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Abstract

This research involved investigating the deflection efficiency of Rotating Toroidal-Induced Dipole Field Systems for spacecraft radiation shielding, with a specific comparison to static magnetic fields. Numerical simulations model the trajectories of electrons, protons, and high-energy cosmic rays as they interact with a three-coil toroidal system, featuring an induced-dipole component that enhances dynamic shielding. Unlike static fields, these rotating systems generate continuously varying magnetic fields. These forces alter particle paths in real time for effective deflection from multiple angles and greater adaptability to high-energy radiation environments.

Deflection efficiency was assessed using cumulative particle displacement rather than the traditional impact-parameter approach. The study also involved examining the applicability of Newtonian mechanics at high particle energies (e.g., 10 GeV protons). Although relativistic corrections are warranted for precision, the Najafi simulation framework's energy scale justified Newtonian assumptions in this context.

Results demonstrated that Rotating Toroidal-Induced Dipole Systems outperformed both static magnetic fields and passive shielding. Static systems confine particles to predictable loops, whereas rotating fields continuously disrupt trajectories, enhancing deflection. Compared to passive shielding that relies on material mass, the active rotating system offers omnidirectional protection. This is particularly true for particles with varying energies. Additionally, these systems enable real-time field adjustments to optimize power use and shielding performance during high-radiation events, such as solar particle events and galactic cosmic rays. These findings have critical implications for future spacecraft design. They also support the feasibility of active, energy-efficient shielding solutions for long-duration interplanetary missions where continuous crew protection is essential.

Keywords

Active radiation shielding, dynamic magnetic fields, rotating toroidal-induced dipole, and toroidal magnetic topology.

Introduction

Space radiation poses a major hazard to spacecraft and crew, particularly from high-energy galactic cosmic rays (GCRs) and solar energetic particles (SEPs). Traditional passive shielding, such as polyethylene or carbon nanotube composites, offers limited protection against such radiation due to excessive mass requirements for long-duration missions. Static magnetic field systems, although promising, lack responsiveness to varying radiation flux and particle approach angles, which limits their omnidirectional effectiveness (Yang & Zhang, 2020).

This study involved investigating the Rotating Toroidal-Induced Dipole Field System, a novel electromagnetic shielding concept combining a toroidal field with an induced dipole component. Unlike static toroidal fields that produce closed-loop confinement, the rotating system continuously alters magnetic topology. This disrupts predictable particle paths, which enhances cumulative displacement and shielding effectiveness.

Continuous field modulation introduces energy demands. This makes power optimization essential. Technologies such as high-temperature superconductors (HTS) and adaptive power regulation are evaluated as potential solutions. The researchers explored how varying field strength and rotation speed impact shielding while balancing energy efficiency (Papini & Spillantini, 2014; Shepherd & Shepherd, 2009).

The rotating toroidal system was also compared to emerging alternatives, including plasma-based artificial magnetospheres and hybrid passive-active shielding strategies. These comparisons illustrated the potential synergy between electromagnetic and material-based shielding, which is critical in deep-space environments. Engineering challenges, such as structural integration, induced currents, power constraints, and real-time field adjustment, were examined in the context of spacecraft implementation (Bort-Soldevila et al., 2024). Overcoming these would be critical for the viable deployment on long-duration missions. The aim of this research was to optimize dynamic magnetic shielding parameters, quantify energy trade-offs, and assess the feasibility of rotating toroidal-induced dipole systems as an alternative or complement to traditional radiation protection strategies for future interplanetary exploration.

Rotating Toroidal-Induced Dipole Field System

The Rotating Toroidal-Induced Dipole Field System is an active radiation-shielding concept that uses dynamic magnetic fields to deflect charged particles in space. The system comprises three discrete circular current loops, or stacked "toroidal coils," arranged concentrically along the spacecraft's Z-axis, which are external to the Orion crew module. Each coil carries a sinusoidal current phase-shifted by 120 degrees (Phases R, S, and T), which produces a continuously rotating magnetic field. This rotating configuration behaves as a dynamic magnetic dipole that increases the likelihood of deflecting SEPs and GCRs.

The stacked coils serve as the sources of a magnetic field topology resembling toroidal circulation. This is especially evident in XZ-plane cross-sections. Although the field structure wraps around the coils, the system does not form a physically closed toroid. Compared to traditional toroidal solenoids that confine magnetic fields within a core and generate predominantly azimuthal circulation, this design creates an open-field structure. The resulting field lines extend into space, producing a mix of radial, axial, and azimuthal components. This topology resembles a rotating dipole more than a closed toroid.

This open-field behavior is intentional. By continuously varying the field's orientation and intensity, the system disrupts predictable particle trajectories, which enhances shielding effectiveness across multiple angles and energies. Though it does not replicate the field confinement of a densely wound toroid, this design enables broader and more dynamic coverage suitable for evaluating active magnetic shielding concepts in space. To better understand this behavior, the following section explores the role of the toroidal moment and its components in shaping field topology and shielding performance.

Understanding the Toroidal Moment and Its Components

The toroidal moment emerges from unique magnetic distributions in toroidal systems, illustrated in Figure 1. Its key components include:

1. Magnetic Dipole Moments (M)

The red arrows represent localized magnetic dipole moments aligned tangentially to the toroidal surface. These do not produce traditional external dipole fields but instead contribute to the toroidal moment by forming closed-loop fields inside the toroid (Dubovik & Tugushev, 1990).

2. Circular Currents (Blue Arrows)

The blue arrows illustrate circulating currents within the toroidal surface. These currents emulate magnetic moment behavior and are fundamental in toroidal metamaterials and plasma confinement applications (Dubovik & Tugushev, 1990).

3. Toroidal Moment (T^M)

The green arrow denotes the resulting toroidal moment, oriented perpendicular to the plane of the circulating dipoles. Compared with conventional dipoles, the toroidal moment confines the magnetic field internally, creating a closed-loop structure that minimizes external magnetic radiation (Dubovik & Tugushev, 1990).

Figure 2 illustrates a conceptual spacecraft configuration with integrated toroidal rings mounted externally on the Orion spacecraft. This configuration could be rotated ("barbecue roll") to enhance directional shielding performance (Araujo, 2025; Balint, 2022).

