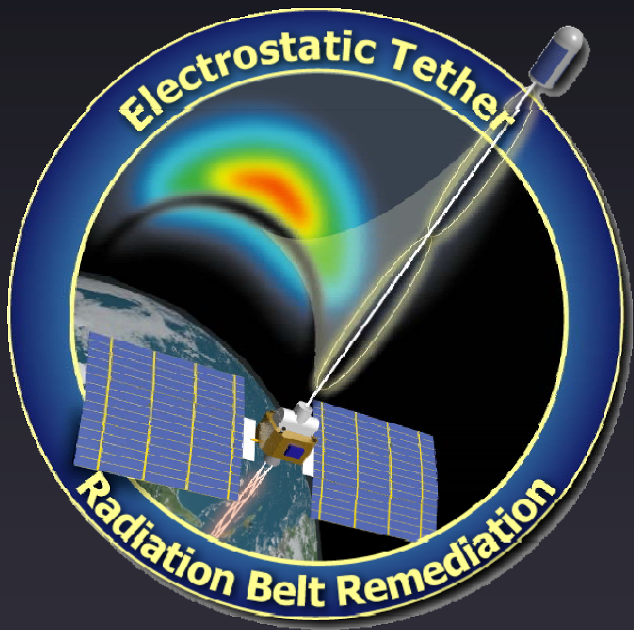
Reduction of Trapped Energetic Particle Fluxes in Earth and Jupiter Radiation Belts



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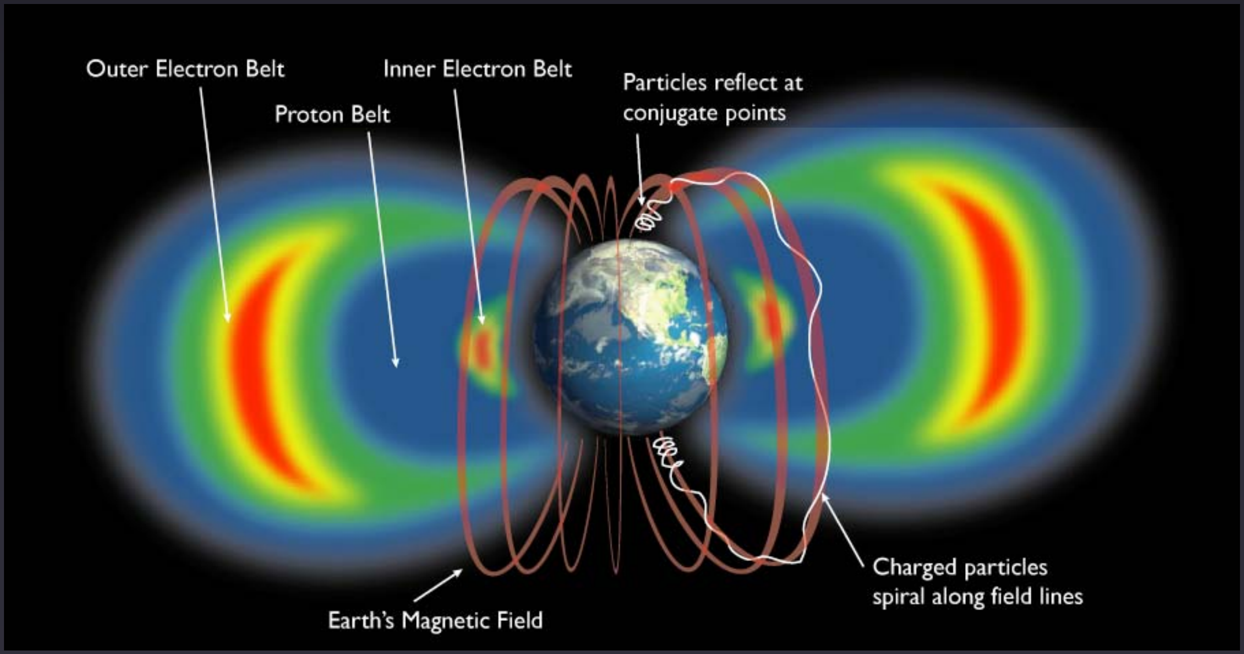
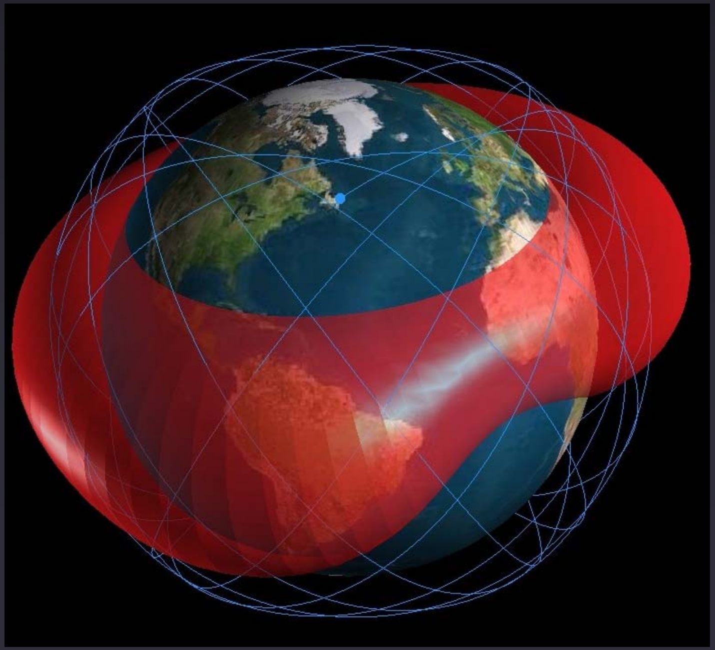
Radiation Belts

- Planetary magnetic fields trap energetic electrons and ions in ‘belts’ that encircle the planet
  - Electrons and ions with pitch angle w.r.t. magnetic field lines greater than the ‘loss cone angle’ reflect before reaching upper atmosphere and are trapped in the belt
- Electron fluxes are most intense in:
  - Inner Electron Belt from 1.3 to 1.7 R_e
  - Outer Electron Belt from 3.5 to 11 R_e

Focus of this effort

- Spacecraft in lower orbits (LEO) pass through the ‘horns’ of the belts due to ‘crescent’ cross-section of belts



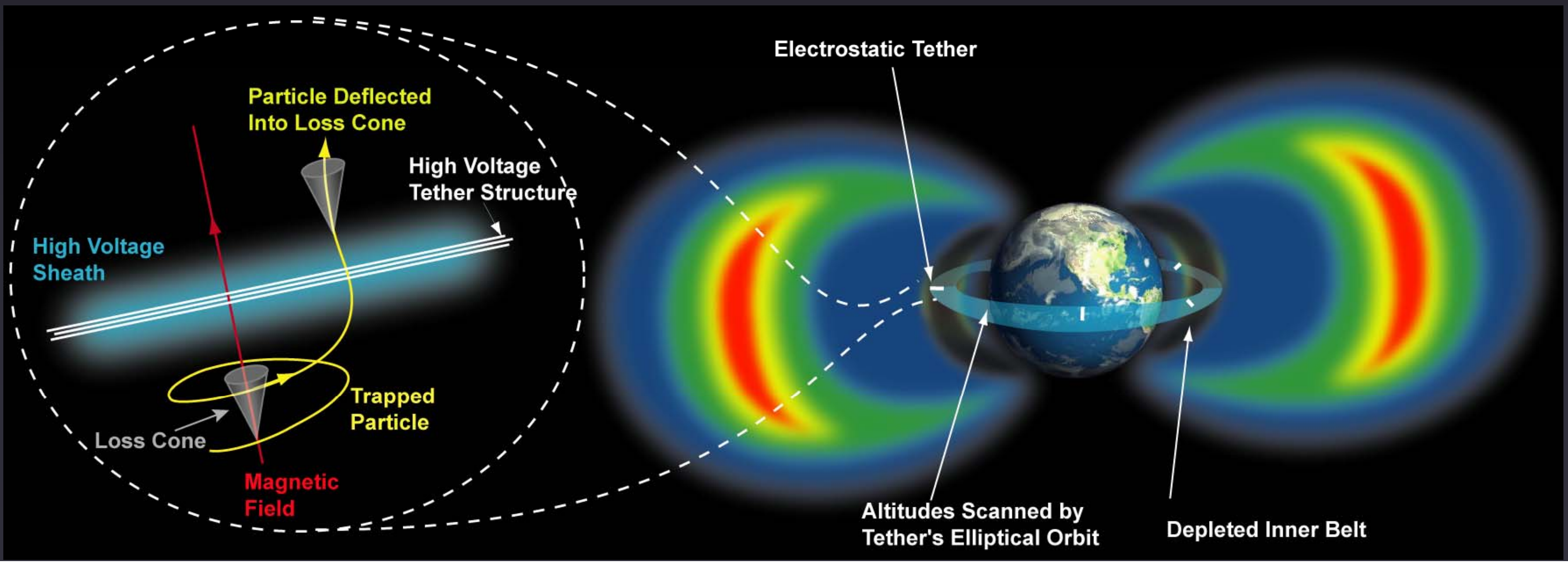


Radiation Effects

- Energetic electrons and protons disrupt and degrade spacecraft systems:
  - Degradation of electronic component performance
  - Cause single-event upsets in avionics
  - Darken optics & coatings
  - Weaken structural materials
  - Reduce power generation capabilities of solar panels
- In biological systems, energetic particles cause cellular damage:
  - Cancers
  - Weaken immune systems
  - Cellular breakdown (apoptosis)

