MARMARA UNIVERSITY
FACULTY OF ENGINEERING

Shielding Materials and Methods Against Ionization for the Satellite

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GRADUATION PROJECT REPORT
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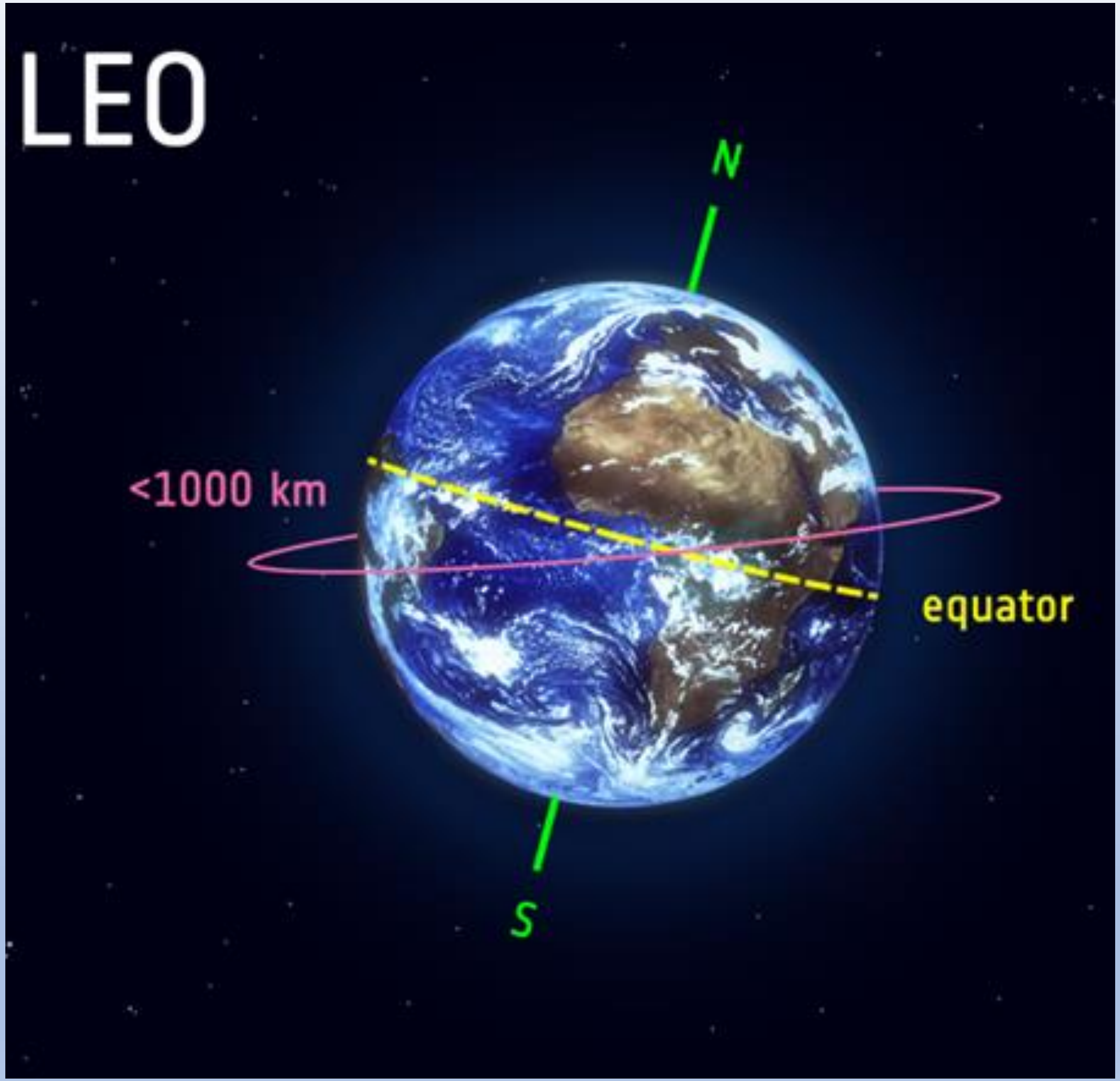
What is the LEO Orbit?

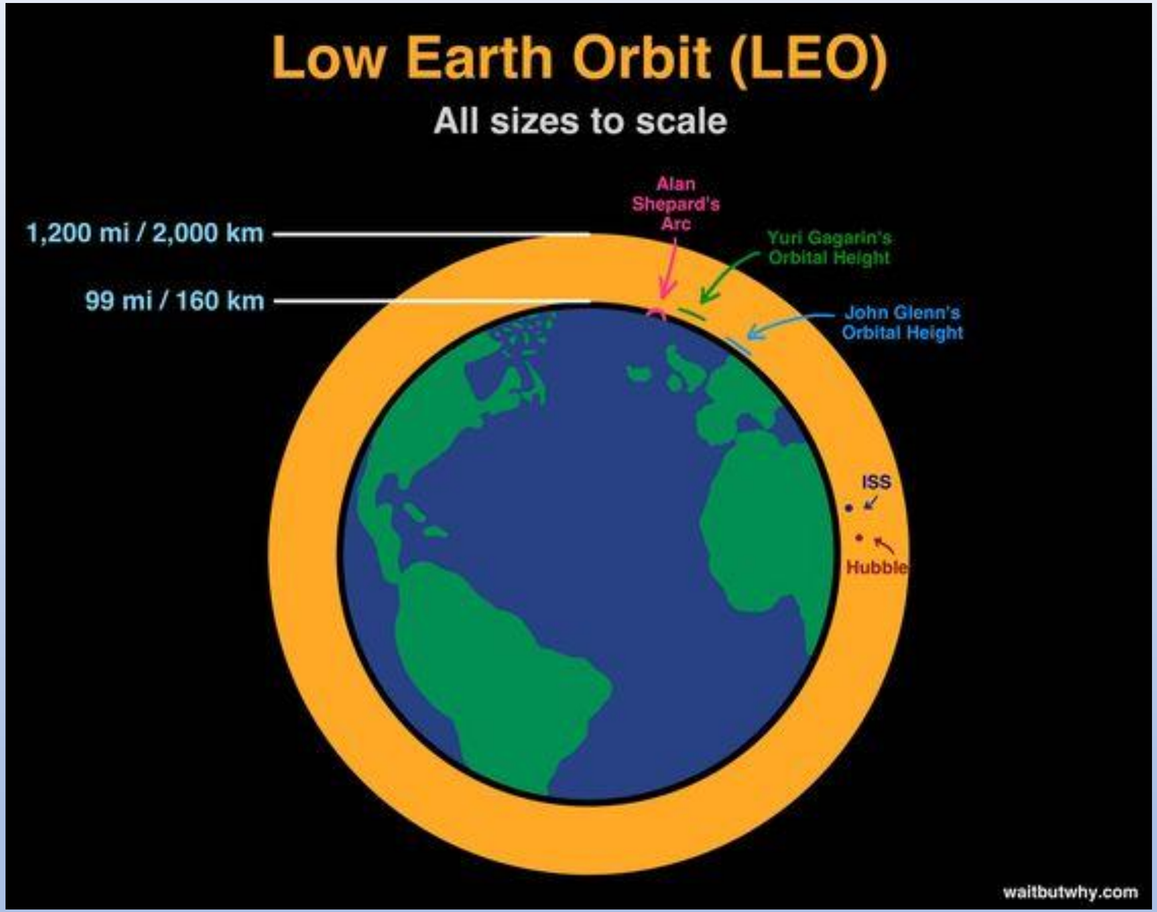
A low Earth orbit (LEO) is, as the name suggests, an orbit that is relatively close to Earth’s surface. It is normally at an altitude of less than 1000 km but could be as low as 160 km above Earth – which is low compared to other orbits, but still very far above Earth’s surface.



Advantages and Usage Areas of the LEO

LEO’s close proximity to Earth makes it useful for several reasons:

- It is the orbit most commonly used for satellite imaging, as being near the surface allows it to take images of higher resolution.
- It is also the orbit used for the International Space Station (ISS), as it is easier for astronauts to travel to and from it at a shorter distance.
- However, individual LEO satellites are less useful for tasks such as telecommunication, because they move so fast across the sky and therefore require a lot of effort to track from ground stations.
- Communications satellites in LEO often work as part of a large combination or constellation, of multiple satellites to give constant coverage.



Solar Activity and the Space Radiation Environment

Solar Activity

- The Sun’s activity varies with time and position on the Sun, and characterized by 11-year cycle, which can be divided into solar minimum and solar maximum phases. The sunspots (and other solar indices such as solar radio flux) are viewed as main indicators of solar activity cycle.
- Figure show a historic sunspot number. The latest solar cycle (cycle 24) peaked around year 2014. Currently, solar activity is on the decline and has been predicted to reach its minimum in late 2019 or 2020, while the solar maximum is expected to occur between 2023 and 2026 .

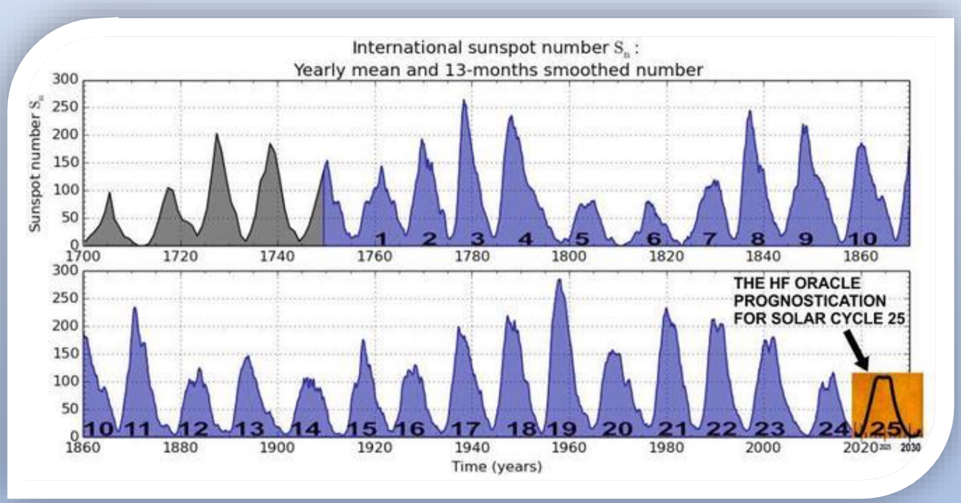


Figure: Historic sunspot number (source: SILSO graphics (http://sidc.be/silso) Royal Observatory of Belgium).

The Space Radiation Environment

Solar energetic events such as high-speed solar wind streams (HSS), solar flares and CMEs that give rise to solar particle events and geomagnetic storms affecting the space environment are more frequent during solar maximum.

Therefore, their impact on the atmosphere and air-based technology are expected to be higher during this phase of the solar cycle than the declining or minimum phase.

Solar events and associated phenomena mainly contribute to trapped and transient energetic particles in near space that constitute the space radiation environment, in addition to galactic cosmic ray from outer space.

The summary of types of space radiation, their origin or sources, and where they are important is shown in Figure.

