sansa
SOUTH AFRICAN NATIONAL SPACE AGENCY

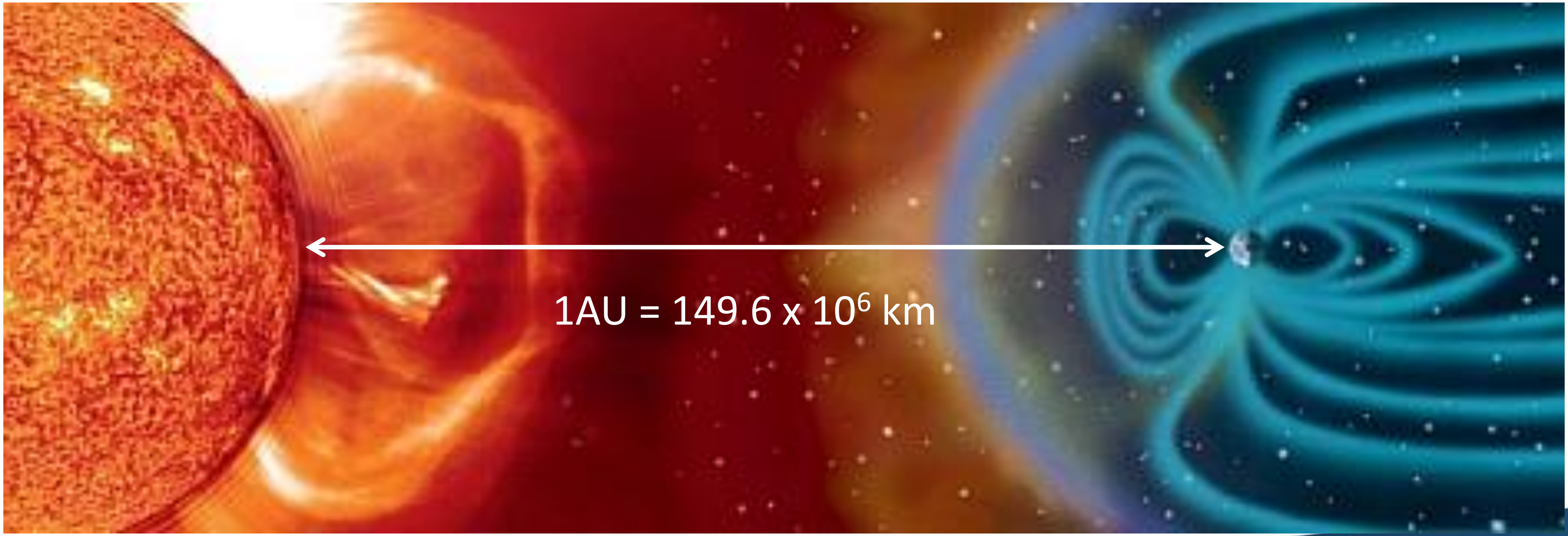
Space Weather: Why should we care?

Mike Kosch

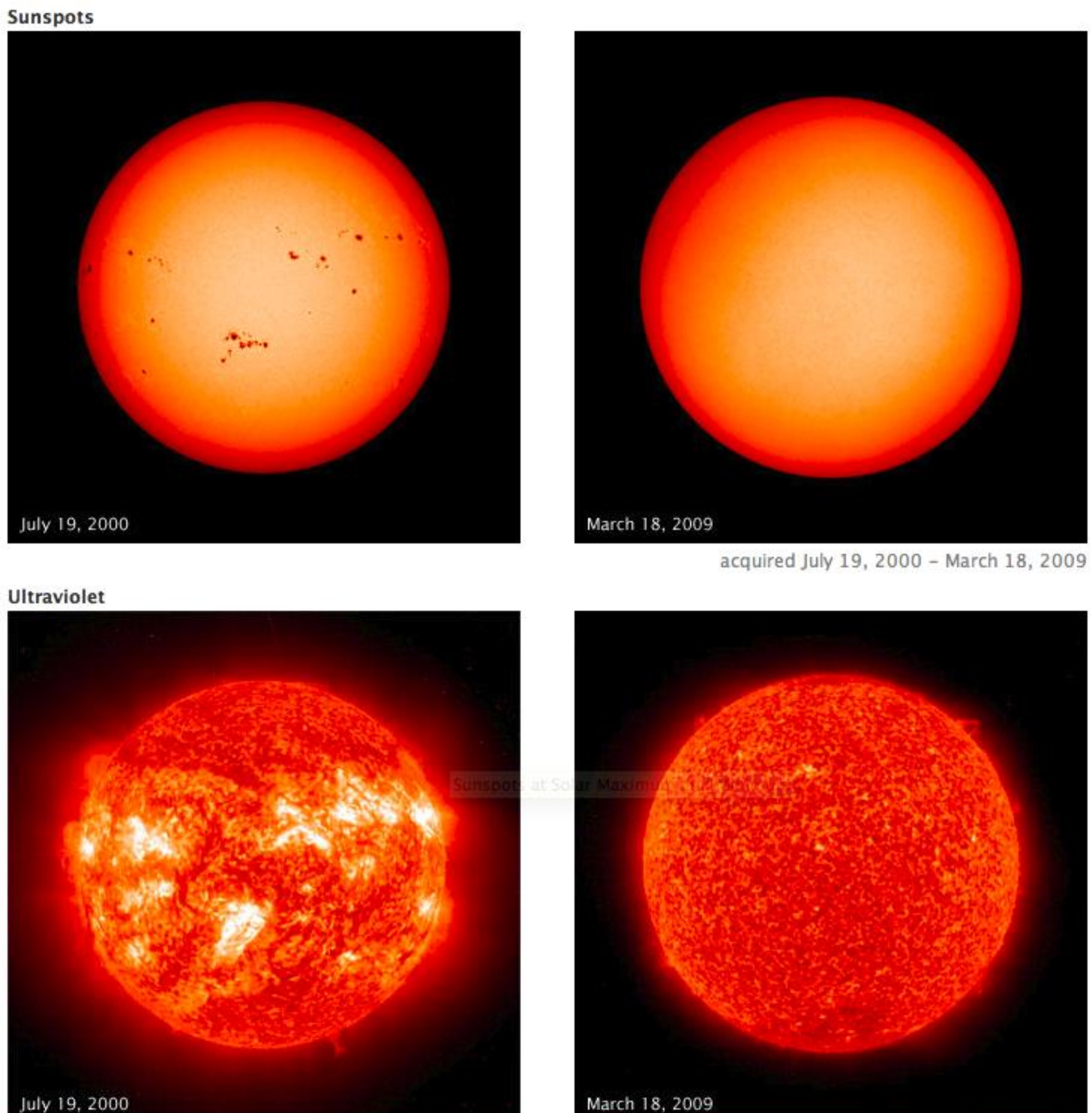
What is Space Weather?

Space Weather describes the condition of space environment between the Sun and the Earth as well as the effect on technological systems.

Space weather is a consequence of the behaviour of the sun, the nature of Earth's magnetic field and atmosphere, and our location in the solar system.



