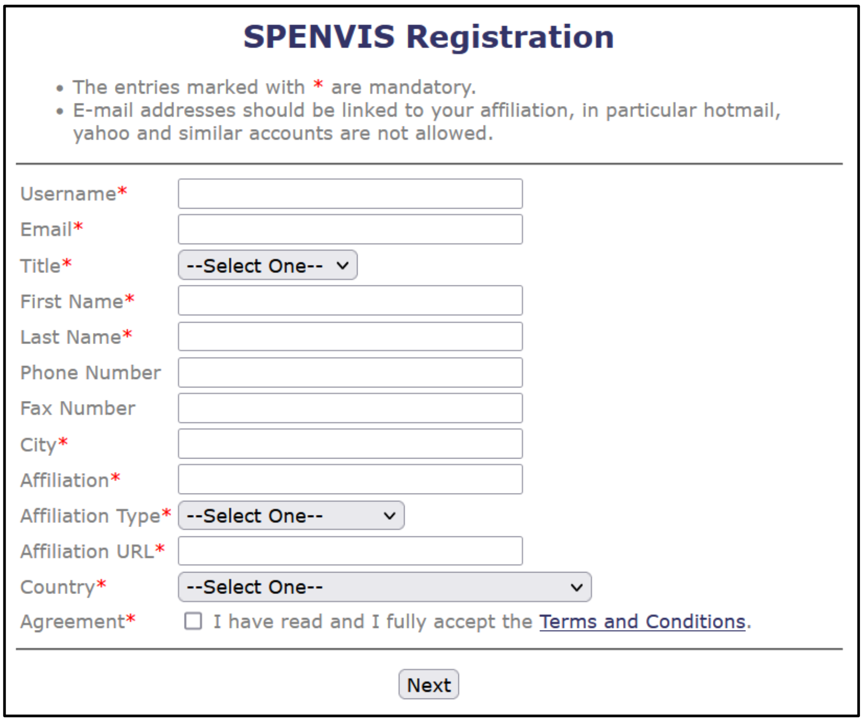
Guidelines for teachers

Using SPENVIS as an educational tool

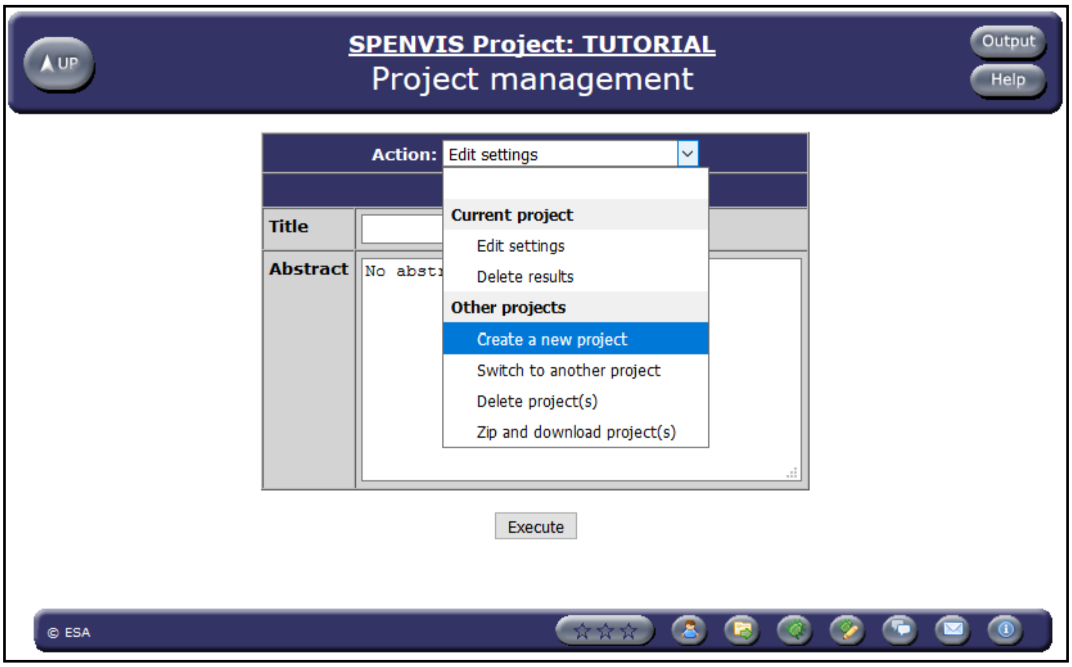
The SPace ENVironment Information System (SPENVIS) is an ESA operational software that has been developed and maintained by the Royal Belgian Institute for Space Aeronomy (BIRA-IASB) since 1996. It provides free access to an integrated set of space environment and effect models through a user-friendly Web interface.

It was initially designed to help spacecraft engineers to perform a quick analysis of issues related to the space environment for specific space missions. However, SPENVIS has become over the years a multi-purpose tool that is used by a worldwide user community, including spacecraft designers and operators, electronic component designers, scientists and teachers.

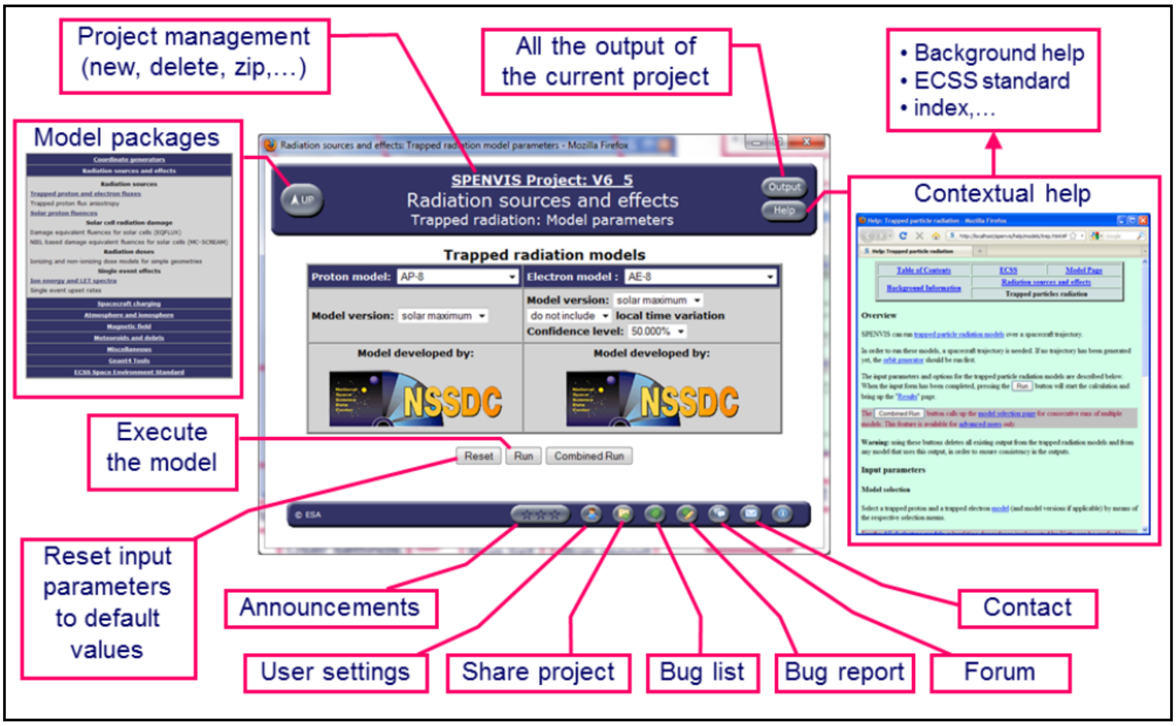
The system can be accessed by either using the Web link https://www.spenvis.oma.be or via ESA's Space Weather Service Network (https://swe.ssa.esa.int/). One can register to SPENVIS by simply filling an online form with some mandatory fields and accepting the Terms and Conditions for using the system. Note that the provided e-mail addresses should be linked to user affiliation. After that you will receive a message that you have successfully registered and you will be given instruction of how to reset your passwords.



SPENVIS works with projects that collect all the inputs and the outputs of users' runs. This allows one to perform work in more than one session and the results are not lost when leaving a session. A user must create a project when login into the system for the first time. The default maximum number of projects is two. However, this can be increased by a request to the SPENVIS team (email: spenvis_team@aeronomie.be).



SPENVIS users can manage their projects by editing settings, delete results or even delete a project they no longer need. They can also easily switch between different projects. Furthermore, they have possibility to download their results as ZIP.



A user can click on the Access button on the Navigation menu (left hand side of the main SPENVIS page) to get access to the various model packages that are available in SPENVIS (Coordinate generators, Radiation sources and effects, Spacecraft charging, Atmosphere and ionosphere, Magnetic field, Meteoroids and debris, Miscellaneous and Geant4 tools). Note that the availability of some models depends on the planet selection. Also, some models depend on the type of coordinate generator (spacecraft trajectories or geographical coordinate grids).

SPENVIS has an extensive help system. More specifically, each model template has a help button directing users to dedicated help pages displaying basic information about that particular model and explanation about how to use it in SPENVIS. In addition, the SPENVIS system has a set of auxiliary help pages that contain background information about the various models and the science involved, a glossary, FAQ etc.

Finally, it should be pointed out that SPENVIS allows the creation of special user accounts for teachers known as student accounts. Note that one must already have a SPENVIS account before asking for student accounts. Teachers who make this request will be asked to provide some basic information including the title, duration and a short description of their course, an estimate of the number of students and the name of their SPENVIS account. A teacher can manage these accounts, for example reset the passwords and clear projects.

Good to know

- There is a ‘help’ button at the right upper corner on every page. By clicking it you get a help page about the content you are currently working on.

- When working in SPENVIS, don’t use the ‘back’ and ‘forward’ buttons of the browser, because parameters will not be saved then.

Classroom exercises

The following classroom exercises are designed around four different space mission scenarios:

- Sun Synchronous Orbit (a type of low Earth orbit)
- Typical Galileo spacecraft orbit (medium Earth orbit)
- Geostationary orbit
- Lunar mission (trip a future Lunar Gateway space station)

The duration of the mission is assumed to be one year. However, the different spacecraft will travel through different parts of our neighbouring space exposing them into different radiation environments. This in turn will affect the accumulated dose and it is reflected in the calculated total mission dose.

Below there are step by step instructions of how to do the aforementioned exercises in the classroom using SPENVIS. The main question the students will have to answer with these exercises is what the total mission doses is (i.e. total ionising doses) behind the specified spacecraft shielding.

EXERCISE 1: Sun synchronous orbit

For a spacecraft on a Sun Synchronous Orbit (SSO) calculate the total dose it will experience during a one-year mission.

What is a Sun Synchronous Orbit?

Imagine you would draw a plane that goes through the centre of the Earth, and that is perpendicular to the ecliptic. The plane stays constantly at the same angle relative to the line Earth-Sun. So, this plane looks fixed relative to the Sun, but seems to rotate about 1 degree per day relative to Earth.

This is the plane in which a Sun Synchronous Orbit is running. So seen from Earth, it is a near-polar orbit. Because a satellite in this orbit is in a fixed relation with the Sun, it will always pass over any place on Earth at the same moment of the day.

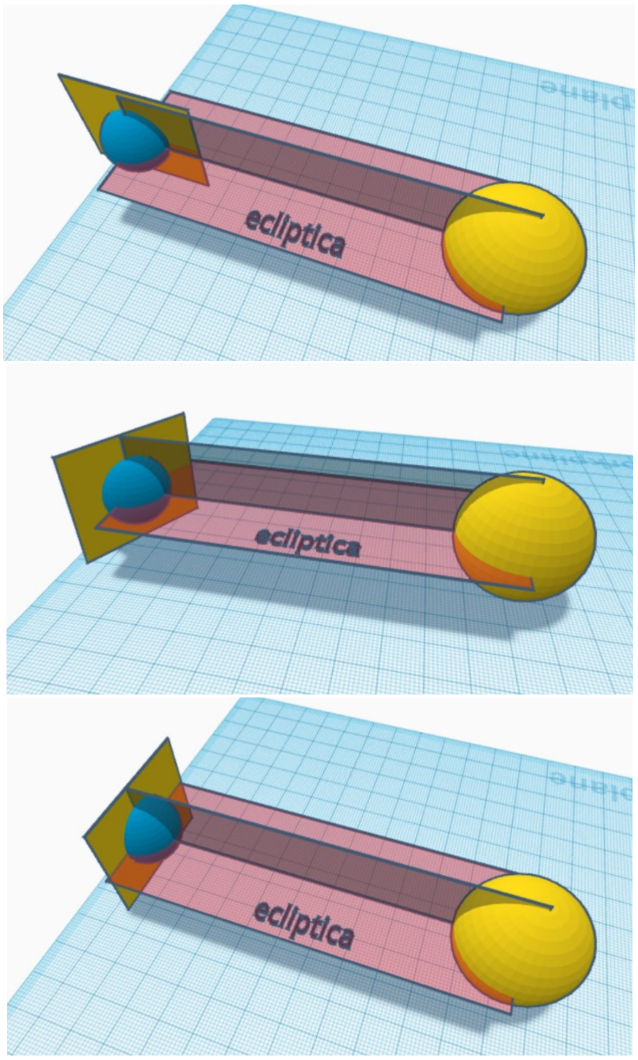


Figure 19 The plane of 3 different Sun Synchronous Orbits in brown, always perpendicular on the ecliptica. The corner between the orbital plane and the line Sun-Earth is different for each of the orbits shown above (up: 0°, middle: 60°, bottom: 90°), but for 1 orbit it will constantly remain the same each day of the year. The images only show one moment of the year.

Credits: ESERO Belgium, created with Tinkercad.

Some characteristics of this orbit:

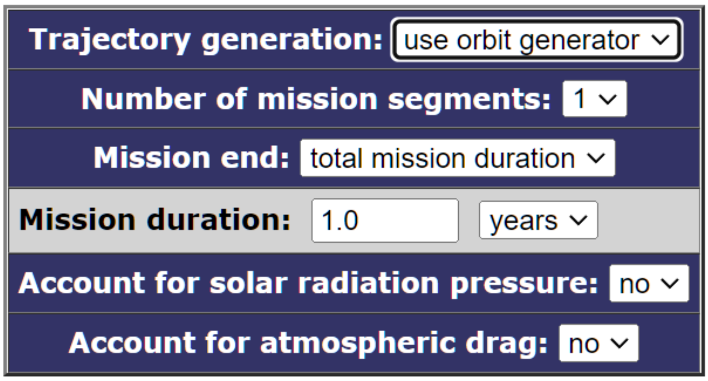
- This orbit around the Earth is circular.
- There are Sun Synchronous Orbits at altitudes between 100 and 5973 km
- Any satellite on SSO passes over any given point of the planet's surface at the same local mean solar time.
- This orbit is often used for weather and spy satellites imaging Earth’s surface in visible or infrared wavelengths. Another example is satellites carrying ocean and atmospheric remote-sensing instruments that require sunlight.
- An SSO that has a 90° angle with the Sun-Earth-line is a special one:
- It has constant sunlight, and never passes the Earth’s shadow. So, it can also constantly use solar energy (solar panels).
- It can always observe the Sun. The Belgian Proba-2 satellite is such a solar observation satellite in an SSO.
- Looking down, it will always see the Earth surface in the evening or morning.

