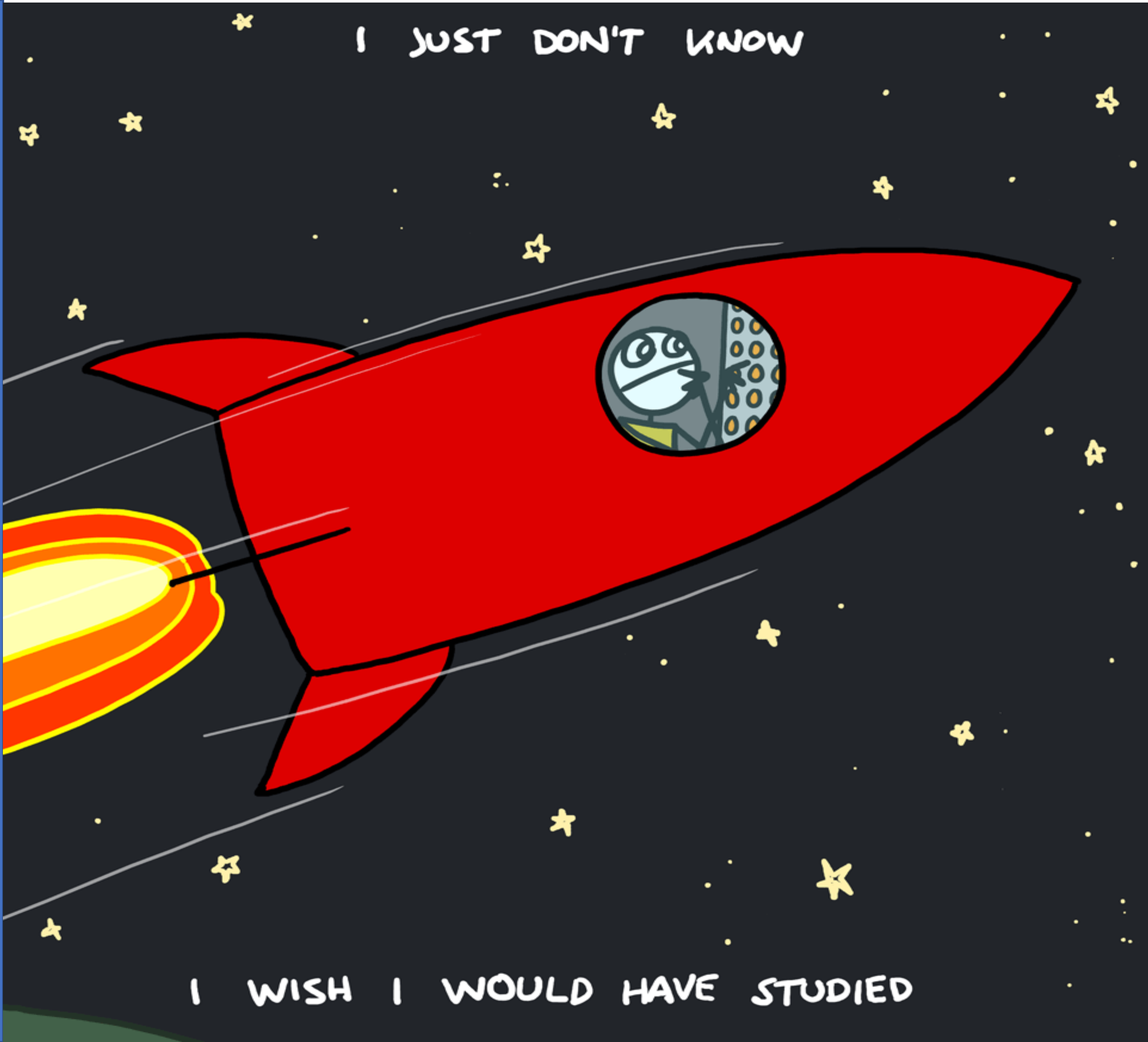
Space Weather: How Does it Impact Satellites and Power Grids?

Heliophysics Summer School 2020

Janet Green

Space Hazards Applications, LLC



Bio

Academia

PHD from UCLA

‘Testing Relativistic Electron Acceleration Mechanisms’

Government

National Resource Council Post doc at NOAA

Academia

Post doc at University of Colorado, Boulder

Government

9 years at the NOAA SWPC/NCEI

Commercial/Industry

Non-profit work using machine learning to target members (Public Interest Network)

Commercial/Industry

founded Space Hazards Applications, LLC (spacehaz.com)

Question:

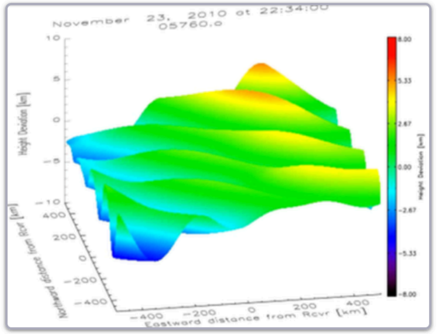
- What type of career are you considering?
  - Academic
  - Government
  - Commercial Industry

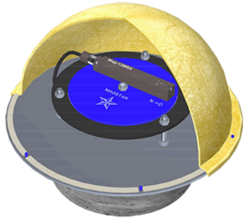
Respond in the chat with one of the above

Commercial Providers

American Commercial Space Weather Association (ACSWA)

- http://www.acswa.us/
- 16 groups doing space weather research, modeling, application development, instrumentation (small sats, radiation monitors, magnetometers)





Magnetometers

Monitors of local GIC hazard conditions

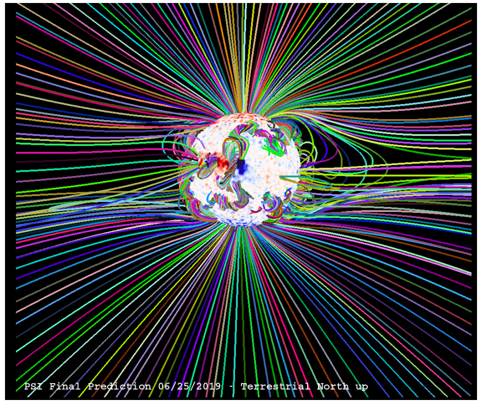
Benefits

- Ultimate flexibility, many funding options, new learning opportunities, tremendous variety

"I want to do what I want to do when I want to do it" –my 4 year old niece

Challenges

- Not highly secure, requires self motivation, willingness to learn new things (finances, IT, contracts, etc.)



Outline

Space Weather Impacts to Satellites

- Satellite anomalies caused by particle radiation
  - Impacts:
  - Physics and modeling
  - Applications
- Orbital drag
  - Impacts,Physics and modeling, applications

< *Intermission* >

Space Weather Impacts to Power Grids

- Outage and system degradation
  - Impacts,Physics and modeling, applications

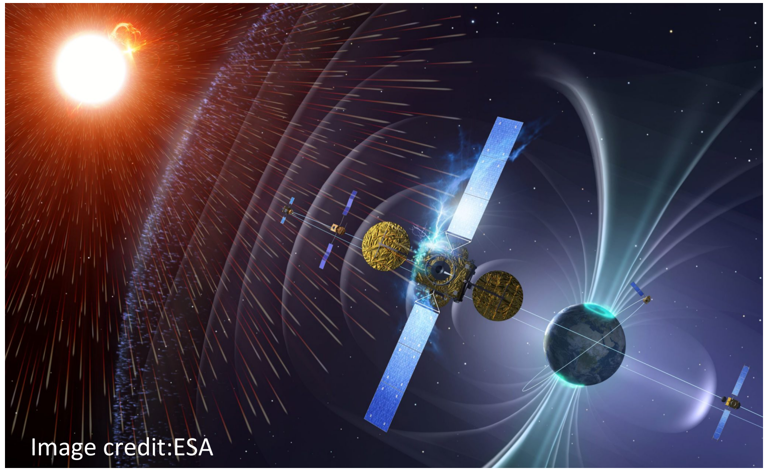


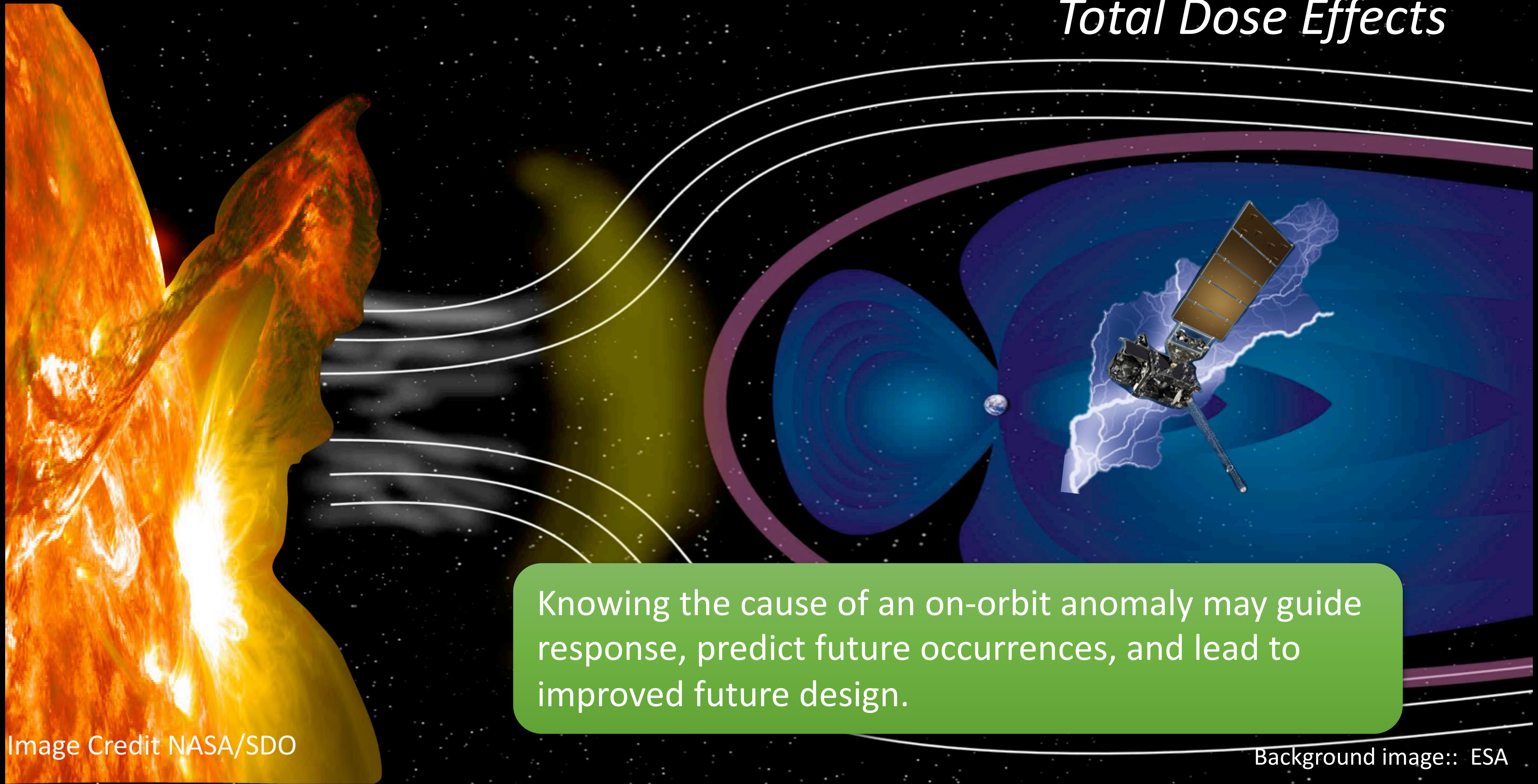
Image credit:ESA

Image credit: K.L. *Turnbull*, J.A. Wild (Lancaster University) and the SOHO/
consortium

The Issue

Space weather → *Intensifies Particle Radiation* →

- *Surface Charging*
- *Internal Charging*
- *Single Event Effects*
- *Total Dose Effects*



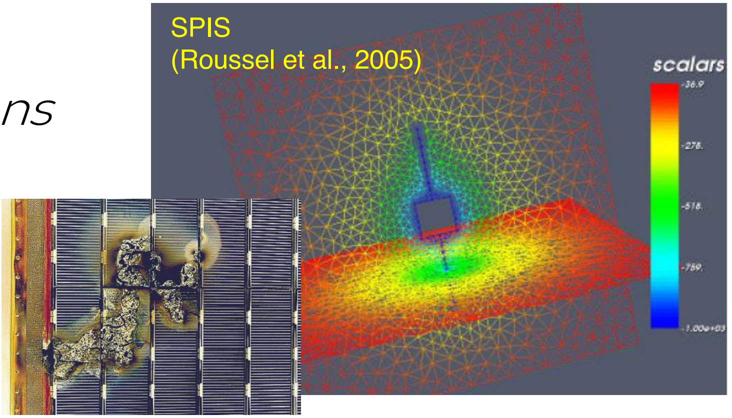
Knowing the cause of an on-orbit anomaly may guide response, predict future occurrences, and lead to improved future design.

Image Credit NASA/SDO

Background image:: ESA

The Impacts

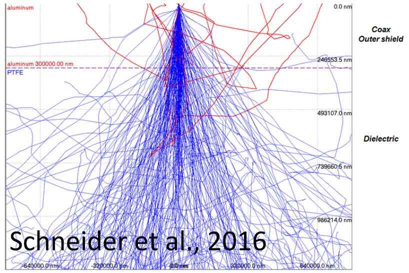
Space weather causes satellite anomalies and disrupts operations



SPIS
(Roussel et al., 2005)

Surface Charging:

Charged particles collect on satellite surfaces producing high voltages, damaging arcs (electrostatic discharges), and electromagnetic interference.



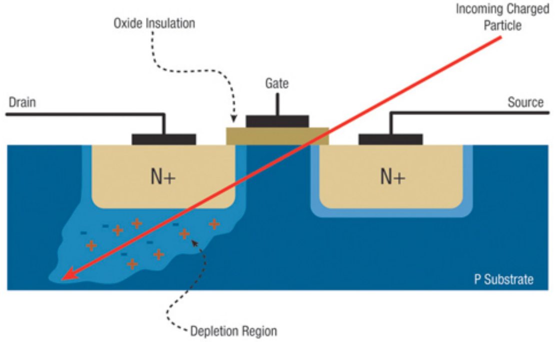
Schneider et al., 2016

Internal Charging:

Energetic electrons accumulate in interior dielectrics (circuit boards or cable insulators) and on ungrounded metal (spot shields or connector contacts) leading to electrical breakdown in the vicinity of sensitive electronics.

Single Event Upsets:

Energetic ion passage through microelectronic device node causes instantaneous catastrophic device failure, latent damage, or uncommanded mode / state changes requiring ground intervention.



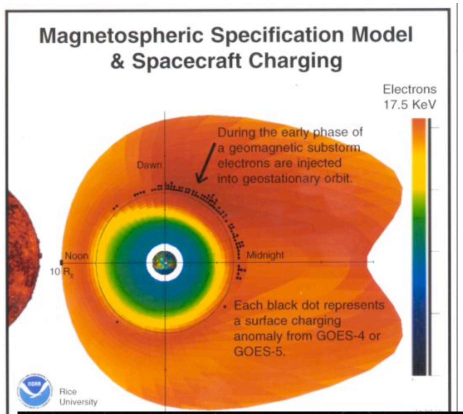
https://semiwiki.com/x-subscriber/silvaco/3604-single-event-upsets/

Total Dose:

Energy loss (deposited dose) from proton or electron passage through microelectronic device active region accumulates over mission (or step-wise during high dose rate events) causing device degradation and reduced performance at circuit or system level.

The Challenge (Space Weather)

Effects are caused by distinct particle populations that intensify under varying conditions and in different regions



Surface Charging:

Low to medium energy particles (ev-10 keV) associated with substorms during moderate Kp activity in the dusk magnetospheric regions.

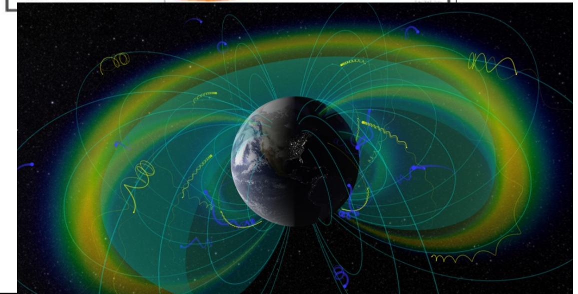
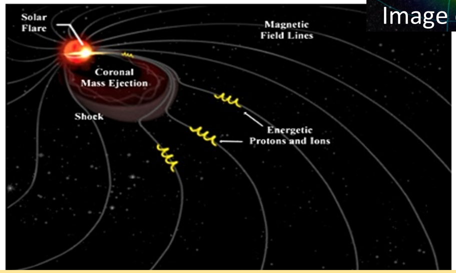


Image credit: NASA

Internal Charging:

Higher energy electrons (100 keV->10 MeV) associated with some storms that peaks around L=4



Single Event Upsets:

Solar Proton Events associated with solar flares and coronal mass ejections

Total Ionizing Dose:

All of the above.

In order to predict and preform anomaly attribution requires models/measurement of magnetospheric particles from eV-MeV from 400 km out to 6.6 Re and models/measurements of SEPs and their access in the magnetosphere

Question:

Which hazard causes the most reported problems?