Active and Quiet Sun

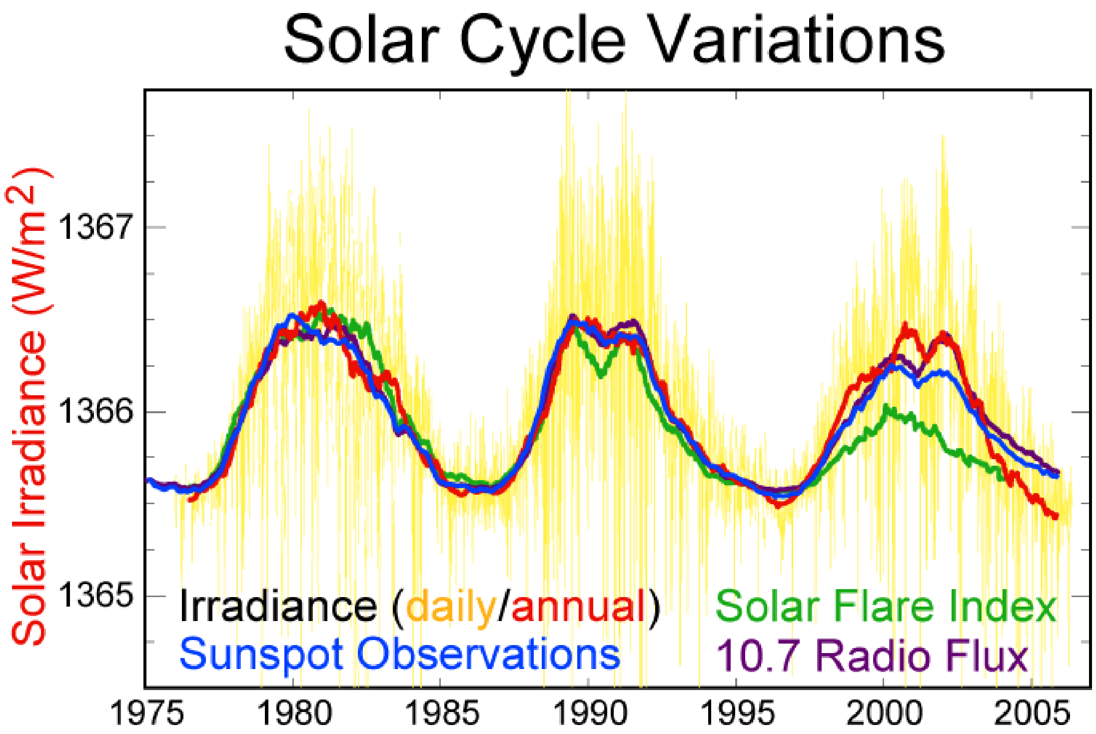


Visible light

UV light

The Solar Cycle

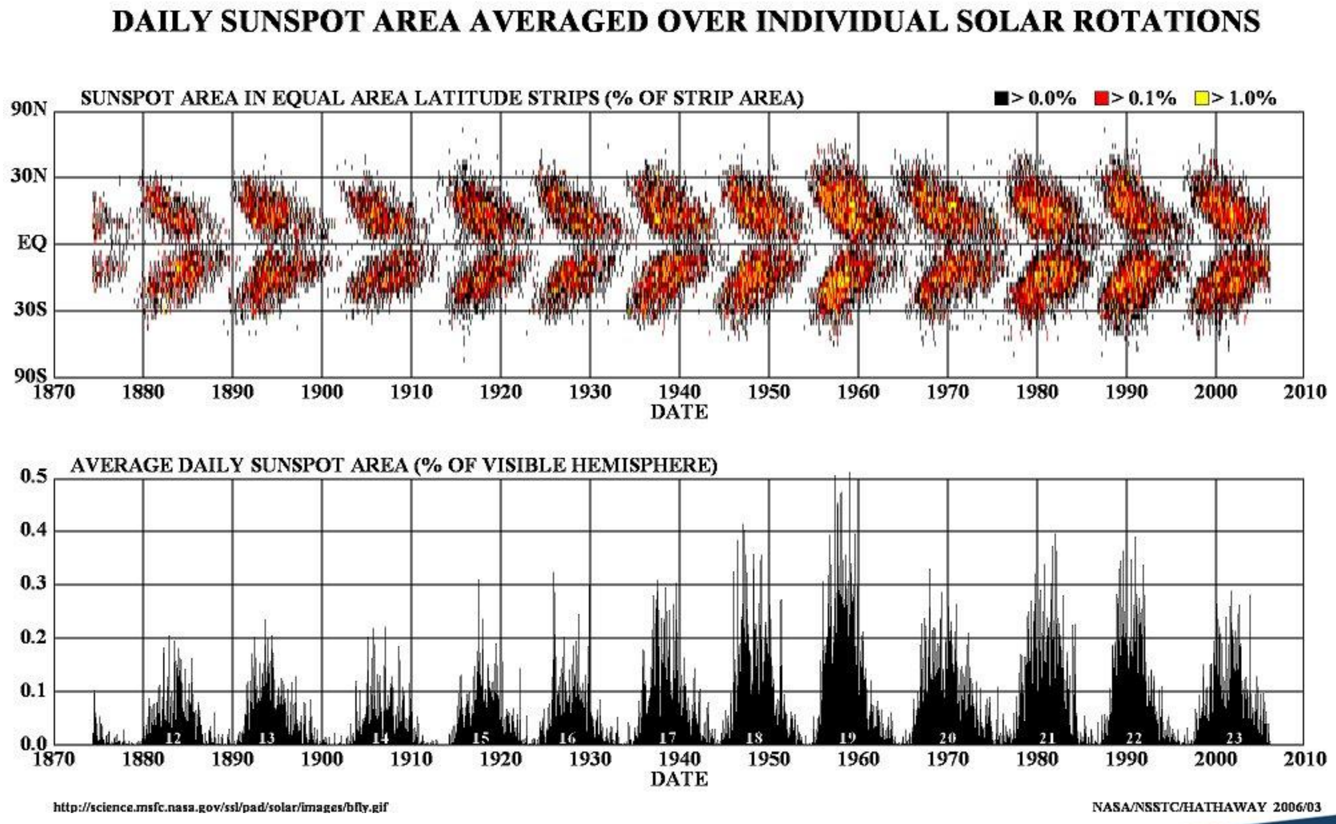
- Solar Cycle is the periodic change of solar activity
- The period is about ~11 years
- The magnetic field polarity flips every ~22 years



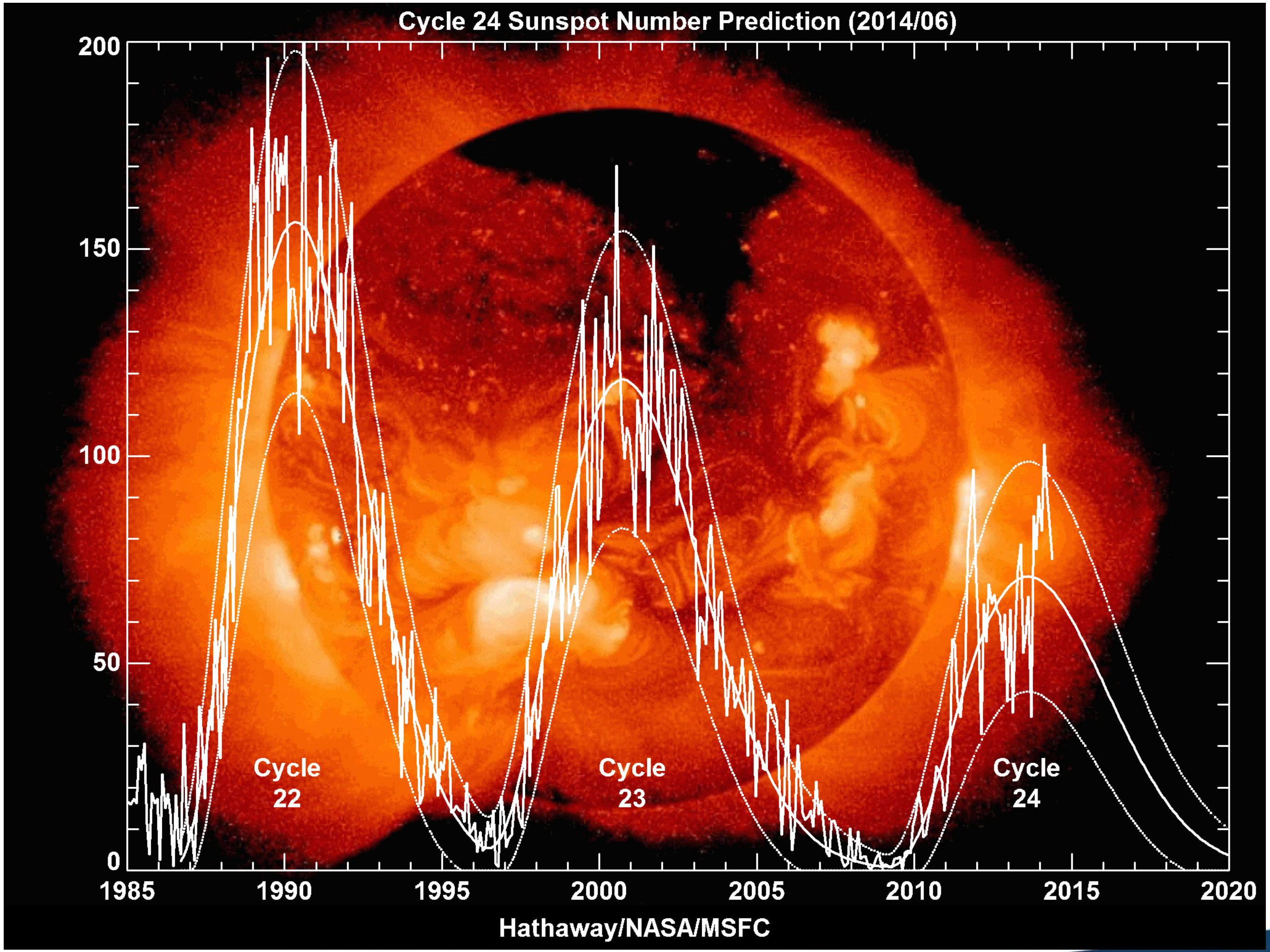
Variation ~0.1%

The Solar Cycle

- Sunspots – darker regions on the solar surface because they are cooler.
- Over the solar cycle, sunspots move towards the equator.