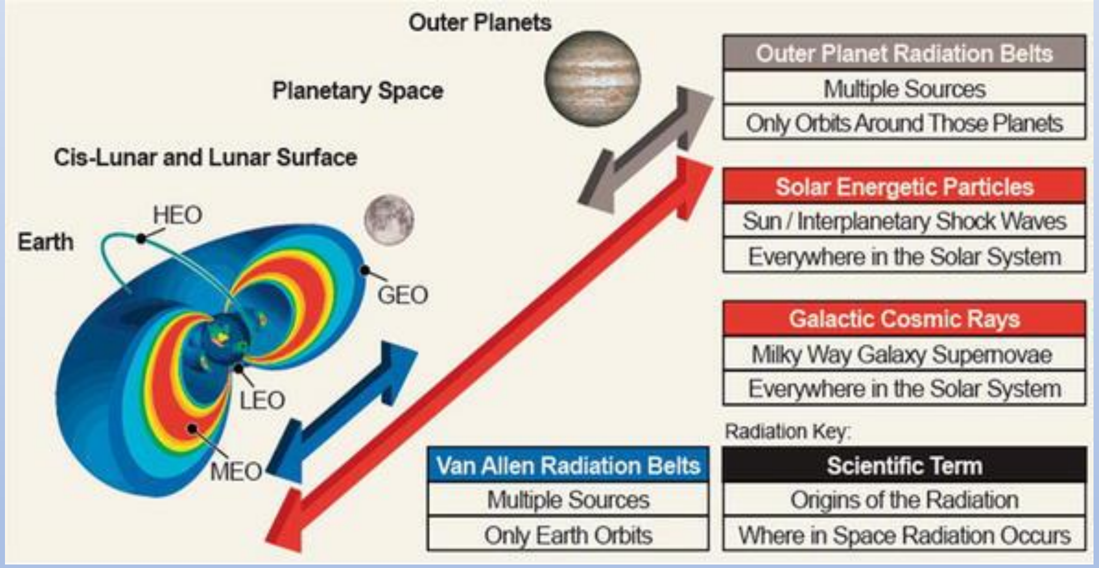


Figure: Summary of types of space radiation, their origin or sources, and where they are important in the outer planets, planetary space and Earth, including the low Earth orbit (LEO), geostationary orbit (GEO), medium Earth orbit (MEO) and high Earth orbit (HEO)

The Space Radiation Environment

Trapped radiation

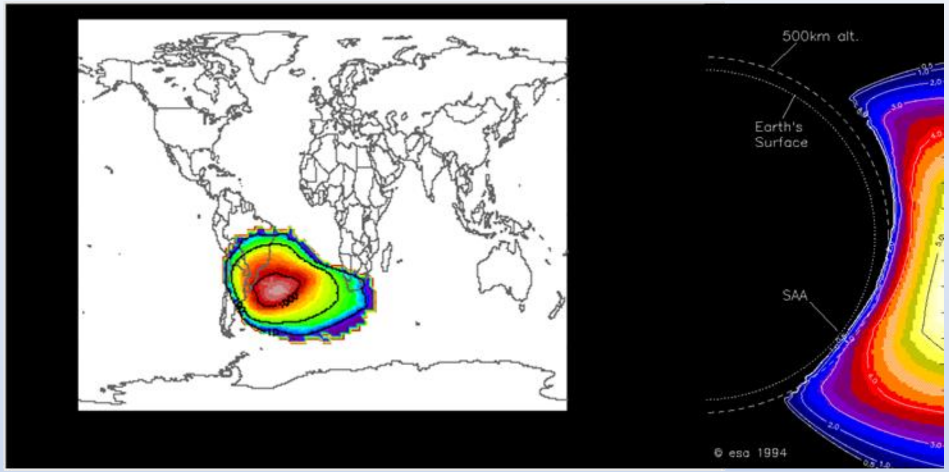
- Electrons ~< 10 MeV
- Protons ~< 10^2 MeV

Solar radiation

- Protons, heavy ions, electrons, neutrons, gamma rays, X-rays…

Cosmic rays

- Lower intensity
- Heavy ions



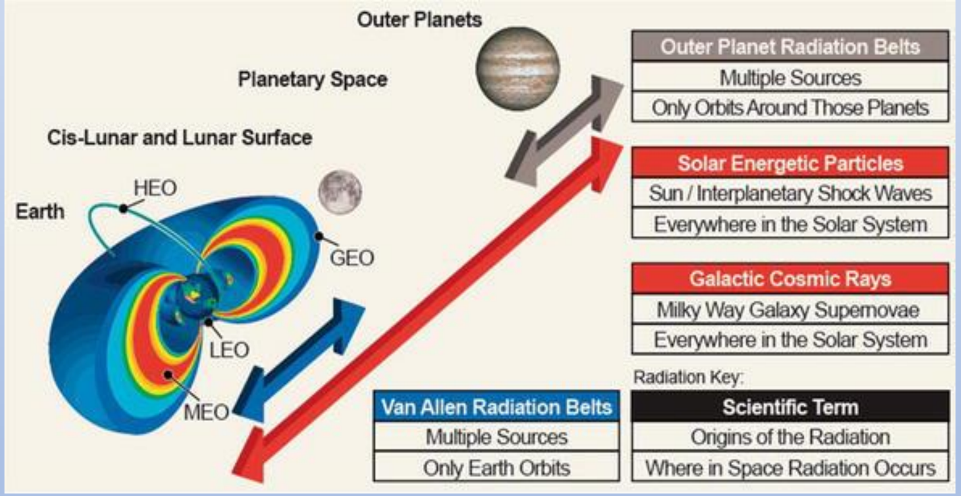


Figure: Summary of types of space radiation, their origin or sources, and where they are important in the outer planets, planetary space and Earth, including the low Earth orbit (LEO), geostationary orbit (GEO), medium Earth orbit (MEO) and high Earth orbit (HEO)

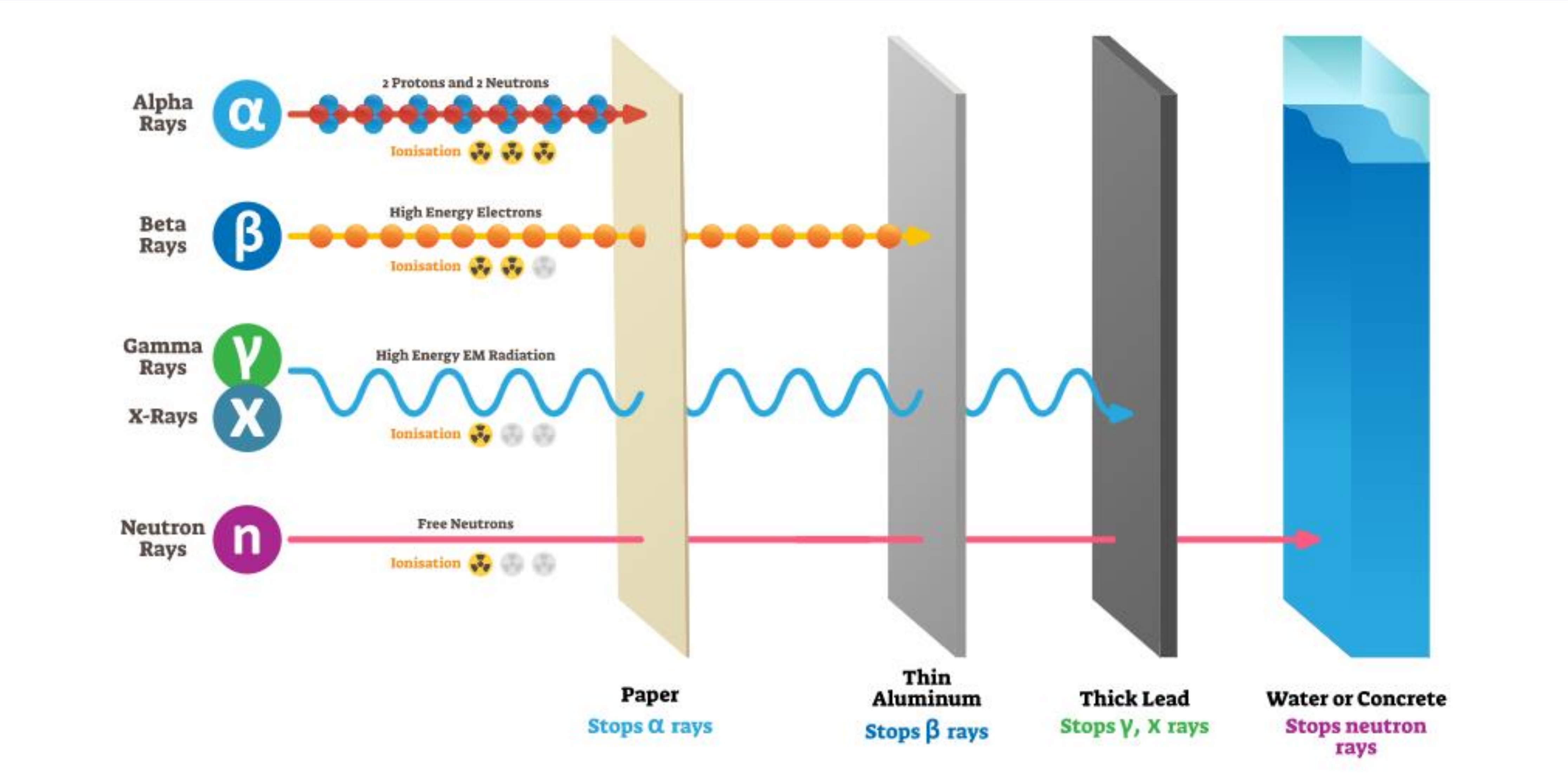
Types of Radiation

α ALPHA : can be stopped after traveling through about 1.2 inches of air, about 0.008 inches of water, or a piece of paper. Your skin provides adequate shielding because alpha particles can’t penetrate it. Alpha particles can be very harmful if inhaled or ingested, though.

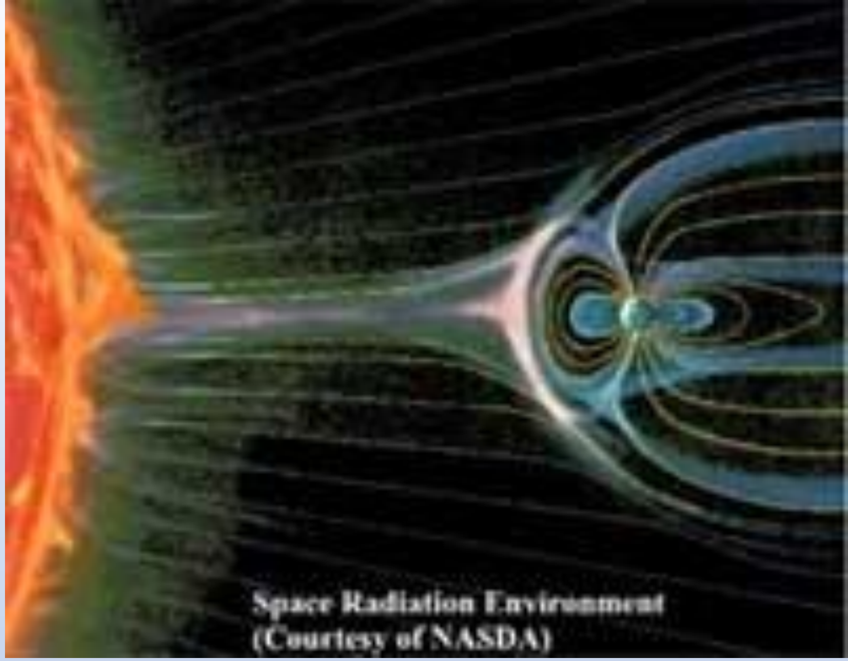
β BETA : Beta particles are more penetrating than alpha particles. They travel farther in air than alpha particles, but can be stopped by a layer of clothing or by a layer of a metal.