- Surface Charging
- Internal Charging
- Single Event Effects
- Total Ionizing Dose

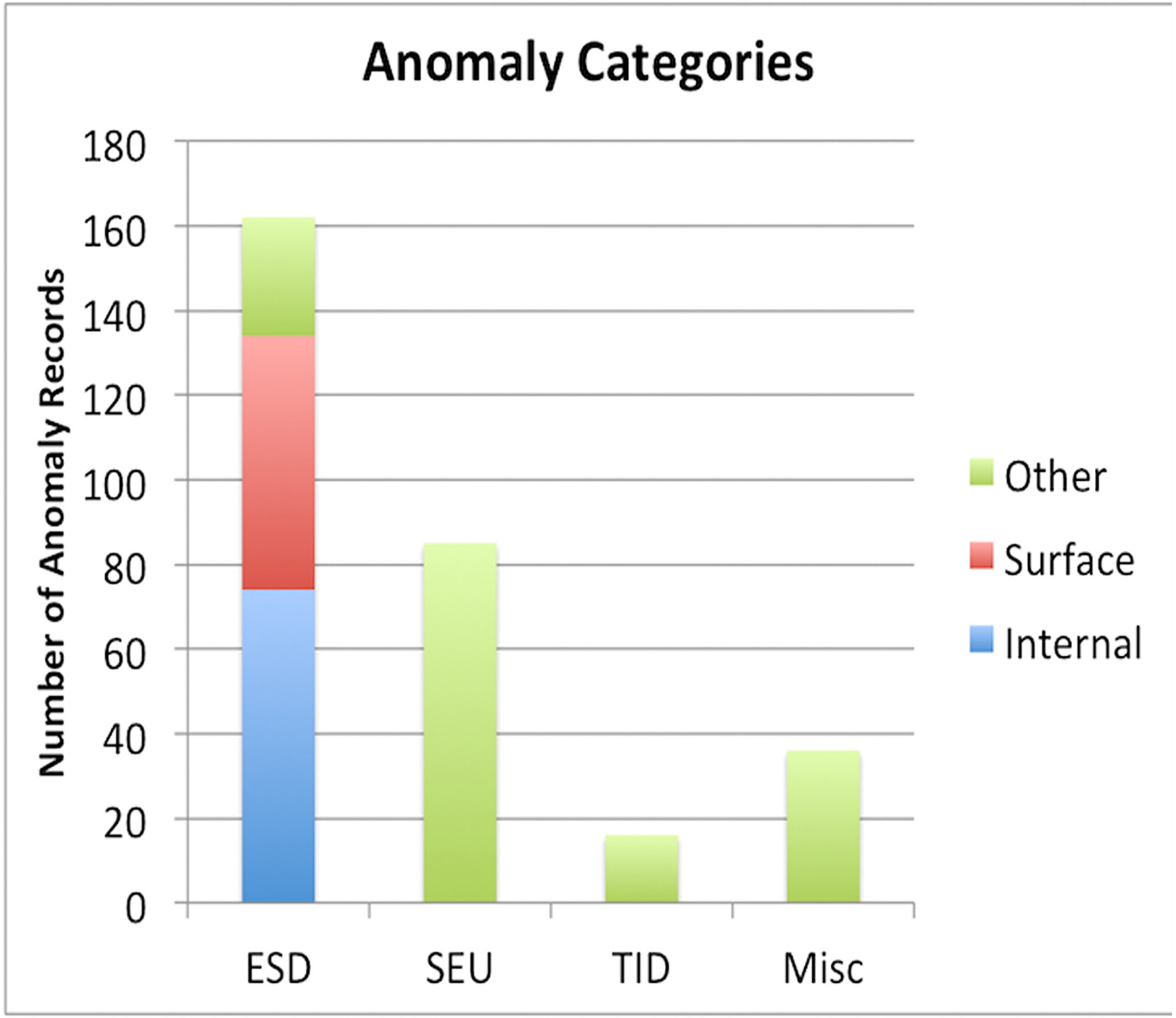
Respond in the chat with one of the above

ANSWER

ESD's: Internal Charging:

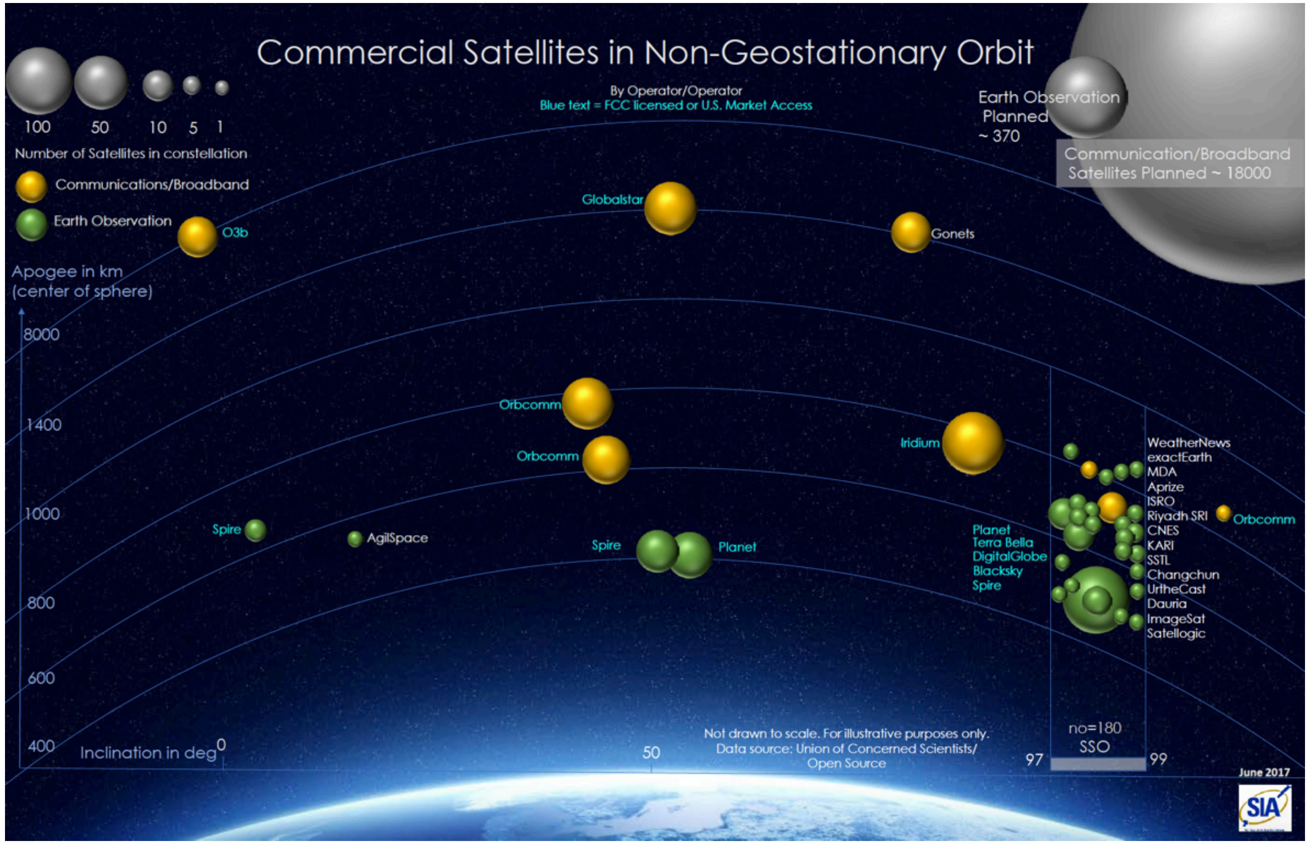
- Most likely at GEO
- A typical communications satellite at GEO costs ~250 million
- Intelsat 29e loss in 2019, and Galaxy 15 anomaly in 2010 suspected internal charging

But anomalies aren't formally tracked and this study is from 1999 …



Adapted from Koons et al, 1999

The Concern: New Space



Commercial Satellites in Non-Geostationary Orbit

By Operator/Operator

Blue text = FCC licensed or U.S. Market Access

Not drawn to scale. For illustrative purposes only.
Data source: Union of Concerned Scientists/
Open Source

June 2017

New services rely large constellations:

- Satellite internet
- Satellite Imaging

Hazards for LEO satellites:

- Internal charging- unlikely because the time spent in the radiation belts is small
- Surface charging-potentially in the auroral regions
- SEU’s- potentially large for polar orbiting satellites
  - No significant SEP events since 2017 before many constellations were launched

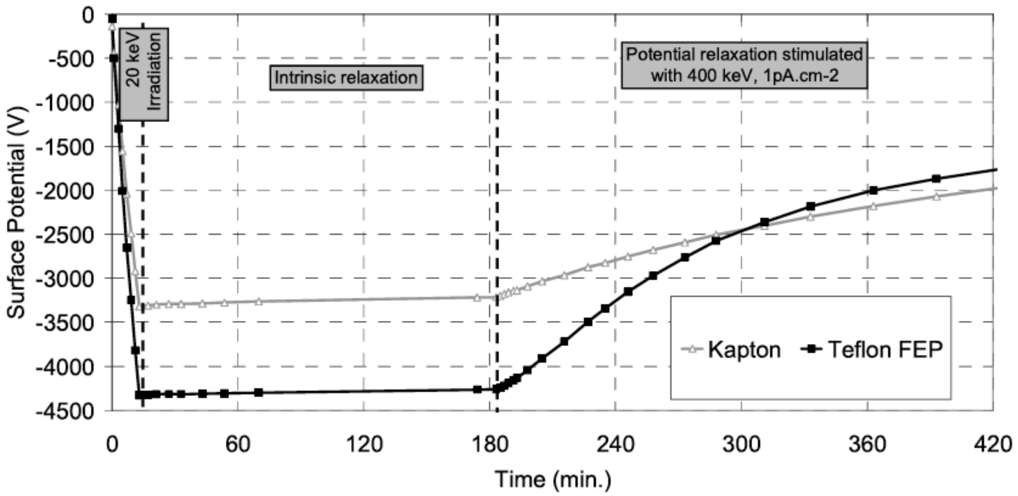
The Challenge (Engineering)

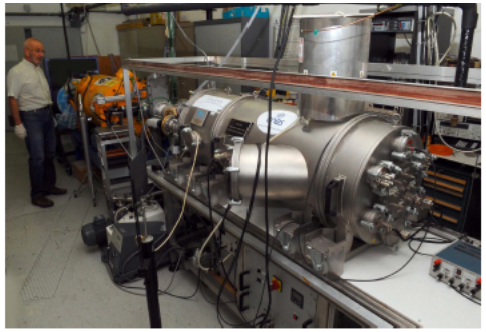
Material properties are not well known

Even if the environment is known precisely, many material properties are uncertain especially as they age in space.

Example- Radiation induced conductivity may reduce internal charging effects

Paulmier et al. [2014]





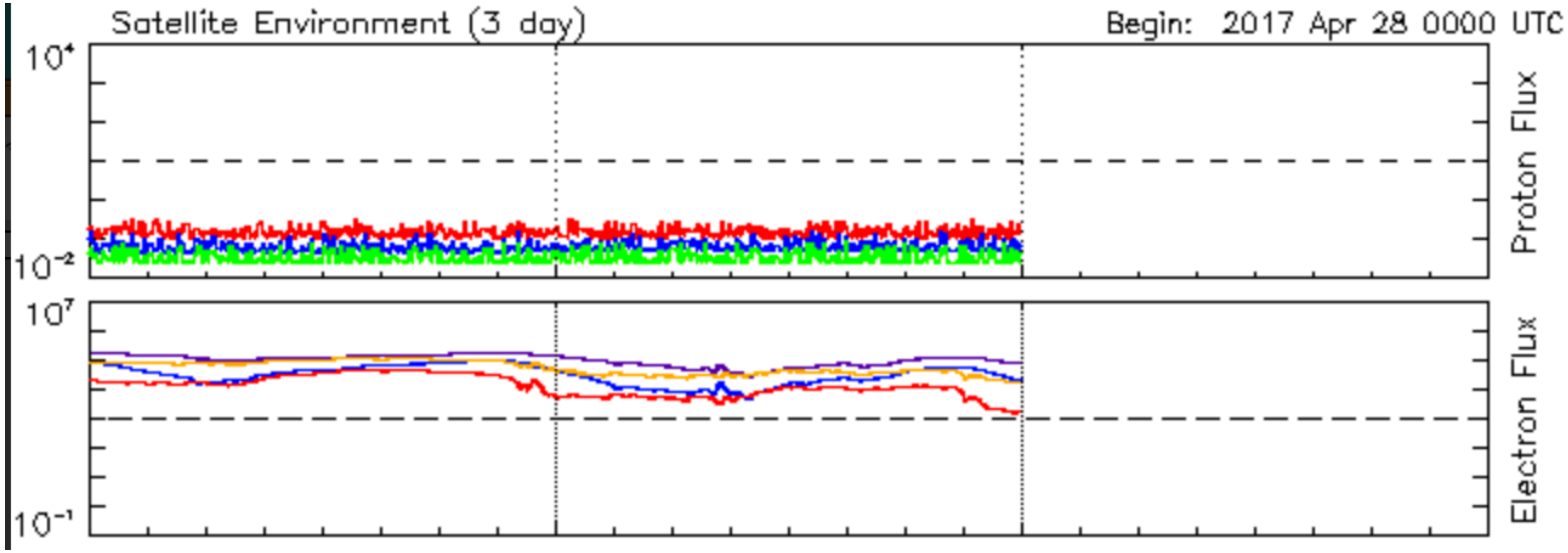
The Challenge (Attribution)

Anomaly Investigation/Monitoring

Some anomalies go undiagnosed because attribution is a research project requiring significant time and expert knowledge

- Coordination about anomalies between operators and manufacturers is ill-defined
- Limited data difficult to compare to full mission
- Fluxes need to be translated into the four specific hazards
- Fluxes at GEO do not describe full magnetosphere

Knowing what we know now this process should be automated.
- M. Bodeau [2017]



The Challenge

In order to respond to space weather impacts 3 components are needed

Environment

Physical understanding captured in real time models, data, both

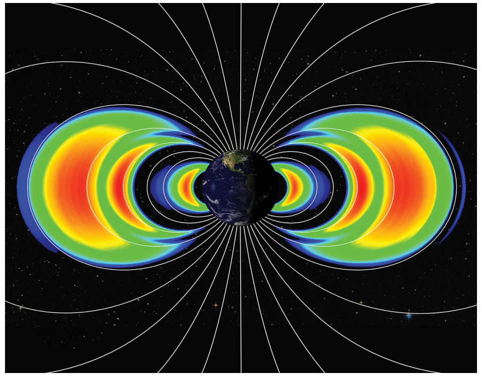
Engineering Effect

Understanding of how the environment interacts with the system

User Interface /Application

A tool to bring the knowledge together and enable decisions by the user

Internal Charging- Radiation Belts



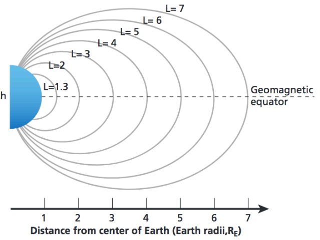
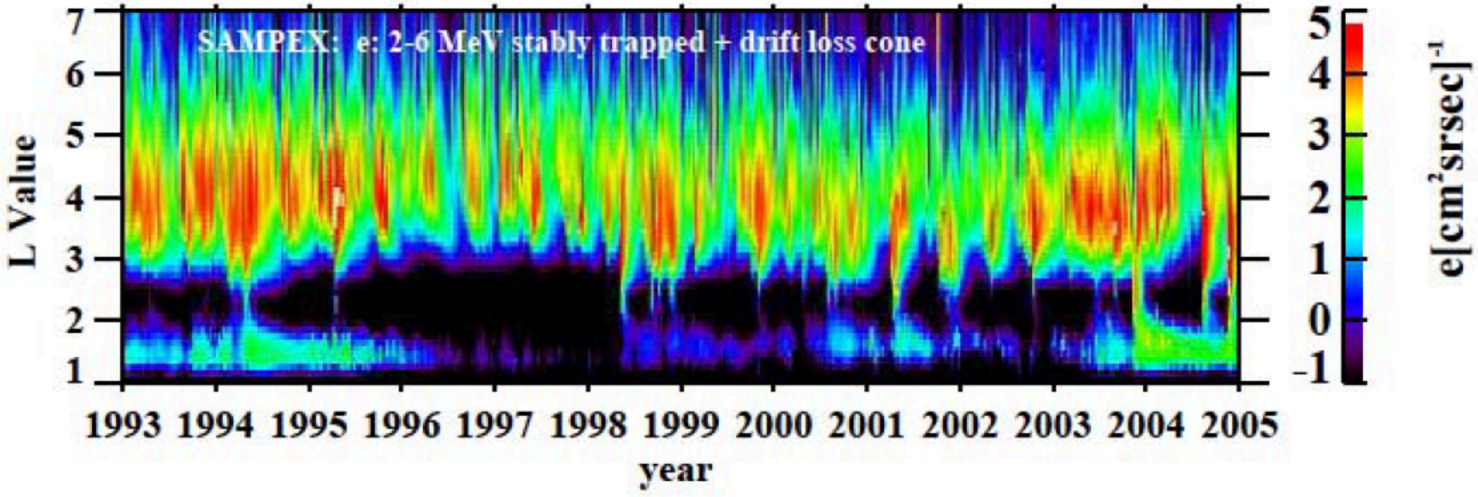


Figure 2.3
Illustration of L-shell Parameter

RAND *RR460-2.3*

- Electron Radiation Belts Overview
    - Extend from L=1 to L=~7
    - 2 belts: inner L=~1-3, outer L=3-7



- Dramatic changes result from competing acceleration and losses

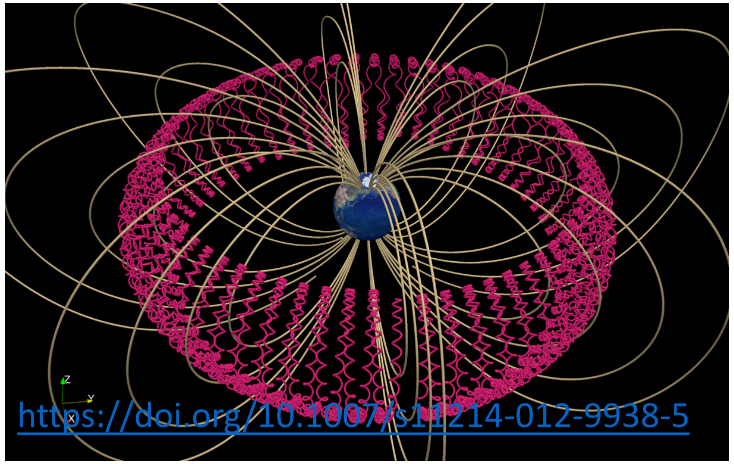
Radiation Belt Physics

Dominant Acceleration Mechanisms

- Interaction with waves
  - Particles have 3 types of motion that can interact with waves: drift, bounce, gyro

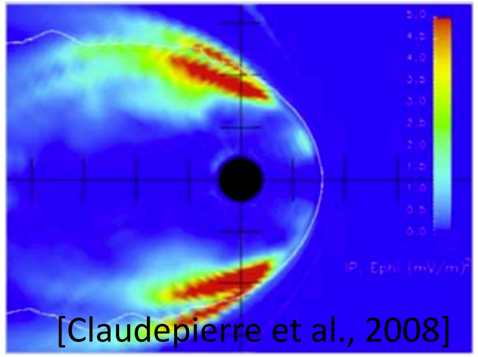
- ULF waves (drift resonance)
  - *Low* frequency low m number waves created from solar wind interaction with the magnetosphere (Kelvin Helmholtz, pressure changes)
  - Interact with particle drift around Earth
  - Push them inward (acceleration) and outward (deceleration)
  - Net acceleration depends on radial gradient of particles
  - A source of particles at large L results in net acceleration a depletion at large L results in net deceleration

Electron Motion



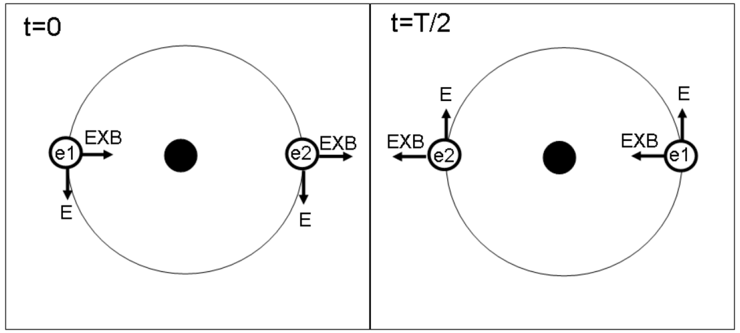
https://doi.org/10.1007/s11214-012-9938-5

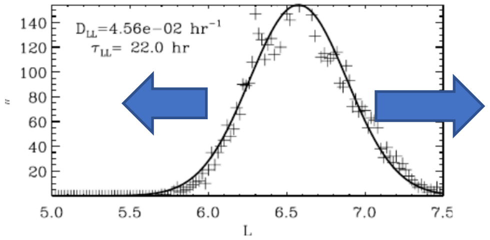
KH waves



[Claudepierre et al., 2008]