Electrostatic Remediation Concept

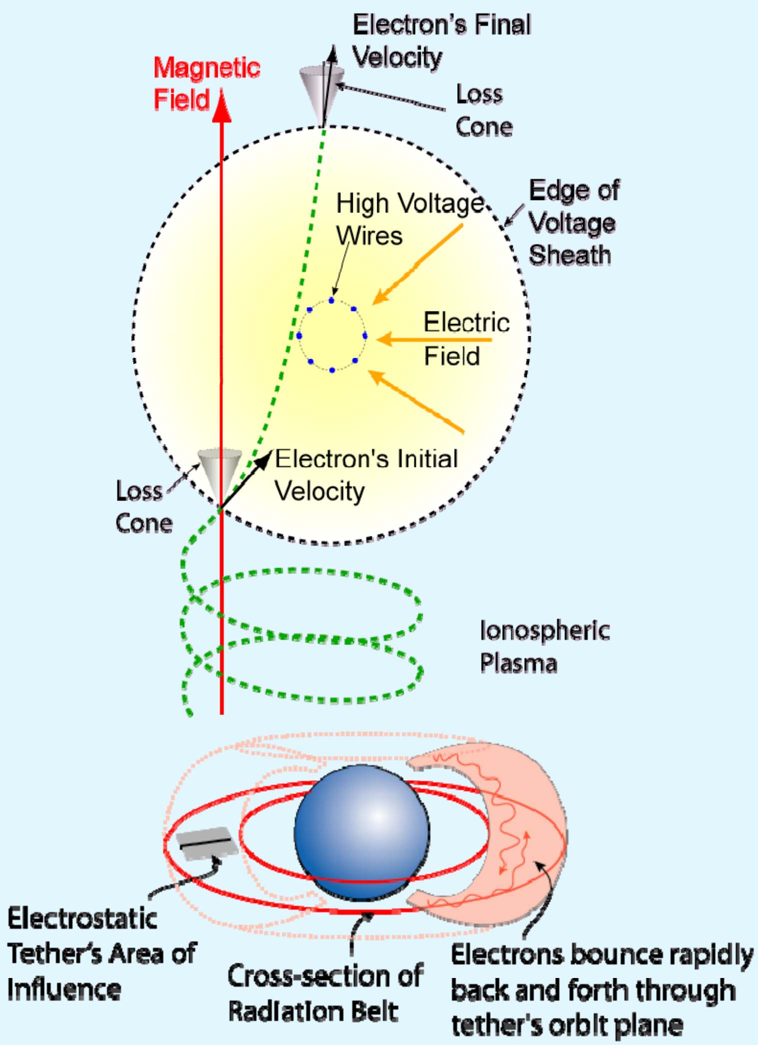
- Particles will leave the belts if their pitch angle is deflected into the loss cone
  - Pitch angle scattering caused naturally by coulomb collisions and EM wave interactions
  - Particles precipitate into atmosphere and dissipate energy through collisions
- Place long conducting tether structures into orbit within the radiation belts and bias the structures to large negative voltage
  - Bounce & azimuthal drift of relativistic electrons, along with orbital motion of ES Structures, ensures that essentially all electrons will encounter HV sheath several times per day
- Strong electric fields near the tether structures will scatter pitch angle of particles that pass close by
  - Voltage on structures must be comparable to particle energy to cause significant scattering



Electrostatic Radiation Remediation Challenges

Approach

- High voltage wires create strong electric fields that scatter energetic electrons into the loss cone

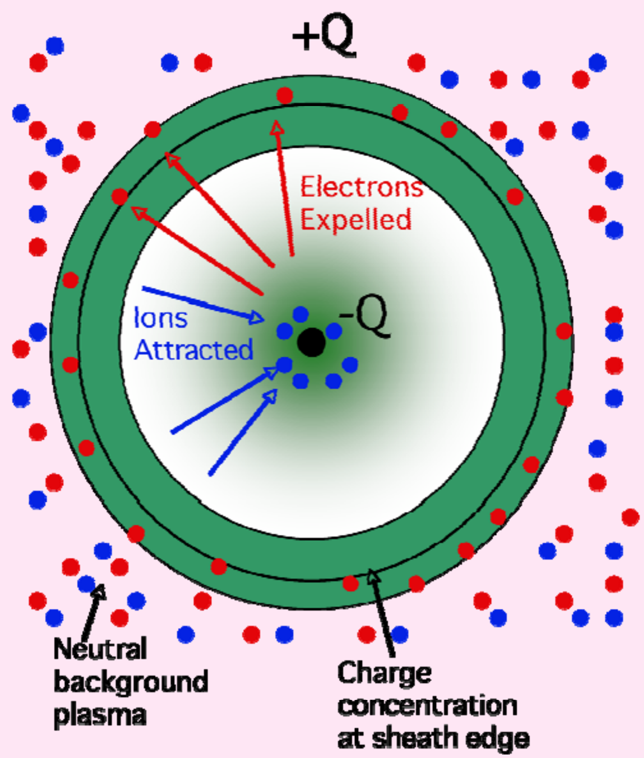


Challenges

- Ions & electrons in ionospheric plasma react to the high voltage:
- Charge redistribution limits range of wire's electric field
- Ions attracted to wire requires power input to maintain charge & voltage on wire

- **ES Remediation feasibility requires creating large high-voltage sheath with low power requirements**

–Single wire not good enough



Analytical Model

- Number of ES Structures required to remediate a given radiation belt:

$$N_{sats} = F_{HAND} \frac{1}{L} \left[\left(\frac{2\pi e}{\pi/2 - \alpha_{LC}} \right) K \frac{K + 2m_e c^2}{K + 2m_e c^2} \frac{e n_{plasma}}{\varepsilon_o} \right]^2 \frac{1}{\rho_s^5} \left[\ln \left(\frac{\rho_s}{d_w/2} \right) \right]^2$$