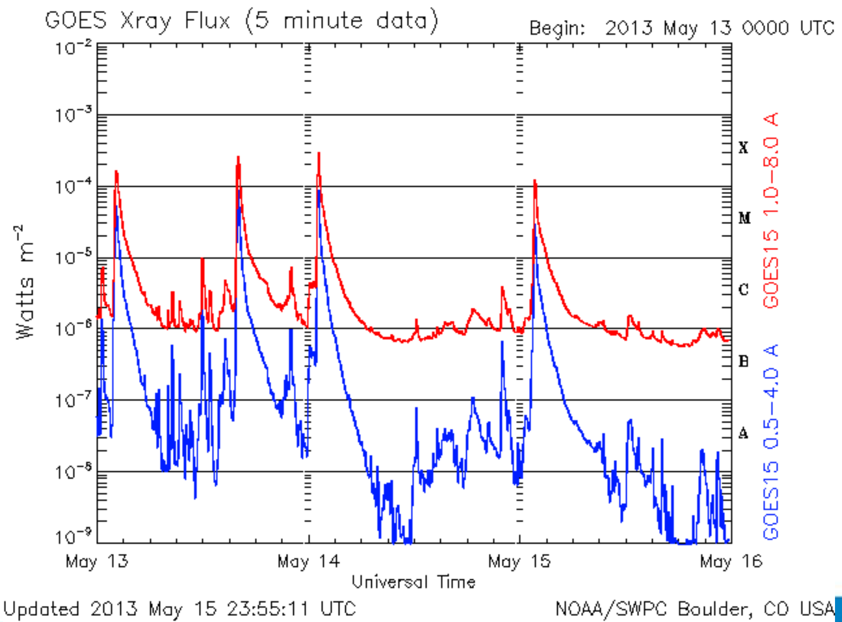


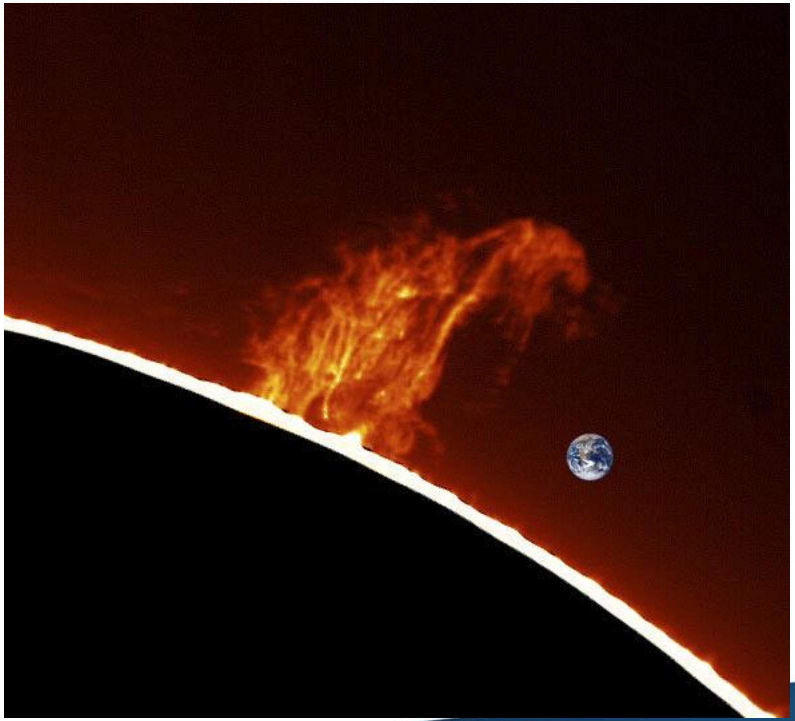
The Solar Cycle



Solar Flares

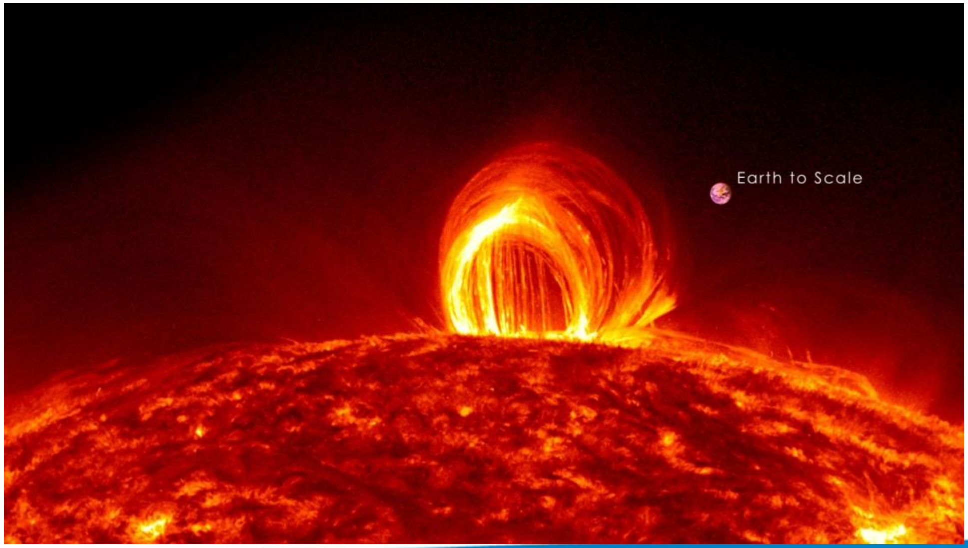
- Solar flare – sudden flash of brightness. Duration = minutes.
- Large X-ray and UV flux. Transit time = 8 minutes.
- Up to $6x10^{26}$ Joule released (50 billion Hiroshima-sized nuclear bombs)
- Frequency at solar min: <1 per week
- Frequency at solar max: several per day

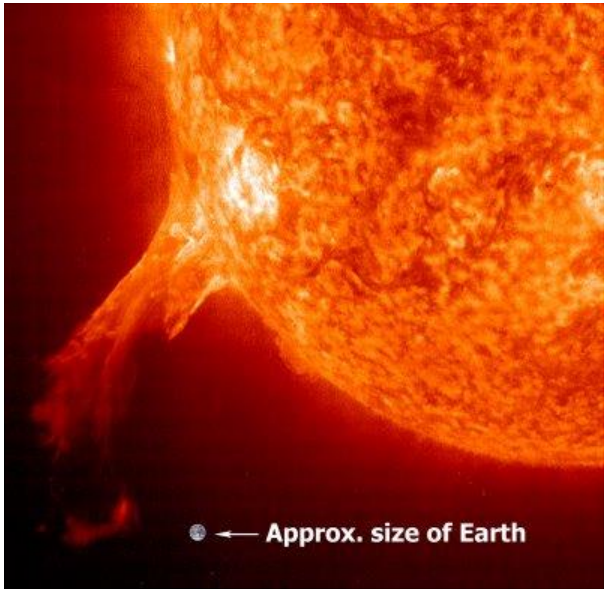




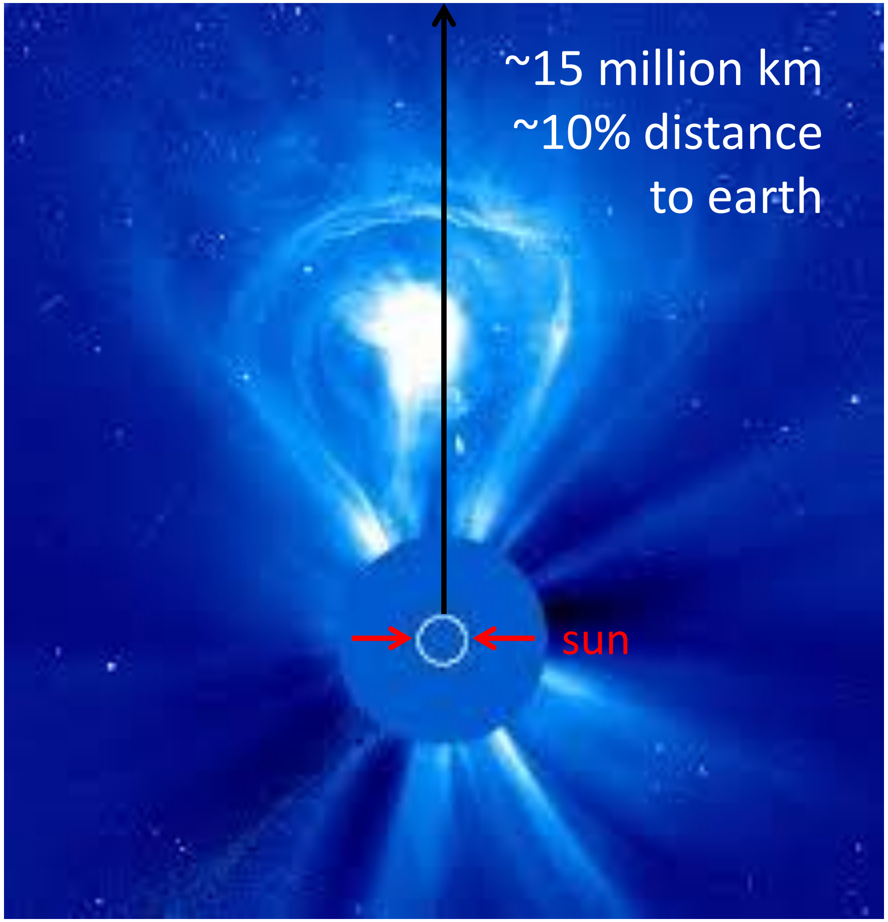
Coronal Mass Ejections

- Large ejection of charged particles (up to 10^{10} tons, average 1.6 $x10^9$ tons). Duration = hours.
- Velocity = 20 – 3200 km/s (average 500 km/s)
- Transit time = 0.5 – 5 days (average 3.5 days)
- Frequency at solar minimum: 0.2 per day
- Frequency at solar maximum: 3.5 per day