γ GAMMA : Thick, dense materials are necessary to shield from gamma rays. The higher the energy of the gamma ray, the thicker the shield must be. X-rays also require thicker shielding. This is why x-ray technicians often give patients receiving x-rays a lead apron to cover other parts of their body. Barriers of lead, concrete, or water provide protection from penetrating gamma rays.

Neutron Radiation : Neutron radiation is a form of ionizing radiation that presents as free neutrons. Typical phenomena are nuclear fission or nuclear fusion causing the release of free neutrons, which then react with nuclei of other atoms to form new isotopes—which, in turn, may trigger further neutron radiation. Able to travel hundreds or even thousands of meters in air, they are however able to be effectively stopped if blocked by a hydrogen-rich material, such as concrete or water.


Alpha Rays
α
2 Protons and 2 Neutrons
Ionisation
Beta Rays
β
High Energy Electrons
Ionisation
Gamma Rays
γ
X-Rays
X
High Energy EM Radiation
Ionisation
Neutron Rays
n
Free Neutrons
Ionisation
Paper
Stops α rays
Thin Aluminum
Stops β rays
Thick Lead
Stops γ, X rays
Water or Concrete
Stops neutron rays

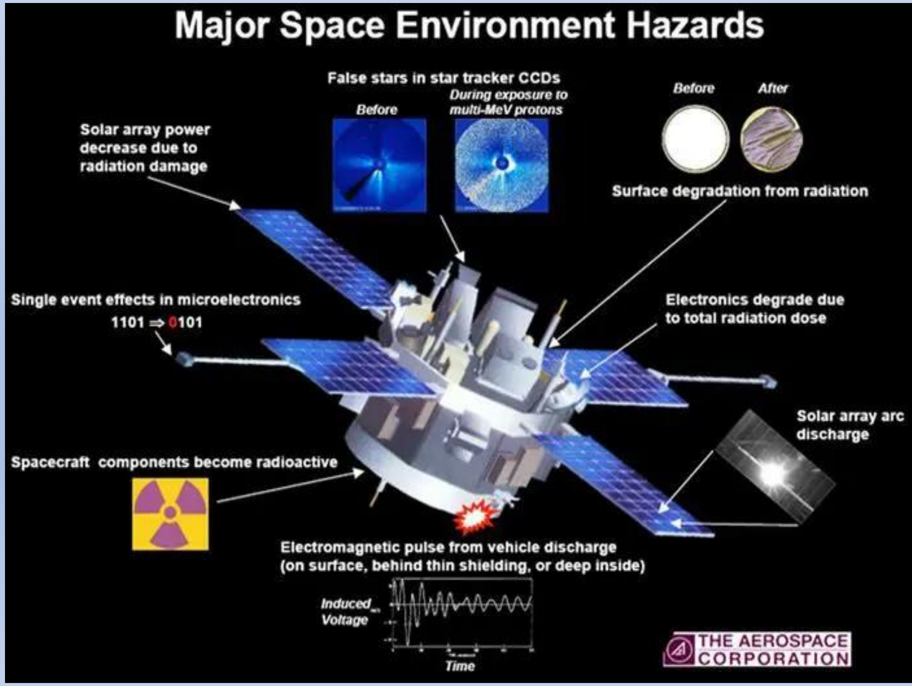
Space Radiation and Radiation Damage in Space Systems



Space radiation is one of the most important issues in the design of space systems. The electronic equipment used in the satellite missions is encountered with ionizing particles, which may cause some problems in their normal operation.

The radiation damage in the electronic equipment can be divided into three categories:

- total ionizing dose (TID)
- displacement damage (DD)
- single event effect (SEE)

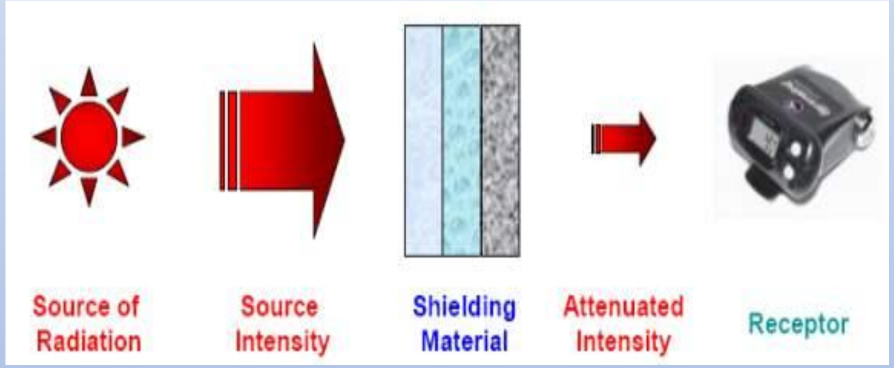


Radiation Damage and Shielding

To successfully perform a space mission in designing space systems to deal with radiation damage. One of the most effective solutions is using the appropriate shielding to protect sensitive electronic parts.

These shields should be designed by considering the satellite mass and volume budgets. The shielding material type, optimal shielding thickness, material type, and sorting of the shielding layers can be varied depending on the desired radiation environment.

It should be mentioned that lightweight materials cannot efficiently attenuate the energetic electrons and protons, and heavy materials can create secondary particles, so the combination of high-density (High-Z) shielding materials such as tantalum and tungsten and low-density (Low-Z) ones such as polyethylene can be considered as an ideal strategy.



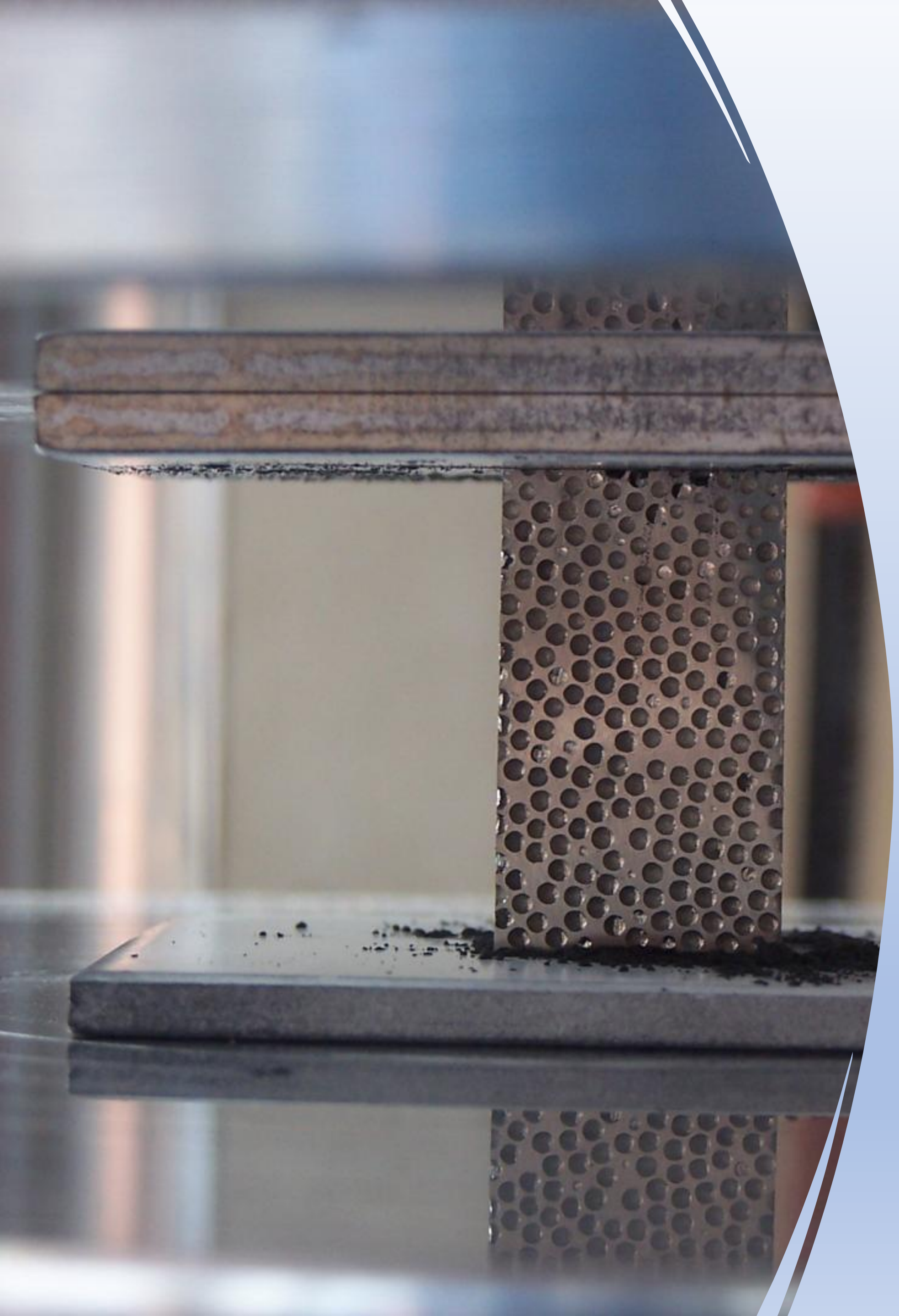
High-Density (High-Z) and Low-Density (Low-Z) Materials

Low-Density (Low-Z) Materials

Generally, low-Z materials that require the fewest atomic collisions to stop high energy particles (least mass) also require the most volume to serve as effective shields, due to their low density/high hydrogen content.

The low-Z materials such as:

- liquid hydrogen
- polypropylen
- polyethylethyl-ketone
- aluminum
- polyethylene
- carbon fiber
- aramid fiber
- silica fiber
- boron fiber



High-Z Materials

- The possible high-Z materials the common selection is between tungsten, tantalum, and gadolinium due to their availability, but each with differing good high-Z characteristics.
- Gadolinium is most beneficial when there is a large number of secondary neutrons due to its very large neutron absorption cross section. However, for small spacecraft this is not commonly a problem, so materials with better electron and photon attenuation are used, such as tungsten and tantalum.
- Tungsten is a slightly better electron attenuator than tantalum and has essentially the same high energy photon shielding characteristics due to their nearly identical atomic numbers, with the added benefit of being 20% denser. It should be noted that although tungsten is a decent neutron absorber, it is the worst of the three mentioned. It(tungsten) can be selectable as the example high-Z microparticle over tantalum primarily due to its higher availability and lower cost.

Space Radiation in LEO Orbits

Trapped electrons and protons have the largest contribution of space radiation in LEO orbits. Therefore, the MCNPX code simulation is performed by using these two types of particles, electrons and protons in the worst-case scenario.

Photons are also the most penetrating particles, so in experimental experiments, gamma rays are used to estimate the worst conditions, also.