Drift Resonance

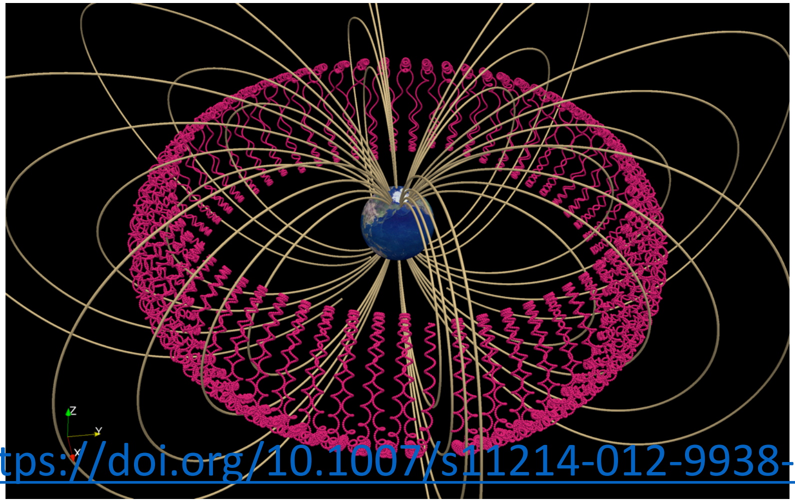




Radiation Belt Physics

Dominant Acceleration Mechanisms

- VLF Chorus waves (gyro- resonance)
  - High frequency waves created from lower energy electrons injected by substorms creating an unstable distribution
  - Chorus waves interact with particles as the bounce and gyrate
  - Particle moving at the right velocity along the field will see a constant electric and magnetic field
  - Particles that are pushed towards 90 degree pitch angles are accelerated
  - The net acceleration depends on the particle gradients in pitch angle and energy



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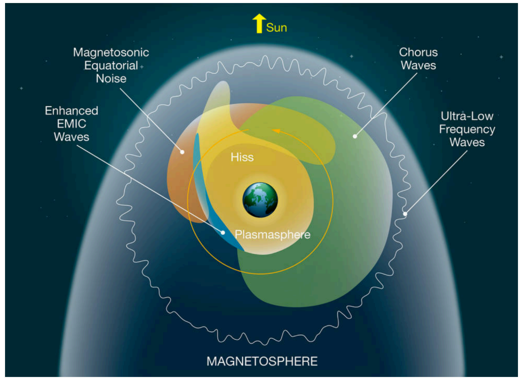
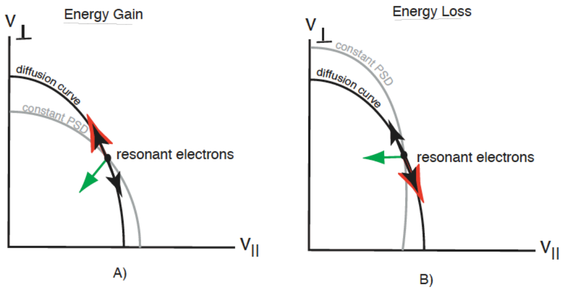
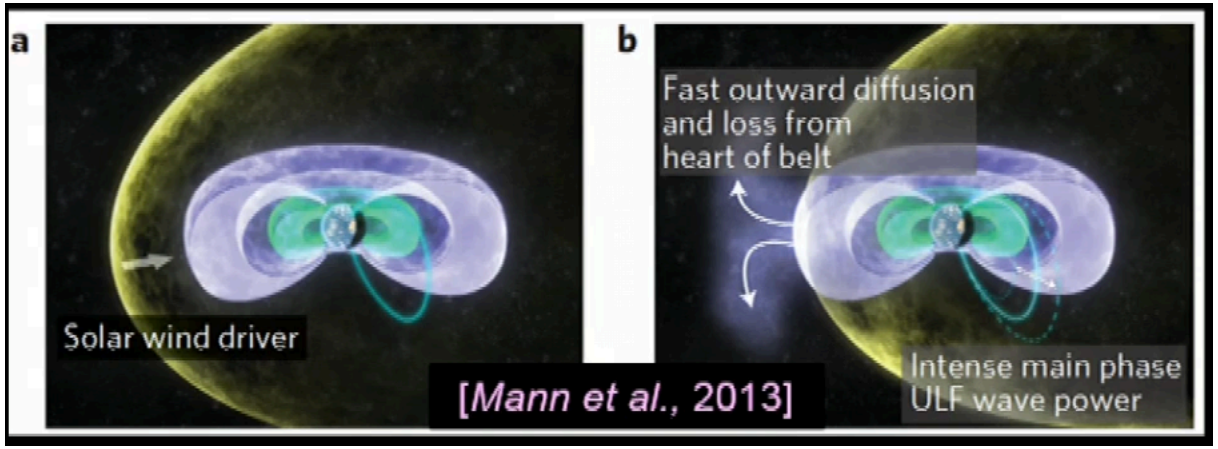


Credits: NASA's Goddard Space Flight Center/Mary Pat Hrybyk-Keith



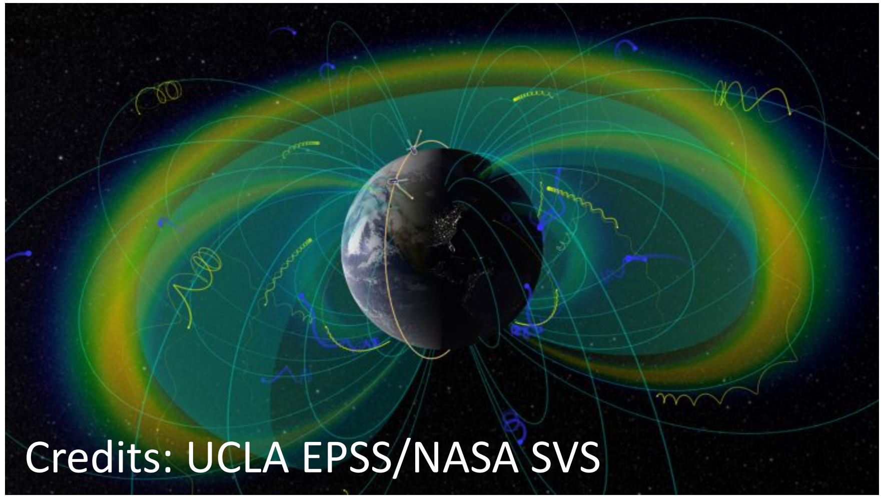
Radiation Belt Physics



[*Mann et al.*, 2013]

Dominant Losses

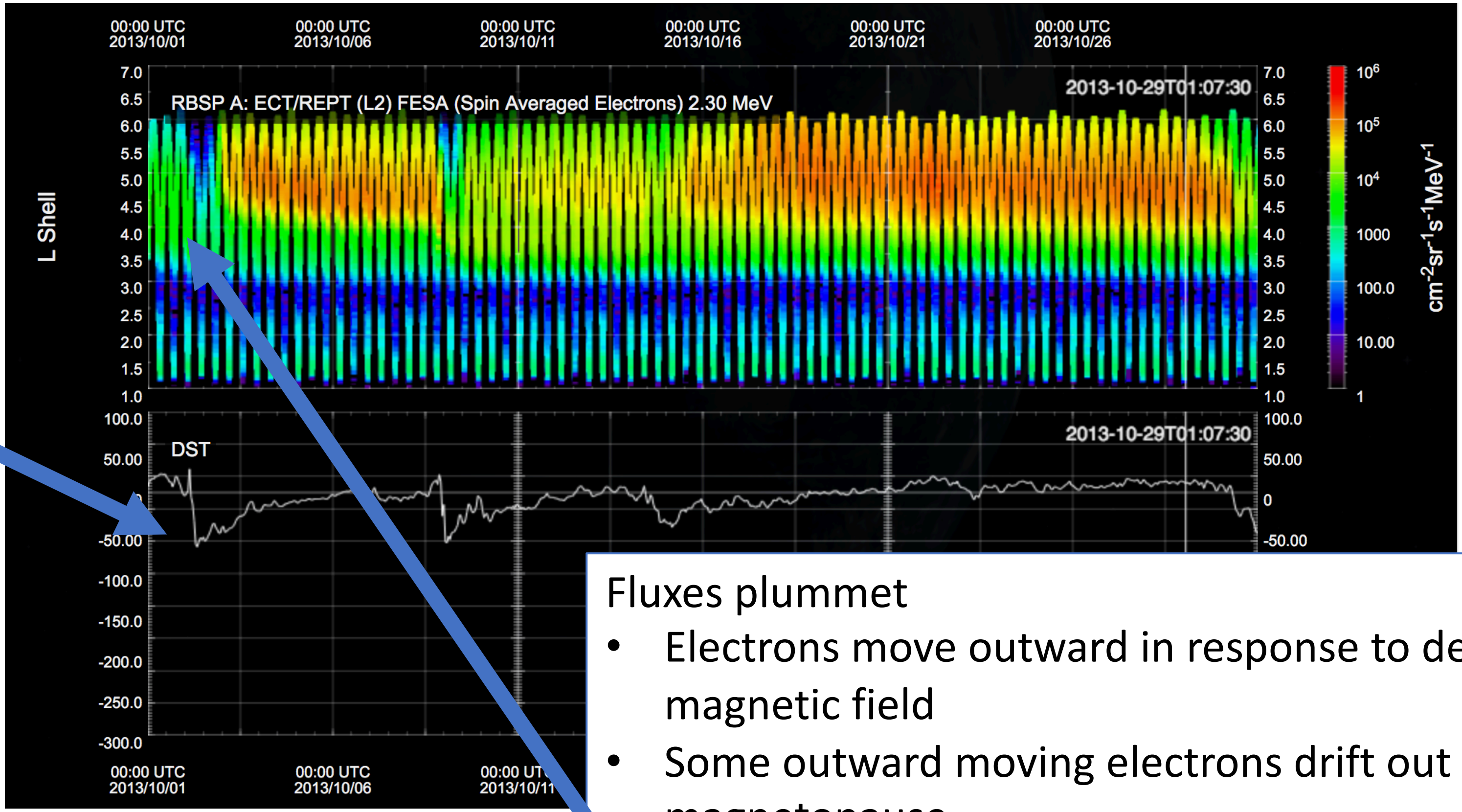
- Drift out the magnetopause
  - Compression from solar wind
- Loss into the atmosphere
  - Electromagnetic Ion Cyclotron (EMIC) waves produced by ring current ions change the particle pitch angle and force them into the atmosphere



Credits: UCLA EPSS/NASA SVS

Radiation Belt Evolution: Storm Main Phase

- Low energy particles injected through substorms and enhanced convection.
- Inner magnetospheric field decreases due to build up of ring current

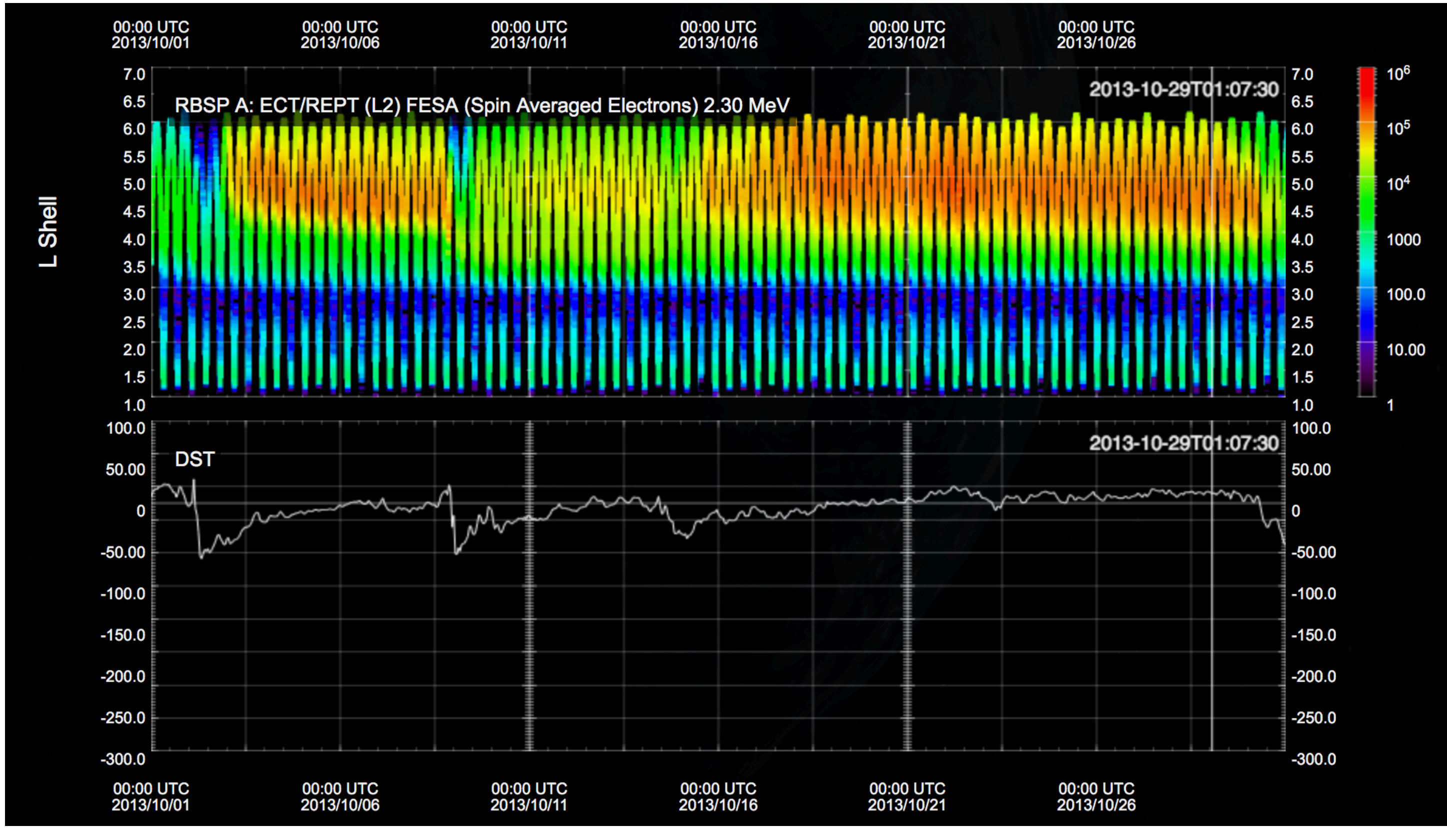


Fluxes plummet

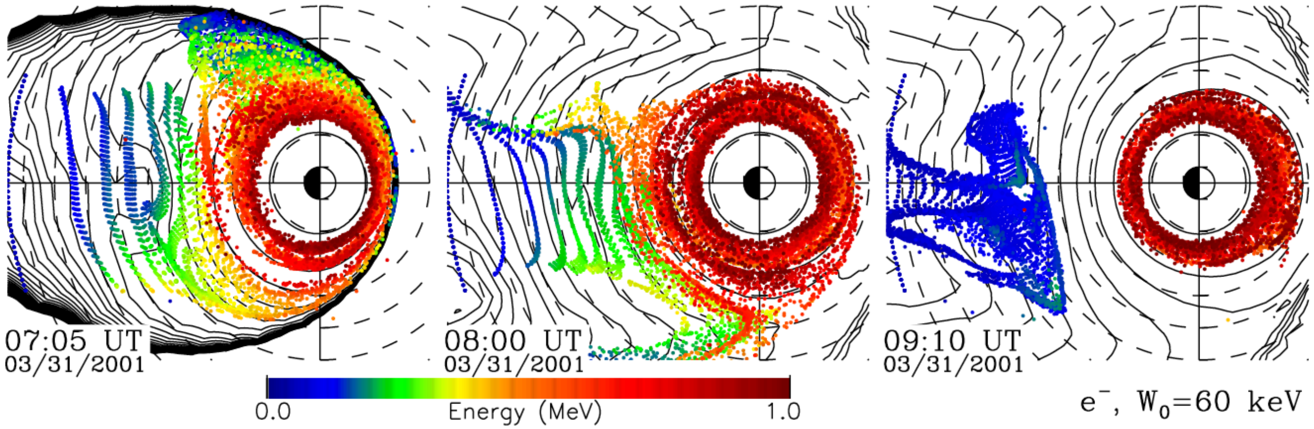
- Electrons move outward in response to decreasing magnetic field
- Some outward moving electrons drift out the magnetopause
- Outward motion enhanced by interaction with ULF waves (outward diffusion)
- EMIC waves created by the ring current push electrons into the loss cone and atmosphere

Radiation Belt Evolution

- Storm Recovery Phase
  - ULF wave power increases with high speed solar wind
    - Pushes electrons inward while increasing their energy
  - VLF Chorus wave power increases due to substorm injected particles
    - Changes the pitch angle and energy of the particle



Radiation Belt Modeling



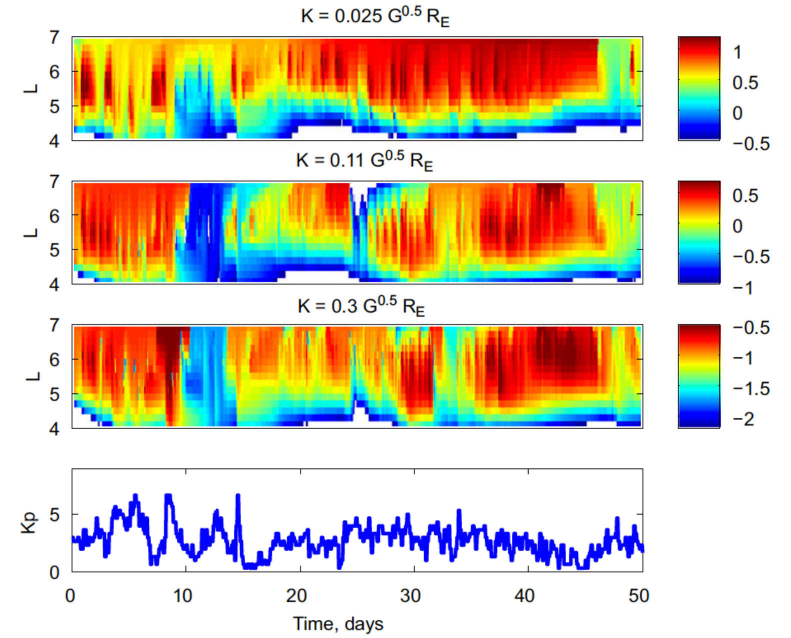
Elkington et al., 2004

MHD/Particle Codes

- Place test particles in MHD codes of the magnetosphere
- Solve for the drift motion of the particle using the MHD magnetic/electroc fields
- Can capture ULF wave acceleration and magnetopause losses
- Can't capture interaction Chorus and EMIC waves
- Computationally expensive

Radiation Belt Modeling

Shprits et al., 2007



Diffusion Models

- Interaction with ULF and VLF waves are treated as a random diffusive process
    - ULF waves diffuse particles inward or outward
    - VLF waves diffuse particle in pitch angle and energy
    - The rate of diffusion depends on the strength of the waves
- Described by a Fokker-Plank equation
    - Boundary conditions and wave diffusion parameterized by indices

$$
\begin{aligned}
\frac{\partial f}{\partial t} = {} & L^{*2} \left.\frac{\partial}{\partial L^*}\right|_{\mu,J} \left(D_{L^*L^*} L^{*-2} \left.\frac{\partial f}{\partial L^*}\right|_{\mu,J} \right) + \\
& + \frac{1}{p^2} \left.\frac{\partial}{\partial p}\right|_{\alpha_0,L} p^2 \left(\langle D_{pp} \rangle \left.\frac{\partial f}{\partial p}\right|_{\alpha_0,L} + \langle D_{p\alpha_0} \rangle \left.\frac{\partial f}{\partial \alpha_0}\right|_{p,L} \right) + \\
& + \frac{1}{T(\alpha_0)\sin(2\alpha_0)} \left.\frac{\partial}{\partial \alpha_0}\right|_{p,L} T(\alpha_0)\sin(2\alpha_0) \left(\langle D_{\alpha_0\alpha_0} \rangle \left.\frac{\partial f}{\partial \alpha_0}\right|_{p,L} + \langle D_{\alpha_0 p} \rangle \left.\frac{\partial f}{\partial p}\right|_{\alpha_0,L} \right) - \frac{f}{\tau},
\end{aligned}
\tag{1}
$$

Shprits et al. (2008)Review of modeling of losses and sources of relativistic electrons in the outer radiation belt I: Radial transport
Shprits et al. (2008) Review of modeling of losses and sources of relativistic electrons in the outer radiation belt II: Local acceleration and loss

