Module 1 – Natural Space Environment

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Academy for Radiation Effects and Survivability
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Space Environment

Space Weather

Big solar storm hitting Earth

By Amanda Barnett, CNN

3 minute read · Updated 11:13 AM EDT, Tue September 16, 2014

Solar storms can destroy satellites with ease — a space weather expert explains the science

Solar storm set to strike Earth today: From Internet disruption to GPS signals, what to expect?

Here comes the sun and, for satellite operators, it's not alright

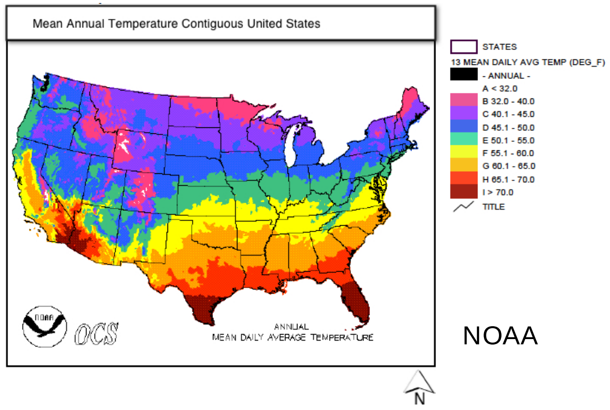
Geomagnetic storm likely to impact Earth through Tuesday: What we know

- Over last 60+ years, we've increased our understanding of the space environment and made strides in building resilient systems: The space radiation environment is not as scary as it once was
- But…
  - The space environment is still hazardous; it can have significant impacts, even outside of "big events"

Understanding and preparing for the space environment is more important than ever

Climate vs Weather

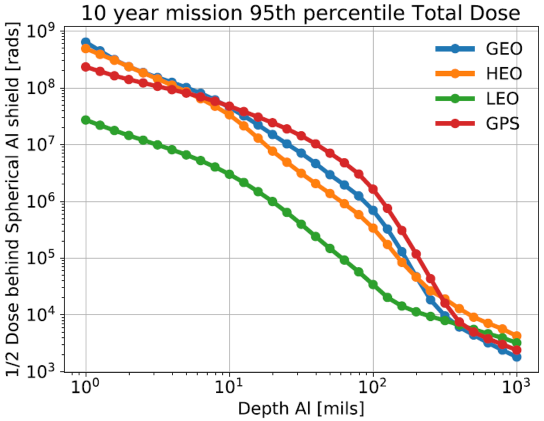
- Climate: What is the average winter temperature? What's the average precipitation?



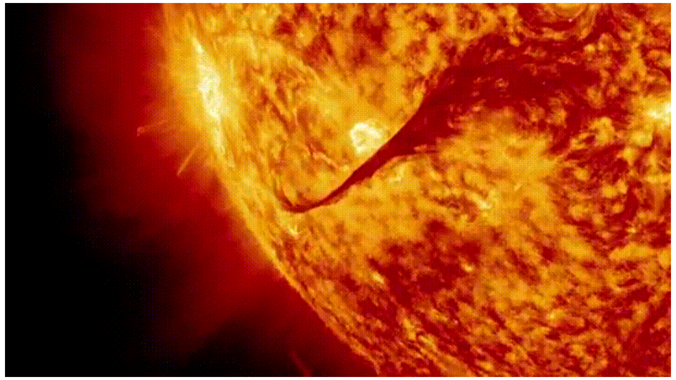
NOAA

- Weather: Will it rain on Tuesday? Will this hurricane impact my area?

- Space Environment Climatology: For a chosen orbit, how severe is the radiation environment? In a 10 year mission, what impacts can I expect from the space environment?

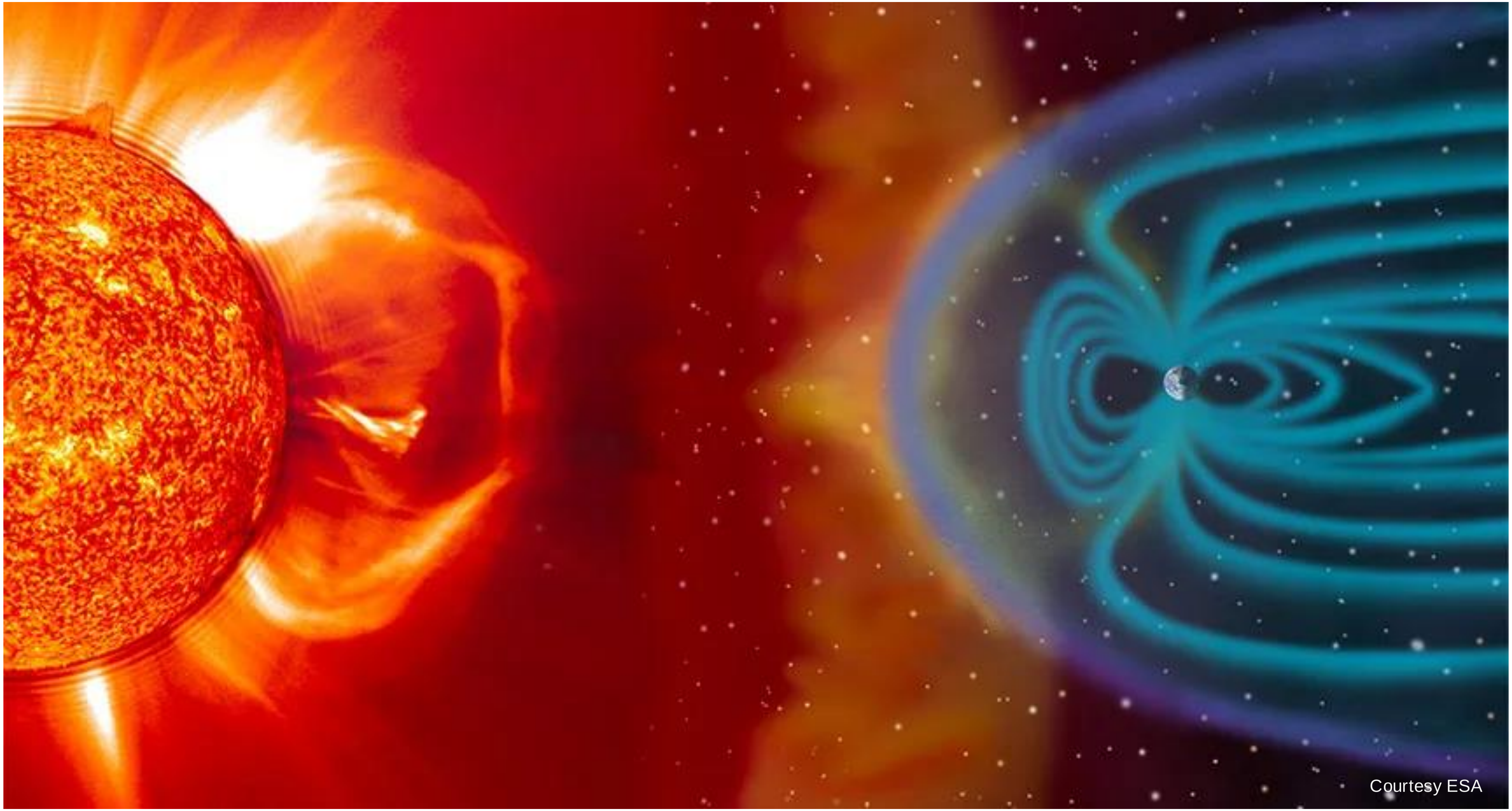


- Space Weather: Will there be a geomagnetic storm on Friday?