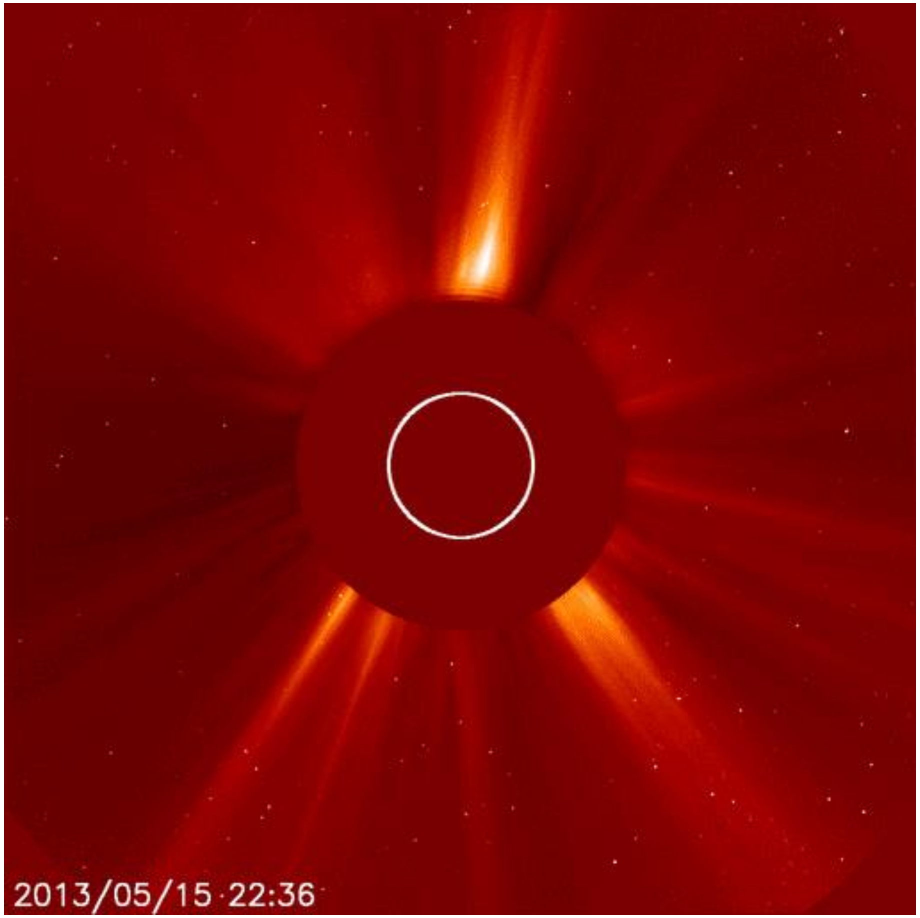




Coronal Mass Ejections



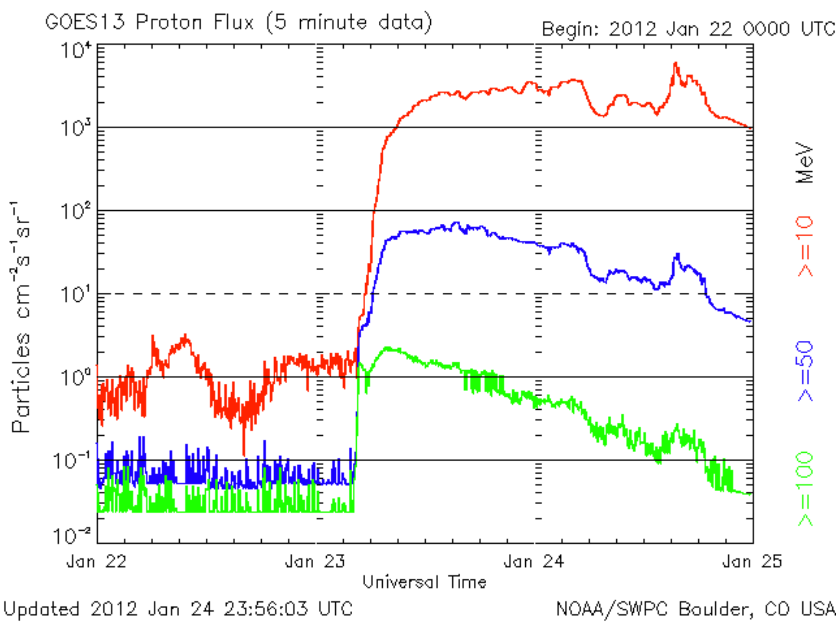
Earth radius = sun radius / 110



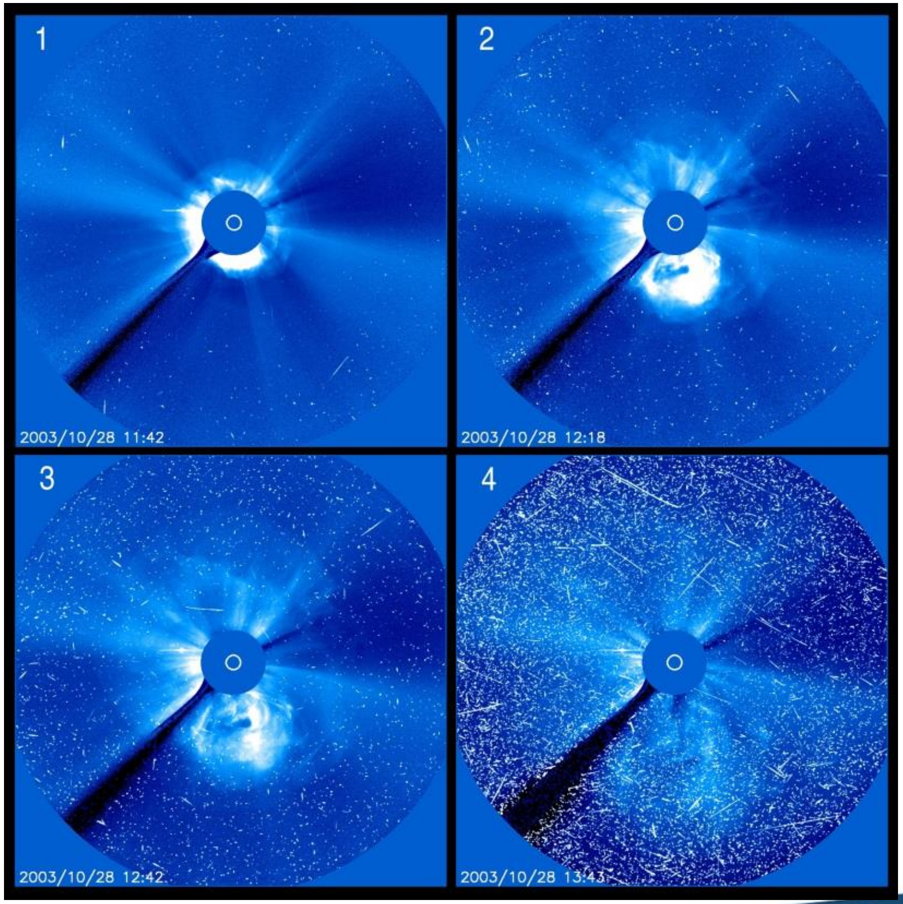
LASCO coronagraph on SOHO satellite

Solar Energetic Protons

- Relativistic energies
- Transit time = 15 minutes to hours

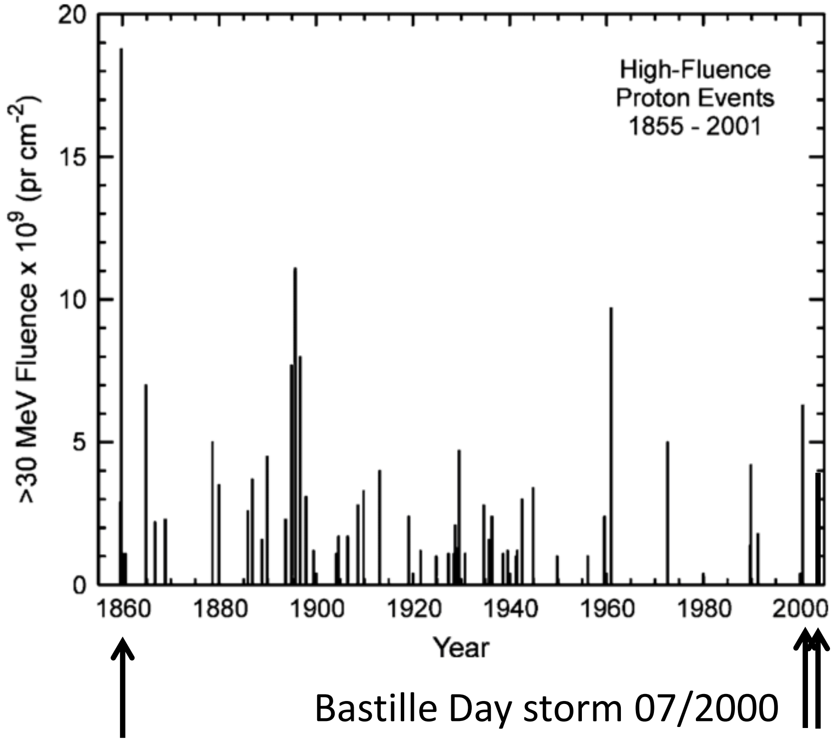


LASCO coronagraph on SOHO satellite



Solar Energetic Protons

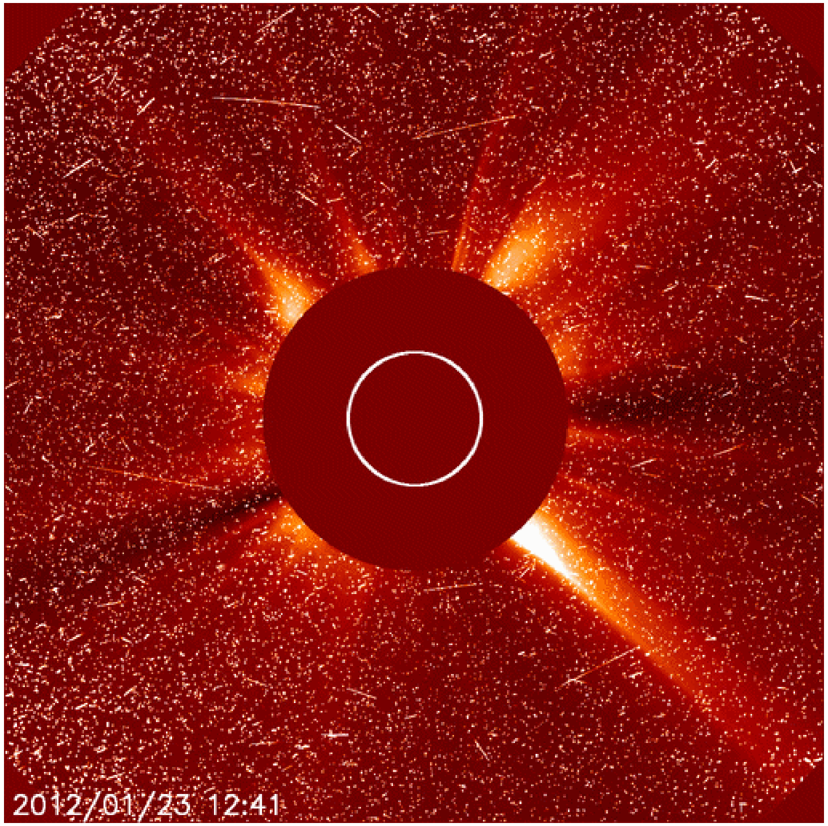
Proxy records to ~1600



Bastille Day storm 07/2000

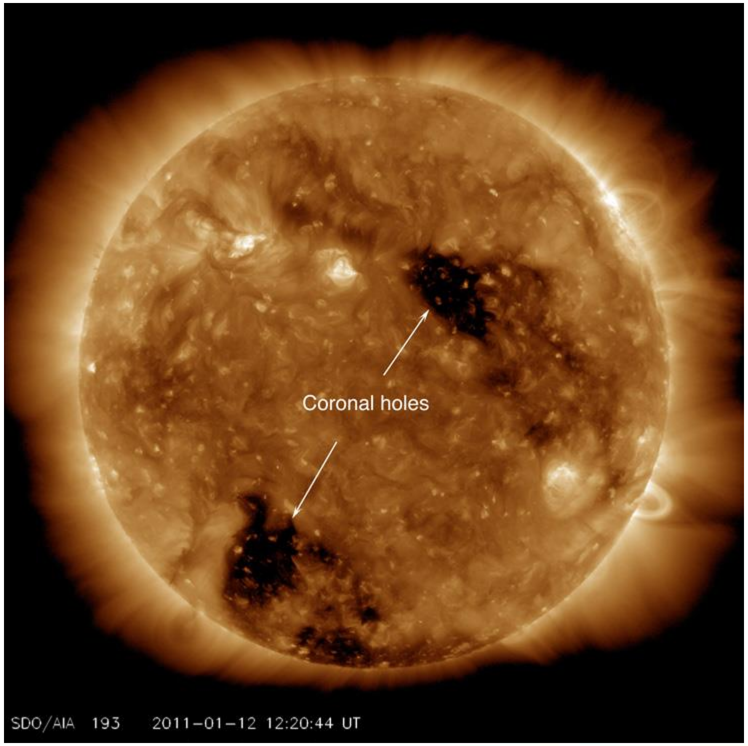
Halloween storm 10/2003

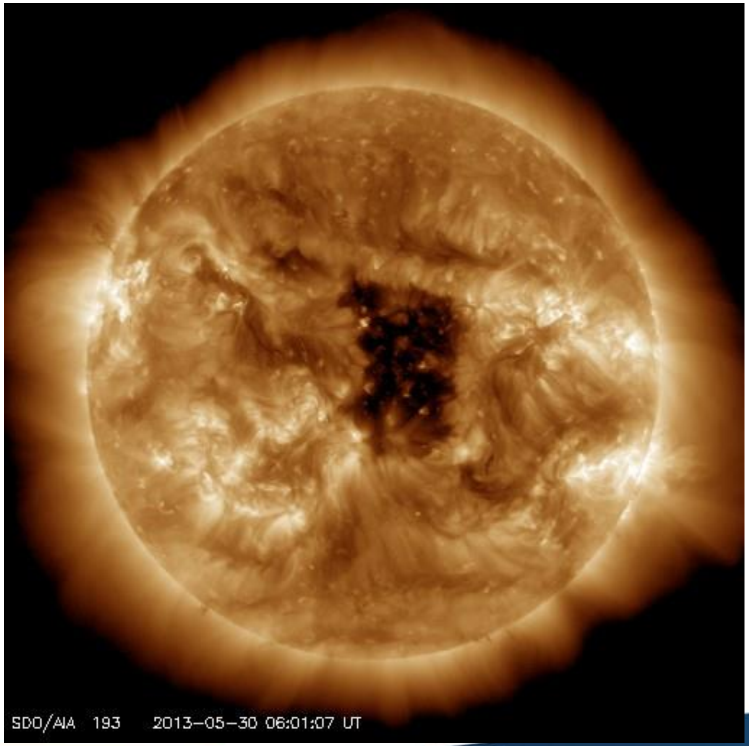
Carrington storm 09/1859



Coronal Holes

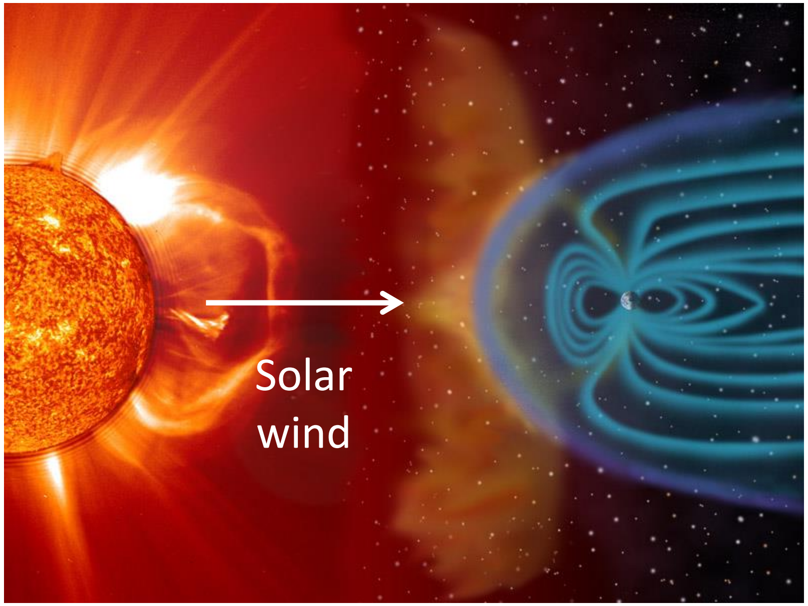
- Coronal holes: Regions where solar magnetic field does not close
- Solar wind: Protons and electrons escape the sun
- Sun weight loss: ~1 x 10^6 tons per second
- Sun's mass: ~10^{30} Kg. Lifetime: ~30,000 billion years



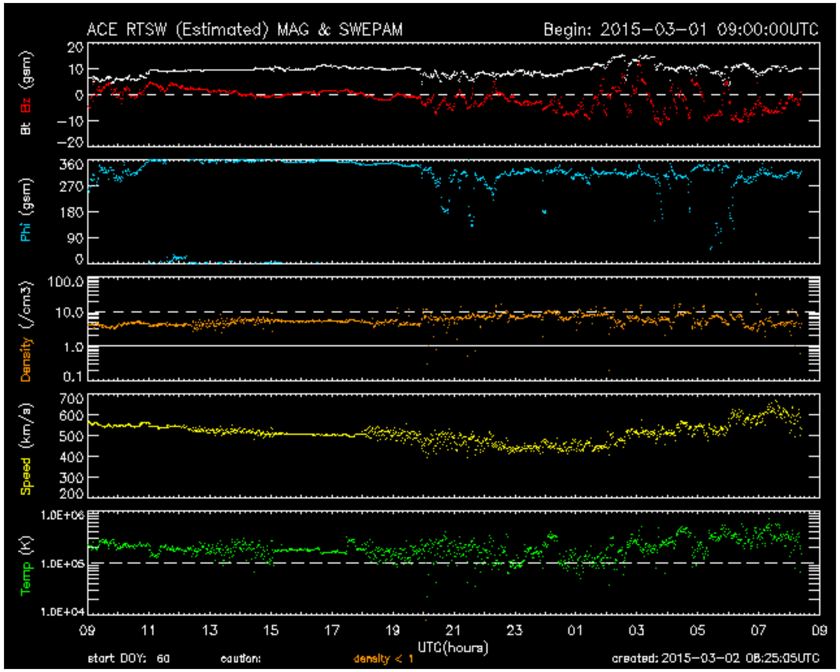


Solar Wind

- Protons and electrons escaping the sun
- Density: 1 – 10 particles per cm^{-3}
