Impacts of Space Weather

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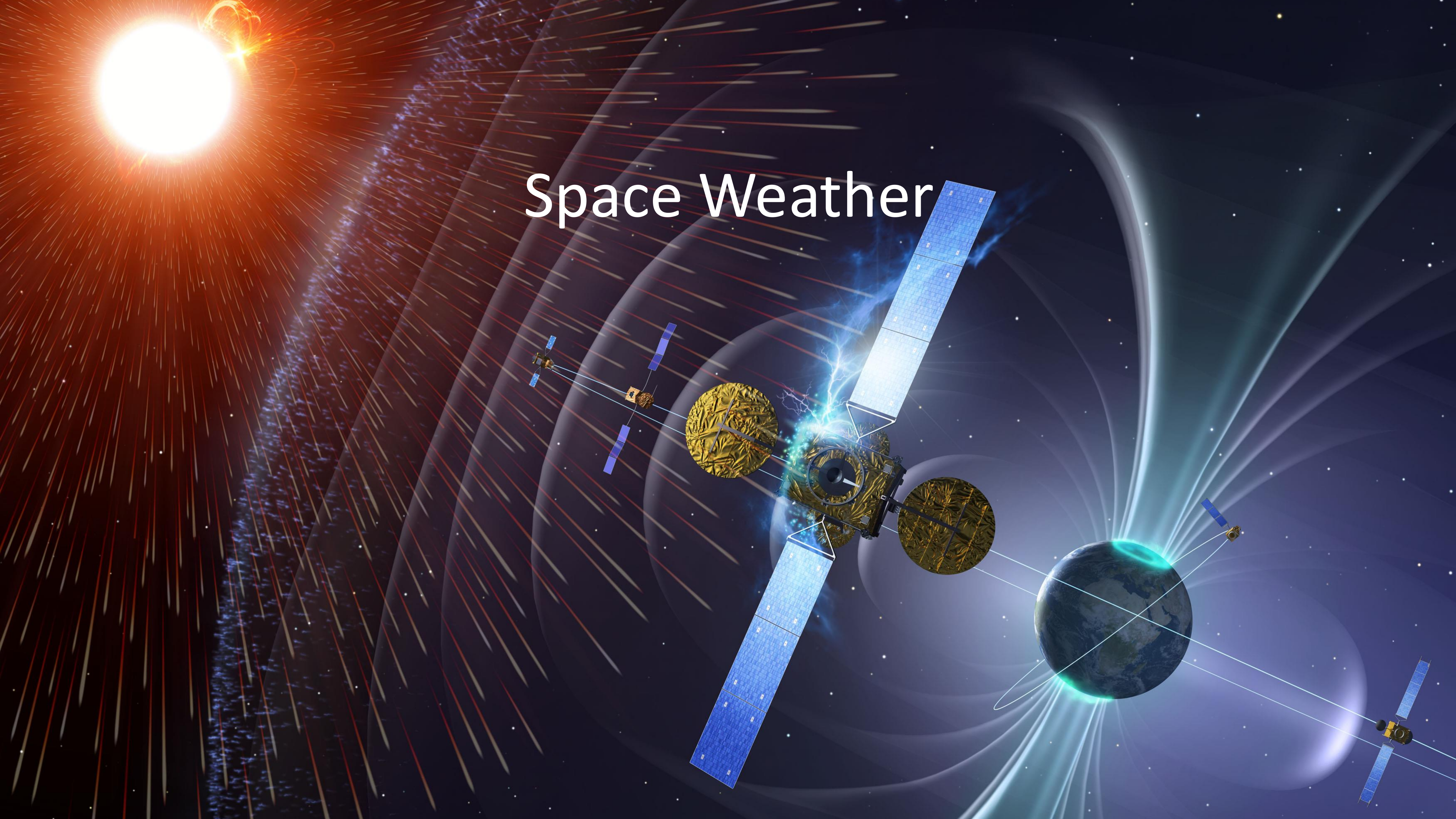
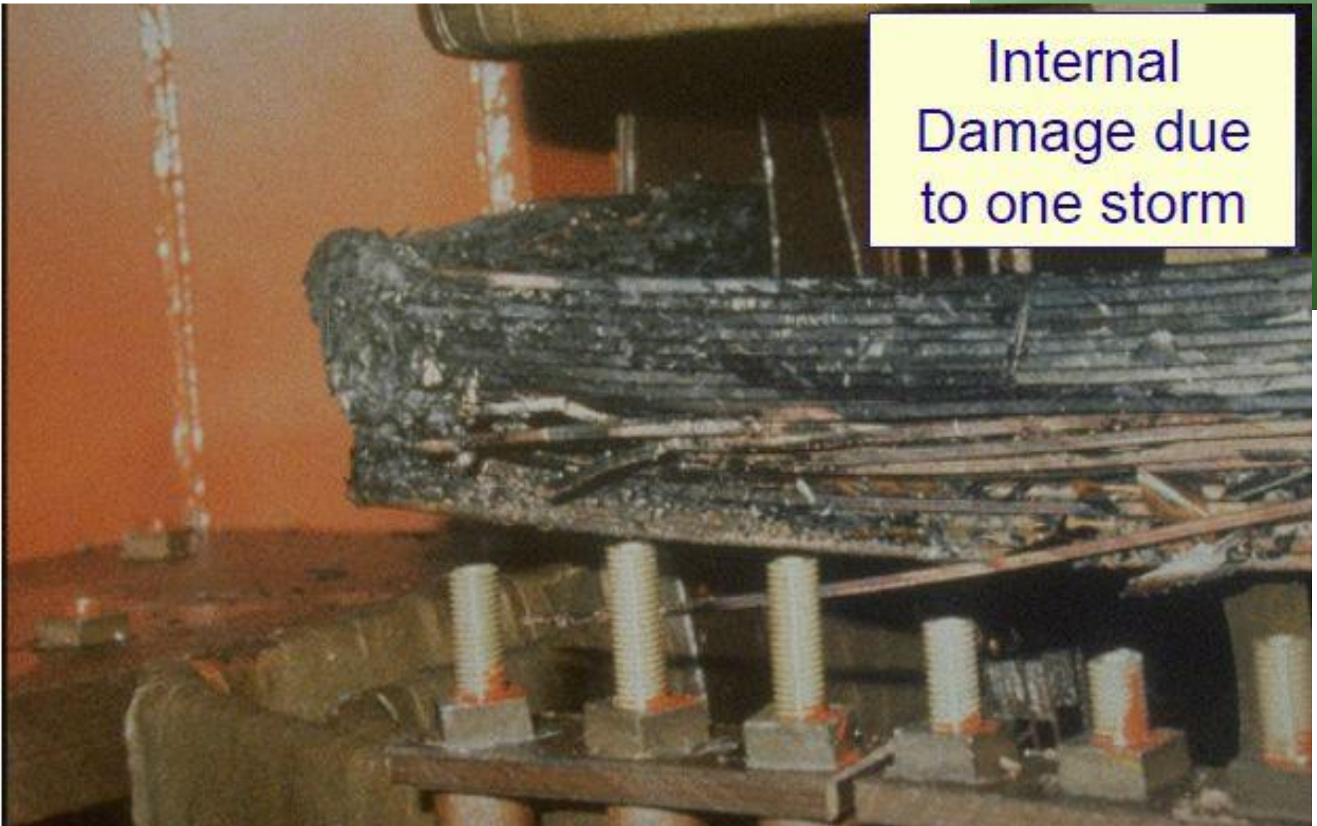
Space Weather




Internal
Damage due
to one storm

Space Weather as a Risk

- Space weather refers to changes in the ambient magnetic fields, radiation, plasma and other matter in space.
- We must understand the space environment around the earth, which is dominated by magnetic fields: the sun's and the earth's
- It is of interest when these changes reach and impact the Earth, satellites, or spacecraft.
- To understand space weather risk we must break down the likelihood, hazard and vulnerability.

Risk = Likelihood x Hazard x Vulnerability

Space Weather as a Risk

- Awareness of the risk from space weather has been increasing in the last two decades with technology advancements creating an exposure to it.
- USA are world leaders in-terms-of recognizing the risk from space weather. UK works in partnership with NOAA and NASA to provide worldwide space weather forecasts
- 2010 – Lloyd’s commissioned a report into space weather risk
- 2012 - Space weather added to the UK National Risk Register
- 2014 – Royal Academy of Engineering Report on Space Weather
- 2015 – BIS UK Gov. Space Weather Preparedness Strategy
- 2016 – Helios Solar Storm Scenario, Cambridge Centre for Risk Studies
- 2025 – UKRI SWIMMR report: Severe Space Weather Impacts on UK Critical National Infrastructure.

Impact		1 <0.2%	2 0.2-1%	3 1-5%	4 5-25%	5 >25%
Catastrophic	5	7, 27, 28		25a	38, 56	
Significant	4	21	23, 37, 58a	9, 10, 26, 51, 53a, 53b, 53c, 65	22, 41, 42, 49, 52, 57, 64	3
Moderate	3	17, 19, 31, 32, 33, 34, 35, 58c	54	4, 12, 24, 25b, 30a, 43, 46, 47, 55, 58b, 58d	11, 39, 45, 50, 59b, 60, 62	30b, 48
Limited	2	18, 29, 36	5, 16, 40, 44	20, 61, 63	2, 8, 13, 14	6, 59a
Minor	1				1, 15	

Likelihood

Nuclear War

National Power Loss

National Water Loss

Pandemic

Heat Wave

Severe Space Weather

22 Disruption of space-based services

41 National disruption to data infrastructure

42 Digital resilience failure

49 Severe space weather

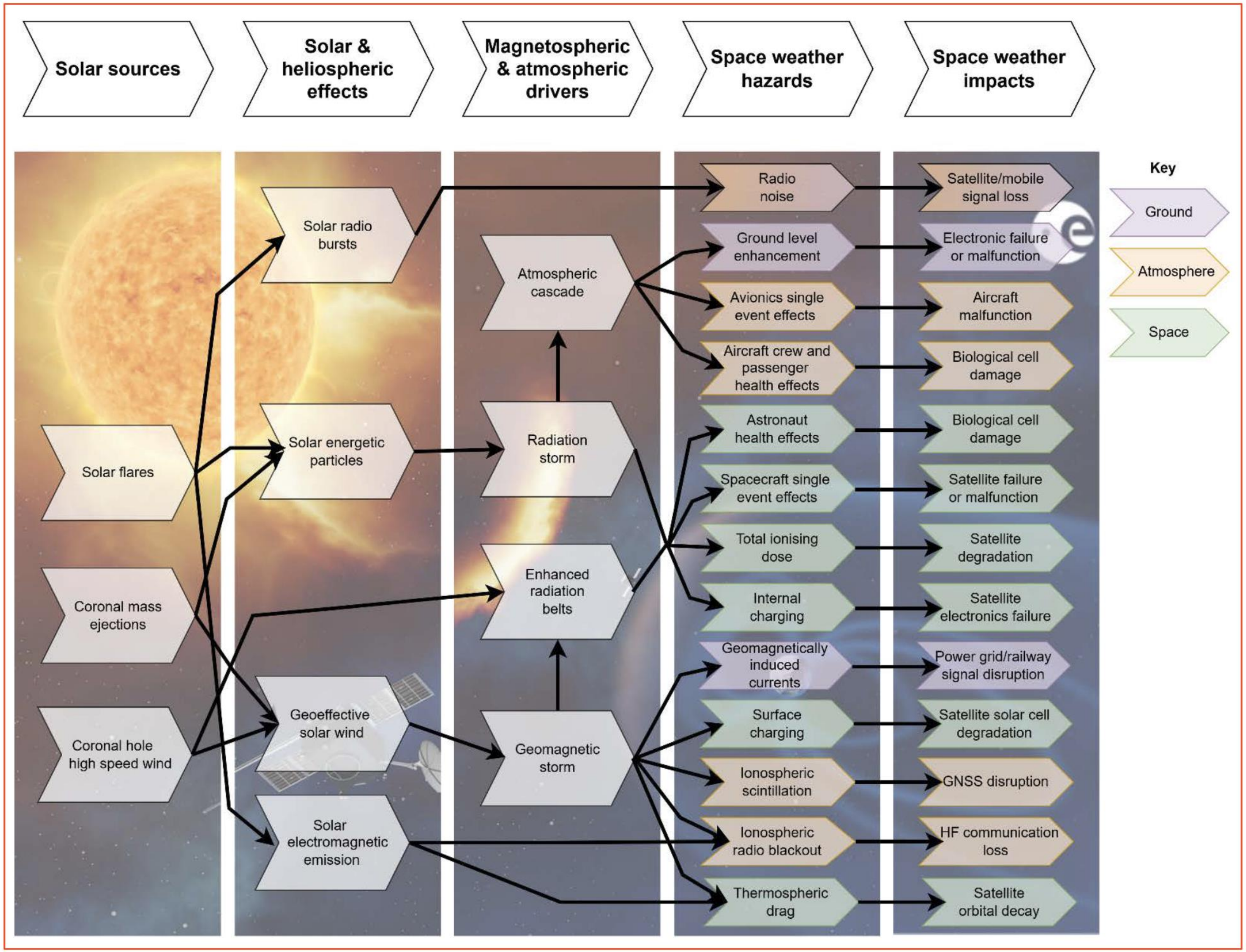
52 Low temperatures and snow

57 Outbreak of an emerging infectious disease

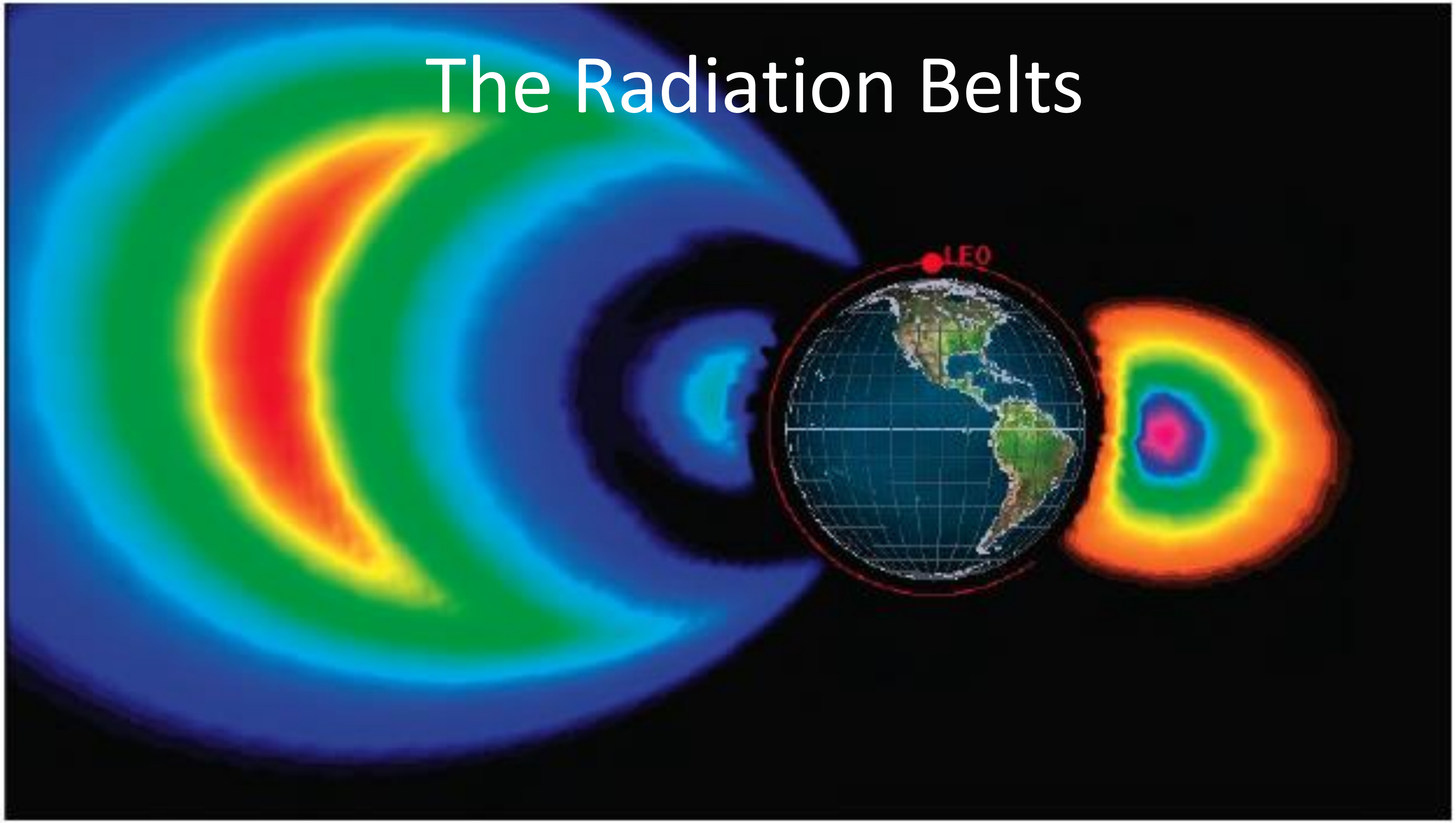
64 Deliberate disruption of UK space systems and space-based services

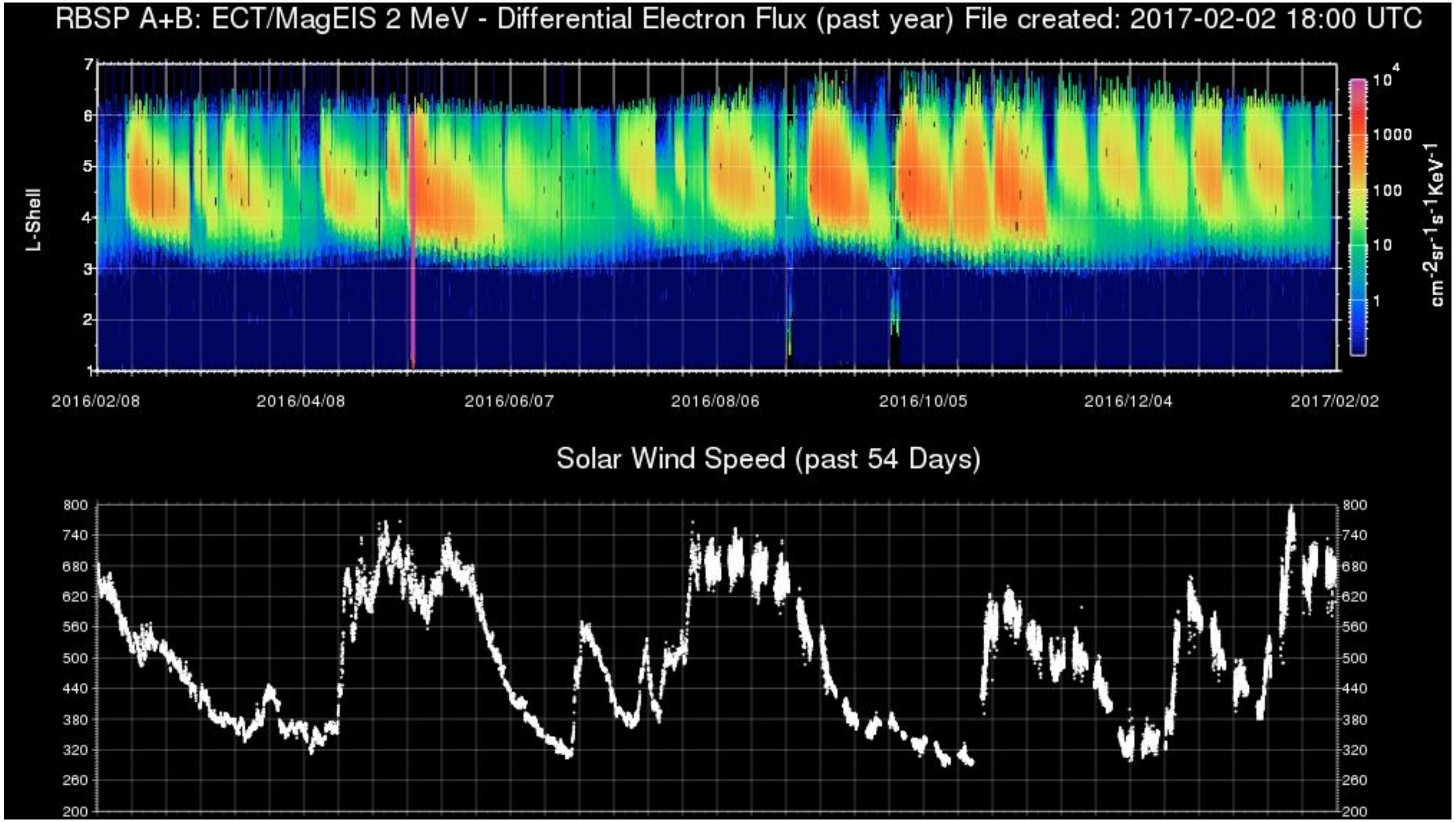
Overview of Space Weather

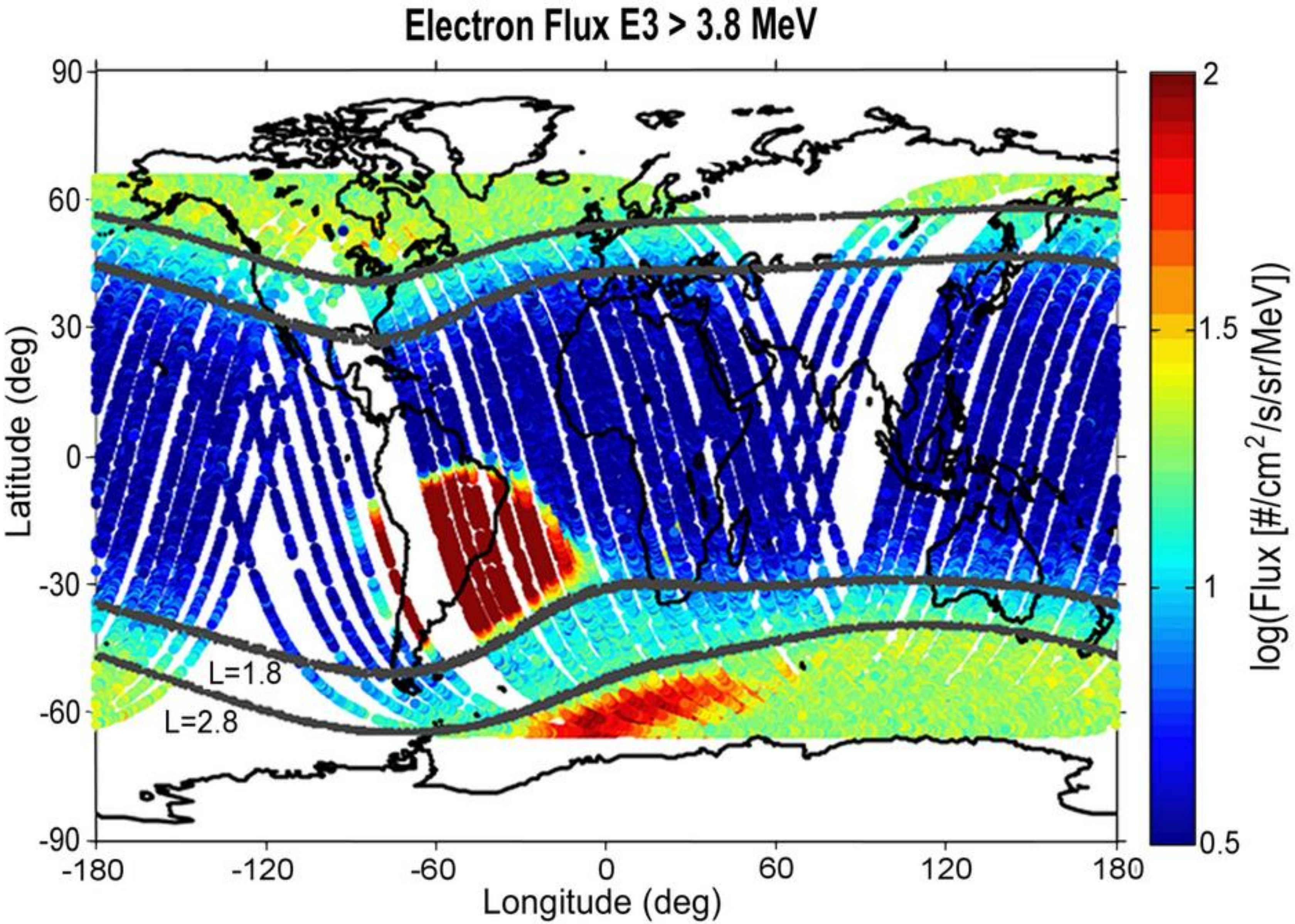
- Space weather is caused by the interaction of the Sun and the Earth.
- The Sun is a magnetically active star and generates the solar wind, solar flares and Coronal Mass Ejections (CMEs)
- These phenomena travel outwards from the Sun and hit the Earth.
- The Earth has a magnetic field which deflects some of these effects, in the process it compresses, and this compression generates radiation belts, geomagnetic currents and aurora.
- The main physical mechanisms of impacts are:
  - Radiation
  - Ionisation / density changes of the ionosphere
  - Ground induced currents