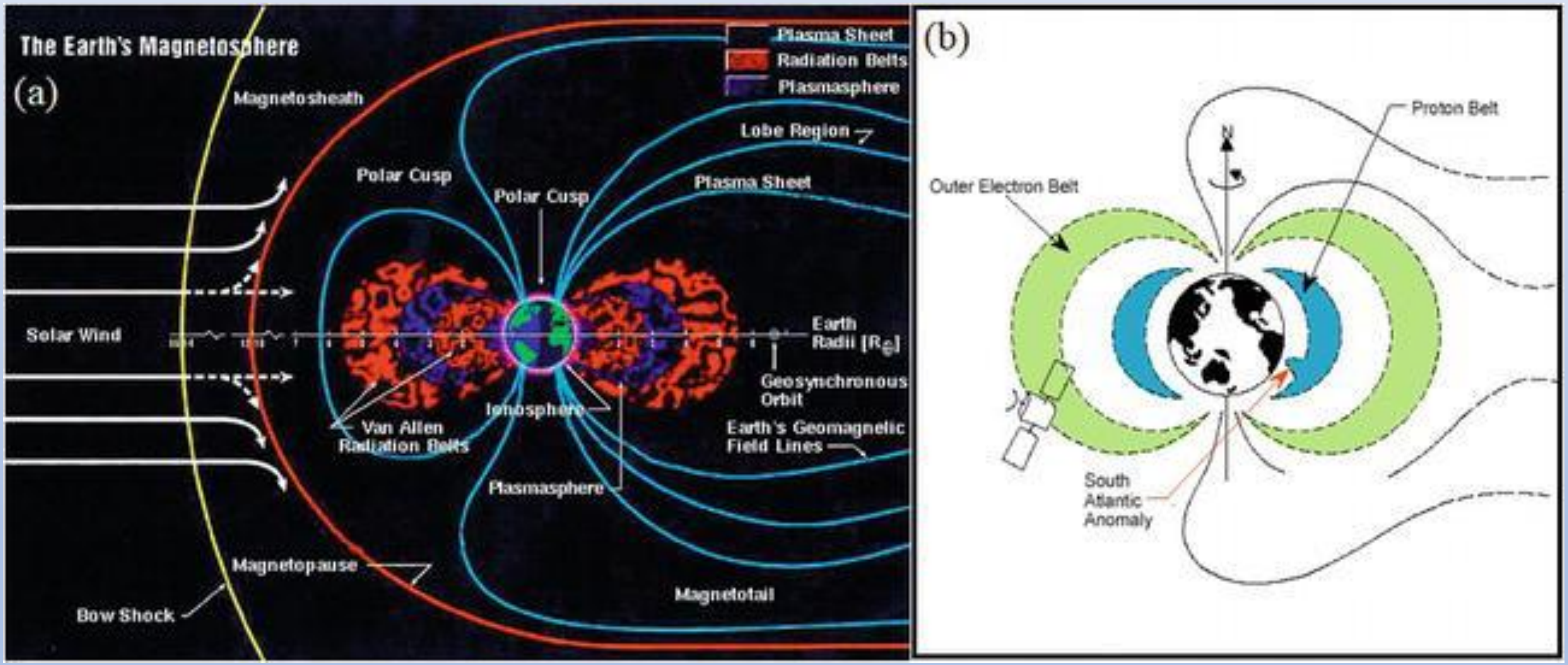


Figure: (a) The Earth's magnetosphere showing the Van Allen radiation belt. (b) Outer and inner (proton) belt

What is the MCNPX?

- MCNPX (Monte Carlo N-Particle eXtended) is a general-purpose Monte Carlo radiation transport code with three-dimensional geometry and continuous-energy transport of 34 particles and light ions.
- It contains flexible source and tally options, interactive graphics, and support for both sequential and multi-processing computer platforms.
- MCNP is a highly stable code tracking neutrons, photons and electrons, and using evaluated nuclear data libraries for low-energy interaction probabilities. MCNPX has extended this base to a comprehensive set of particles and light ions, with heavy ion transport in development.

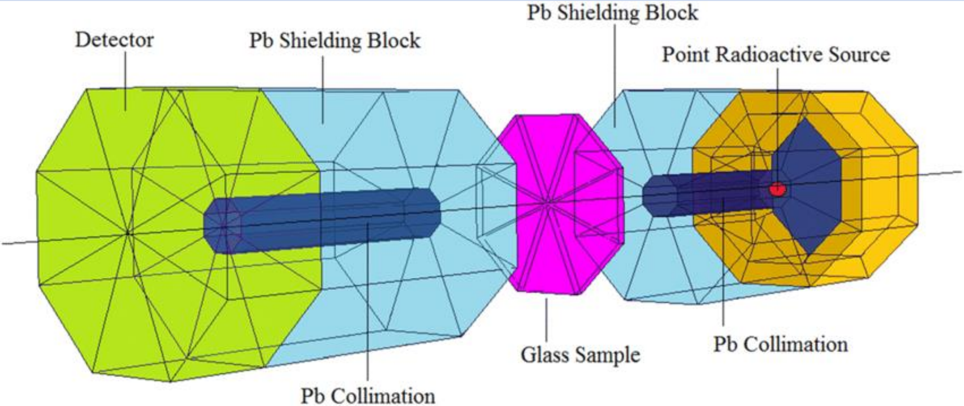
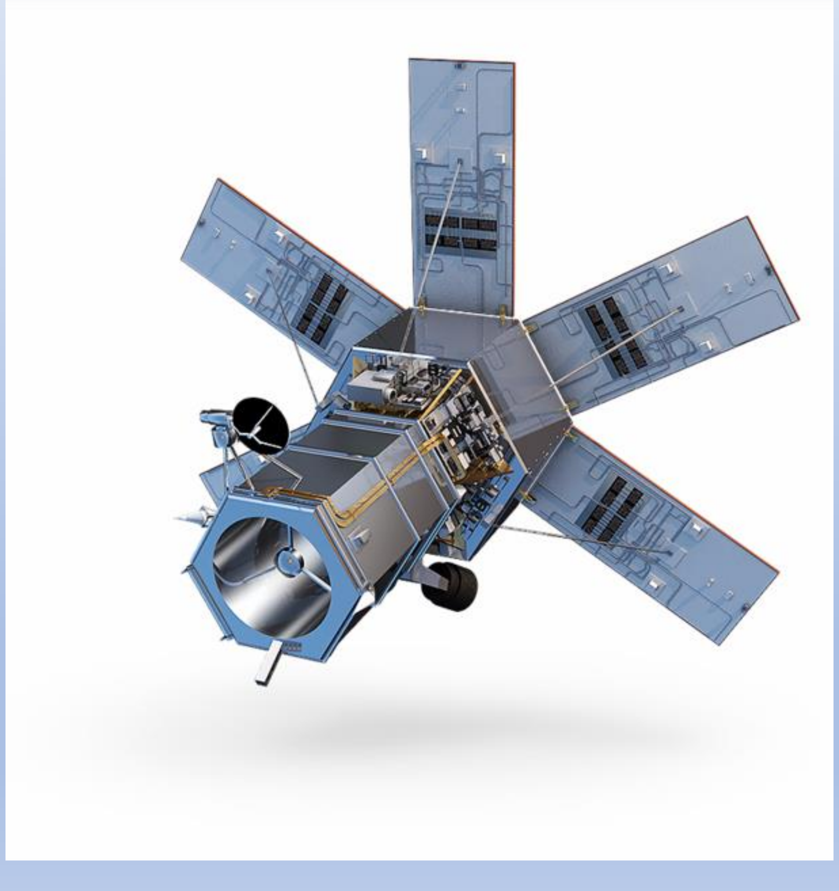


Figure: MCNPX simulation setup obtained from MCNPX visual editor (VE X_22S)

Satellite Structure and Multi-layer Shields

The satellite structure is the first radiation shield layer where its weight, vibration tolerance, natural frequency range and ability to withstand against space radiation should be considered in its design process.

- In the first level of protection, the satellite structure absorbs all or some of the emitted flux, depending on its material and thickness.
- In the second level, holder boxes named local shields, metal boxes containing electronic boards and sensitive equipment are used.



Design of Multi-layer Radiation Shield Structure

- A multi-layer radiation shield structure can be designed using a Genetic algorithm (GA) to protect electronic devices against electrons and protons in space environments, especially LEOs.
- The type of materials and shield layer thicknesses are two set parameters that should be designed to achieve the best protection against space radiation.
- In such a study, random numbers are generated for these two set parameters via GA. The MCNPX code analyses the shield structure according to them, where its outputs include ionization dose, mass and secondary particles. These outputs are added according to their importance via cost function, and imported in MATLAB to be used in the optimization process. This process iterates until the optimization converge into the best thickness and material based on the output dose and secondary particles. In fact, these two set parameters (material type and thickness) are optimized by using GA in electron and proton space environments (by linking MCNPX code with MATLAB software.

What is the Genetic Algorithm(GA)?

- The genetic algorithm is a method for solving both constrained and unconstrained optimization problems that is based on natural selection, the process that drives biological evolution.
- The genetic algorithm repeatedly modifies a population of individual solutions. At each step, the genetic algorithm selects individuals from the current population to be parents and uses them to produce the children for the next generation. Over successive generations, the population "evolves" toward an optimal solution.
- You can apply the genetic algorithm to solve a variety of optimization problems that are not well suited for standard optimization algorithms, including problems in which the objective function is discontinuous, nondifferentiable, stochastic, or highly nonlinear.
- The genetic algorithm can address problems of mixed integer programming, where some components are restricted to be integer-valued.

Multi-layer Structure Design

There are two important points in the shield design for space systems that are placed in front of the charged particles:

- reduction of secondary particles due to the collision of charged particles with the shield material
- reduction of the received dose of the subsystems

These two factors can be controlled according to nature of the charged particles. Due to higher penetration of photons than charged particles, the quantity of “attenuation coefficient” is considered to design of shields.

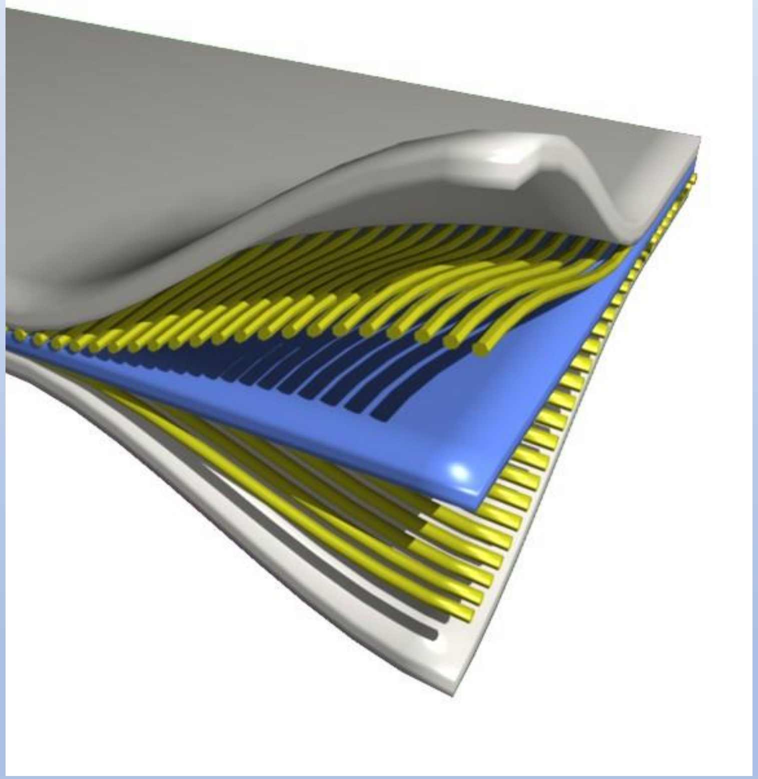


Figure: Multi-layered composite material

Multi-layer Structure Design

The schematic of the multi-layer structure is presented in Figure 2. When a shield layer is placed in the front of a photon source, such as X- and gamma rays, for the low thickness of the absorber and narrow or well-collimated beam (Figure 1), the gamma-ray flux follows the Beer-Lambert equation as

$$I = I_0 e^{-\mu x} \quad (1)$$

- I: the intensity of the rays after passing through the shield
- I_0: the intensity of the initial rays, x is the shield thickness
- μ: the radiation attenuation coefficient.