- Slow solar wind: Velocity = 400 km/s. Temperature = 1.5×10^6 K.
- Fast solar wind: Velocity = 750 km/s. Temperature = 0.8×10^6 K.

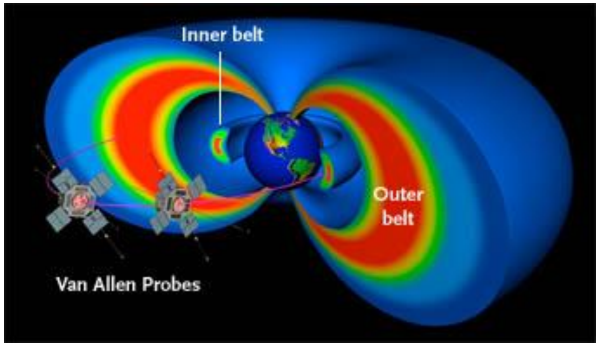


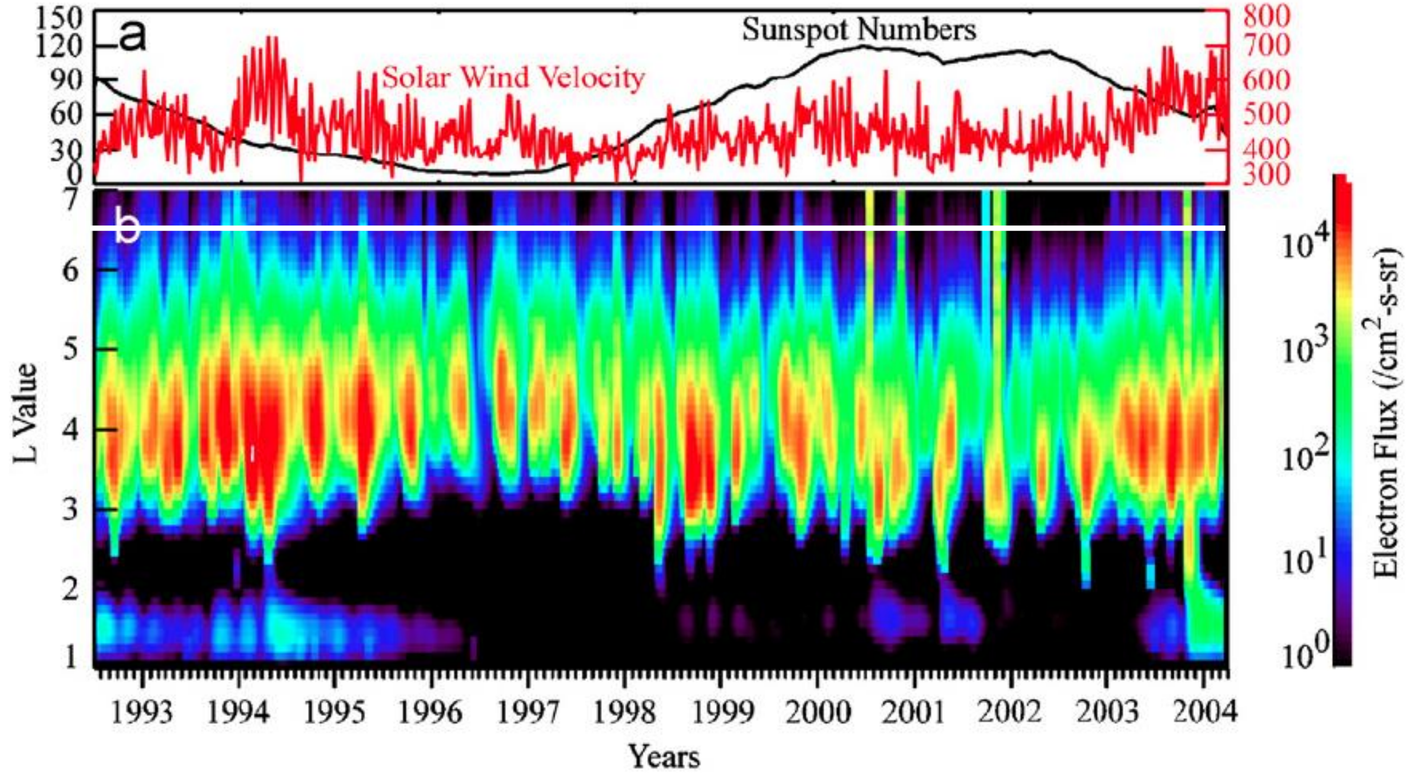
Mostly, the solar wind is benign but occasionally it is stormy.



Radiation Belts

- Discovered by Van Allen (USA) 1958.
- Inner belt: 0.2 – 2 R_E, mostly high-energy protons.
- Outer belt: 3 – 7 R_E, mostly high-energy electrons.
- Geostationary orbit: 6.6 R_E.





SAMPEX
2-6 MeV

Auroras

- Solar wind particles causes auroras (but that is another story)

NASA IMAGE satellite

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Impacts

Coronal Mass Ejection

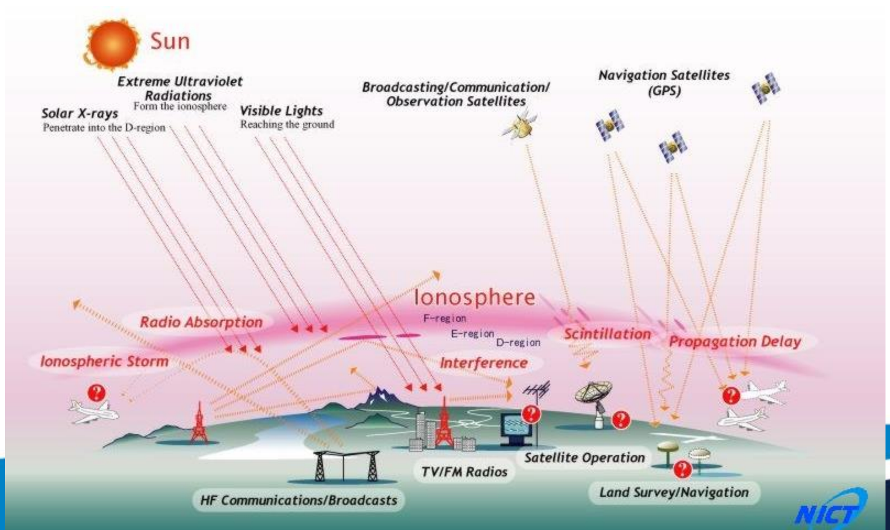
- Accelerate particles within the magnetosphere (radiation belts) and into the ionosphere (auroras)
- Impacts:
    - HF radio communications
    - Satellite navigation (scintillations)
    - Industry (e.g. timing for banks)
    - Magnetic navigation
    - Industry (e.g. aviation & oil drilling)
    - Electric power grids and pipelines
    - Satellite lifetime (drag <800 km)
    - Auroras