Solar sources
Solar & heliospheric effects
Magnetospheric & atmospheric drivers
Space weather hazards
Space weather impacts
Solar flares
Coronal mass ejections
Coronal hole high speed wind
Solar radio bursts
Solar energetic particles
Geoeffective solar wind
Solar electromagnetic emission
Atmospheric cascade
Radiation storm
Enhanced radiation belts
Geomagnetic storm
Radio noise
Ground level enhancement
Avionics single event effects
Aircraft crew and passenger health effects
Astronaut health effects
Spacecraft single event effects
Total ionising dose
Internal charging
Geomagnetically induced currents
Surface charging
Ionospheric scintillation
Ionospheric radio blackout
Thermospheric drag
Satellite/mobile signal loss
Electronic failure or malfunction
Aircraft malfunction
Biological cell damage
Biological cell damage
Satellite failure or malfunction
Satellite degradation
Satellite electronics failure
Power grid/railway signal disruption
Satellite solar cell degradation
GNSS disruption
HF communication loss
Satellite orbital decay
Key
Ground
Atmosphere
Space

Satellites



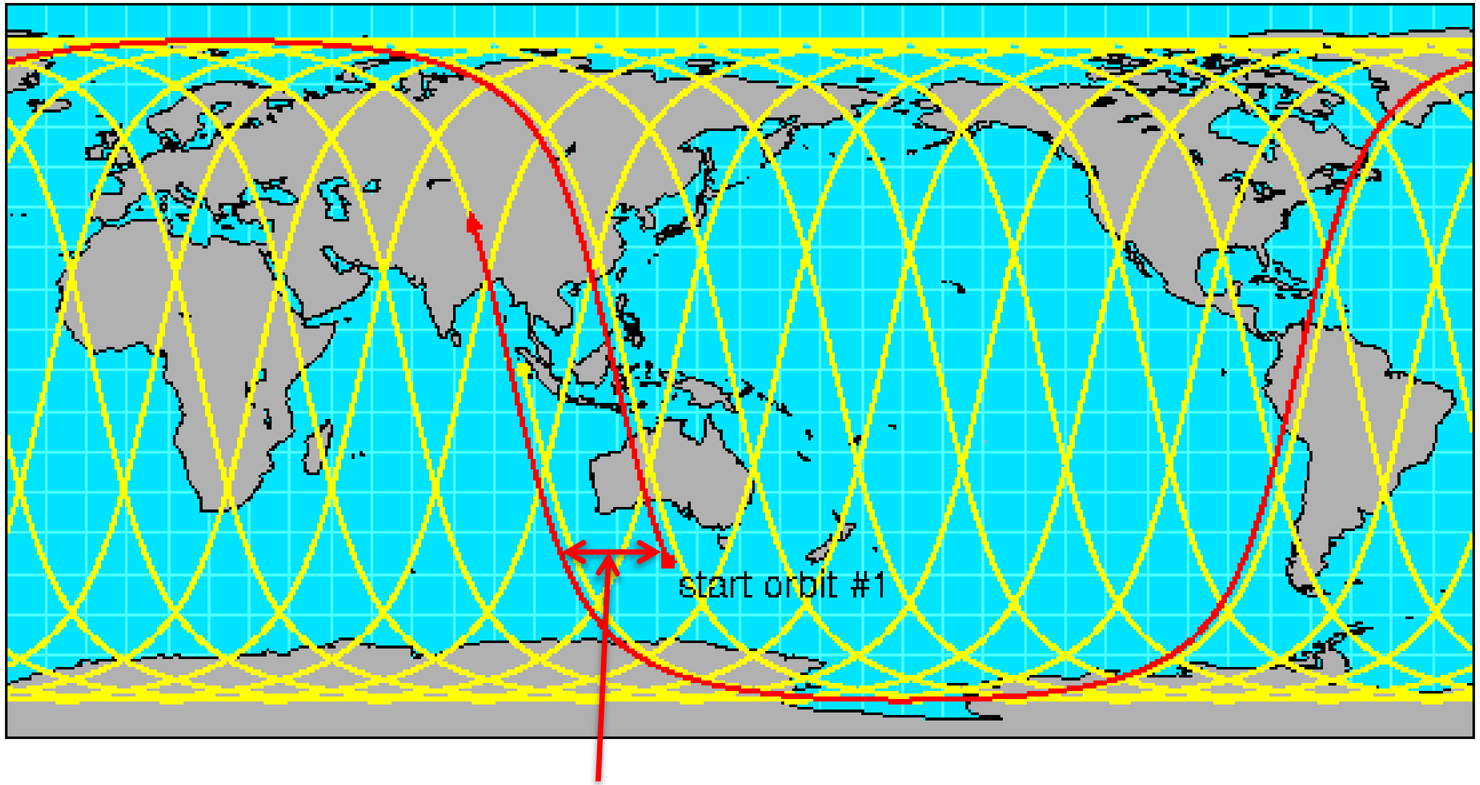

RBSP A+B: ECT/MagEIS 2 MeV - Differential Electron Flux (past year) File created: 2017-02-02 18:00 UTC
L-Shell
7
6
5
4
3
2
1
2016/02/08
2016/04/08
2016/06/07
2016/08/06
2016/10/05
2016/12/04
2017/02/02
10^4
1000
100
10
1
$cm^{-2}sr^{-1}s^{-1}KeV^{-1}$
Solar Wind Speed (past 54 Days)
800
740
680
620
560
500
440
380
320
260
200


Electron Flux E3 > 3.8 MeV
Latitude (deg)
Longitude (deg)
90
60
30
0
-30
-60
-90
-180
-120
-60
0
60
120
180
L=1.8
L=2.8
log(Flux [#/cm2/s/sr/MeV])
2
1.5
1
0.5

Orbits: LEO

- LEO = Low Earth Orbit
- 160 < r < 2000 km
- LEO is useful for Earth observation if you want rapid refresh, response, or high resolution imagery.
- Orbital period: T(500 km) = 5700 s ~ 90 minutes.
- The drawback is that the satellite moves across the sky very fast, so getting data back is hard, a ground station can only see the satellite for a few minutes each orbit.

Orbits: LEO

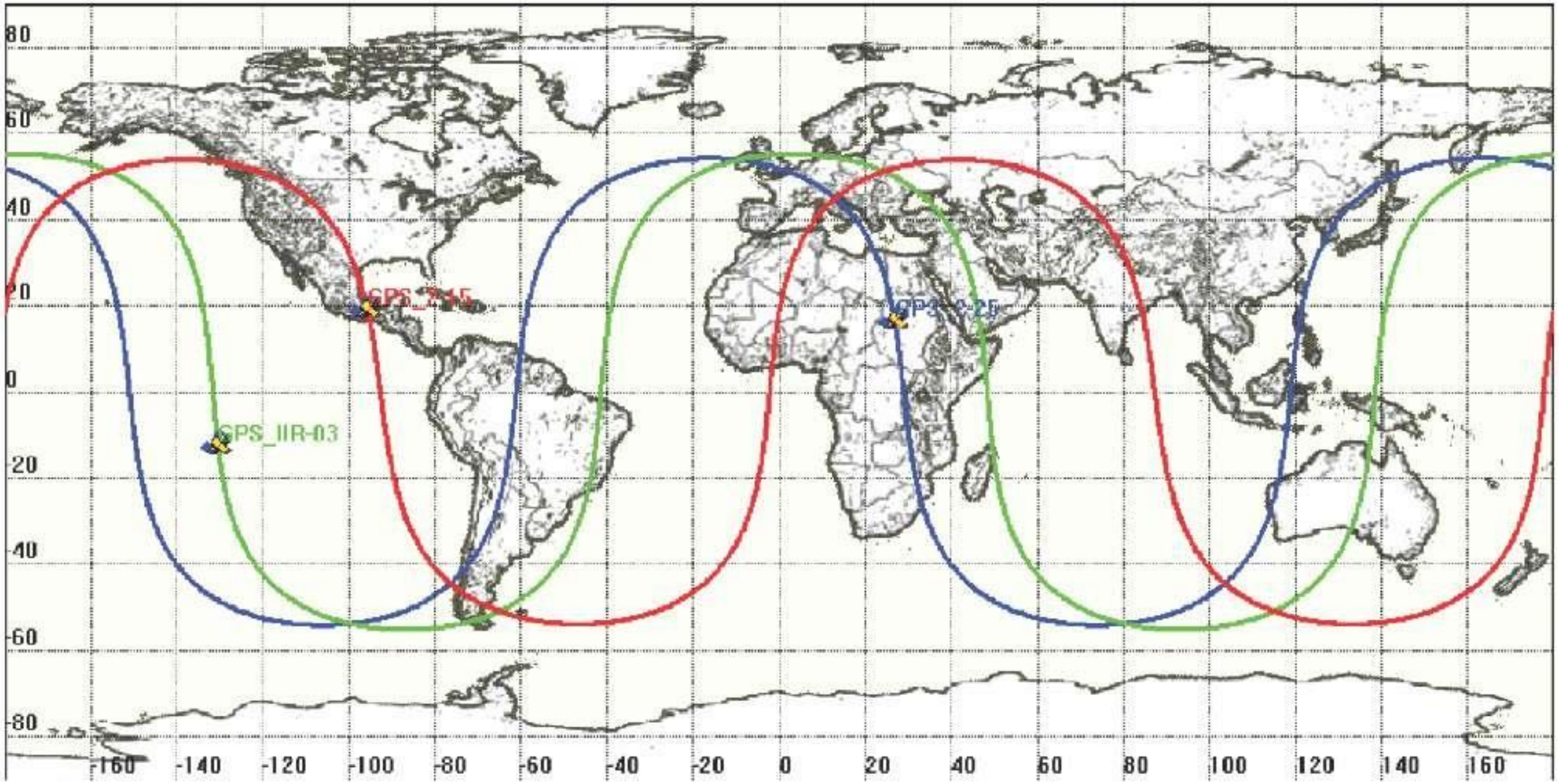


90 minutes – 16 orbits per day

Orbits: MEO

- MEO = Medium Earth Orbit
- 2000 < r < 36000 km
- MEO is useful for GPS, because you get stronger signal than Geostationary (closer to the Earth) but satellites stay in view for longer than LEO.
- Orbital period: T(1000 km) = 21000 s ~ 3600 minutes = 6 hours.
- The drawback is that the satellites move in and out of view (although relatively slowly) but don't spread cover the Earth in as much detail as LEO.

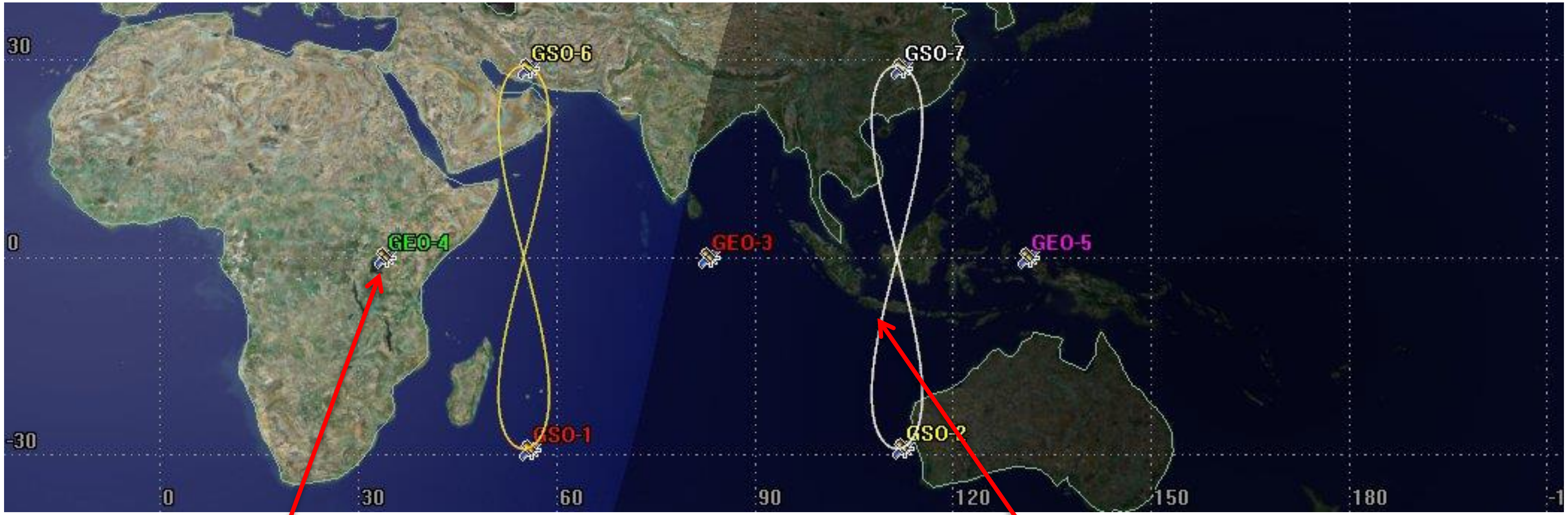
Orbits: MEO


80
60
40
20
0
-20
-40
-60
-80
-160
-140
-120
-100
-80
-60
-40
-20
0
20
40
60
80
100
120
140
160
GPS_IIR-03

Orbits: GEO

- GEO = Geosynchronous Earth Orbit
- R = 35,786 km (calculated exactly because T = 24 hours)
- GEO is useful for telecommunications, because the satellites do not move much relative to the ground and so antennae can be directed at them easily. Also imaging weather systems and
- Orbital period: T = 24 hours.
- The satellites do not move relative to the ground (or only in a mostly north-south direction) and so one satellite cannot see the whole Earth, at least 3 must be used for global coverage.

Orbits: GEO



Geostationary, perfect for TV and telecoms

Geosynchronus, useful for science, or reaching telecoms to higher latitiude

Impacts of space weather:

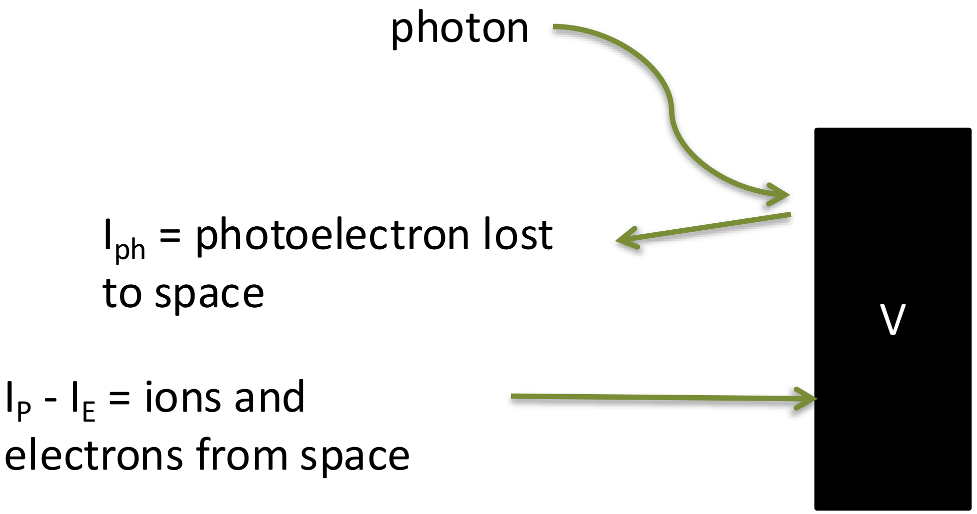
- Surface charging (radiation)
- Interior charging (radiation)
- Computer malfunctions / single event upset (radiation)
- Radio blackout (ionosphere)
- Orbital drag (ionosphere)

Charging by radiation

- SEPs from flares and CMEs and radiation belt particles have high energy -> they hit the atoms that make up the satellite and knock electrons out, causing charge to build up, in particular if the material is a dielectric (insulator).
- Charge builds up (static electricity) until it reaches a high enough voltage to 'spark' across the dielectric.
- This causes current to flow where it is not supposed to, deposits heat and damages components.

Charging by radiation

- To find out how much a component of a spacecraft charges up, balance the currents in and out of the component:



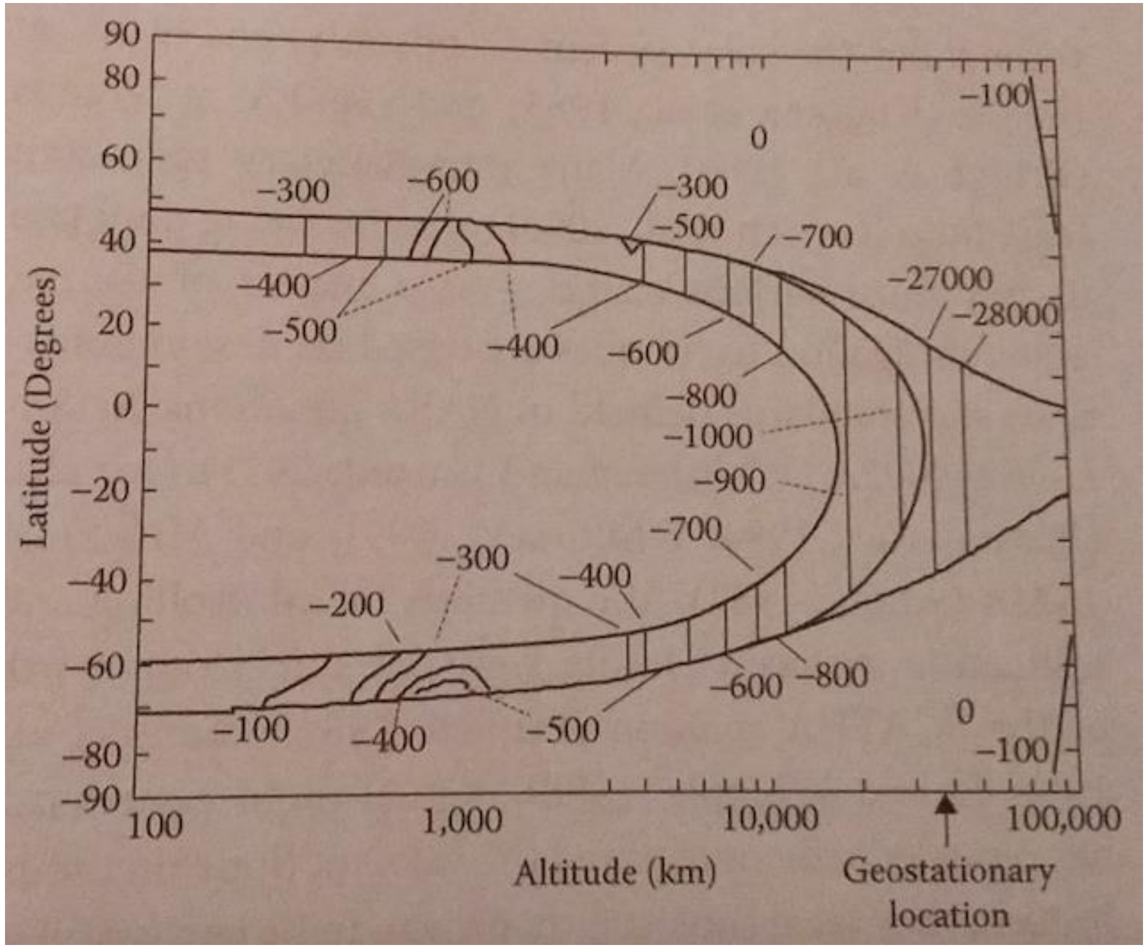
As photoelectrons are lost a positive charge will build up, reducing the number of photoelectrons that are made.

If there are many electrons coming from space the material will become negatively charged.

Charging by radiation

- There are many secondary processes that can also generate or lose charge from a surface, but in general one can consider a situation where these processes are in balance and the surface reaches a constant charge.
- Electrostatic Discharge (ESD) occurs when different parts of the spacecraft charge up to different voltages. If the voltage difference is larger than the breakdown potential of the materials, then a current will flow.
- For this reason (as well as other thermal reasons) as much of the surface of satellites is covered in highly conducting material. High conductivity will mean all of the surface is at the same voltage and so no ESD will occur.