NASA

Local Space Environment

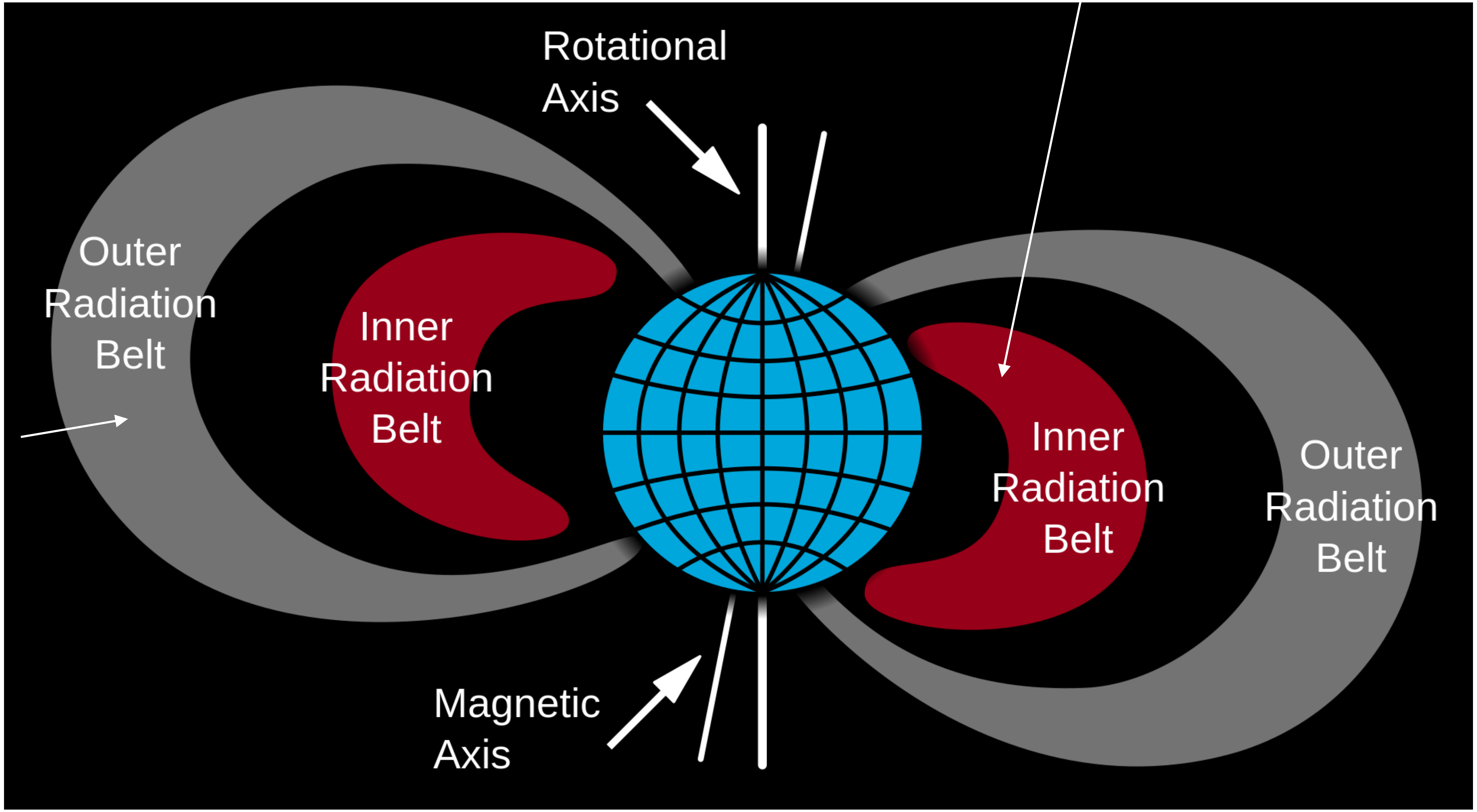


Radiation Belts

Trapped

Energetic Protons
Very stable over time

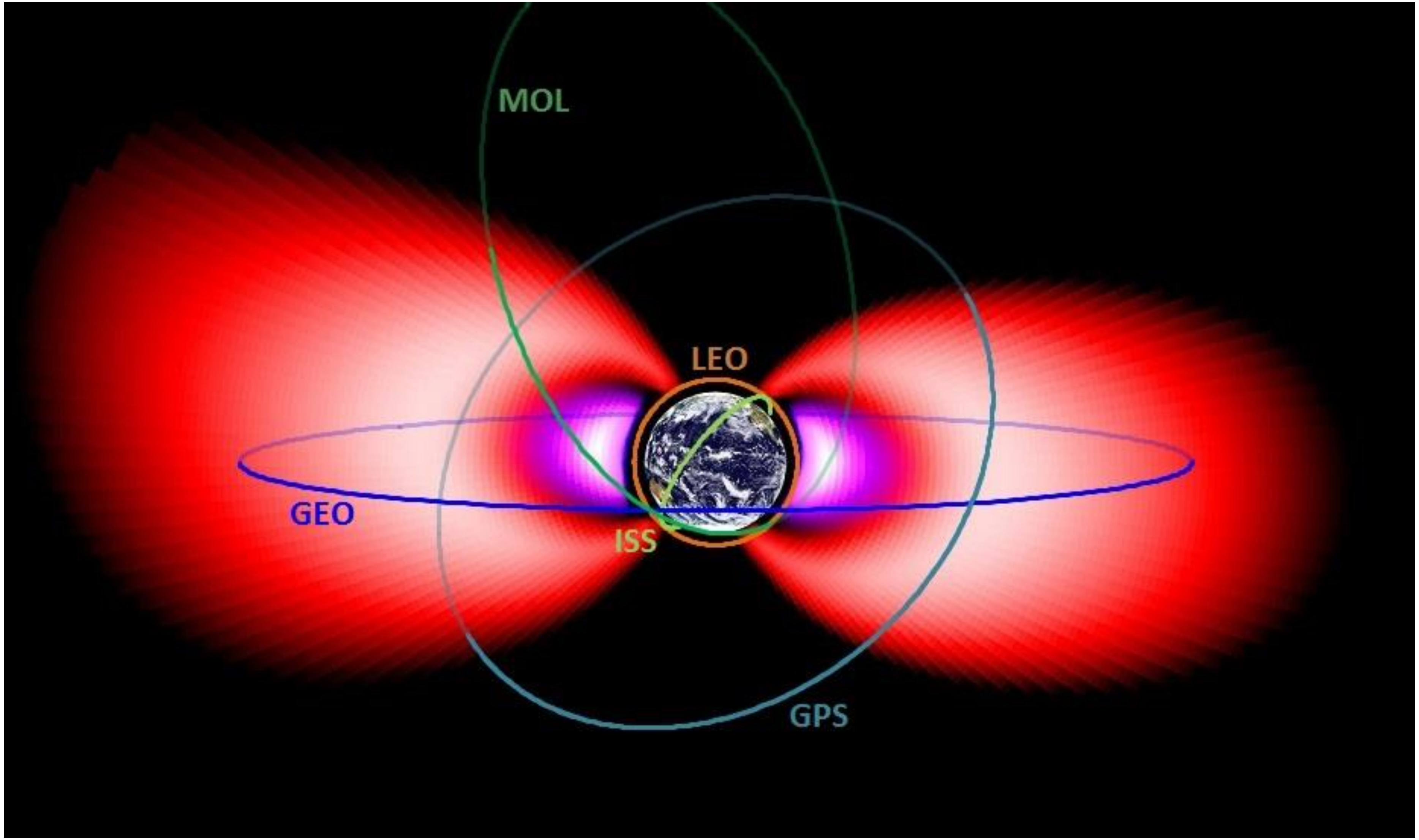
Energetic Electrons
Dynamic: varies on weekly/monthly timescales



Courtesy Wikipedia

Different Orbits will sample different parts of the trapped environment

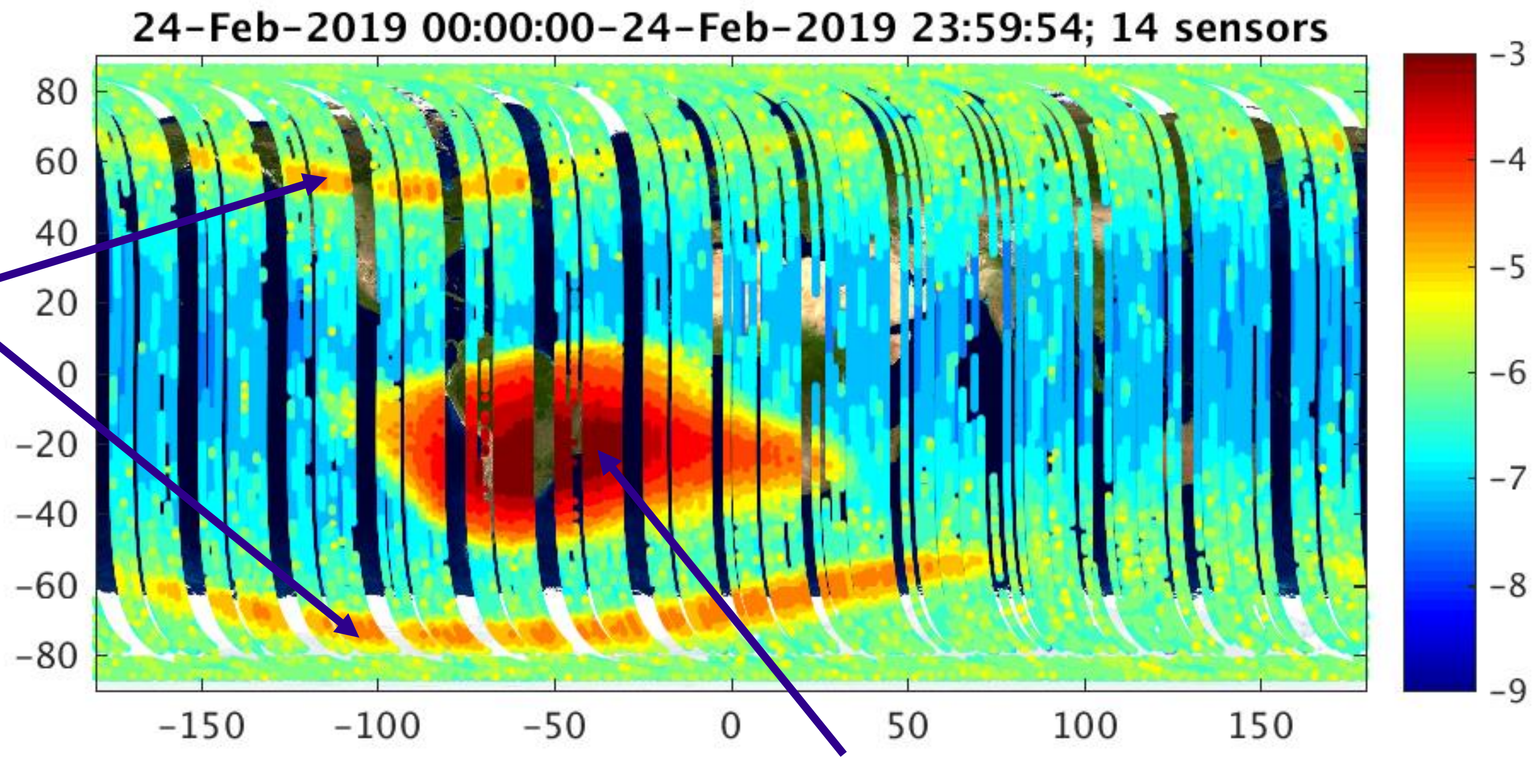
Radiation Belts



Space Environment

View from Low Earth Orbit (LEO)

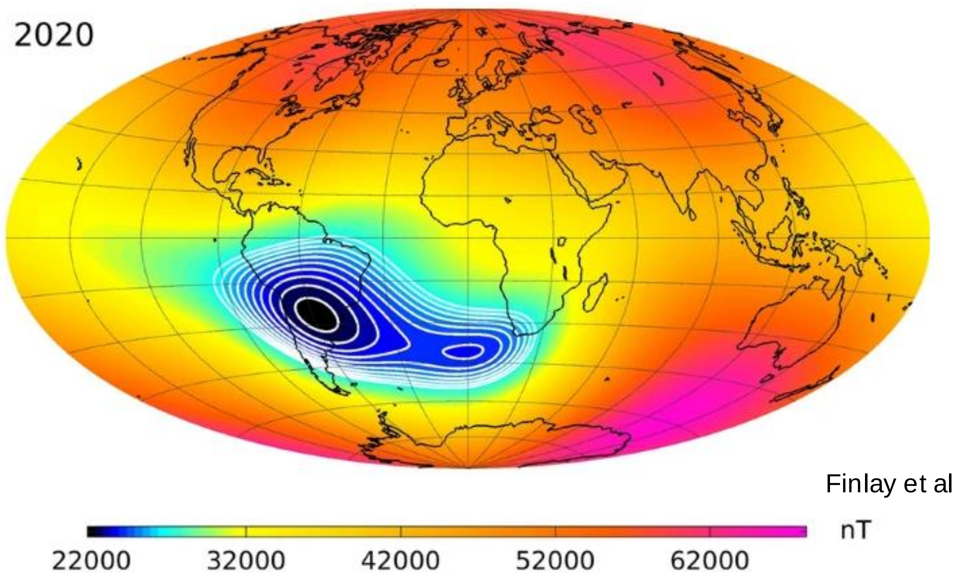
Outer Belt



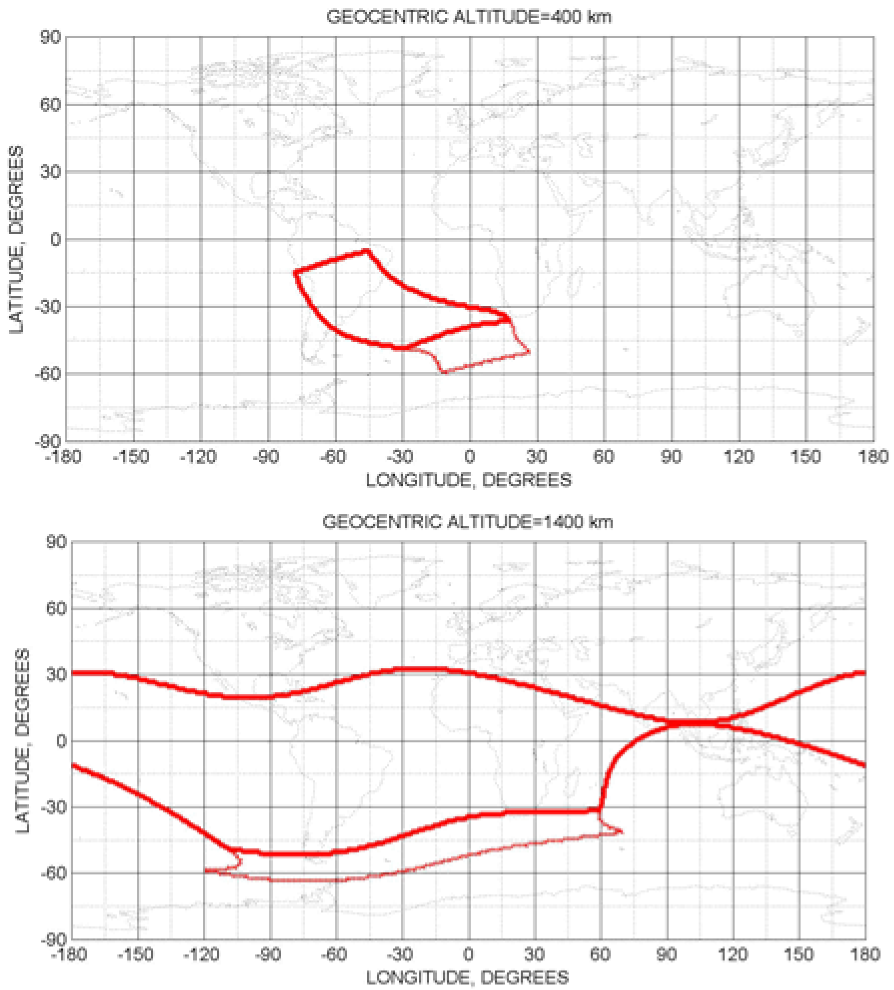
Inner Belt (South Atlantic Anomaly)

Data from Aerospace sensors on IRDIUM-Next (REACH)

South Atlantic Anomaly



Finlay et al. (2020)