Model examples

VERB

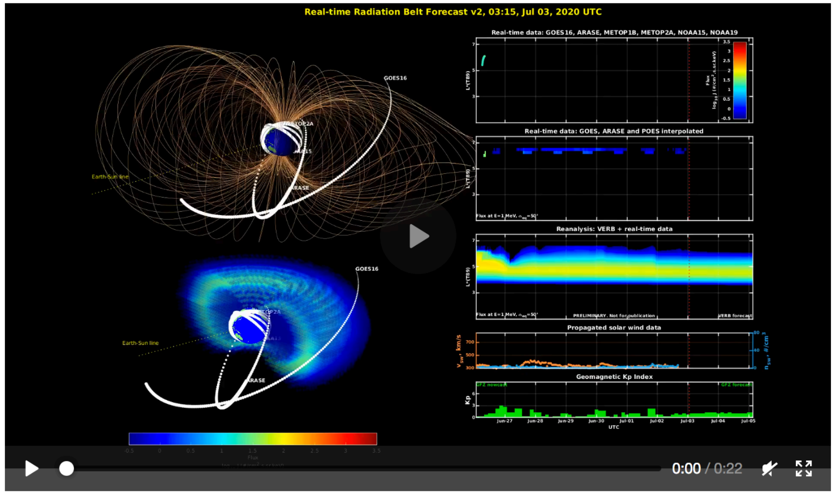
- Diffusion model
- Runs in real time at UCLA
- Assimilates available data
- New data available every 2 hours
- Includes a 3 day forecast

Fok model

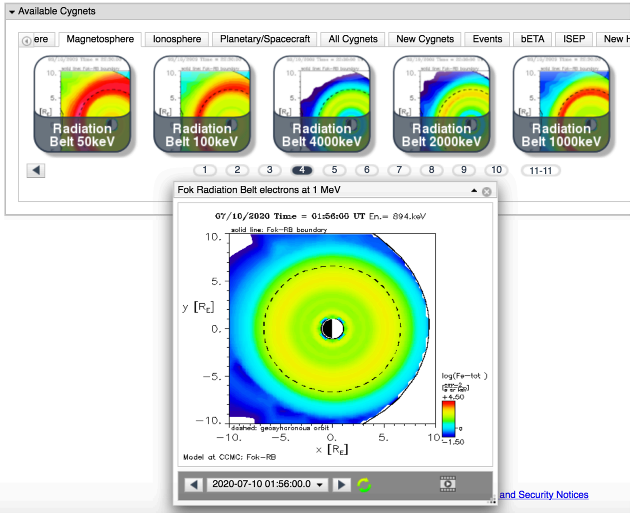
- Diffusion model
- Runs in real time at NASA/CCMC
- Data files not readily available

BAS model

- Diffusion model
- Now runs in real time at ESA



https://rbm.epss.ucla.edu/realtime-forecast/



https://iswa.gsfc.nasa.gov/IswaSystemWebApp/

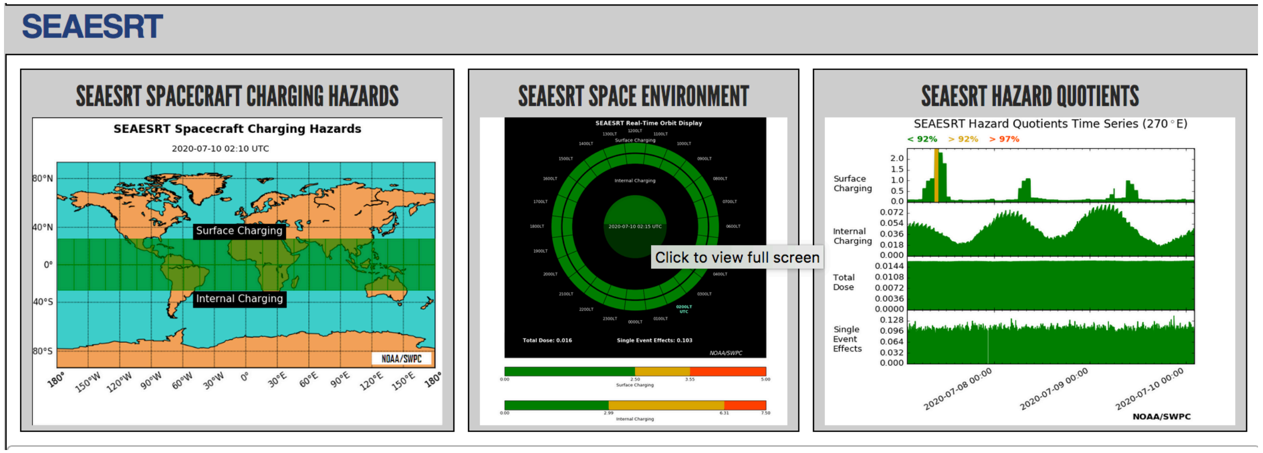
Applications Examples

SEAESRT (SWPC)

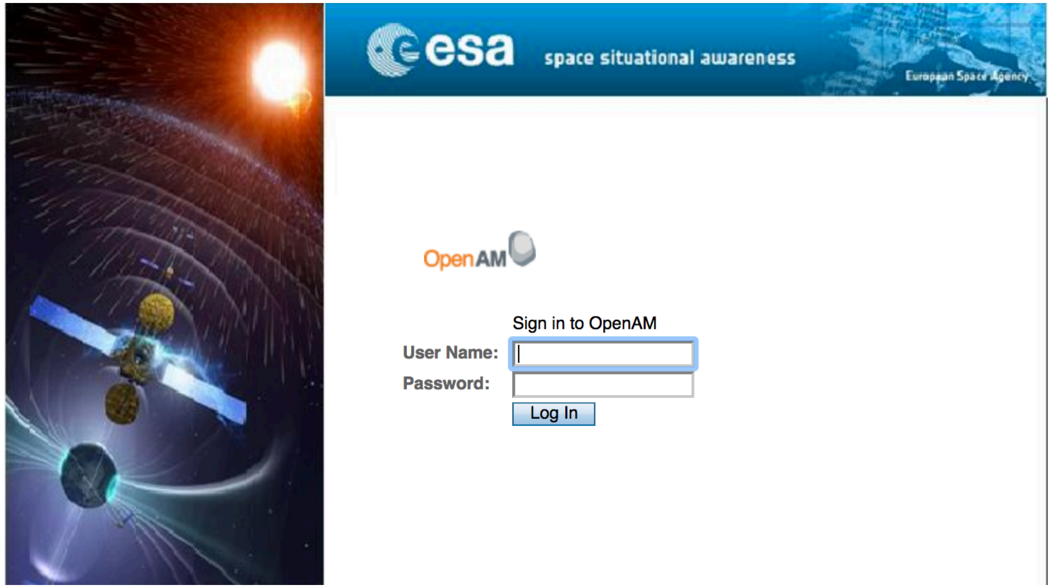
- Specifies the hazard of an internal charging event at GEO based on statistical correlation of fluxes and anomaly databases
- Has been updated to include other orbits but not publicly available

Spacestorm (ESA)

- Provides stop light charts at several orbits based on electron fluxes from the BAS diffusion model



https://www.swpc.noaa.gov/products/seaesrt



http://swe.ssa.esa.int/web/guest/sarif-federated

Applications Examples

SatCAT

Calculates historical and real time internal charging based on VERB fluxes for user specified satellite shielding, materials, orbits

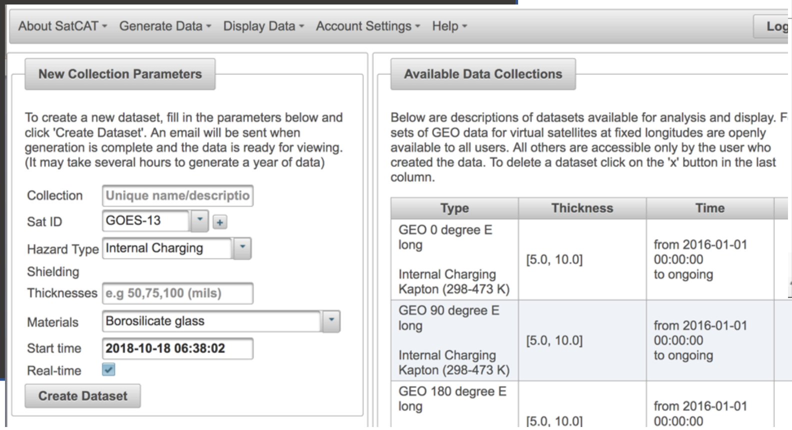
www.spacehaz.com

Intelsat 29E failure analysis

Component	Shielding (mils)	Material and decay constant	% level	Likely Cause
Cables	5, 10	Teflon generic (τ = 2.2d)	88%	Possible
Cables	5, 10	Teflon FEP (τ = 68.12 d)	70%	No
Circuit Board	100	Fr4 (τ = 4.17 d)	60%	No

01/01/2018 00:00 to 12/01/2019 00:00

01/01/2018 00:00 to 12/01/2019 00:00



To create a new dataset, fill in the parameters below and click 'Create Dataset'. An email will be sent when generation is complete and the data is ready for viewing. (It may take several hours to generate a year of data)

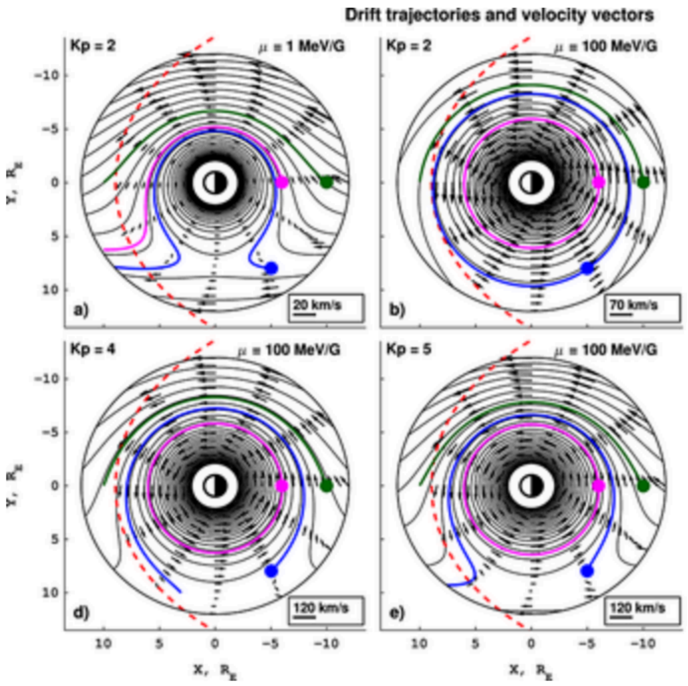
Collection	Unique name/descriptio
Sat ID	GOES-13
Hazard Type	Internal Charging
Shielding Thicknesses	e.g 50,75,100 (mils)
Materials	Borosilicate glass
Start time	2018-10-18 06:38:02
Real-time	☑

Below are descriptions of datasets available for analysis and display. F sets of GEO data for virtual satellites at fixed longitudes are openly available to all users. All others are accessible only by the user who created the data. To delete a dataset click on the 'x' button in the last column.

Type	Thickness	Time
GEO 0 degree E long Internal Charging Kapton (298-473 K)	[5.0, 10.0]	from 2016-01-01 00:00:00 to ongoing
GEO 90 degree E long Internal Charging Kapton (298-473 K)	[5.0, 10.0]	from 2016-01-01 00:00:00 to ongoing
GEO 180 degree E long	[5.0, 10.0]	from 2016-01-01 00:00:00

Surface Charging: Substorm particles

- Need to add and advective term to the diffusion equation to capture convection
  - Efforts are underway to update models to include this term
- Need to capture substorm injections



Shprits et al., 2015

$$\frac{df}{dt} = \langle v_\varphi \rangle \frac{\partial f}{\partial \varphi} + \langle v_R \rangle \frac{\partial f}{\partial R} + \frac{1}{G} \frac{\partial}{\partial L} G \langle D_{LL} \rangle \frac{\partial f}{\partial L} + \frac{1}{G} \frac{\partial}{\partial V} G \left(\langle D_{VV} \rangle \frac{\partial f}{\partial V} + \langle D_{VK} \rangle \frac{\partial f}{\partial K} \right) + \frac{1}{G} \frac{\partial}{\partial K} G \left(\langle D_{KV} \rangle \frac{\partial f}{\partial V} + \langle D_{KK} \rangle \frac{\partial f}{\partial K} \right) - \frac{f}{\tau}$$

Applications Examples

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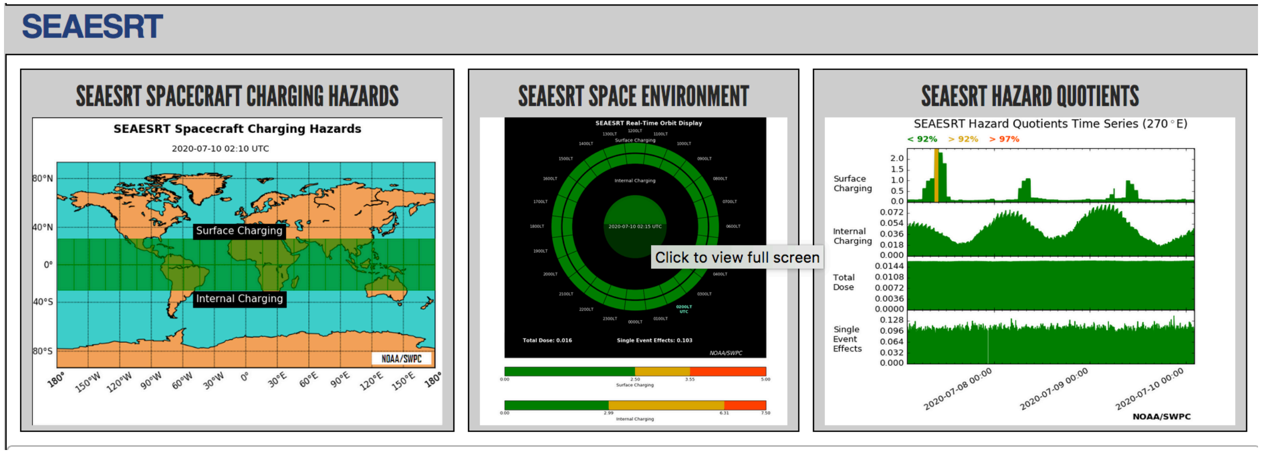
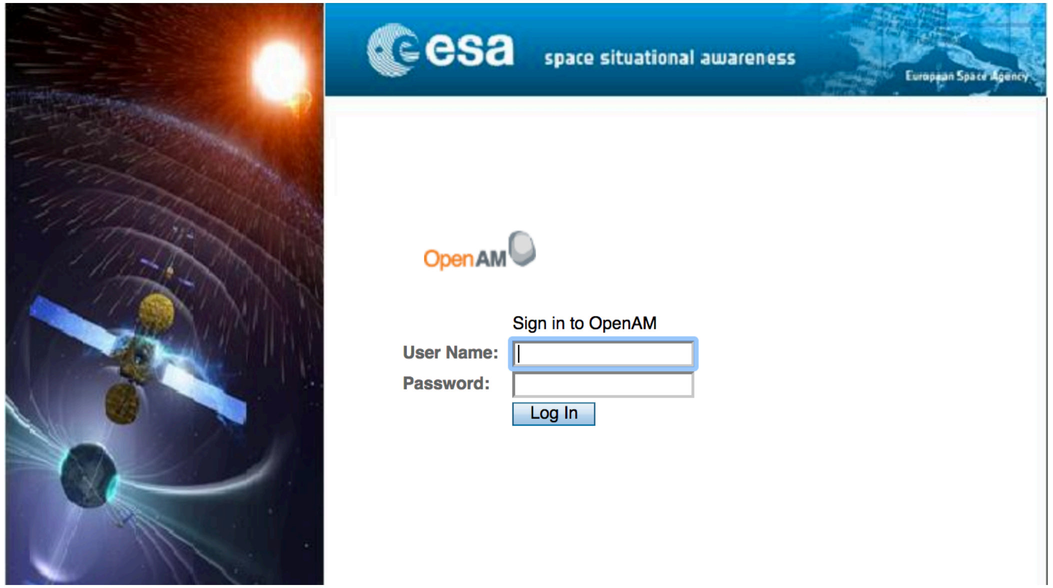
Spacestorm (ESA)

- Provides stop light charts at several orbits based on electron fluxes from the IMPTAM model



https://www.swpc.noaa.gov/products/seaesrt

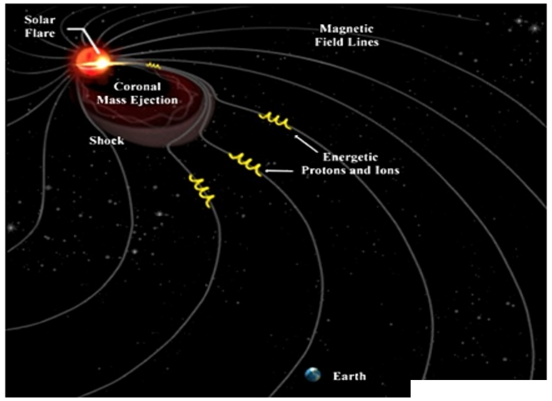


http://swe.ssa.esa.int/web/guest/sarif-federated

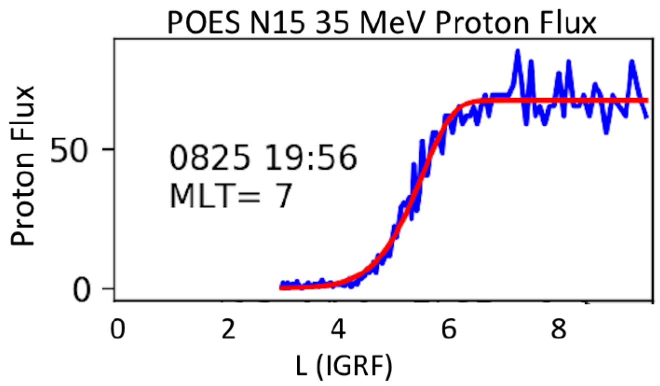
Single Event Effects: SEP’s

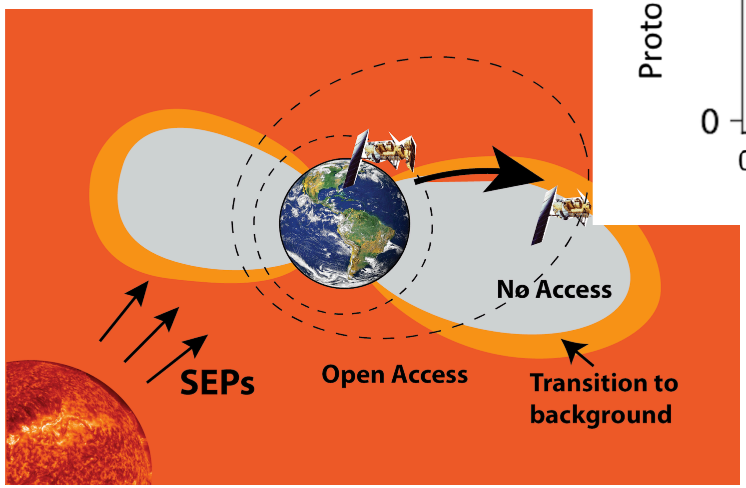
Access Regions

- Earth’s magnetic field deflects some ions
- Access depends on the ion gyroradii (energy and charge)
- High fluxes are observed over the polar cap and decrease at lower latitudes