- Insulators are bad because they will charge differently depending on sunlight illumination and radiation. Common necessities are:
  - Glass (telescopes, lenses, solar panels)
  - Semiconductors (solar panels)
- Worst-case surface charging is shown in the figure here, the potentials are very high!
- Most surface ESD occur on solar panels (glass, semiconductor, sunlight)



Credit: Space Weather Fundamentals, G. V. Khazanov, CRC Press

Internal charging

- Internal charging only occurs due to penetrating radiation.
- The rate of charge increase is proportional to the ratio of the dielectric constant to the conductivity of the material.
- Internal materials are harder to control than external (you need to use computers, which are plastic, semiconductors and metals).

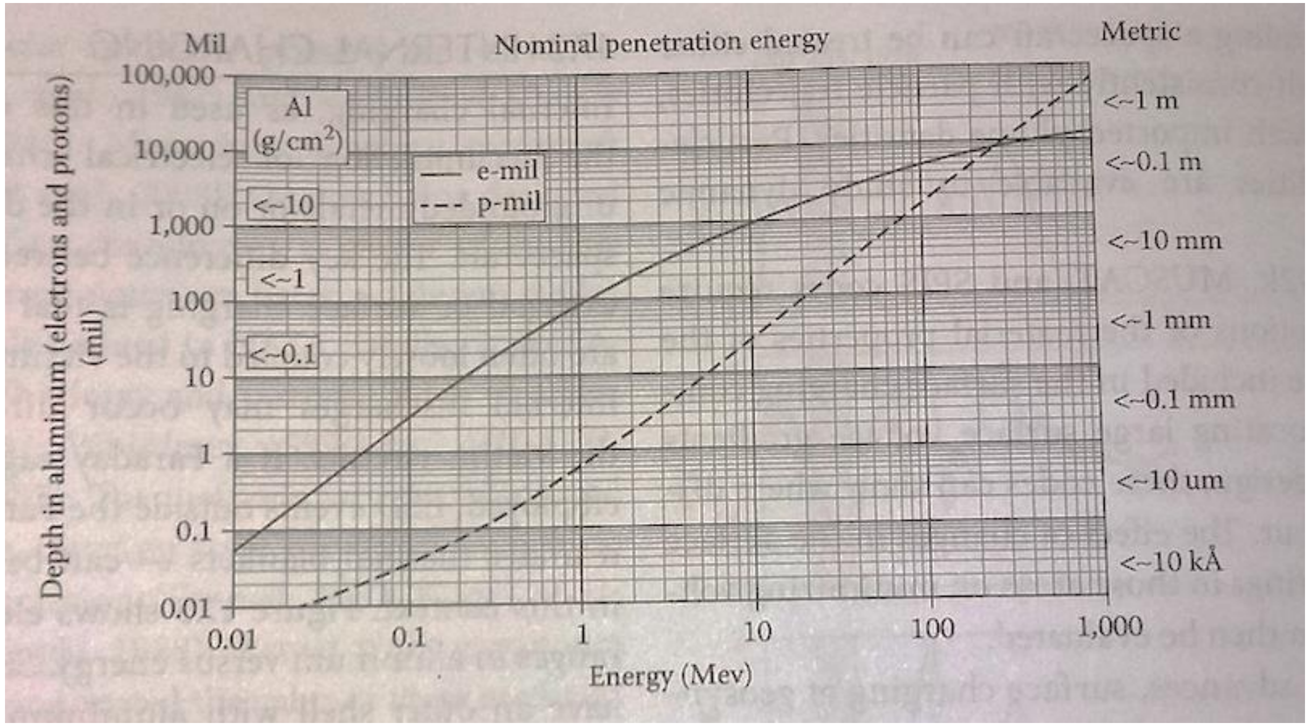
$$\varepsilon \frac{d\mathbf{E}}{dt} + \sigma \mathbf{E} = \mathbf{J}$$

$$E = E_0 \exp\left(\frac{-\sigma t}{\varepsilon}\right) + \left(\frac{J}{\sigma}\right)\left(1 - \exp\left(\frac{-\sigma J}{\varepsilon}\right)\right)$$

$$\tau = \frac{\varepsilon}{\sigma}$$

Internal charging

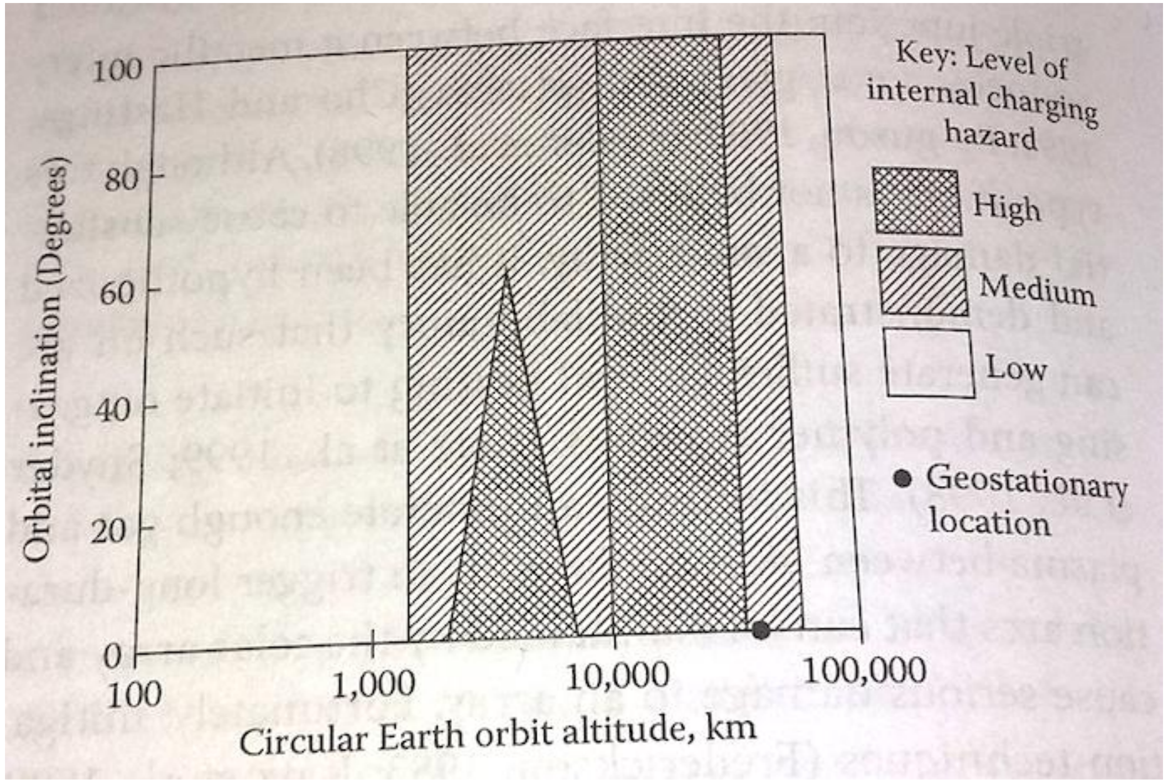
- Stopping energetic electrons and ions from hitting components or careful design so that components with very different charging properties are not near one another are the only ways to stop this effect.
- Stopping the radiation requires shielding. Dense material or thick material helps, these are both heavy.
- Put the computers or other sensitive parts in the middle of the satellite so everything else protects them (not easy or always desirable for other reasons).



Credit: Space Weather Fundamentals, G. V. Khazanov, CRC Press

Internal charging

- Internal charging is the most dangerous source of ESD.
- Charging can occur directly on essential components.
- ESD risk can be decreased by:
  - choice of orbit
  - Good design of internal components
  - Operations of spacecraft (turn off computers when ESD risk is high to reduce voltages)



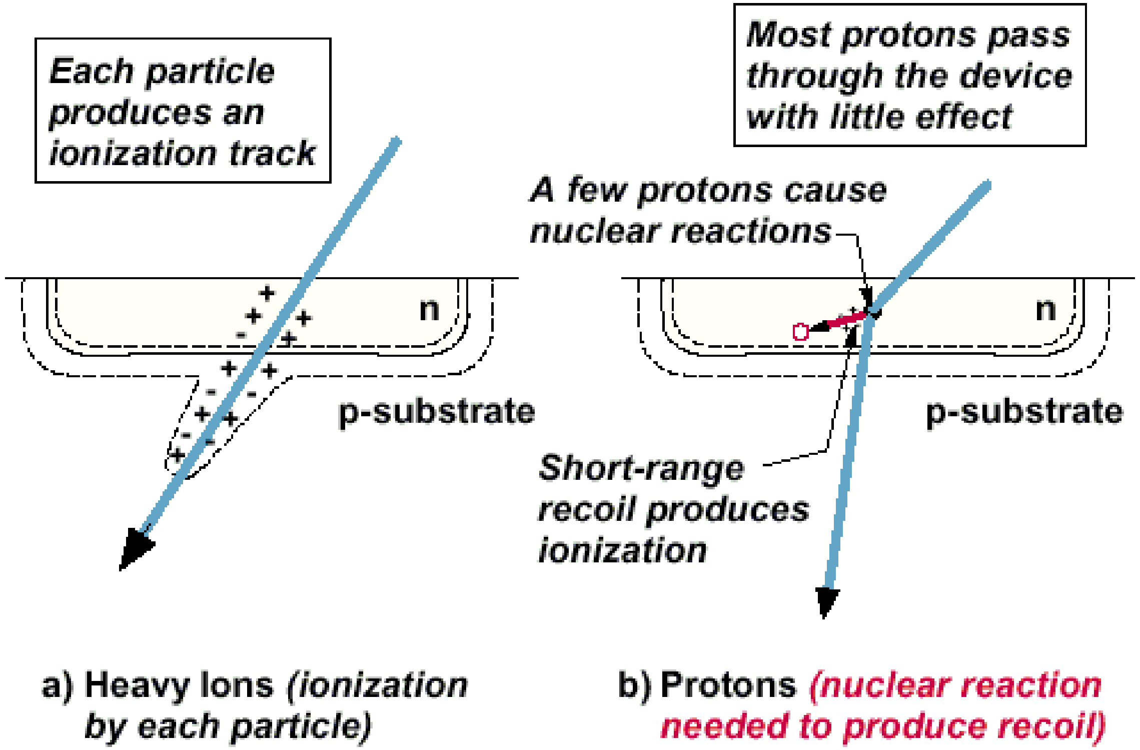
Credit: Space Weather Fundamentals, G. V. Khazanov, CRC Press

Damage from ESD

- ESD can permanently damage electronic components. This is rare, and can be mitigated:
  - Essential systems can be made fault-tolerant or fully redundant.
- It is more likely that ESD causes a temporary upset:
  - Sudden currents cause faults in the computer processing.
  - This can often be caught with sophisticated software, but not always.
  - Temporary upsets cause lost business, extra work for control room staff, extra wear on systems.

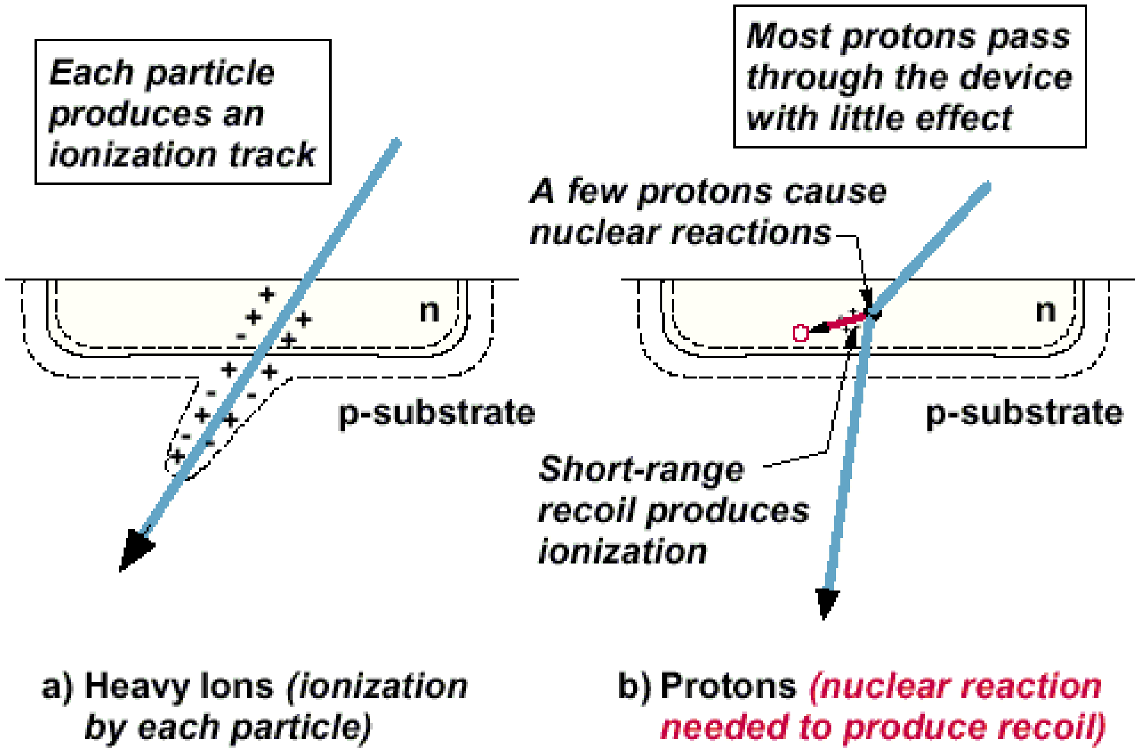
Computer Single Event Upset

- When energetic heavy ions pass through electronic chips they cause disruption.
- Each bit on a chip is stored in a transistor made of semiconductor.
- The radiation charges up the transistor and can 'flip' the bit from 0 to 1 or vice-versa.
- This scrambles the electronics ability to process commands and store data.
- Leads to a computer crash.

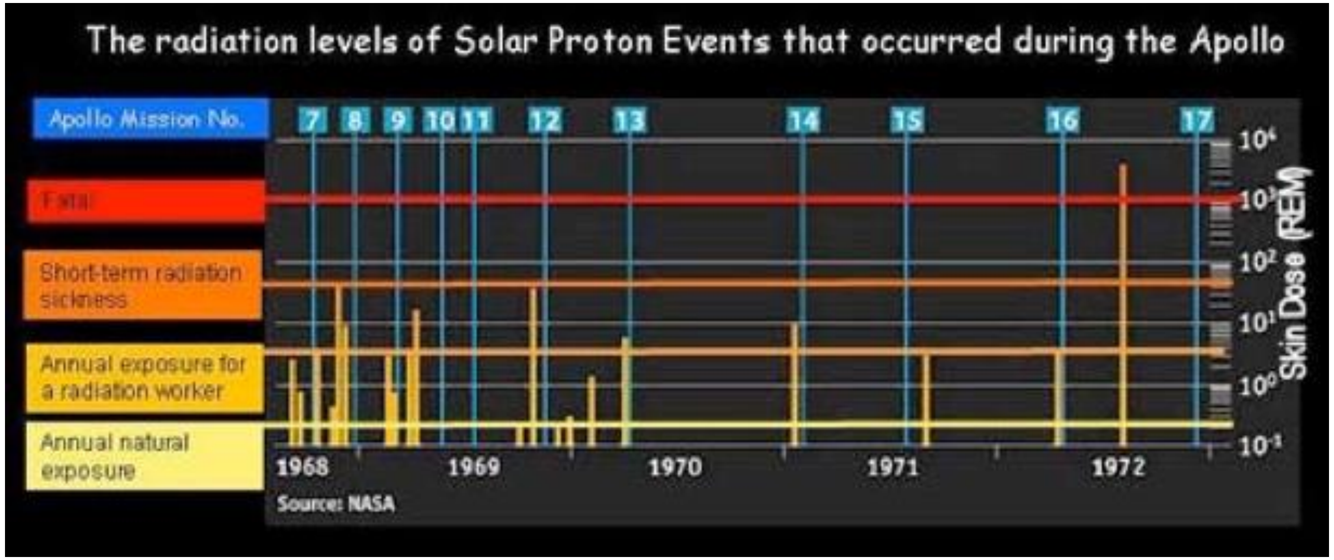


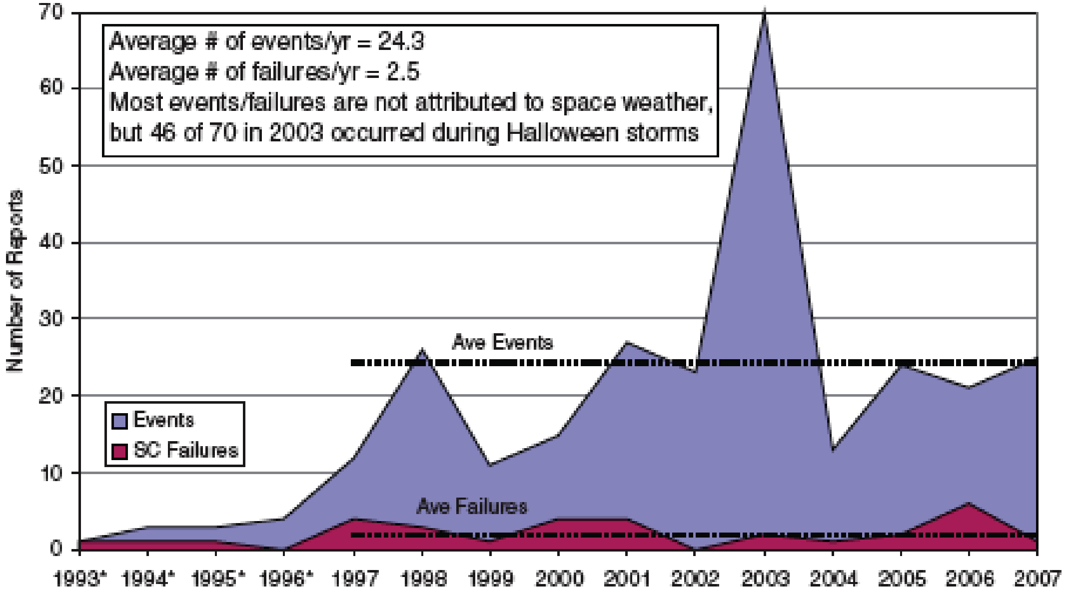
Computer Single Event Upset

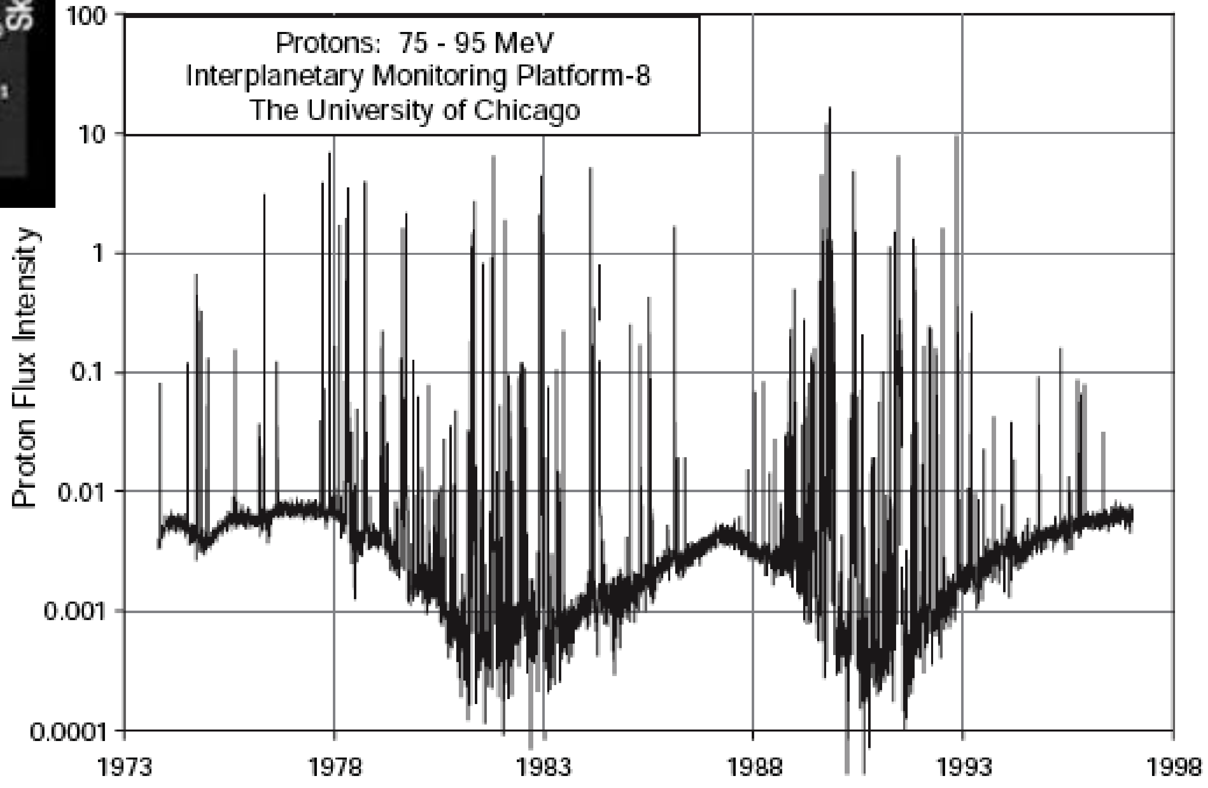
- SEU is the most common hazard to electronics posed by radiation.
- It is least damaging to the hardware, but requires fault correcting software and multiple rapid SEUs are very hard to protect against.
- Electronic chips can be designed to be radiation hardened:
  - Made of materials resistant to radiation
  - Increased shielding on the chip.