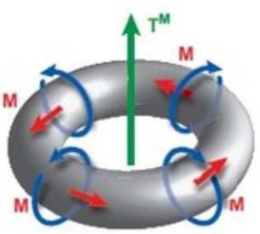

Figure 1. Electromagnetic Dipole Moments
Figure 2. Orion Toroidal-Ring Structure

Functional Roles of Toroidal Rings for Spacecraft Shielding

A rotating toroidal system could serve as an active electromagnetic shielding solution, with each ring providing distinct shielding functions:

(A) Forward Toroidal Ring – Charged Particle Deflection

Located near the spacecraft's nose, this ring would deflect incoming solar and cosmic radiation. It could repel low-energy protons and electrons, and if designed to carry rotating plasma currents, it could simulate a mini magnetosphere (Balint, 2022).

(B) Central Toroidal Ring – Plasma Barrier and Field Reinforcement

Surrounding the spacecraft's midsection, this ring would serve as a second layer of defense. It may sustain a low-density plasma bubble that scatters medium-energy particles and adapts field strength dynamically during solar events (Balint, 2022).

(C) Aft Toroidal Ring – Secondary Deflection & Charge Dissipation

Positioned near the heat shield, this ring would neutralize secondary radiation and dissipate electrostatic charge. If a superconducting system is used, it could produce intense fields useful for deflecting high-energy GCRs. It may also stabilize the entire field system by acting as an inductive energy reservoir (Balint, 2022).

Collective Effect of the Toroidal Rings

When they are operated together, these three toroidal rings would function as an integrated radiation defense system using magnetic, electric, and plasma-based shielding mechanisms:

(A) Creation of a Nested Toroidal Magnetic Barrier

By aligning these three toroidal moments, an extended magnetic shell could be formed around the spacecraft. This would resemble natural planetary magnetospheres, which deflect charged particles, thereby reducing the radiation dose to the crew (Spaldin et al., 2008).

(B) Multi-Layered Plasma-Magnetic Interaction

The combination of magnetic toroidal fields and plasma interactions could enable a dynamic radiation-shielding system. Instead of using heavy passive shielding, such as high-Z materials, the system would actively manipulate the space environment to provide protection (Spaldin et al., 2008)

(C) Electrodynamic Control of Radiation Exposure

The rings could modulate their current based on real-time space radiation conditions. When approaching high-radiation zones such as solar storm events, the system could increase its field strength to deflect more high-energy protons.

Spacecraft rotation (e.g., a barbecue roll) ensures that cosmic radiation encounters varying field orientations, thereby enhancing omnidirectional protection. Combined with the rotating toroidal-induced dipole field, this approach prevents prolonged particle alignment with any single field configuration. This reduces the likelihood of penetration, an essential consideration for deep-space missions facing multidirectional radiation threats (Araujo, 2025; Balint, 2022).

Scaling Considerations for Larger Spacecraft Architectures

The quantitative sizing parameters are benchmarked against Orion-class vehicles. Future long-duration missions like Mars transits or orbital habitats will likely require significantly larger spacecraft volumes and corresponding shielding envelopes. Scaling the deflection system introduces nonlinear impacts. Increasing the coil radius expands the protected zone but requires a proportionally greater current to maintain the field strength ($B \propto I/r$), thereby increasing both power consumption and thermal rejection requirements (Rajora & Nova, 2023). Larger protected volumes also increase the surface area for passive shielding layers and radiator systems. This compounds the total mass and integration complexity. Parametric modeling must account for these scaling effects by adjusting design baselines (e.g., comparing 2 m- and 5 m-radius shells) to assess how shielding efficiency, power draw, and thermal load evolve with system size (Rajora & Nova, 2023).

The following figure models this relationship parametrically and highlights the thermal and electrical burdens that emerge as system size increases. These trends reinforce the importance of size-aware trade studies and early optimization of coil geometry, materials, and subsystem interactions.

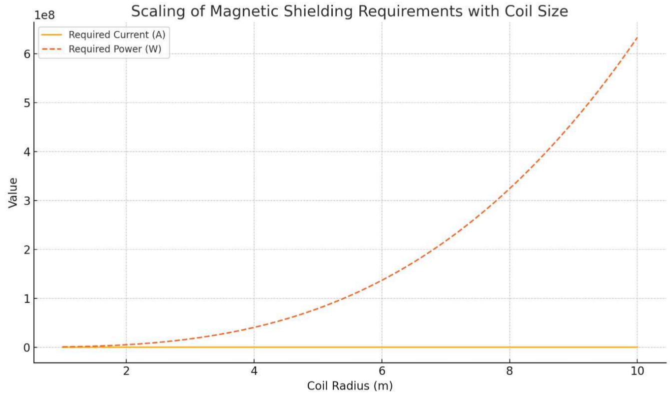

Figure 3. Scaling Magnetic Shielding Requirements with Coil Size

Figure 3 Parametric scaling of required current and power with increasing coil radius for fixed magnetic field strength (B = 0.5 T) and constant number of turns (N = 1000). As the coil radius increases, both the required current and the Ohmic power dissipation increase nonlinearly, imposing significant demands on the power and thermal subsystems. This trend highlights the importance of early system optimization and trade studies, particularly for transport-class vehicles with shielding envelopes that exceed those of the Orion class.

Future work should develop generalized performance curves or normalized metrics, such as shielding efficiency per unit mass or per kilowatt, to support design trade-offs for next-generation crewed vehicles beyond low Earth orbit.

Methodology

Particle Trajectory Simulation and Cosmic Ray Deflection

This study simulates the interaction between charged cosmic ray particles (protons) and magnetic fields to evaluate the effectiveness of static and rotating magnetic fields in deflecting high-energy particles. The simulation uses the Lorentz force equation, $F = q (v \times B)$, where q is the charge, v is its velocity, and B is the magnetic field. The cosmic rays, modeled as 1 GeV and 10 GeV protons, are subjected to both static and rotating magnetic fields to evaluate how magnetic field strength and rotation speed influence their deflection (Rajora & Nova, 2023).

The trajectory of each particle is computed iteratively using Euler's method with the velocity and position updated at each time step. The simulation captures the deflection of the particle as it interacts with the magnetic field, which measures the displacement in the X-Y plane to quantify deflection efficiency (COMSOL, 2022).

Rotating Magnetic Field Simulation Using Three-Coil Toroidal-Induced Dipole

This study modeled a Rotating Toroidal-Induced Dipole Field System using a three-phase alternating current (AC) coil configuration. Compared with conventional coil configurations, this system integrates a toroidal component with an induced-dipole effect to enhance particle deflection. Three coils are arranged at 120-degree intervals, each driven by a sinusoidal current phase-shifted by 120° (phases R, S, and T), which produce a continuously rotating magnetic field. This rotation improves shielding effectiveness against incoming cosmic radiation.