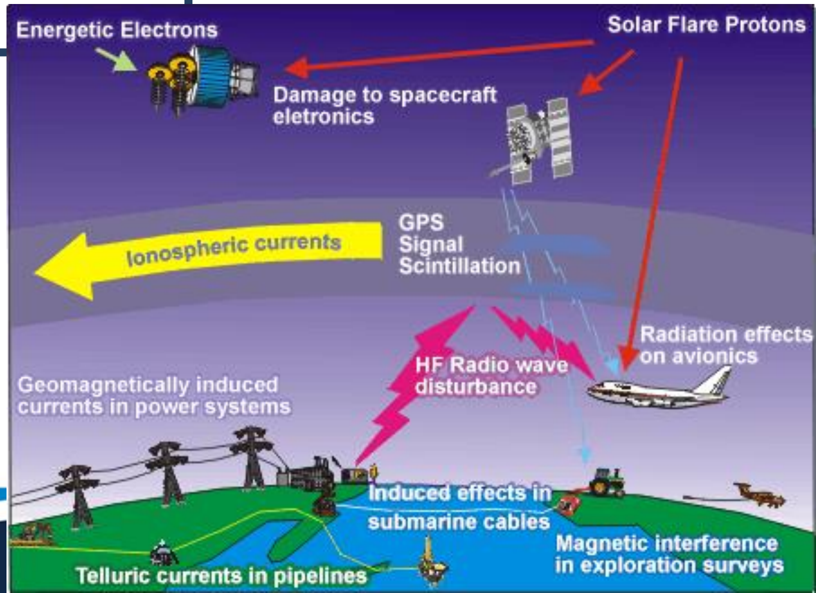
Solar Energetic Protons

- Increase ionization in the high latitude ionosphere
- Ionizing radiation penetrates into the atmosphere
- Disrupt HF radio communication
- Impacts:
    - Airline, civilian & DoD HF communications
    - Aircraft radiation exposure
    - Astronaut survival (radiation)
    - Satellite failures (electronics)
    - Industry (e.g. timing)

Solar Flares

- Increase ionization in the ionosphere
- Disrupt HF radio communication
- Impacts:
    - Airline, civilian & DoD HF communications
    - Satellite Communications





Impacts - 1

NOAA Space Weather Scale for Geomagnetic Storms USA)

Category Scale	Descriptor	Effect Duration of event will influence severity of effects	Physical measure	Average Frequency (1 cycle = 11 years)
Geomagnetic Storms			Kp values* determined every 3 hours	Number of storm events when Kp level was met; (number of storm days)
G 5	Extreme	**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. **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,	Kp = 9	4 per cycle (4 days per cycle)
G 4	Severe	**Power systems:** possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Other systems:** induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted,	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
G 3	Strong	**Power systems:** voltage corrections may be required, false alarms triggered on some protection devices. **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)
G 2	Moderate	**Power systems:** high-latitude power systems may experience voltage alarms, long-duration storms may cause transformer damage. **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)
G 1	Minor	**Power systems:** weak power grid fluctuations can occur. **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)

Impacts - 2

NOAA Space Weather Scale for Geomagnetic Storms USA)

Category Scale	Descriptor	Effect Duration of event will influence severity of effects	Physical measure	Average Frequency (1 cycle = 11 years)
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G 1	Minor	**Power systems:** weak power grid fluctuations can occur. **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)

Impacts - 3

NOAA Space Weather Scale for Geomagnetic Storms USA)

Category Scale	Descriptor	Effect Duration of event will influence severity of effects	Physical measure	Average Frequency (1 cycle = 11 years)
Geomagnetic Storms			Kp values* determined every 3 hours	Number of storm events when Kp level was met; (number of storm days)
G 5	**Extreme**	**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. **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,	Kp = 9	4 per cycle (4 days per cycle)
G 4	**Severe**	**Power systems:** possible widespread voltage control problems and some protective systems will mistakenly trip out key assets from the grid. **Other systems:** induced pipeline currents affect preventive measures, HF radio propagation sporadic, satellite navigation degraded for hours, low-frequency radio navigation disrupted,	Kp = 8, including a 9-	100 per cycle (60 days per cycle)
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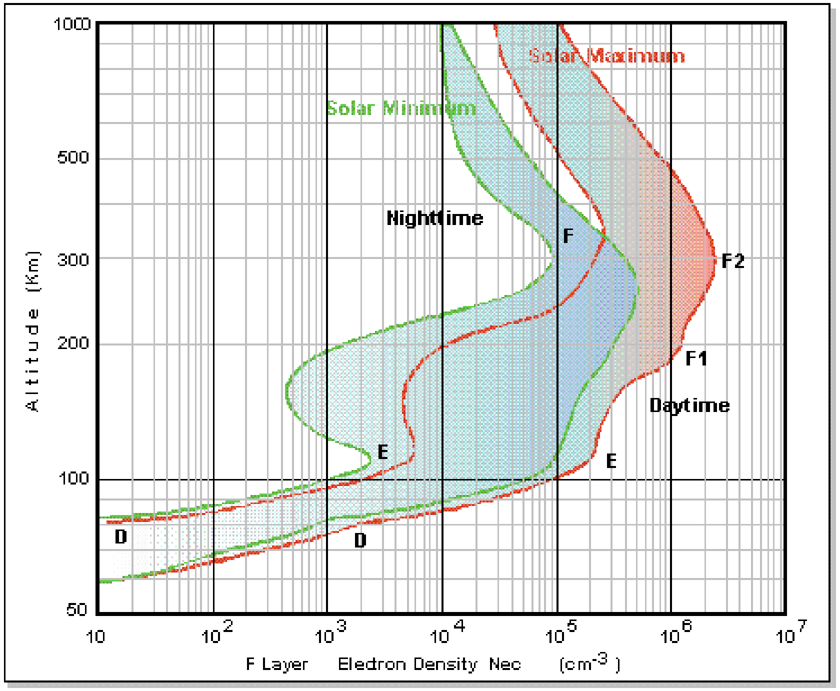
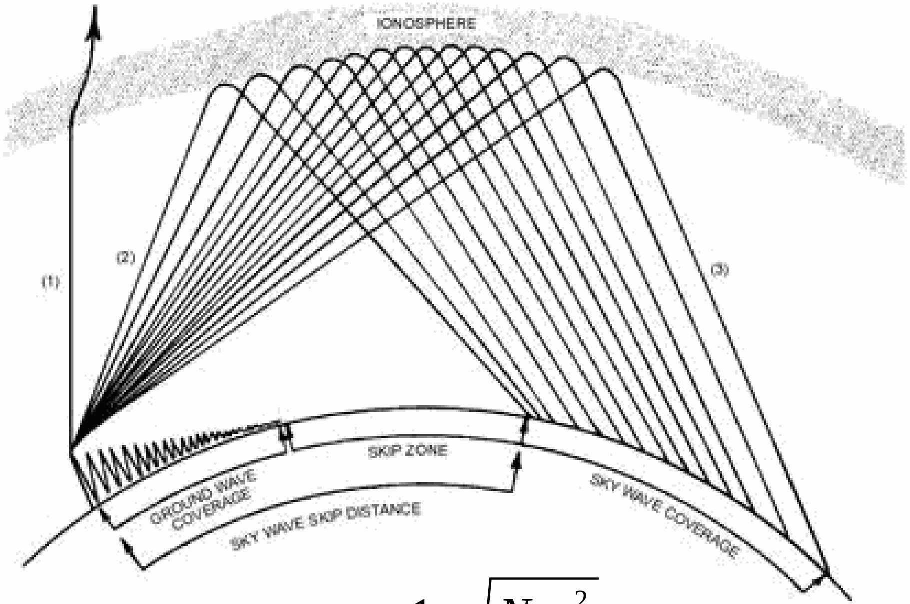
HF Communications

- Who uses HF communications?
- Aircraft (civilian & air force)
- Ships (civilian & navy)



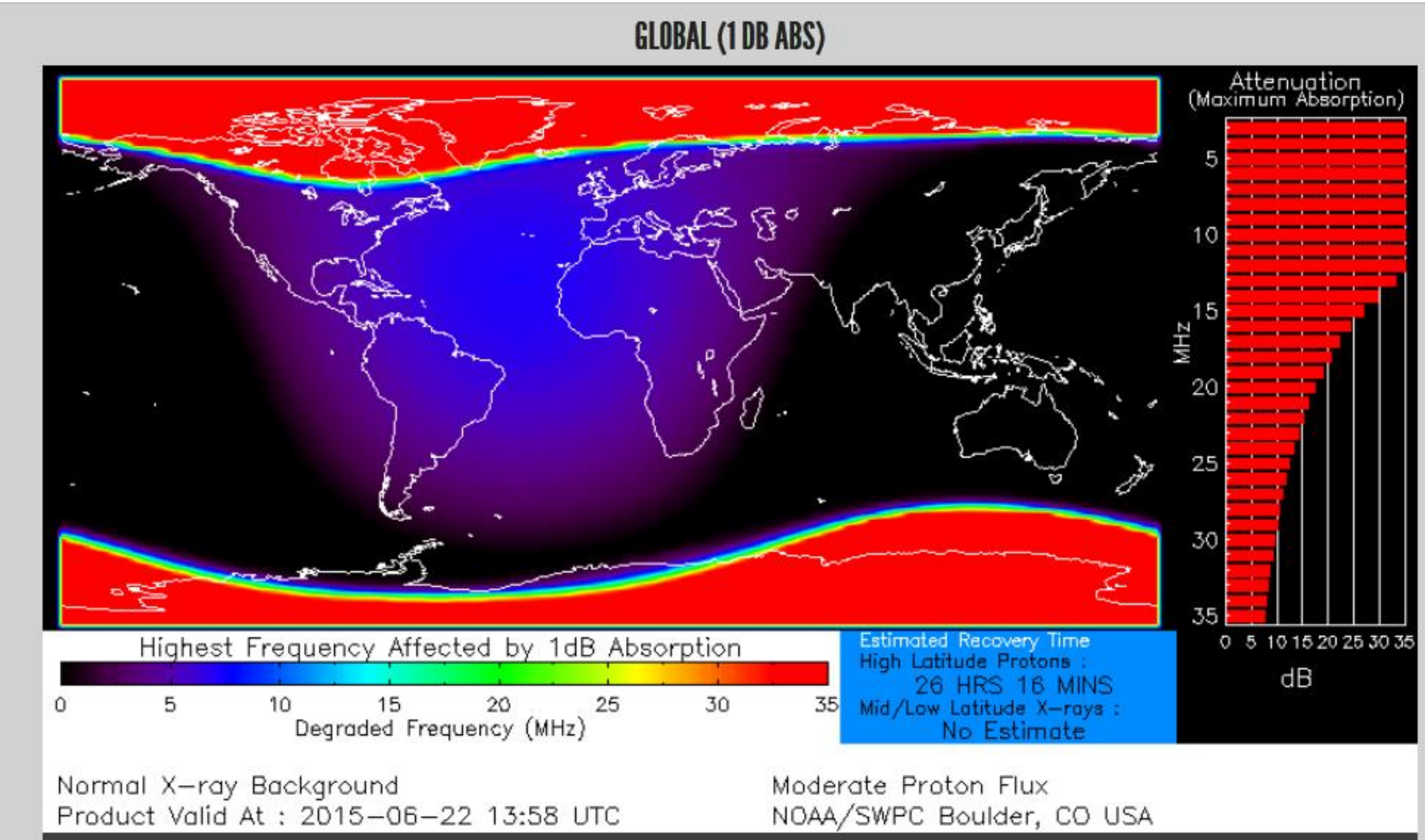


$$f = \frac{1}{2\pi}\sqrt{\frac{N_e q^2}{\varepsilon_o m_e}}$$

$$Loss(\mathrm{dB}) \propto \int \frac{N_e v_{en}}{(2\pi f \pm \Omega_e)^2 + v_{en}^2} dh$$