SEPs


The radiation levels of Solar Proton Events that occurred during the Apollo
Apollo Mission No.
7 8 9 10 11 12 13 14 15 16 17
Fatal
Short-term radiation sickness
Annual exposure for a radiation worker
Annual natural exposure
1968 1969 1970 1971 1972
Skin Dose (REM)
Source: NASA

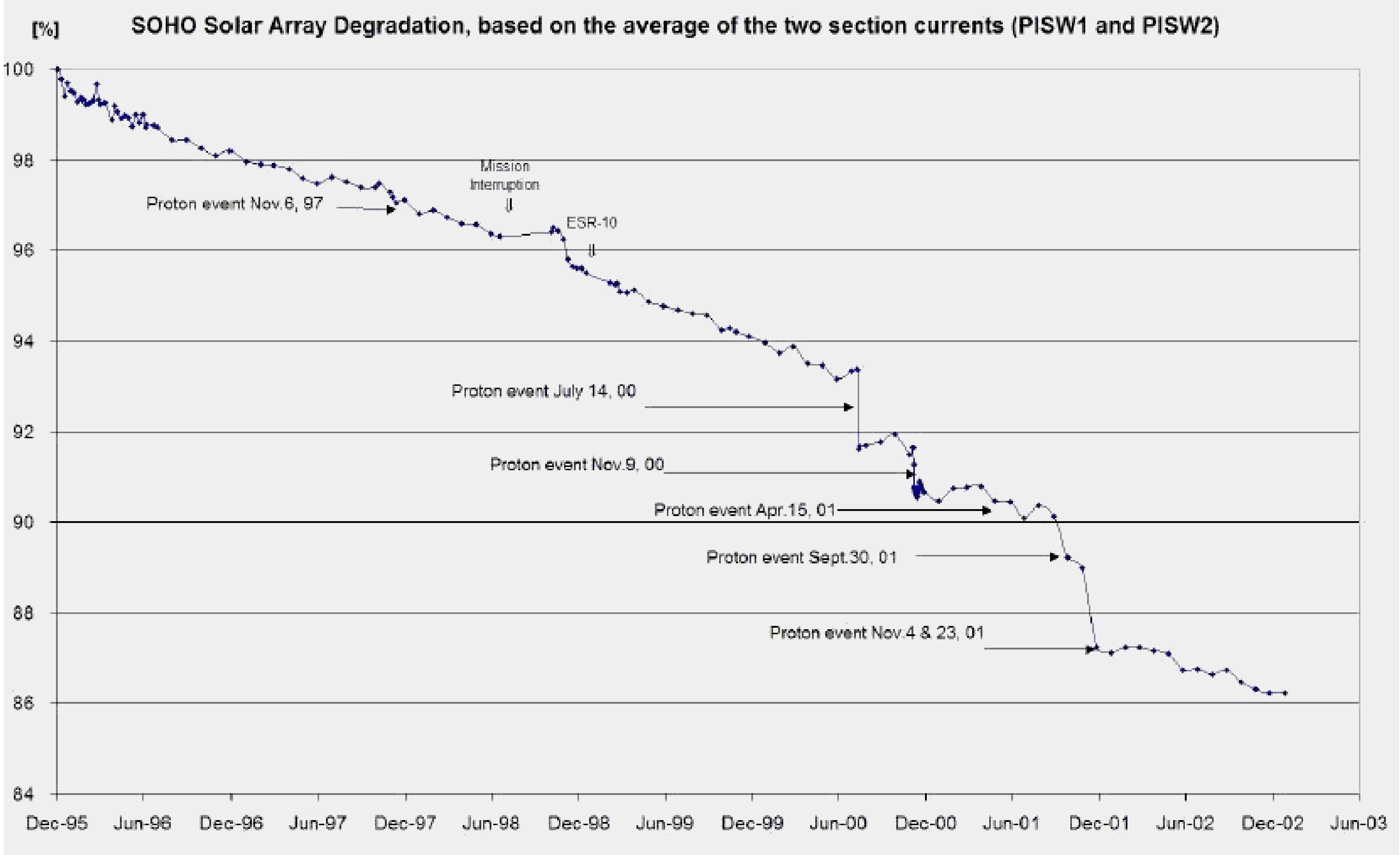

Average # of events/yr = 24.3
Average # of failures/yr = 2.5
Most events/failures are not attributed to space weather, but 46 of 70 in 2003 occurred during Halloween storms
Number of Reports
Ave Events
Ave Failures
Events
SC Failures
1993* 1994* 1995* 1996* 1997 1998 1999 2000 2001 2002 2003 2004 2005 2006 2007


Protons: 75 - 95 MeV
Interplanetary Monitoring Platform-8
The University of Chicago
Proton Flux Intensity
100
10
1
0.1
0.01
0.001
0.0001
1973 1978 1983 1988 1993 1998

SEPs: Recent Example

- Instruments on some spacecraft had to stop observing.
- Degradation of images observing the Sun making it hard to study the details of the CMEs.
- SEP event on the 28 Oct caused significant ozone depletion between 50-80 km from the ground (Jackman et al., 2005)
- 59% of spacecraft were affected by the SEP events – electronic upsets, housekeeping and science noise, proton degradation to solar arrays, changes to orbit dynamics, high levels of accumulated radiation and proton heating were observed.
- Most earth-orbiting spacecraft were put into safe-mode to protect from the radiation.

SEPs: Recent Example



Radiation and Air Travel

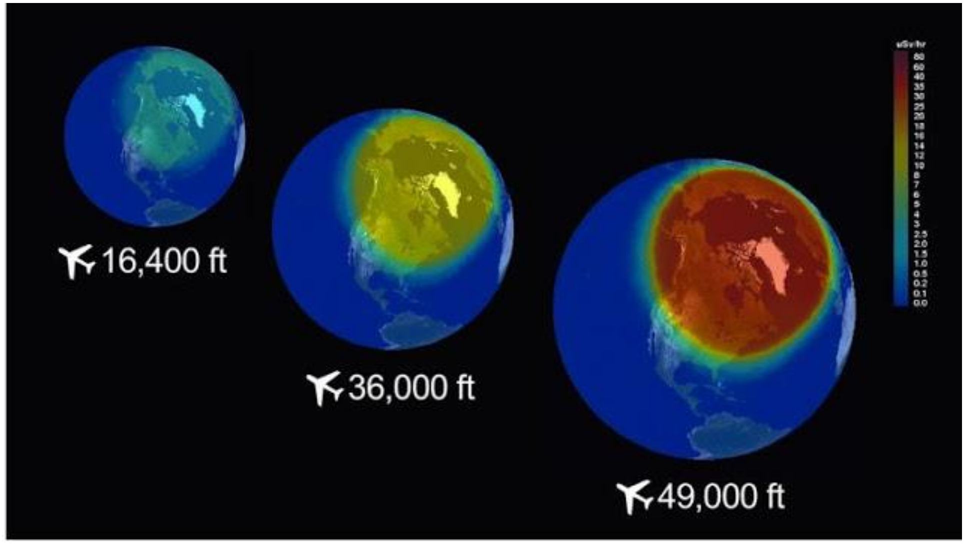
- Radiation is absorbed by the upper atmosphere.
- If you are higher up, your dose increases.
- Aircraft fly at up to 10 km altitude, so annual radiation doses for crew are higher than average.
- Air crew are legally radiation workers and must have their dose tracked and work modified to keep doses within legal limits.

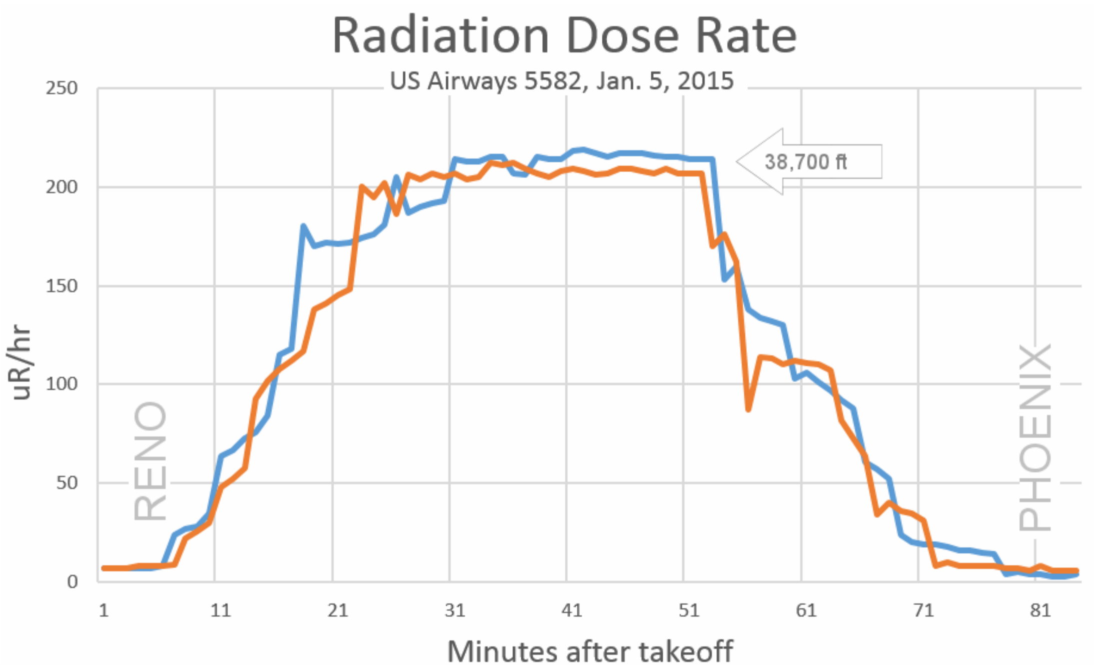
Radiation and Air Travel

- Radiation dose is measured in Sieverts (Sv).
- Annual radiation dose to average person is 2.2 mSv
- Aircrew (and all radiation workers) must be monitored if their dose is expected to exceed 4 mSv per year.
- Legal limit is 6 mSv per year.
- Monitoring is allowed by computer program.
- The times and altitudes of flights are recorded and then the average expected radiation dose is calculated.

Radiation and Air Travel

- Transatlantic flights are roughly 40 micro Sv, so only 100 per year!
- Polar routes would have a higher dose.
- The USA and Canada have higher than average radiation on flights because of geomagnetic latitude.





- Radiation dose in South Atlantic Anomaly is not considered.
- These are averages, there is very little active measurement on commercial flights.

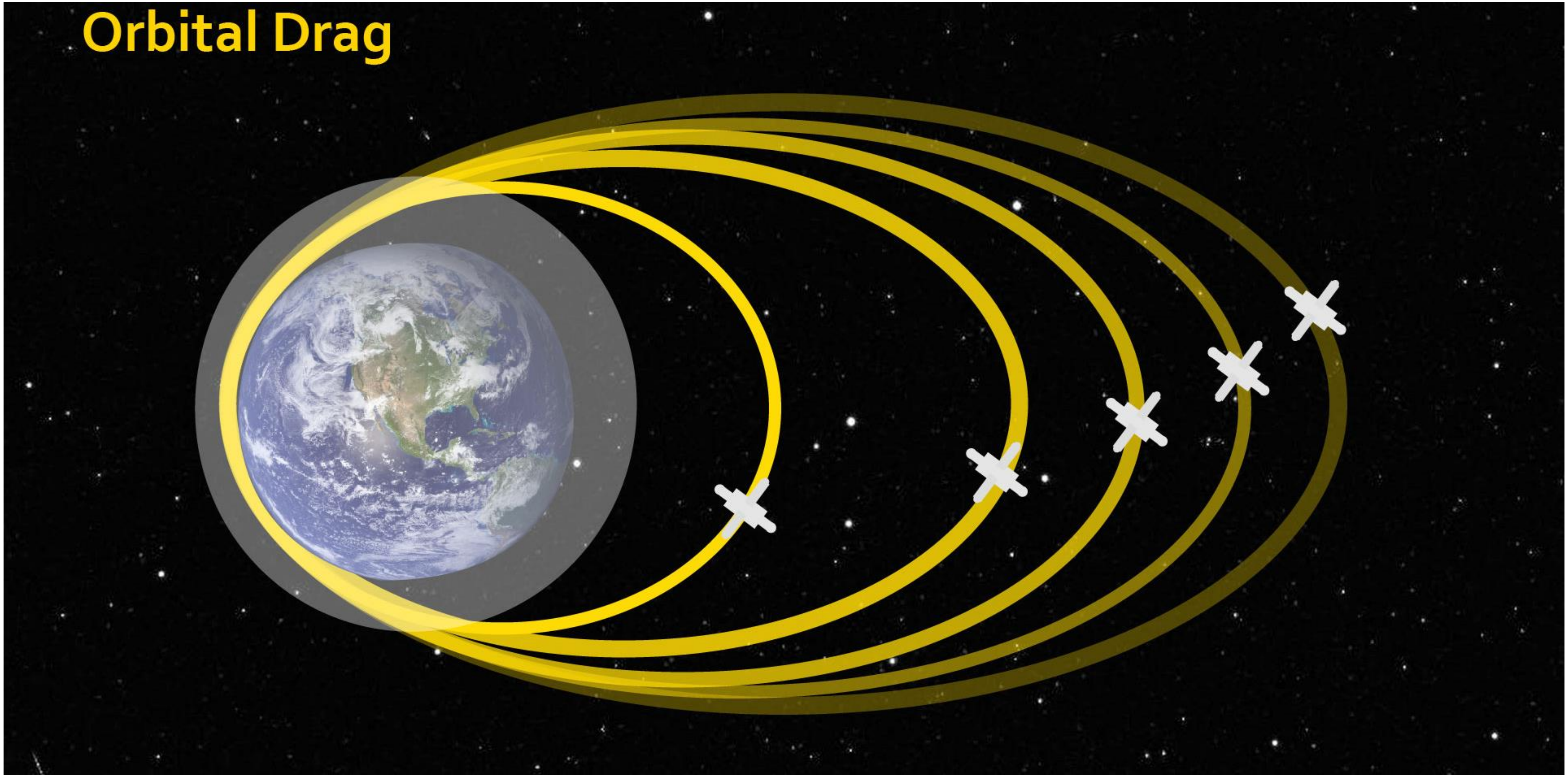
Radiation and Air Travel

- As with satellites, radiation can cause SEUs in the computers that control planes.
- Autopilot and other control electronics must be radiation hardened and redundant.
- UK Cosmic Ray Advisory Group (CRAG) works with government and industry to set standards and review legislation on radiation exposure.

- https://www.caa.co.uk/Our-work/About-us/Aircrew-exposure-to-cosmic-radiation/

Atmospheric drag

- LEO and some low-altitude MEO satellites experience significant atmospheric drag.
- Atmospheric drag depends on the density of the thermosphere, the surface area of the satellite, and its speed.
- Drag slows down the satellite, which decreases its orbital radius.
- Once a satellite gets below ~ 300 km the time to atmospheric re-entry and destruction is only a few weeks.
- Most satellites cannot operate effectively at altitudes other than those they are designed for, so uncontrolled orbital changes are not desireable.
- Satellites below 800 km require regular orbital maneuvers (=fuel) to remain in place.


Orbital Drag

The orbital drag equation

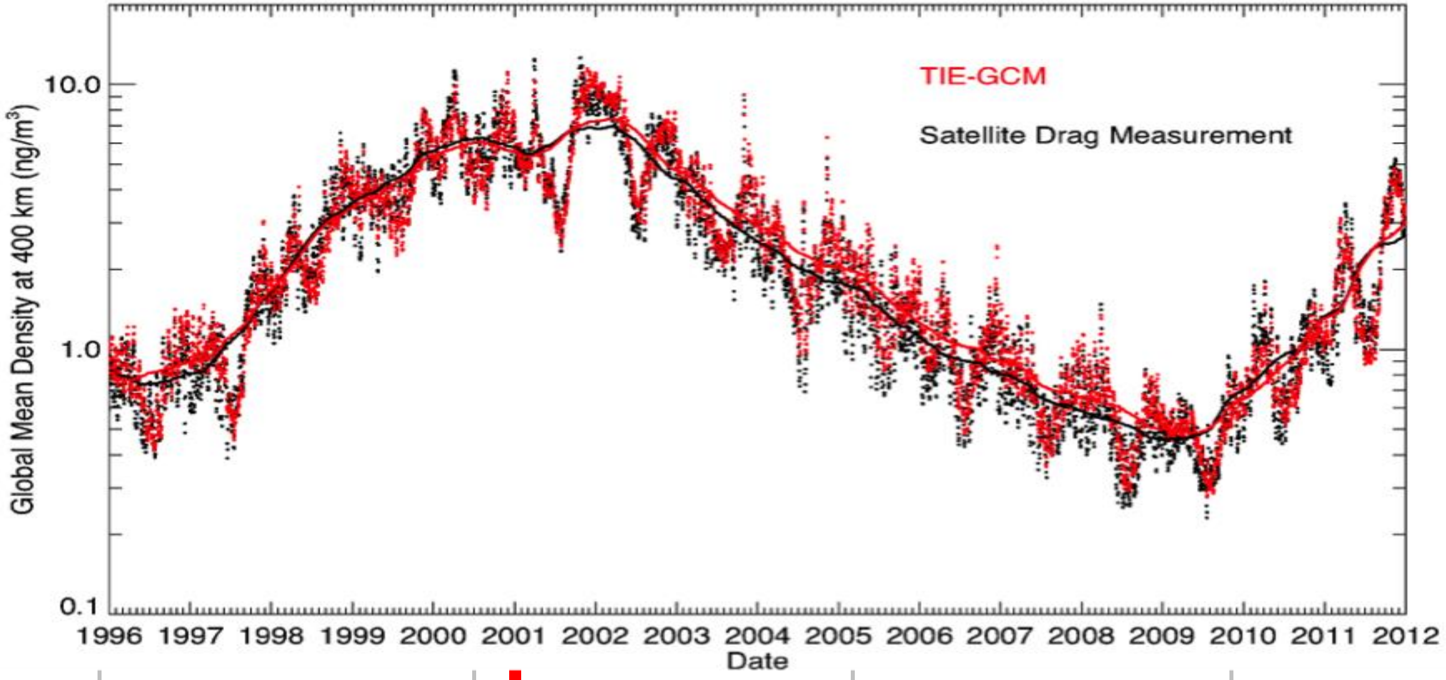
$$a_D = -\frac{1}{2} C_D \frac{A}{M} \rho V^2$$

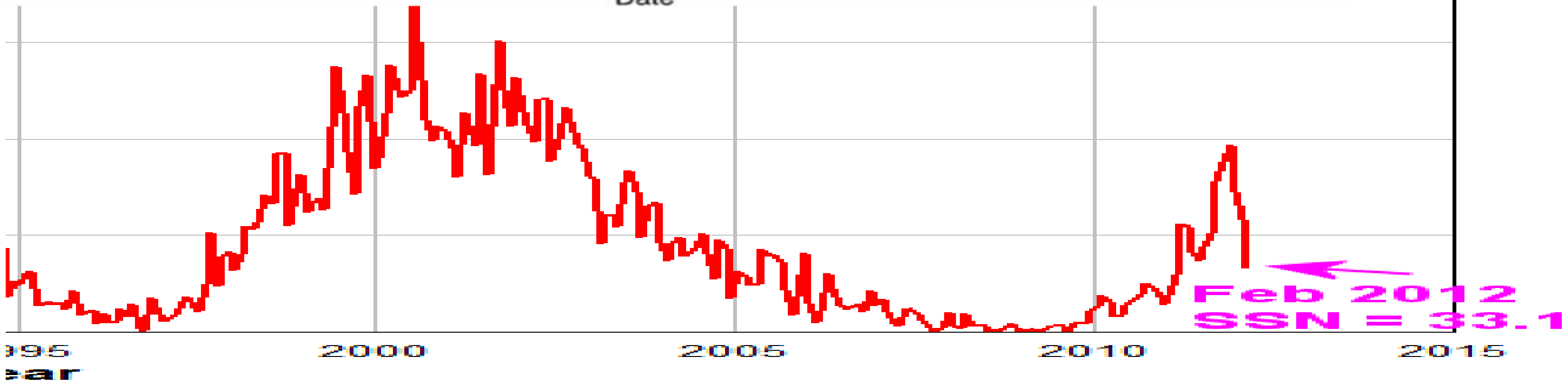
- C_D is the drag coefficient, it has to be measured or simulated for every satellite, it depends on the exact shape and materials of the satellite.
- A is the surface area presented to the direction of motion.
- M is the mass of the satellite.
- ρ is thermospheric density.
- V is the speed of the satellite.

Space weather impact on drag

- Space weather heats the thermosphere leading to winds and density fluctuations.
- X-rays and UV heat directly in the day side, ionising radiation heats most at the poles, moving magnetic fields stir the ionosphere causing heating and v x B forces lift plasma from the ionosphere along field lines.
- Predicting this precisely is currently impossible, but empirical trends have been measured and can be applied.

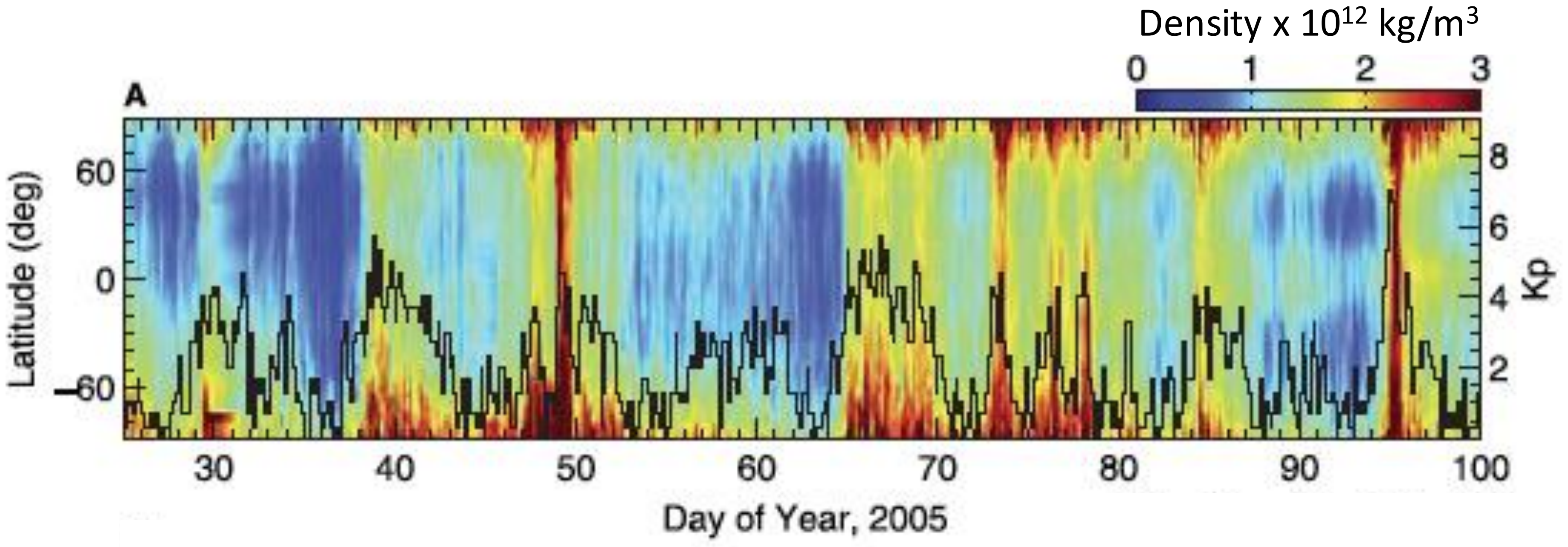
Space weather impact on drag





Space weather impact on drag

- Geomagnetic activity is often directly related to thermosphere density.
- Strong flows stir and heat, energetic substorm electrons heat the poles.

