# CubeSat payload: proposal about magnetic shielding

Rosario Pullano

## Abstract

Space exploration is a primary goal for leading companies in the aerospace market. One of the major challenges in this environment is the high intensity of space radiation, which poses a serious threat to both human health and spacecraft instrumentation. For instance, while humans can only tolerate up to 4 Sv of radiation, exposure in space can reach 12 Sv. The main sources of this radiation are solar emissions and cosmic rays from deep space. This work focuses on developing a solution to protect against space radiation. Our proposal is inspired by the Earth's magnetosphere, aiming to replicate its protective features on a smaller scale. The technology could be tested on a CubeSat, with the goal of studying the effectiveness of this magnetic shielding system for future applications in space missions.

**Introduction** The project focuses on designing an alternative form of shielding, replacing conventional physical barriers. Typically, the most sensitive components onboard a spacecraft, especially semiconductor devices, are protected using radiation hardening technologies. These methods provide physical protection from electrically charged particles, which are responsible for both non-destructive events, such as Single Event Upsets and Single Event Latchups, and irreversible destructive events, such as Single Event Burnout. The proposed idea leverages magnetic field theory, aiming to reduce the reliance on physical shielding materials. This approach could lead to significant cost savings and reduced weight for onboard electronic equipment. Additionally, the choice to pursue this solution highlights the interdisciplinary nature of the project, which integrates both technical engineering aspects and fundamental physics principles. There is extensive scientific literature on the principles of magnetic shielding. However, existing studies have primarily focused on its use as a solution for medium to large satellites. On a smaller scale, the effectiveness of such shielding is constrained by the limited energy available. In this project, the focus will be on the deflection of low-energy particles.

**Goals** Implementing this technology presents a significant challenge from a physical and engineering perspective, with several critical issues and potential solutions outlined below. The generated magnetic field could interfere with the CubeSat's magnetorquers, thereby affecting its orientation. This issue can be addressed through precise real-time measurement of the generated magnetic field and appropriate coordination with the actuators to minimize energy expenditure and orbital effects. Given the small size of CubeSats, their energy storage and/or generation capacity is significantly limited. Specifically, generating a magnetic field strong enough to deflect high-energy particles requires a considerable amount of energy. Additionally, the energy needed for all other payload components and possible cooling of the coils within the apparatus must be considered. Energy expenditure can be minimized by using appropriate magnet configurations; detailed discussion of this will be found in later sections. Moreover, the operation of the entire experimental apparatus might be restricted to short intervals and coordinated with other onboard systems to ensure optimal use of battery-supplied energy. Several scientific articles suggest that energy costs can be reduced by confining "cold" plasma present in the orbital environment; however, this solution appears challenging to implement under operational conditions of CubeSats. A recurring issue in modeling and designing electromagnets is managing the force exerted by various coils on each other; the magnet filaments, due to the electric current flowing through them, tend to repel each other. This can be addressed by encasing the entire magnet within a suitable support and containment structure. Space optimization is another challenge due to limited room available for system placement. However, through efforts in miniaturization, achievable via targeted construction technologies and mathematical models, it is possible to reconsider the dimensions of components, particularly the magnet, and find optimal sizes.

**Quantitative analysis** The operation of the payload is inspired by Earth's typically dipolar magnetosphere, which contains ionized gas (plasma) consisting of free electrons and positive ions at low density. Subjected to the Lorentz force, these particles remain trapped within the magnetosphere, spiraling around magnetic field lines while simultaneously moving toward the poles where their motion reverses. This interaction results in a "magnetic mirror" effect that reflects charged particles. To evaluate the shielding effectiveness onboard, a redundant system of three CCD sensors (more if necessary) will be utilized. Identical in shape, size, and materials, these sensors will be strategically placed both near the shield and outside it. This arrangement will allow for precise measurement of particles impacting the shield and the shield's ability to protect the designated area. Comparisons of the effects on different sensors will be made to test the shielding's efficacy. The design of the CCD is thus a critical part of the total payload, facilitating the experiment with minimal bulk and weight. Measurements of LET (Linear Energy Transfer), which is the energy deposited on an electronic component following a particle impact, will be conducted. This impact probability depends on the infinitesimal distance traveled, the material's density, and the component's cross-section. The CCD's photosites (hardware equivalent of pixels) become excited upon electron impact, enabling the measurement of the number of incident particles. This measurement will be made by correlating the number of incident electrons to the number of affected photosites through a suitable mathematical relation, which can be derived during the design phase through experimental measures. For a quantitative description of the payload's operation, a cylindrical solenoid with a radius larger than its height was chosen as a simplifying model. According to Ampere's equivalence principle, this approximates the field generated by a magnetic dipole (similar to Earth's) with sufficient accuracy. However, this is just a schematic representation, as the shape and possibly the arrangement of the magnet may be suitably modified if more efficient configurations are found during the process, necessitating appropriate adjustments to the results. Furthermore, the solenoid's internal cavities will be filled with a suitable ferromagnetic material, which will increase the magnetic field by many orders of magnitude (specifically by a factor equal to the relative magnetic permeability $\mu$ of the material). This material will be selected to have as narrow a hysteresis loop as possible, allowing for complete control over the magnetic field. Incident electrons in the target area interact with the artificially generated magnetic field, experiencing a Lorentz force that deflects them, preventing most from impacting the protected CCD. In orbit, data will be collected by exploiting the satellite's transit through regions where the incident radiation flux is particularly intense. Below is a graph, created using SPENVIS - software implemented by ESA-, which shows the flux of electrons trapped in Earth's magnetosphere as a function of latitude and longitude. The color legend highlights a particularly high particle flux in the South Atlantic Anomaly and at the magnetic poles.