- An SSO that has a 0° angle with the Sun-Earth-line will pass a point on Earth on exact midday and another point on exact midnight every day.

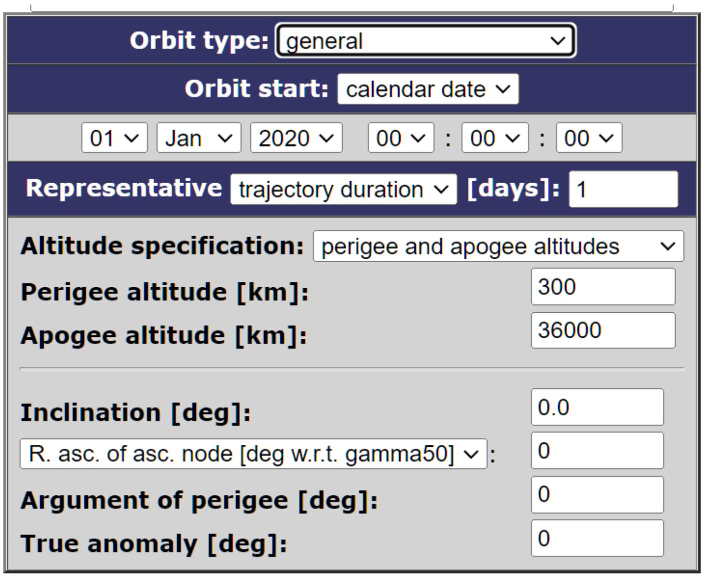
STEP 1 - Defining the mission in SPENVIS

First, we need to specify the type of the orbit before start modelling.

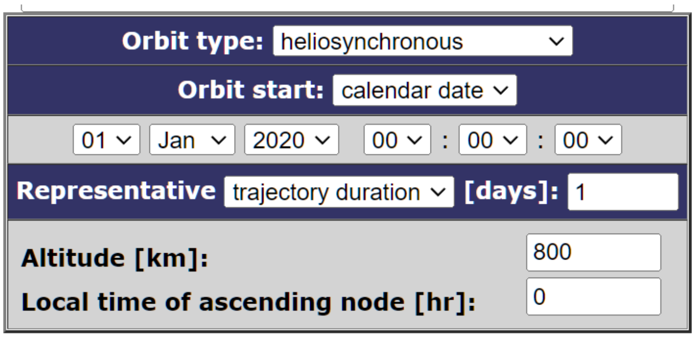
Select “Coordinate generators” > “Spacecraft trajectories”



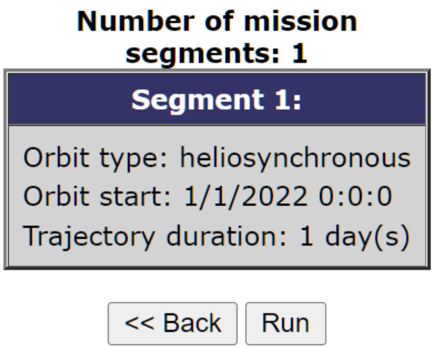
Make sure the “Mission duration” is set to 1 year (= default value). Then click “next”.



In the upper line, you can choose the orbit type. Define this one as “Heliosynchronous” (another name for Sun Synchronous).



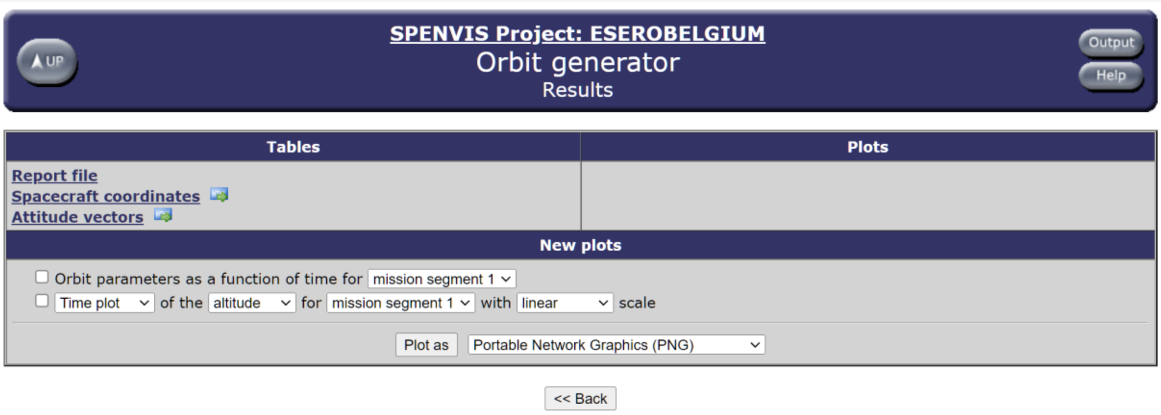
Now choose the orbit start date: 01 Jan 2022. The hour and minutes can stay on zero. Then choose a “trajectory duration” of 1 day (= default value). Choose the altitude of 800 km (= default value) and “local time of ascending node” 0 hours (= default value). Then click “next”.



Then click “run”. The program will now generate the mission orbit with your preferences. We can go now to step 2.

STEP 2 – Environment definition

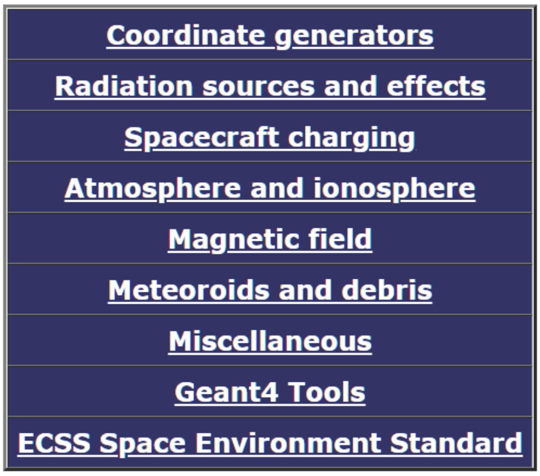
This is the image you ended with in STEP 1:



We will now define the environment, meaning we will let the model calculate the expected fluxes of high energy particles on our orbit.

a) **'trapped particles' (protons & electrons)**

Click the "Up" button (upper left corner), to go back to the main menu, and choose "Radiation sources and effects":

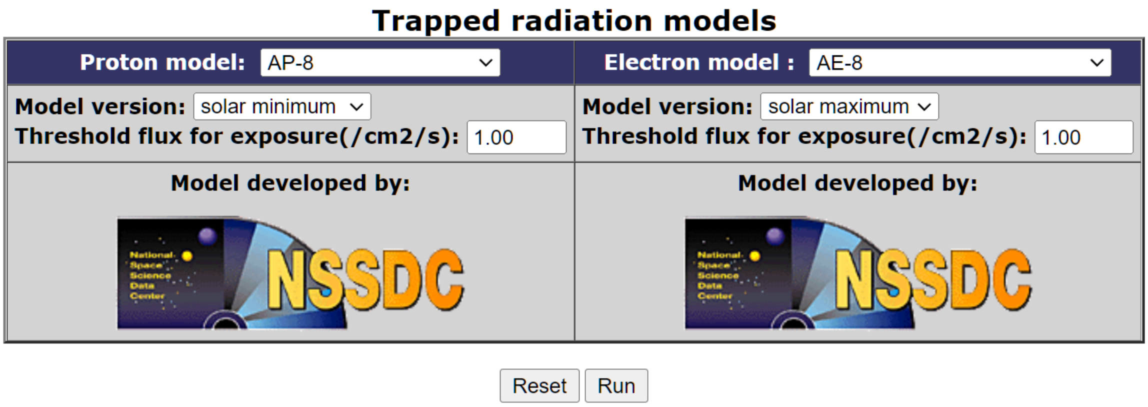


This submenu will open.

Select "**Trapped proton and electron fluxes**"

Here we will use the default settings:

- AP-8 solar minimum for trapped proton model
- AE-8 solar maximum for trapped electron model



Click "Run" to calculate the particle fluxes

Now to go back, we will click again the "up" button at the upper left.

b) **Solar proton fluences**

Select "**Solar particle mission fluences**" from the menu:

Radiation sources and effects

Radiation sources

Trapped proton and electron fluxes
Trapped proton flux anisotropy
Solar particle peak fluxes (only for SEU)
Solar particle mission fluences
Galactic cosmic ray fluxes
Shielded flux

Solar cell radiation damage

Damage equivalent fluences for solar cells (EQFLUX)
NIEL based damage equivalent fluences for solar cells (MC-SCREAM)

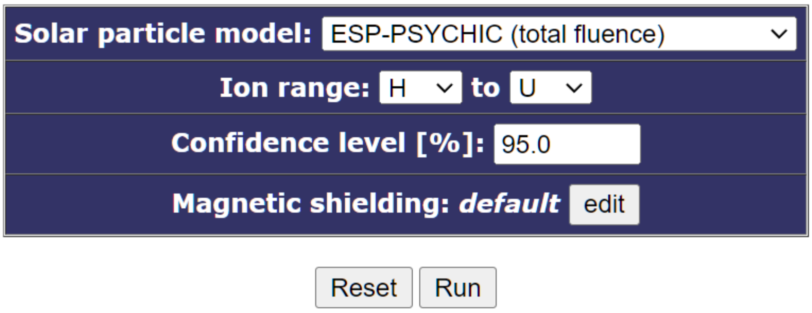
Long-term radiation doses

Ionizing dose for simple geometries
Non-ionizing energy loss for simple geometries
Effective dose and ambient dose equivalent

Single event effects

Short-term SEU rates and LET spectra
Long-term SEU rates and LET spectra

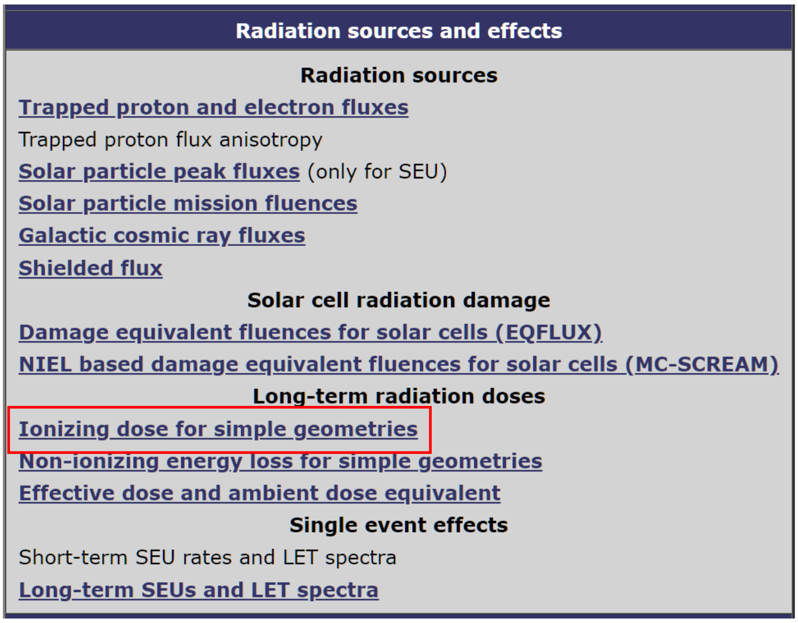
Again, we will use the default settings:



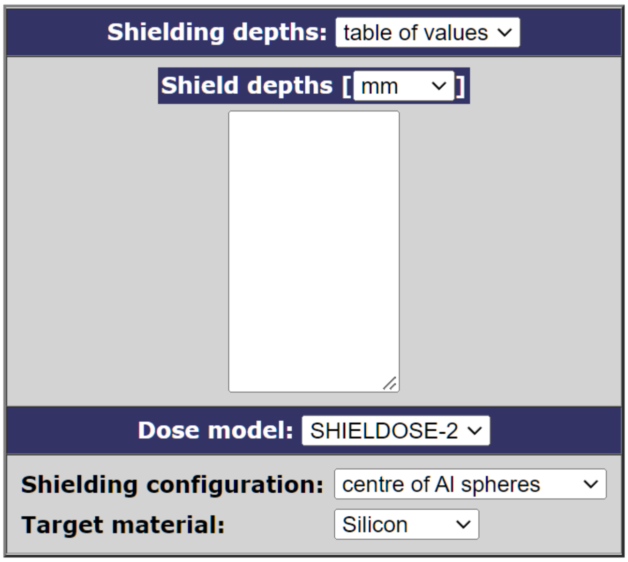
Simply click “run” to let the model calculate the solar proton fluences. Then click the “Up” button again to go back.

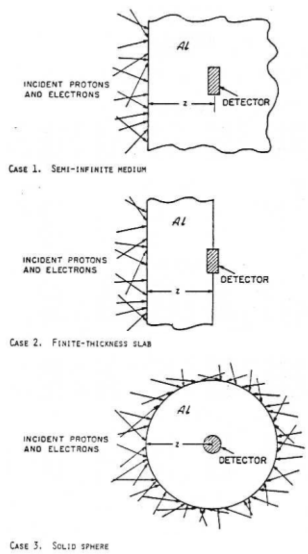
STEP 3 - Total Ionising Dose (TID) calculation

Now we will let the model calculate the radiation doses. Back in the main menu, you will see that most of the options are now ‘clickable’. Choose “**Ionizing dose for simple geometries**” (under the subtitle “Long term radiation doses”):



To keep it simple, we will consider our target spacecraft or instrument as a simple solid sphere, which is indeed a simple geometry. For ‘shielding depth’ we select “table of values”, which will allow us to define our own choice of radiation shield.

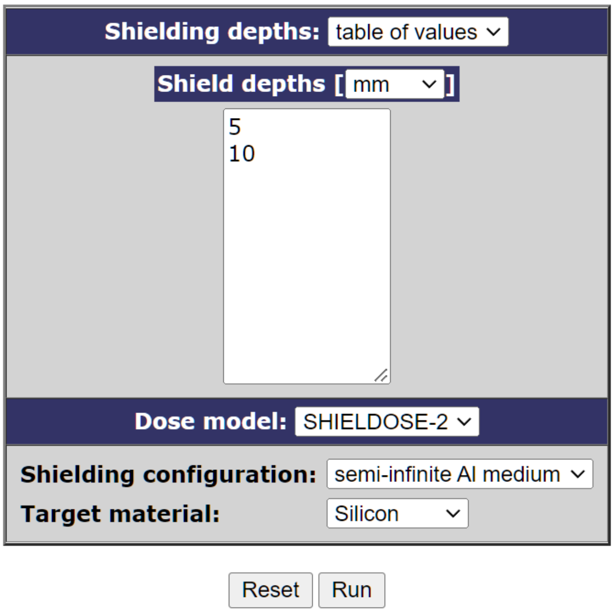




(the various geometry configurations, ref. S. M. Seltzer, 1980)

We will choose the following parameters:

- A shield of 5 mm and a shield of 10 mm (put these numbers under each other in the white field),
- Dose model: keep the default “SHIELDOSE-2”,
- Shielding configuration: “Semi-infinite aluminium medium”,
- Target material: “Silicon” (because we will look at the radiation effect on electronic instruments).



Then click “Run”.