For wide beams, the build-up factor, B is added to this equation for correction as

$$I = B I_0 e^{-\mu x} \quad (2)$$

In the case of multi-layered shields, the intensity of the source passing through these multiple layers follows the equation as

$$I = B_1 B_2 B_3 I_0 e^{-(\mu_1 x_1+\mu_2 x_2+\mu_3 x_3)} \quad (3)$$

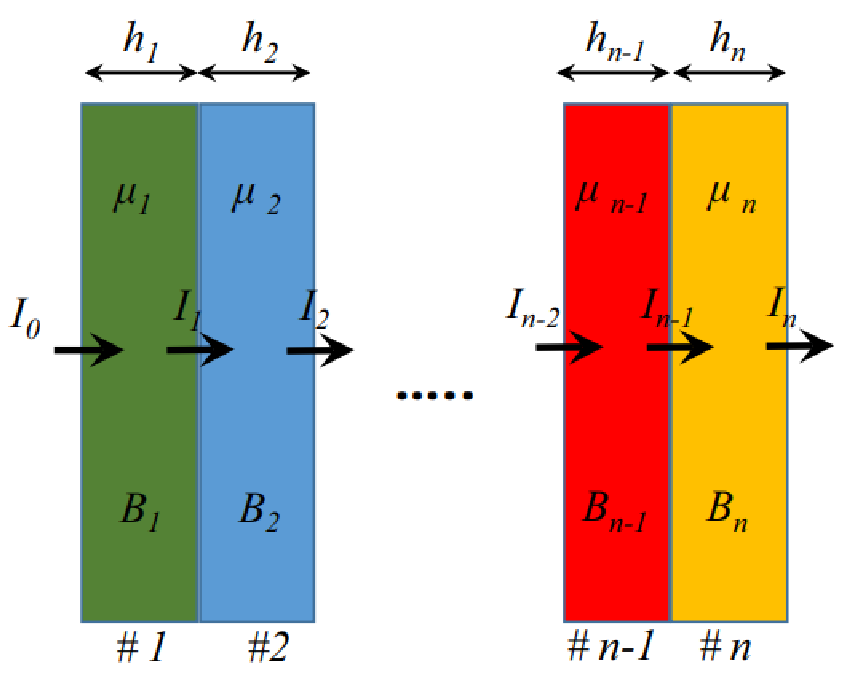


Figure 2: Schematic of multi-layer radiation shield.

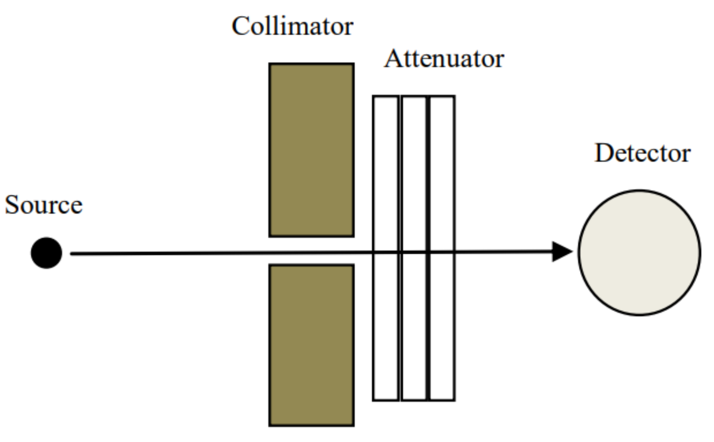


Figure 1: The irradiation geometry

Multi-layer Structure Design

How to Determine the Radiation Attenuation Coefficient?

Various analytical and simulation methods can be used to determine the radiation attenuation coefficient of multilayer protections, μ. However, using transport methods to determine this coefficient can only be performed for simple geometries used in several similar articles for different applications.

- The MCNPX code and MULASSIS tool are used to determine the radiation attenuation coefficient in simulation.
- XCOM software is also used to determine the attenuation coefficient as an analytical method. Using these three programs, it is possible to validate the results.

Simulation Method

MCNPX code + MULASSIS tool

Analytical Method

XCOM software

Multi-layer Structure Design

MULASSIS tool (Multi-Layered Shielding Simulation Software tool)

MULASSIS permits simulation of a wide range of particle physics in almost any shielding material, including treatment of ionization and nuclear interactions of energetic protons, electromagnetic cascades for electrons and photons, and low-energy neutron transport, with the tracking of all secondary particles that are produced by interactions.

Outputs of MULASSIS include particle fluence at boundary layers, total ionizing dose to layers, non-ionizing energy loss at boundary layers and pulse height energy deposition spectra.

Mulassis uses the Geant4 radiation transport toolkit.

What is Geant4?

Geant4 is a toolkit for the simulation of the passage of particles through matter. Its areas of application include high energy, nuclear and accelerator physics, as well as studies in medical and space science.

Geant4 was designed from the start as an integrated toolset to provide three-dimensional simulation to the various needs of comprehensive, all-space applications, while also being a flexible software environment that allows the user to tailor the system.

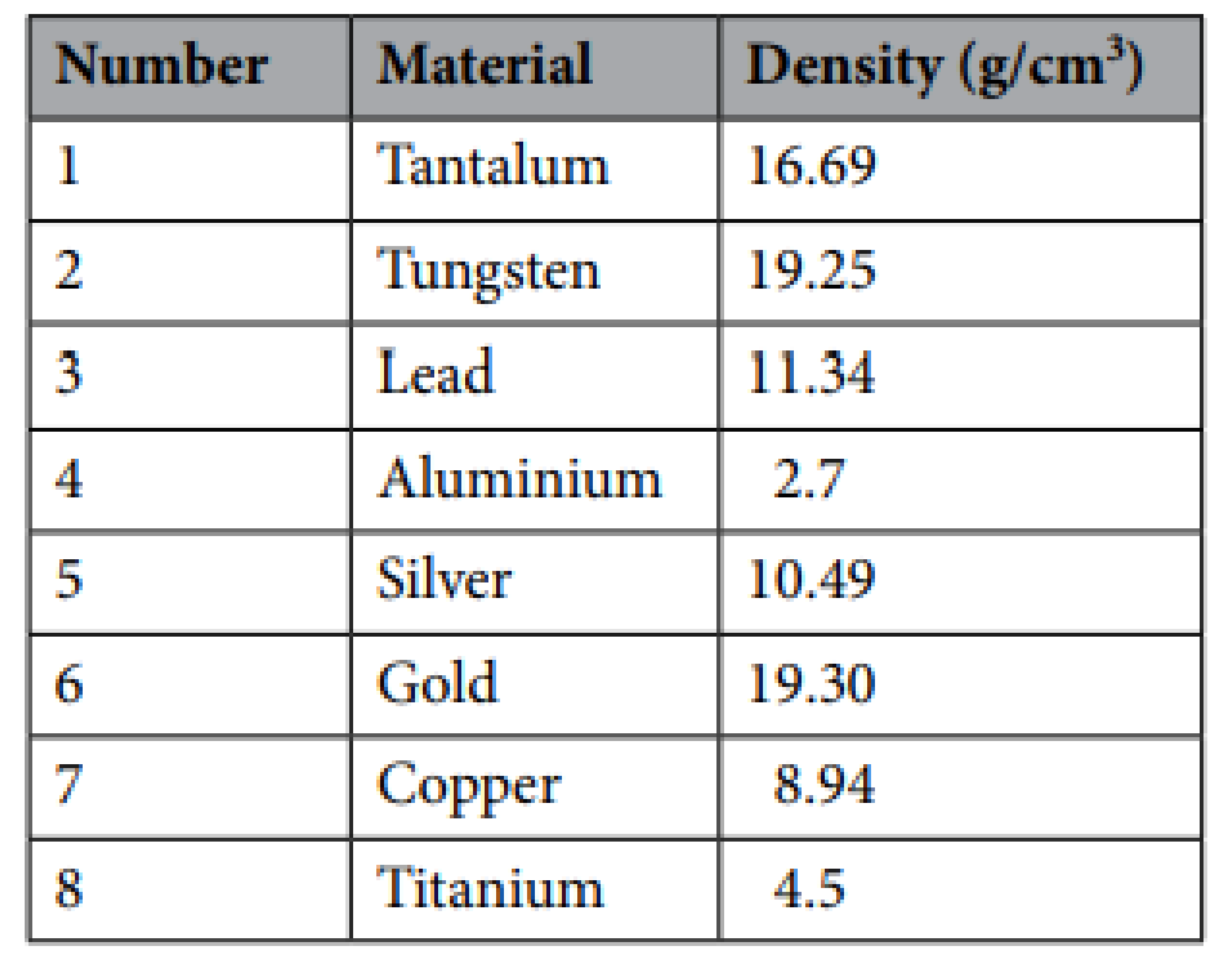
Multi-layer Structure Design

XCOM Software

A web database is provided which can be used to calculate photon cross sections for scattering, photoelectric absorption and pair production, as well as total attenuation coefficients, for any element, compound or mixture ($Z \leq 100$), at energies from 1 keV to 100 GeV.

Common Materials Used for Designing the Radiation Shields

- Table provides some of the materials that have been reported in the literature data for using in radiation shield design.
- This table contains eight pure materials that are very common for shield design and used to design and optimize the proposed multi-layer radiation shielding structures.



Number	Material	Density (g/cm^3)
1	Tantalum	16.69
2	Tungsten	19.25
3	Lead	11.34
4	Aluminium	2.7
5	Silver	10.49
6	Gold	19.30
7	Copper	8.94
8	Titanium	4.5

Cost Function and Genetic Algorithm

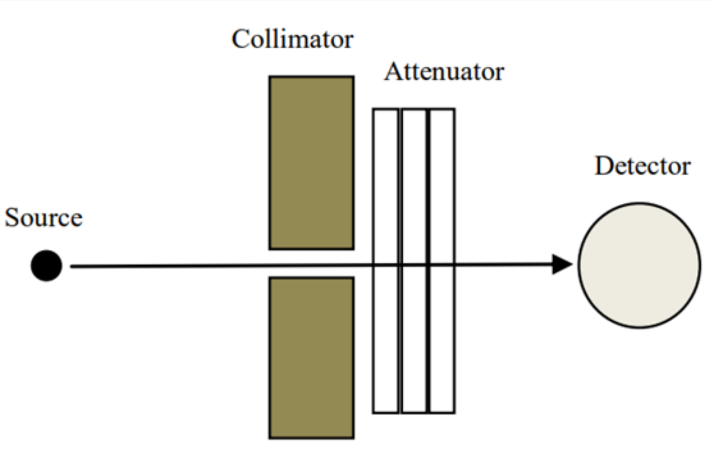
The cost function for optimization is defined as

$$Cost = a \times TID + \beta \times SP \qquad (4)$$

where the sum of total ionizing dose (TID) and the secondary particles (SP) are added together with appropriate weighting coefficients, α, and β. TID and SP calculations are performed using MCNPX code.

The radiation dose is defined as the energy deposited in the material, where its unit is the ratio of energy to the mass of material (J/g). To achieve optimal shield, the combination of these two parameters in (4) should have the lowest cost, and therefore an optimization method would be used. The optimization method is the Genetic Algorithm, so the MCNPX code is linked to MATLAB software for optimization implementation.

The output of this optimization is the thickness of each layer as well as its material. The optimization flowchart in Figure depicts how to implement this design process.