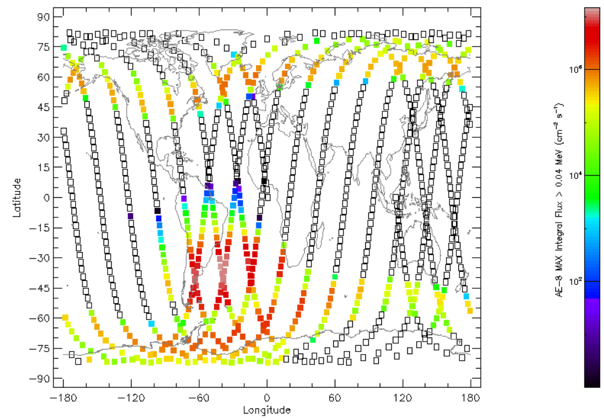


Figure 1: Electron flux as a function of latitude and longitude

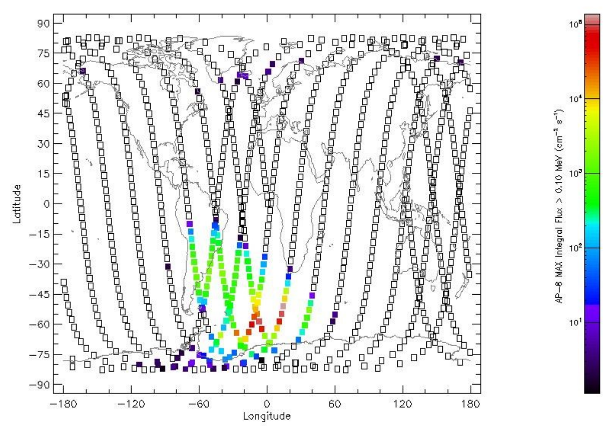


Figure 2: Proton flux as a function of latitude and longitude

A three-dimensional model will be utilized to study the trajectory of electrons in the region affected by the magnetic field generated by the payload. The following assumptions will be made:

- The magnetic field is stationary and uniform in the space near the payload and directed along the positive z-axis (in the chosen reference system).

- The particle enters the magnetic field with an initial velocity $\vec{V_0} = (v_{0x}, v_{0y}, v_{0z})$ and initial position $\vec{X_0} = (x_0, y_0, z_0)$.

- It is assumed that the magnetic field is equivalent to that generated inside a solenoid with a ferromagnetic core: $\vec{B} = (0, 0, B_z) = (0, 0, \mu_0 \mu_r n I)$, where $n$ is the number of turns per unit length.

The electrons will thus be subjected to the Lorentz force, which is expressed as $\vec{F_L} = e\vec{B} \times \vec{V}$, with $\vec{V}$ being the velocity of the particle and $e$ the charge of the electron. By applying this equation and Newton's second law, we arrive at a system of homogeneous second-order differential equations. Once solved, this system provides the motion equations of the particle based on the initial conditions and the applied magnetic field. This system is given by
$x'' = -ky'$
$y'' = kx'$
$z'' = 0$
with $k = \frac{eB_z}{m_e}$, where $m_e$ is the electron mass. The motion equations are then
$x = \frac{|V_{0xy}|}{k} \sin(kt + \phi_0)$
$y = -\frac{|V_{0xy}|}{k} \cos(kt + \phi_0)$
$z = v_{0z}t + z_0$
where $V_{0xy}$ is the initial velocity in the xy-plane, $\phi_0$ is the initial angle formed by $V_{0xy}$ with the x-axis, and $t$ is time. The particle thus undergoes cylindrical helical motion around the z-axis with a radius equal to $\frac{|V_{0xy}|}{k}$ and rotates clockwise (note that the curvature radius is inversely proportional to the magnetic field strength). These equations allow us to estimate the intensity of the magnetic field necessary to keep most particles out of a protected area, based on the physical characteristics of the magnet. It aims to demonstrate how, with an appropriate ferromagnetic core, it is possible to realize the desired shielding configuration, respecting design constraints. Assuming the goal is to create a protected zone at the center of the unit with a radius of 2 cm (thus, the maximum allowed electron penetration radius is 3 cm), and assuming a current of 0.33A flows through the solenoid and the electron may impact at the speed of light, a numerical value for the product $n\mu_r$ of approximately 13,577,906 (with $n$ being the number of turns per meter) is derived. This value was calculated using the previously derived relation:

$$\mu_r n = \frac{|V_{0xy}| m_e R_s}{e \mu_0 I}$$

where $R_s$ is the penetration radius of the particle. Assuming a relative magnetic permeability ($\mu_r$) of 640 (ferrite), an $n$ value of approximately 21,215 turns per meter is achievable and results in a magnetic field $B = \mu N I l = 5.7T$. Note that $n$ can be further reduced either by using higher-quality materials such as Permalloy ($\mu_r = 8000$) or Mu-metal ($20000 < \mu_r < 50000$), or by increasing the current's intensity. The study compares three different scenarios where the CubeSat delivers power of 0.5W, 0.8W, and 1W at a voltage of 3V. Using Ohm's Second Law, the resistance is given by:

$$R = \frac{\rho l}{S} = \frac{V}{I}$$

and since the system delivers a power $P = VI$, it is possible to determine the length of the wire as a function of its diameter

$$l_{wire} = \frac{\pi V}{4 \rho I D^2}$$

Given a wire diameter of only 0.2 mm and a power of 0.8W, it is possible to have a wire approximately 20 meters long. Despite being based on approximate assumptions, these arguments still provide a good estimate of the orders of magnitude of the physical and geometrical variables involved, allowing for the verification of the payload's feasibility. Despite being based on approximate assumptions, the previous arguments still provide a good estimate of the orders of magnitude of the physical and geometrical variables involved, allowing us to verify the actual feasibility of the payload.

**Observations** This study introduced an innovative approach to shielding electronic components on spacecraft, using magnetic fields to deflect charged particles as an alternative to traditional physical barriers. While the initial results are promising, several areas require further investigation to enhance the feasibility and effectiveness of the proposed technology. A crucial aspect involves advanced energy management. The adoption of storage technologies, such as supercapacitors or advanced batteries, could effectively handle the energy demand peaks associated with generating intense magnetic fields. Additionally, using solar concentrators to harness ambient energy in space could help meet the system's energy requirements without overburdening the satellite's resources. Thermal management is another significant challenge. Innovative thermal control methods, such as high-emissivity coatings or phase-change materials, could improve heat dissipation through radiative cooling, keeping operational temperatures within acceptable limits. To optimize the system, it is essential to explore alternative magnetic configurations. Designs like toroidal configurations or Helmholtz coils could provide more uniform magnetic fields and reduce stray fields that may affect other onboard systems. The integration of permanent magnets with electromagnets could also reduce overall energy consumption. The use of high-temperature superconducting materials offers promising prospects for generating strong magnetic fields with minimal losses, but it requires innovative solutions for cooling in space. Research in this area could lead to more efficient and effective shielding systems. It is crucial to conduct electromagnetic compatibility (EMC) testing on the ground using prototype hardware to identify and mitigate potential interference issues before launch, ensuring the shielding system does not compromise other satellite systems. Further research should explore the scalability of the technology for larger spacecraft, considering the differences in available resources and mission requirements, thus broadening the impact of the proposed solution. Long-term operational considerations are necessary to ensure the durability and reliability of the system throughout the satellite's lifespan, analyzing the effects of radiation on materials and components. Regulatory and safety implications must be carefully examined, assessing potential concerns related to generating strong magnetic fields in space and ensuring compliance with international standards. Interdisciplinary collaboration will be essential to address the identified challenges, involving experts in plasma physics, materials science, and aerospace engineering. Finally, ground-based experimental validation using particle accelerators or plasma chambers will be crucial to validate the shielding concept in controlled conditions, refining the design and mitigating associated risks. By recognizing these development areas and proposing them for future research, the study demonstrates awareness of the challenges and takes a proactive approach to advancing the field of spacecraft protection. Implementing these improvements will strengthen the feasibility of the proposed technology and contribute to the evolution of shielding techniques for future space missions.

## References


[1] R.A. Bamford, B. Kellett, J. Bradford, T.N. Todd, M.G. Benton Sr., R. Stafford-Allen, E.P. Alves, L. Silva, C. Collingwood, A. Crawford, and R. Bingham. An exploration of the effectiveness of artificial mini-magnetospheres as a potential solar storm shelter for long term human space missions. 2014.

[2] R. Battiston et al. Superconducting magnets for astroparticle shielding in interplanetary manned missions. 2013.

[3] E.R. Benton and E.V. Benton. Space radiation dosiometry in low-earth orbit and beyond. 2001.

[4] Franklin H. Cock and Seth Watkins. Magnetic shielding of interplanetary spacecraft against solar flare radiation.

[5] L. Gargatè et al. Hybrid simulations of mini-magnetospheres in the laboratory. 2008.

[6] H.R. Levy and F.W. French. Plasma radiation shield: Concept and applications to space vehicles, 2008. Lectures.

[7] Tsoline Mikaelian. Spacecraft charging and hazards to electronics in space, 2001.