Finally, we can have a look at the results on the resulting window: click ‘Report file”. You will get this report:

Total mission dose (rad)

Al absorber thickness (mm)	(mils)	($g\ cm^{-2}$)	Total	Trapped electrons	Brems-strahlung	Trapped protons	Solar protons	Tr. electrons+ Bremsstrahlung	Tr. el.+Bremss. +Tr. protons
5.000	196.850	1.350	3.213E+02	1.981E+01	3.409E+00	2.022E+02	9.591E+01	2.322E+01	2.254E+02
10.000	393.700	2.700	1.865E+02	4.716E-02	1.916E+00	1.484E+02	3.613E+01	1.963E+00	1.503E+02

Copy the ‘total doses’ for the two shielding values in the table below. If needed, you can change the notation: 3.213E+02 actually means 3,213*10^2 or simply 321,3 rad.

Aluminium thickness	Total ionising dose (rad)
5 mm	
10 mm	

➔ **Homework**

Look up what Bremsstrahlung is.

Answer

Radiation due to the acceleration of a charge in the Coulomb field of another charge is called bremsstrahlung or free-free emission. (ref. Radiative processes in astrophysics, G. Rybicki, A. Lightman, 2004)

EXERCISE 2: Medium Earth orbit (MEO) mission

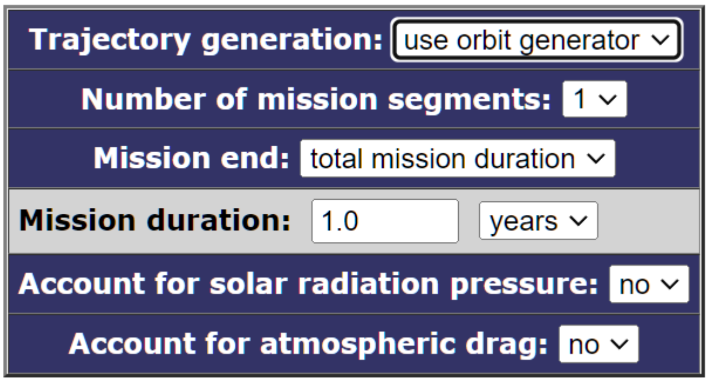
What is a medium Earth orbit?

A Medium Earth Orbit (MEO) is a circular orbit with an altitude in the range between 2000 and 35786 km. The navigation satellites are typical examples of objects moving on MEOs (e.g. Galileo, GPS and GLONASS).

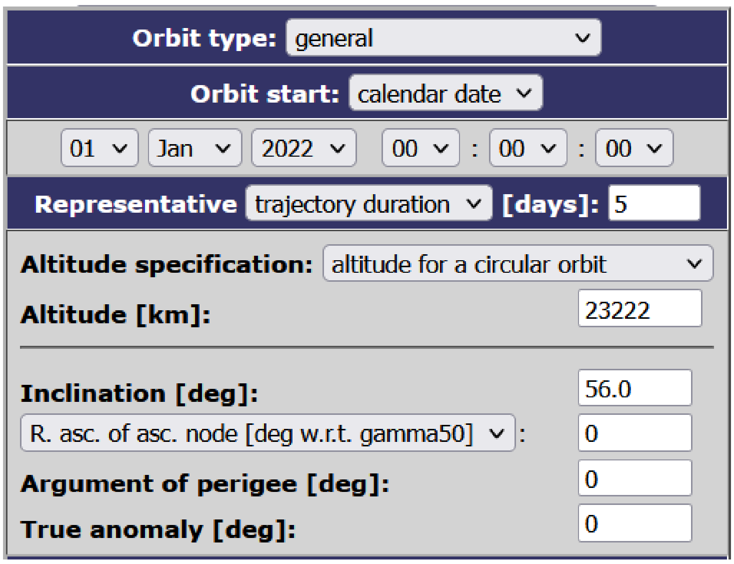
STEP 1 - Defining the mission in SPENVIS

First, we need to specify the type of type of orbit we will start modelling.

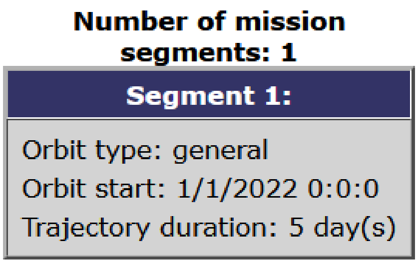
Select “Coordinate generators” > “Spacecraft trajectories”



Make sure the “Mission duration” is 1 year (= default value). Then click “next”.
In the upper line, you can choose the orbit type. Define this one as “general” (= default value).



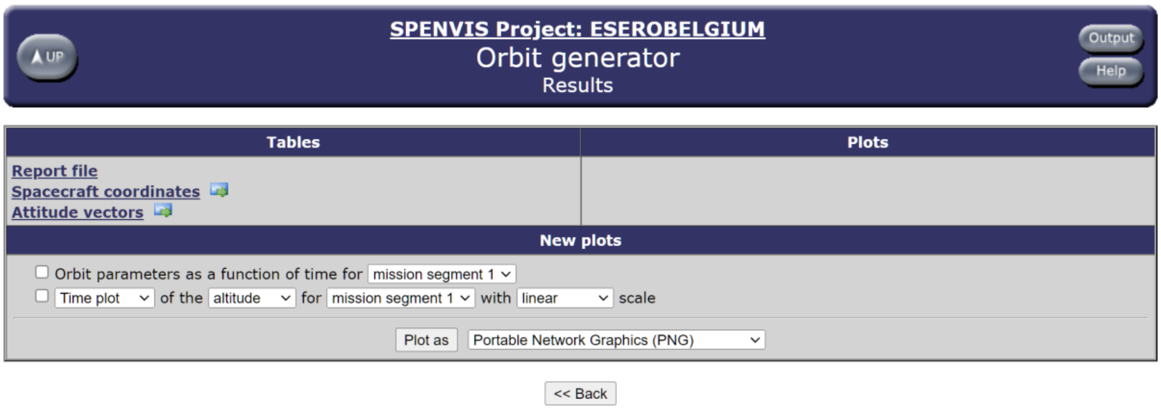
Next choose the orbit start date: 01 Jan 2022. The hour and minutes can stay on zero. After that choose a “trajectory duration” of 5 days. Select “altitude for a circular orbit” for the Altitude specification. Choose the altitude of 23222 km and an inclination of 56 degrees. Leave the rest of the input to the default values. Then click “next”.



Then click “run”. The program will now generate the mission orbit with your preferences. We can go to step 2.

STEP 2 – Environment definition

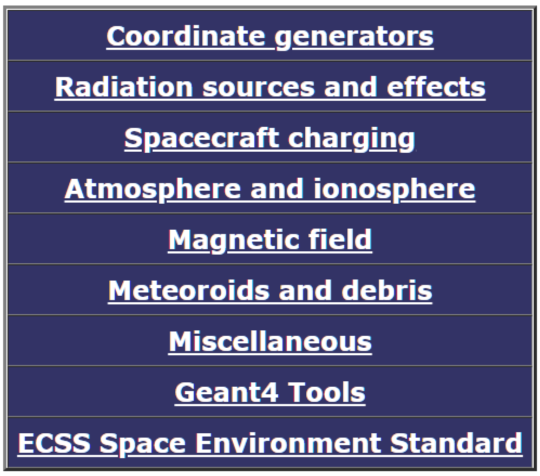
This is the image you ended with in STEP 1:



We will now define the environment, meaning we will let the model calculate the expected fluxes of high energy particles on our orbit.

a) ‘trapped particles’ (protons & electrons)

Click the “Up” button (upper left corner), to go back to the main menu, and choose “Radiation sources and effects”:

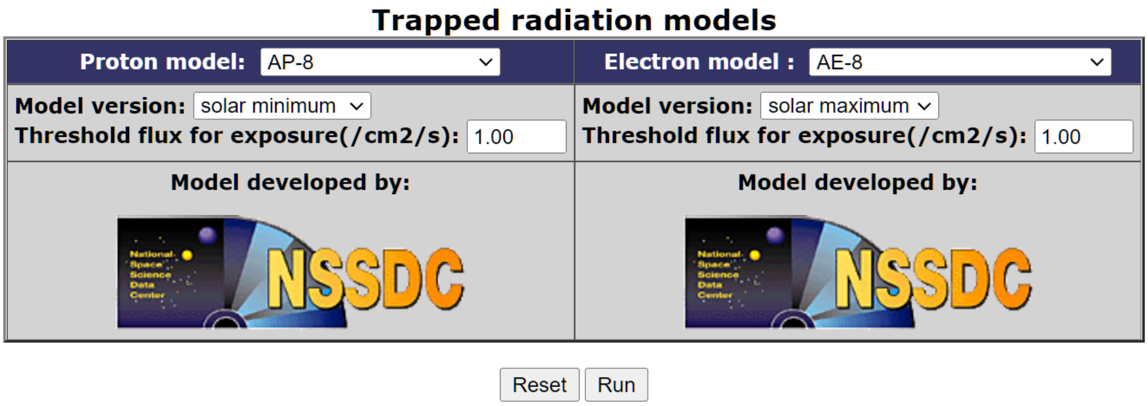


This submenu will open.

Select “**Trapped proton and electron fluxes**”

Here we will use the default settings:

- AP-8 solar minimum for trapped proton model
- AE-8 solar maximum for trapped electron model

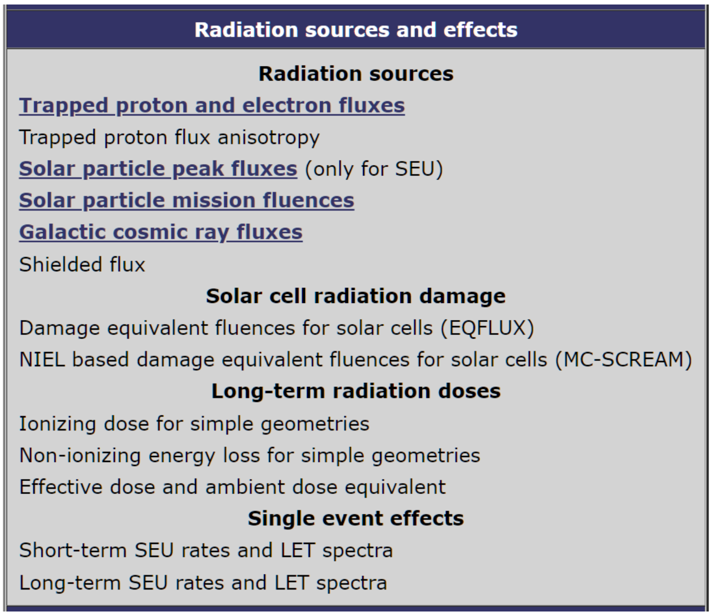


Click “Run” to calculate the particle fluxes

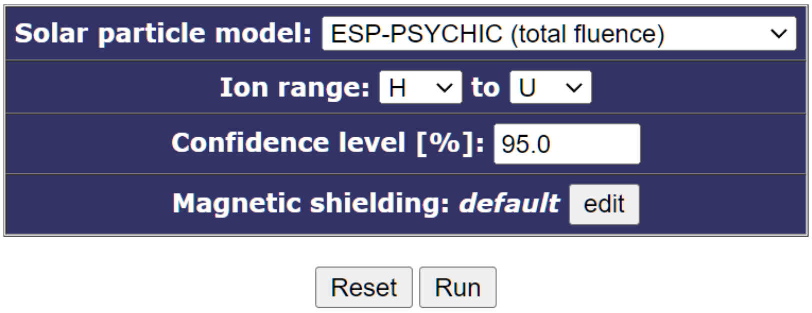
Now to go back, we will click again the “up” button at the upper left.

b) Solar proton fluences

Select “**Solar particle mission fluences**” from the menu:



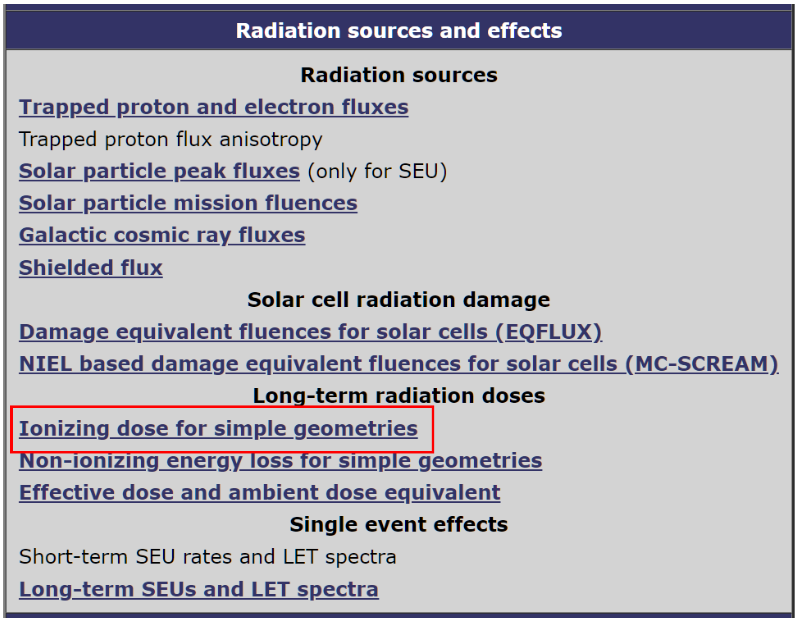
Again, we will use the default settings:



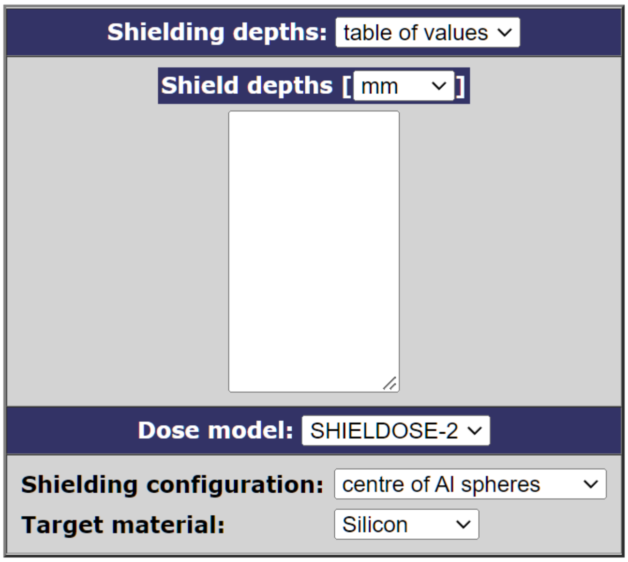
Simply click “run” to let the model calculate the solar proton fluences. Then click the “Up” button again to go back.