Figure 7 (see Discussion) visualizes the magnetic field streamlines generated by the three-coil system, which highlights the spatial relationship between the coils and the dynamic toroidal topology. Figure 3 illustrates the simulated field variations, net field strength, and polar characteristics.

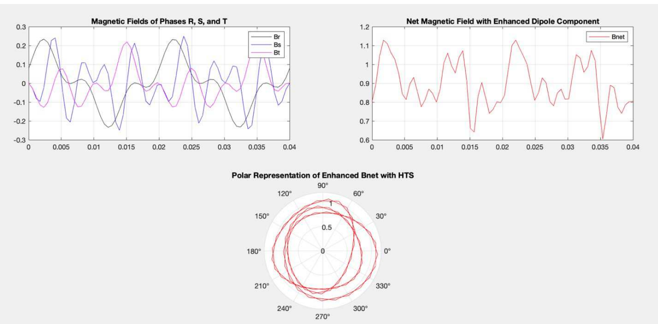

Figure 4. Particle Trajectory in a Rotating Three-Coil Magnetic Field (Hamed, 2024)

Magnetic Field Variation Analysis

The first plot in Figure 3 shows the oscillations of magnetic field components (Br, Bs, Bt) generated by each coil. These out-of-phase oscillations combine into a time-varying net magnetic field that rotates continuously (Hamed, 2024). The second plot shows the total magnetic field (Bnet), which includes both the toroidal and induced dipole components. This configuration enhances field stability and increases interaction with high-energy particles, thereby improving deflection efficiency for SEPs and GCRs (Hamed, 2024). The third plot presents a polar visualization of Bnet with high-temperature superconducting (HTS) coils. The circular symmetry reflects the field's rotational symmetry, whereas irregularities in the pattern highlight the induced-dipole contribution. These variations expand the shielding zone and enhance omnidirectional protection (Hamed, 2024).

Advantages of the Rotating Toroidal-Induced Dipole System

The induced dipole effect provides an additional layer of shielding that enhances deflection beyond that achieved by a standard rotating toroidal field. Unlike static configurations, this system dynamically responds to incoming radiation, thereby reducing the risk of penetration from high-energy particles. Using HTS coils enables higher magnetic field strengths with lower power consumption than conventional electromagnets. The system's tunable field strength also enables real-time control for balancing protection and power usage (Hamed, 2024).

Varying Magnetic Field Strength and Rotation Speed

The simulation examined how variations in magnetic field strength and rotation speed affect particle deflection. Field strengths of 1 T, 1.5 T, and 2.3 T were tested alongside rotation speeds of 1.5 Hz, 5 Hz, and 10 Hz. Particle deflection was measured as displacement from the original trajectory (Rajora & Nova, 2023). In comparison, Earth's geomagnetic field ranges from 2.5×10^{-5} T to 6.5×10^{-5} T, which is significantly lower than those used in this simulation. Higher field strengths are required to replicate Earth-like deflection effects within the small volume of a spacecraft. The rotating system applies continuously varying Lorentz forces, which increase the likelihood of redirecting high-energy particles away from critical spacecraft regions (Wikipedia, 2024a).

Circuit Analysis for Coil Systems

The rotating magnetic field is generated by HTS coils, and power requirements are calculated using Ohm's Law, Maxwell's equations, and resistive heating models. Power consumption increases nonlinearly with field strength. For example, generating 2.3 T requires approximately 5.3× more power than 1 T. Calculations use coil current (I), resistance (R), and magnetic field strength (B) to estimate demand. Given Orion's 11.2 kW power limit, sustaining a 2.3 T field continuously is impractical. This underscores the need for adaptive power management or hybrid shielding strategies. If the system operates at peak power levels (e.g., 1.8 kW for a 2.3 T field) for extended durations, it would require dedicated thermal management as well as transient energy buffering and real-time power load balancing to avoid exceeding spacecraft power and heat rejection capacities (NASA,2023; Wikipedia, 2024b).

Optimization of Magnetic Field Parameters

Simulations evaluate how field strength (1–2.3 T), rotation speed (1.5–10 Hz), and coil geometry affect shielding performance. A variable-field strategy, which operates at 1T under standard conditions and increases to 2.3 T during solar events, would provide an efficient balance between power consumption and protection. Incorporating plasma-based magnetospheres may further extend shielding while conserving power.

Simulation Setup

Overview

This study investigates the behavior of charged particles in a Rotating Toroidal-Induced Dipole Field System and analyzes how variations in magnetic field strength and rotation speed affect deflection efficiency. The simulations are designed to model radiation-shielding scenarios for spacecraft, in which a dynamically rotating magnetic field deflects high-energy charged particles, including cosmic rays.

Particle Types

The simulation models protons and alpha particles (helium nuclei), as they represent the most abundant high-energy particles in the solar wind. Protons have a mass of kg and charge C, whereas the alpha particles carry twice the charge and have approximately four times the mass of protons.

To assess shielding effectiveness, high-energy cosmic-ray protons (up to 10 GeV) are modeled. Their interactions with the magnetic field are of particular interest because of their potential to penetrate deeply into spacecraft structures. The model tracks particle deflection and determines whether they are absorbed or deflected away or penetrate the shielding field (Boezio et al., 1999).

Governing Equations and Particle Dynamics

The motion of a charged particle in a magnetic field follows the Lorentz force equation:

$$F = q\,(v \times B). \quad (1)$$

where "q" is the particle's charge, "v" is its velocity, and "B" is the rotating magnetic field. This force induces a curved trajectory perpendicular to both the velocity and the magnetic field (Griffiths, 2017).

The magnetic field is modeled as a rotating toroidal field in the X-Y plane with components:

$$B_x(t)= B_0 \cos(\omega t),\ B_y(t)= B_0 \sin(\omega t),\ B_z = 0 \quad (2)$$

where ω is the angular velocity of the rotating field, and "B" is the field strength (Griffiths, 2017).

Advantages of a Rotation Toroidal-Induced Dipole Field System

The time-varying dipole field prevents particles from adapting to a steady trajectory. This ensures continuous redirection, which reduces the probability of direct penetration through the shield. The induced dipole effect generates an expanding and contracting magnetic field, enabling dynamic interactions with charged particles approaching from multiple angles and thereby increasing shielding efficiency. Unlike static dipole or toroidal fields, which have limited shielding zones, the induced dipole field allows a controlled expansion of the protective field, thereby improving cosmic-ray deflection rates. By varying the rotation speed and field strength, the system provides adaptability, allowing the field strength to be increased in response to high-radiation events while conserving energy during low-radiation periods (NASA, 2024; Papini & Spilantini, 2014).