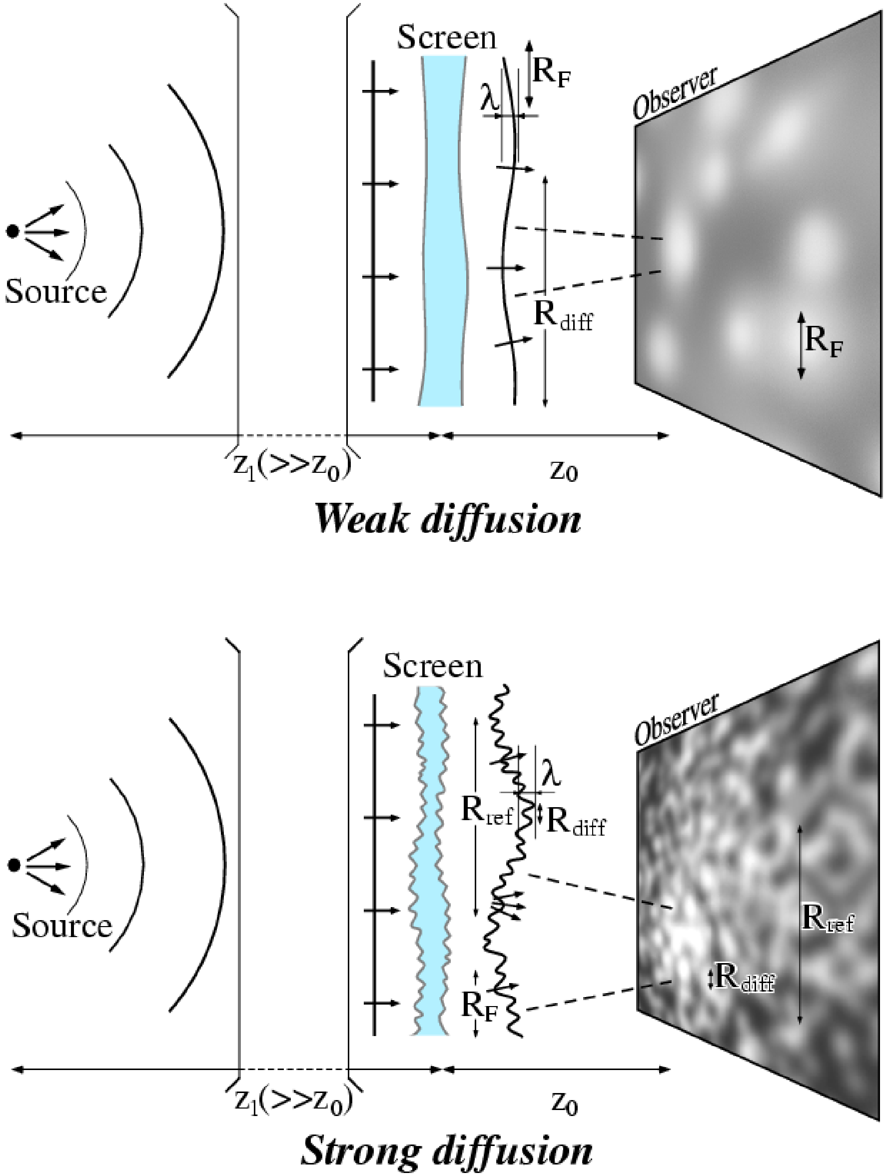


Radio blackout

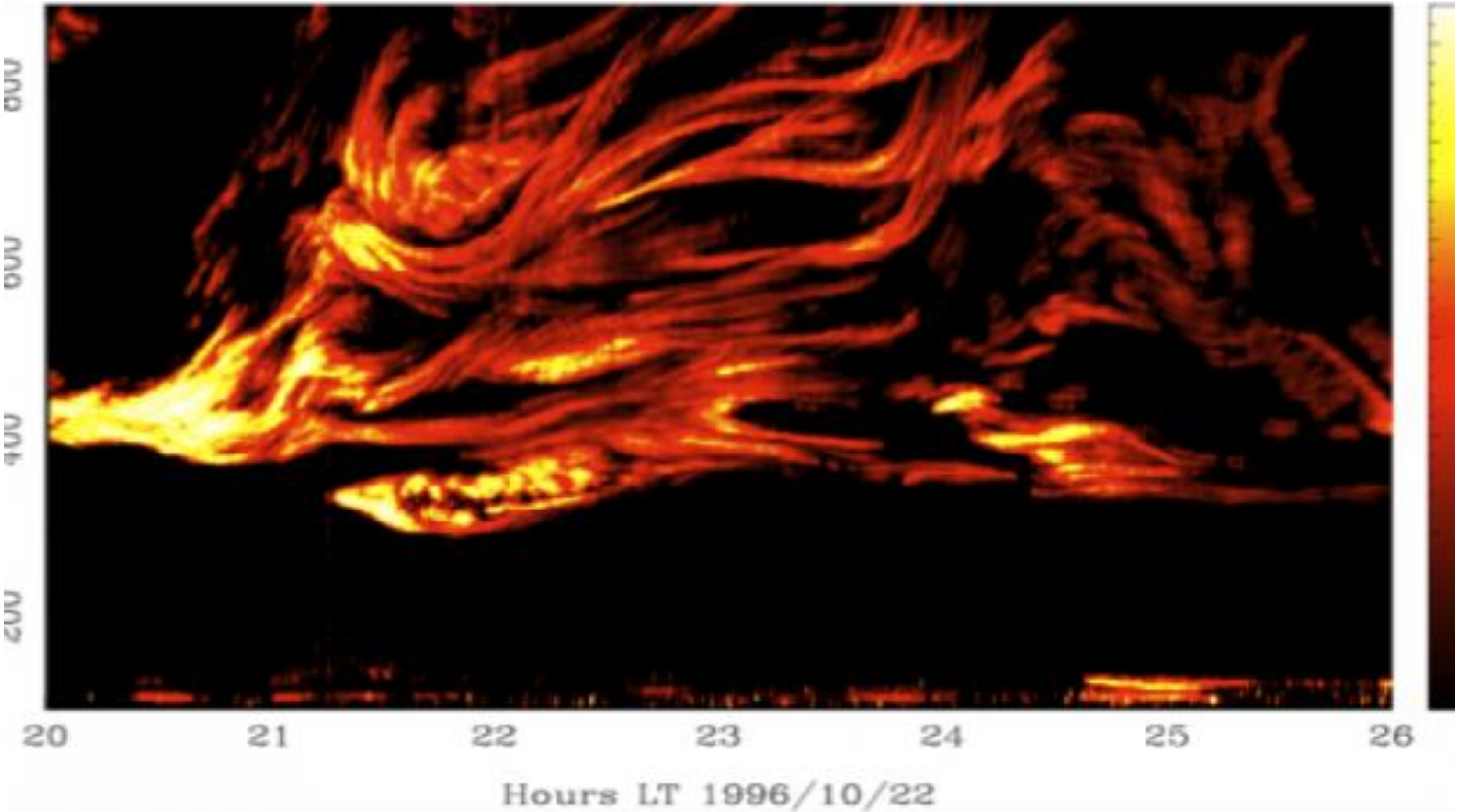
- Satellites rely on radio communications with ground stations to control operations and for most primary functions (telecommunications)
- If there is a chance of collision, or other maneuvers are scheduled, then loss of radio link is very severe.
- Continual radio contact is mandatory during maneuvers and loss of control of a satellite is often difficult to recover.
- Many, many other functions of modern states are also dependent on radio signals.

- The phase fronts (wavelengths) of the waves get distorted by travelling through electron patches of a similar size to the wavelength.
- This gives rise to very patchy reception on the ground.
- The patchiness is quantified by two numbers:

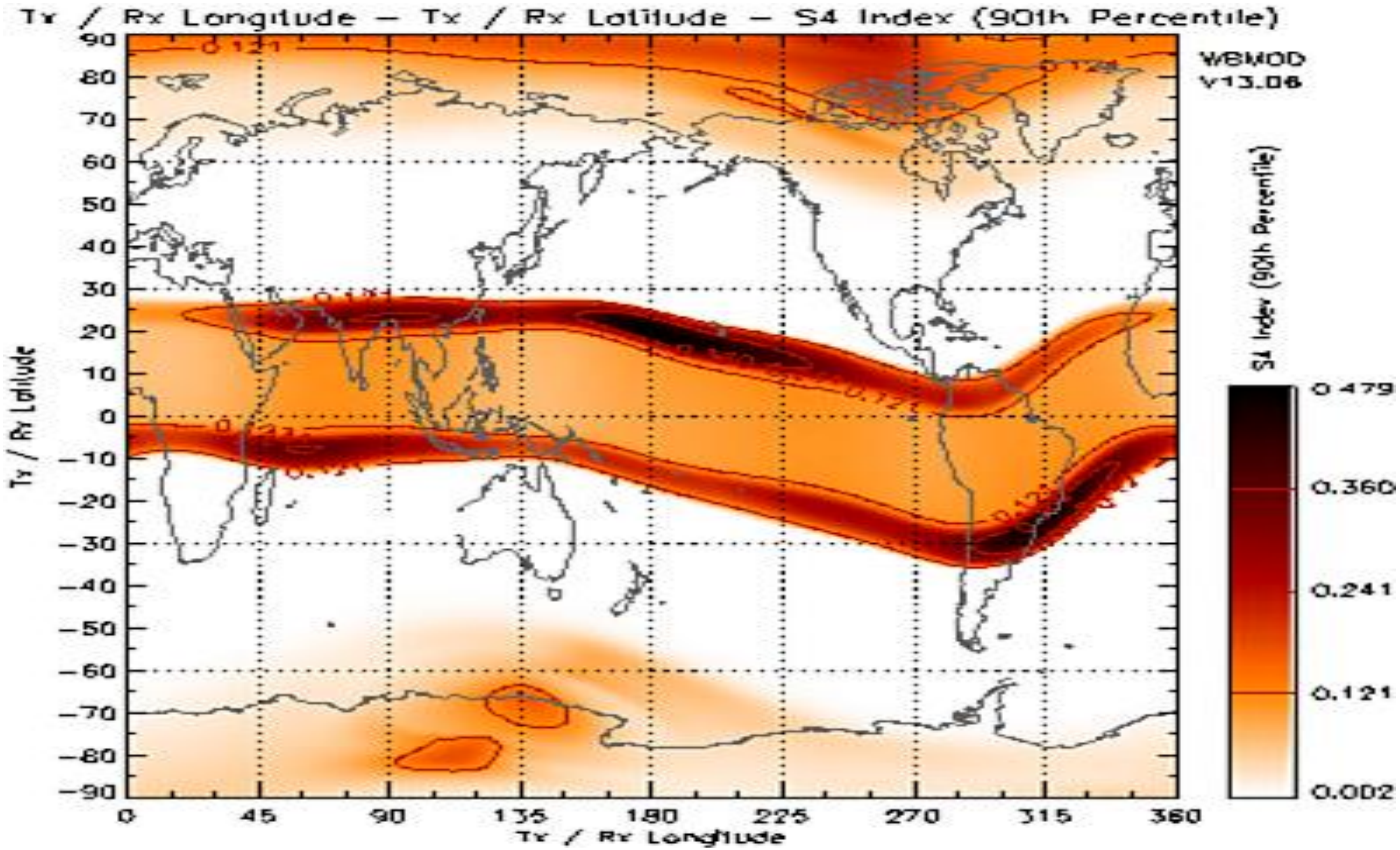
$$S_4^2 = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2} \qquad \sigma_\phi^2 = \langle \phi^2 \rangle - \langle \phi \rangle^2$$



❑ When and where does scintillation happen?

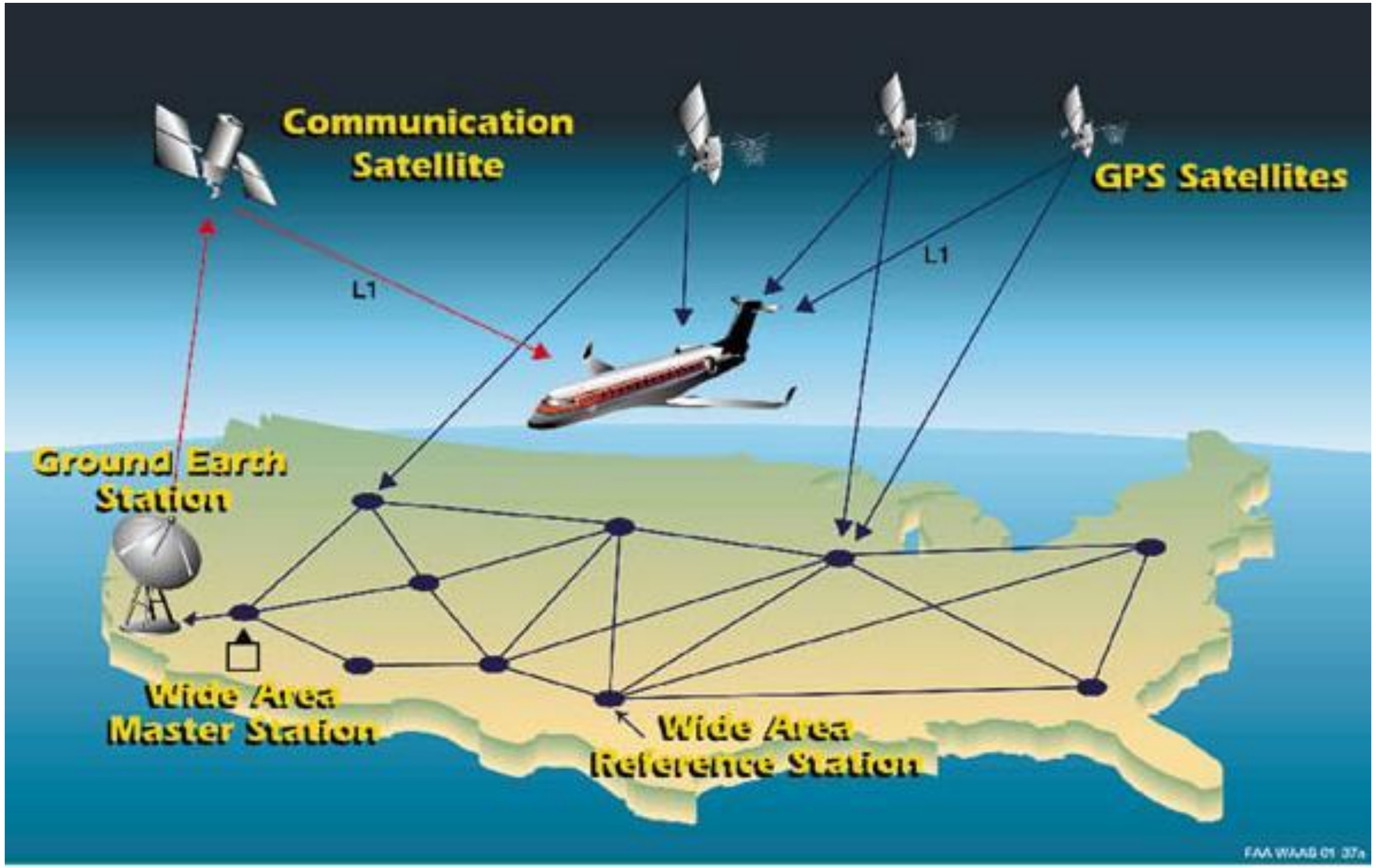


When and where does scintillation happen?



Who cares?

- GPS
- Radio
- Air traffic control
- Satellite Comms

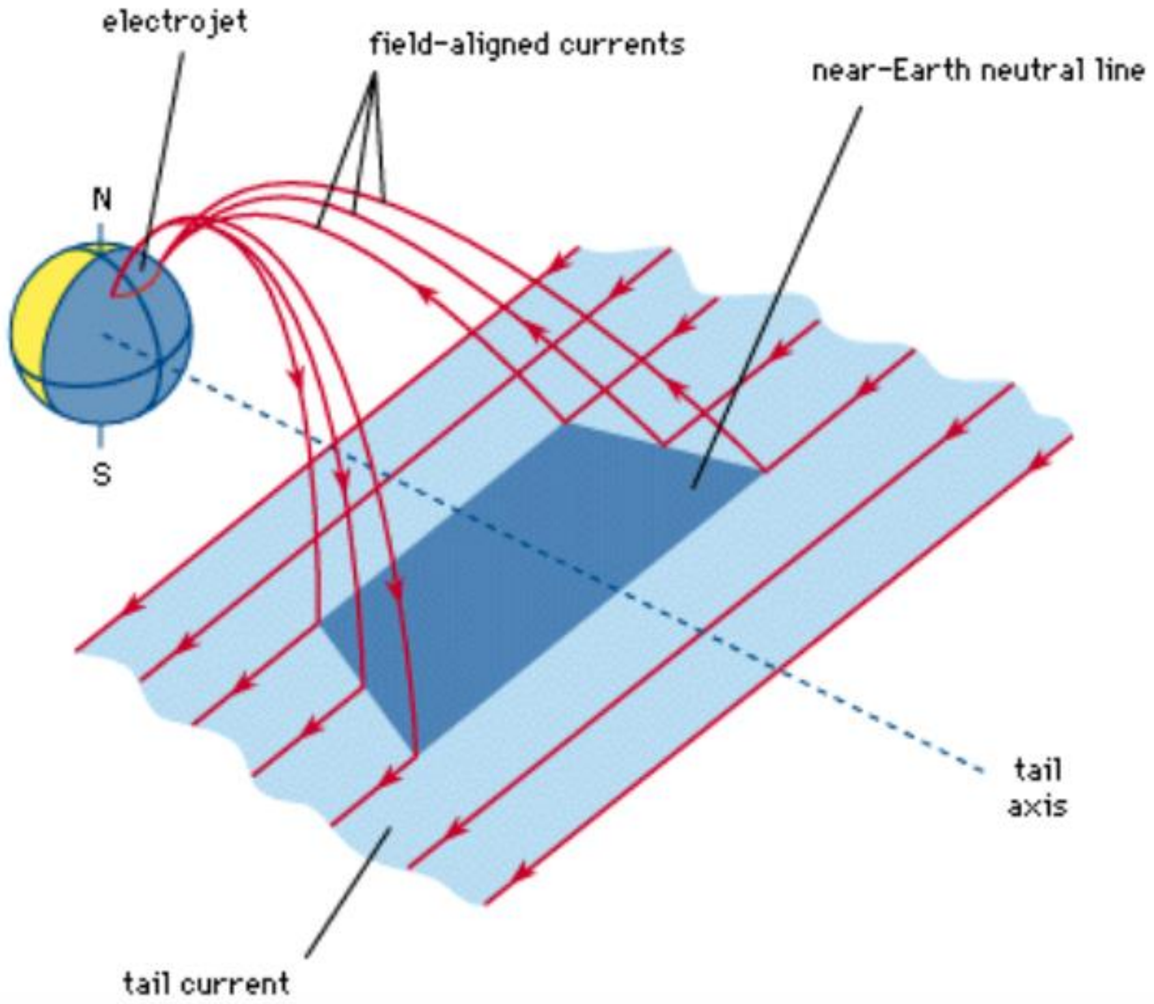


Ground Induced Currents

- Fluctuating magnetic fields caused by geomagnetic storms and substorms drive currents in the ground and in critical infrastructure.
- Currents flow more easily in highly conductive materials = high voltage electricity lines, railways, pipes, telephone lines.
- The current itself is not usually thought to do damage, however electronics are designed to operate under specific conditions and excess current stops correct functions.
- Malfunctions can lead to damage, blackout, incorrect signals, or unusual behaviour.
- When technology stops working or malfunctions we have a risk.

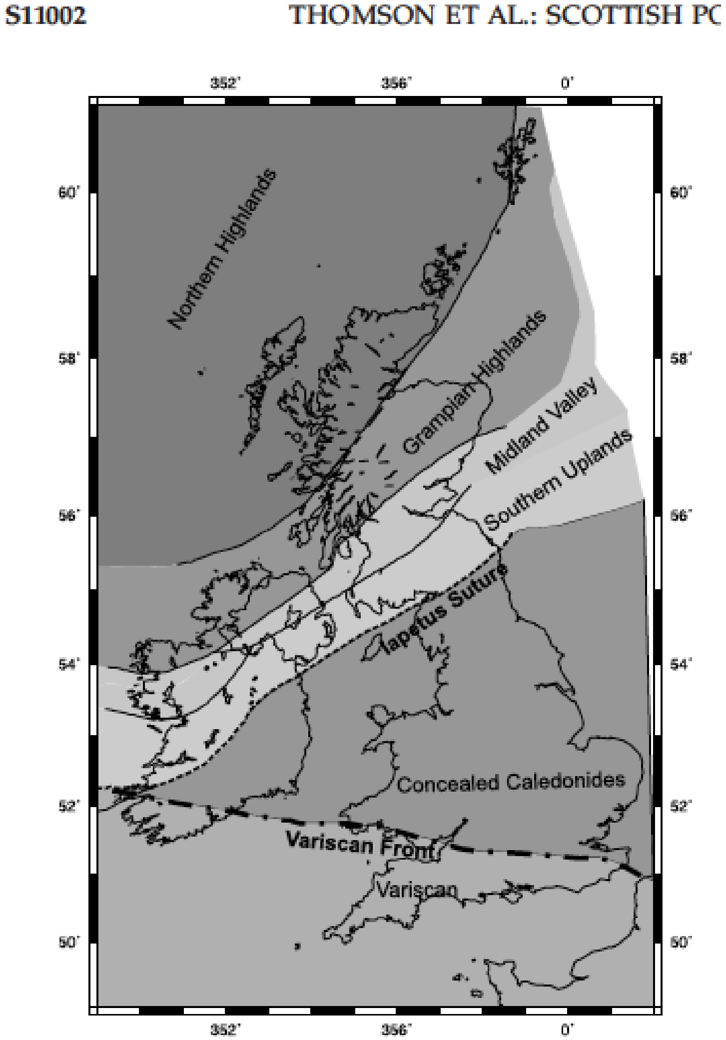
Ground Induced Currents

- There are currents that flow in the ionosphere due to storms and substorms.
- A general background current always exists but very intense patches occur in the auroral electrojet
- GIC and electrical power transformers work on very similar principles:
  - Faraday's Law of electromagnetic induction – a time varying magnetic field induces an electromotive force which makes a current.