STEP 3 – Total Ionising Dose (TID) calculation

Now we will let the model calculate the radiation doses. Back in the main menu, you can see that most of the options are now ‘clickable’. Choose “**Ionizing dose for simple geometries**” (under the subtitle “Long term radiation doses”):

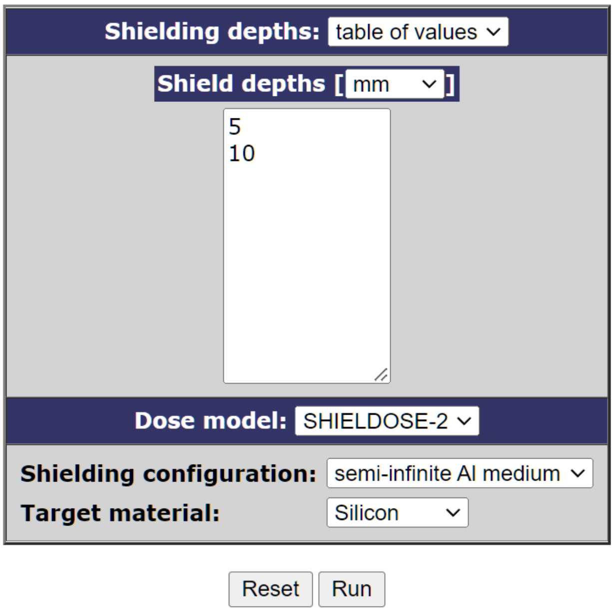


To keep it simple, we will consider our target spacecraft or instrument as a simple solid sphere, which is indeed a simple geometry. For ‘shielding depth’ we select “table of values”, which will allow us to define our own choice of radiation shield.



We will choose the following parameters:

- A shield of 5 mm and a shield of 10 mm (put these number under each other in the white field),
- Dose model: keep the default “SHIELDOSE-2”,
- Shielding configuration: “Semi-infinite aluminium medium”,
- Target material: “Silicon” (because we will look at the radiation effect on electronic instruments).



Then click “Run”.

Finally, we can have a look at the results on the resulting window: click ‘Report file”. You will get this report:

Total mission dose (rad)

Al absorber thickness			Total	Trapped electrons	Brems-strahlung	Trapped protons	Solar protons	Tr. electrons+ Bremsstrahlung	Tr. el.+Bremss. +Tr. protons
(mm)	(mils)	(g cm^{-2})							
5.000	196.850	1.350	2.457E+03	1.739E+03	3.706E+02	0.000E+00	3.475E+02	2.109E+03	2.109E+03
10.000	393.700	2.700	3.540E+02	1.591E+00	2.206E+02	0.000E+00	1.318E+02	2.222E+02	2.222E+02

Copy the ‘total doses’ for the two shielding values in the table below. If needed, you can change the notation: 2.457E+03 actually means 2,457*10^3 or simply 23457 rad.

Aluminium thickness	Total ionising dose (rad)
5 mm	
10 mm	

EXERCISE 3: Geostationary Orbit (GEO) mission

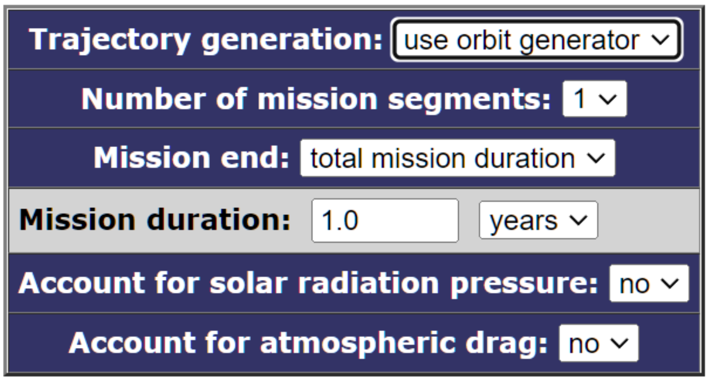
What is a Geostationary Orbit?

Geostationary Orbits (GEOs) are equatorial circular orbits with an altitude of about 35786 km. Satellites moving in such orbits have orbital periods equal to the Earth’s rotational period (one sidereal day) and thus appear motionless (at a fixed position in the sky) to ground observers. Most of the communications and weather satellites are placed on GEOs.

STEP 1 – Defining the mission in SPENVIS

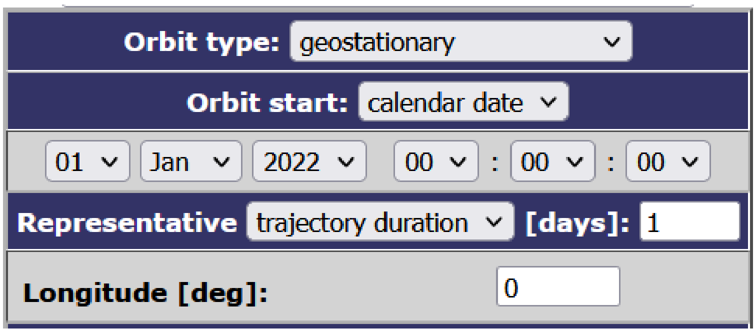
First, we need to specify the type of type of orbit we will start modelling.

Select “Coordinate generators” > “Spacecraft trajectories”

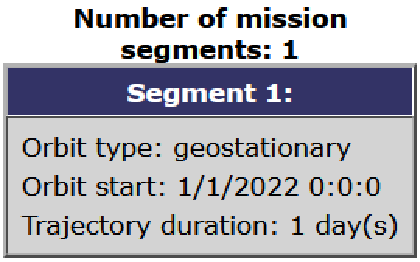


Make sure the “Mission duration” is 1 year (= default). Then click “next”.

In the upper line, you can choose the orbit type. Define this one as “geostationary”.



Next choose the orbit start date: 01 Jan 2022. The hour and minutes can stay on zero. After that choose a “trajectory duration” of 1 day. Choose a longitude equal to 0 degrees. Then click “next”.

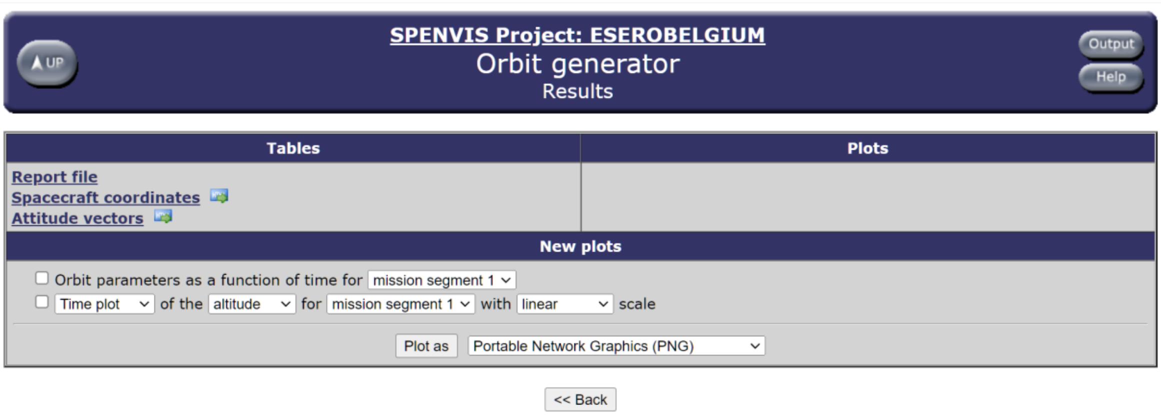


Then click “run”.

The program will now generate the mission orbit with your preferences. We can go to step 2.

STEP 2 – Environment definition

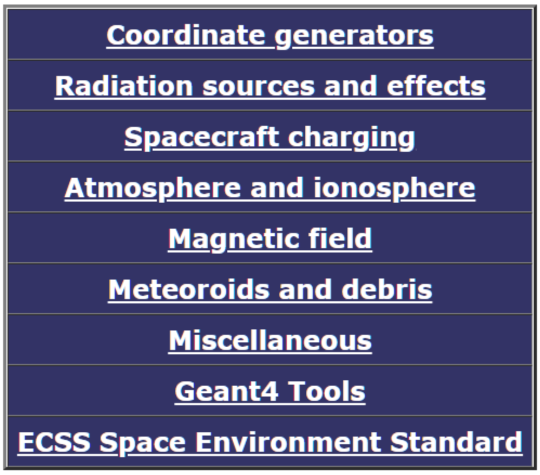
This is the image you ended with in STEP 1:



We will now define the environment, meaning we will let the model calculate the expected fluxes of high energy particles on our orbit.

a) **‘trapped particles’ (protons & electrons)**

Click the “Up” button (upper left corner), to go back to the main menu, and choose “Radiation sources and effects”:

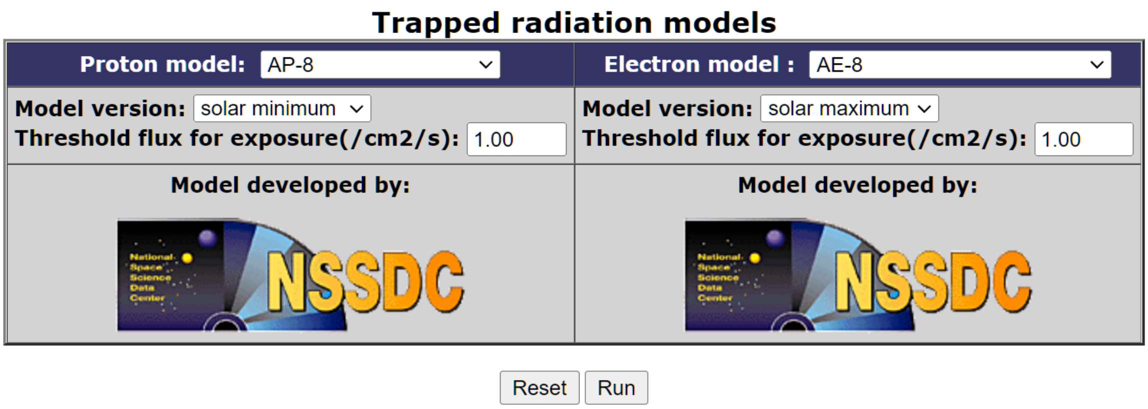


This submenu will open.

Select “**Trapped proton and electron fluxes**”

Here we will use the default settings:

- AP-8 solar minimum for trapped proton model
- AE-8 solar maximum for trapped electron model

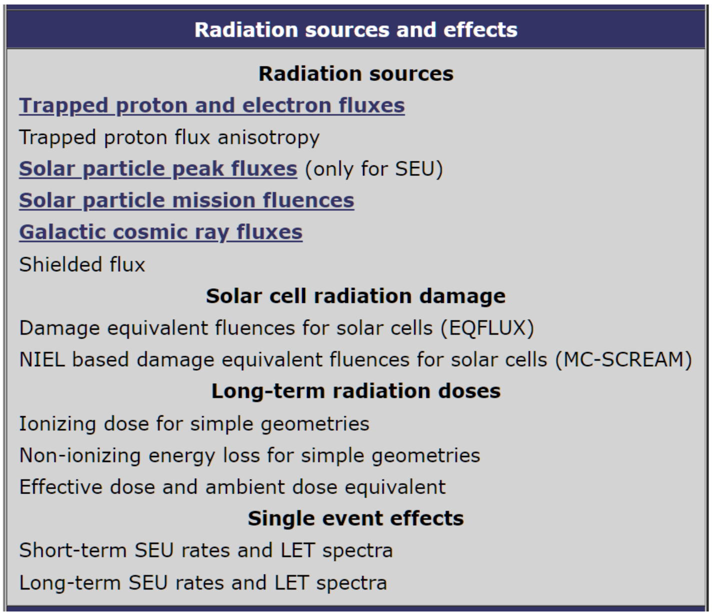


Click “Run” to calculate the particle fluxes

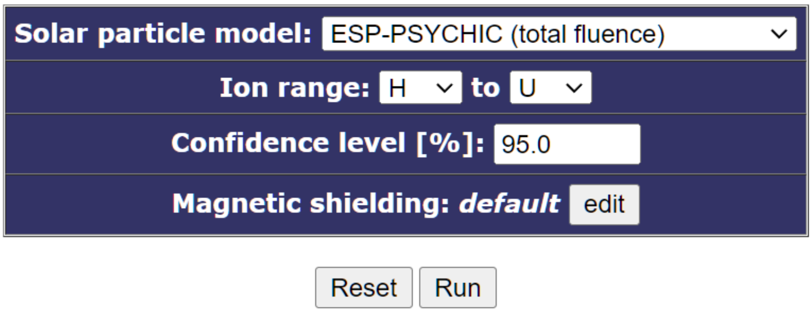
Now to go back, we will click again the “up” button at the upper left.

b) **Solar proton fluences**

Select “**Solar particle mission fluences**” from the menu:



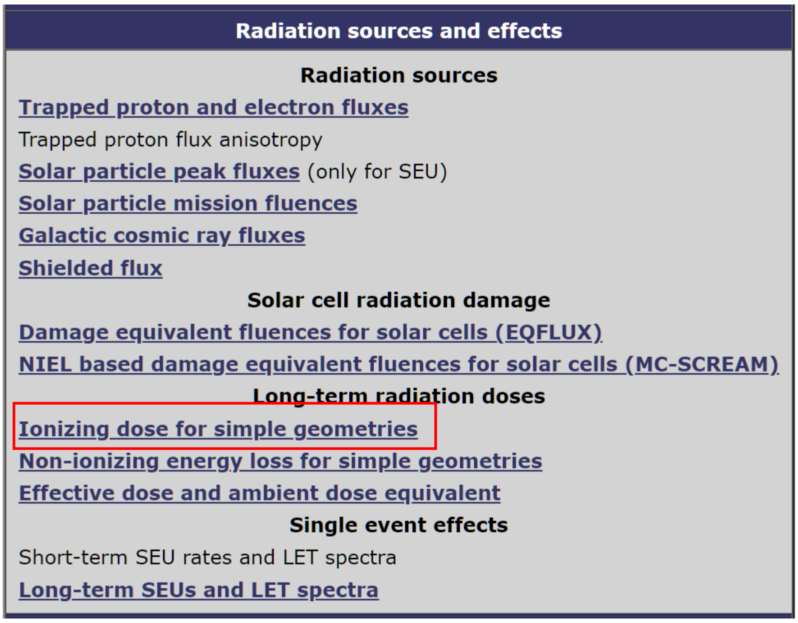
Again, we will use the default settings:



Simply click “run” to let the model calculate the solar proton fluences. Then click the “Up” button again to go back.

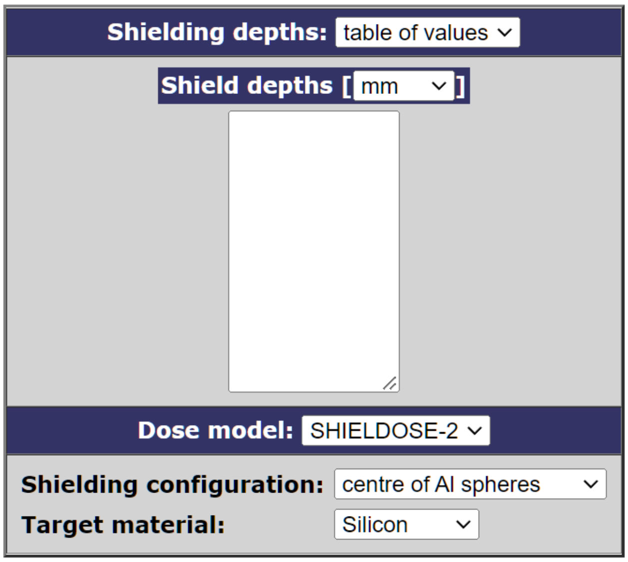
STEP 3 – Total Ionising Dose (TID) calculation

Now we will let the model calculate the radiation doses. Back in the main menu, you can see that most of the options are now ‘clickable’. Choose “**Ionizing dose for simple geometries**” (under the subtitle “Long term radiation doses”):



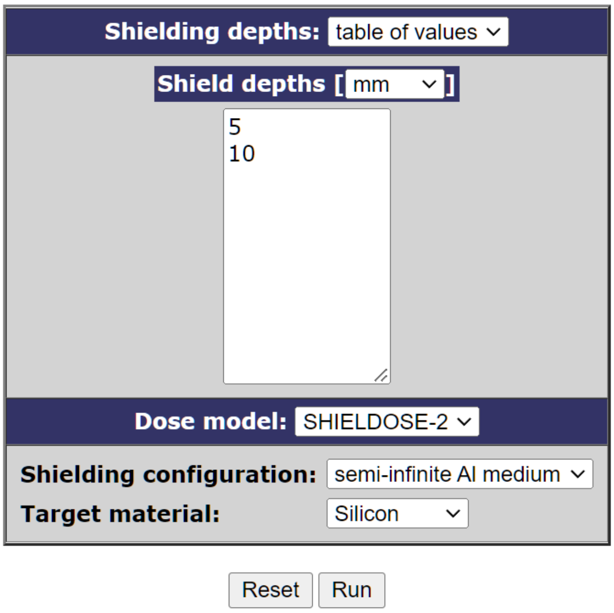
To keep it simple, we will consider our target spacecraft or instrument as a simple solid sphere, which is indeed a simple geometry.