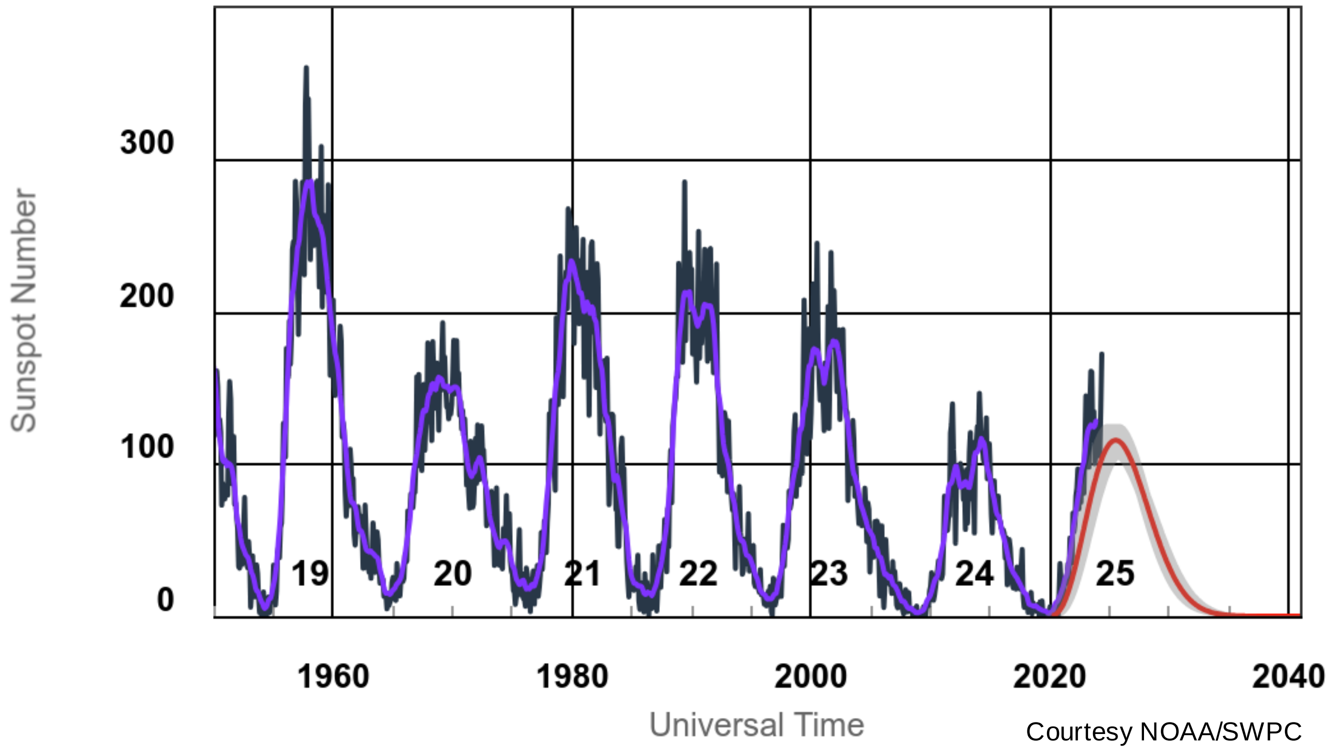


The size of the SAA varies with altitude

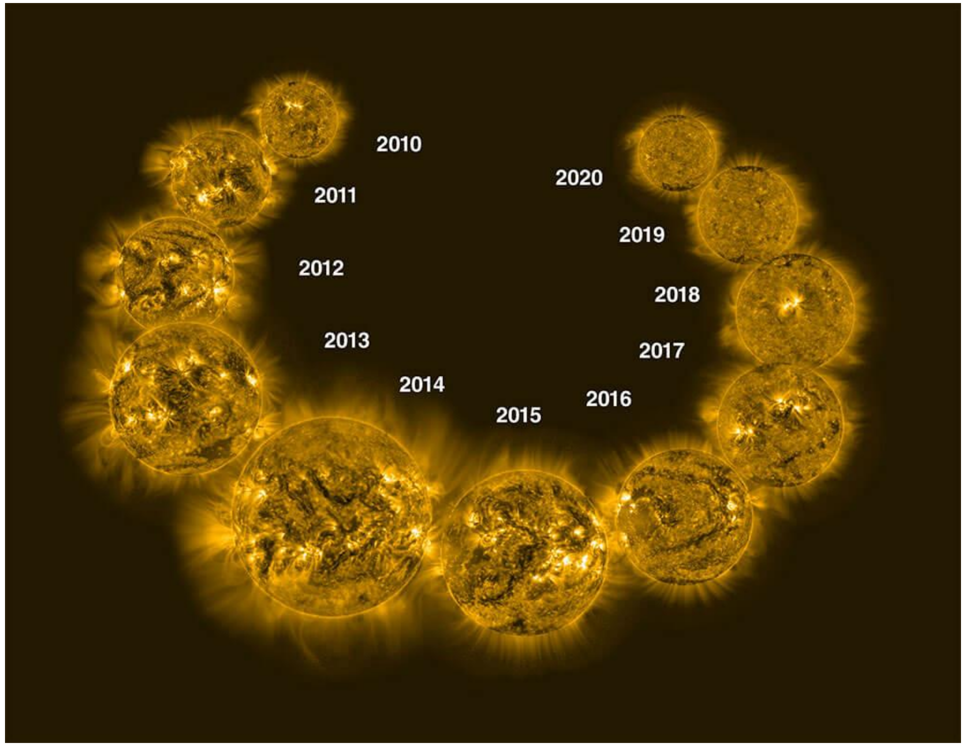
- The SAA is a region near South America where the magnetic field is weaker, allowing inner belt protons to reach down to lower altitudes
- Due to asymmetry of rotational and magnetic axes

The inner belt in the SAA is the biggest hazard for LEO vehicles

Solar Cycle



Courtesy NOAA/SWPC



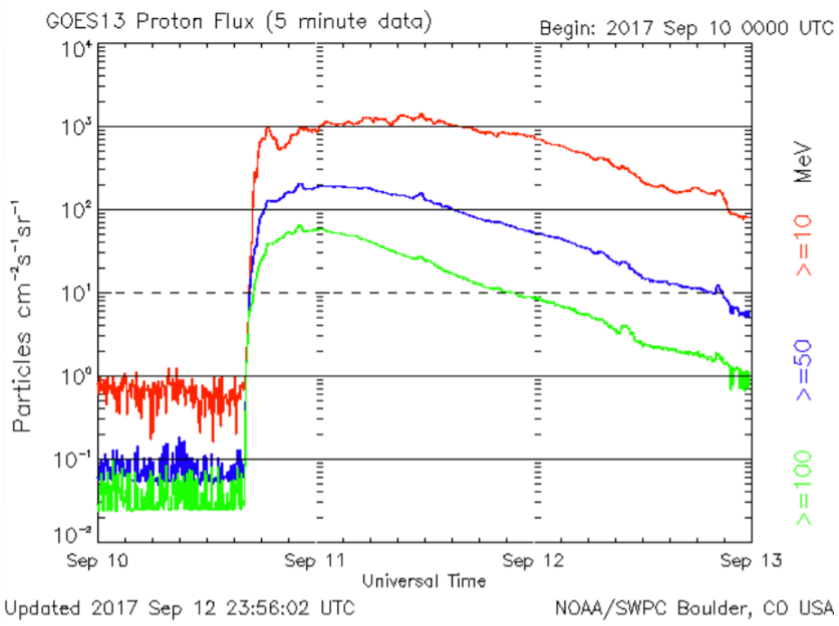
Courtesy NASA

- Solar activity varies on an 11-year cycle
- More space weather activity near solar maximum, but space environment can be hazardous at any part of the cycle

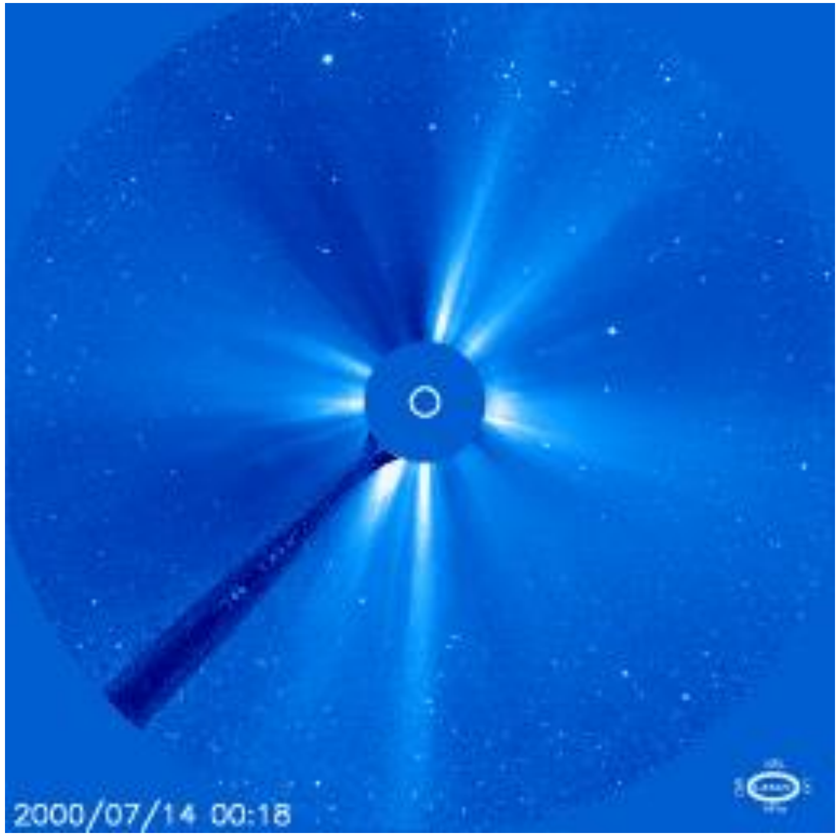
Solar Particle Events

- Solar energetic particles originate at the Sun and reach into the magnetosphere at high altitudes and high latitudes
- Energetic Protons, heavy Ions with energies up to 100s of MeV (depending on size of event)

Observations from GEO



Courtesy NOAA/SWPC

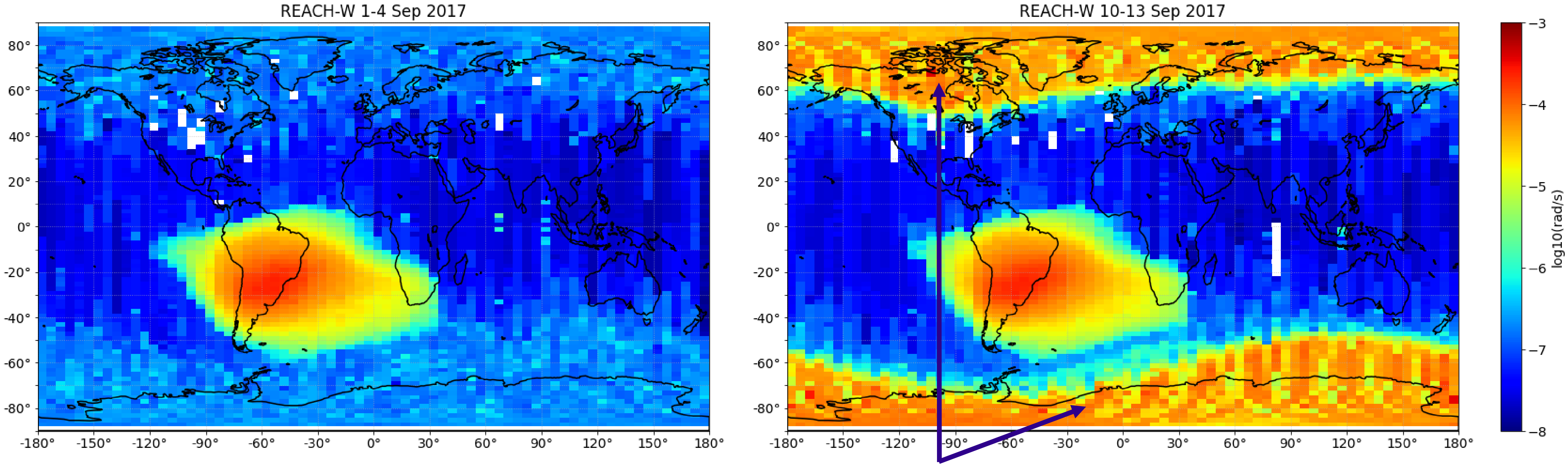


Courtesy ESA/**NASA SOHO**

Solar Particle Events in LEO

Sep 2017 Event

Large SPE in September 2017,
observed by REACH (>12 MeV protons)



Highly enhanced proton fluxes over the poles
Rapid increase, persist for a few days

Galactic Cosmic Rays

- Highly energetic (**very high energy** up to > 1 TeV) originating from outside the solar system
- Mostly protons, some heavy ions