High energy ions are accelerated at the shock front that forms ahead of CME’s

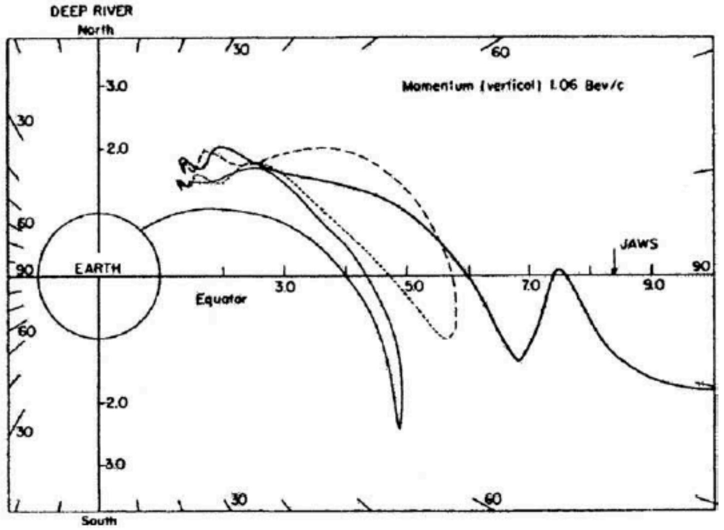


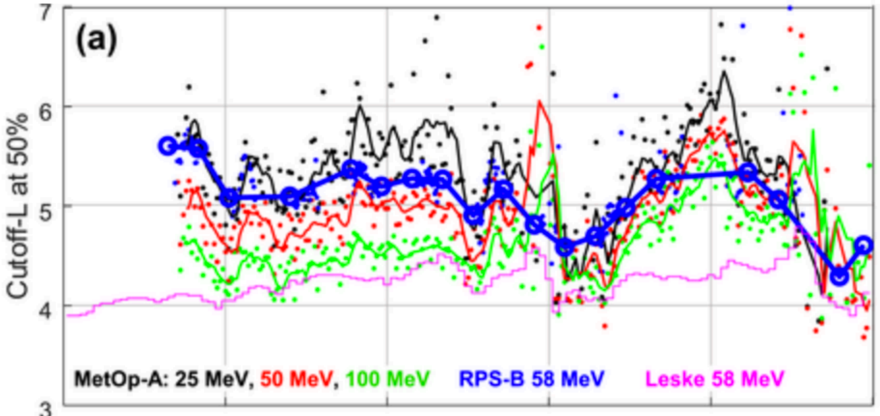


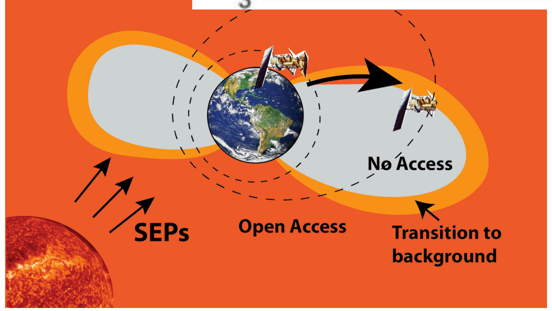
Single Event Effects: SEP’s

Modeling Access Regions

- Real-time particle tracing
  - CISM-Dartmouth model defines particles that can access a 100 km shell around Earth in real time by tracing particle trajectories outward from gridded locations in a dynamic magnetic field.
  - Being used as a boundary condition for proton impacts at airline altitudes (NAIRAS)
  - Computationally intensive
- Pre-determined particle tracing
  - Smart and Shea model parameterizes access with Kp and T89 field model but doesn’t capture observed variability of access
- Real time measurement models
  - SPAM model uses POES data to map access regions throughout the magnetosphere





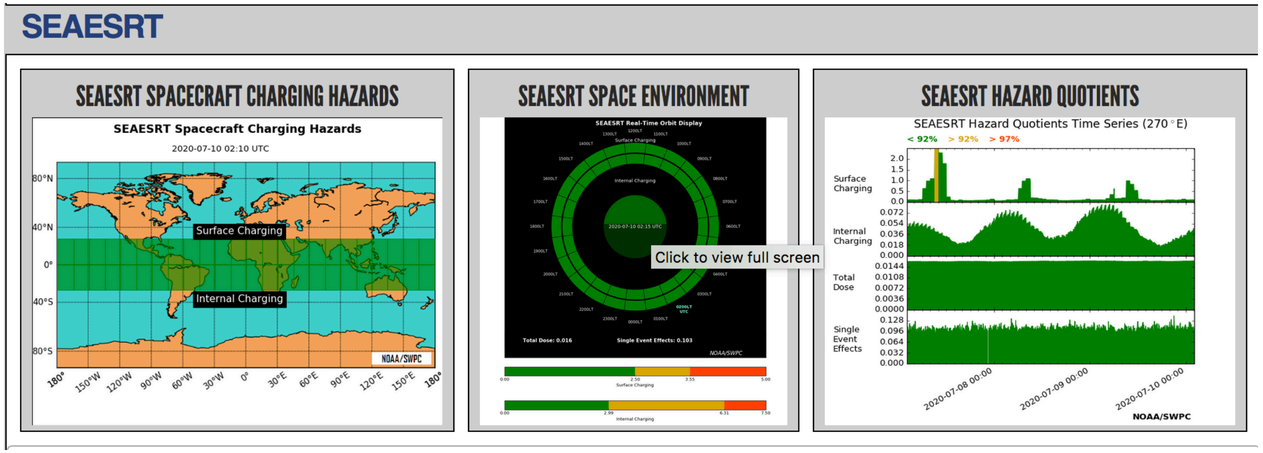


Earth’s magnetic field deflects some of the ions near the equator

Applications Examples

SEAESRT (SWPC)

- Specifies hazard of a SEU anomaly at GEO based on statistical correlation of Kp and anomaly databases



https://www.swpc.noaa.gov/products/seaesrt

Review Question:

Which hazard should be the focus for new observations, research, application development?

- Surface Charging – Caused significant anomalies in the past, challenging to model, very few applications available, affects LEO to GEO
- Internal Charging- Caused significant anomalies in the past, some real time models available, some applications available, significant at GEO
- Single Event Effects – Caused fewer anomalies in the past, feasible to model, few applications available, happens infrequently, affects GEO and could have a big impact on new space LEO/MEO satellites

Questions?

The Issue

Space weather → *Increases energy input to the ionosphere/ thermosphere* → *Increases height and neutral density* → *Increases drag and trajectory uncertainties*

Image Credit NASA/SDO

Image Credit NASA Goddard

Response:

Raise your hand if you are working with cubesats?

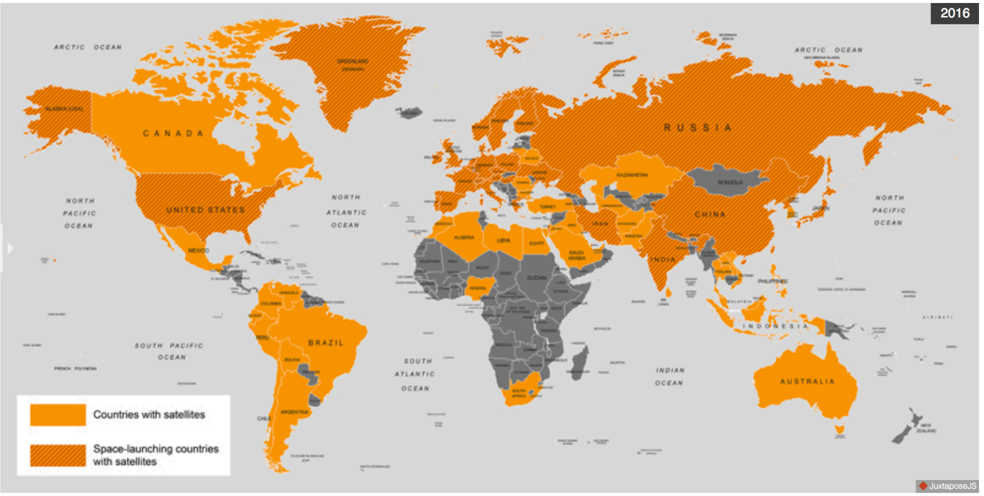
(Push the raise hand button next to your name)

The Issue

Total number of operating satellites: 2,666 (through 03/2020)

- United States: 1,327, Russia: 169, China: 363, Other: 807
- LEO: 1,918 MEO: 135 Elliptical: 59 GEO: 554

  - https://www.ucsusa.org/resources/satellite-database



The Issue: Satellites, satellites everywhere

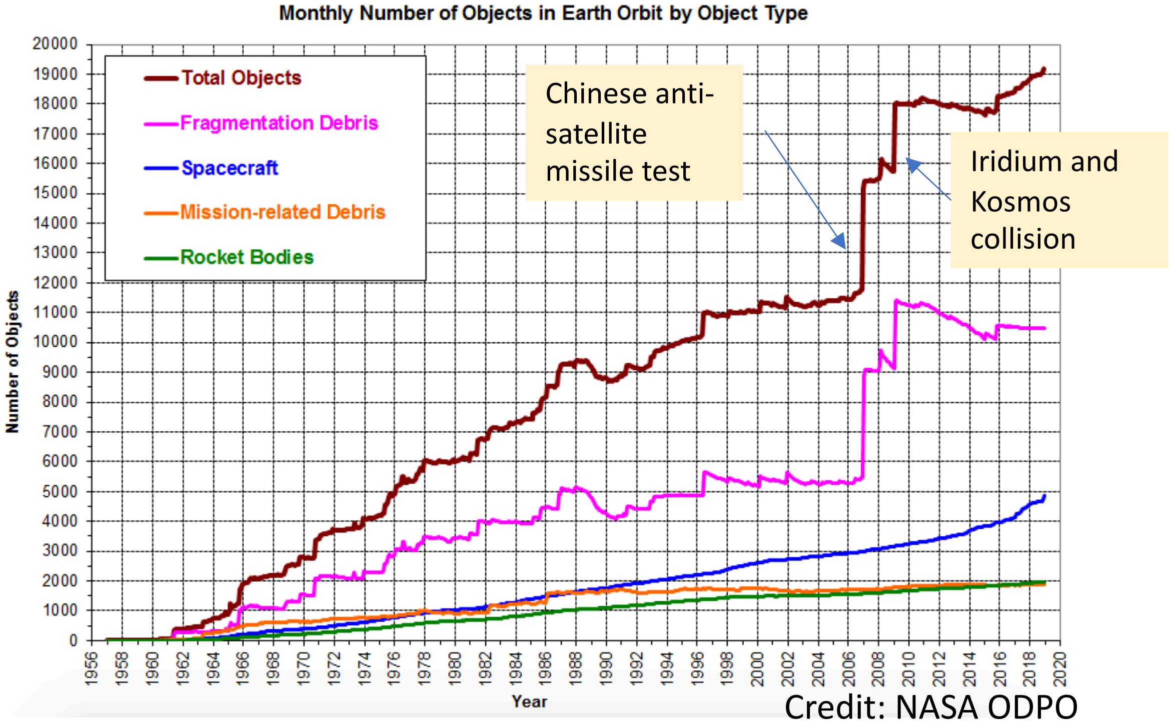
2017	Globalstar
2018	ExactView, Iridium
2019	HawkEye 360, Helios, PlanetiQ, SpaceX, Spire Global
2020	ICEYE, Karousel, OneWeb, Satellogic, SkySat, Space Norway, SpaceX, Spire Global
2021	GeoOptics, OneWeb, SpaceX, Spire Global, Umbra, ViaSat
2022	AISTech, Amazon, Astrocast, BlackSky, Dauria, Efir, Hongyan, Kepler, LaserFleet, NorthStar, OneWeb, SpaceX, Spire Global, UrTheCast
2023	Amazon, Astro Digital, Boeing, Efir, ExactView, Hera Systems, Hiber, O3B, OneWeb, Orora Tech, Planet Labs, SpaceX, Spire Global, Swarm, [illegible]
2024	Amazon, Boeing, Efir, EightyLEO, Harris, LeoSat, LuckyStar, NSLComm, OneWeb, SpaceX
2025	AISTech, Amazon, AprizeSat, Axelspace, Boeing, Capella, CommSat, Earth-I, Efir, Fleet Space, GHGSAT, OneWeb, OrbComm, Reaktor, SpaceX Technologies, Xingyun, Yaliny
2026	Boeing, OneWeb, SpaceX, Spire Global, Telesat
2027	Boeing, Canon, OneWeb, Sky and Space Global, SpaceX
2028	Audacy, Boeing, SpaceX, Theia
2029	Boeing, SpaceX

- 57,000 planned satellites through 2029

https://www.youtube.com/watch?v=oqiO2xeMkY0

AGI
Analytical Graphics, Inc.
4.06K subscribers

The Issue: Space Debris



Chinese anti-satellite missile test

Iridium and Kosmos collision

Credit: NASA ODPO

https://orbitaldebris.jsc.nasa.gov/modeling/legend.html

Knowledge of debris from the U.S. DoD Space Surveillance Network (SSN) catalogue and work by parallel groups in other countries

Intact objects, > 1 m

- **–Old rocket bodies and spacecraft**
- **–“Operational” debris –shrouds, mounts, lens caps, etc**

Fragmentation debris, 1 mm –1 m

- **–Deliberate or accidental explosions from on-board energy sources**
  - Unvented rocket fuel
  - Active batteries
  - Self-destruct mechanisms
- **–Deliberate or accidental collisions**
  - Weapons tests
  - Random collisions
- **–Solid rocket motor slag**

Small debris, < 1 mm

- **–Deterioration of satellite surfaces in space environment**
  - Small debris impact ejecta
  - Deterioration of paint and other materials

[Mark Matney, SEAF meeting 2018]

The Issue: Kessler syndrome

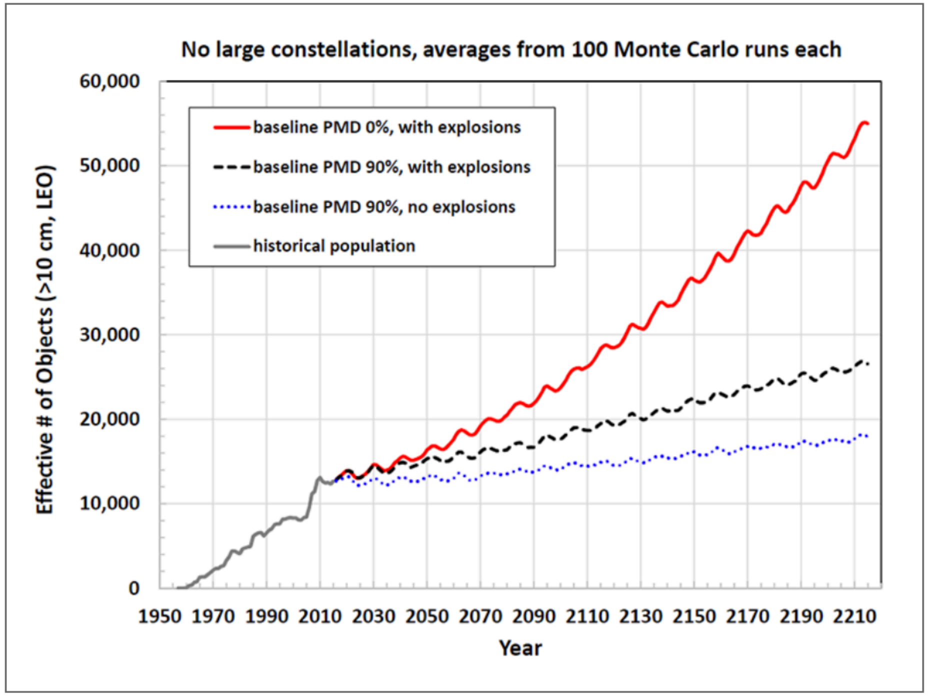


Figure 2. LEGEND-simulated historical LEO environment and results from three different future projection scenarios. Each projection curve is the average of 100 MC runs. The effective number is defined as the fractional time, per orbital period, an object spends between 200 km and 2000 km altitudes.

NASA Legend simulations shows 330% increase in debris over 200 years without Post-Mission Disposal (PMD) even without including planned mega-constellations

- The simulation assumes future launches repeat those from 2008-2015
- Accidental explosions are based on past occurrence frequencies

[MANIS, A AND D. GATES, 2019]

https://orbitaldebris.jsc.nasa.gov/quarterly-news/pdfs/ODQNv22i3.pdf

Physics: Trajectory Prediction

- Acceleration from atmospheric drag

$$\vec{a}_{drag} = -\frac{1}{2}\rho\frac{c_D A}{m}v_{rel}^2\frac{\vec{v}_{rel}}{|\vec{v}_{rel}|}$$

Neutral density

- Changes in density due to space weather caused by
  - solar radiative heating in the ultraviolet (UV) to extreme UV (EUV)
  - Joule heating
  - particle precipitation

Modeling

Semi-empirical models

- Densities inferred from observed changes in satellite trajectories
- Parameterized by measured indices
  - JB2008 (Bowman et al., 2008)
  - NRLMSISE-00 (Picone et al., 2002)

Physics based models

- Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM Richmond et al., 1992; Roble et al., 1988)
- Coupled thermosphere-ionosphere-plasmasphere electrodynamics (CTIPe; Fuller-Rowell et al., 1996)
- Global Ionosphere Thermosphere Model (GITM Ridley et al., 2006)

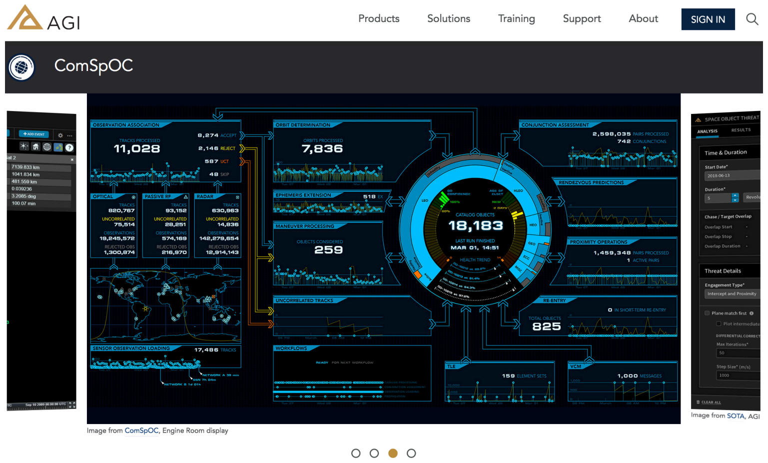
Assimilative/Ensemble model

- Dragster (Pilinski et al, 2019) uses ensembles of TIE-GCM and NRLMSIS and assimilates measured satellite location

Applications

- AGI Commercial Space Operations Center
    - Tracking satellites and providing conjunction assessments
    - Uses optical telescopes, radar systems, and passive rf (radio frequency) sensors

- Space Data Association
    - Collates independently pooled data from operators to prevent collisions
    - Space Data Center (SDC) utilises member provided ephemerides, with integrated manoeuvre information and fuses this with TLE (Two Line Elements) and SP (Special Perturbation) data from the public catalogue.



https://www.agi.com/products/comspoc

SPACE DATA ASSOCIATION

https://www.space-data.org/sda/

Summary

- The number of objects (satellites and debris) in space continues to grow at an unprecedented rate

- Inevitably, there will the need for better modeling and predictions

The Issue

Space weather → *Creates ground induced currents (GIC's)* → *Causes large scale power outage*