For ‘shielding depth’ we select “table of values”, which will allow us to define our own choice of radiation shield.



We will choose the following parameters:

- A shield of 5 mm and a shield of 10 mm (put these number under each other in the white field),
- Dose model: keep the default “SHIELDOSE-2”,
- Shielding configuration: “Semi-infinite aluminium medium”,
- Target material: “Silicon” (because we will look at the radiation effect on electronic instruments).



Then click "Run".

Finally, we can have a look at the results on the resulting window: click 'Report file". You will get this report:

Total mission dose (rad)

Al absorber thickness			Total	Trapped electrons	Brems-strahlung	Trapped protons	Solar protons	Tr. electrons+ Bremsstrahlung	Tr. el.+Bremss. +Tr. protons
(mm)	(mils)	(g cm^{-2})							
5.000	196.850	1.350	1.104E+03	3.773E+02	2.845E+02	0.000E+00	4.422E+02	6.618E+02	6.618E+02
10.000	393.700	2.700	3.307E+02	2.761E-01	1.641E+02	0.000E+00	1.663E+02	1.644E+02	1.644E+02

Copy the 'total doses' for the two shielding values in the table below. If needed you can change the notation: 1.104E+03 actually means 1,104*10^3 or simply 1104 rad.

Aluminium thickness	Total ionising dose (rad)
5 mm	
10 mm	

EXERCISE 4: Lunar mission

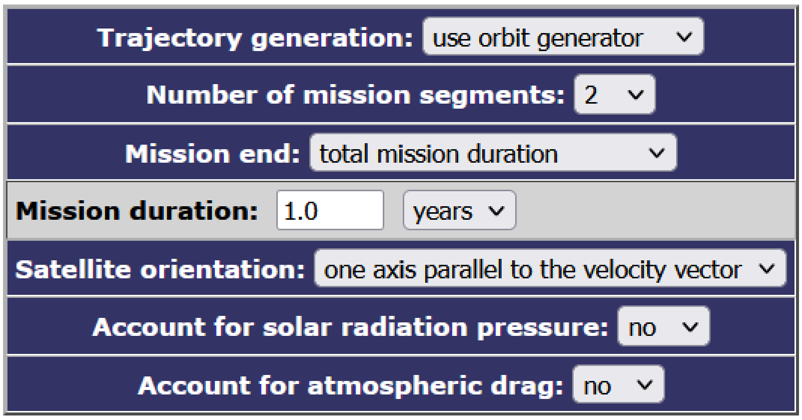
What is a typical trajectory to the Moon?

Any mission to the Moon will require the spacecraft to perform a transfer trajectory before injecting itself into a lunar orbit. During this transfer the spacecraft will have to cross the Earth's radiation belts exposing it to the trapped particle radiation. Therefore, a typical baseline trajectory would be a quick transfer to the Moon with possibly only a short duration intermediate orbit around the Earth to limit the radiation risks from the trapped particles.

STEP 1 - Defining the mission in SPENVIS

First, we need to specify the type of the orbit before start modelling. For simplicity, we will consider here a two-segment mission where the first segment represents the transfer trajectory and the second one represents a circular orbit (around Earth) with an altitude corresponding to the potential position of the Lunar Gateway (a space station that will be orbiting the Moon).

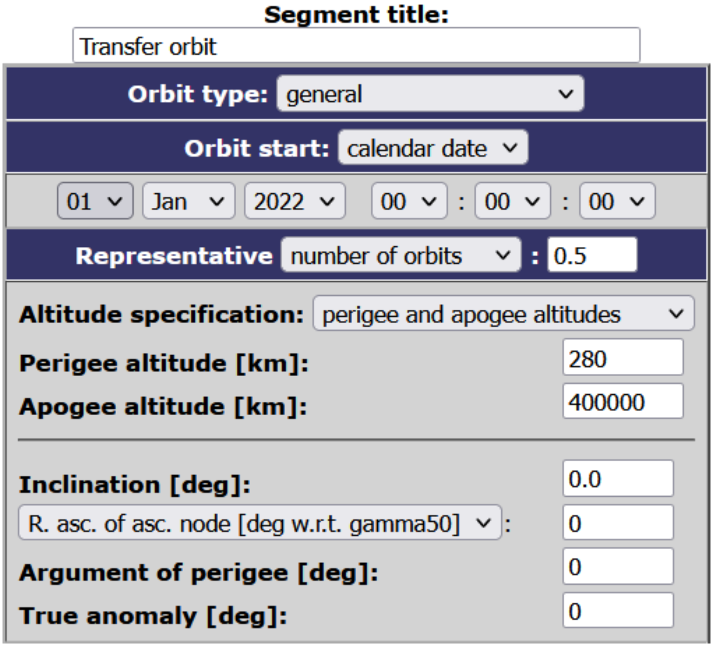
Select “Coordinate generators” > “Spacecraft trajectories”



Set the number of mission segments equal to 2. Make sure the “Mission duration” is set to 1 year (= default value). Then click “next”.

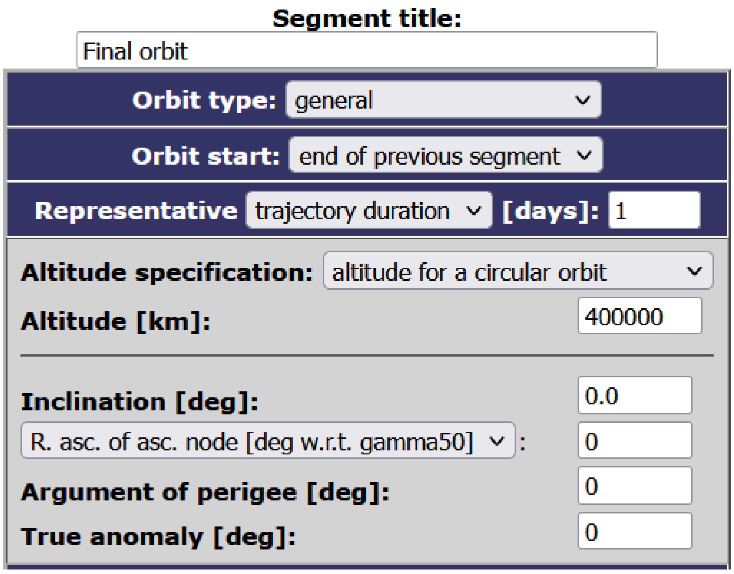
Write in the segment title box “Transfer orbit”. In the upper line, you can choose the orbit type for the first segment. Define this one as “general” (= default value).

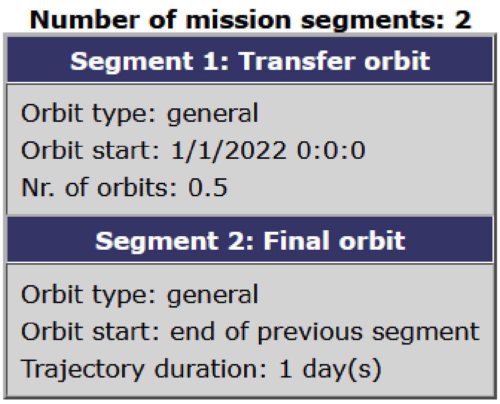
Next choose the orbit start date: 01 Jan 2022. The hour and minutes can stay on zero. After that choose a representative number of orbits equal to 0,5 days. Choose “perigee and apogee altitudes” for Altitude Specification and set the perigee altitude equal to 280 km and the apogee altitude equal to 400000 km. Leave the rest of the input to default values. Then click “next”.



For the second mission segment write in the segment title box “Final orbit”. In the upper line, you can choose the orbit type for the second segment. Define this one also as “general” (= default).

Next choose as orbit start date: end of previous segment. After that choose a “trajectory duration” of 1 day. Select “altitude for a circular orbit” for the Altitude specification. Choose the altitude of 400000 km and leave the rest of the input to the default values. Then click “next”.



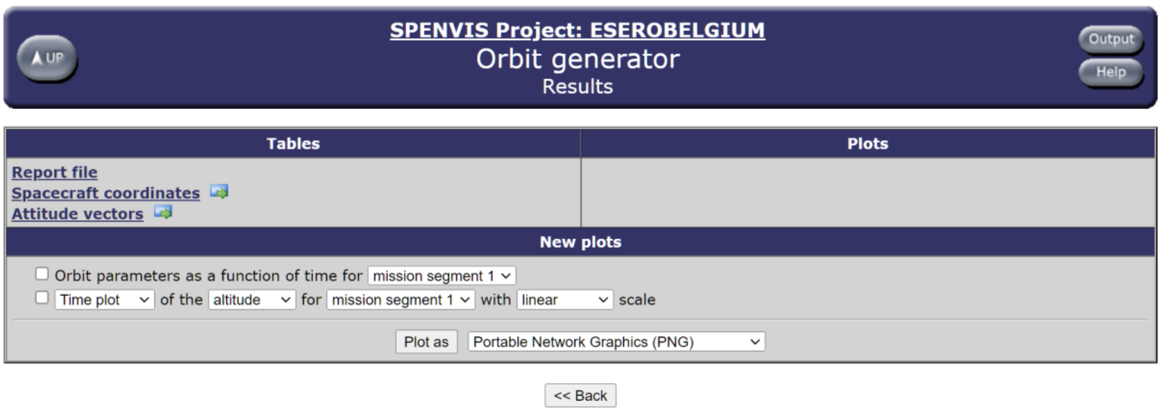


Then click “run”.

The program will now generate the mission orbit with your preferences. We can go to step 2.

STEP 2 – Environment definition

This is the image you ended with in STEP 1:



We will now define the environment, meaning we will let the model calculate the expected fluxes of high energy particles on our orbit.

Click the “Up” button (upper left corner), to go back to the main menu, and choose “Radiation sources and effects”:

Coordinate generators
Radiation sources and effects
Spacecraft charging
Atmosphere and ionosphere
Magnetic field
Meteoroids and debris
Miscellaneous
Geant4 Tools
ECSS Space Environment Standard

This submenu will open.

a) 'trapped particles' (protons & electrons)

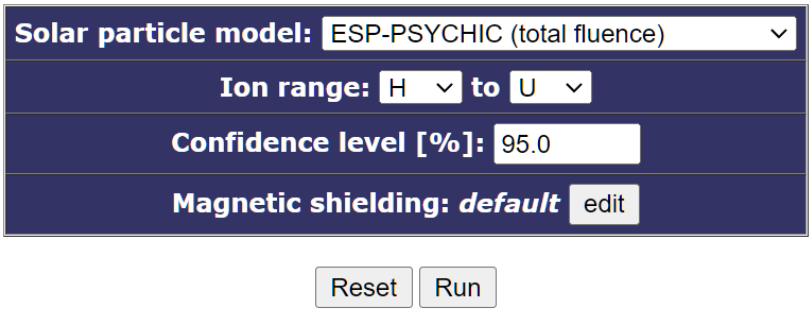
Note that there is no significant contribution to the radiation dose from trapped particles for this exercise so there is no need to calculate the trapped proton and electron fluxes. Also, it should be pointed out that the SPENVIS trapped proton and electron models provide no results for the orbit defined in segment 2 (model out of range).

b) Solar proton fluences

Select "**Solar particle mission fluences**" from the menu:

Radiation sources and effects
Radiation sources
Trapped proton and electron fluxes
Trapped proton flux anisotropy
Solar particle peak fluxes (only for SEU)
Solar particle mission fluences
Galactic cosmic ray fluxes
Shielded flux
Solar cell radiation damage
Damage equivalent fluences for solar cells (EQFLUX)
NIEL based damage equivalent fluences for solar cells (MC-SCREAM)
Long-term radiation doses
Ionizing dose for simple geometries
Non-ionizing energy loss for simple geometries
Effective dose and ambient dose equivalent
Single event effects
Short-term SEU rates and LET spectra
Long-term SEU rates and LET spectra

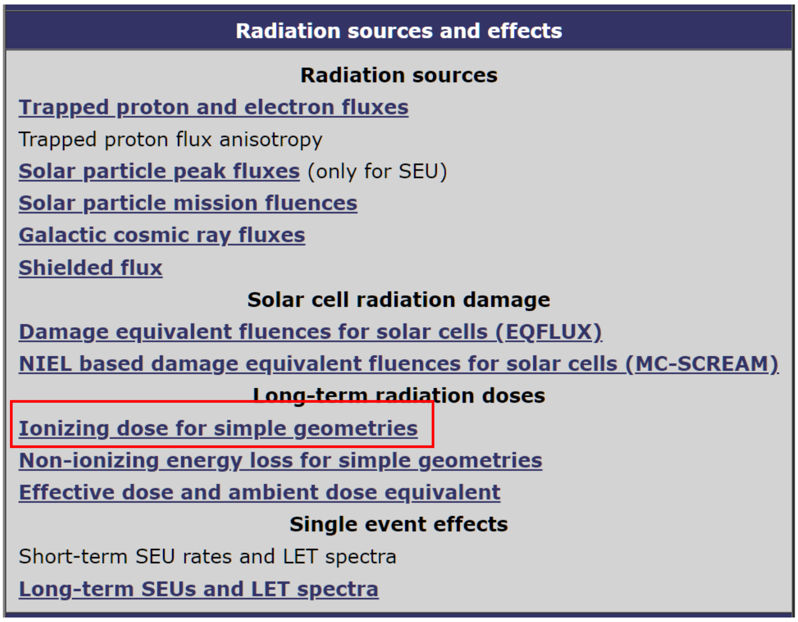
Again, we will use the default settings:



Simply click “run” to let the model calculate the solar proton fluences. Then click the “Up” button again to go back.