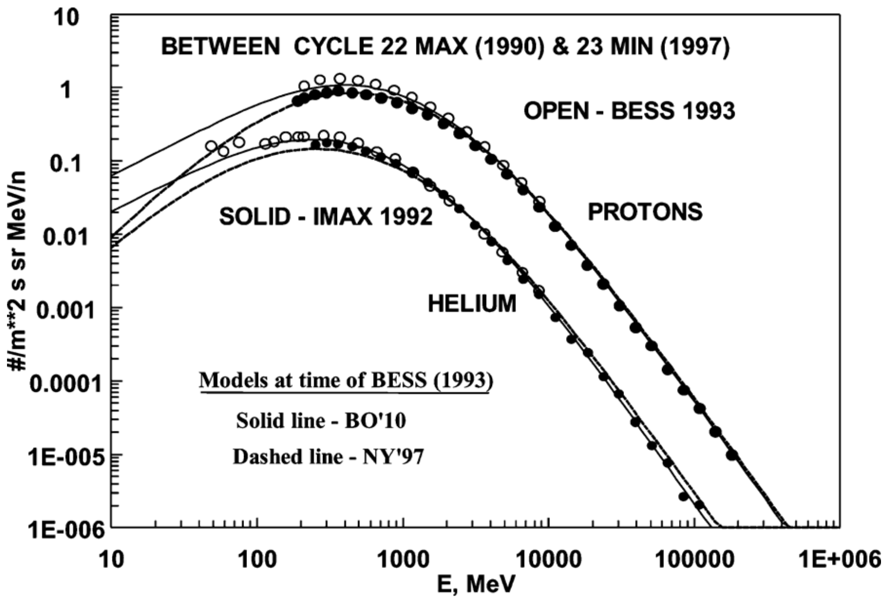


Figure from Xapsos et al., IEEE, TNS, 2013

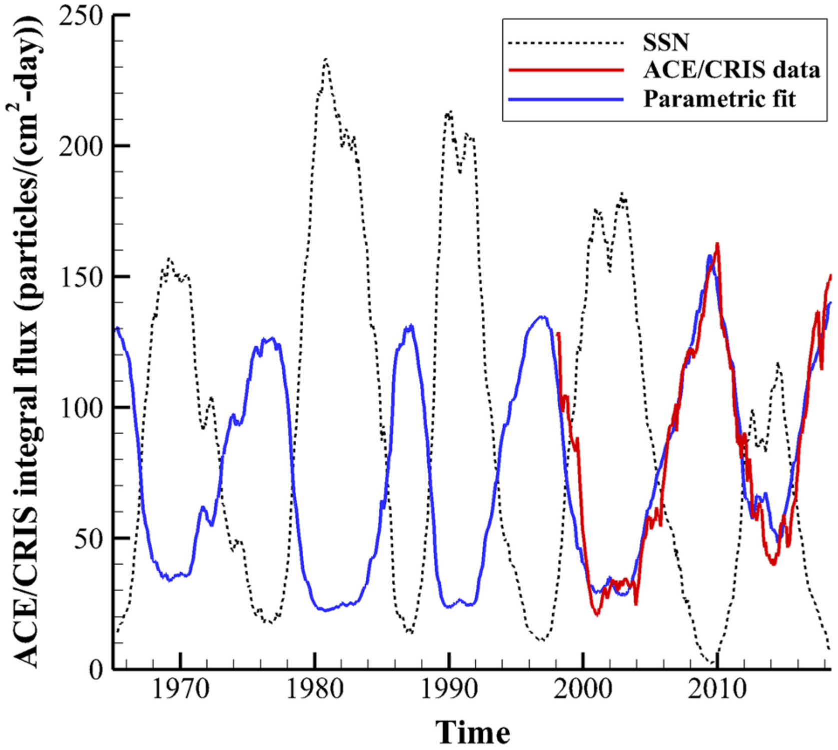
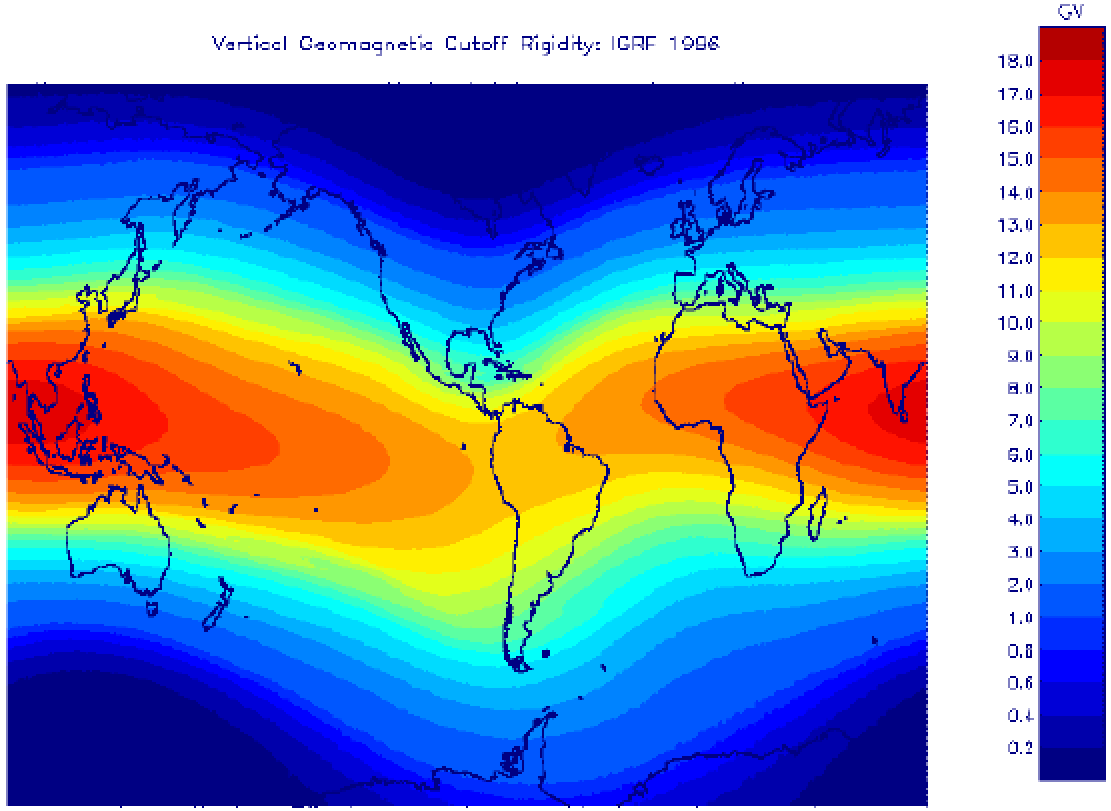


Figure from Slaba and Whitman, Space Weather, 2020

GCR flux is highest during solar minimum, but can be observed at low levels any time during the solar cycle

Geomagnetic Cutoffs

- The Earth's magnetic field offers some shielding from SEPs and GCRs
- Close to the Earth (at low latitudes in LEO), there is a cutoff where only particles of a certain energy will be able to reach
- During a solar particle event, this cutoff can be dynamic



Mertens et al. (2012)

Reference Orbit Environments

Reference Orbits

Orbit		Description
Equatorial LEO	Trapped Protons, GCR	Passes through SAA multiple times a day, minimal exposure to GCR
High LEO	Trapped Protons, SPE, GCR	Passes through SAA multiple times a day, exposure to solar protons, GCR over the poles
HEO	Trapped Protons, SPE, GCR	Passes through inner belt near perigee, exposed to SPE and GCR
GEO	SPE, GCR	No trapped proton environment, exposed to SPE and GCR

Other Orbits

Space hazard	Spacecraft charging		Single-event effects			Total radiation dose		Surface degradation		Plasma interference with communications	
Specific cause	Surface	Internal	Cosmic rays	Trapped radiation	Solar particle	Trapped radiation	Solar particle	Ion sputtering	O^+ erosion	Scintillation	Wave refraction
LEO <60°	Not applicable	Not applicable	Relevant	Important	Not applicable	Important	Relevant	Relevant	Important	Important	Important
LEO >60°	Relevant	Not applicable	Important	Important	Important	Important	Relevant	Relevant	Important	Important	Important
MEO	Important	Important	Important	Important	Important	Important	Important	Relevant	Not applicable	Important	Important
GPS	Important	Important	Important	Not applicable	Important	Important	Important	Relevant	Not applicable	Important	Important
GTO	Important	Important	Important	Important	Important	Important	Important	Relevant	Not applicable	Important	Important
GEO	Important	Important	Important	Not applicable	Important	Important	Important	Relevant	Not applicable	Important	Important
HEO	Important	Important	Important	Important	Important	Important	Important	Relevant	Not applicable	Important	Important
Cislunar Inter-planetary	Not applicable	Not applicable	Important	Not applicable	Important	Not applicable	Important	Relevant	Not applicable	Relevant	Relevant

Important Relevant Not applicable

Space environment hazards for typical orbits. Key: LEO <60°—low Earth orbit, less than 60 degrees inclination; LEO >60°—low Earth orbit, more than 60 degrees inclination; MEO—medium Earth orbit; GPS—Global Positioning System satellite orbit; GTO—geosynchronous transfer orbit; GEO—geosynchronous orbit; HEO—highly elliptical orbit; O^+—atomic oxygen.

Mazur, J.E, Aerospace Crosslink, 2003

Space Environment Tools

Best Practices TOR

- Aerospace TOR in 2021 to describe the “right way” to develop a natural environment specification
- Includes background, description of latest models for different aspects of the space environment
- Includes worked examples for LEO, GPS, GEO and HEO

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TOR-2022-00016

Best Practices for Generating Space Environment Specifications with Modern Tools

December 31, 2021

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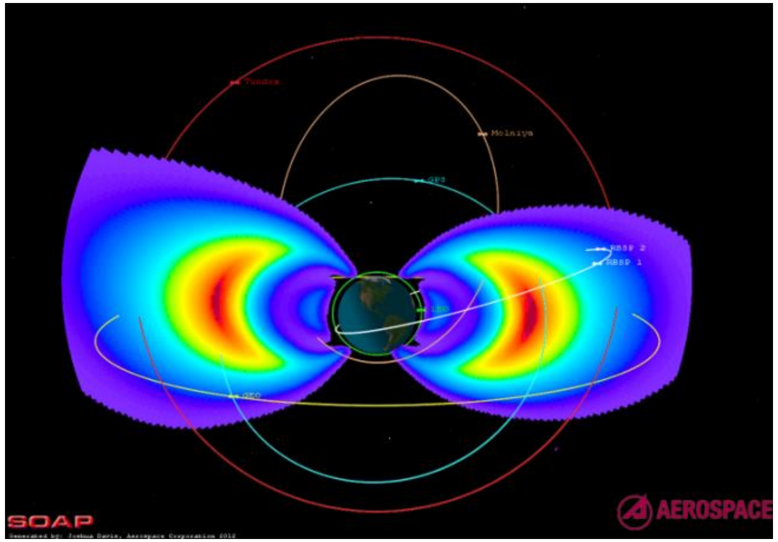
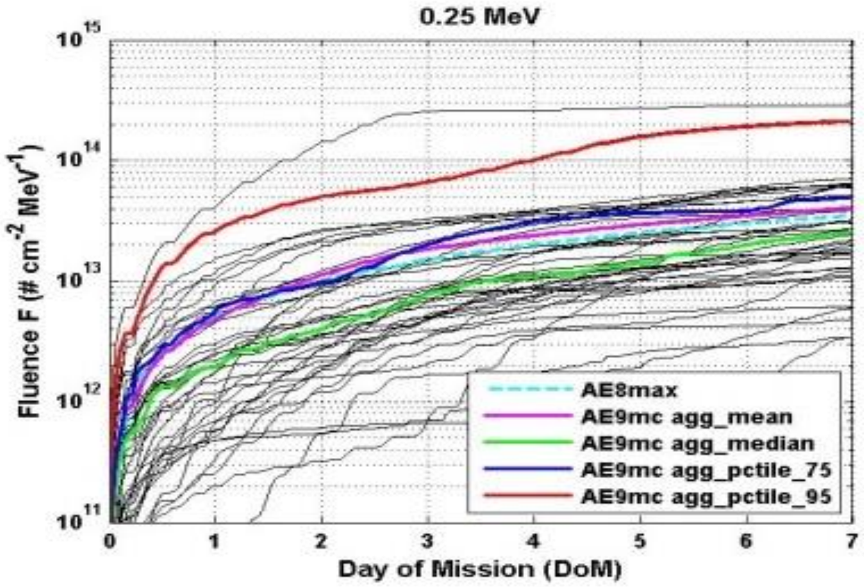
AE9AP9-IRENE

- IRENE-AE9/AP9 specifies the natural trapped radiation environment for satellite design and mission planning
  - IRENE = International Radiation Environment Near Earth
  - Lead by AFRL/RVBX
  - It improves on legacy models to meet modern design community needs:
    - Uses 45 long duration, high quality data sets
    - Full energy and spatial coverage—plasma added
    - Introduces data-based uncertainties and statistics for design margins (e.g., 95th percentile)
    - Dynamic scenarios provide worst case estimates for hazards (e.g., SEEs)
    - Architecture supports routine updates, maintainability, third party applications
- V1.00 released in 2012, V1.50 in Dec 2017
- V1.57 released in Oct 2022