Tether Structure Length

Ratio of ES Structure Voltage to Particle Energy

Plasma Sheath Radius

Constant describing intensity & extent of radiation belt

Loss Cone Angle

Plasma Density

Wire Diameter

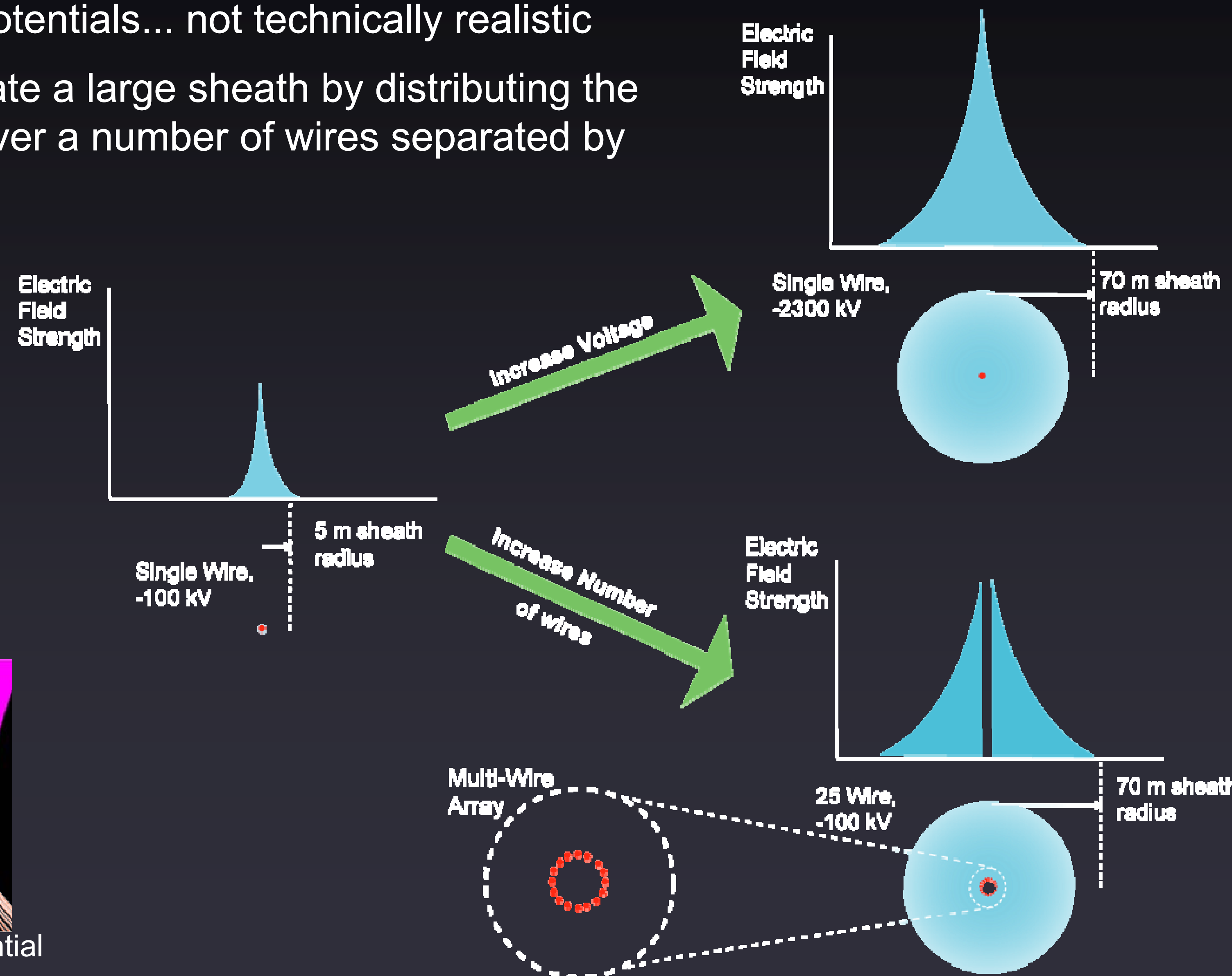
$$N_{sats} = C_1 \left[\ln \left(\frac{\rho_s}{d_w/2} \right) \right]^2 \frac{1}{\rho_s^5}$$

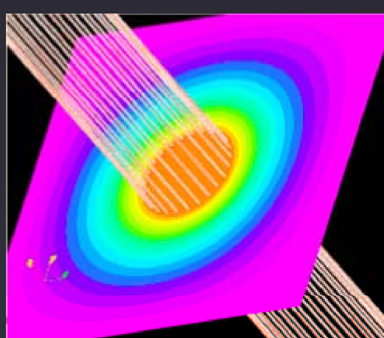
where C_1 is a constant

- Remediation effectiveness is STRONGLY dependent upon sheath size
- Net result: Single-wire tether structure sheath size is insufficient to enable remediation with a reasonable number & length of ES structures

Multi-Wire Structure Increases Sheath Size

- Creating a sufficiently large sheath with a single wire requires megavolt potentials... not technically realistic
- Instead, we can create a large sheath by distributing the same total charge over a number of wires separated by several meters





Multi-Wire Electric Potential

ES Structure Power Requirements

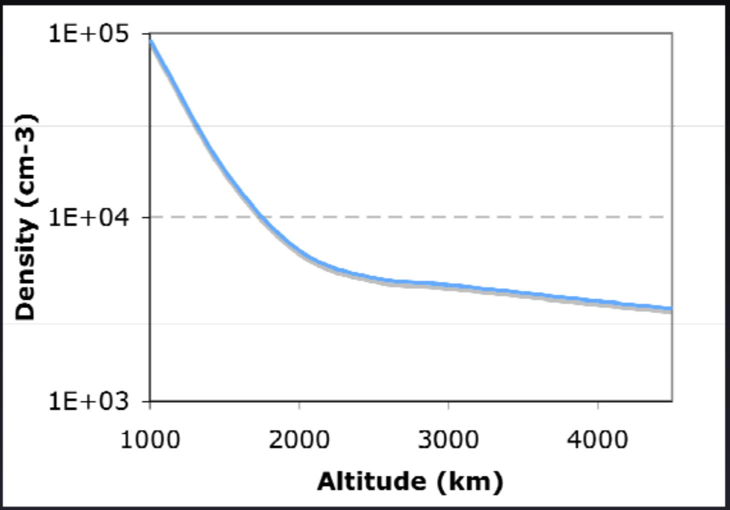
- System power requirements are driven by collection of current from plasmasphere (P = I V)
- Bias structure negatively so that it collects protons rather than more mobile electrons
- Amount of current collected is bounded by two models:
  - Orbit Motion Limit (OML)

$$I = n_{plasma} e 2 r_w L (1+Y)\sqrt{\frac{2e|V|}{m_i}}$$

  - Beam Collection Model

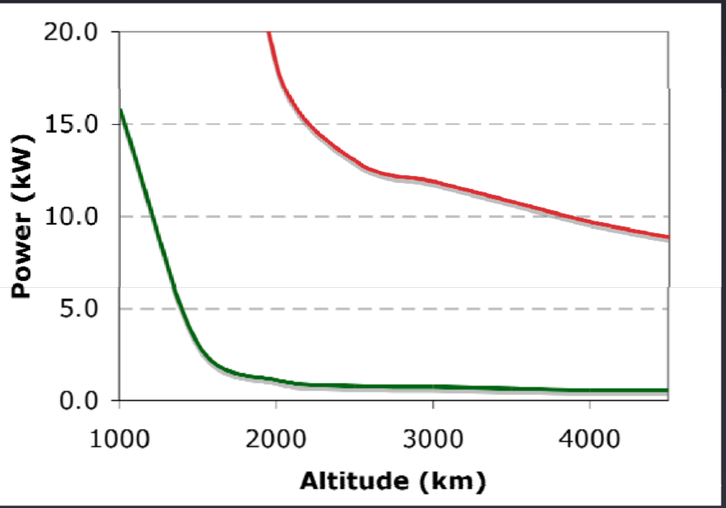
$$I_{\substack{multi-\\wire}} = 2\left[n\,L\,2r_w\left(1+Y_s\right)\left\{e\,n_\infty\sqrt{\frac{kT_i}{2\pi m_i}}\right\}\frac{\rho_s}{R}\sqrt{1+\frac{(1-F)}{F}}\right]$$