Ground Induced Currents

- Ground conductivity of the UK and Europe



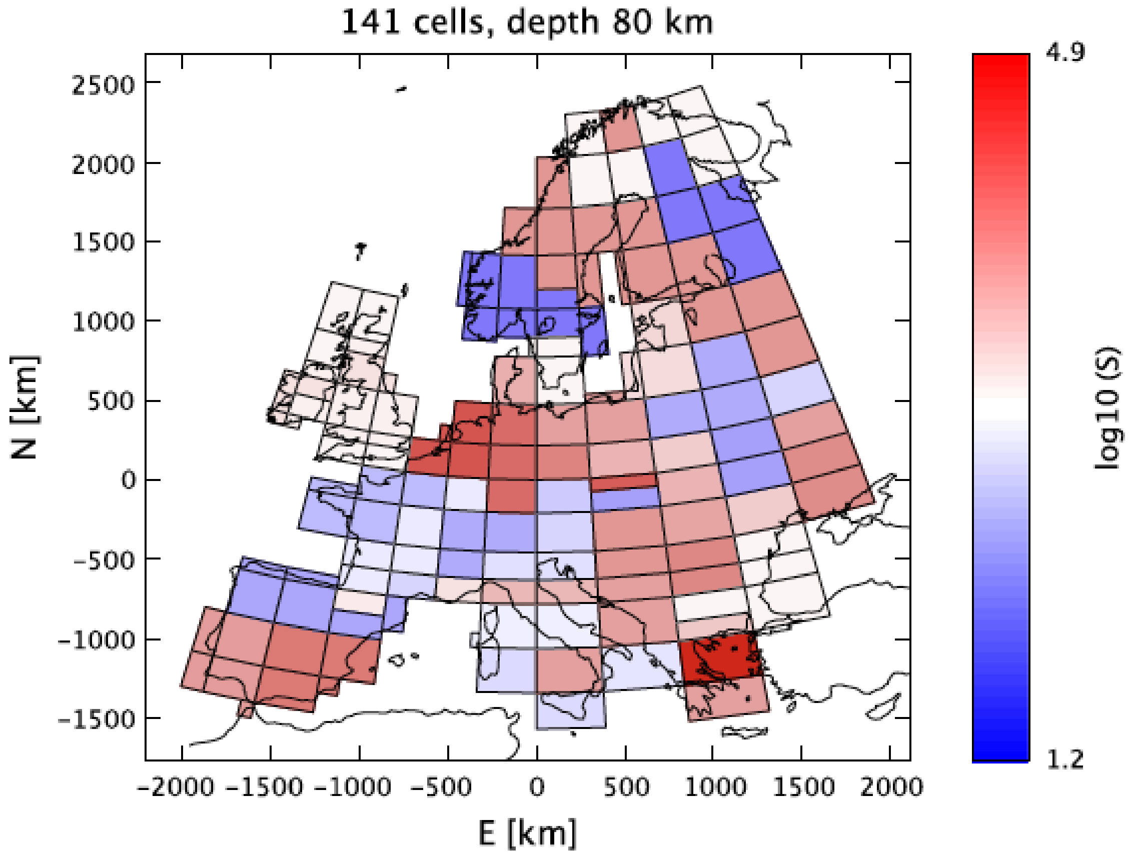


Fig. 2. Conductances all over Europe obtained by the integration of the conductivity down to the depth of 80 km. Figure based on Ádám et al. (2012). Numerical values are available at http://real.mtak.hu/2957/.

Ground Induced Currents

- Electricity grid structure.

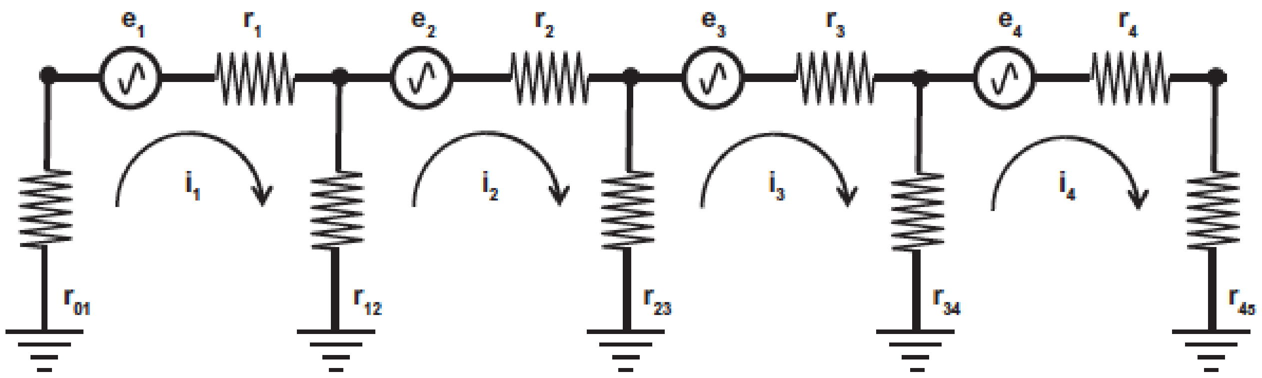


Fig. 1. Single-phase diagram of a power network illustrating mesh resistances, *r*, induced emfs, *e* and loop currents, *i*.

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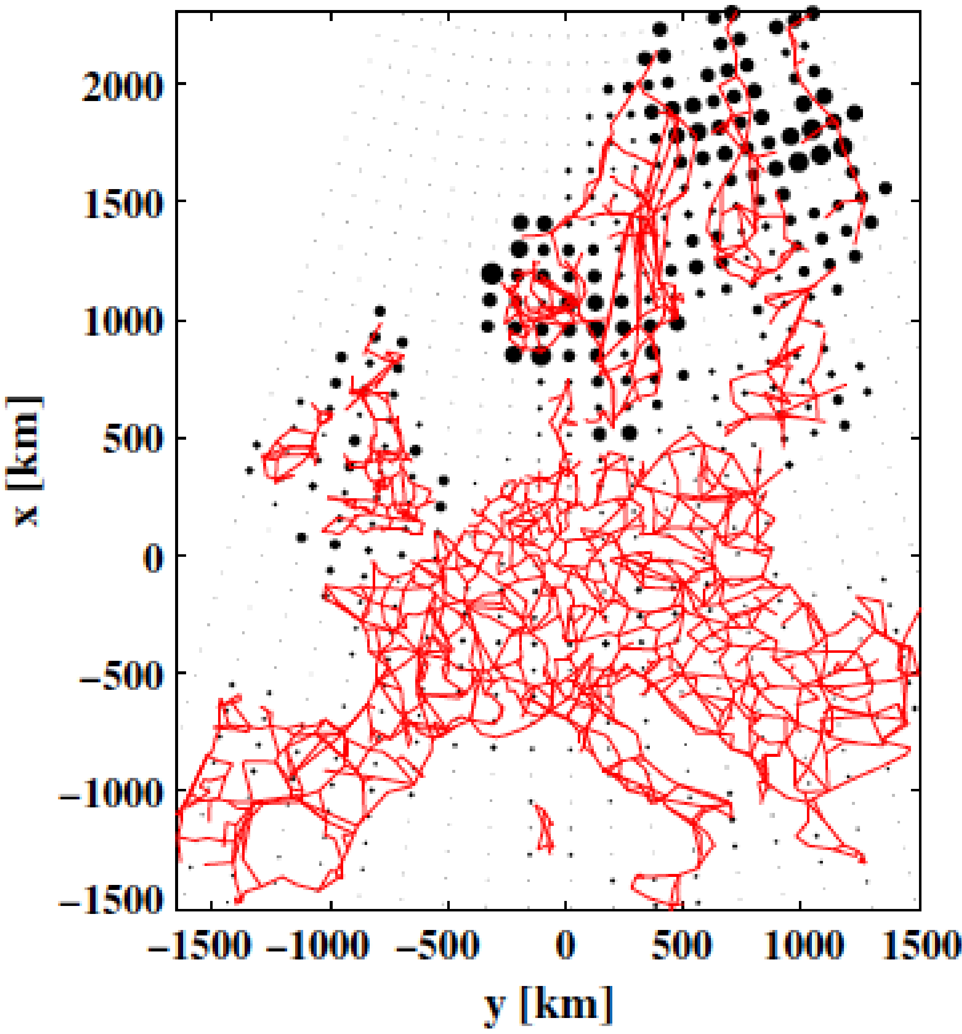
DOI: 10.1051/swsc/2014018

Max = 184 A, method: mean (4 points)



Ground Induced Currents

- Electricity grid structure.

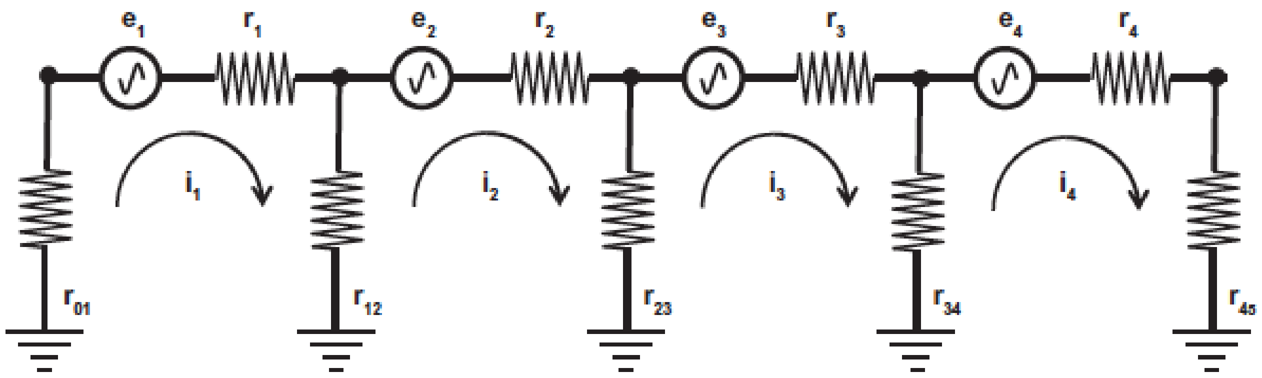
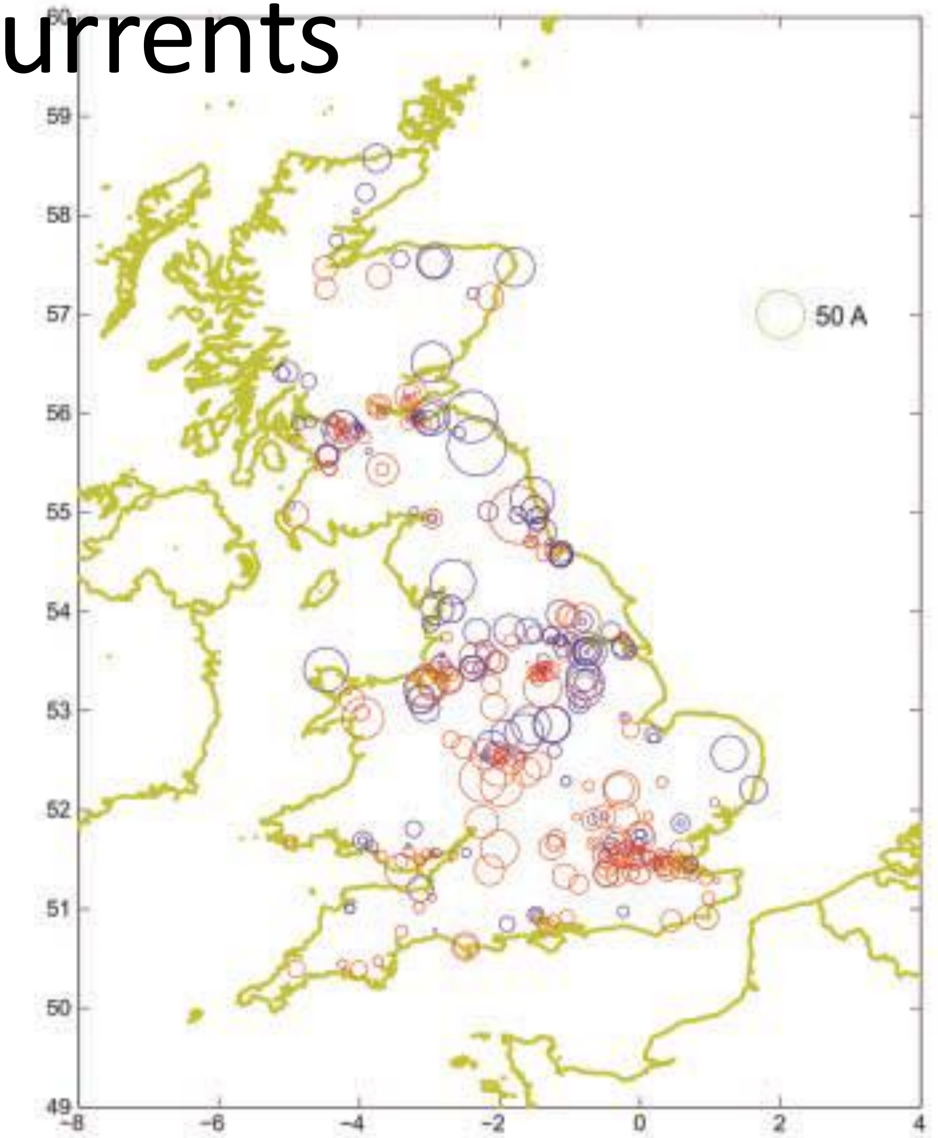


Fig. 1. Single-phase diagram of a power network illustrating mesh resistances, *r*, induced emfs, *e* and loop currents, *i*.



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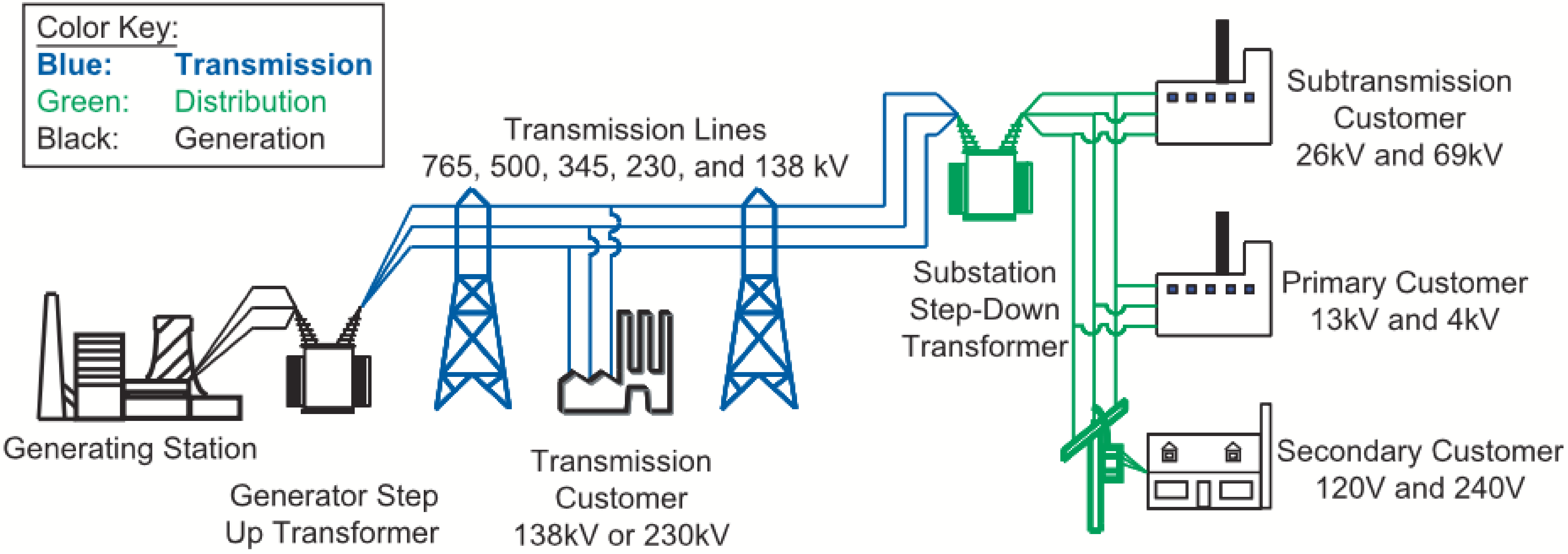
High-Voltage Power Grids

- The most likely infrastructure to experience GIC is HV electricity grid.
- HV grid is designed to have low impendence so that electricity transmission is efficient.
- HV cables are made of aluminium, supported by steel.
- Transmission lines are often many hundreds of thousands of volts.
- Lines are often hundreds of km long.

High-Voltage Power Grids



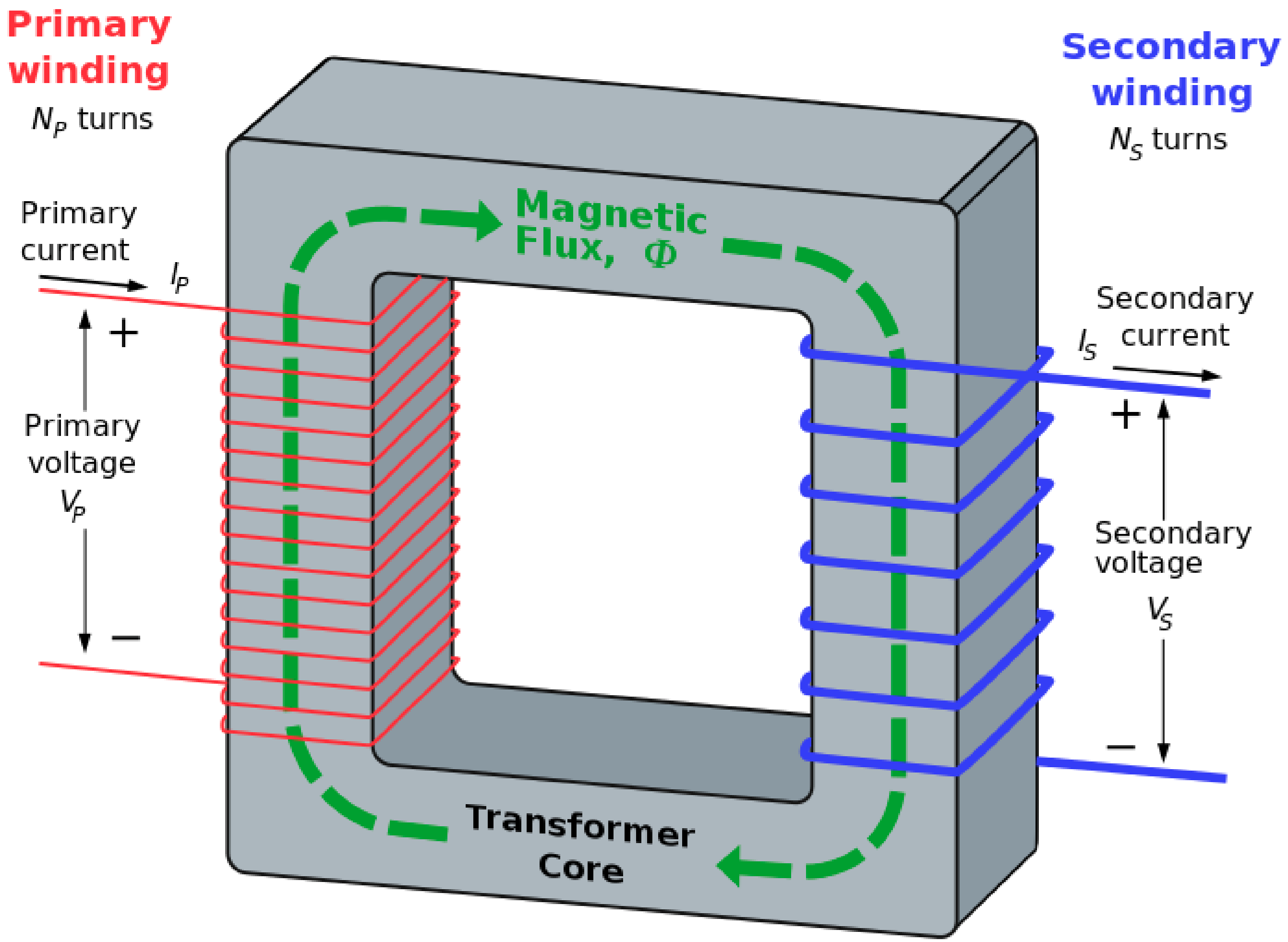
High-Voltage Power Grids

- Transformers:

Used to change the voltage of an electrical circuit.

When operated ‘eddy currents’ can flow in the core which create heat and distort the voltage and current from that which is desired.

Design is optimised to reduce eddy currents from the expected input; GIC disrupts this.



High-Voltage Power Grids

- Half-cycle saturation and heating
  - When a GIC is added to the sinusoidal signal of AC current it pushes the current up and out of the range of linear response of the transformer.
  - The excess current is lost to eddy currents and so the 'high' half of the cycle appears saturated and the transformer gets hot.