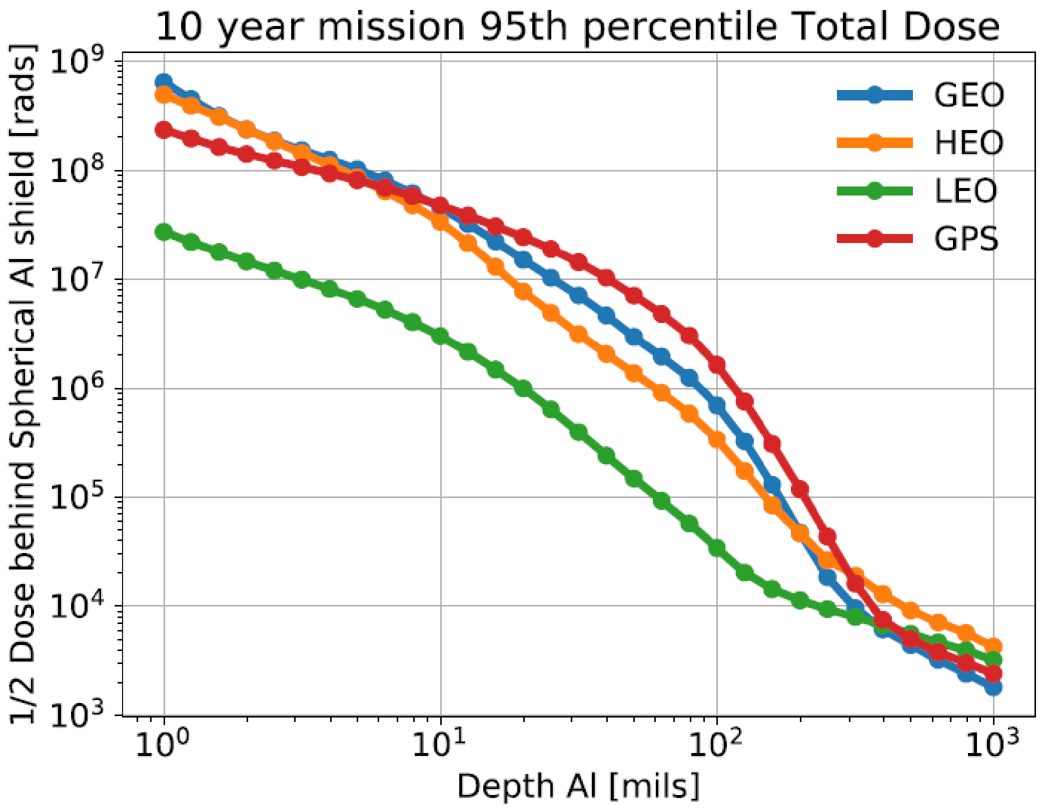




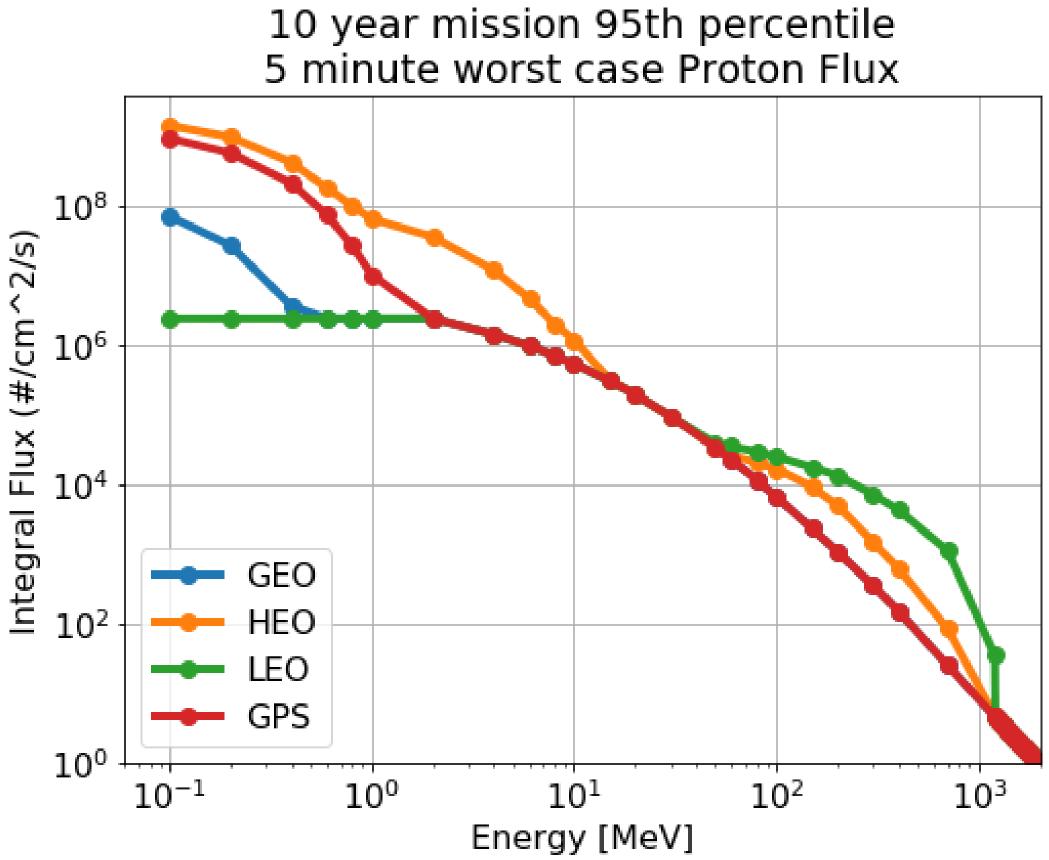
AE9/AP9-IRENE

Output Examples

- Whole mission quantities (perturbed mean/Monte Carlo)
  - Total Ionizing Dose
  - Proton Fluence
  - Electron Fluence

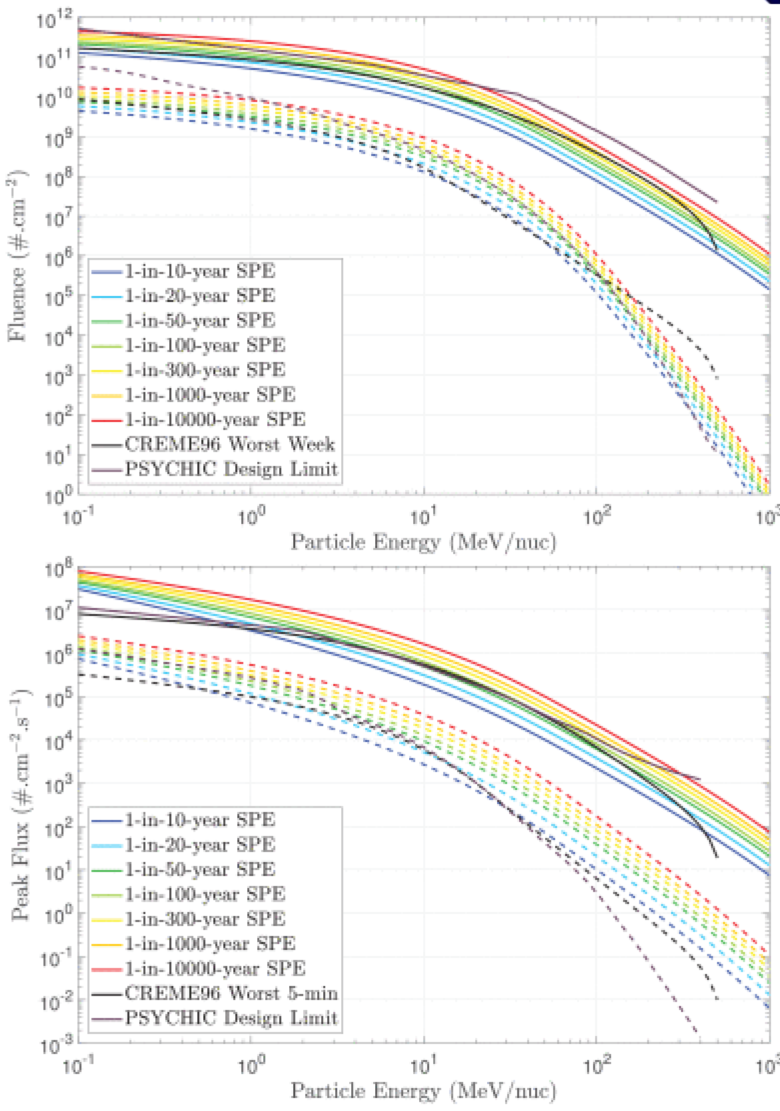


- Worst case quantities (Monte Carlo)
  - Worst case proton flux
  - Worst case electron flux



Solar Particle Models

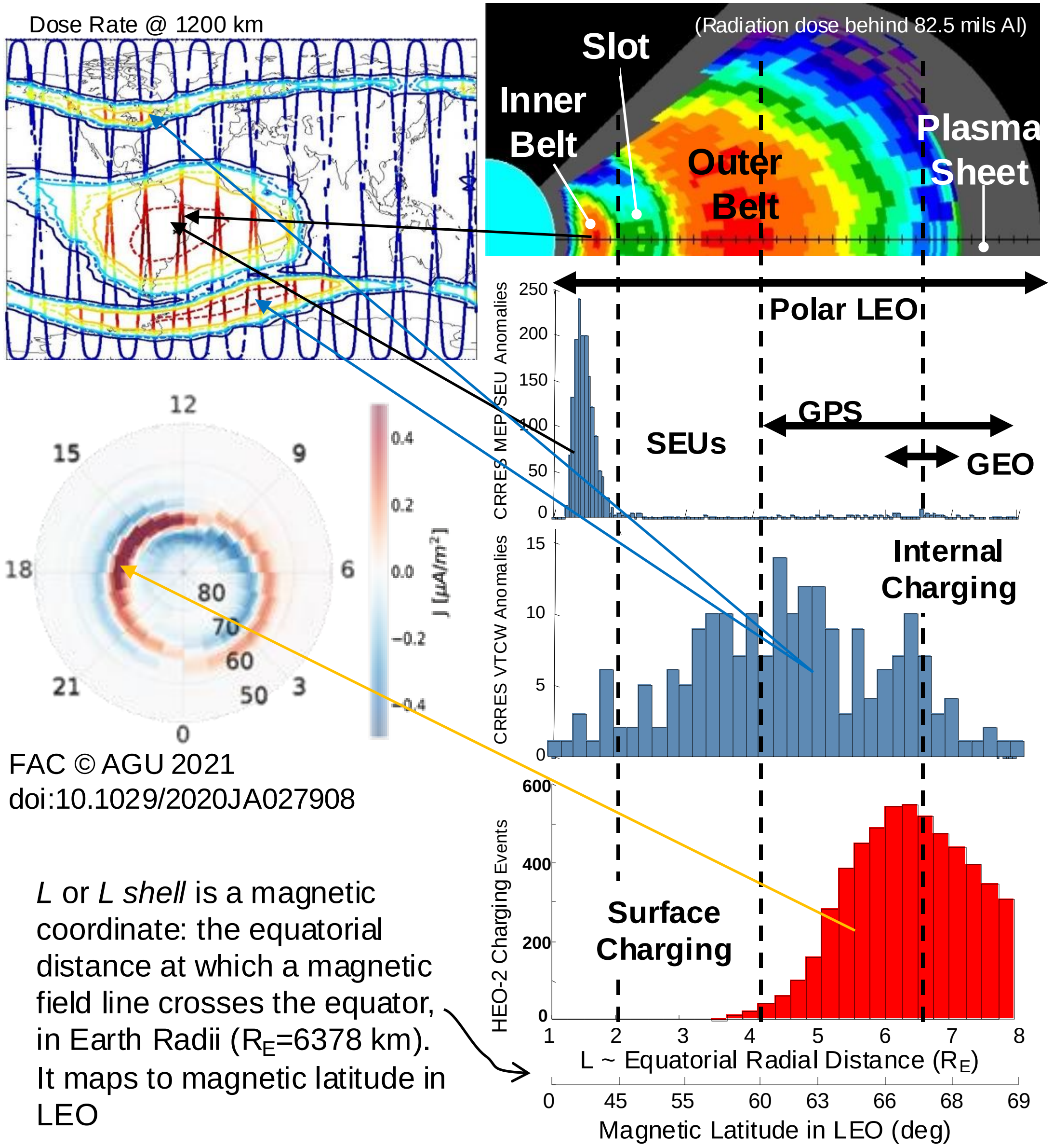
- 2 main quantities for specifying the solar particle environment (protons and heavy ions)
- SEP fluence: Over the course of N year mission, how much solar particle fluence can I expect to see (within confidence level)
  - Meant to quantify likely impact to spacecraft parts (in particular dose)
  - ESP/PSYCHIC, SAPPHIRE
- SEP worst case fluxes: Based on October 1989 event, worst 5-min, worst day, worst week
  - Quantify stressing scenario for spacecraft
  - CREME96, SAPPHIRE
- GCR fluxes: solar min vs solar max
  - CREME96



Jiggens et al (2018)

Why do we care?