GCPM Ionospheric Plasma Density



Peak Power Requirement

100 kV, 100 km, 25 wire structure

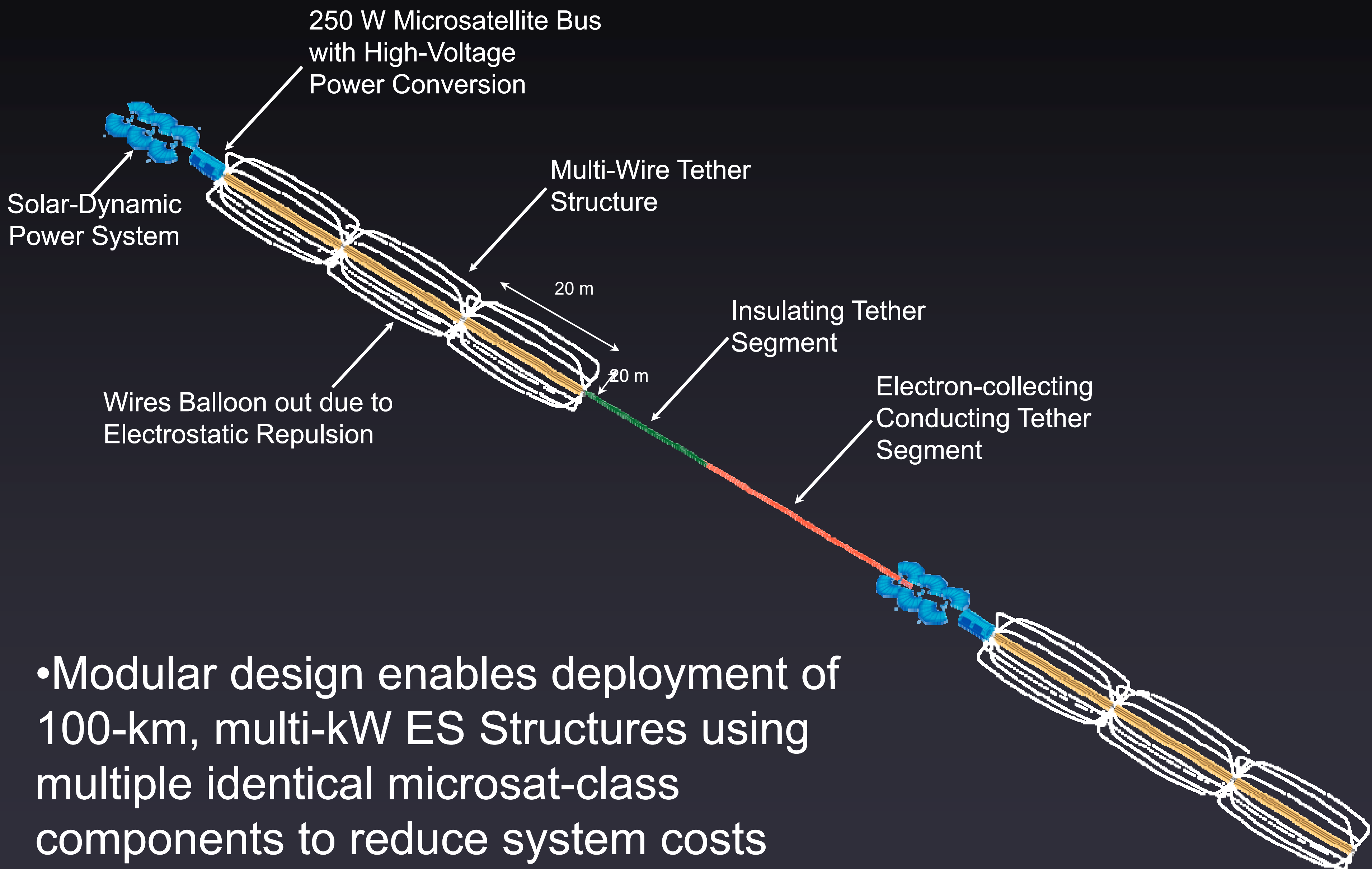


ES System Power Requirements Are

ES Remediation System Architecture

- System Architecture:
  - Each ES Tether Structure:
    - 100 km long tether structure composed of 25 wires in a 20-meter diameter cylinder
    - -100 kV bias
    - Power supply: 2 kW (best case) -12 kW (worst case) per tether
  - 25 ES Tether Structures in equatorial orbit
    - 15 in 2000 x 4400 km orbits to cover inner belt (1.3<L<1.7)
    - 10 in 3000 x 4000 km orbits to act as ‘fence’ to catch particles diffusing in from outer belt
    - ES Structures within 1.3<L<1.7 94% of the time

Modular ES System Architecture

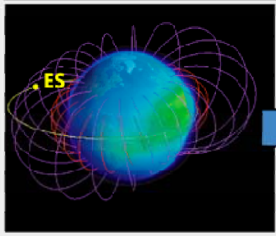


- Modular design enables deployment of 100-km, multi-kW ES Structures using multiple identical microsat-class components to reduce system costs

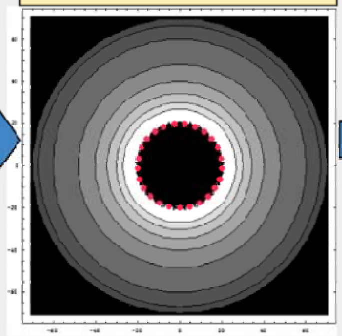
Remediation Simulation Tool

Electrostatic Scattering Science Module

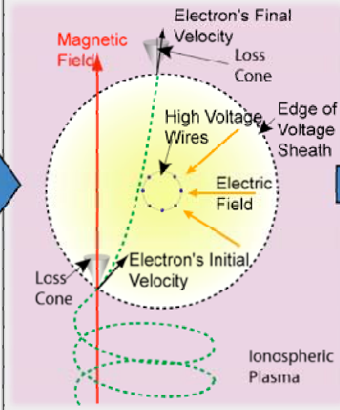
Local Ionospheric Conditions and ES System Design



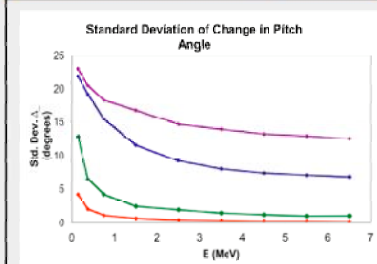
Calculate Electrostatic Structure's Plasma Sheath Potential



Calculate Electron Scattering Statistics
• Monte Carlo Trajectory Simulation



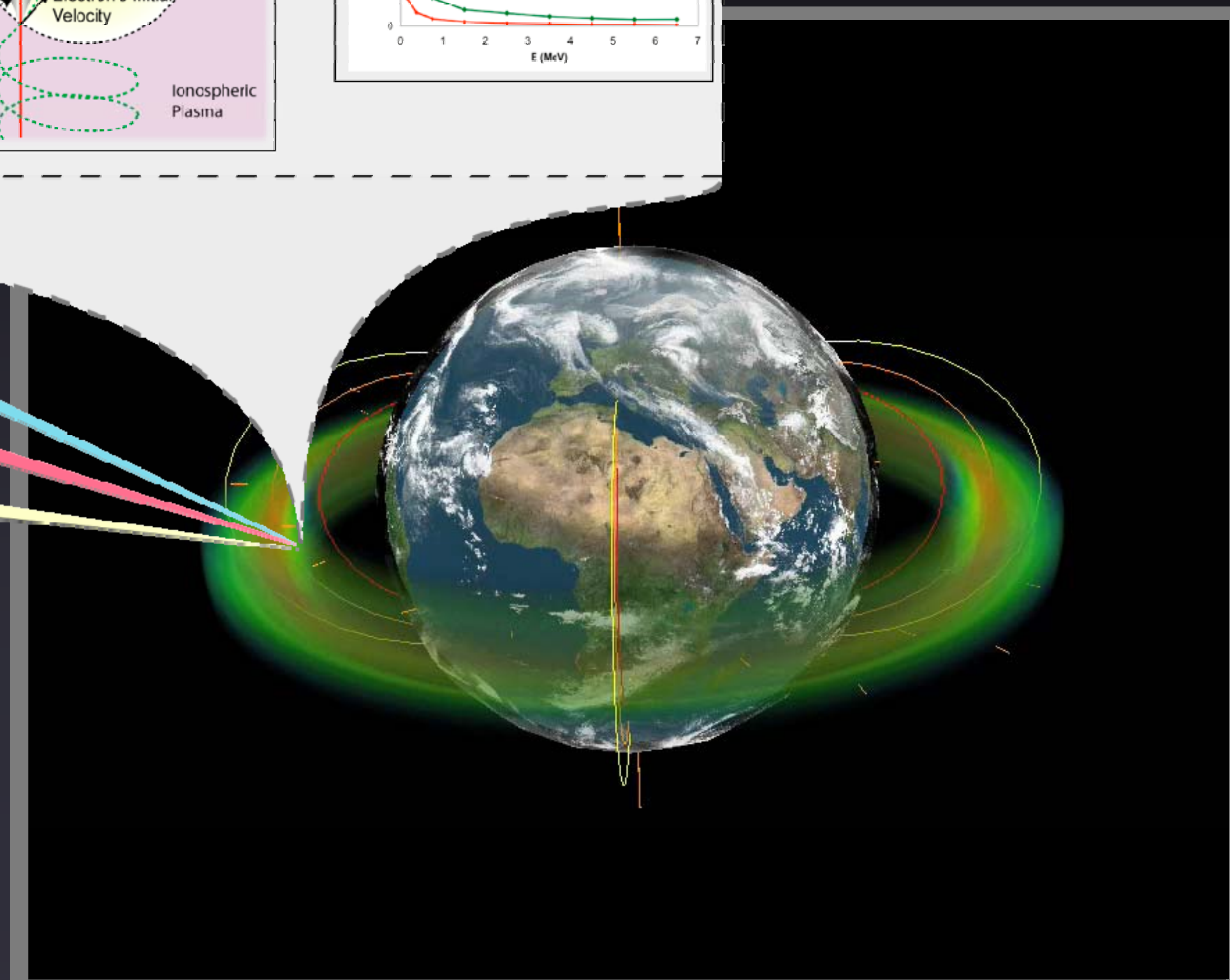
Statistical Description of Energetic Electron Scattering