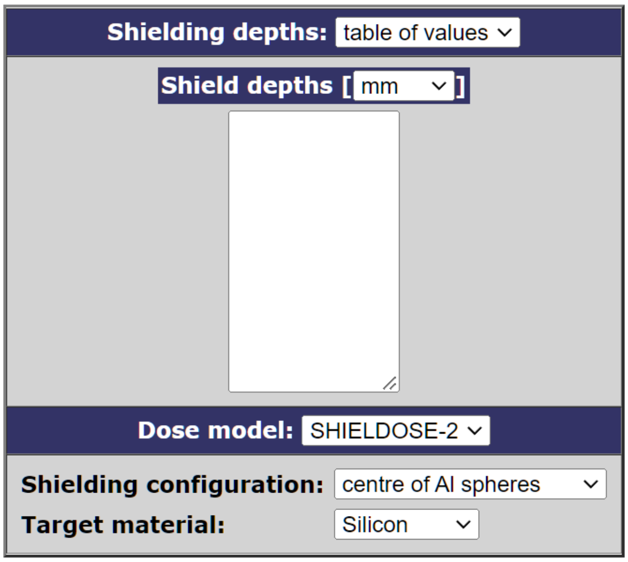
STEP 3 – Total Ionising Dose (TID) calculation

Now we will let the model calculate the radiation doses. Back in the main menu, you can see that most of the options are now ‘clickable’. Choose “**Ionizing dose for simple geometries**” (under the subtitle “Long term radiation doses”):



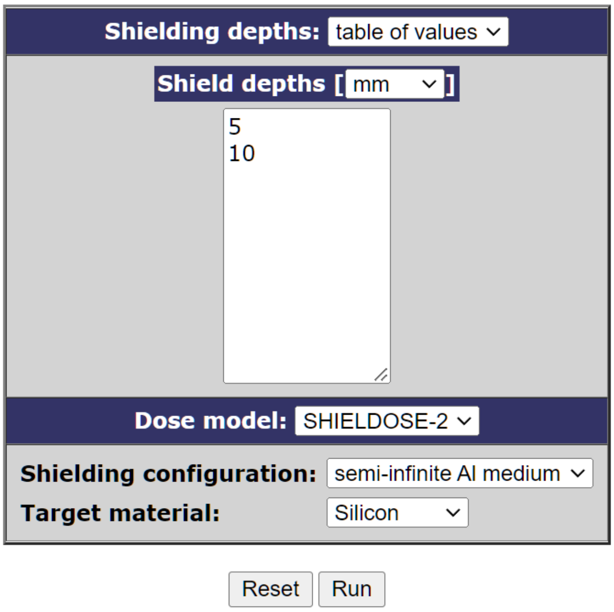
To keep it simple, we will consider our target spacecraft or instrument as a simple solid sphere, which is indeed a simple geometry.

For ‘shielding depth’ we select “table of values”, which will allow us to define our own choice of radiation shield.



We will choose the following parameters:

- A shield of 5 mm and a shield of 10 mm (put these number under each other in the white field),
- Dose model: keep the default “SHIELDOSE-2”,
- Shielding configuration: “Semi-infinite aluminium medium”,
- Target material: “Silicon” (because we will look at the radiation effect on electronic instruments).



Then click “Run”.

Finally, we can have a look at the results on the resulting window: click ‘Report file”. You will get this report:

Total mission dose (rad)				
Al absorber thickness			Total	Solar protons
(mm)	(mils)	(g cm^{-2})		
5.000	196.850	1.350	4.446E+02	4.446E+02
10.000	393.700	2.700	1.673E+02	1.673E+02

Copy the 'total doses' for the two shielding values in the table below. If needed, you can change the notation: 4.446E+02 actually means 4,446*10^2 or simply 444,6 rad.

Aluminium thickness	Total ionising dose (rad)
5 mm	
10 mm	

Understanding the results

A comparison of the total ionising dose (in units of rad) can be seen in the table below. To understand these results, one must look at the radiation environments for the different missions in more detail.

Aluminium thickness	Total ionising dose (rad) for 1 year mission			
	SSO	MEO	GEO	Lunar mission
5 mm	321,3	2457,0	1104,0	444,6
10 mm	186,5	354,0	330,7	167,3

Sun Synchronous Orbit (SSO)

The main contribution to the dose for a spacecraft on a Sun Synchronous Orbit (which is a low Earth orbit) is due to the trapped protons of the inner radiation belt. The fact that is flying closer to the Earth means that is better shielded from solar protons by the Earth's magnetic field.

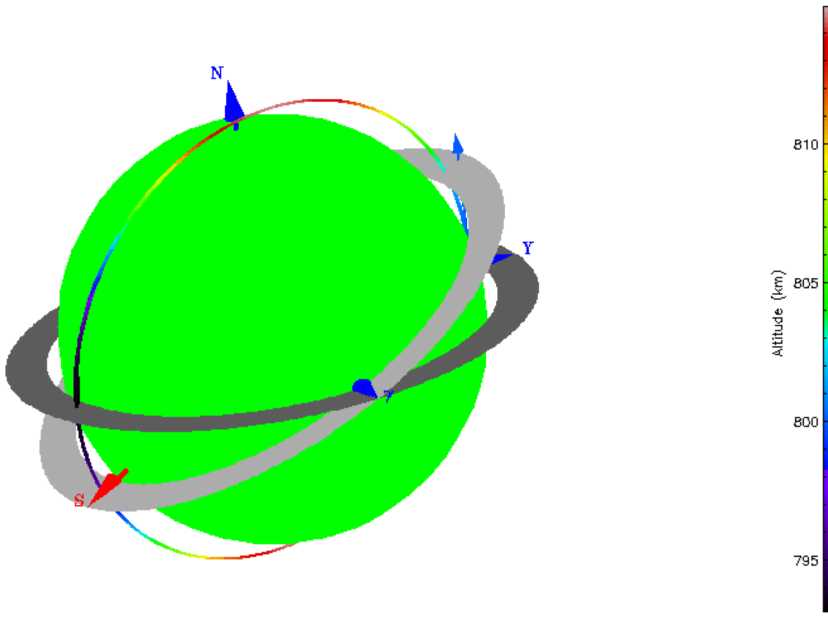


Figure 20 The representative trajectory for our SSO mission.

The following plots show the exposed radiation environments for our SSO mission.

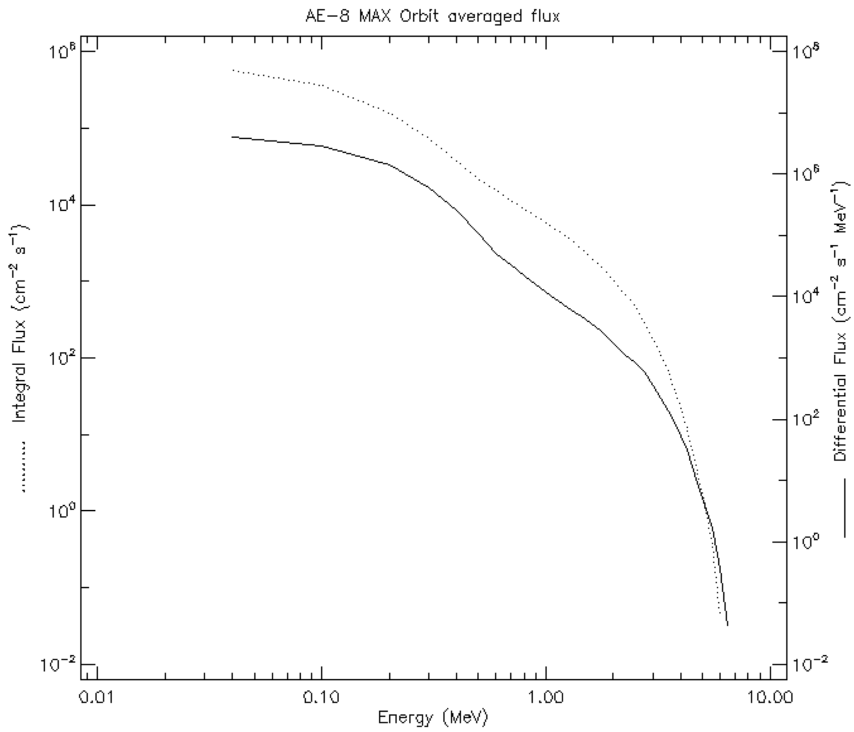


Figure 21 Calculated averaged electron energy spectra (i.e. integral and differential fluxes vs electron energies) for our SSO mission

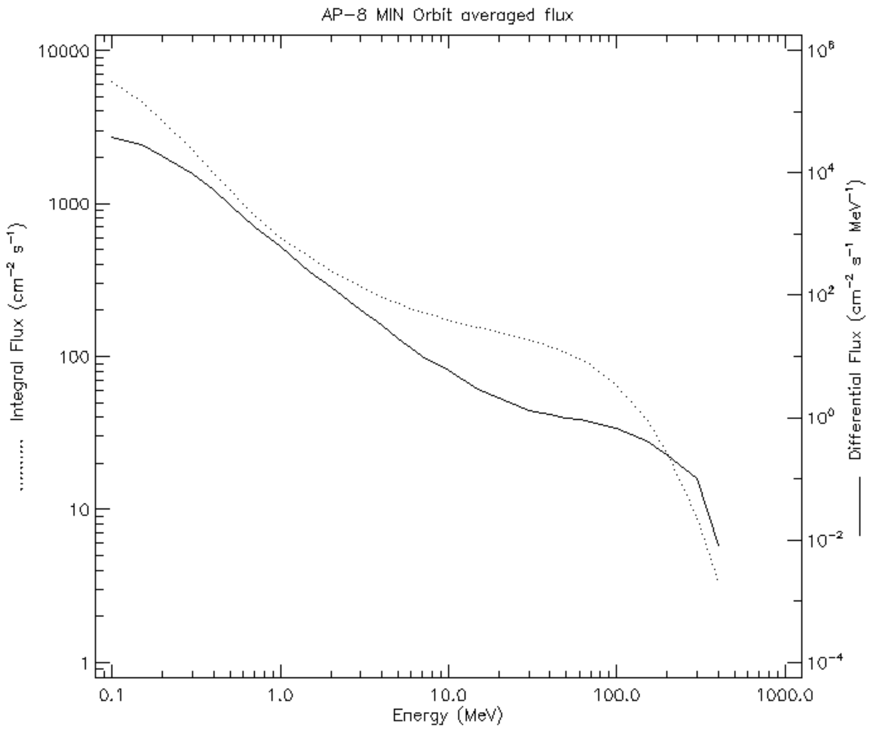


Figure 22 Calculated averaged proton energy spectra (i.e. integral and differential fluxes vs proton energies) for our SSO mission

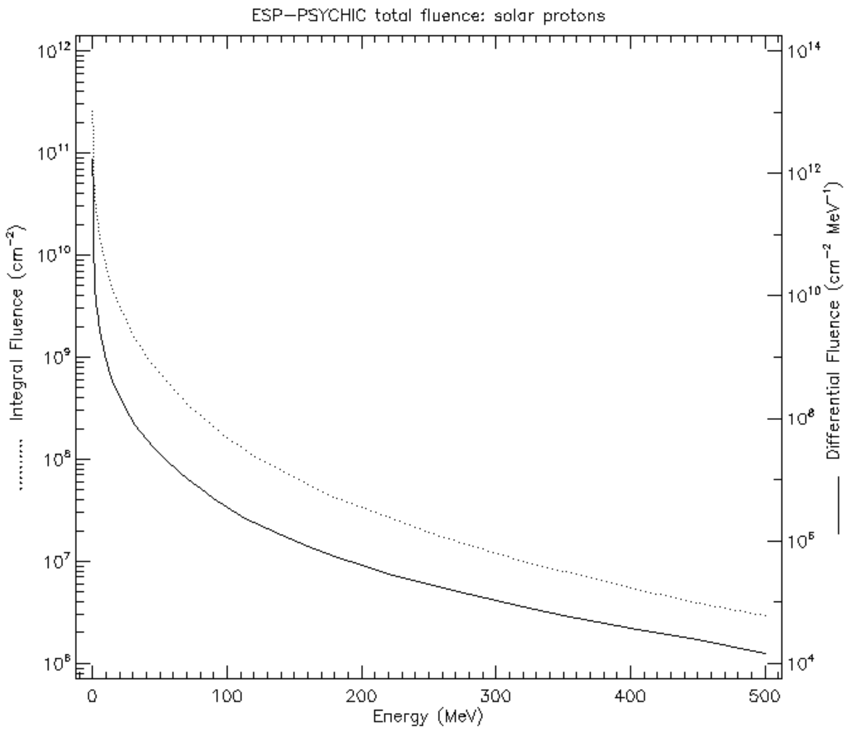


Figure 23 Calculated solar proton fluences (i.e. integral and differential fluences vs proton energies) for our SSO mission

Finally, the last plot shows the exposed radiation environments for our SSO mission. From this image we can see that most of the dose is due to the trapped protons. This is expected since the spacecraft is exposed only into the inner radiation belt that is dominated by the protons.

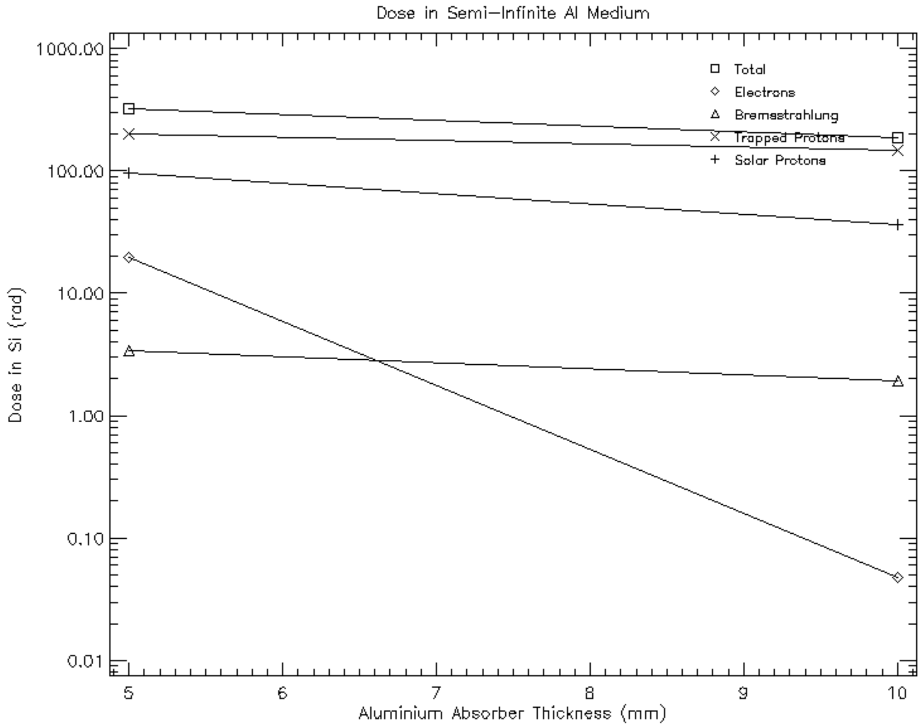


Figure 24 Calculated dose in silicon (measured in units of rad) due to the different radiation environments encountered during our SSO mission for the two shielding thicknesses

Total mission dose (rad)

Al absorber thickness (mm)	(mils)	($g\ cm^{-2}$)	Total	Trapped electrons	Brems-strahlung	Trapped protons	Solar protons	Tr. electrons+ Bremsstrahlung	Tr. el.+Bremss. +Tr. protons
5.000	196.850	1.350	3.213E+02	1.981E+01	3.409E+00	2.022E+02	9.591E+01	2.322E+01	2.254E+02
10.000	393.700	2.700	1.865E+02	4.716E-02	1.916E+00	1.484E+02	3.613E+01	1.963E+00	1.503E+02

The SSO is an almost polar orbit. You can confirm this by checking the orbit inclination in the SPENVIS orbit generator output file (should be equal to 98.6 degrees). This means that the spacecraft will receive more radiation when passing close to the poles (why?) or above the South Atlantic Anomaly (i.e. the region where the inner radiation belt comes closest to Earth's surface).