Space Environment Hazards to Space Vehicles



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doi:10.1029/2020JA027908

L or *L shell* is a magnetic coordinate: the equatorial distance at which a magnetic field line crosses the equator, in Earth Radii (R_E=6378 km). It maps to magnetic latitude in LEO

- **Event Total Dose** Damage accumulates over entire mission through ionizing and non-ionizing mechanisms. Caused by solar particle events (SEP) and transient slot or outer belts. Not an issue in LEO due to dominance of stable South Atlantic Anomaly (inner belt)

- **Single Event Effects (SEE)** tend to occur in the inner (proton) belt and at higher L shells when a solar particle event is in progress. Galactic Cosmic Rays (GCR) also cause SEE at all orbits.

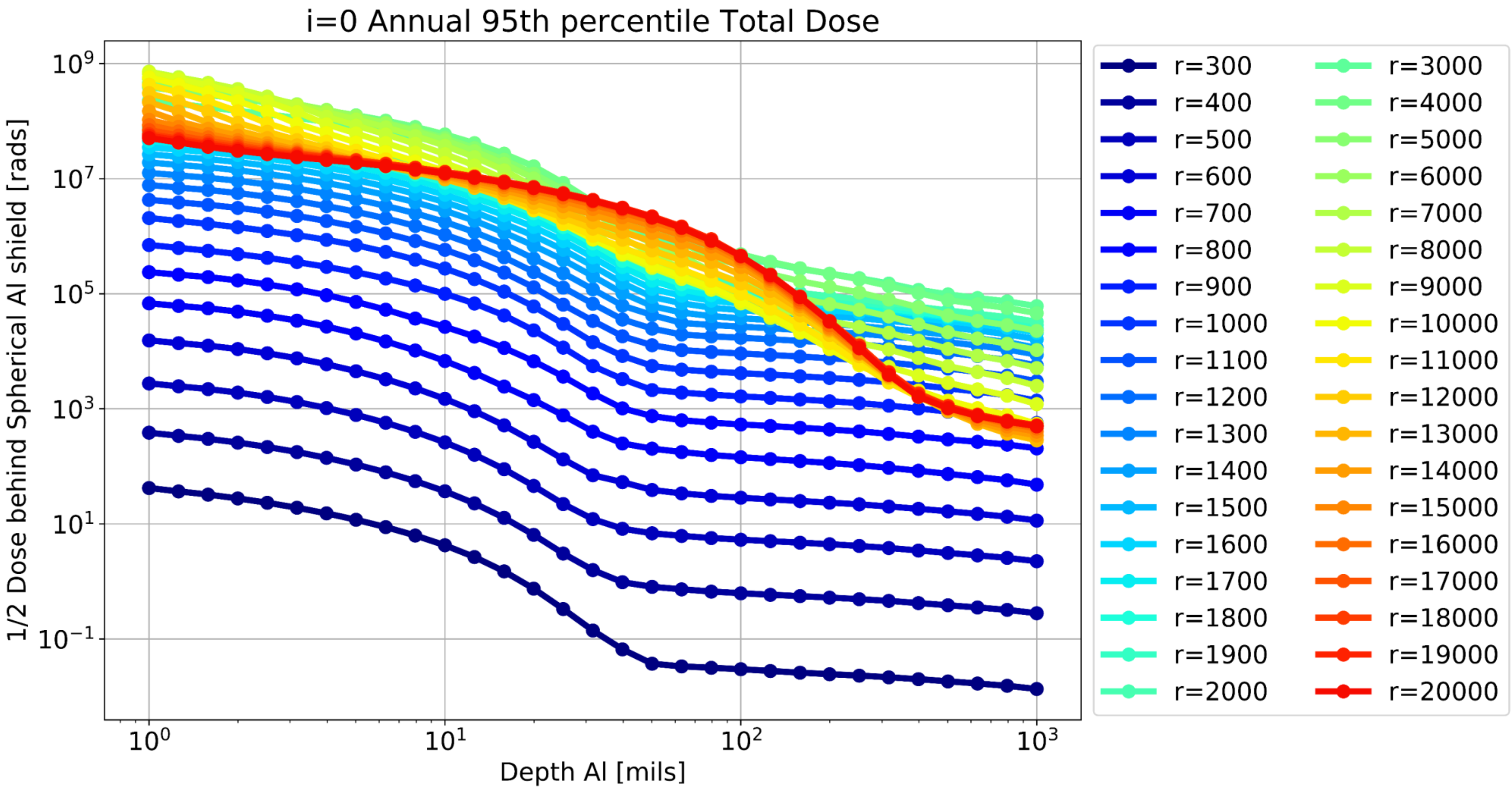
- **Internal electrostatic discharges (ESD)** occur over a broad range of L values corresponding to the outer belt, when penetrating electron fluxes are high over extended periods of time.

- **Surface ESD** tends to occur when the spacecraft or surface potential is elevated: at 2000-0800 local time in the plasma sheet and in regions of intense field-aligned currents, e.g., auroral arcs.

Summary

- The near-Earth space environment is driven by the sun, and which hazards a satellite will face is dependent on its orbit regime
- Trapped Environment
  - Outer Belt Electrons, Inner Belt Protons
  - Example model: AE9/AP9-IRENE
- Solar/GCR
  - Episodic events (SPE) or continuous low level fluxes (GCR)
  - Geomagnetic shielding for some orbits
  - Example model: ESP/PSYCHIC, SAPPHIRE, CREME96
- **The space environment can have significant impacts on satellite systems, both during large events and on a "Tuesday"**

Backup


i=0 Annual 95th percentile Total Dose
1/2 Dose behind Spherical Al shield [rads]
10^9
10^7
10^5
10^3
10^1
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10^0
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10^2
10^3
Depth Al [mils]
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r=400
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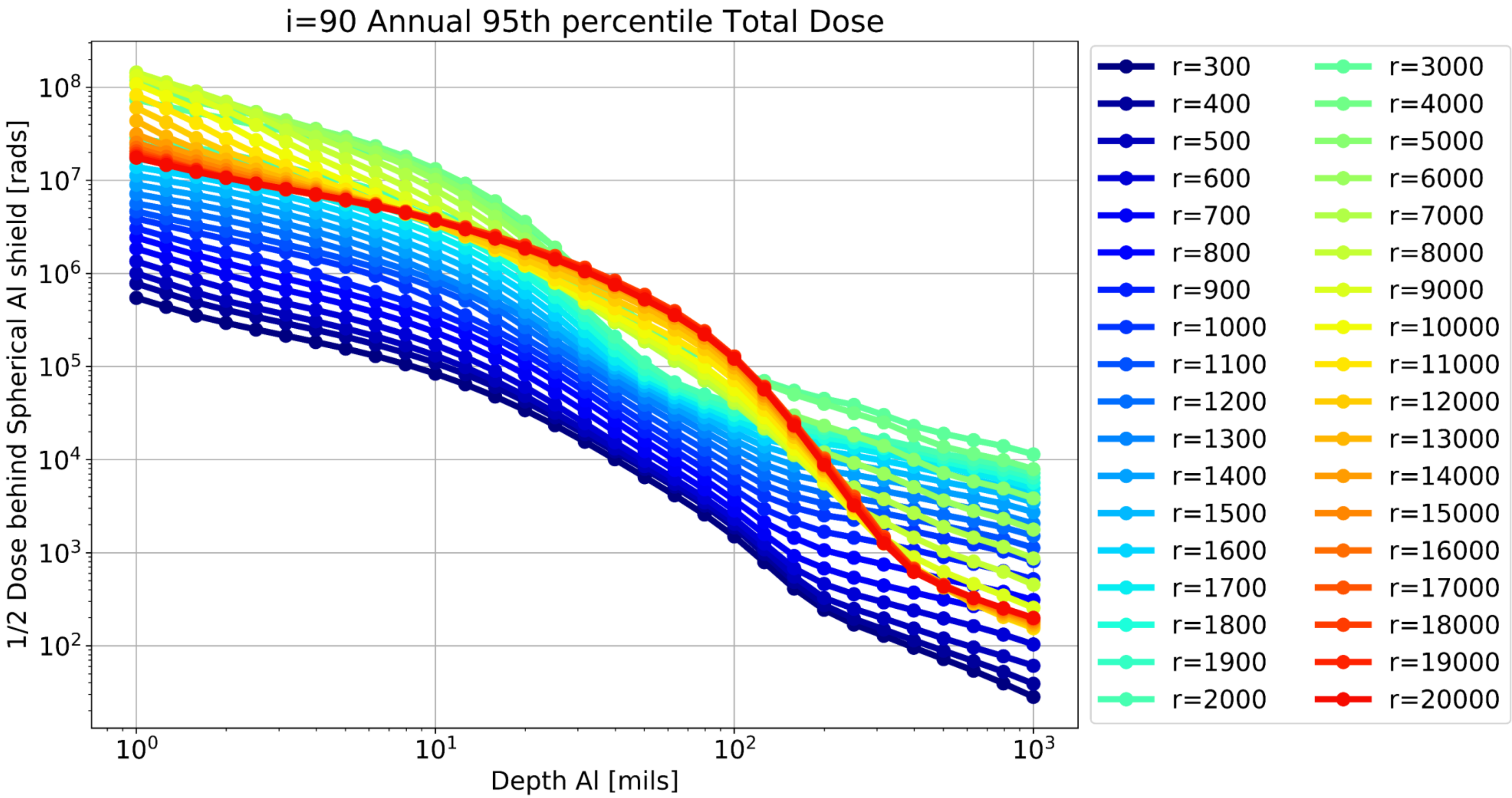
i=90 Annual 95th percentile Total Dose
1/2 Dose behind Spherical Al shield [rads]
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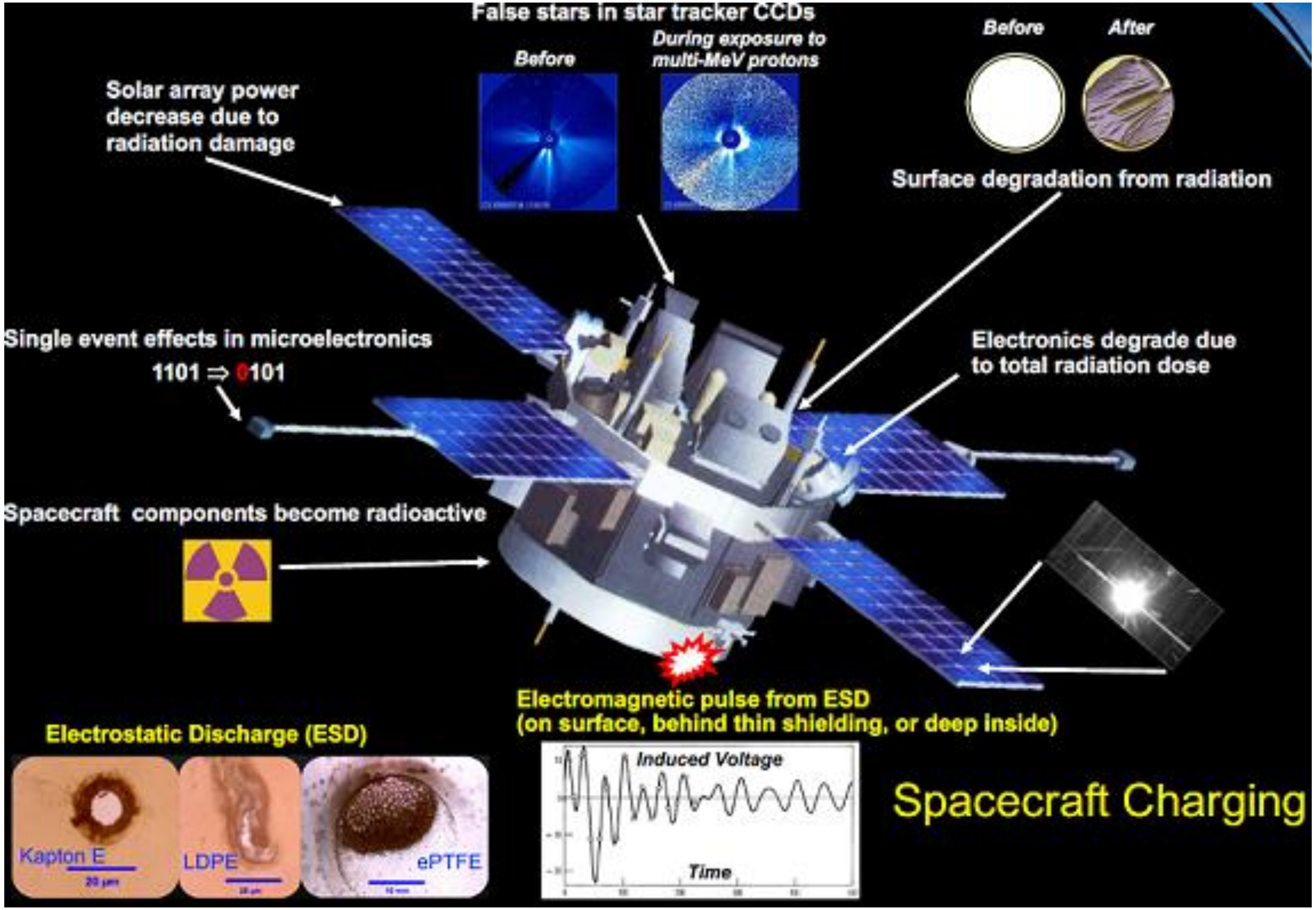
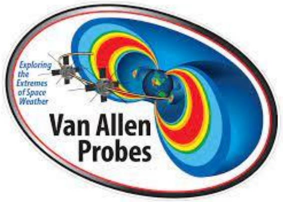
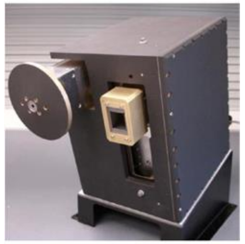