Remediation System Orbit Tracking

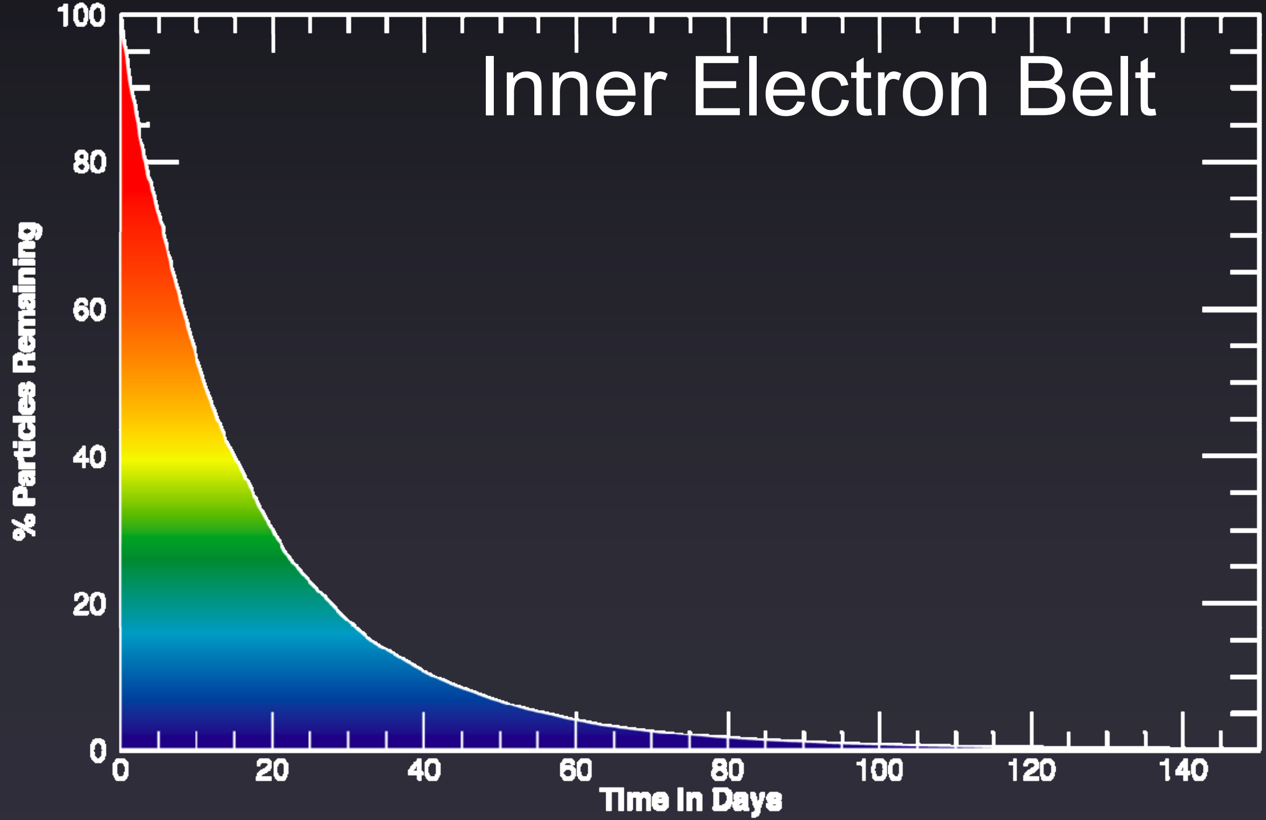
ES System Induced Precipitation
- Calculate Local Particle Fluxes
- Calcuate Pitch Angle Scattering
- Calculate Induced Precipitated Flux

Natural Sources & Sinks
- Radial Diffusion
- Precipitation (Coulomb, Whistler)



Remediation Simulation: Solar Quiet Period

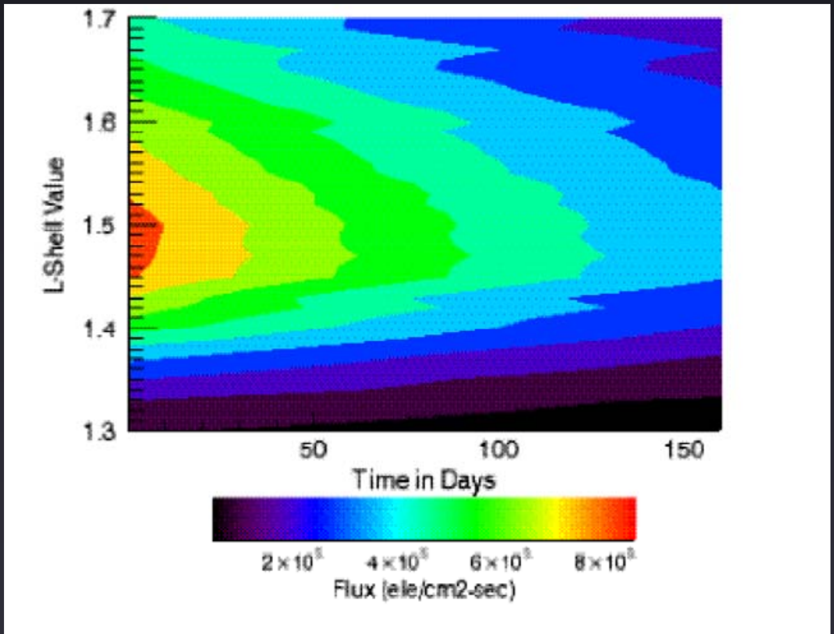
- Simulated remediation of ‘nominal’ radiation belt flux using 25 Electrostatic Structures
  - No sources or sinks



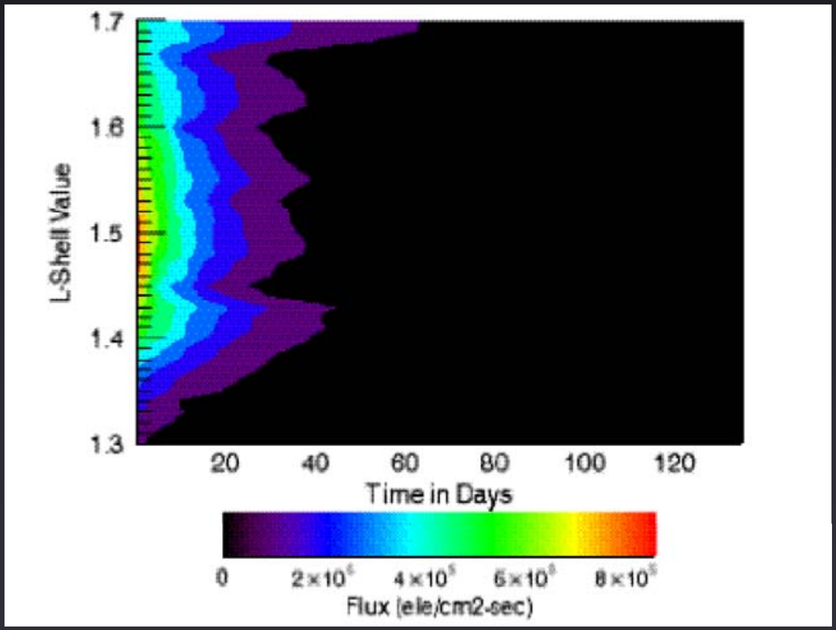
Remediation Simulation: Solar Quiet Period