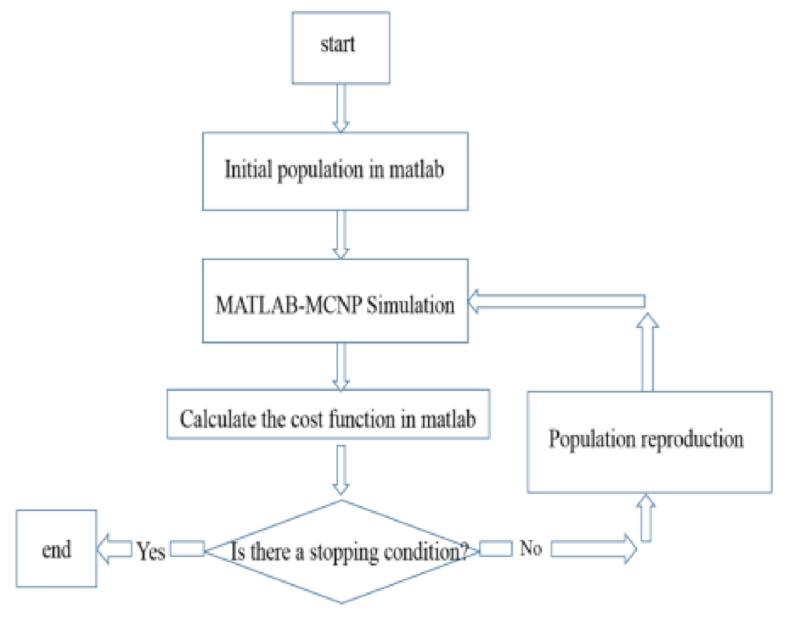


Figure: Flowchart of the Genetic Algorithm design process

Different Shields Design

- The satellite platform is considered cube-shaped, with dimensions of 1 x 1 x 1 m3 in the MCNP simulation process and the worst radiation orbital conditions are also considered to design an effective shield in all orbits. For this purpose, the source is considered as a single particle spherical around the satellite.
- The general structure for the satellite is shown in Figure, which is simulated by the MCNPX code.

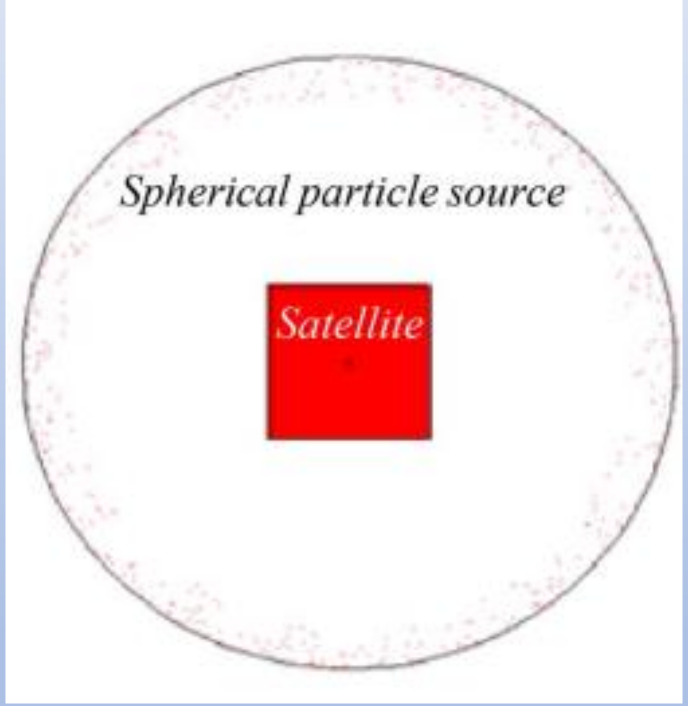
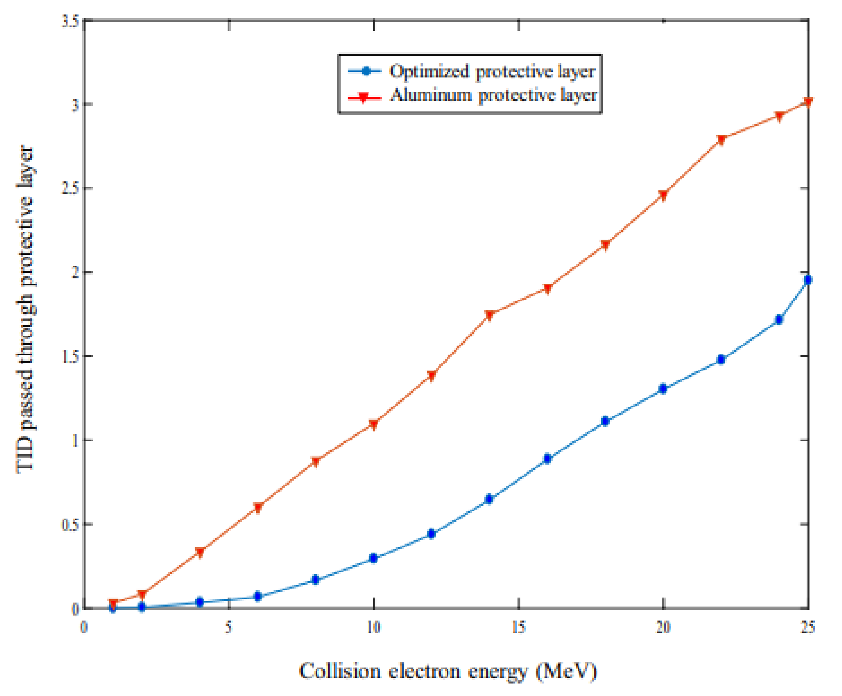
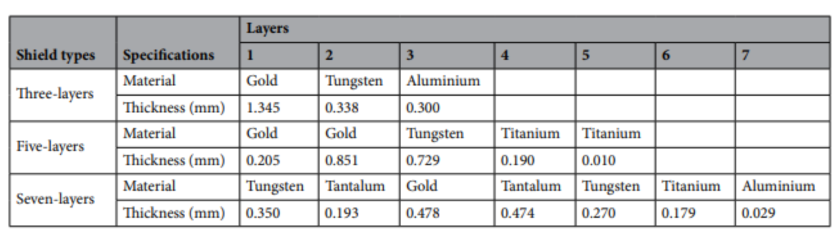


Figure: 2D display of the problem structure with a spherical source

Low Dose Environment

- Optimization of the radiation shield for electron environments can be performed for three types:three, five, and seven-layer shields. The shields are taken into account under the worst space conditions and optimized for electron environments, including electrons with the energy spectrum in the range of 1-25 MeV.
- Damage on satellite electronic is produced by total ionizing dose and secondary particles. To minimize the damage induced by the factors mentioned above, the radiation shield should be optimized so that sum of these two factors is as minimal as possible, as formulated in cost function.





Shield types	Specifications	Layers						
		1	2	3	4	5	6	7
Three-layers	Material	Gold	Tungsten	Aluminium				
	Thickness (mm)	1.345	0.338	0.300				
Five-layers	Material	Gold	Gold	Tungsten	Titanium	Titanium		
	Thickness (mm)	0.205	0.851	0.729	0.190	0.010		
Seven-layers	Material	Tungsten	Tantalum	Gold	Tantalum	Tungsten	Titanium	Aluminium
	Thickness (mm)	0.350	0.193	0.478	0.474	0.270	0.179	0.029

Low Dose Environment

- In the seven-layer model, although the dosage is slightly improved, the fabrication cost is increased compared with the three-layer one. In the construction of multi-layer shields, more layers require more costs and on the other hand, the fabrication would be more complicated technically.
- The designed shield must be capable of repelling radiation effects across all energy ranges and operating better than an Aluminum shield with the same thickness (2 mm) in all conditions of electron energy.

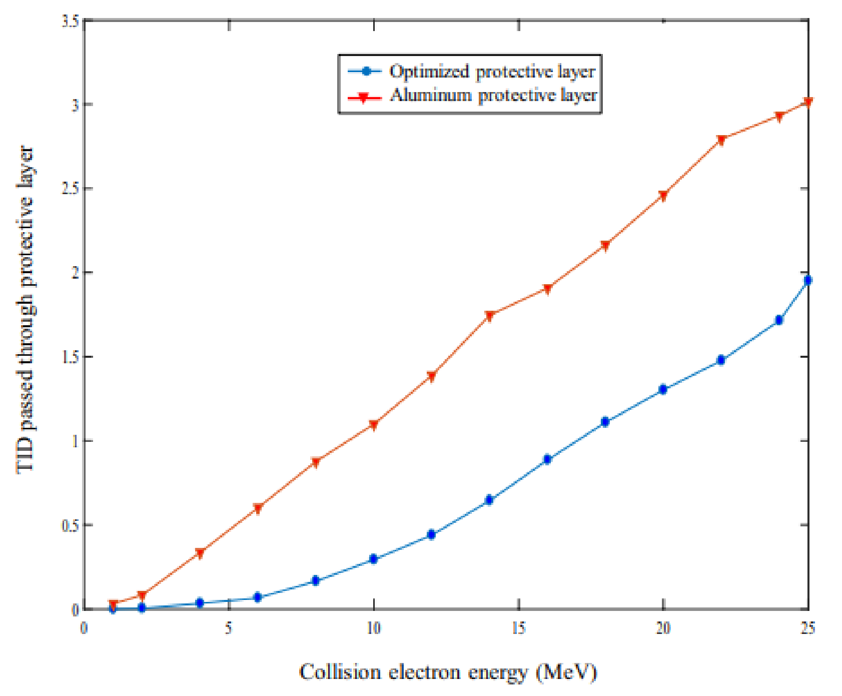
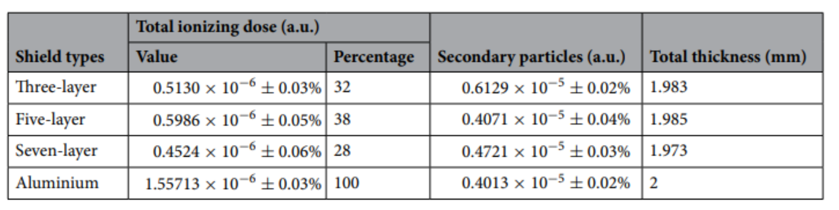


Figure: Curve of total ionizing dose passing through optimal shield and a 2 mm aluminum shield in different energies (the blue curve is related to a three-layer shield).



Shield types	Total ionizing dose (a.u.)		Secondary particles (a.u.)	Total thickness (mm)
	Value	Percentage		
Three-layer	$0.5130 \times 10^{-6} \pm 0.03\%$	32	$0.6129 \times 10^{-5} \pm 0.02\%$	1.983
Five-layer	$0.5986 \times 10^{-6} \pm 0.05\%$	38	$0.4071 \times 10^{-5} \pm 0.04\%$	1.985
Seven-layer	$0.4524 \times 10^{-6} \pm 0.06\%$	28	$0.4721 \times 10^{-5} \pm 0.03\%$	1.973
Aluminium	$1.55713 \times 10^{-6} \pm 0.03\%$	100	$0.4013 \times 10^{-5} \pm 0.02\%$	2

Table: Specifications of multi-layer radiation shields and aluminum.

High Dose Environment

- Optimization and analysis of the radiation shield can also be studied for proton environments. The designed shields are optimized for the worst space conditions, which can be used in any space environment. For this purpose, the proton energy is considered in the range of 1 to 100 MeV.
- The optimization process is performed to provide a suitable protection structure for proton environments optimized in terms of ionization dose, secondary particles, and the number of layers.