Image Credit NASA/SDO

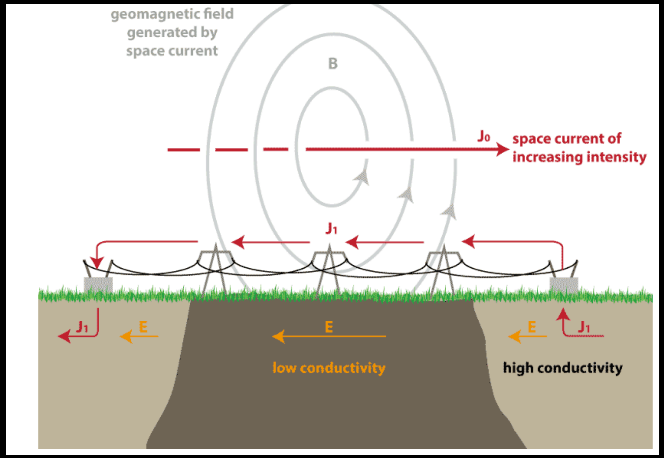
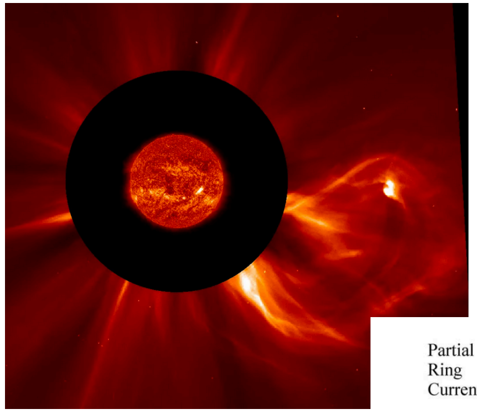
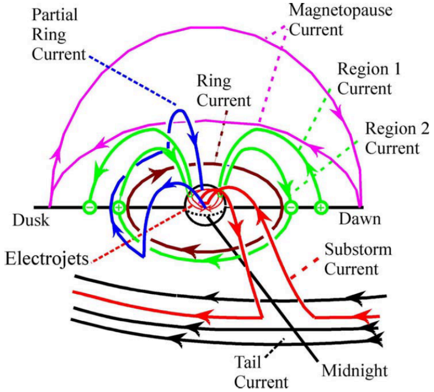


Image Credit: USGS

The Impacts

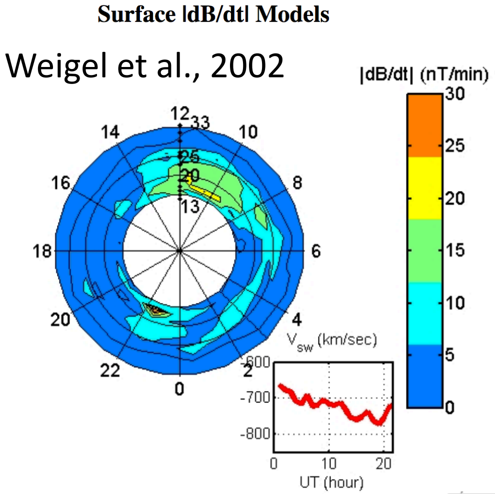


Large CME's are associated with power grid issues

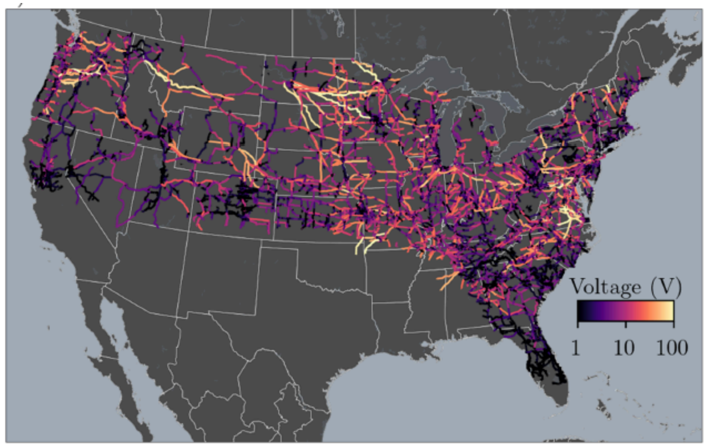


The impact of the CME and sudden dynamic pressure increase (SSC) followed by the ensuing storm and substorms increase currents that close in the ionosphere.

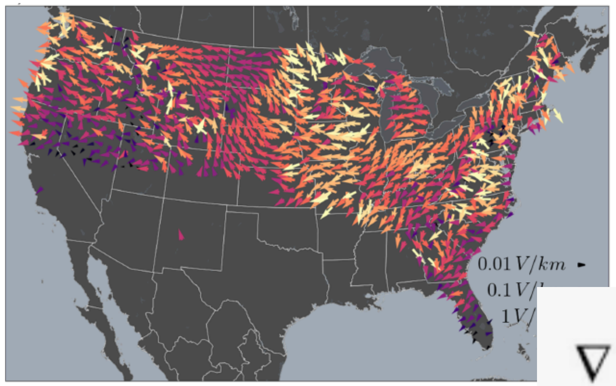
Weigel et al., 2002



The currents create dB/dt measured on the ground

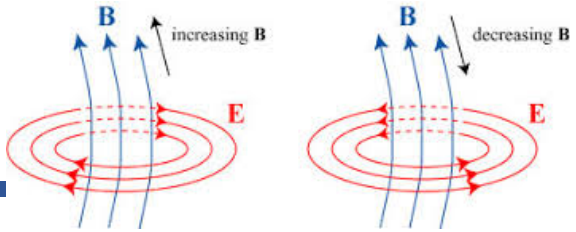


The E field creates a potential and DC currents along transmission lines



The dB/dt creates an induced E field at Earth's surface

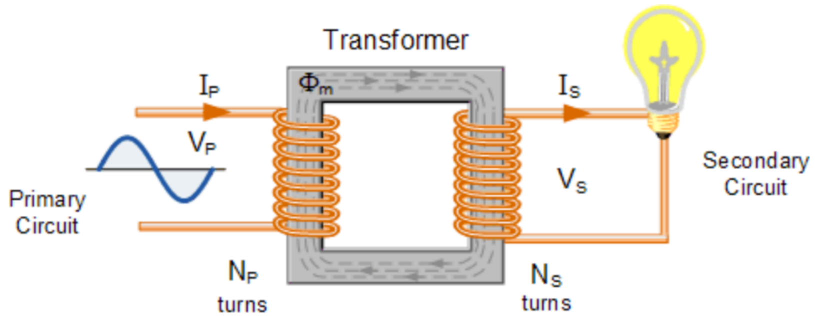
$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$

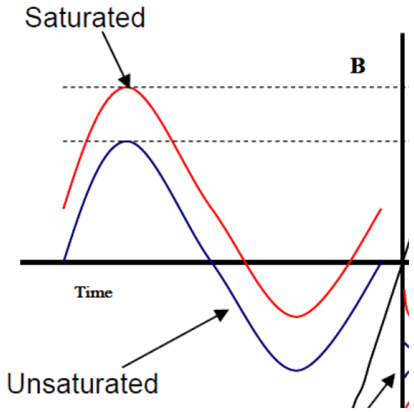


The Impacts: Engineering

GIC interaction with high voltage transformers connecting long distance transmission lines to the grid

- DC current creates an offset in the transformer’s oscillating magnetic field called half cycle saturation [*Price,* 2002]
- The unusual magnetic field creates harmonic signals which can trip protective equipment and disconnect parts of the grid
  - Caused the 2 space weather blackouts
- Can cause transformer heating and incremental damage or melting of copper wiring [*Kappenman,* 2010].
  - Less concerning because heating has to be sustained
  - FERC has identified 30 high voltage transformers as critical
  - Loss of 9 could result in coast to coast blackout [Weiss and Weiss, 2019; Parfomak 2014)
- Can cause an increase in reactive power absorption and voltage instability
  - Most concerning to industry (Abt Associates, 2017)





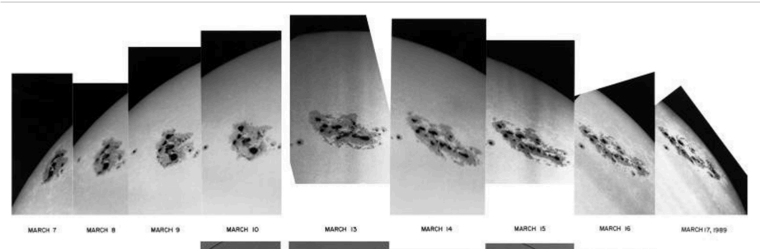
Source: NERC GMDTF Interim Report, February 2012

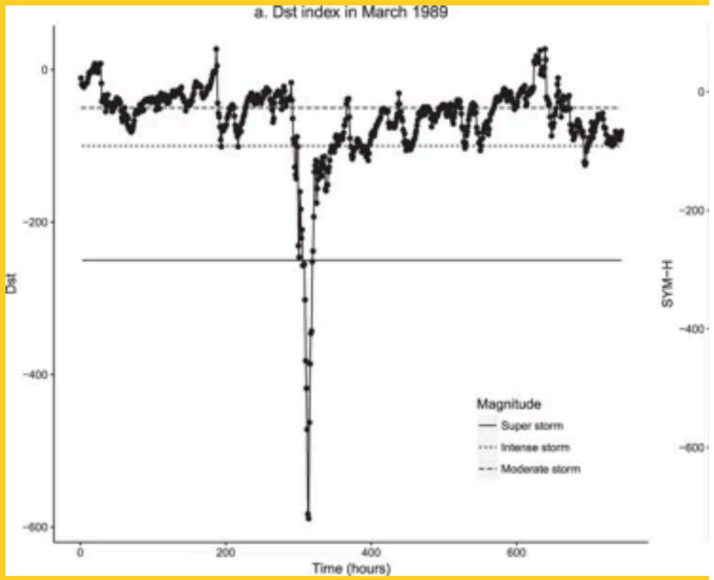
Reactive power: when the current and voltage wave forms are out of phase

The Impacts: Examples

March 1989 Hydro Quebec power system outage [Boteler, 2019]

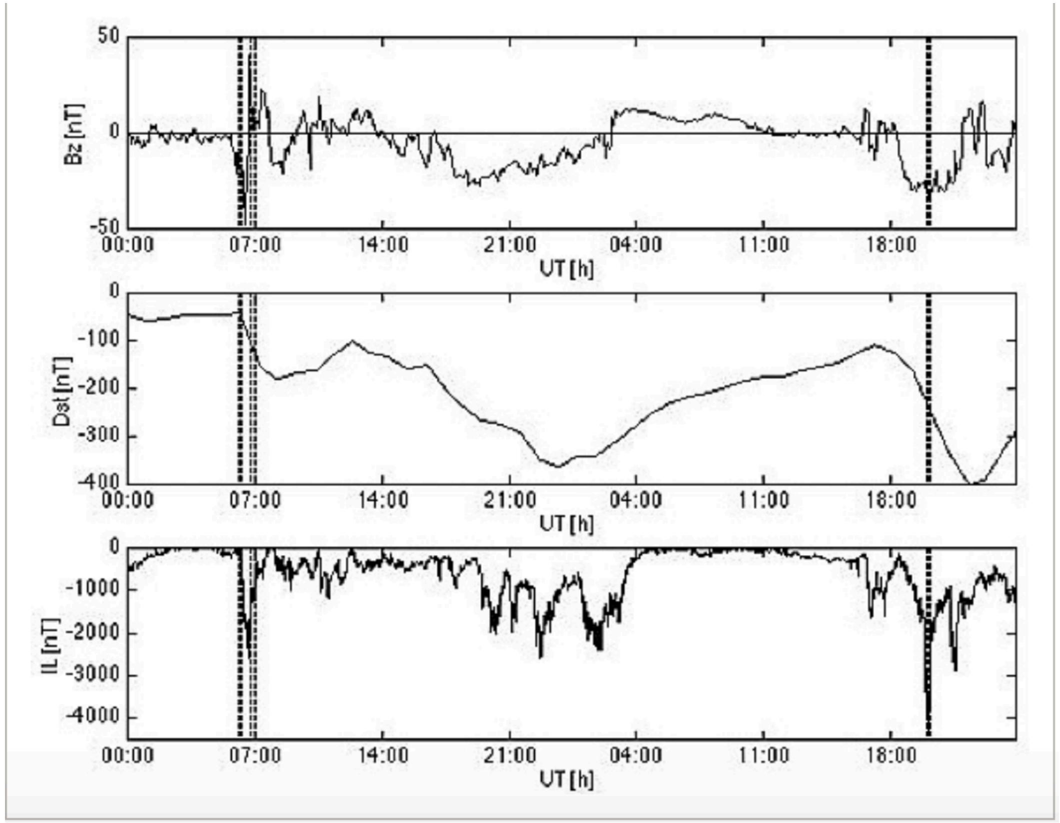
- One of the most active sunspot groups observed Mar 6-18
- 19 >M5 Xray flares
- No available solar wind data but flares and ground magnetic field data suggest 2 ICMES: 760 km/s and 1,320 km/s
- Magnetic storm ensued (Dst -589)
- Large substorm current signature was observed at the time of the outage with ground magnetometers in Canada
- Power system went unstable and protection relays shut down the system (Bolduc, 2002; Czech et al., 1989; Guillon et al., 2016).
- Blackout lasted 9 hours for 6 million people
- Destroyed transformer at the Salem nuclear plant in New Jersey
- Until this event, impacts to power grids had been discounted





(Morina etal., 2019)

The Impacts: Examples

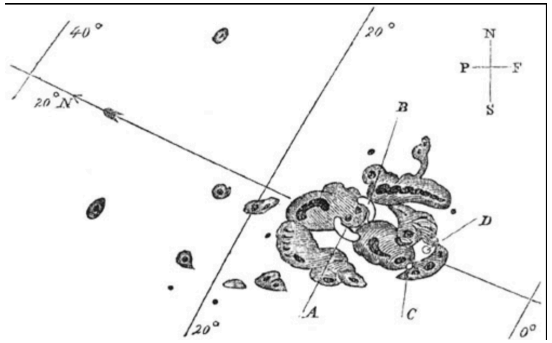


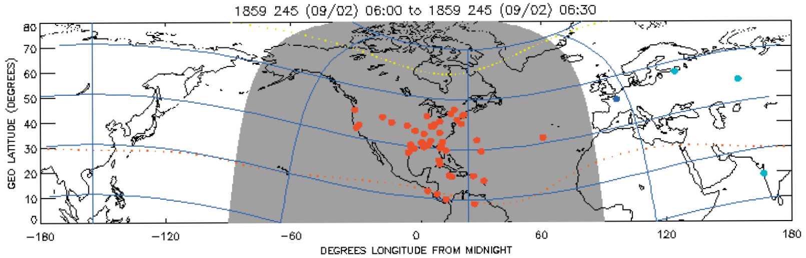
Oct 29-31 2003 Sweden power outage [Pulkkinen et al, 2005]

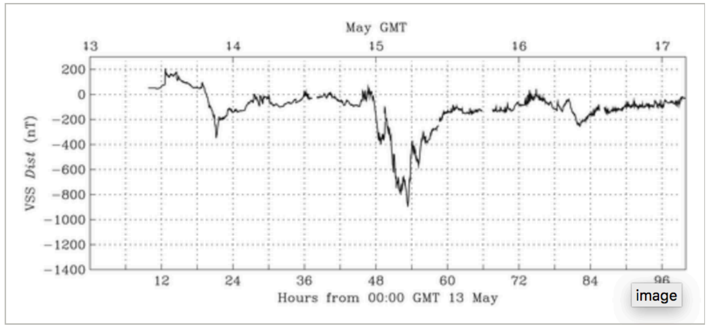
- Period of intense solar activity lasted from from October 19 to November 05, 2003
- 2 CMEs on the 29th
- First caused a 2 phase storm Dst -180, -360
- Second caused 3 step storm -400 Dst
- Substorms, SSCs and enhanced ionospheric convection produced large GIC's
- Harmonics tripped circuit breaker caused the power outage
- Oct 30 50,000 customers in without power for 1 hour
- Economic losses in terms of unserved electricity estimated to be ~0.5 million US $

The Impacts: Superstorms

- Carrington Sep 1859
  - >X10 SXR flare event (in top 100) (Cliver and Dietrich, 2013)
  - Dst = -900 (+50, -150) nT (Cliver and Dietrich, 2013)
  - Aurora was so bright that gold miners in the Rocky Mountains woke up and ate breakfast at 1 a.m (Oldenwald and Green, 2008; National Academies Press, 2008)
  - Philadelphia Evening Bulletin reported, “and there were numerous side displays in the telegraph offices where fantastical and unreadable messages came through the instruments, and where the atmospheric fireworks assumed shape and substance in brilliant sparks.” (National Academies Press, 2008)
  - Risk of another Carrington
    - 12% per decade (Riley, 2012)
    - 0.46% and 1.88% per decade (Morina, 2019)
- New York Railway Storm May 1921
  - Dst from 4 low latitude observatories -907 nT (Love et al., 2019)
  - Lowest latitude observation of aurora Apia, Samoa (13.83 S 171.75 W; 15.3 S geomagnetic latitude, ca. 1920; Angenheister & Westland 1921).
- July 2012
  - Non Earthward CME observed by Stereo would have generated a Carrington scale event (Baker et al., 2013)







(Love et al., 2019)

The Impacts: Economic Impacts

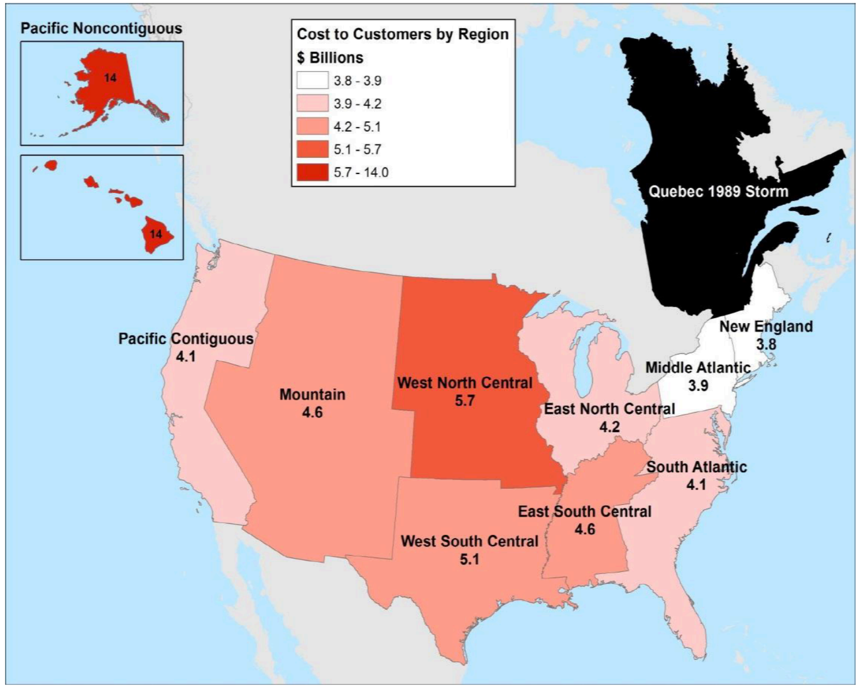


Figure 5. Cost estimate for moderate event that causes a ~6 hour outage impacting ~6 million customers in different regions of the country. Estimates derived using state-level data provided by the Energy Information Agency and the Department of Energy's Interruption Cost Estimate (ICE) Calculator (see Table 8).