Inner Electron Belt

No Remediation
Natural Sources & Losses Only

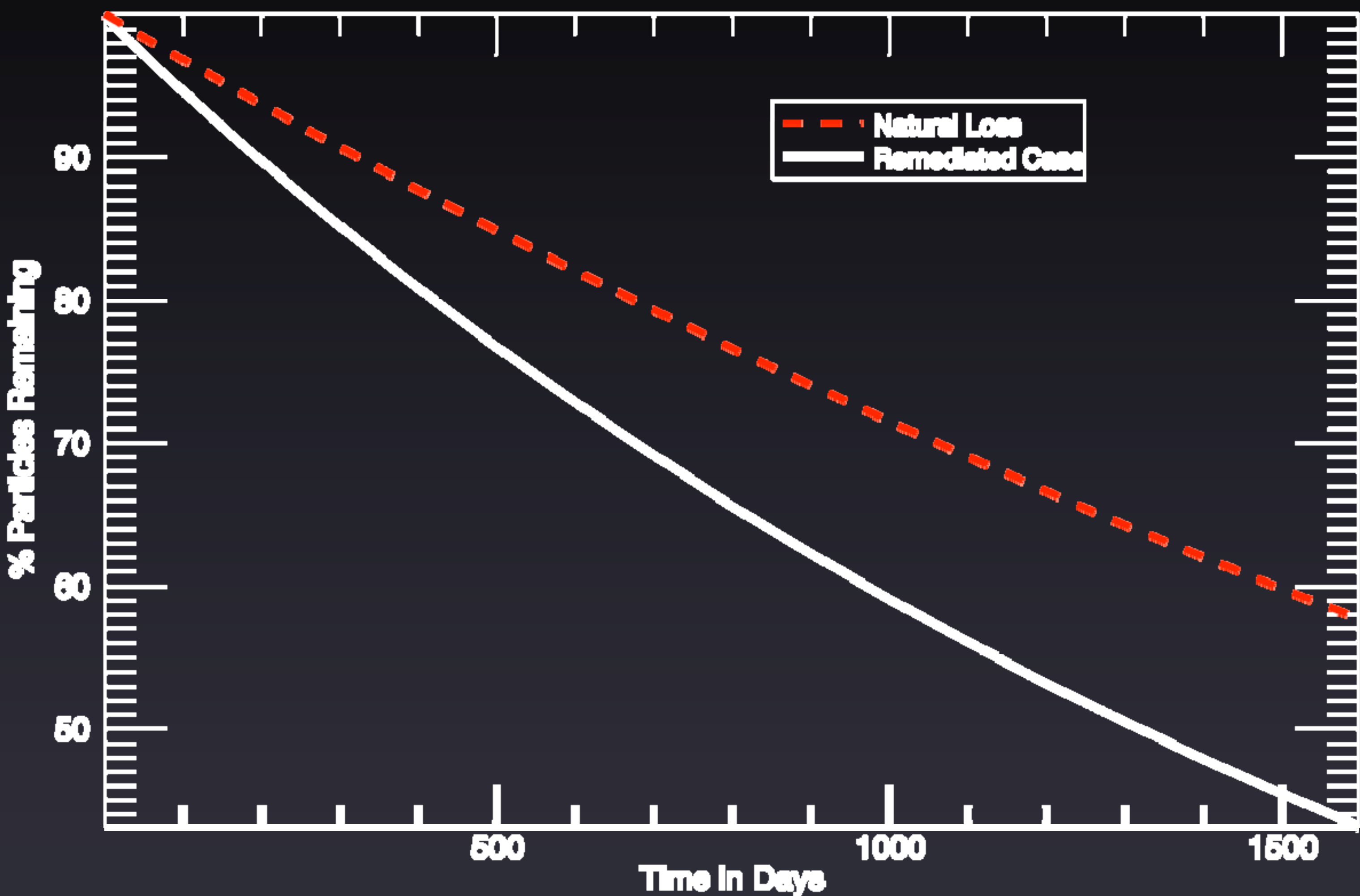


With Remediation
Natural Sources & Losses



Remediation Simulation: Solar Quiet Period

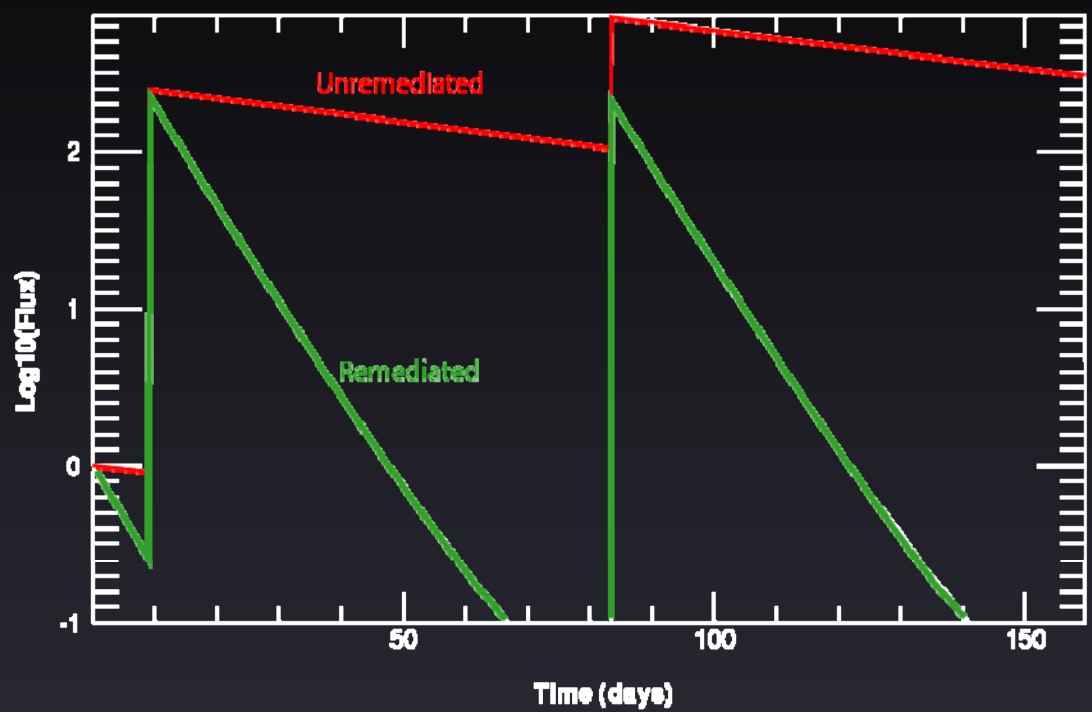
Proton Flux:

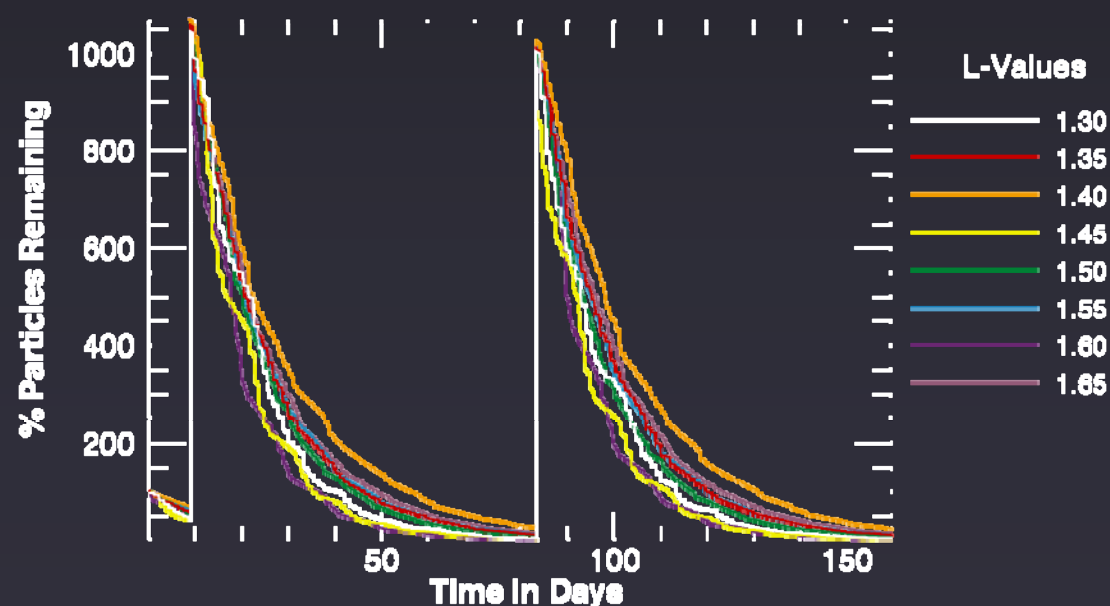


- More ES systems required to dramatically lower proton fluxes

Remediation Simulation: Solar Active Period

- Two large solar storms inject radiation flux 10X 'nominal' levels 75 days apart
- Model includes natural sources and sinks
  - Radial diffusion
  - Precipitation due to collision and wave scattering
- ES Remediation System reduces radiation flux by two orders of magnitude within 50 days
- Reduces net dosage by 95%