False stars in star tracker CCDs
Before
During exposure to multi-MeV protons
Before
After
Solar array power decrease due to radiation damage
Surface degradation from radiation
Single event effects in microelectronics
1101 ⇒ 0101
Electronics degrade due to total radiation dose
Spacecraft components become radioactive
Electromagnetic pulse from ESD
(on surface, behind thin shielding, or deep inside)
Electrostatic Discharge (ESD)
Kapton E
LDPE
ePTFE
Induced Voltage
Time
Spacecraft Charging

Observing the Space Environment

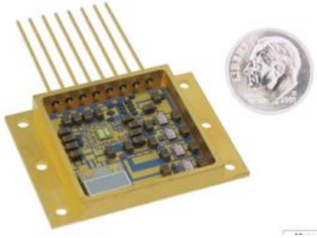
- Long standing observations from vehicles from NOAA, NASA, USAF, ESA
- Aerospace has provided many instruments to observe of the radiation environment
- Also look at other aspects of space environment
  - Ionosphere/Thermosphere (Satellite Drag, Communications, GPS Occultation, etc.)

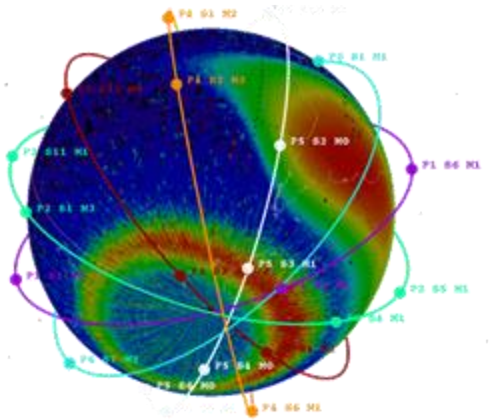
NASA Van Allen Probes: MagEIS and RPS





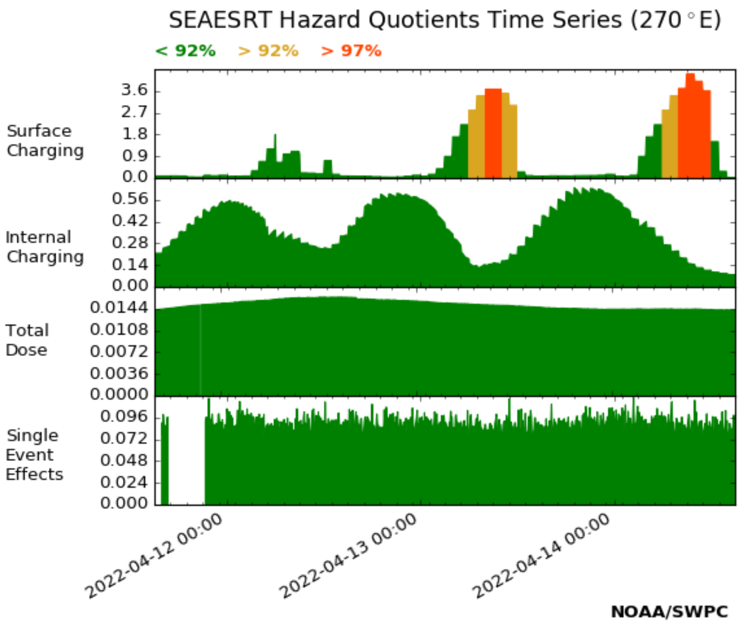
REACH: 64 sensors currently operating on IRDIUM-Next



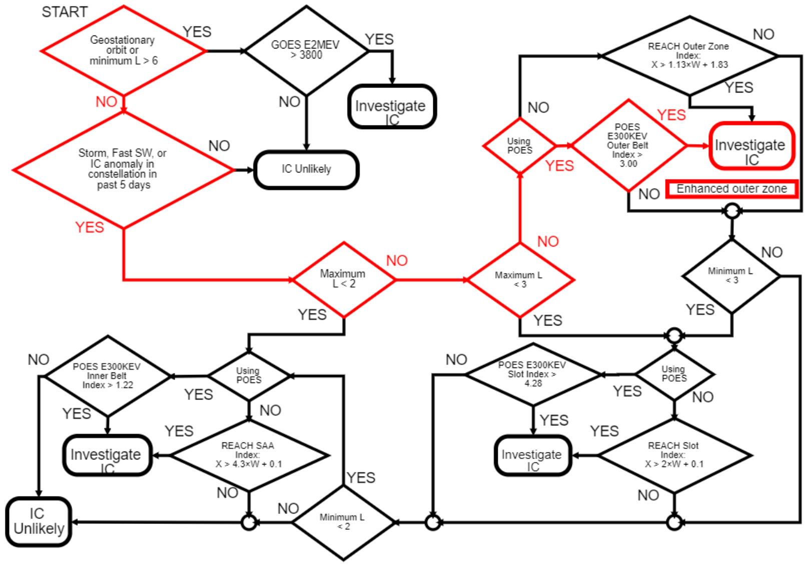


Looking at Space Environment Hazards

- Satellite Design
  - Will my satellite survive in my orbital environment for the mission duration?
  - How much shielding do I need? can I operate through worst case environment?
- On-Orbit Anomaly Attribution
  - Something went bump in the night – was it the space environment?



Internal Charging Flow Chart



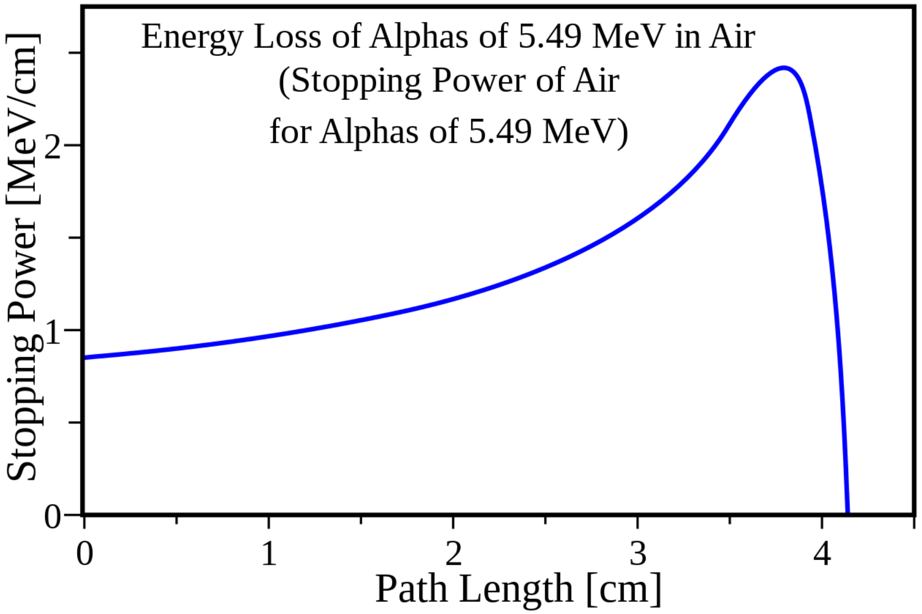
Results

Hazard	Conclusion	Explanation
Surface Charging	SC Unlikely	Does not fit SAMPEX or DMSP pattern
Internal Charging	Investigate IC	Enhanced outer zone
Event Total Dose	Investigate ETD	Enhanced Electrons in Outer Belt
Single Event Effects	SEE Unlikely	Ruled out SEP, SAA/inner belt, slot belt, GCR

Linear Energy Transfer (LET)

- The concept of LET is very important to understand how particles affect electronics.
  - LET = $\dfrac{dE}{dx}$ $\begin{array}{l} \leftarrow \text{Energy deposited} \\ \leftarrow \text{Unit distance} \end{array}$
  - Often useful to think of as a "damage" value. Higher LET usually means more damage done by a particle.
  - The dose that a particle deposits is tied to LET (high LET = high dose)

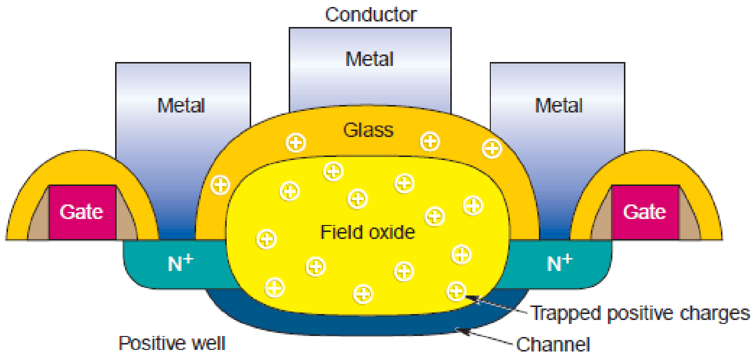
- LET increases based on the charge state (heavier atoms will have a higher LET) and varies based on material the particle goes through and the particle energy.
  - At most space energies, the LET is low and constant with energy (MIP region), but when the particles loses enough energy, the LET increases quickly and the particle will deposit energy very quickly.
  - This LET behavior is the key behind using protons for cancer treatment (set proton energy to have the highest LET In the cancer cells not in the healthy cells).

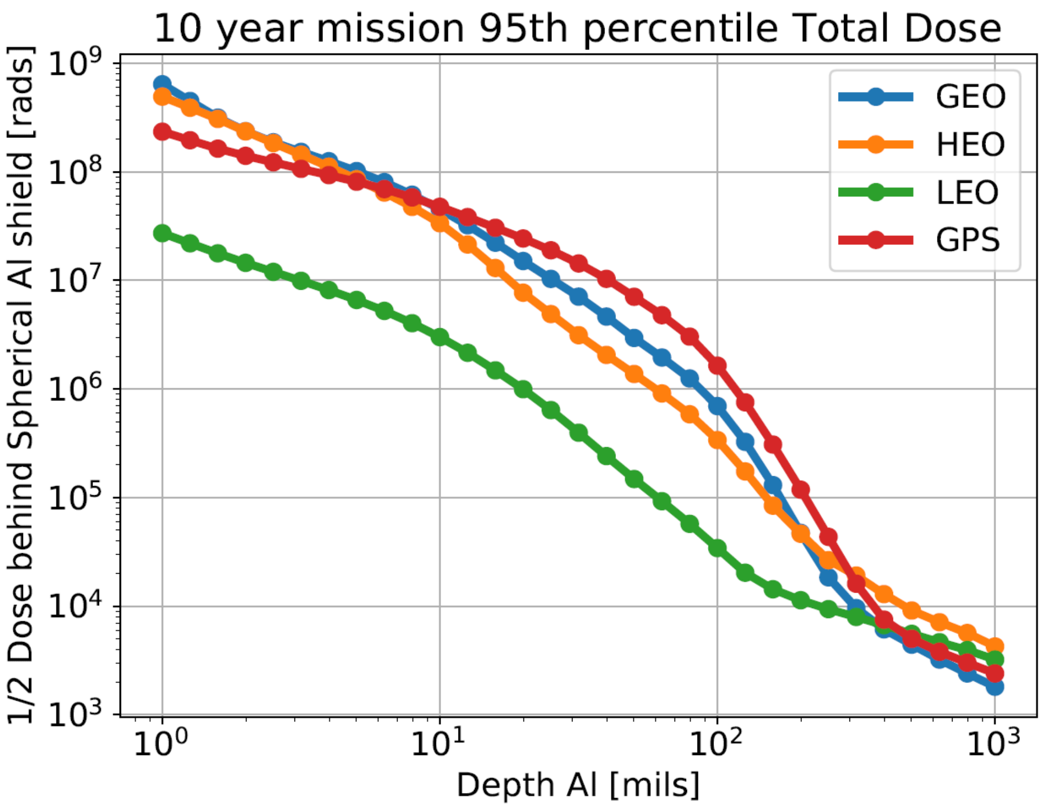


Total Ionizing Dose

- What are Total Ionizing Dose (TID)?
  - TID is a “wear out” mechanism by which particles free charge which, over time, accumulate and can change device properties and eventually cause failure.
    - Usually, this mechanism causes charge to accumulate in insulators which are supposed to be neutral.
    - This is an accumulated damage effect that shortens the lifetime of a part.
- Typically see this shown with a dose-depth curve
  - Different amounts of shielding can block parts of the input particle spectrum
- While it can be important, **TID almost never leads to on orbit failures** (lots of implicit margin built in)