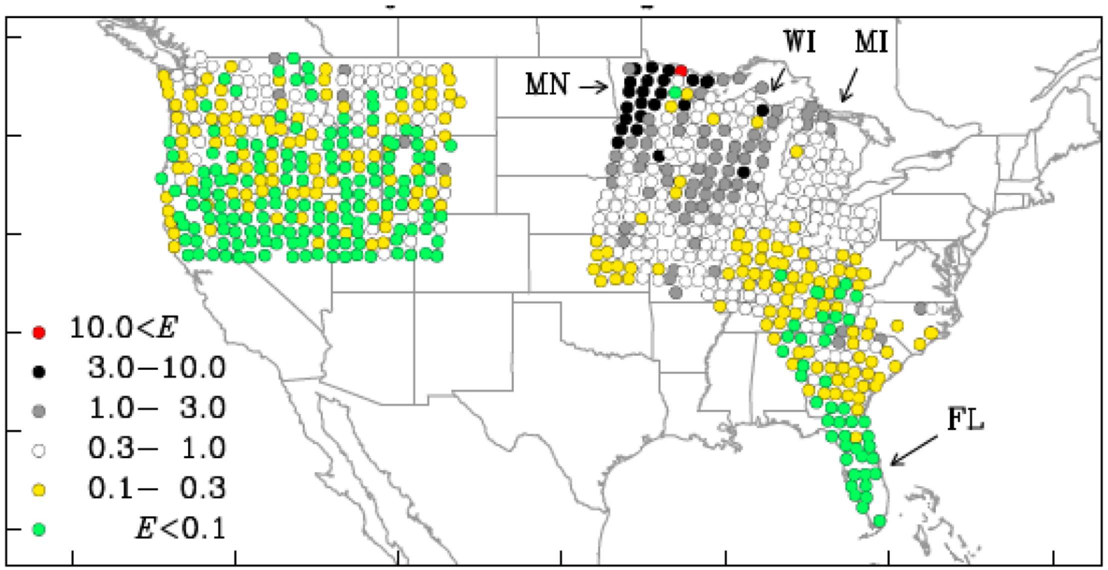
Social and Economic Impacts of Space Weather in the United States

ABT Associates study (2017)

https://www.weather.gov/media/news/SpaceWeatherEconomicImpactsReportOct-2017.pdf

- Hardening the US power grid ~$50 million to $1 billion
  - ~2000 Extra High Voltage transformers are the greatest concern ($ 4.5-7.5 million)
  - 1-10% might be vulnerable, replacement up to $ 1 billion
  - GIC blocking devices ~$500,000 but might push problem elsewhere
- Service Interruptions from a blackout
  - $ 400 million to 10 billion (moderate 1989 type event 6 h over a portion of US)
  - $ 1-20 billion (extreme events 9 h entire US)
  - Based on lost power cost estimates and the cost to customers from (www.icecalculator.com) or Value of Lost Load (VOLL), $5,000 to $10,000 per MWh (*London Economic International LLC,* 2013),

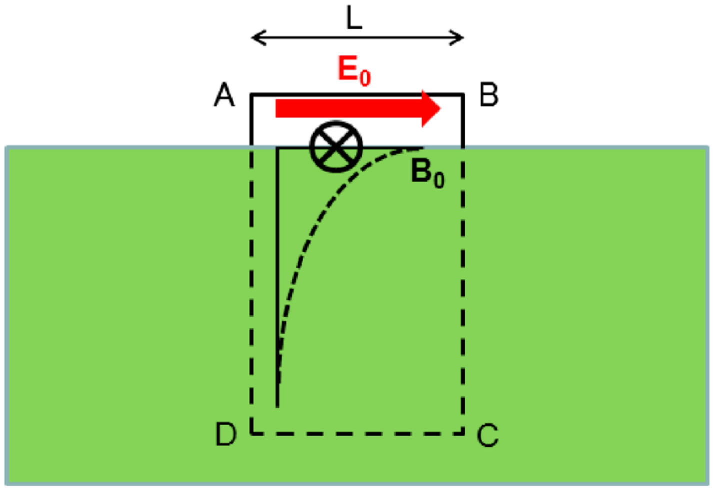
The Impacts: Benchmarks



Source: Love et al., “Geoelectric Hazard Maps for the Continental United States,” *Geophysical Research Letters* 43 (18, 2
9415–9424, doi:10.1002/2016GL070469
Note: No estimates are available outside of survey sites shown.

- Recognizing the severity of the impacts the US created a Space Weather Action Plan that called for the definition of benchmarks that would give the 1/100 value and theoretical maximum of the E field
- The median 1/100 value in the US was given as .26 V/km
- No theoretical maximum was defined
- Work to refine the estimates is ongoing

GIC’s: The Physics



Boteler and Pirjola, 2106

The simplest picture assumes the conductivity is uniform

- Assume **B** = $B_0e^{i\omega t}$
- From Maxwells equations

$$\nabla X\boldsymbol{E} = -\frac{d\boldsymbol{B}}{dt} = -\,i\omega\boldsymbol{B} \qquad \nabla X\boldsymbol{B} = \ \mu_0\sigma\boldsymbol{E}$$

- Take the curl of the first and plug in the second

$$\nabla^2\boldsymbol{E} = i\omega\mu_0\sigma\boldsymbol{E}$$

- The solution is $E = \ E_0e^{-\frac{z}{p}}$, $p = 1/\sqrt{i\omega\mu_0\sigma}$ assuming only variation in z and uniform σ
- Plugging into the first relates E and B
- $-\frac{E_0}{B_0} = \left(\frac{i\omega}{\mu_0\sigma}\right)^{\frac{1}{2}} = Z/\ \mu_0$ where Z is the magnetotelluric surface impedance
- Low conductivity => large E
- High frequency=> large E
- Large dB/dt => large E
- In this 1-D constant conductivity approximation E is always perpendicular to B

GIC’s: 3-D Impedances

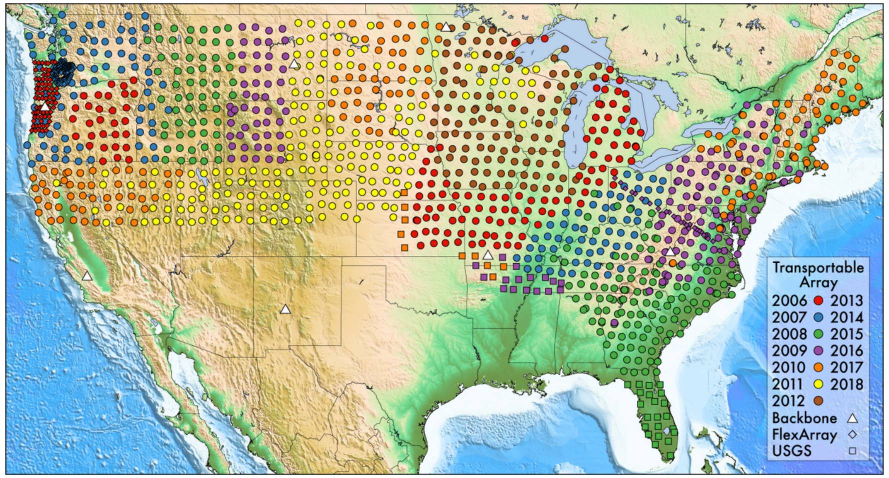
- Earth is not a uniform conducting slab
- Measure the empirical relationship (impedance) between E and B as a function of ω at all locations
- Impedances are being measured across the US by the Earthscope project
  - Using a fluxgate magnetometer and electrodes in the north south direction, the E and B fields are measured simultaneously for a week at 70 km spacing
- In the frequency domain $\mathbf{E}(\omega) = \mathbf{Z}(\omega)\mathbf{B}(\omega)/\mu,$
- In the one dimensional model

$$\begin{bmatrix} E_x(\omega) \\ E_y(\omega) \end{bmatrix} = \begin{bmatrix} 0 & Z(\omega) \\ -Z(\omega) & 0 \end{bmatrix} \begin{bmatrix} B_x(\omega) \\ B_y(\omega) \end{bmatrix}$$

- In the 3-D model

$$\begin{bmatrix} E_x(\omega) \\ E_y(\omega) \end{bmatrix} = \begin{bmatrix} Z_{xx}(\omega) & Z_{xy}(\omega) \\ Z_{yx}(\omega) & Z_{yy}(\omega) \end{bmatrix} \begin{bmatrix} B_x(\omega) \\ B_y(\omega) \end{bmatrix}$$

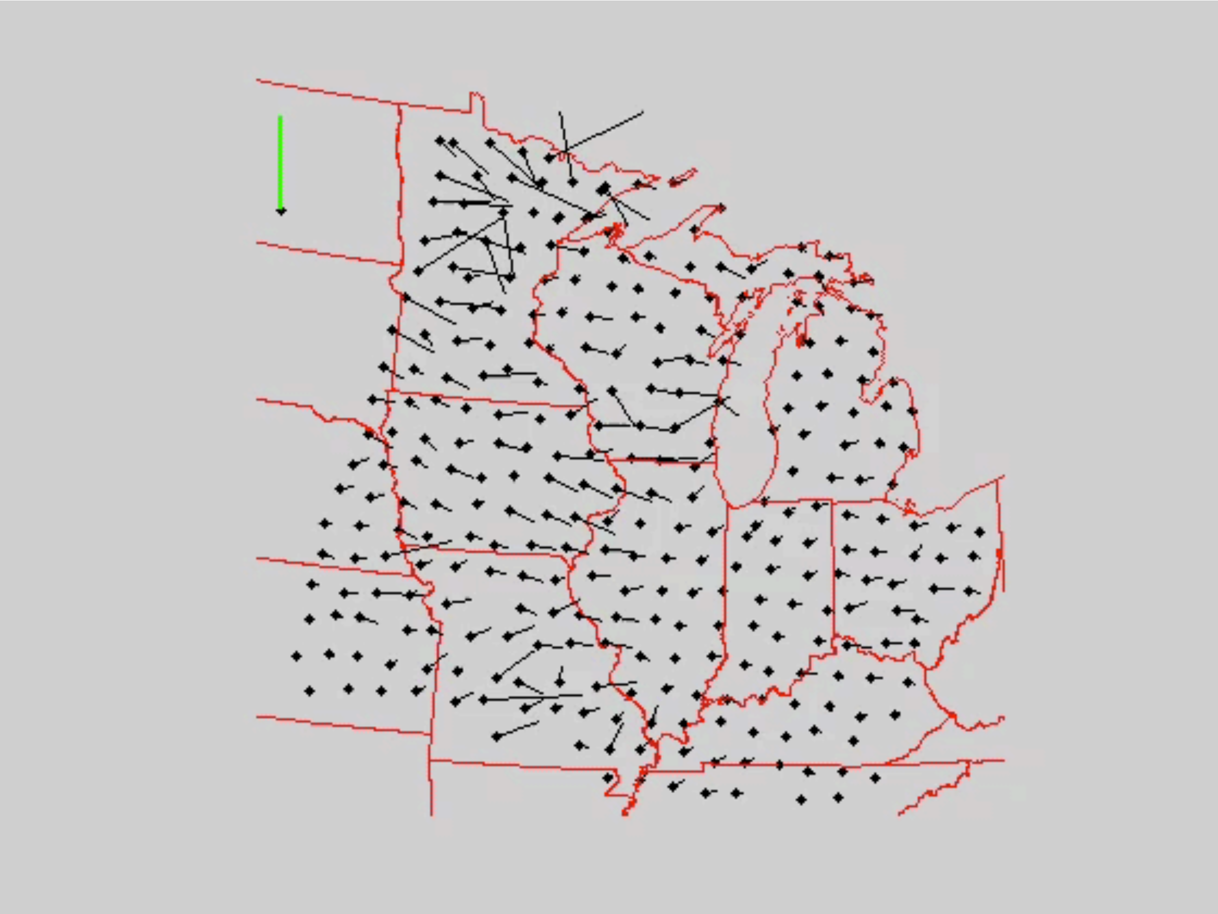
Status Map



Footprints of MT-TA (by year), MT-BB, and MT-FA (iMUSH, MOCHA onland, and MAGIC) stations that were operated from 2006-2018 during EarthScope. Click to enlarge

http://www.usarray.org/researchers/obs/magnetotelluric/

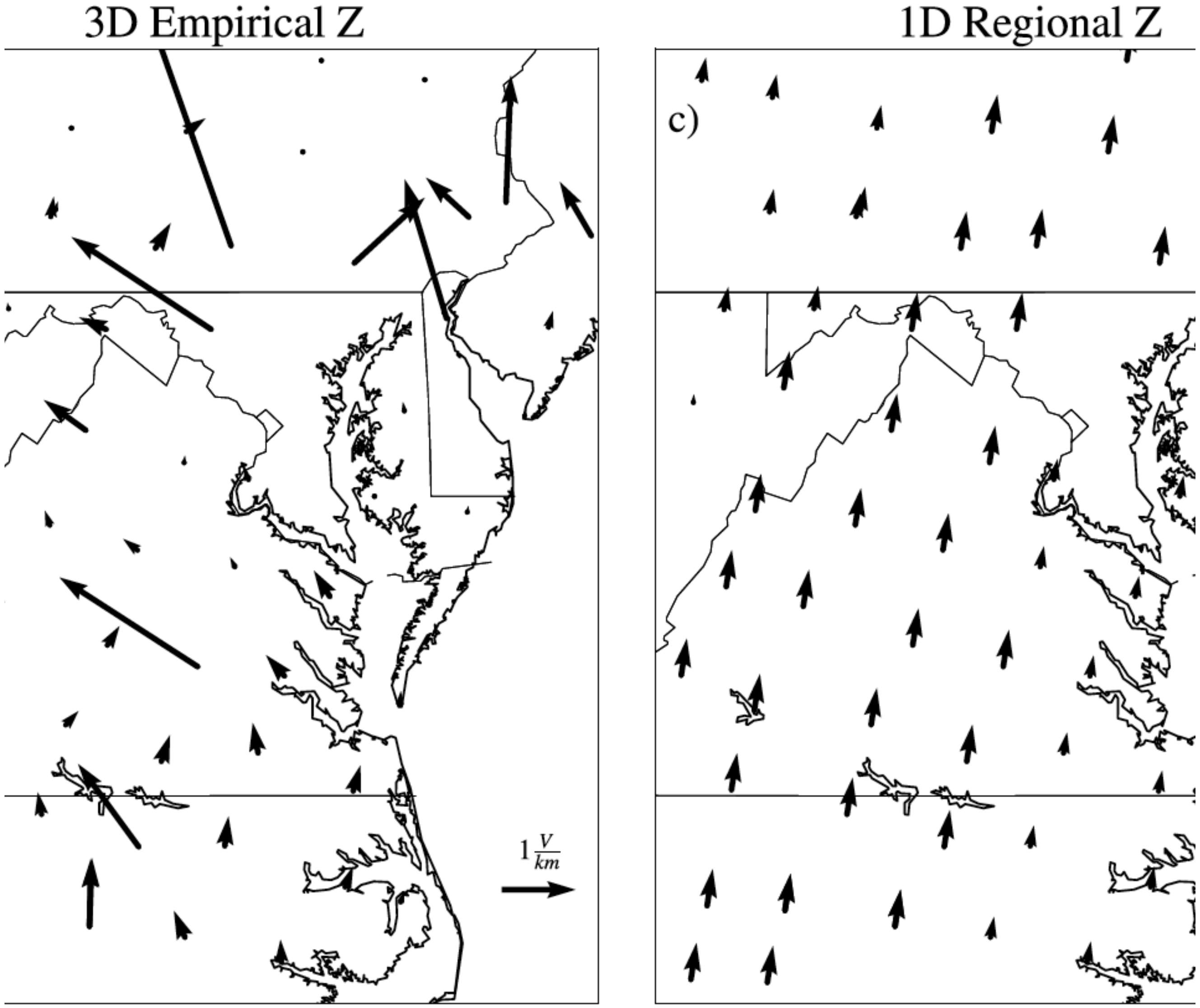
Effect of 3-D Impedances



Bedrosian et al., 2016

1-D versus 3-D

- 3-D impedances creates significant changes in the induced E field

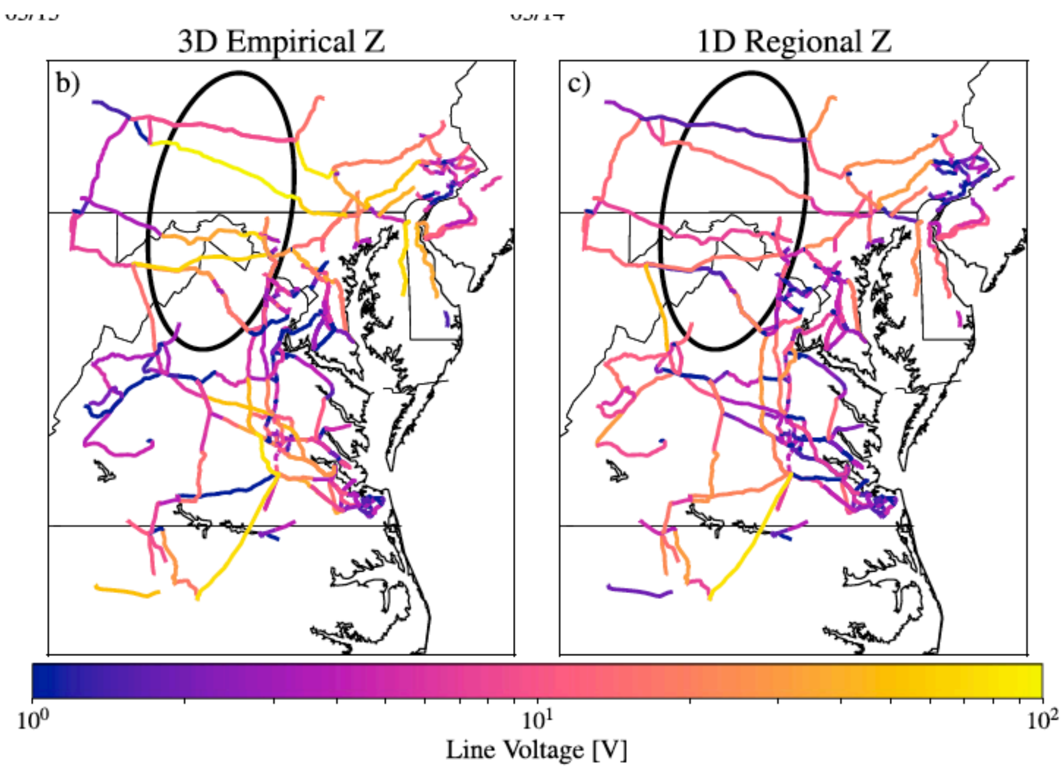


Lucas et al., 2017

GIC’s: Potentials across the grid

- E fields need to be interpolated
- Potentials are calculated across the grid lines between power substations