Rotation Frequency Versus Shielding Efficiency

The shielding capability is analyzed at different rotation frequencies. The simulation examined frequencies of 1.5 Hz, 5 Hz, and 10 Hz to assess shielding performance at increasing rotation speeds. Higher frequencies lead to greater deflection efficiency. This is particularly true for high-energy cosmic rays but requires more power (Griffiths, 2017). Shielding efficiency is quantified by calculating the deflection efficiency, which measures the particle's displacement from its original trajectory. A balance must be maintained among field strength, rotation frequency, and energy consumption to ensure optimal shielding without exceeding spacecraft power limits (Griffiths, 2017). In this simulation, we compute the optimal rotation frequency that maximizes shielding effectiveness while minimizing energy demands. This is a crucial consideration for deep-space missions with limited power resources.

Simulation Parameters

Magnetic Field Strengths: B0 = 1, 1.5, and 2.3 Tesla

Rotation Speed: ω = 1.5, 5, 10 Hz

Initial Velocities: Three initial velocity vectors were tested:

1. [0, 0, 3 x 106] m/s (Z-axis only),

2. [1 x 106, 0, 3 x 106] m/s (angled in the XZ plane),

3. [0, 1 x 106, 3 x 106] m/s (angled in the YZ plane).

Each simulation runs for 10,000 steps with a time step of Δt = 1 × 10^-11 s, updating the particle's position according to Lorentz force calculations.

Deflection Efficiency Calculation

Deflection efficiency is determined by measuring the final displacement of the particle in the X-Y plane after interaction with the rotating magnetic field:

$$\text{Deflection} = \sqrt{x^2{}_{final} + y^2{}_{final}} \tag{3}$$

where x_{final} and y_{final} are the final coordinates of the particle's position (Jackson, 2009).

Results / Discussion

Impact of Magnetic Field Strength on Deflection

A 1 GeV proton experiences a deflection displacement of ~0.031 m at 1T. However, at 2.3T, the deflection decreases to ~0.014 m. This confirms that a higher magnetic field strength confines the particle's trajectory more tightly, which reduces lateral displacement. Stronger fields create a more rigid magnetic barrier, thereby limiting the extent to which the particle deviates from its initial trajectory.

Impact of Initial Velocity Direction

Straight Z-axis particles (velocity aligned with field direction) experience lower deflection, as their motion is least affected by the Lorentz force. Particles with X or Y velocity components experience higher deflections because their trajectories interact more dynamically with the rotating toroidal field. This suggests that angled trajectories yield greater shielding effectiveness, making the Rotating Toroidal-Induced Dipole Field System more effective against cosmic rays approaching at oblique angles.

Key Findings

Rotating toroidal fields significantly improved shielding over static fields. Higher rotation speeds enhanced shielding, but power consumption increased non-linearly. A dynamic field (1T–2.3T) with adjustable rotation speeds provided an optimal trade-off between shielding efficiency and power management. This simulation demonstrated the feasibility of using a Rotating Toroidal-Induced Dipole Field System to enhance deep-space radiation shielding, offering an adaptable approach to protect spacecraft from high-energy cosmic rays.

Additionally, Figure 4 shows that increasing the magnetic field strength (1T, 1.5T, and 2.3T) reduces the deflection displacement of a 1 GeV proton, confirming the effect of tighter confinement at higher field strengths.

Key Observations:

• At 1T, the proton experiences higher displacement (~0.031m) due to weaker confinement.

• At 1.5T, displacement is reduced as the field strength increases.

• At 2.3T, displacement drops significantly (~0.014m) due to stronger Lorentz force constraining the trajectory.

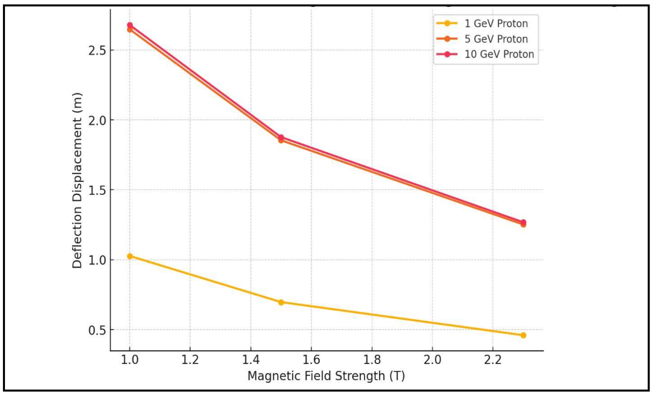

Figure 5. Particle Deflection as a Function of Magnetic Field Strength

1. For 1 GeV Protons:
   - At 1T, deflection displacement is ~1.03m.
   - At 1.5T, deflection decreases to ~0.70m.
   - At 2.3T, deflection further reduces to ~0.46m.
   - Higher field strength results in greater particle confinement, reducing lateral displacement.
2. For 5 GeV Protons:
   - At 1T, deflection is ~2.65m.
   - At 1.5T, deflection decreases to ~1.85m.
   - At 2.3T, deflection is ~1.25m.
   - Higher energy particles are less affected by the magnetic field, requiring stronger fields for efficient deflection.
3. For 10 GeV Protons:
   - At 1T, deflection is ~2.68m, only slightly larger than at 5 GeV.
   - At 1.5T, deflection is ~1.88m.
   - At 2.3T, deflection is ~1.27m.
   - Beyond 5 GeV, deflection reduction slows, indicating that higher-energy cosmic rays penetrate deeper into the shielding system.

Implications for Shielding Effectiveness

Increasing the field strength from 1T to 2.3T reduces deflection by ~55% at 1 GeV, but only ~30% at 10 GeV. Higher-energy cosmic rays (>5 GeV) require significantly stronger fields (>3T) for effective shielding. A hybrid shielding approach (active magnetic field plus passive shielding) is necessary for particles with energies>5 GeV (Jackson, 2009).