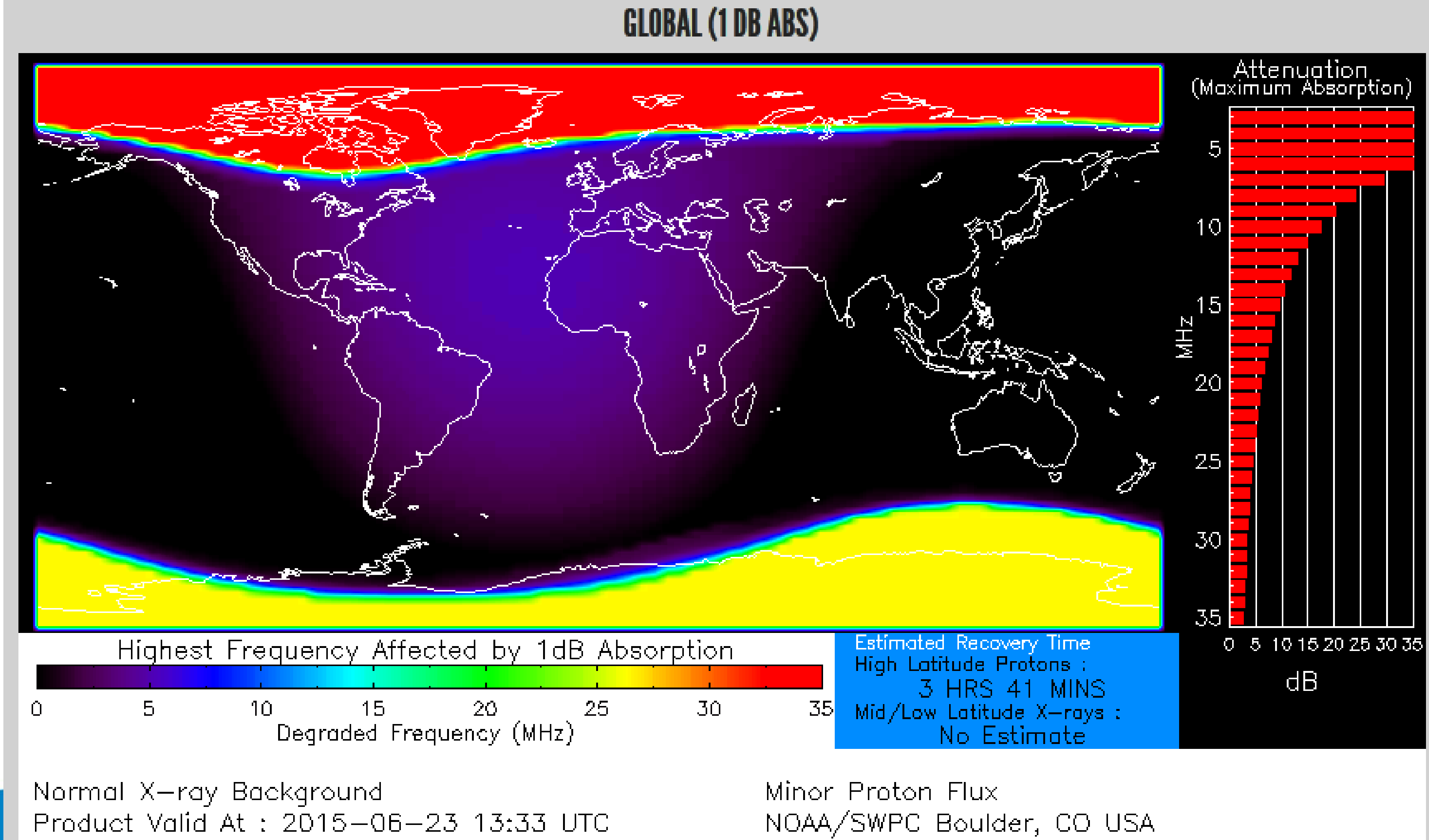
HF Communications

At time of solar flare

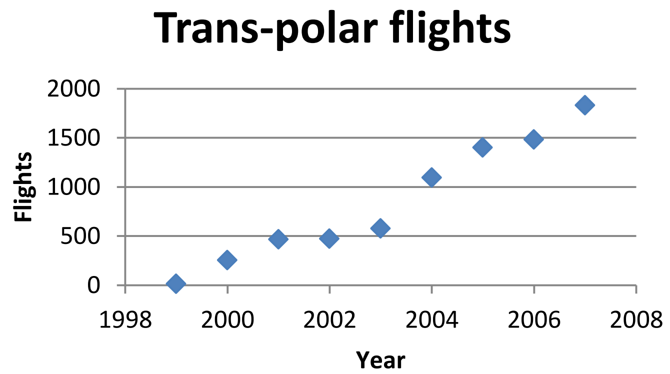


HF Communications

At time of CME arrival

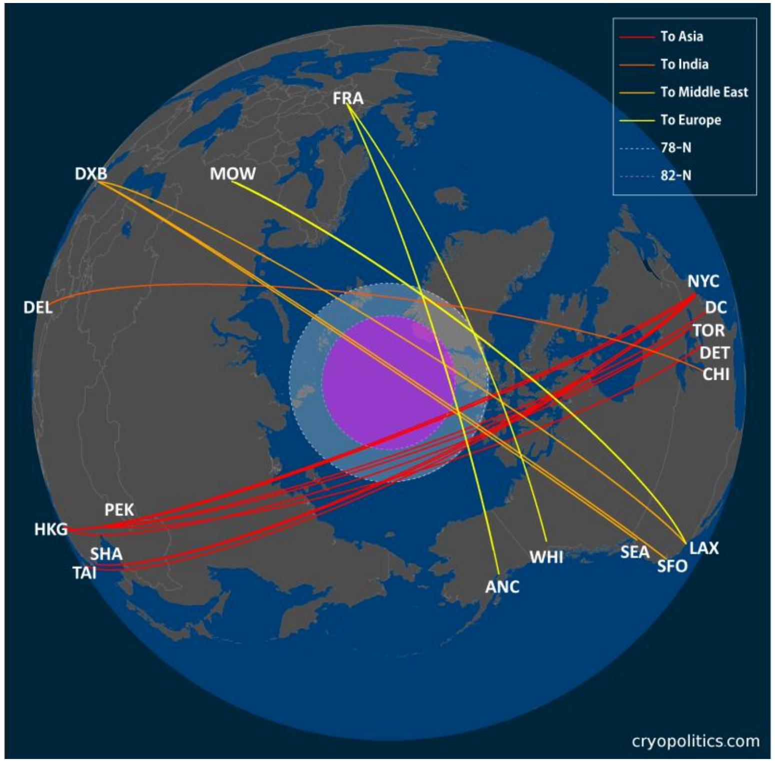


Aircraft Communications



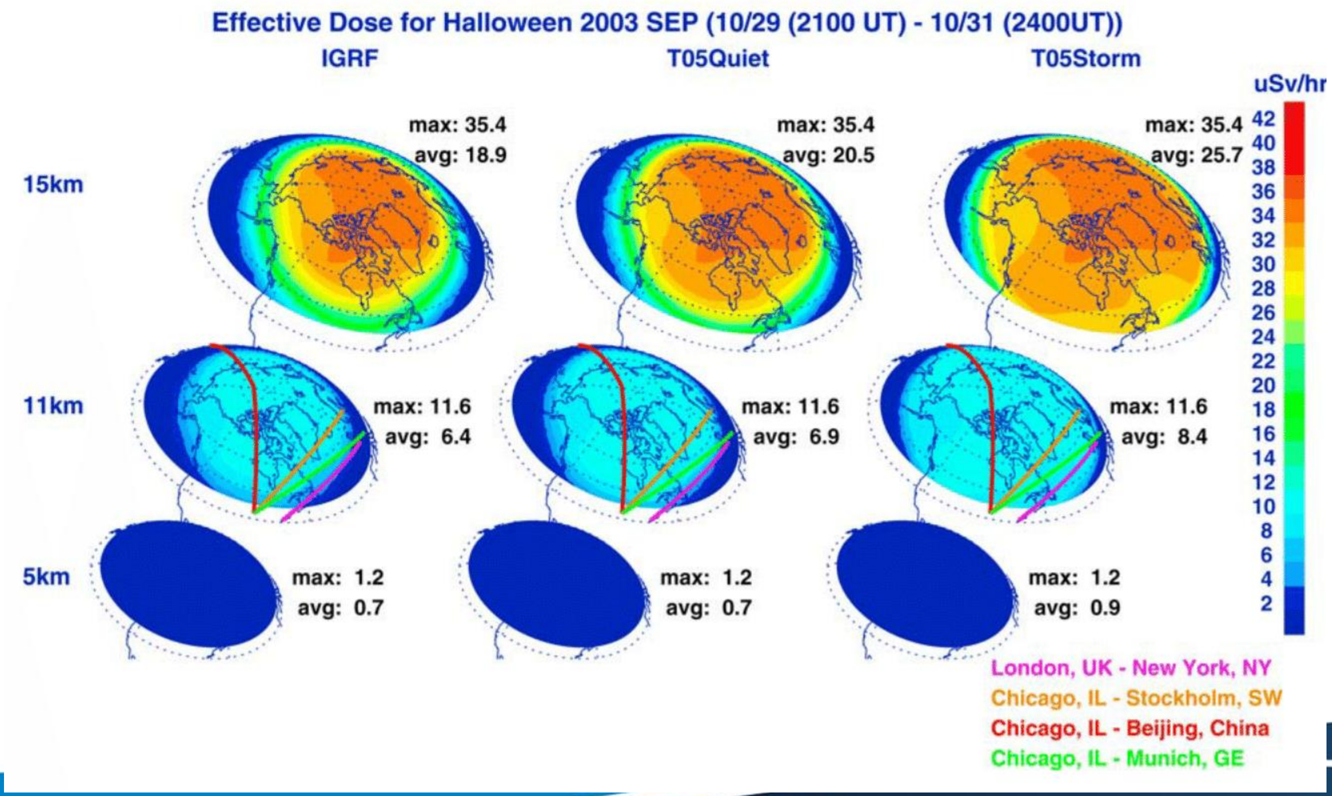
Aircraft Communications

- No satellite communications above 82° (geometry)
- No VHF communications above 78° (availability)
- Communications must be 100% guaranteed (HF radio is only option)