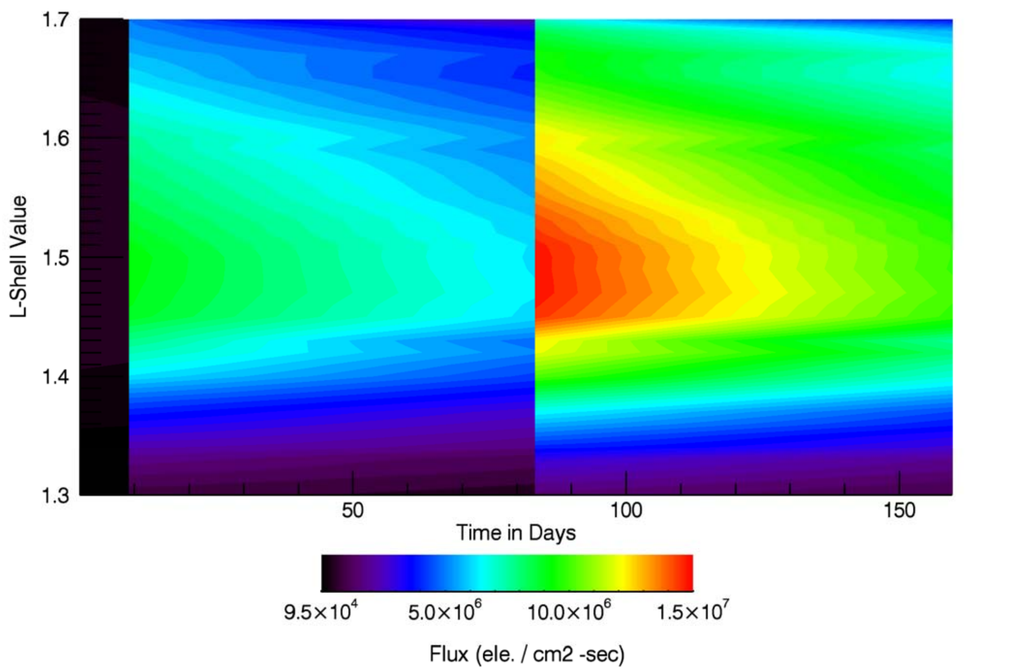




Remediation Simulation: Solar Active Period

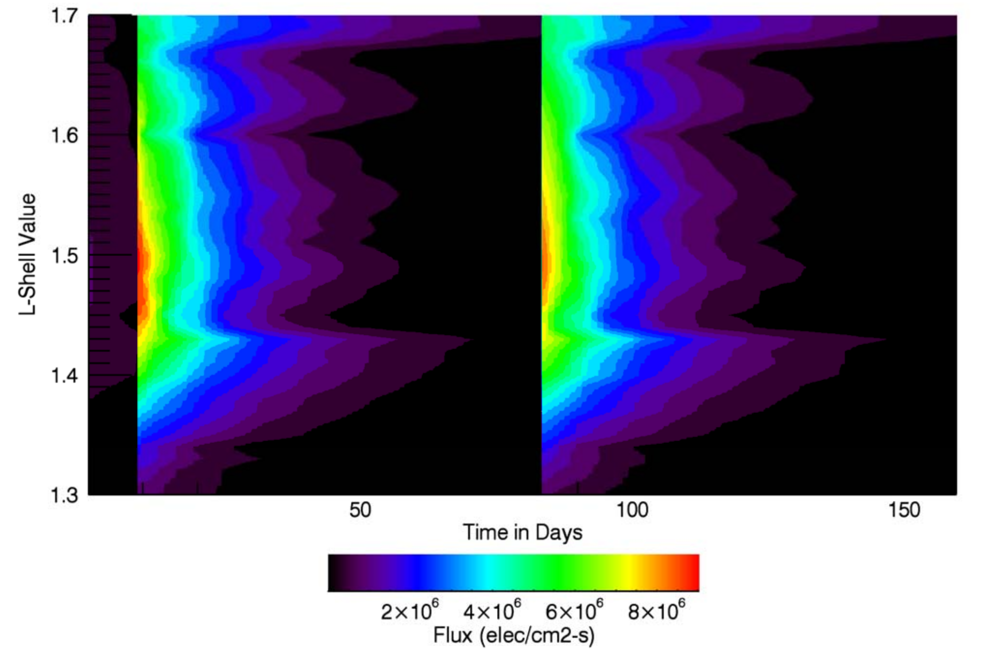
Particle Injection

Particle Injection



Particle Injection

Particle Injection



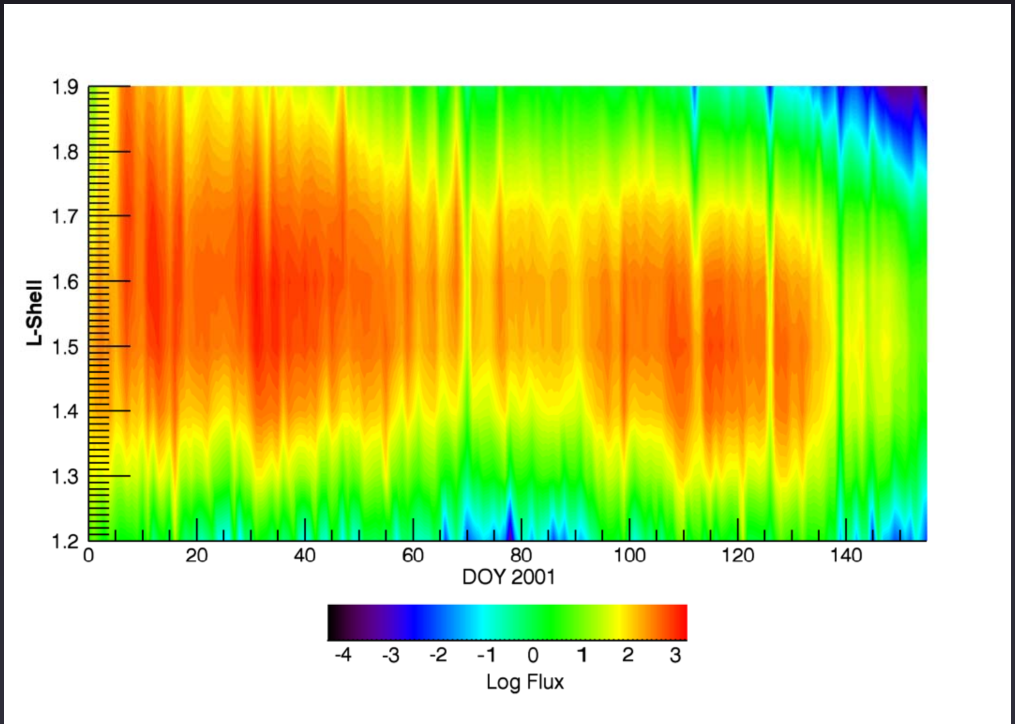
No Remediation
Natural Sources & Losses Only