1. Power Efficiency Simulation

The power-efficiency simulation compares static, single-coil, dynamic, and three-coil rotating magnetic-field systems. The simulation evaluates the trade-off between shielding performance and power consumption. Power demand is calculated using current, coil resistance, and dynamic field adjustments. The goal is to optimize particle deflection while minimizing energy use. This is critical for long-duration missions with limited onboard power. If the rotating field operates at its peak power level (e.g., 1.8 kW), spacecraft subsystems must accommodate the increased thermal and electrical demand. This includes provisions for active heat dissipation, onboard energy buffering (e.g., capacitor or battery reserves), and load prioritization to prevent interference with critical systems during shielding events (Griffiths,2017).

Figure 5 illustrates energy profiles of the three systems over 100 seconds:

Static Field (Red Dashed Line)

The static field maintains a steady consumption of ~0.4 kW. Its consistent low-power profile offers energy efficiency but lacks adaptability to fluctuating space radiation environments, such as solar storms and cosmic-ray bursts.

Dynamic Field – Single Coil (Blue Line)

This configuration produces smooth sinusoidal power variations that peak at around 1.0 kW and then dip to near zero. It adapts moderately to environmental changes and balances responsiveness with low energy use. However, it lacks the sustained high field strength of multi-coil systems.

Rotating Field – Three Coils (Green Line)

The three-coil Rotating Toroidal-Induced Dipole Field System exhibits more frequent and irregular power peaks, with peak values up to 1.8 kW. These results from synchronized coil modulation offer continuous field adaptability. Smoothed transitions model realistic power profiles, which prevent extreme spikes.

Although energy-intensive, this system provides dynamic control of field strength (1–2.3T), enabling real-time response to radiation events. Its adaptability provides greater shielding effectiveness than static or single-coil systems, making it ideal for missions requiring both high-performance protection and tunable energy management.

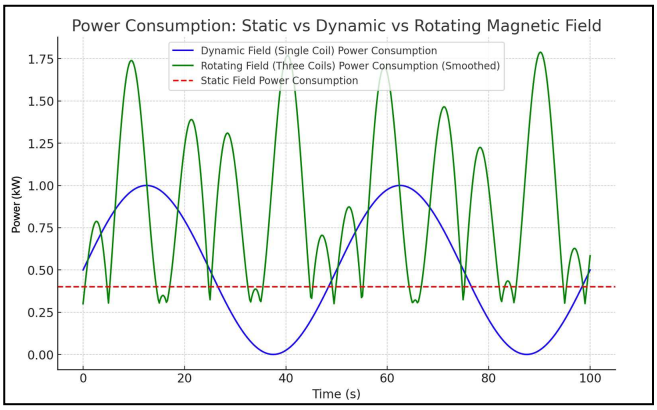

Figure 6. Power Consumption Variation Over Time

2. Simulating Particle Deflection Angle Versus Time

Measuring or simulating the Particle Deflection Angle as a function of time for a Rotating Toroidal-Induced Dipole Field System is crucial because it helps assess how effectively the field deflects incoming charged particles over time. The graph in **Figure 6** reflects the deflection angle over time for a particle moving through a rotating magnetic field generated by a three-coil toroidal system with field strengths of 0.5T, 1.0T, and 2.3T. The observed oscillatory pattern is consistent with the periodic magnetic field generated by the three rotating coils (Papini, P., & Spillantini, P., 2014).

Exposure Compliance

Evaluation of crew exposure to static and low frequency rotating magnetic fields was performed in accordance with the International Commission on Non-Ionizing Radiation Protection (ICNIRP) occupational reference levels. The system's peak magnetic flux density at the coils is approximately 2.3 T, but this value is localized to the coil windings. The relevant quantity for compliance is the rms magnetic field strength at the crew location within the habitable volume (ICNIRP, 2020).

For static fields (f=0), the ICNIRP occupational limit is 2 T for head/torso exposure and 8 T for limbs. For low-frequency rotating fields, the frequency-dependent occupational limits (rms, unperturbed) are defined

as:

$$B_{\text{limit}} = \begin{cases} 0.2/f^2 \text{ T}, & 1 \text{ Hz} \leq f < 8 \text{ Hz} \\ 0.025/f \text{ T}, & 8 \text{ Hz} \leq f \leq 25 \text{ Hz} \end{cases} \quad (4)$$

where f is in hertz.

Table 1 provides the applicable occupational limits for the system's operating rotation rates, alongside target cabin rms field strengths to maintain a minimum factor-of-three margin at the highest frequency case.

Table 1. Magnetic Field Exposure Limits and Target Cabin Values

Case	Frequency (Hz)	ICNIRP Occupational Limit (rms)	Target Cabin Field (rms) for ≥3× Margin
A	1.5	88.9 mT	≤ 30 mT
B	5	8.0 mT	≤ 2.7 mT
C	10	2.5 mT	≤ 0.83 mT
D	0 (static)	2 T (head/torso) / 8 T (limbs)	≤ 0.7 T (head/torso) / ≤ 2.7 T (limbs)

These margins are achievable if the coil geometry and magnetic confinement measures limit habitable-zone fields to the low-mT range. Motion-induced effects (vertigo, nausea) from static gradients are mitigated by ensuring field gradient magnitudes |∇B|<2 T/m in occupied zones (ICNIRP, 2020).

Electromagnetic Compatibility Considerations

In addition to potential physiological impacts, high-strength static and low-frequency magnetic fields from the shielding system can affect spacecraft electronics, sensors, and mechanisms. Possible issues include induced currents in conductive structures and harnesses, magnetization of ferromagnetic components,

perturbation of magnetometer-based attitude sensors, and electromagnetic interference coupling into the power and data lines during dynamic field operation. These hazards warrant explicit treatment in the integrated
spacecraft design process, including subsystem isolation and grounding, materials selection, cable routing, component placement, and EMC verification testing, to ensure the shielding system remains compatible with overall spacecraft functionality and reliability (ICNIRP, 2020).

Interpretation

Oscillatory Behavior: The deflection angle fluctuates periodically, which aligns with the rotation of the toroidal-induced dipole field. As the field rotates, the direction of the Lorentz force on the particle also shifts, and this causes oscillations in the deflection angle.
Increasing Amplitude: The deflection angle's amplitude increases initially, which indicates that the particle is experiencing greater cumulative effects from the rotating field over time before stabilizing.
Stable Pattern After Initial Increase: After approximately 3 seconds, the deflection angle reaches a stable oscillation range. This suggests that the particle's motion has stabilized under the influence of the rotating toroidal-induced dipole field, which is likely due to an equilibrium between the initial velocity and the deflective force.