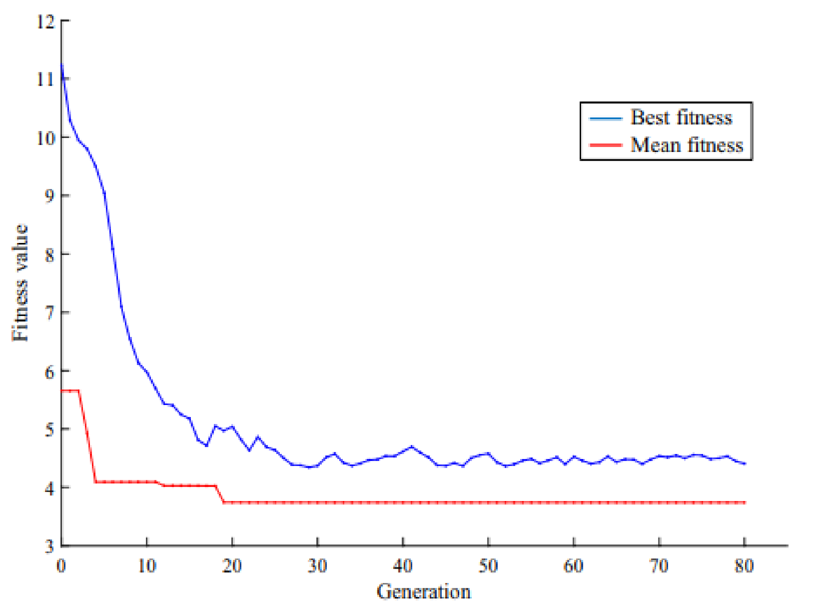
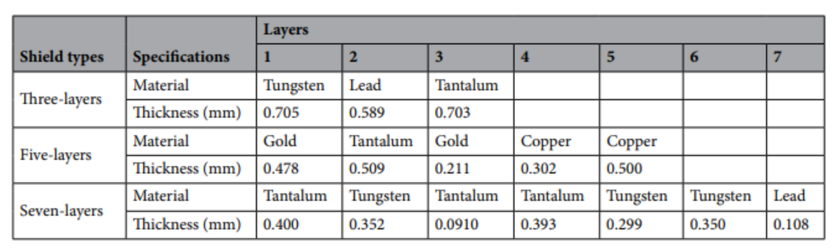


Figure: Convergence curve of GA for three-layer radiation shielding applied for proton space environments.



Shield types	Specifications	Layers						
		1	2	3	4	5	6	7
Three-layers	Material	Tungsten	Lead	Tantalum				
	Thickness (mm)	0.705	0.589	0.703				
Five-layers	Material	Gold	Tantalum	Gold	Copper	Copper		
	Thickness (mm)	0.478	0.509	0.211	0.302	0.500		
Seven-layers	Material	Tantalum	Tungsten	Tantalum	Tantalum	Tungsten	Tungsten	Lead
	Thickness (mm)	0.400	0.352	0.0910	0.393	0.299	0.350	0.108

Table: The results of the GA for three, five, and seven-layer shields.

High Dose Environment

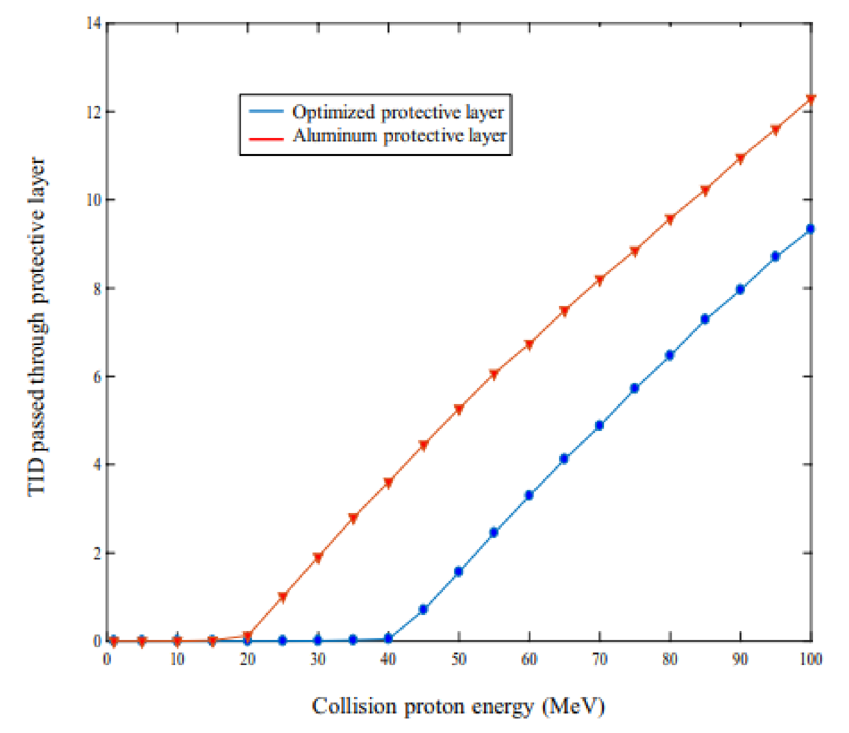
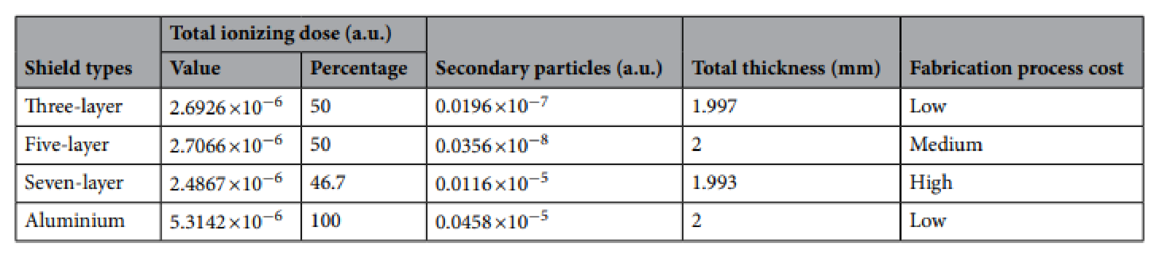


Figure : Total ionizing dose versus particle energy for optimized three-layer and Aluminum shield (the blue curve is related to a three-layer shield).



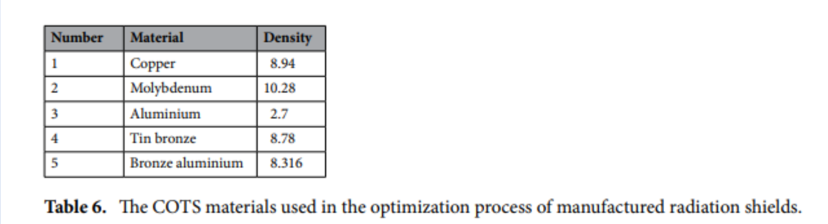
Shield types	Total ionizing dose (a.u.)		Secondary particles (a.u.)	Total thickness (mm)	Fabrication process cost
	Value	Percentage			
Three-layer	2.6926×10^{-6}	50	0.0196×10^{-7}	1.997	Low
Five-layer	2.7066×10^{-6}	50	0.0356×10^{-8}	2	Medium
Seven-layer	2.4867×10^{-6}	46.7	0.0116×10^{-5}	1.993	High
Aluminium	5.3142×10^{-6}	100	0.0458×10^{-5}	2	Low

Table: Typical specifcations of multi-layer radiation and Aluminum shields.

Design To Build

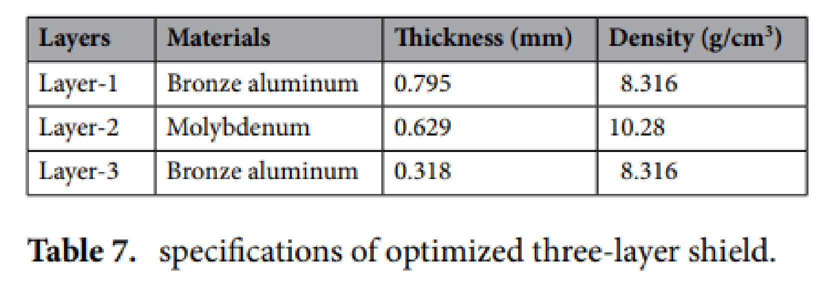
A Right three-layer shield due to unavailability of all materials and economic conditions, that case is considered for demonstration using the COTS materials given in Table 6. For design reasons, a copper layer with a thickness of 0.2 mm can be used as a shield carrier. Therefore, the other total layer thickness is considered to be 1.8 mm. because it is very important Proton damage in LEO satellites, research focuses on the use of this source in the energy range of 1-100 MeV.

The optimization results of different layers show that the best case is that the tree layer masks interact with each other proton. The results of this optimization are shown in Table 7. The specifcations of the frst, second, and third layers are presented in this table, respectively. Notice that the zero layer is related to 0.2 mm copper carrier.



Number	Material	Density
1	Copper	8.94
2	Molybdenum	10.28
3	Aluminium	2.7
4	Tin bronze	8.78
5	Bronze aluminium	8.316

Table 6. The COTS materials used in the optimization process of manufactured radiation shields.

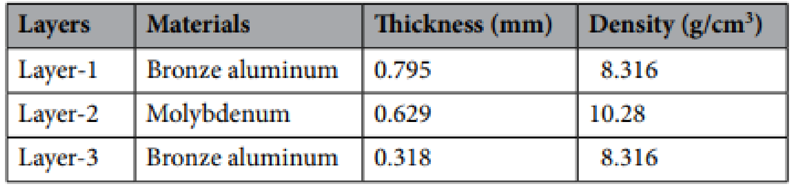


Layers	Materials	Thickness (mm)	Density (g/cm^3)
Layer-1	Bronze aluminum	0.795	8.316
Layer-2	Molybdenum	0.629	10.28
Layer-3	Bronze aluminum	0.318	8.316

Table 7. specifications of optimized three-layer shield.

Design To Build

- The optimization results of different layers show that the best case is that the tree layer masks interact with each other proton. The results of this optimization are shown in Table 7. The specifcations of the frst, second, and third layers are presented in this table, respectively. Notice that the zero layer is related to 0.2 mm copper carrier.
- The specifications of the first, second, and third layers are presented in this table, respectively. Notice that the zero layer is related to 0.2 mm copper carrier. The convergence process of the Genetic Algorithm is also shown in Fig. 7.



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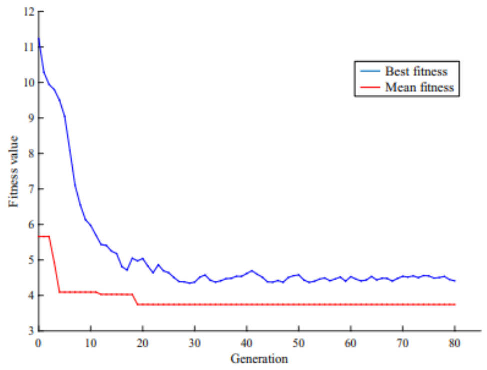

Figure 7. Convergence curve of Genetic Algorithm for constructed shield.

Fabrication Test

The three-layer shield is implemented by using spotting metal method on 0.2 thickness copper sheet as discussed previously. The constructed shield sample with 5 cm × 5 cm size. This protection material produced is as in figure 8.

Figure 8. Fabricated three-layer radiation shield sample.

The MCNPX code is used to determine the attenuation coefficient through the simulation. By having the flux in the presence and absence of the radiation shield using, the radiation attenuation coefficient is obtained.