With Remediation
Natural Sources & Losses

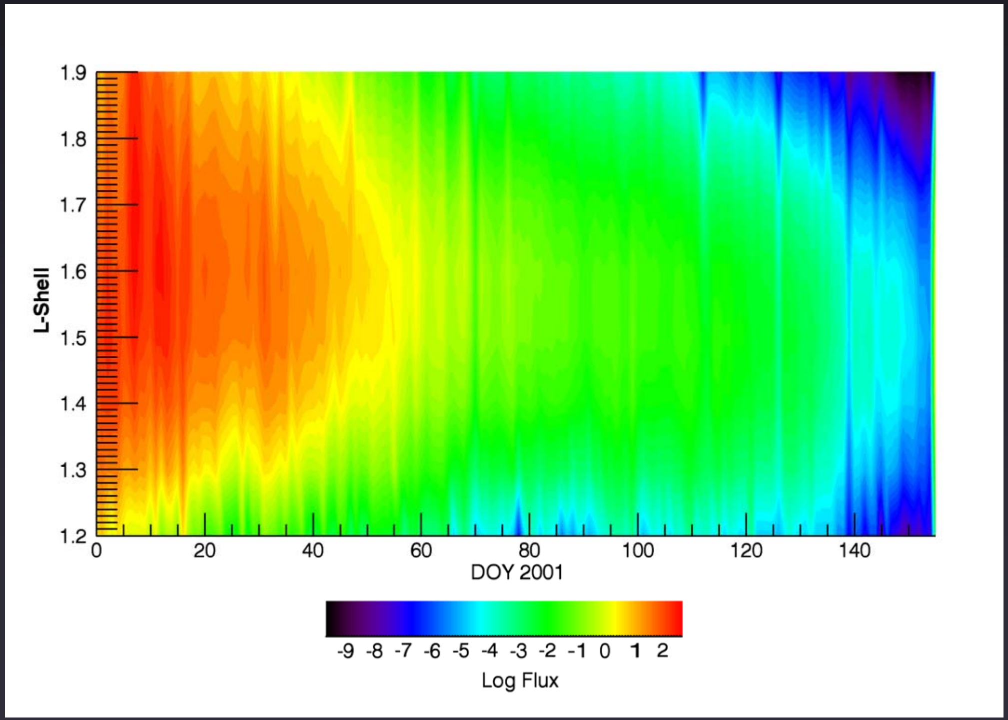
Solar Storm Remediation Simulation

- SAMPEX data for Spring 2001 Solar Storm

No Remediation
Natural Sources & Losses Only

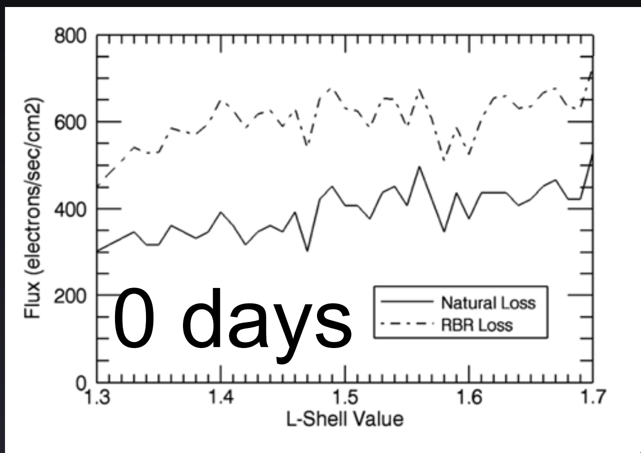


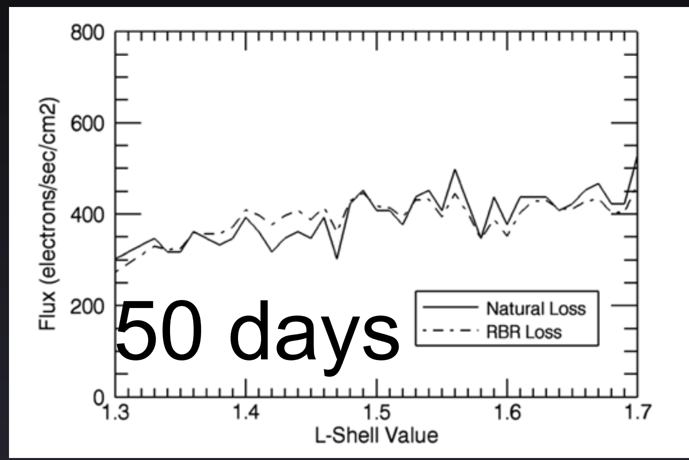
With Remediation
Natural Sources & Losses

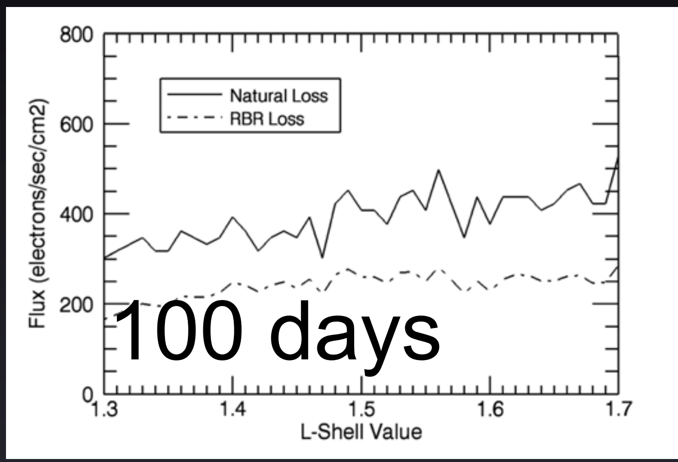


Potential Side-Effects

- Enhancement of precipitating electron flux:







- Effects on Ozone Layer
  - Slight reduction in ozone densities only during period of enhanced precipitating flux - short-lived effect only
- RF Disruption
  - Comparable to mild “B1” solar flare -- very minimal effects

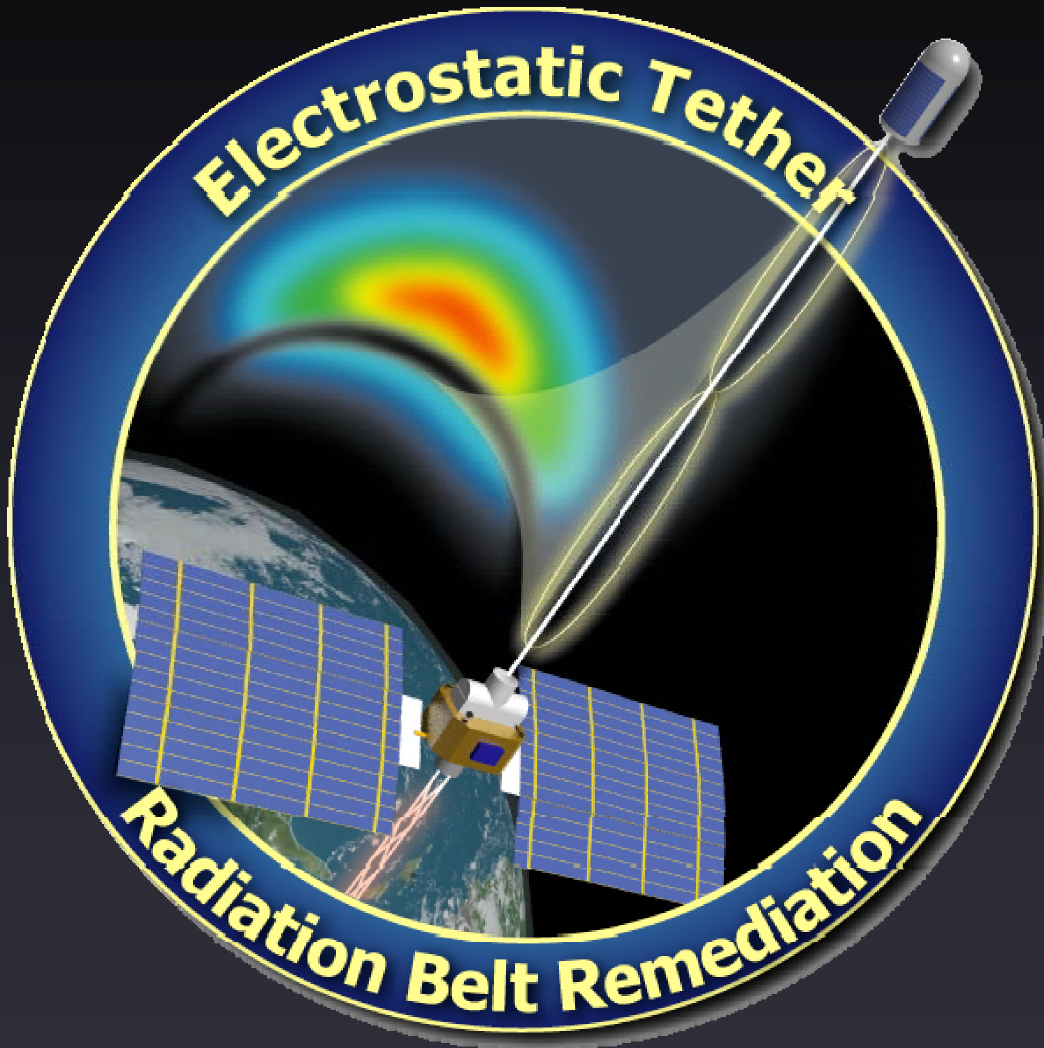
Side Effects are Minimal and Short-Lived

Technology Tall Tentpoles

- Models for size & structure of multi-wire structure high-voltage plasma sheath need to be validated
- Models for current collection by multi-wire structure need validation
- High-Voltage & High-Power:
  - Tether & S/C materials technology to enable -100 kV tether bias without arcing
  - Need high voltage power system for ≥100-kV, ≥1 kW
  - HV spacecraft engineering
  - HV system design to keep spacecraft bus near local potential
- Radiation tolerant power generation & avionics

Conclusions

- Analytical and detailed numerical simulations indicate remediation of Electron & Proton fluxes in Inner Belt using electrostatic structures IS Feasible
- Number of ES systems and total power required is reasonable
  - ~25 100-km, 100 kV satellites, ~2 kW each
- Remediation of Inner Belt would reduce exposure of people & spacecraft in LEO to trapped radiation by >95%
  - Extends lifetime of spacecraft
  - Reduce risks & costs of long-duration manned spaceflight
  - Protection against cosmic rays and solar event fluxes still needed
- Further investigation of high-voltage plasma sheath physics needed to validate ES Radiation Belt Remediation feasibility



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