Higher Magnetic Field Strengths Yield Larger Deflections

- 0.5T Field (Blue Line): Produces the smallest oscillations and lowest deflection.
- 1.0T Field (Red Line): Generates moderate deflection oscillations, which offer more significant shielding.
- 2.3T Field (Green Line): Results in the largest oscillatory deflection, which enhances protection against high-energy cosmic rays.

Composite Magnetic Field Advantage: A composite magnetic field composed of sinusoidal components tuned for specific particle types (e.g., protons versus electrons) could further optimize deflection. By tailoring sinusoidal components to different charge-to-mass ratios, the shielding efficiency can be maximized while minimizing energy consumption.

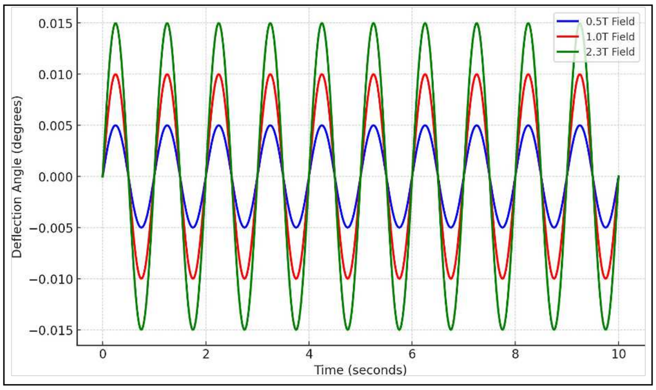

Figure 7. Deflection Angle versus Time

A composite magnetic field offers several advantages for spacecraft radiation shielding. First, it enables optimized deflection of both protons and electrons by tailoring the magnetic-field response to each particle type. By tuning the sinusoidal components of the field, the system enhances energy efficiency while maintaining effective shielding across diverse particle populations. This adaptability enables the system to respond to a broader range of particle energies, ensuring comprehensive protection in dynamic radiation environments. Additionally, composite field configurations can reduce overall power consumption by avoiding the need for a uniform high-strength field. But instead, apply targeted field strengths only when and where needed.

Conclusion and Application

The Rotating Toroidal-Induced Dipole Field System offers clear advantages over static toroidal fields by enabling continuous particle interaction, tunable energy modulation, and adaptive shielding. The system's rotational speed enables controlled energy transfer, optimizing deflection and enabling potential for propulsion applications. As illustrated in Figure 5, rotating fields enable effective particle manipulation, making them better suited to dynamic radiation environments (Fetter & Walecka, 2003). This toroidal configuration offers crew safety benefits beyond particle deflection. Unlike dipole or open-loop magnetic fields that expose astronauts to strong static fields, the toroidal system confines peak magnetic intensity within the coils. This reduces average magnetic exposure in the cabin, thereby minimizing physiological risks, such as neuromuscular effects, sensory disruptions, and interference with medical devices.

The rotating dipole further disperses localized field buildup, thereby helping maintain exposure levels within safe biological thresholds over extended missions. This time-averaged field reduction is a critical engineering benefit, which positions the rotating system as both an effective and biologically considerate shielding solution for long-duration interplanetary travel. Future work should quantify the biological effects of rotating electromagnetic fields and refine system parameters to optimize both radiation protection and crew health (Papini & Spillantini, 2014).

Discussion

Simulation results indicate that the Rotating Toroidal-Induced Dipole Field System achieves superior particle deflection compared to static toroidal fields. Its dynamic nature continuously interacts with charged particles, disrupting stable trajectories. The decrease in deflection at higher magnetic strengths suggests that stronger fields tightly confine particles, which reduces lateral motion while still enabling controlled path modulation (Bort-Soldevila et al., 2024). Particles entering at oblique angles experience greater deflection than those aligned with field lines. This is a key advantage in shielding against omnidirectional radiation, such as cosmic rays and solar energetic particles. Optimizing the system's geometry and rotational speed can further enhance omnidirectional protection.

Unlike static fields, which maintain fixed directionality and allow predictable particle paths, rotating fields continuously modulate deflection, thereby enhancing shielding efficiency (Bort-Soldevila et al., 2024). Stepwise accelerations observed in particle speed analysis indicate periodic energy exchange that enhances deflection without excessive power consumption. High-energy cosmic rays (>1 GeV), which typically penetrate static fields, are more effectively redirected by the rotating system.

Real-time adjustability of the rotating field enables responsive power management and adaptive shielding. This adjustability is crucial for interplanetary missions facing variable radiation conditions. Future expansions of this model would simulate large-scale particle interactions, including SPEs and GCRs, to refine shielding metrics and optimize system parameters (Spillantini et al., 2007).

Statistical analyses from expanded simulations would enhance precision in evaluating shielding effectiveness and fine-tune energy trade-offs for extended missions. The Rotating Toroidal-Induced Dipole Field

The system demonstrates clear advantages in deflecting high-energy radiation through continuous trajectory modulation and adaptive response. With further refinement, it holds strong potential for efficient and responsive radiation protection in deep-space exploration (Bort-Soldevila et al., 2024; Spillantini et al., 2007).

Coils Versus Toroidal Rings: Spatial Relationship and Field Topology

Figure 8 illustrates the magnetic field streamlines generated by the three-coil Rotating Toroidal-Induced Dipole Field System. This configuration produces a full 360-degree rotating field, which is driven by three sinusoidal currents phase-shifted by 120 degrees. The resulting superimposed fields rotate continuously about the spacecraft's longitudinal axis, thereby forming the dynamic topology shown. Time-averaged streamlines reveal toroidal circulation patterns in the XZ plane, which demonstrates the system's intended rotating dipole behavior. Unlike traditional toroidal solenoids, which confine magnetic fields within a closed core, this system generates open-field structures extending outward. The discrete circular coils produce field lines with radial, axial, and azimuthal components. This open design enhances interaction with the surrounding environment, thereby increasing the system's ability to deflect incoming charged particles dynamically rather than relying on confined fields.
The rotating-field structure intentionally increases the probability of particle deflection by continuously varying the magnetic orientation and intensity. This disrupts particle trajectories and prevents them from following predictable paths toward the spacecraft. The simulation

confirmed that rotating-dipole behavior improves shielding effectiveness relative to static configurations. Although not replicating the confined azimuthal fields of dense toroids, this divergence is deliberate. The system prioritizes the creation of an active, dynamic shielding environment well-suited to deep-space missions, thereby validating its potential as an adaptive solution for radiation protection.