Medium Earth orbit (MEO)

The main contribution to the dose for a spacecraft on an orbit like the Galileo spacecraft is due to the trapped electrons from both the inner and outer radiation belt. There is also some contribution to the dose from energetic solar protons reaching the orbit of the spacecraft.

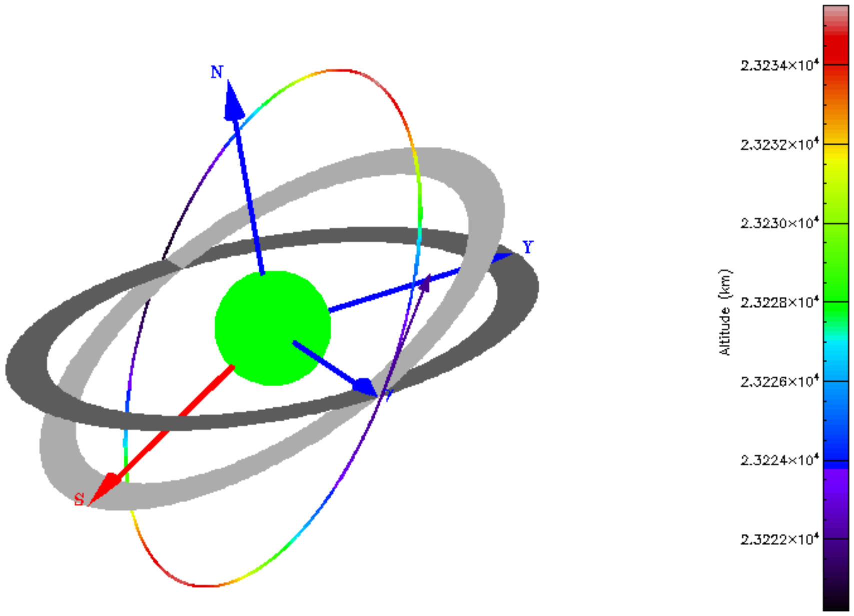


Figure 25 The representative trajectory for our Galileo spacecraft MEO mission

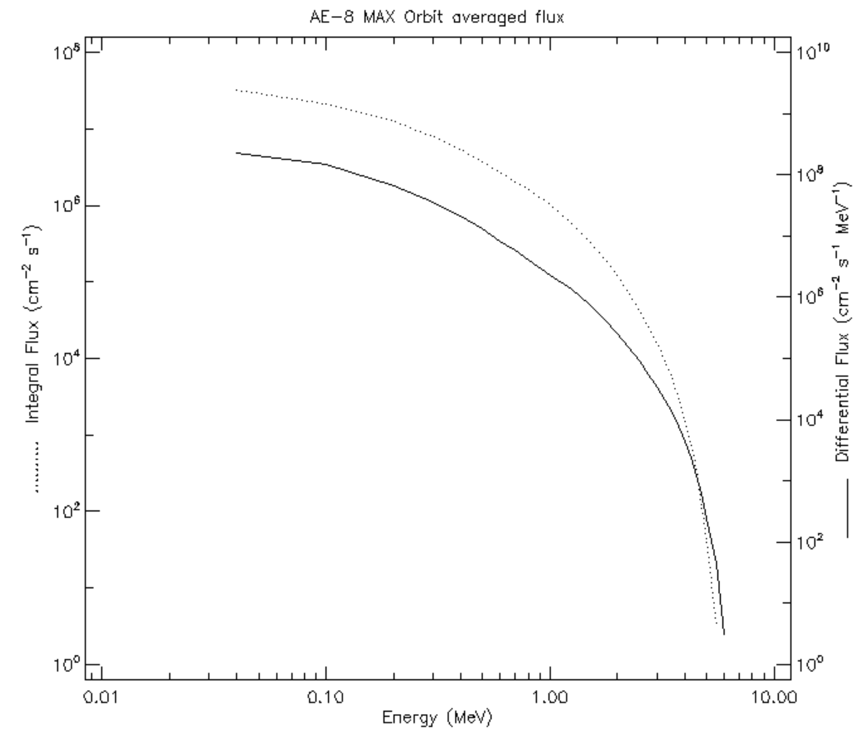


Figure 26 Calculated averaged electron energy spectra (i.e. integral and differential fluxes vs electron energies) for our MEO mission

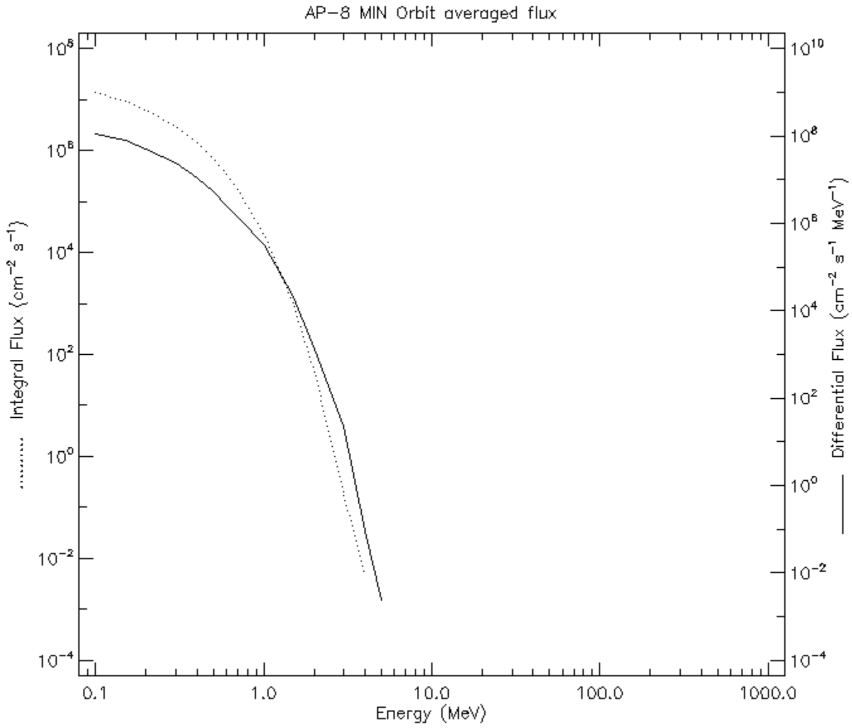


Figure 27 Calculated averaged proton energy spectra (i.e. integral and differential fluxes vs proton energies) for our MEO mission

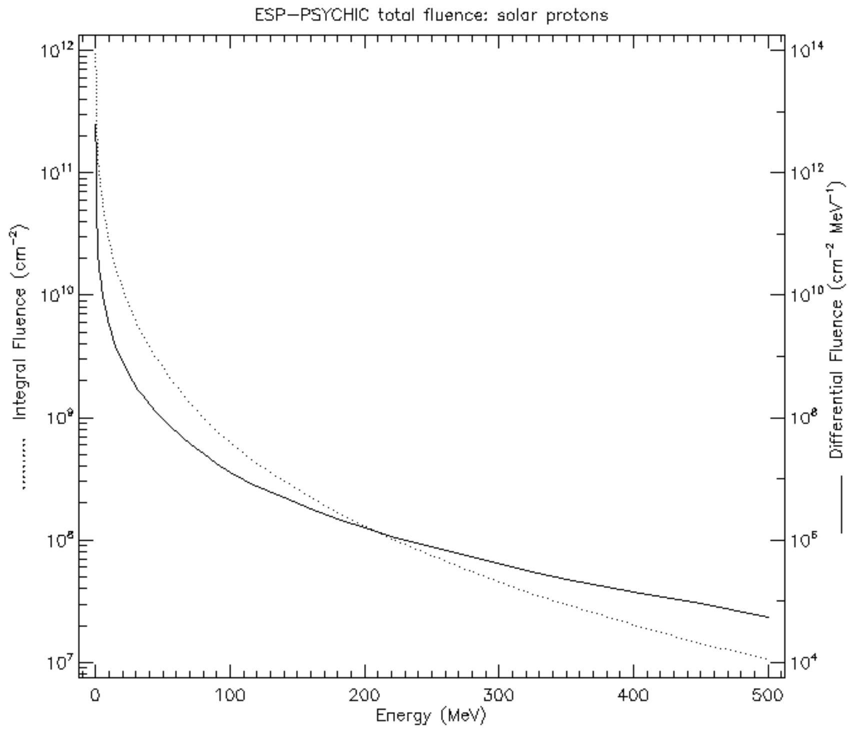


Figure 28 Calculated solar proton fluences (i.e. integral and differential fluences vs proton energies) for our MEO mission

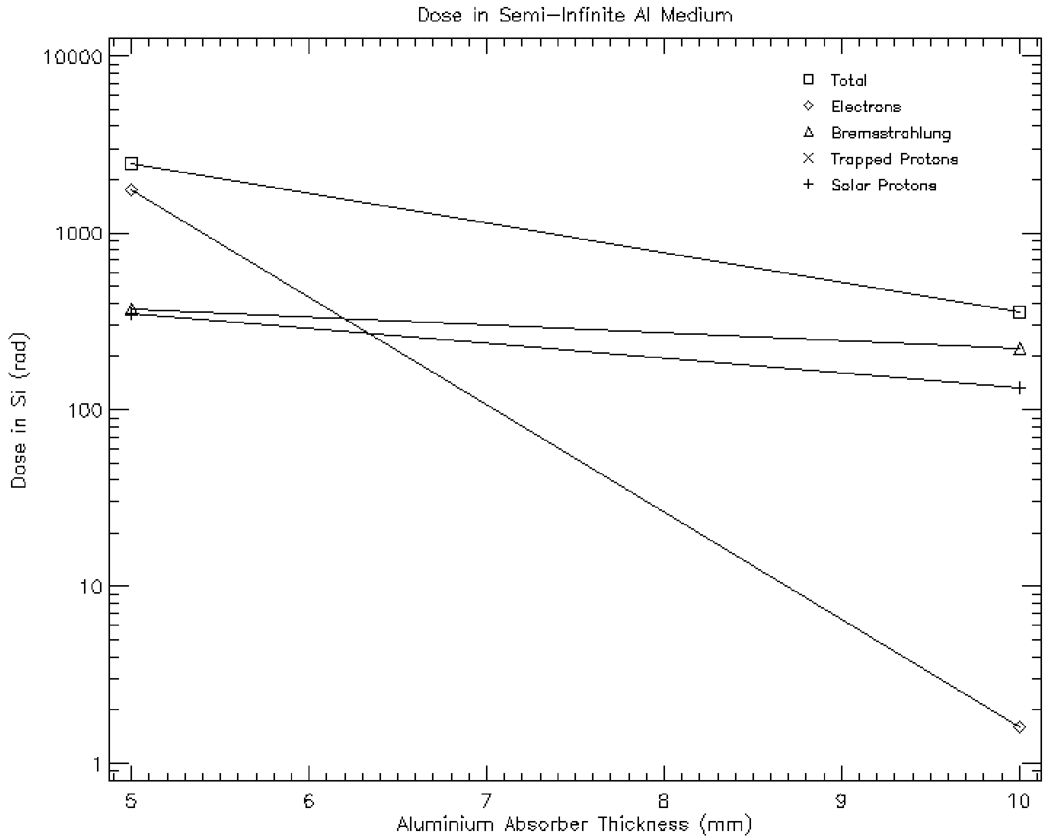


Figure 29 Calculated dose in silicon (measured in units of rad) due to the different radiation environments encountered during our MEO mission for the two shielding thicknesses

Total mission dose (rad)

Al absorber thickness			Total	Trapped electrons	Brems-strahlung	Trapped protons	Solar protons	Tr. electrons+ Bremsstrahlung	Tr. el.+Bremss. +Tr. protons
(mm)	(mils)	(g cm^{-2})							
5.000	196.850	1.350	2.457E+03	1.739E+03	3.706E+02	0.000E+00	3.475E+02	2.109E+03	2.109E+03
10.000	393.700	2.700	3.540E+02	1.591E+00	2.206E+02	0.000E+00	1.318E+02	2.222E+02	2.222E+02

The inclination of the Galileo spacecraft orbit (equal to 56 degrees) helps to reduce the time the spacecraft spends in the radiation belt and therefore reducing the received dose.

Geostationary orbit (GEO)

For a geostationary orbit the main contribution to the dose is due to the trapped electrons of the outer radiation belt and the energetic solar protons (the magnetic field provide less shielding at GEO).

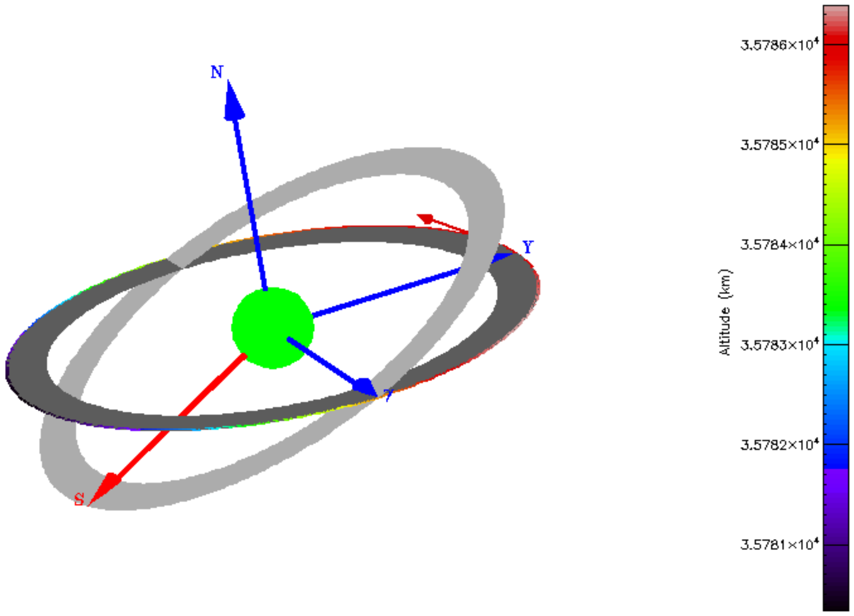


Figure 30 The representative trajectory for our Geostationary mission

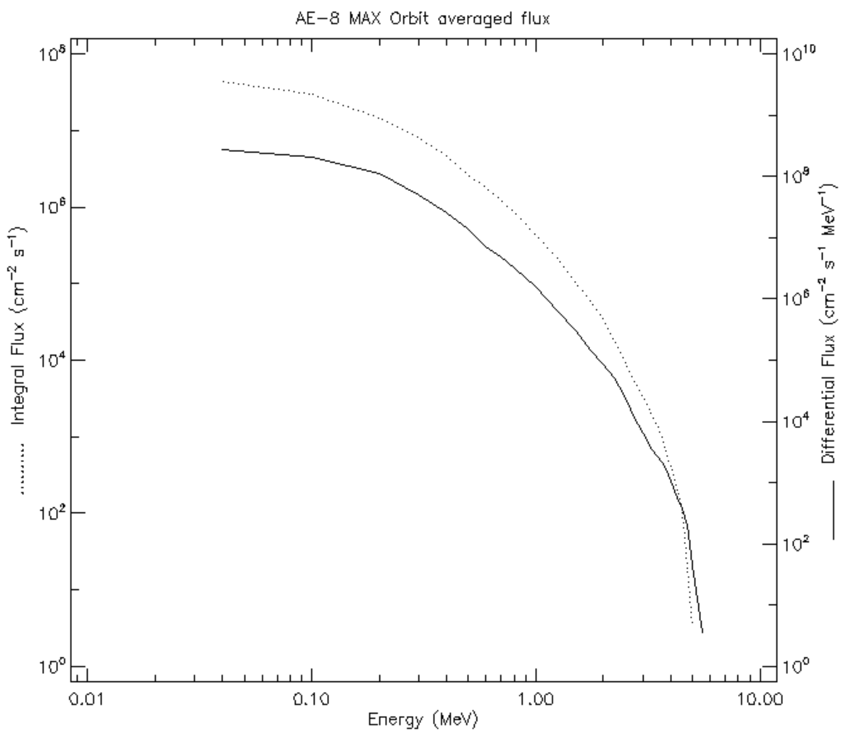


Figure 31 Calculated averaged electron energy spectra (i.e. integral and differential fluxes vs electron energies) for our GEO mission