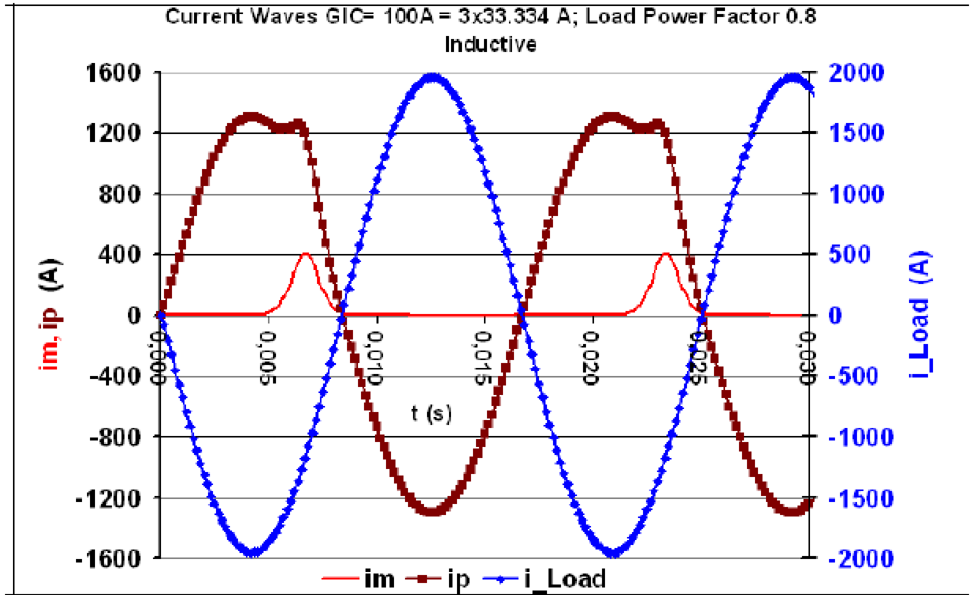


Fig.5-7: On load currents with PF 0.8, under GIC 100A

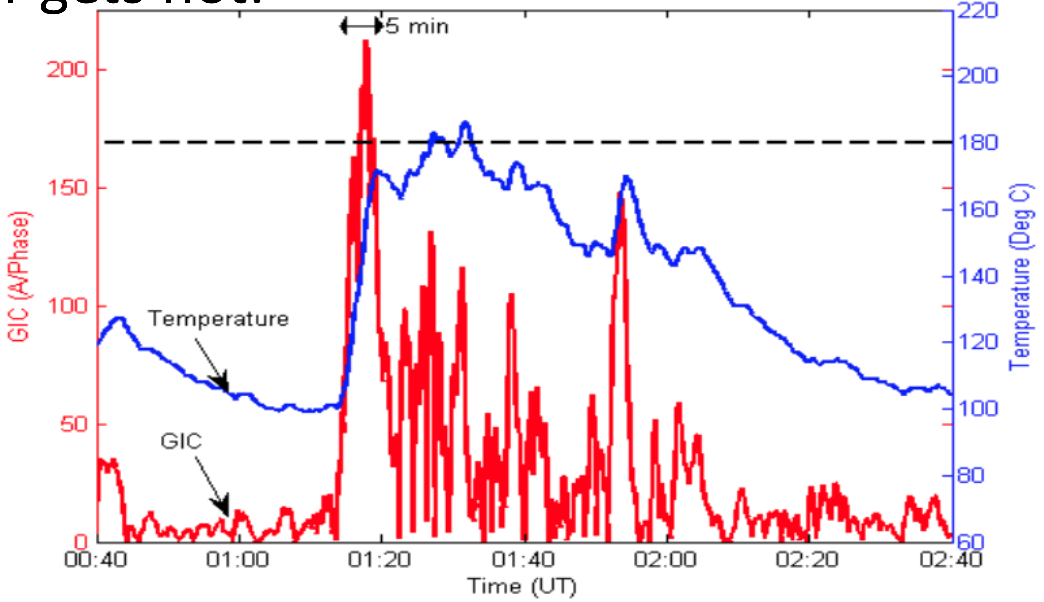


Fig 4: Metallic hot spot temperature for a GIC waveshape derived from the March 1989 GMD event.

High-Voltage Power Grids

- Voltage instability.
  - If the voltage drops too low in any part of the system it will collapse to 0 and a cascade can start that drops the system to 0 volts. = voltage collapse.
  - Systems automatically turn off to protect themselves from damage.
- Time synchronisation loss
  - AC systems all use a characteristic frequency (50 or 60 Hz, typically).
  - If the time synchronisation is lost across the grid then damage can occur, so systems trip off if the wave-form becomes too distorted.

Pipes and Corrosion

- GIC will flow through any conductive medium.
- Pipes carry GIC and there are several effects:
    - Oil / gas pipes carry dangerous contents and uncontrolled currents can cause sparks or cause current issues in control equipment.
    - All pipes corrode faster when subject to an electrical current.
- Pipes that corrode will eventually leak. This can lead to ecological disaster or at least a repair.

Railway Lines and Signals

- Railways are controlled by electrical signals that travel along the tracks or cables near tracks.
- If these signals are distorted by GIC then failures can occur.
  - Some local train lines in Russia are reported to have signal problems during GIC events.
- Incorrect signaling can result in railway collisions.

Financial Cost of Current Fluctuations in the Grid

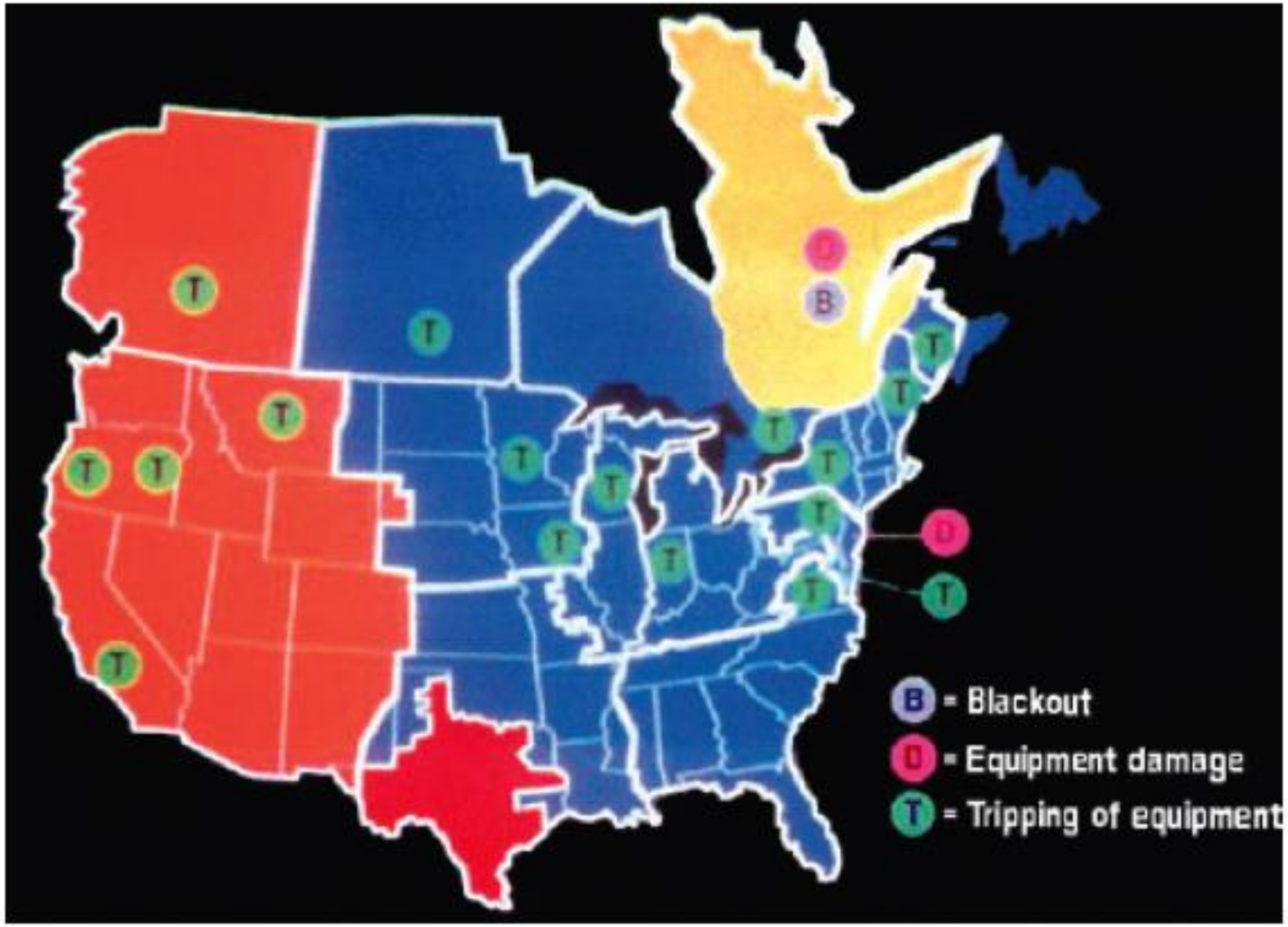
- Electricity costs are one of the simpler financial impacts of space weather to examine.
  - Insurance claims for large machinery increase on days with severe space weather
  - Spot prices of electricity fluctuate with supply and demand but also transmission efficiency and when GIC limits transmission the prices increase even if a blackout does not occur.

FORBES AND ST. CYR: SPACE WEATHER AND THE ELECTRICITY MARKET

Examples of GIC events in the past

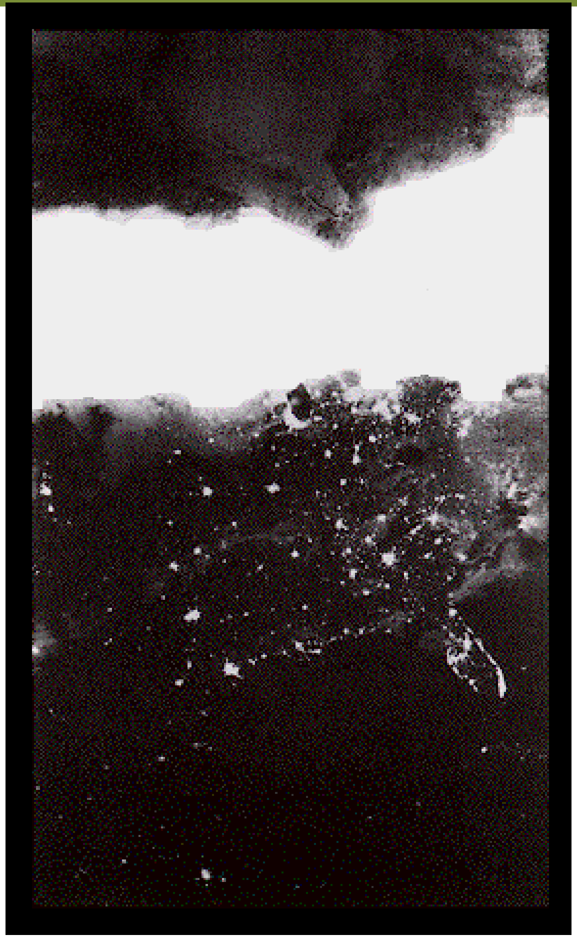
- 1921 – telegraph stations damaged and signals distorted across northern latitudes.
- 1940 – Northern US power systems experience wild swings in voltage.
- 1957/8 – blackouts around Toronto.
- 1989 – blackouts in Quebec, transformers trip across the USA.
- 2003 – blackout in Sweden and cumulative transformer damage attributed to the event in South Africa.

Examples of GIC events in the past



GICs

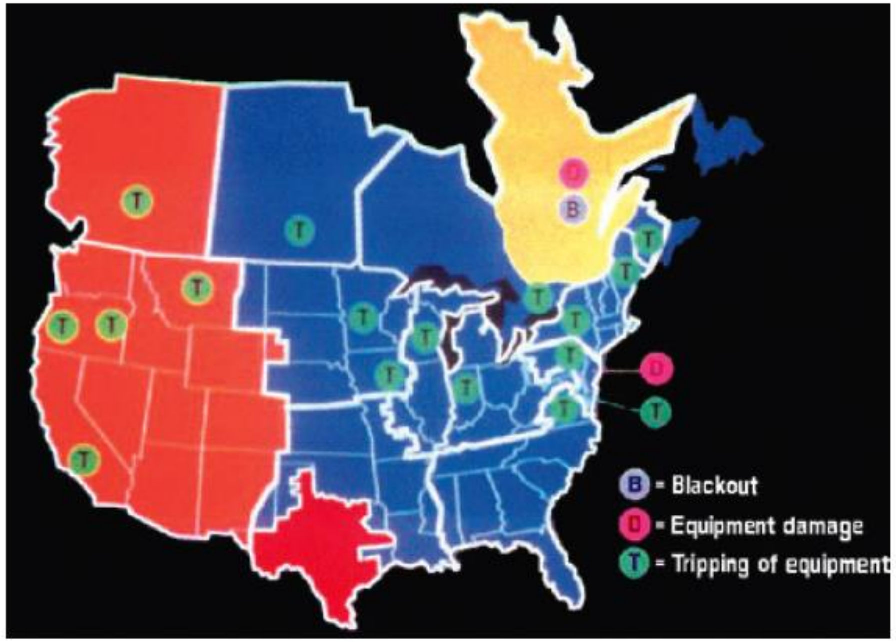
- Large geomagnetic storms cause intense aurora. These represent large currents flowing in the ionosphere.
- The atmospheric electrical circuit is disrupted and currents flow even far away from the auroral zone (although this is where the most intense currents are).
- Current is induce on the ground, this prefers to flow through high-voltage electricity grids, railway infrastructure and pipelines.
- The current does not damage hardware directly, but can cause safety systems to trip as voltage offsets cause transformers and similar hardware to saturate.
- Uncontrolled tripping of systems can cause damaging currents to flow if not handled correctly, this can directly damage transformers etc.
- These are very expensive and difficult to replace. UK has something like 1600 high-voltage transformers, 10 spares. Construction takes months.



The image is taken around 04:00 Universal Time on 14 March 1989 by the DoD F9 meteorology satellite, from figure 1.17 of Physics of the Plasma Universe, by Anthony L. Peratt

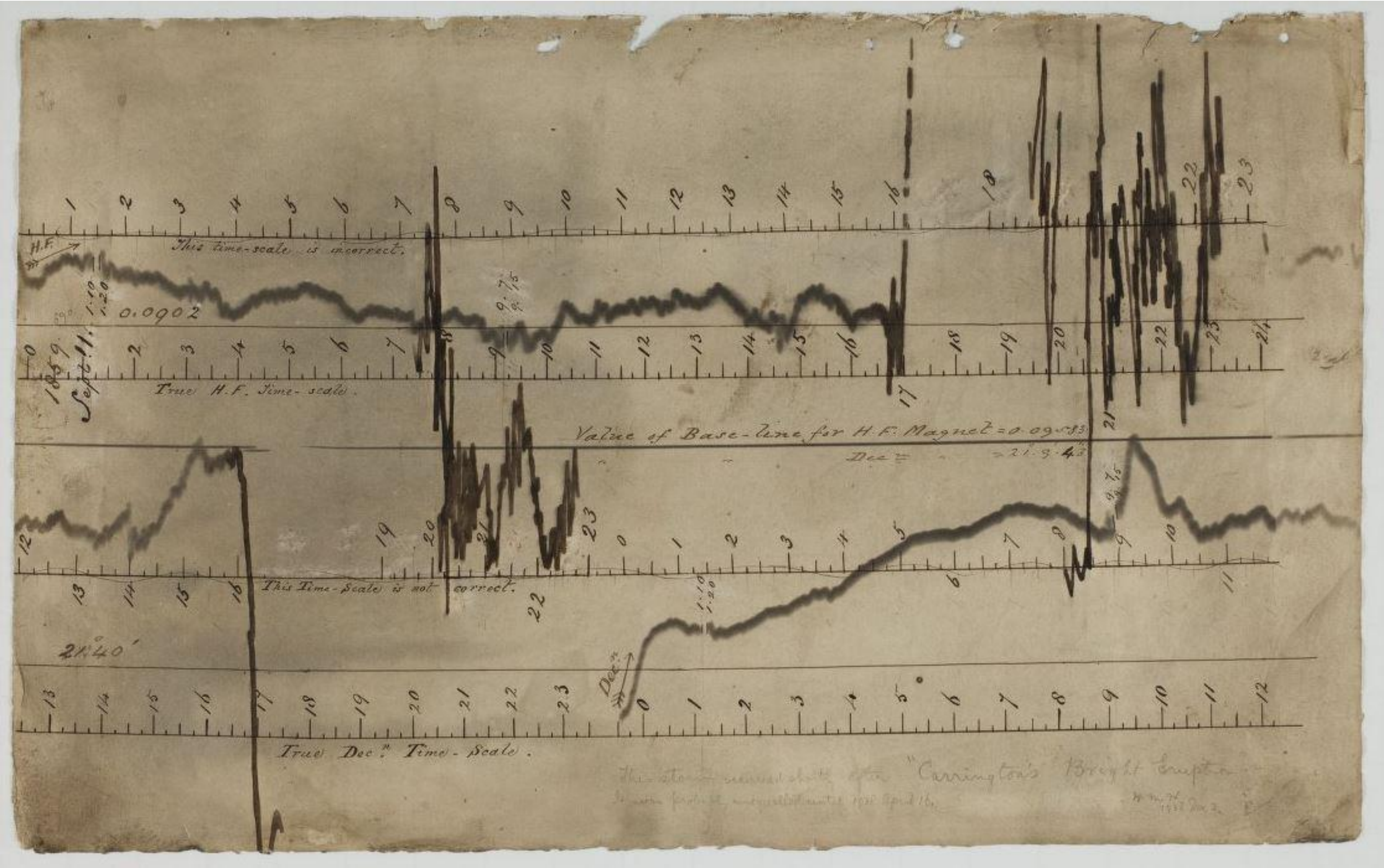
GICs: Recent Example

- 1989, The Quebec power grid collapsed.
- 6 million people were without electricity for 9 hours.
- NASA lost track of some if its spacecraft.
- The northern lights glowed as far south as London.



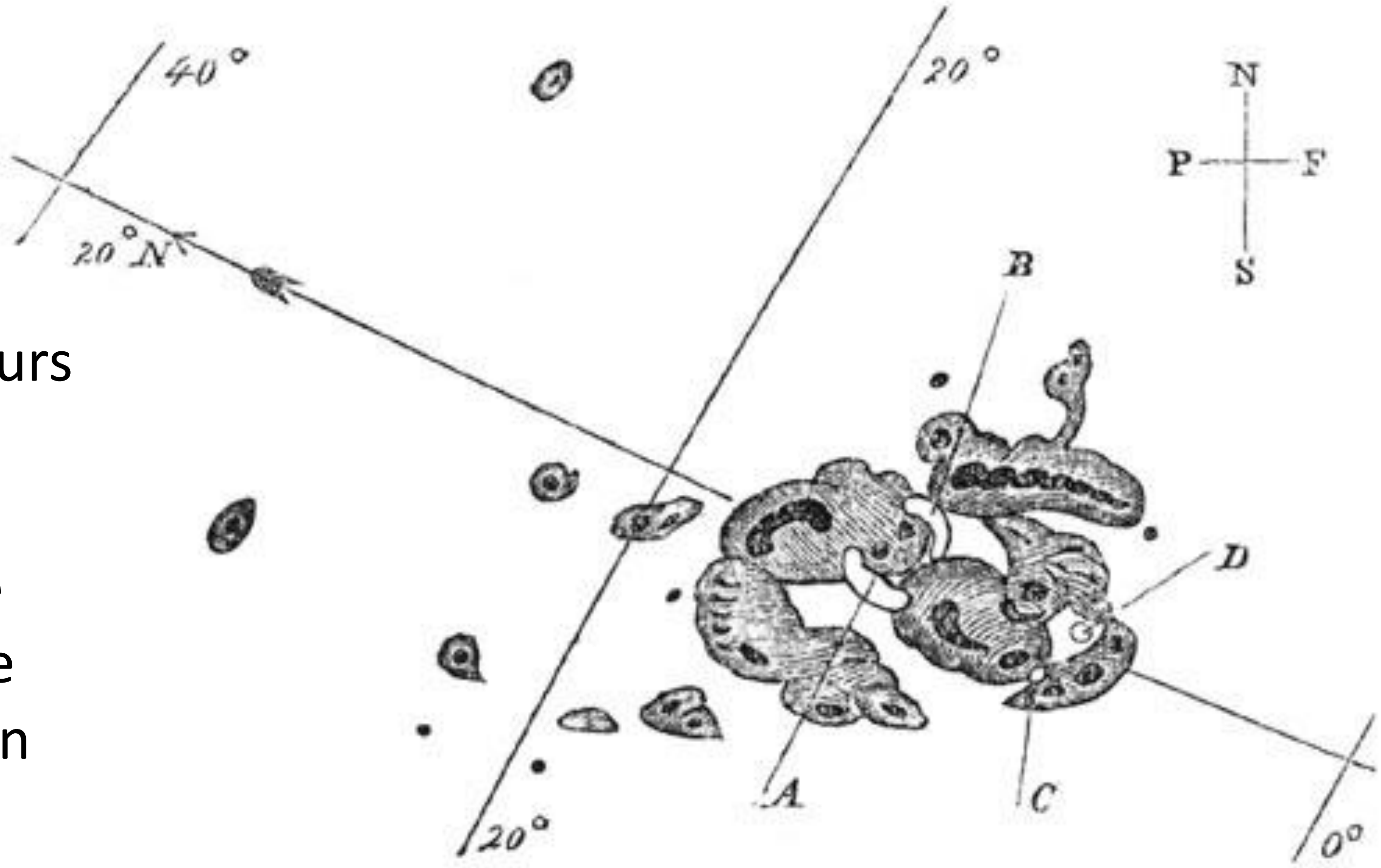
Reasonable Worst Case: Carrington

- The most severe recorded geomagnetic storm was associated with the first observation of space weather: the Carrington event in 1859.
- Greenwich Observatory recorded the magnetic field deviation, but it was larger than the roll of paper it was recorded on and so went off the scale.
- The telegraph between UK and USA ran without power or was inoperable, heat in the wires started fires in some buildings.
- Aurora were seen close to the equator.