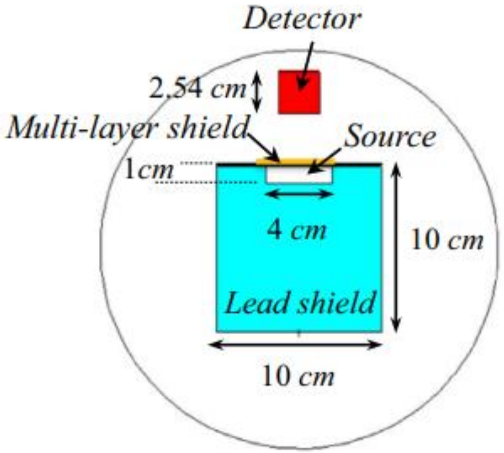

Figure 9. Configuration of the source, detector and shield in the MCNPX code.

XCOM Results

- The XCOM program is also used to determine the radiation attenuation coefficient of these different layers. These results are taken into account by considering the coherence and non-coherence distribution, photoelectric effects, and pair production. The results of the Aluminum-Bronze mass attenuation coefficient can be seen in Figure as representative.

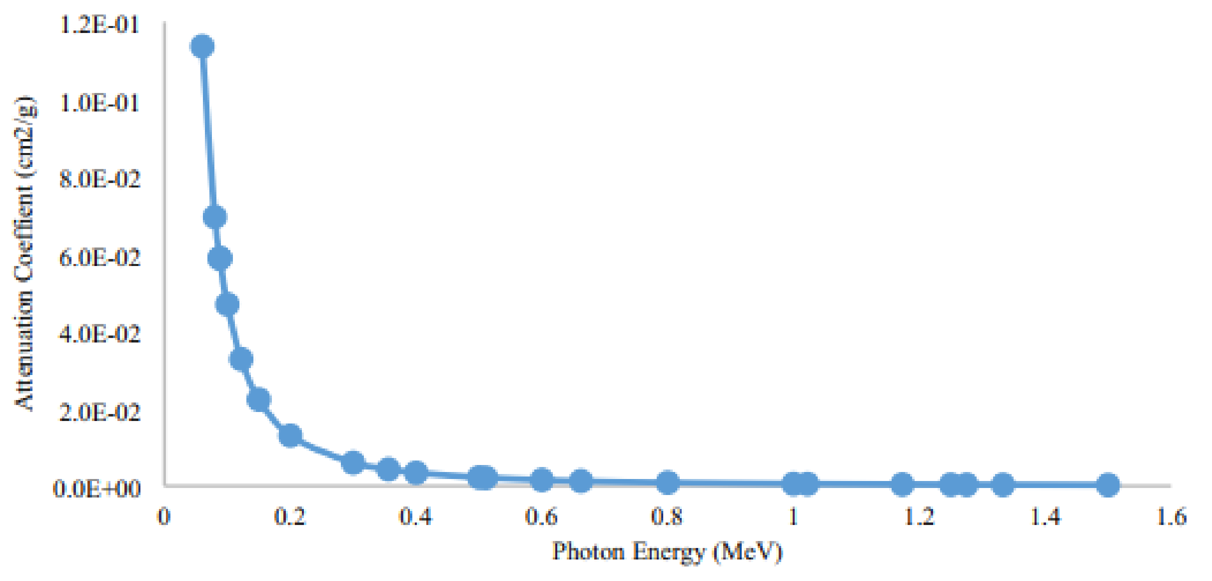

Figure: Mass attenuation coefcient of Aluminum Bronze using the XCOM.

Determination of the Attenuation Coefficient of Multi-layer Shield Using XCOM

To determine the radiation attenuation coefficient, we assume B = 1, therefore, by using (1), the radiation attenuation coefficient can be calculated by the experimental methods and Monte Carlo simulations.

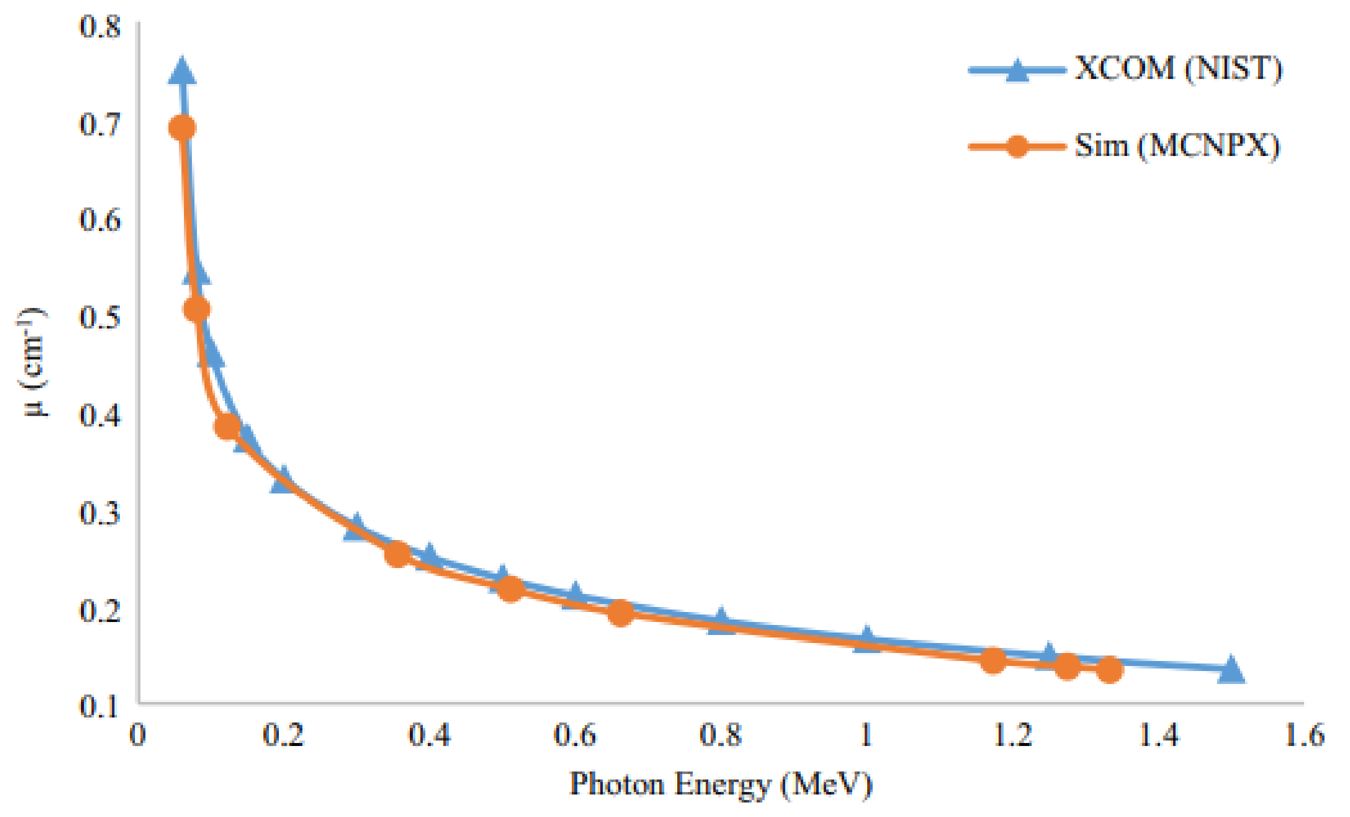

Figure: Comparison of attenuation coefcient of Aluminium extracted from XCOM and MCNPX.

Comparison of Radiation Attenuation Coefficients

The radiation attenuation coefficient is obtained by using the online program XCOM under NIST. The results show us, attenuation coefficient of a multi-layer shield are depicted in Figure via various approaches, including experimental, analytical, and simulation methods.

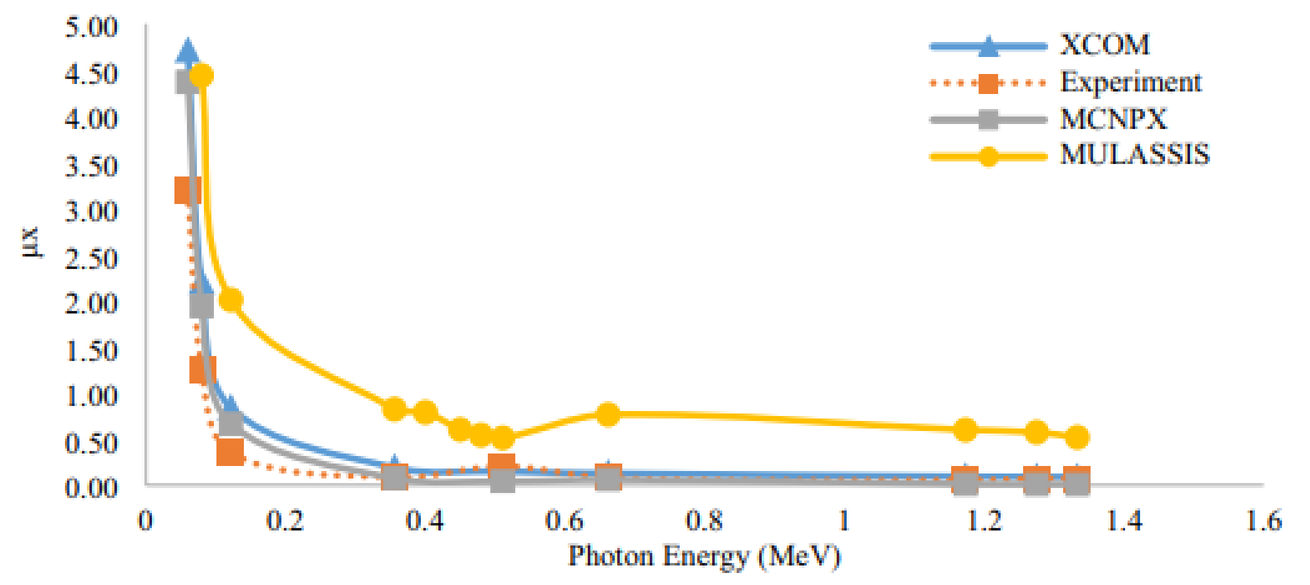

Figure: Comparison of radiation attenuation coefcient of multi-layer shield obtained from experimental, analytical and simulation results.

Conclusion

- Based on what we've seen so far, various types of multi-layer shields in space conditions were designed, optimized, and analyzed for electron and proton environments. This is done for various suitable metals to be used as a local shield for the safety of electronic components, using the MCNPX Monte Carlo method and the Genetic Algorithm.
- These designed shields are discussed at different energies in all space conditions and compared with 2 mm thick Aluminum shields.
- These are demonstrated the full superiority of shields optimized for electrons that improved the total ionizer dose by up to 70%, and the shield designed for proton also improved the total ionizer dose by up to 50%. All designed shields have succeeded in preventing secondary radiation.
- Optimizations were made for three, five, and seven-layer shields. Moreover, the Tree-layer shield showed advantages over traditional shields such as Aluminum due to the diversity and lower number of layers, and lower construction cost.
- Considering the cost, weight, volume and accessibility conditions, the most optimal case is a combination of three layers of Bronze- Aluminum and Molybdenum.
- To confirm the results of these tests, It is necessary to protect satellite tools from a proton shield with a maximum energy of 100 MeV. Due to the limitations of using proton sources, gamma radioisotope sources with an energy range of 60–1333 keV were used for irradiation.
- The results Show us a good correlation between the experimental data, simulation, and analytical calculations using the MCNPX code and the XCOM program. Accordingly to results, this issue can be generalized to other similar situations.