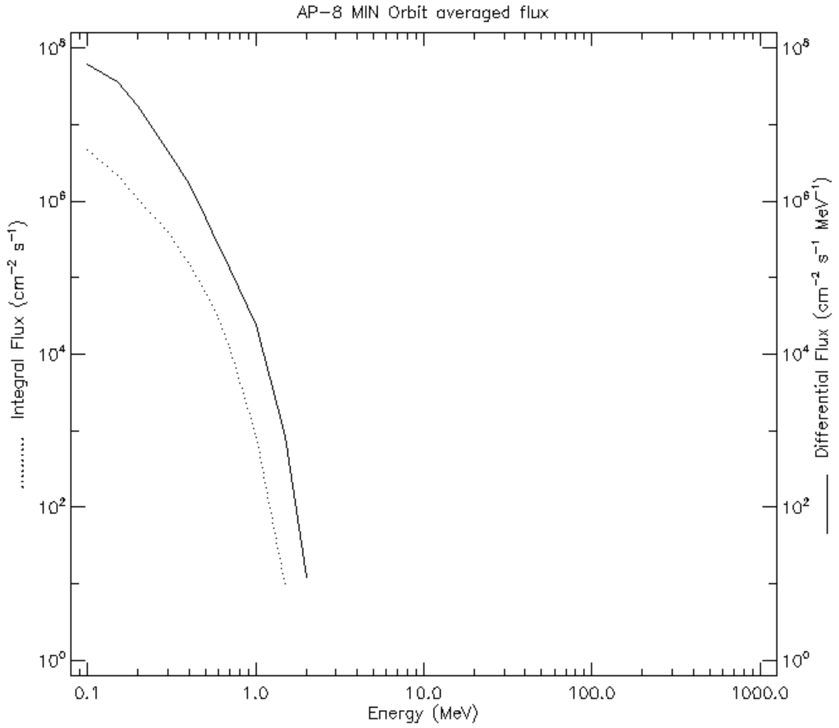


Figure 32 Calculated averaged proton energy spectra (i.e. integral and differential fluxes vs proton energies) for our GEO mission

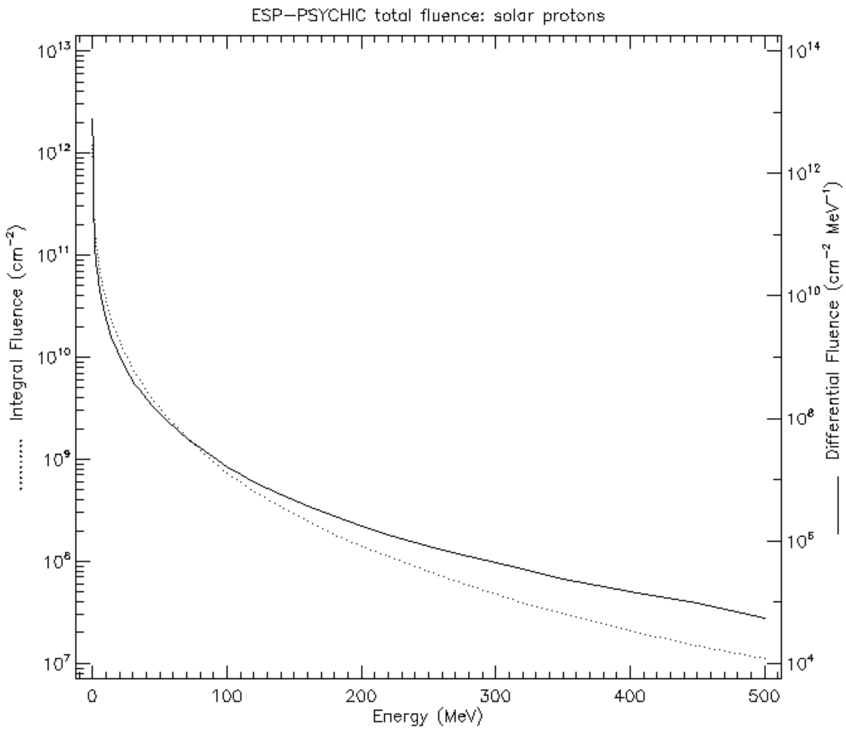


Figure 33 Calculated solar proton fluences (i.e. integral and differential fluences vs proton energies) for our GEO mission

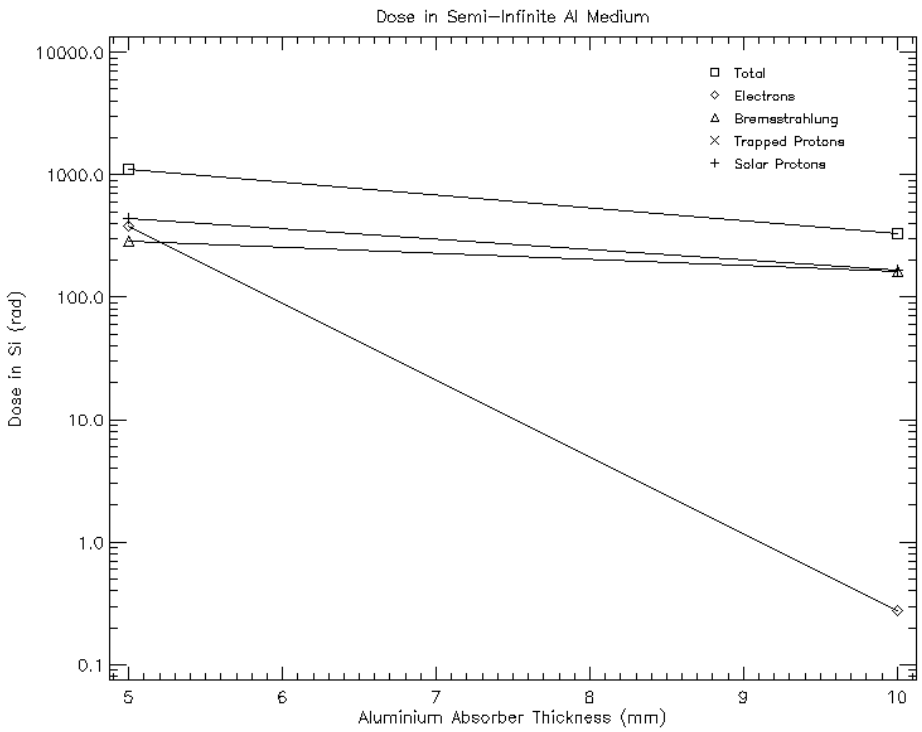


Figure 34 Calculated dose in silicon (measured in units of rad) due to the different radiation environments encountered during our GEO mission for the two shielding thicknesses.

Total mission dose (rad)

Al absorber thickness			Total	Trapped electrons	Brems-strahlung	Trapped protons	Solar protons	Tr. electrons+ Bremsstrahlung	Tr. el.+Bremss. +Tr. protons
(mm)	(mils)	(g cm^{-2})							
5.000	196.850	1.350	1.104E+03	3.773E+02	2.845E+02	0.000E+00	4.422E+02	6.618E+02	6.618E+02
10.000	393.700	2.700	3.307E+02	2.761E-01	1.641E+02	0.000E+00	1.663E+02	1.644E+02	1.644E+02

Lunar mission

Any spacecraft travelling to the Moon will have to pass through the Earth's radiation belts. However, if this passage is quick (e.g. a fast transfer trajectory) like in this exercise there is no contribution from the trapped protons and electrons to the calculated dose. The main contribution is from the energetic protons coming from the Sun.

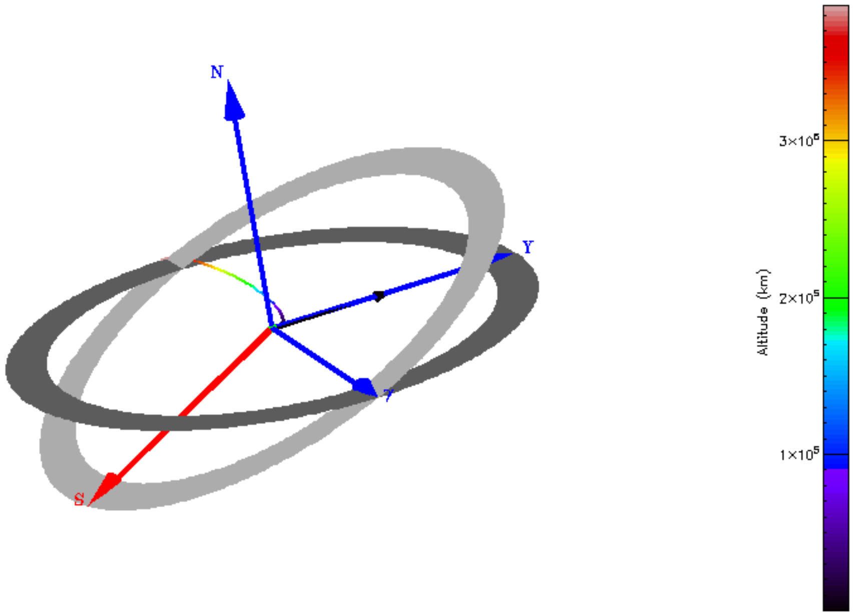


Figure 35 The representative trajectory for our lunar mission

Note that the calculated solar proton fluences for the lunar mission are the same as for the GEO mission. The reason is that the solar proton model calculates the fluxes at 1 AU (the astronomical unit of length is approximately the distance between Earth and the Sun) for both geostationary and lunar orbits.

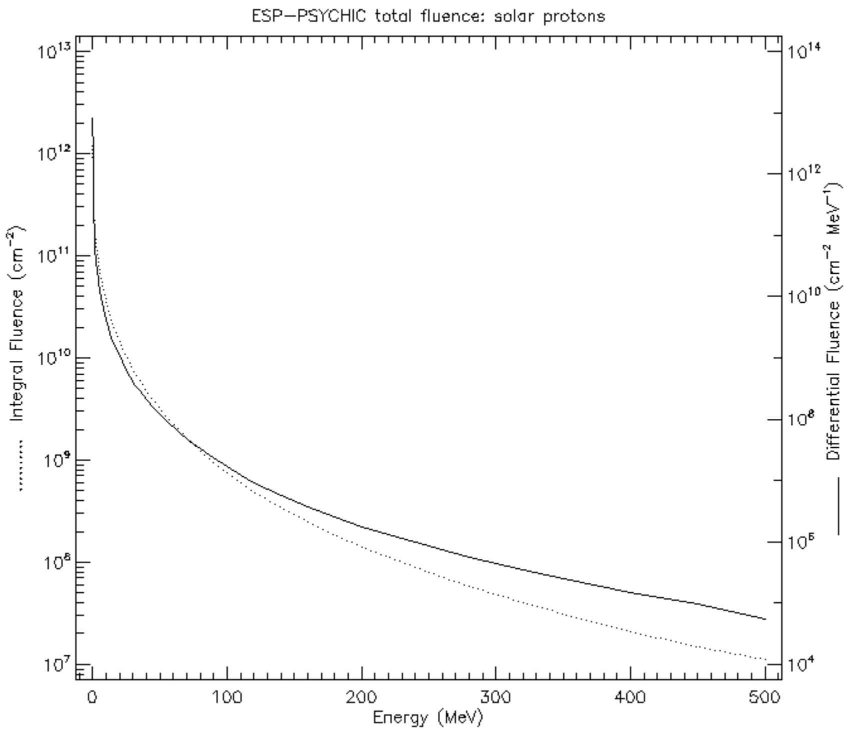


Figure 36 Calculated solar proton fluences (i.e. integral and differential fluences vs proton energies) for our lunar mission

Total mission dose (rad)

Al absorber thickness			Total	Solar protons
(mm)	(mils)	(g cm^{-2})		
5.000	196.850	1.350	4.446E+02	4.446E+02
10.000	393.700	2.700	1.673E+02	1.673E+02

Exercise

Use the total doses calculated by SPENVIS for 1 year mission to calculate the total doses (in silicon) for 8- and 15-year missions of a Galileo navigation satellite on a MEO. Provide you answer in terms of krad (i.e. 10^3 rad)

Answer

Total dose is an accumulated effect. To calculate the total dose for the 8- and 15-year missions you simply need to multiply the doses for the 1-year mission by 8 and 15 respectively (see table below).

Aluminium thickness	Total ionising dose in silicon (krad)		
	MEO 1 year mission	MEO 8 year mission	MEO 15 year mission
5 mm	2,457	19,656	36,855
10 mm	0,354	2,832	5,31

Note that this exercise can be also done for the SSO, GEO and Lunar mission scenarios in a similar way.

Exercise

You have an instrument (e.g. a camera) that you want to send to space. This instrument contains an electronic device that was tested in a laboratory here on Earth to see how much radiation can receive before it breaks down. This is normally done using a Cobalt-60 gamma ray source. Cobalt-60 is a synthetic radioactive isotope of cobalt (Co) with a half-life of 5,2713 years that is produced artificially in nuclear reactors.

All of your device parts passed all tests up to 30 krad dose (in Silicon). Which from the two Aluminium shielding of 5- and 10-mm thickness is suitable for protecting your device during a 15 year MEO mission?

Answer

From the results of the previous exercise we can see that we have a dose (in Silicon) of 36,855 krad behind the 5 mm Aluminium shielding which exceeds our limit of the 30 krad (in Silicon). It is clear that the 10 mm of Aluminium shielding provides a better shielding and the total dose of 5,31 krad is way below the safety limit for our device.

Final remarks

Note that radiation analysis calculations are very important for the preparation of a space mission. Calculations like the above are significant for deciding the right amount of shielding on a spacecraft. Space engineers perform such calculations in order to have an initial estimation of the necessary shielding. Later on they perform more complex radiation analysis taking into consideration the full spacecraft payload to have a more precises calculation.

One of the mission requirements is the mass of the spacecraft since there are limits on the mass we can send to space depending on the launcher transport system (e.g. our rocket) we will use. Deciding on the appropriate amount of shielding is important because more shielding will mean additional mass on the cost of spacecraft payload (e.g. an instrument) and less shielding can be catastrophic for the mission.