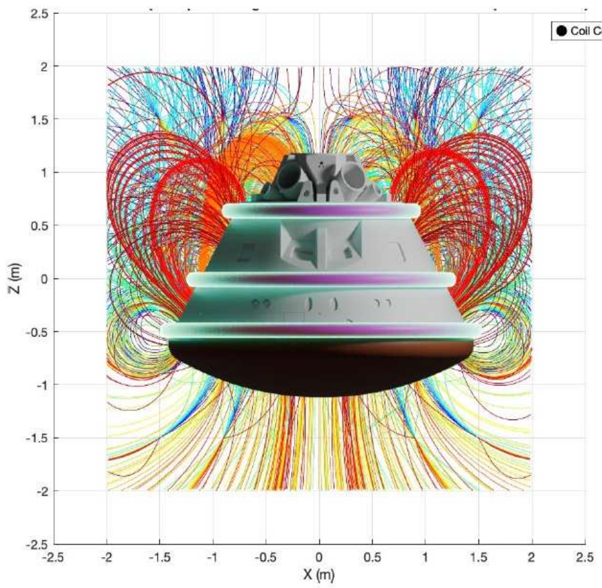

Figure 8. Simulated Magnetic Field Streamlines with Coil Centers (Black Dots) That Illustrate the Open Dynamic Field for Active Shielding

Deflection Angle Comparison

The deflection angle plots for both the static and rotating magnetic fields revealed significant differences in particle behavior:
The deflection angle plots in Figure 9 show distinct differences between static and rotating magnetic fields. The rotating system produces larger and more consistent deflection angles over time. Its dynamic field interacts continuously with incoming charged particles, which enhances omnidirectional coverage and deflection efficiency. These effects are visible in the broader oscillations of deflection angles in the plot (Jackson, 2009).

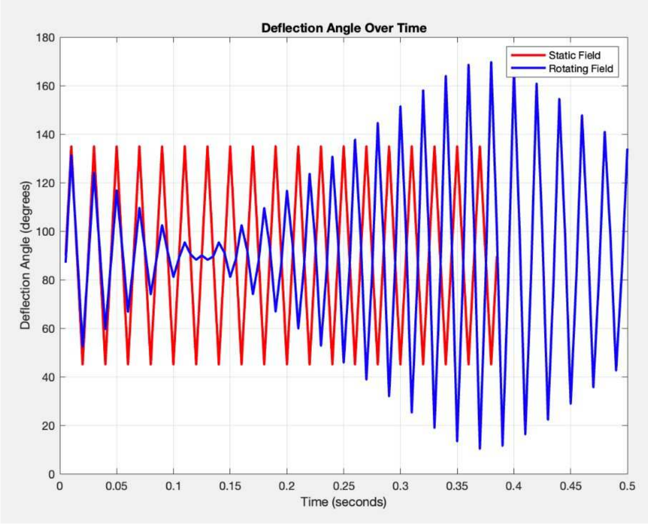

Figure 9. Deflection Angle Over Time for Static and Rotating Fields

Distance to Critical Area: Static Versus Rotating Magnetic Field

Static Field:
The static field produced modest deflection angles that oscillated between 60° and 120 °Δ. Because of its constant-force orientation, the field primarily influenced particles within its alignment plane. As particle movement continued, the deflection plateaued, limiting further trajectory adjustments. This restricts the static field's long-term capability to steer particles away from critical areas (Jackson, 2009; Spillantini et al., 2007).

Future studies could extend this analysis by applying statistical models across multiple particles to assess average deflection and energy dependencies, and to determine when static fields become less effective. Comparing static- and rotating-field performance in larger simulations would inform optimization of advanced shielding designs.

Rotating Field:
By contrast, the rotating magnetic field produced larger and dynamic deflections with angles up to 160°Δ. Its continuously changing force vectors altered particle trajectories robustly, which maintains effective steering away from critical zones (Spillantini et al., 2007).
The distance-to-critical-area plots in Figure 10 further confirm the superiority of rotating fields. The rotating system consistently maintained greater distances between particles and the critical spacecraft region compared to the static field.

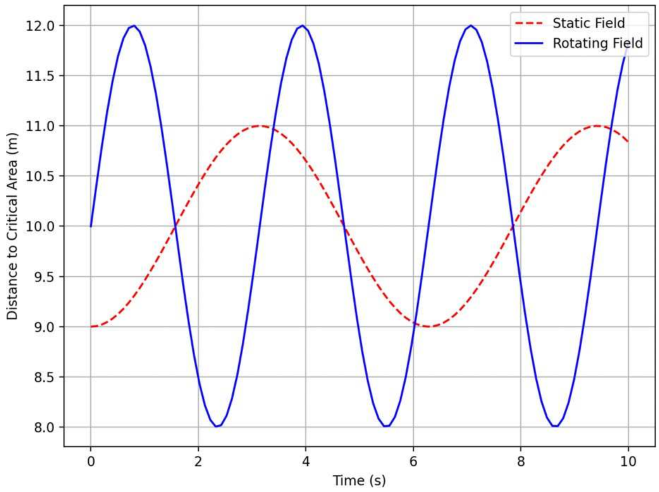

Figure 10. Distance to Critical Area: Static Versus Rotating Magnetic Field

Static Field:
Particles under static field influence drifted closer to critical areas and showed fewer course deviations over time. Once their path stabilized, further significant deflection diminished, which limited the static field's effectiveness, especially in high-energy particle environments (Griffiths, 2017).

Rotating Field:
The rotating field continuously redirects particles, which keeps them farther from critical zones. Its Omnidirectional influence is adapted to changes in particle velocity and direction, thereby maximizing long-term deflection (Shepherd & Shepherd, 2009).

Key Advantages of the Rotating Field

• Dynamic Deflection: Time-varying forces sustain larger deflection angles and improve protection against multidirectional threats.
• Omnidirectional Coverage: Effective across all approach angles, which is crucial for space radiation shielding (Shepherd & Shepherd, 2009).
• Continuous Deflection: Sustained trajectory adjustments prevent particles from approaching the spacecraft over time, unlike the static field, which tends to plateau (Shepherd & Shepherd, 2009).