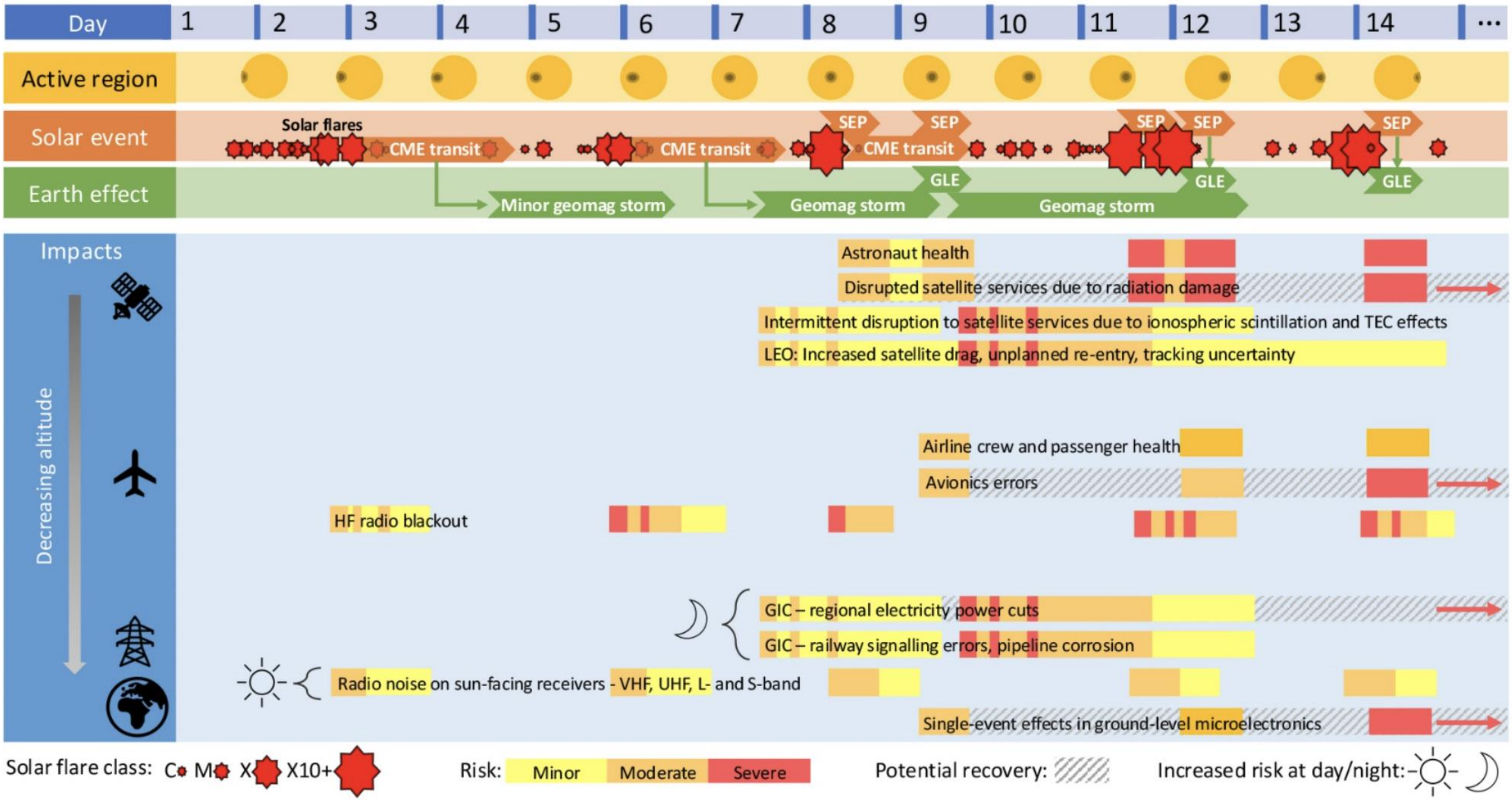

This time-scale is incorrect.
H.F.
0.0902
1859 Sept 11.
True H.F. Time-scale.
Value of Base-line for H.F. Magnet = 0.0983
This Time-Scale is not correct.
21°40′
True Decl. Time-Scale.

- Carrington saw a large flare, no scientific recordings of X-rays, but estimates put it as high-X class.
- CME arrived at Earth after 17.6 hours => 2400 km/s or 8.5 Mkm/hr

- There would have been an intense radiation storm caused by the flare and an even more intense radiation event from the CME.

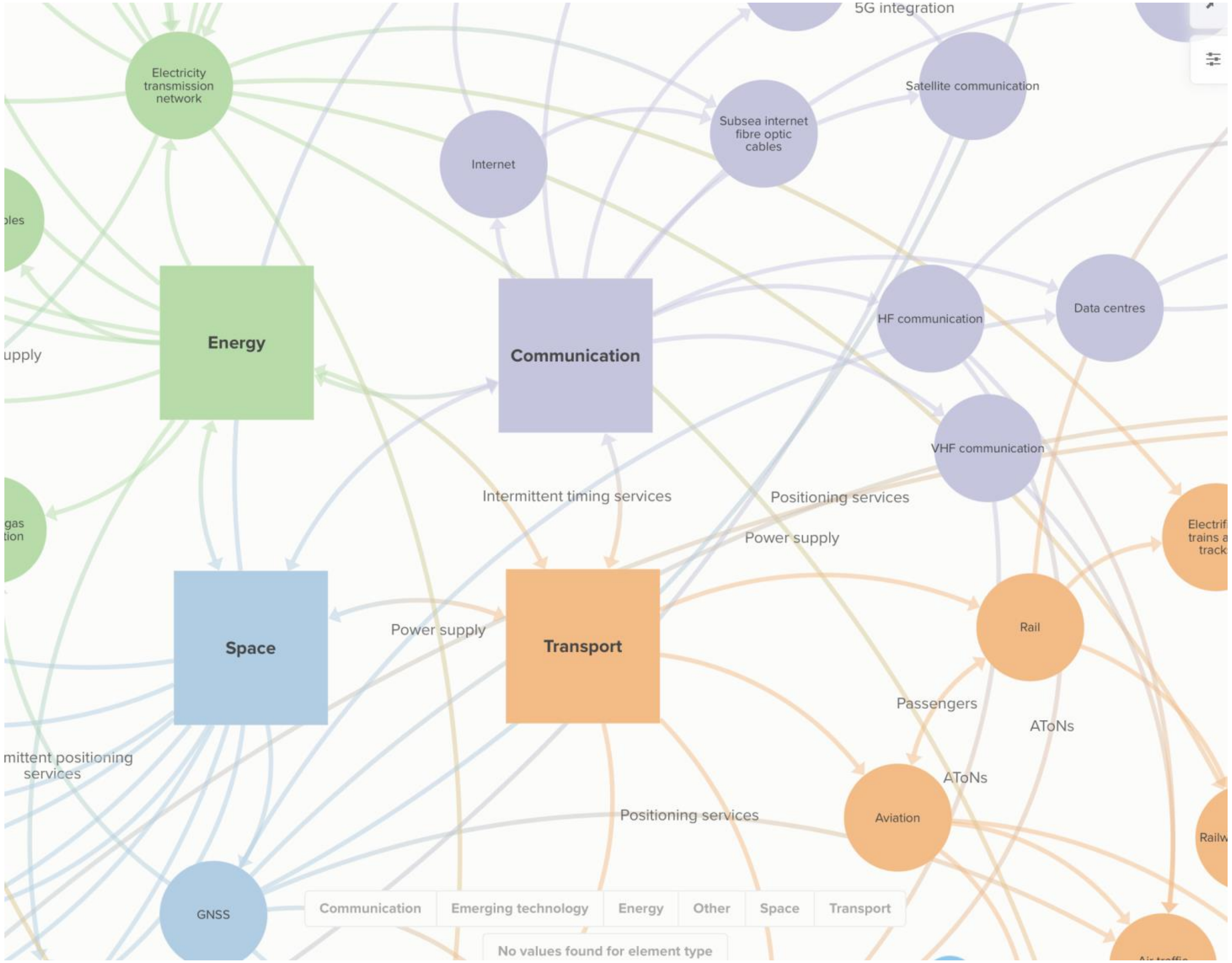


Extreme Space Weather Scenario



Cascading complex risk

- https://kumu.io/swimmr-s6/cni-sector-dependencies
- Severe space weather is a risk to technological systems that rely on satellite data, timing, positioning and electricity.
- These things are woven into modern infrastructure and services.
- Impacts of space weather can be far reaching and hard to predict.



Met Office Forecasts

- The USA (NOAA SWPC) and UK (Met Office MOSWOC) have active space weather forecasts.
- These rely on data from spacecraft that sit between the Earth and the Sun and on images of the Sun.
- When large sunspots are seen they are tracked and an watch is issued.
- When a M or X-class flare is seen, high levels of radiation are detected or a CME is seen heading towards the Earth a warning is issued.
- When it is measured in space, if it is fast, high pressure or has southwards magnetic field an alert is issued.
- https://weather.metoffice.gov.uk/specialist-forecasts/space-weather
- Met Office provide a general overview forecast to the public
- Detailed forecasts are prepared for individual organisations on request.

Met Office Forecasts

Category		UK Effect	US and Global Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects			
Solar radiation storms				Flux level of >= 10 MeV particles (ions)*	Number of events when flux level was met (number of storm days**)
S5	Extreme	**Biological:** Passengers and crew in aircraft on certain routes may be exposed to increased radiation levels. The increase depends on flight path and the detailed storm characteristics.*** **Spacecraft operations:** Some satellites may suffer temporary outages due to memory impacts which can cause loss of control, serious noise in image data or orientation problems and permanent damage to solar panels. **Aircraft operations:** Some aircraft electronic systems may experience single event effects (SEE) which can cause upsets or unexpected behaviour. The rate of SEE depends on flight path and the detailed storm characteristics.***	**Biological:** unavoidable high radiation hazard to astronauts on EVA (extra-vehicular activity); passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** **Satellite operations:** satellites may be rendered useless, memory impacts can cause loss of control, may cause serious noise in image data, star-trackers may be unable to locate sources; permanent damage to solar panels possible. **Aircraft operations:** pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.)**	10^5	Fewer than 1 per cycle
S4	Severe	**Biological:** Passengers and crew in aircraft on certain routes may be exposed to increased radiation levels. The increase depends on flight path and the detailed storm characteristics.*** **Satellite operations:** Some satellites may suffer temporary outages due to single event effects on electronics which can cause unexpected behaviours, noise in image data or orientation problems and permanent damage to solar panels.*** **Aircraft operations:** Some aircraft electronic systems may experience single event effects (SEE) which can cause upsets or unexpected behaviour. The rate of SEE depends on flight path and the detailed storm characteristics.***	**Biological:** unavoidable radiation hazard to astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** **Satellite operations:** may experience memory device problems and noise on imaging systems; star-tracker problems may cause orientation problems, and solar panel efficiency can be degraded. **Aircraft operations:** blackout of HF radio communications through the polar regions and increased navigation errors over several days are likely.	10^4	3 per cycle
S3	Strong	**Biological:** Passengers and crew in aircraft on certain routes may be exposed to increased radiation levels. The increase depends on flight path and the detailed storm characteristics.*** **Satellite operations:** A small number of satellites may experience outages due to single event effects, which can cause unexpected behaviours, noise on imaging systems and orientation problems. **Aircraft operations:** Some aircraft electronic systems may experience single event effects (SEE) which can cause upsets or unexpected behaviour. The rate of SEE depends on flight path and the detailed storm characteristics.***	**Biological:** radiation hazard avoidance recommended for astronauts on EVA; passengers and crew in high-flying aircraft at high latitudes may be exposed to radiation risk.*** **Satellite operations:** single-event upsets, noise in imaging systems, and slight reduction of efficiency in solar panel are likely. **Aircraft operations:**degraded HF radio propagation through the polar regions and navigation position errors likely.	10^3	10 per cycle
S2	Moderate	**Biological:** No additional risk. **Satellite operations:** Infrequent single-event upsets possible. **Aircraft operations:** Unlikely to have significant effect.***	**Biological:** passengers and crew in high-flying aircraft at high latitudes may be exposed to elevated radiation risk.*** **Satellite operations:** infrequent single-event upsets possible. **Aircraft operations:** small effects on HF propagation through the polar regions and navigation at polar cap locations possibly affected.	10^2	25 per cycle
S1	Minor	**Biological:** none. **Satellite operations:** none. **Aircraft operations:** Unlikely to have an effect***	**Biological:** none. **Satellite operations:** none. **Aircraft operations:** minor impacts on HF radio in the polar regions.	10	50 per cycle

Met Office Forecasts

Category		UK Effect	US and
Scale	Descriptor	Duration of event will influence severity of effects	
		Solar radiation storms	
S5	Extreme	**Biological:** Passengers and crew in aircraft on certain routes may be exposed to increased radiation levels. The increase depends on flight path and the detailed storm characteristics.*** **Spacecraft operations:** Some satellites may suffer temporary outages due to memory impacts which can cause loss of control, serious noise in image data or orientation problems and permanent damage to solar panels. **Aircraft operations:** Some aircraft electronic systems may experience single event effects (SEE) which can cause upsets or unexpected behaviour. The rate of SEE depends on flight path and the detailed storm characteristics.***	**Biological:** unavoidable high radiation haza passengers and crew in high-flying aircraft at **Satellite operations:** satellites may be ren control, may cause serious noise in image da permanent damage to solar panels possible. **Aircraft operations:** pipeline currents can propagation may be impossible in many area degraded for days, low-frequency radio navi seen as low as Florida and southern Texas (ty
S4	Severe	**Biological:** Passengers and crew in aircraft on certain routes may be exposed to increased radiation levels. The increase depends on flight path and the detailed storm characteristics.*** **Satellite operations:** Some satellites may suffer temporary outages due to single event effects on electronics which can cause unexpected behaviours, noise in image data or orientation problems and permanent damage to solar panels.*** **Aircraft operations:** Some aircraft electronic systems may experience single event effects (SEE) which can cause upsets or unexpected behaviour. The rate of SEE depends on flight path and the detailed storm characteristics.***	**Biological:** unavoidable radiation hazard to flying aircraft at high latitudes may be expose **Satellite operations:** may experience mem systems; star-tracker problems may cause ori degraded. **Aircraft operations:** blackout of HF radio c increased navigation errors over several days a

Met Office Forecasts

Category		UK Effect	US and Global Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects			
Geomagnetic storms				Kp values*	Number of storm events when Kp level was met; (number of storm days)
G5	Extreme	**Power systems:** Localised voltage control and protective system problems may occur leading to potential for localised loss of power. Transformers may experience damage. **Spacecraft operations:** may experience extensive surface charging, drag may increase on low-Earth-orbit satellites, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** HF (high frequency) radio communication may be impossible in many areas for one to two days, GNSS(GPS) satellite navigation may be degraded for days with possible effects on infrastructure reliant on GNSS (GPS) for positioning or timing, low-frequency radio navigation can be out for hours, and aurora may be seen across the whole of the UK.	**Power systems:** widespread voltage control problems and protective system problems can occur, some grid systems may experience complete collapse or blackouts. Transformers may experience damage. **Spacecraft operations:** may experience extensive surface charging, drag may increase on low-Earth-orbit satellites, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** pipeline currents can reach hundreds of amps, HF (high frequency) radio propagation may be impossible in many areas for one to two days, satellite navigation may be degraded for days, low-frequency radio navigation can be out for hours, and aurora has been seen as low as Florida and southern Texas (typically 40° geomagnetic lat.)**.	Kp = 9	4 per cycle (4 days per cycle)
G4	Severe	**Power systems:** No significant impact on UK power grid likely. **Spacecraft operations:** may experience surface charging and tracking problems, drag may increase on low-Earth-orbit satellites, corrections may be needed for orientation problems. **Other systems:** HF radio propagation sporadic, GNSS(GPS) satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora may be seen across the whole of the UK.	**Power systems:** possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Spacecraft operations:** may experience surface charging and tracking problems, corrections may be needed for orientation problems. **Other systems:** induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora has been seen as low as Alabama and northern California (typically 45° geomagnetic lat.)**.	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G3	Strong	**Power systems:** No significant impact on UK power grid likely. **Spacecraft operations:** Surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** Intermittent GNSS(GPS) satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent. Aurora may be seen in Scotland and Northern Ireland and as low as Mid-Wales and the Midlands.	**Power systems:** voltage corrections may be required, false alarms triggered on some protection devices. **Spacecraft operations:** surface charging may occur on satellite components, drag may increase on low-Earth-orbit satellites, and corrections may be needed for orientation problems. **Other systems:** intermittent satellite navigation and low-frequency radio navigation problems may occur, HF radio may be intermittent, and aurora has been seen as low as Illinois and Oregon (typically 50° geomagnetic lat.)**.	Kp = 7	200 per cycle (130 days per cycle)
G2	Moderate	**Power systems:** No impact on UK power grid. **Spacecraft operations:** Corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora may be seen across Scotland.	**Power systems:** high-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **Spacecraft operations:** corrective actions to orientation may be required by ground control; possible changes in drag affect orbit predictions. **Other systems:** HF radio propagation can fade at higher latitudes, and aurora has been seen as low as New York and Idaho (typically 55° geomagnetic lat.)**.	Kp = 6	600 per cycle (360 days per cycle)
G1	Minor	**Power systems:** No impact on UK power grid. **Spacecraft operations:** Minor impact on satellite operations possible. **Other systems:** Aurora may be seen as low as Northern Scotland.	**Power systems:** weak power grid fluctuations can occur. **Spacecraft operations:** minor impact on satellite operations possible. **Other systems:** migratory animals are affected at this and higher levels; aurora is commonly visible at high latitudes (northern Michigan and Maine)**.	Kp = 5	1700 per cycle (900 days per cycle)

Met Office Forecasts

Category		UK Effect	US and Global Effe
Scale	Descriptor	Duration of event will influence severity of effects	
Geomagnetic storms			
G5	Extreme	**Power systems:** Localised voltage control and protective system problems may occur leading to potential for localised loss of power. Transformers may experience damage. **Spacecraft operations:** may experience extensive surface charging, drag may increase on low-Earth-orbit satellites, problems with orientation, uplink/downlink and tracking satellites. **Other systems:** HF (high frequency) radio communication may be impossible in many areas for one to two days, GNSS(GPS) satellite navigation may be degraded for days with possible effects on infrastructure reliant on GNSS (GPS) for positioning or timing, low-frequency radio navigation can be out for hours, and aurora may be seen across the whole of the UK.	**Power systems:** widespread voltage control problems a occur, some grid systems may experience complete collap experience damage. **Spacecraft operations:** may experience extensive surfa low-Earth-orbit satellites, problems with orientation, uplin **Other systems:** pipeline currents can reach hundreds of propagation may be impossible in many areas for one to t degraded for days, low-frequency radio navigation can be seen as low as Florida and southern Texas (typically 40° g
G4	Severe	**Power systems:** No significant impact on UK power grid likely. **Spacecraft operations:** may experience surface charging and tracking problems, drag may increase on low-Earth-orbit satellites, corrections may be needed for orientation problems. **Other systems:** HF radio propagation sporadic, GNSS(GPS) satellite navigation degraded for hours, low-frequency radio navigation disrupted, and aurora may be seen across the whole of the UK.	**Power systems:** possible widespread voltage control pro will mistakenly trip out key assets from the grid. **Spacecraft operations:** may experience surface chargi may be needed for orientation problems. **Other systems:** induced pipeline currents affect preventi sporadic, satellite navigation degraded for hours, low-frequ aurora has been seen as low as Alabama and northern Calif
G3	Strong	**Power systems:** No significant impact on UK power grid likely. **Spacecraft operations:** Surface charging may occur on satellite components, drag may increase on	**Power systems:** voltage corrections may be required, fal protection devices.

Met Of

Category		UK Effect	US and Global Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	Descriptor	Duration of event will influence severity of effects			
Radio blackouts				GOES X-ray peak brightness by class and by flux	Number of events when flux level was met; (number of storm days
R5	Extreme	**HF Radio:** Complete HF (high frequency*) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector.	**HF Radio:** Complete HF (high frequency*) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. **Navigation:** Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 (2×10^{-3})	Less than 1 per cycle
R4	Severe	**HF Radio:** HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time.	**HF Radio:** HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. . **Navigation:** Outages of low-frequency navigation signals cause increased error in positioning for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	X10 (10^{-3})	8 per cycle (8 days per cycle)
R3	Strong	**HF Radio:** Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth.	**HF Radio:** Wide area blackout of HF radio communication, loss of radio contact for about an hour on sunlit side of Earth. **Navigation:** Low-frequency navigation signals degraded for about an hour.	X1 (10^{-4})	175 per cycle (140 days per cycle)
R2	Moderate	**HF Radio:** Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes.	**HF Radio:** Limited blackout of HF radio communication on sunlit side, loss of radio contact for tens of minutes. **Navigation:** Degradation of low-frequency navigation signals for tens of minutes.	M5 (5×10^{-5})	350 per cycle (300 days per cycle)
R1	Minor	**HF Radio:** Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact.	**HF Radio:** Weak or minor degradation of HF radio communication on sunlit side, occasional loss of radio contact. **Navigation:** Low-frequency navigation	M1 (10^{-5})	2000 per cycle (950 days per cycle)

Met Office Forecasts

Category		UK Effect	US and Global Effect	Physical measure	Average Frequency (1 cycle = 11 years)
Scale	**Descriptor**	**Duration of event will influence severity of effects**			
Radio blackouts				**GOES X-ray peak brightness by class and by flux**	**Number of events when flux level was met; (number of storm days**
R5	**Extreme**	**HF Radio:** Complete HF (high frequency*) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector.	**HF Radio:** Complete HF (high frequency*) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. This results in no HF radio contact with mariners and en route aviators in this sector. **Navigation:** Low-frequency navigation signals used by maritime and general aviation systems experience outages on the sunlit side of the Earth for many hours, causing loss in positioning. Increased satellite navigation errors in positioning for several hours on the sunlit side of Earth, which may spread into the night side.	X20 (2×10^{-3})	Less than 1 per cycle
R4	**Severe**	**HF Radio:** HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during	**HF Radio:** HF radio communication blackout on most of the sunlit side of Earth for one to two hours. HF radio contact lost during this time. . **Navigation:** Outages of low-frequency	X10 (10^{-3})	8 per cycle (8 days per cycle)

Forecast Customers

Impact Area	Customer (examples)	Action (examples)	Cost (examples)
Spacecraft (Individual systems to complete spacecraft failure; communications and radiation effects)	• Lockheed Martin • Orbital • Boeing • Space Systems Loral • NASA, DoD	• Postpone launch • In orbit - Reboot systems • Turn off/safe instruments and/or spacecraft	• Loss of spacecraft ~$500M • Commercial loss exceeds $1B • Worst case storm - $100B
Electric Power (Equipment damage to electrical grid failure and blackout conditions)	• U.S. Nuclear Regulatory Commission • N. America Electric Reliability Corp. • Allegheny Power • New York Power Authority	• Adjust/reduce system load • Disconnect components • Postpone maintenance	• Estimated loss ~$400M from unexpected geomagnetic storms • $3-6B loss in GDP (blackout)
Airlines (Communications) (Loss of flight HF radio communications) (Radiation dose to crew and passengers)	• United Airlines • Lufthansa • Continental Airlines • Korean Airlines • NavCanada (Air Traffic Control)	• Divert polar flights • Change flight plans • Change altitude • Select alternate communications	• Cost ~ $100k per diverted flight • $10-50k for re-routes • Health risks
Surveying and Navigation (Use of magnetic field or GPS could be impacted)	• FAA-WAAS • Dept. of Transportation • BP Alaska and Schlumberger	• Postpone activities • Redo survey • Use backup systems	• From $50k to $1M daily for single company

Reading

- 2010 – Lloyd’s commissioned a report into space weather risk
- 2014 – Royal Academy of Engineering Report on Space Weather
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