$$V(t) = \int_{\mathrm{L}} \mathbf{E}(t) \cdot \mathrm{d}\mathbf{l},$$



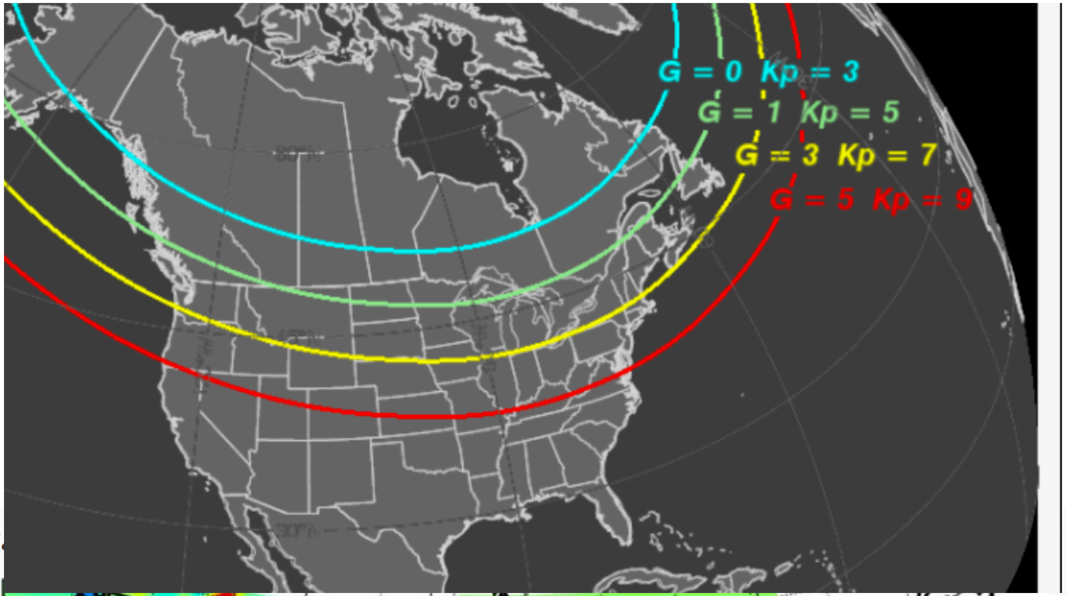
Lucas et al., 2017

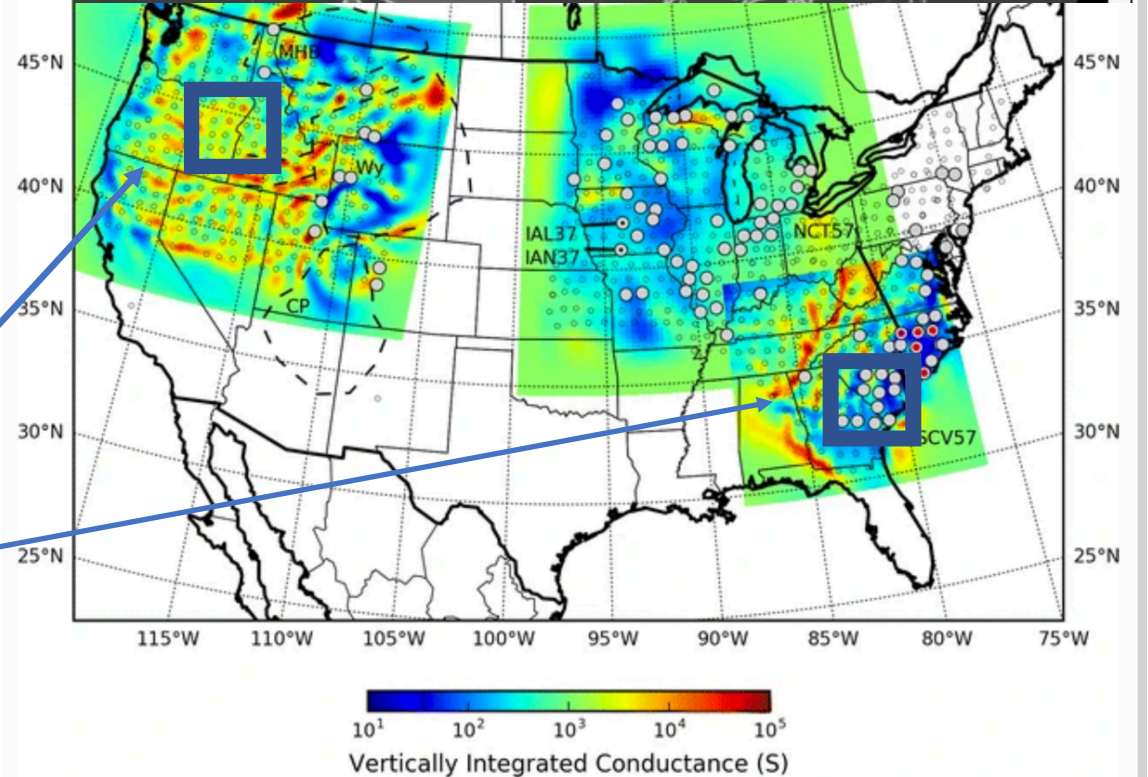
Question:

$$-\frac{E_0}{B_0} = \left(\frac{i\omega}{\mu_0\sigma}\right)^{\frac{1}{2}}$$

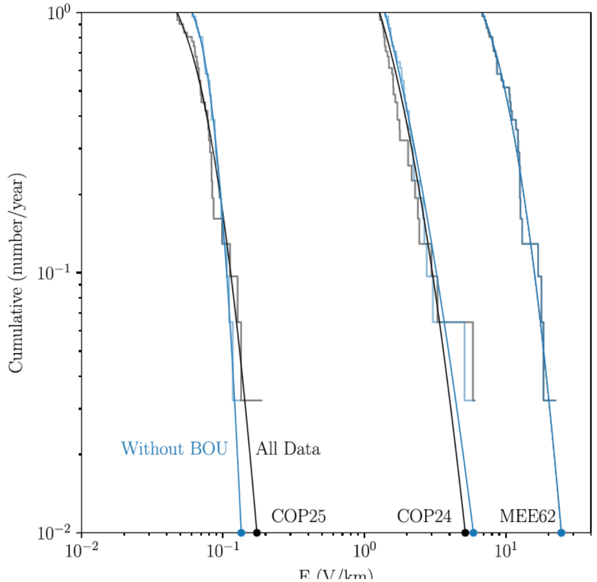
- Large E fields are associated with low conductivity and large dB/dt
- Large dB/dt is observed in the high latitude auroral regions
- Low conductivity is observed in the southeast
- Which region do you think will have a larger E during an extreme event?

box 1: high latitude high conductivity
box 2: low latitude low conductivity



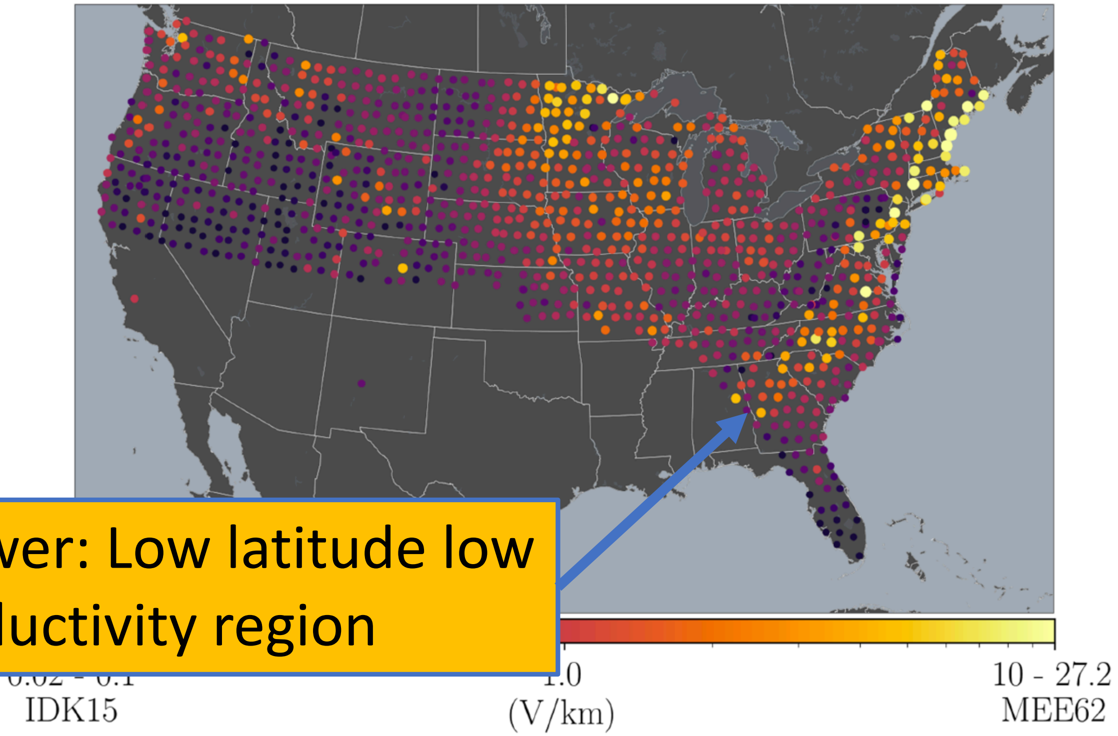


The Impacts: 100 yr E fields



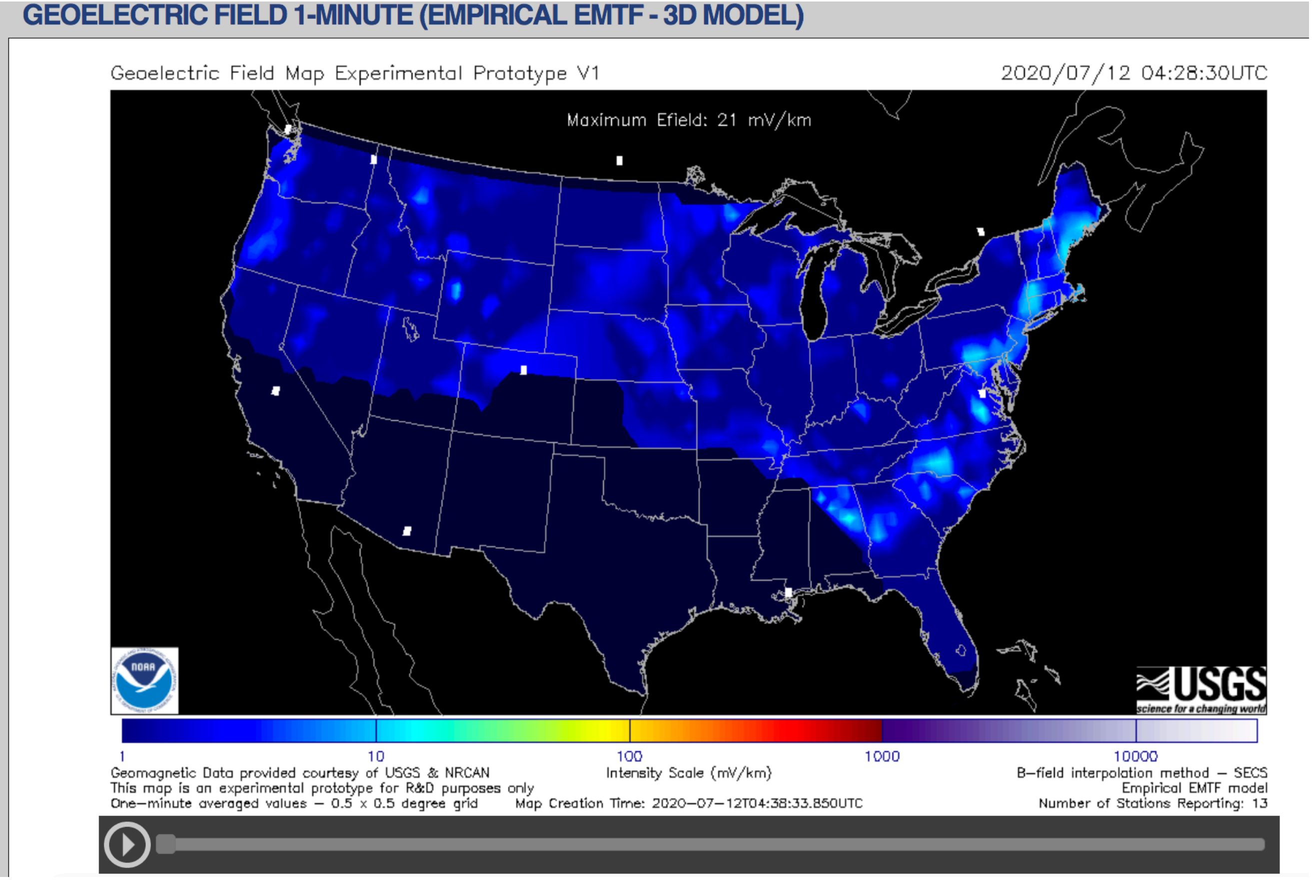
100 yr E fields (Lucas et al., 2019)

- Identified 84 large storms in ~30 years of data(Dst<-140 and Kp>8)
- Used measured B and measured Z to create time series of E for each storm
- Find the max B_{site}, E_{site} and V_{line} at each location
- Calculate cumulative distributions of the # of storms /year with max values above different thresholds
  - fit to a log-normal to extrapolate to 1/100 year value at each location



Answer: Low latitude low conductivity region

Models: Nowcasts


GEOELECTRIC FIELD 1-MINUTE (EMPIRICAL EMTF - 3D MODEL)

Geoelectric Field Map Experimental Prototype V1

2020/07/12 04:28:30UTC

Maximum Efield: 21 mV/km

Geomagnetic Data provided courtesy of USGS & NRCAN
This map is an experimental prototype for R&D purposes only
One–minute averaged values – 0.5 x 0.5 degree grid

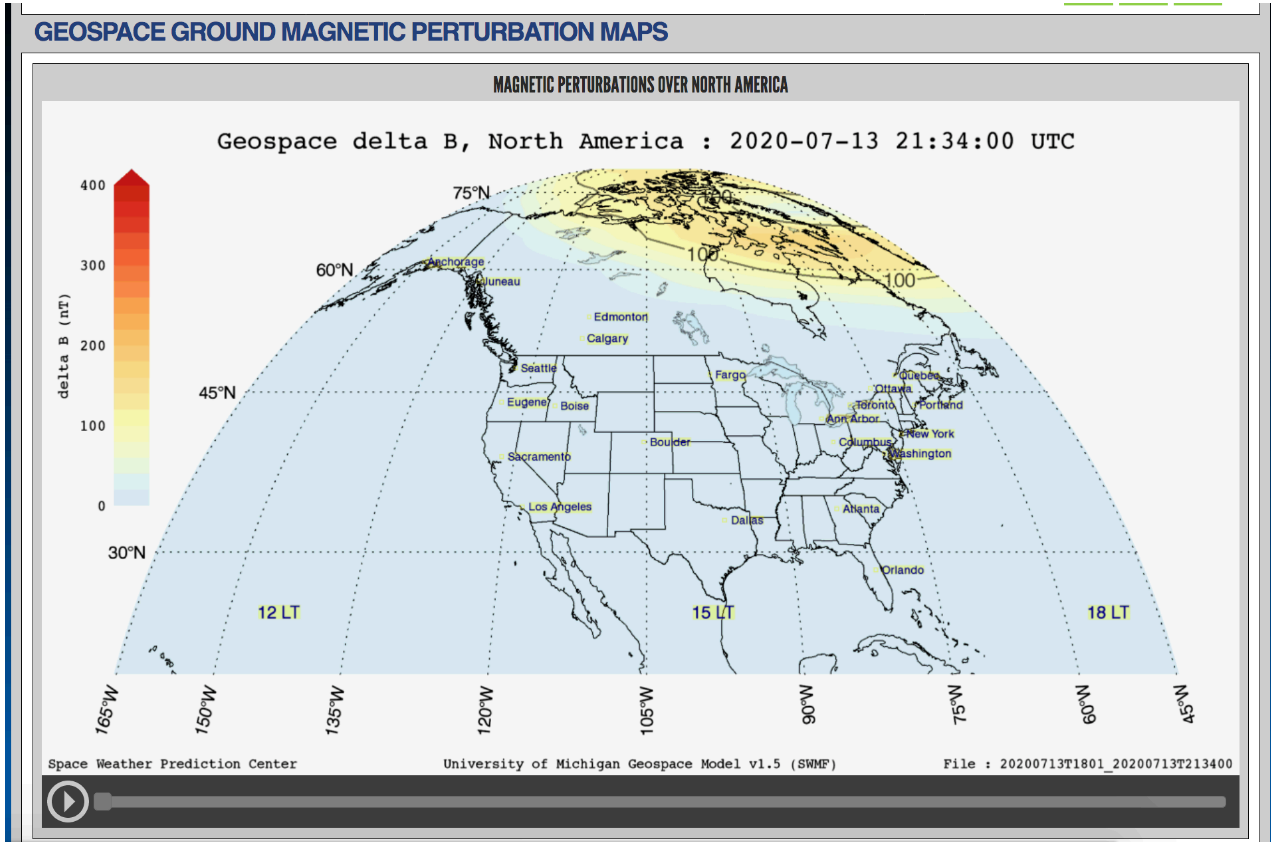
Intensity Scale (mV/km)

Map Creation Time: 2020–07–12T04:38:33.850UTC

B–field interpolation method – SECS
Empirical EMTF model
Number of Stations Reporting: 13

- SWPC provides real time movies of the US Geoelectric field using 3-D conductivities

Models: Forecasts



GEOSPACE GROUND MAGNETIC PERTURBATION MAPS

MAGNETIC PERTURBATIONS OVER NORTH AMERICA

Geospace delta B, North America : 2020-07-13 21:34:00 UTC

Space Weather Prediction Center

University of Michigan Geospace Model v1.5 (SWMF)

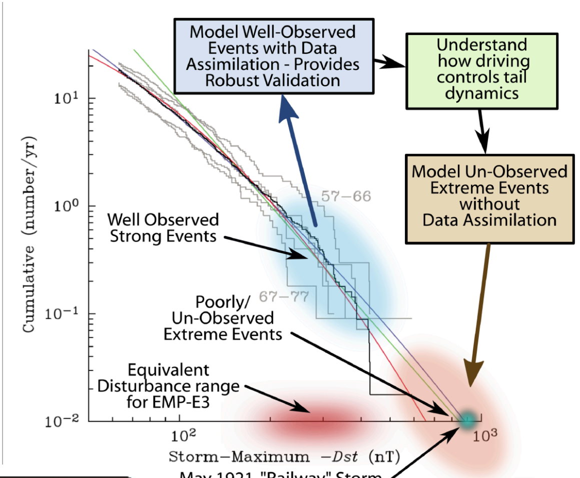
File : 20200713T1801_20200713T213400

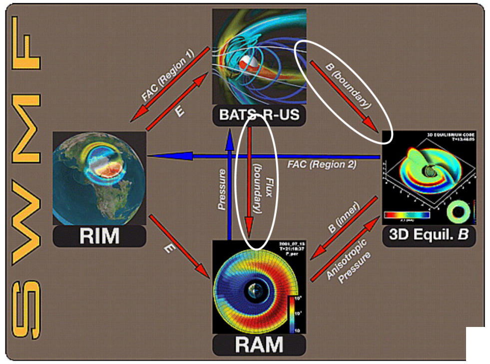
- Power grid operators need 3-6 hour forecast (ABT, 2019)
- One way to forecast E is with dB/dt from physics based models.
- SWPC currently provides a forecast of delta B from the University of Michigan’s Geospace model
- Uses several components in the Space Weather Modeling (SWMF).
  - University of Michigan’s BATS-R-US magnetohydrodynamic (MHD) model of the magnetosphere;
  - Ridley Ionosphere electrodynamics Model (RIM) developed at Michigan;
  - Rice Convection Model (RCM), an inner magnetosphere ring-current model developed at Rice University.

https://www.swpc.noaa.gov/products/geospace-ground-magnetic-perturbation-maps

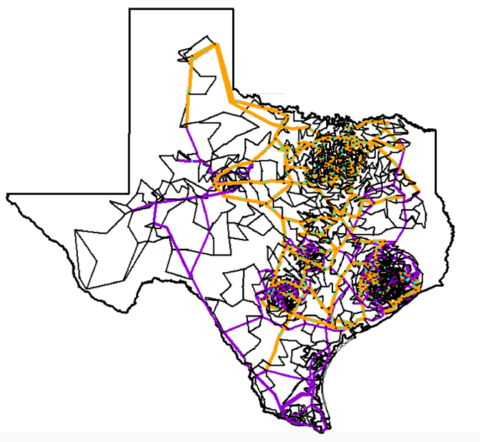
Models

- LANL Carrington-GIC Henderson et al., 2018
  - Improve models so they have a chance with the extreme events.
- Learn how to scale up to a Carrington-class event by modelling well-observed large events.
- Using SWMF, RAM-SCB, AMIE, LANLGeoRad (dB/dt)
- Adding data assimilation
- Include uncertainties via ensemble modelling that uses different realizations of solar wind (Morley et al., 2018)
- Power flow solver to obtain GICs on a network model





Texas 2000 Bus Model



Questions?