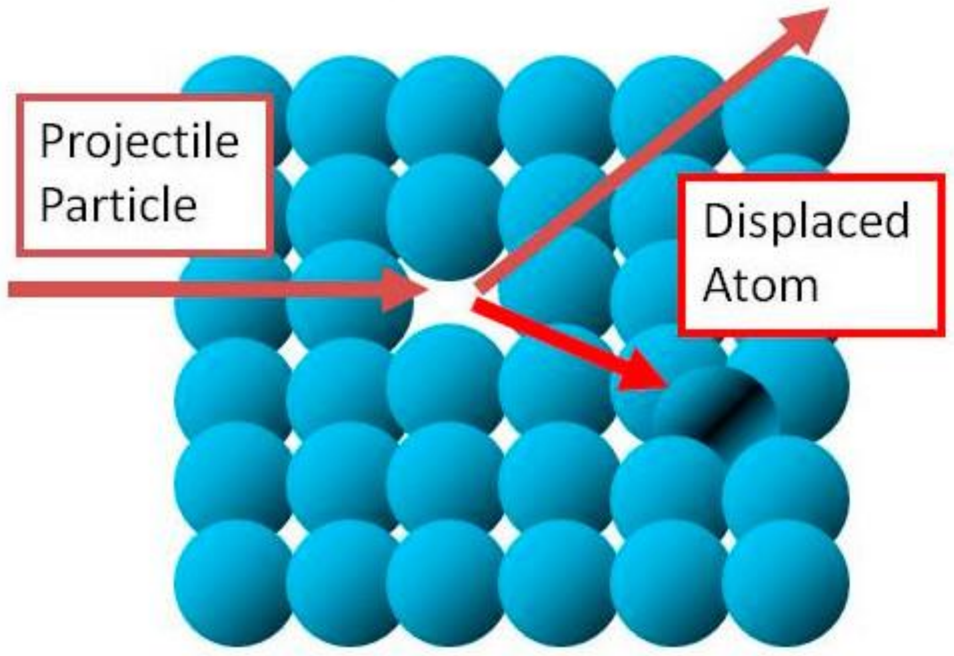
Electrons, Protons, Heavy Ions



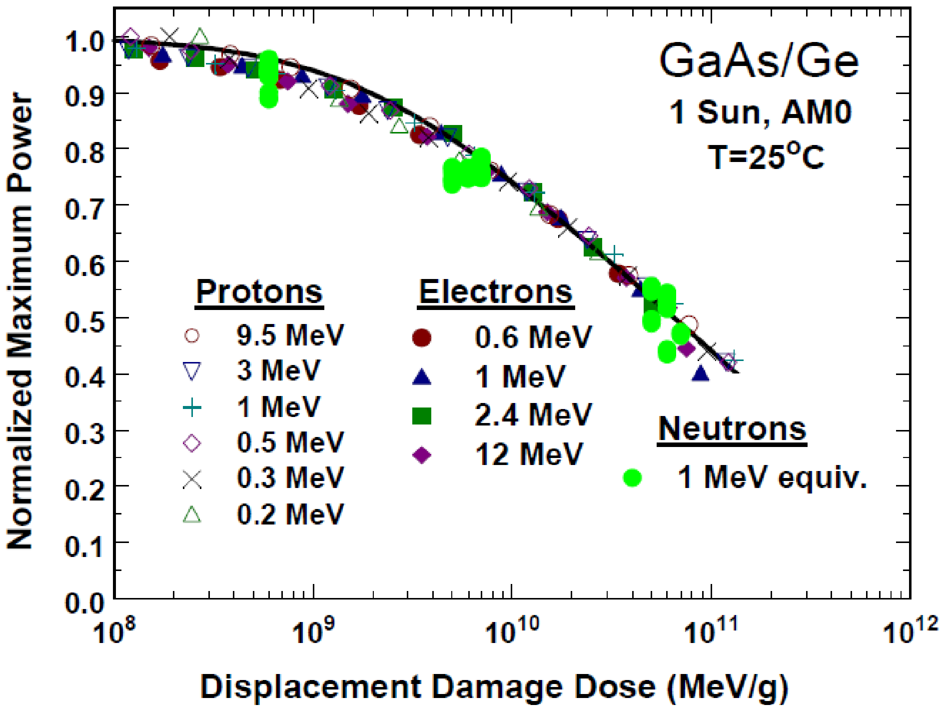


Displacement Damage Dose

- What are Displacement Damage Dose (DDD)?
  - Also called Total Non-Ionizing Dose (TNID), this is a wear-out mechanism similar to TID, but is caused not by freeing charge, but by displacing atoms out of a lattice.
    - In general, this reduces the performance of a device and could cause the device to eventually fail.
    - This type of damage is more important for focal planes, solar cells and optoelectronics



sr-neil.org



Messenger+ (2010), IEEE Photovoltaic Specialists

Charging

- Charging is tied to the radiation environment causing materials to built up charge over time.
  - If neighboring surfaces charge at different rates, then the voltage difference can cause an Electrostatic Discharge (ESD) like touching a doorknob after shuffling on a carpet.
- The resulting ESD can damage the surfaces, electronics, or generate spurious signals in circuits.
- Surface charging generally comes from particles which charge outside surfaces.
  - Associated with low energy electrons (<10 keV) in the environment.
  - ESD can cause damage to external materials and create noise or damage for systems like radio-frequency (RF) communication systems.
- Internal charging comes from higher energy particles which can pass through shielding and charge up circuit boards or cables.
  - Associated with high energy electrons (100s keV – MeVs) in the environment
  - ESD in these systems can appear as a voltage pulse in a circuit which can act like a false signal or could cause physical damage to a downstream component.

NASA-HDBK-4002A

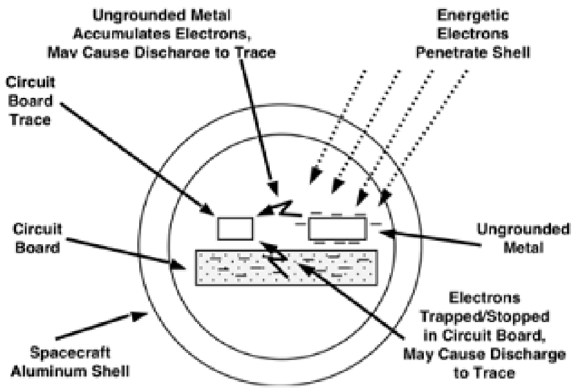
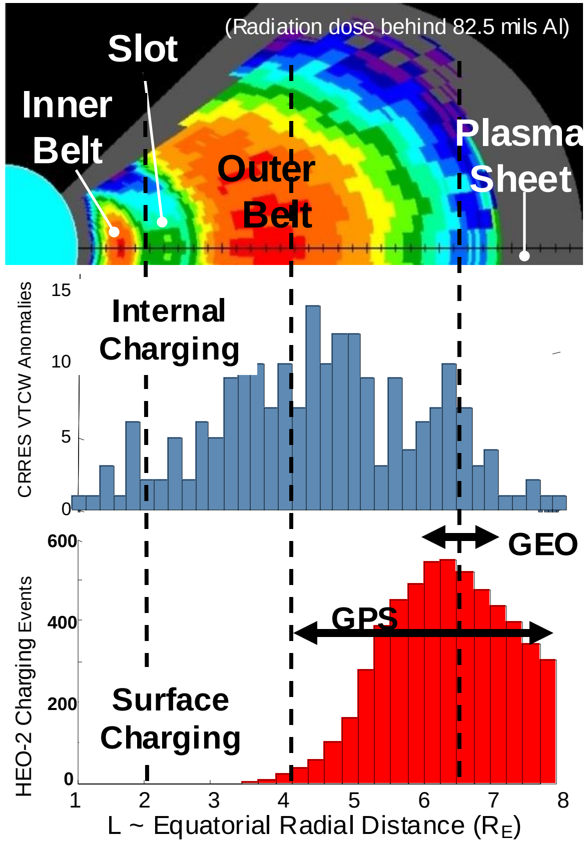
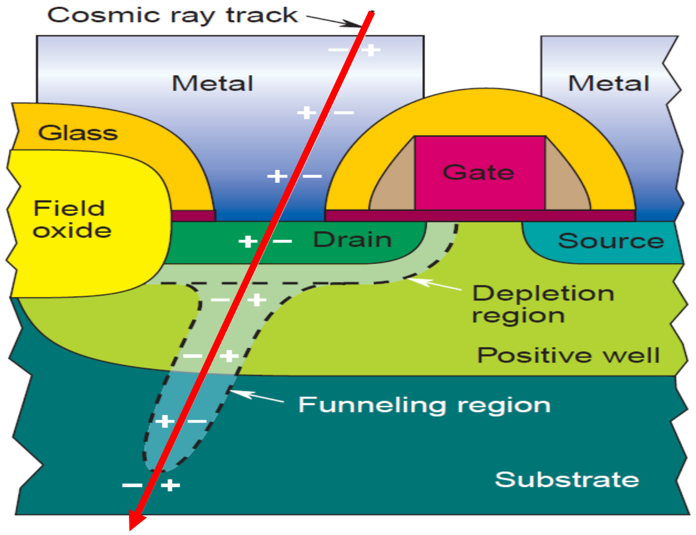


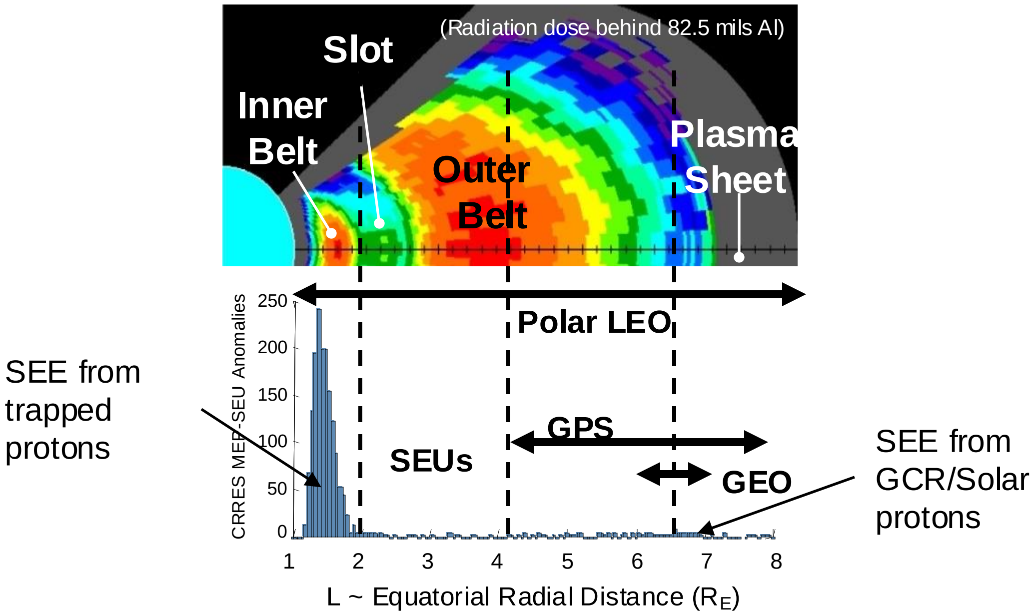
Figure 6—Internal Charging, Illustrated



Single Event Effects

- What causes a SEE?
  - A particle enters the material and ionizes the material. This can create a column of charge which can become a conductive path where there should be none or be collected and cause a current pulse.
  - Can be Direct (primary particle) or Indirect (creation of secondary particles from material nuclei)
  - In general, higher LET = higher probability of an upset
- There are destructive SEE and non-destructive SEE.
  - Destructive: part no longer functions
  - Non-destructive: part will do something odd
  - What types of effects a part has depends heavily on the part design.





SEE is increasingly becoming the preeminent hazard

Thank you