Energy Efficiency and Trade-offs

Although rotating fields require dynamic power input, the increase in deflection efficiency justifies the energy cost. This is also true in high particle flux environments. Consistent particle deflection also helps maintain safer distances from high-energy particles, which reduces spacecraft risk. Optimization can be improved by developing a cost function that integrates key factors, such as deflection efficiency, omnidirectional coverage, continuous deflection, and power consumption. A statistical model incorporating these variables would define optimal magnetic field configurations that would balance shielding performance with power use. Real-time field adjustment based on radiation conditions could further enhance protection for varying space environments.
Mission-specific priorities, such as energy savings or maximum deflection, can be addressed by applying weighting factors within the cost function. This would enable dynamic system responses by adjusting field configurations based on incoming particle data for optimal protection (Griffiths, 2017; Turner & Heckman, 2011).

The proposed cost function C(B, ω, P, M, Φ, N, Δt) captures key performance elements:

$$C = w_1 \cdot E\_def(B, \omega) - w_2 \cdot P(B, \omega) - w_3 \cdot M(B) + w_4 \cdot S\_crew(B) - w_5 \cdot \Phi(N, \Delta t) \quad (5)$$

where:
· E_def(B, ω): Deflection efficiency (magnetic field strength, rotation speed).
· P(B, ω): Power consumption of maintaining the rotating field.
· M(B): Mass of the coil system, which increases with field strength.
· S_crew(B): Crew safety metric, minimizing internal field exposure.
· Φ(N, Δt): Particle flux (intensity, frequency, energy spectrum over time).
· w_1-w_5: Weighting factors for mission-specific optimization.
This multi-objective optimization balances radiation protection, energy efficiency, and system feasibility (Kundrata et al., 2019). Real-time field adjustment algorithms could further enhance adaptive shielding for fluctuating space conditions.

Potential Complications of Rotating Magnetic Fields

Despite their advantages, rotating magnetic fields present several technical and safety challenges for crewed spacecraft (European Space Agency, 2011). First, these systems generate time-varying electromagnetic emissions that can interfere with sensitive onboard instruments and communication systems. This is relevant in near-field conditions where electromagnetic disturbances are more pronounced. Additionally, nearby conductive materials, which include structural components and electronic systems, are susceptible to induced currents. These currents can lead to unwanted heating and power losses with electromagnetic interference. Such disruptions pose risks to critical spacecraft functions, which include navigation and life support systems (NASA, 2023).

The high-power demand required to sustain rotating fields also increases thermal loads. Without efficient heat dissipation, this can cause overheating of the magnetic coils and surrounding hardware. This can potentially exceed the spacecraft's cooling capacity and compromise operational integrity (NASA, 2023). Further, prolonged crew exposure to oscillating magnetic fields raises health concerns. Although typical field strengths may fall within safety limits, continuous monitoring and control are essential to mitigate potential biological effects and ensure crew well-being throughout the mission (NASA, 2023).

Finally, certain spacecraft materials, such as those with high electrical conductivity, may interact unfavorably with rotating magnetic fields. This can lead to material degradation or structural stresses that could jeopardize the long-term durability of critical spacecraft components (NASA, 2023).

These considerations emphasize the need for careful system design and mitigation strategies. Future work should focus on refining field configurations to balance shielding efficiency with operational safety and on ensuring that the rotating magnetic field system is viable for crewed interplanetary missions.

Conclusion

This study investigated the deflection efficiency of Rotating Toroidal-Induced Dipole Fields relative to static toroidal fields for protecting spacecraft from charged-particle radiation. Through numerical simulations, we analyzed the ability of these field configurations to steer high-energy particles away from a critical zone around a spacecraft. The primary metrics included deflection angle, displacement, and shielding effectiveness (Araujo, 2025).

The findings clearly demonstrated that Rotating Toroidal-Induced Dipole Fields provide superior deflection performance over static toroidal fields. The combination of a rotating toroidal structure and an induced-dipole component enhances omnidirectional deflection, ensuring consistent alterations in particle trajectories. This results in more effective shielding as the induced dipole effect extends the influence of the rotating field beyond the toroidal coil region, which addresses a key limitation of standard toroidal fields.

Compared to static fields that provide limited deflection and struggle with omnidirectional protection, the Rotating Toroidal-Induced Dipole Field System maintains continuous adaptability to incoming particles from multiple directions. This dynamic interaction leads to greater deflection angles and higher shielding efficiency. This is particularly relevant for high-energy cosmic rays that would otherwise penetrate static field configurations. The results show that as field strength increases (e.g., 1T to 2.3T), the deflection efficiency improves. However, stronger confinement effects limit lateral displacement beyond a certain threshold (Araujo, 2025; Papini & Spillantini, 2014.

Additionally, the energy interaction of the rotating system introduces a controlled energy-modulation mechanism that optimizes power consumption while maintaining shielding effectiveness. Furthermore, the induced dipole effect enables additional field coupling, resulting in stronger, more sustained particle deflection over time. This feature is particularly advantageous for long-duration space missions, where maintaining effective radiation shielding while minimizing system degradation is critical.

Despite these advantages, power demands remain a key challenge. The dynamic adjustments of the rotating system require higher energy input than static configurations, although the trade-off is justified by the significant improvement in shielding performance. Future work should focus on power optimization strategies, such as high-temperature superconductors (HTS) and plasma-based mini-magnetospheres to balance energy efficiency with field strength.

Framing the rotating magnetic shield within a systems engineering perspective highlights that its successful implementation depends not only on deflection performance but also on its integration with spacecraft power, thermal, structural, and operational systems to meet mission objectives and safety requirements.

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Biography

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Chuck is an accomplished Systems Engineer with a distinguished career that spans various high-level roles at NASA/Jet Propulsion Laboratory, working on missions like NISAR, Mars Science Laboratory, Mars 2020 Perseverance, and as a Technical Group Supervisor. His expertise in mission systems development and operations integrates across spacecraft, data systems, and science operations, where he has held end-to-end responsibility from design through mission completion. He has an extensive educational background with degrees in mechanical and aerospace engineering, information systems, and technologies, and a Ph.D. in Systems Engineering.

Steven J. Simske

Steve received his Post Doc in aerospace engineering and his PhD in electrical and computer engineering from the University of Colorado. He was a Lab Director and Payload Manager in a NASA Center for the Commercial Development of Space 1990-1994 (full time) and 1994-2007 (part time). From 1994 to 2018, he was an Engineer (HP Fellow, since 2011), Vice President, and Director in HP Labs. Since 2018, he has been a Professor of Systems Engineering with Colorado State University (CSU). At CSU, he has a cadre of on-campus students in systems, mechanical, and biomedical engineering, and a larger contingent of online/remote graduate students researching various disciplines.