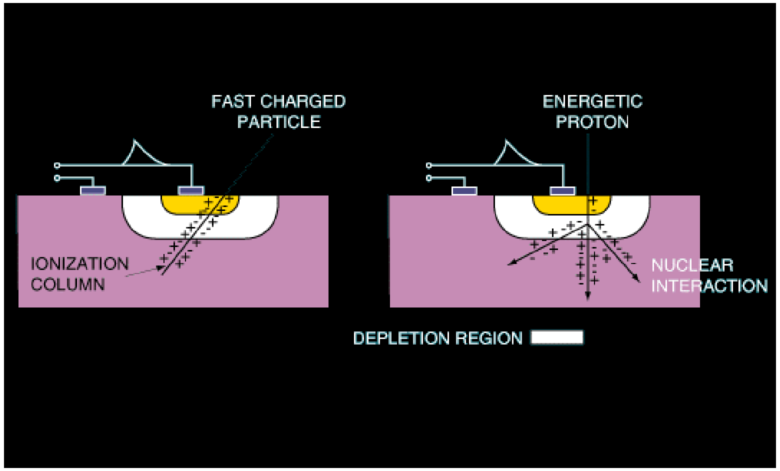


Aircraft Radiation

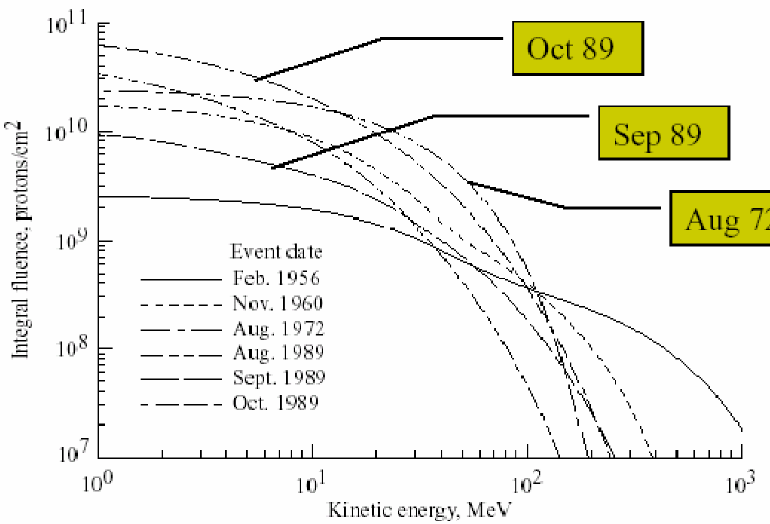
- Annual dose limit: Nuclear industry = 20 mSv, Civilian = 1 mSv.
- Typical flight dose: Crew = 2.2 mSv p.a., Flight ~2-10 μSv/h.
- CT scan: 1 – 10 mSv, X-ray: 0.02 – 0.1 mSv
- Hiroshima atomic bomb: 5 – 20 mSv (survivors only)



Satellite Radiation



>1 MeV protons



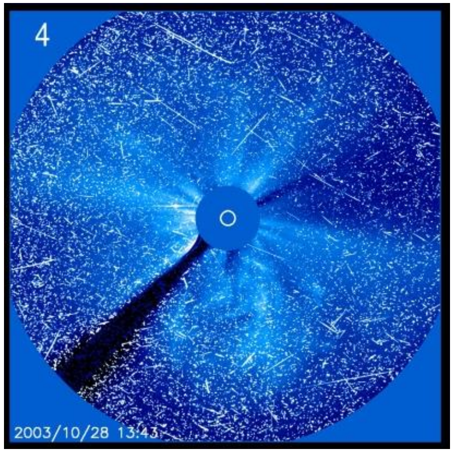
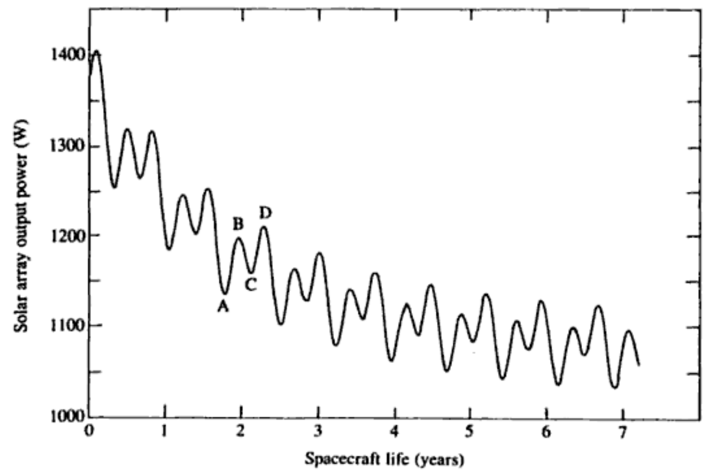


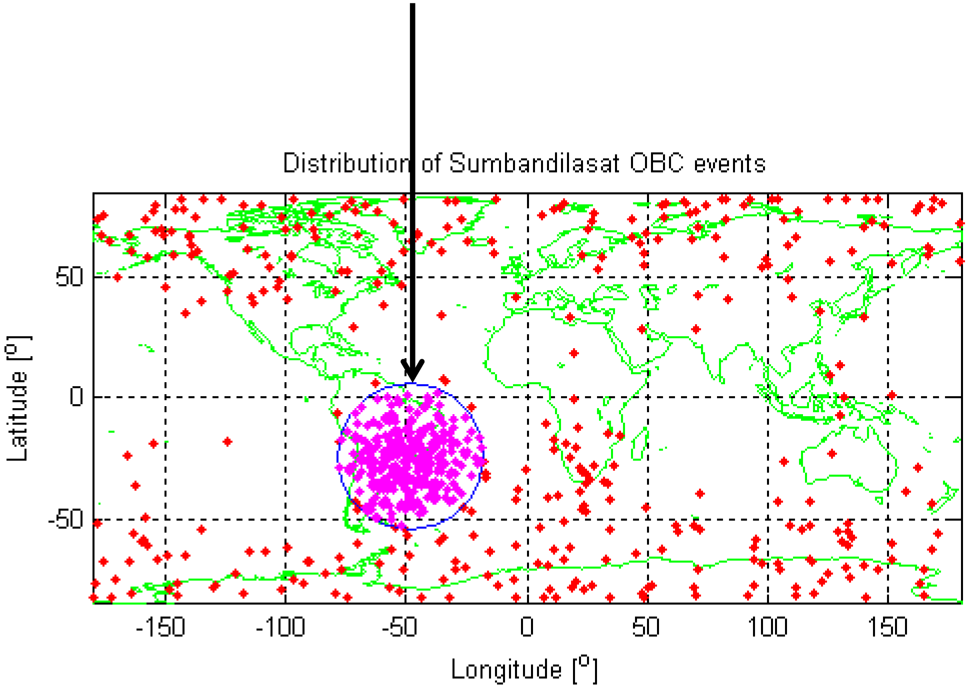
Fig. 8.15. Typical solar array power output profile over 7 years. A, summer solstice; B, autumn equinox; C, winter solstice; D, vernal equinox.

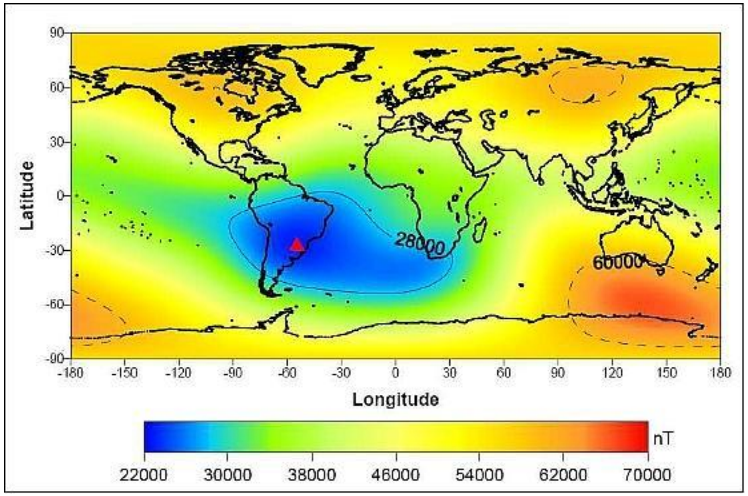


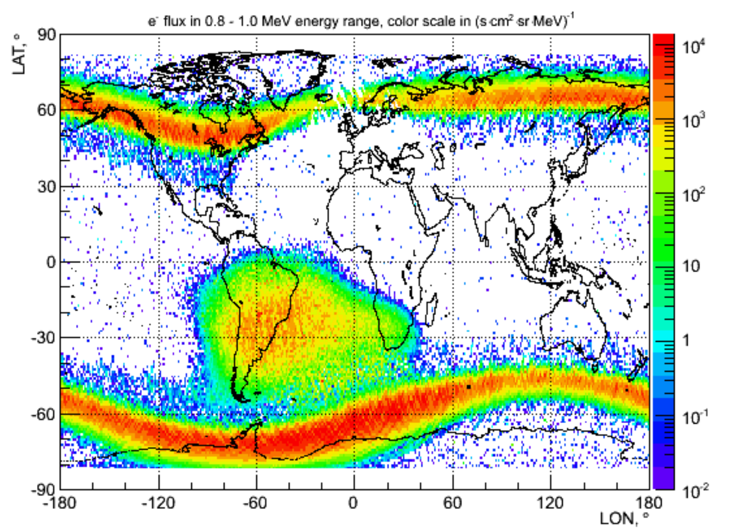
Satellite Radiation

Sumbandilasat launched 17/9/2009
Memory upset events

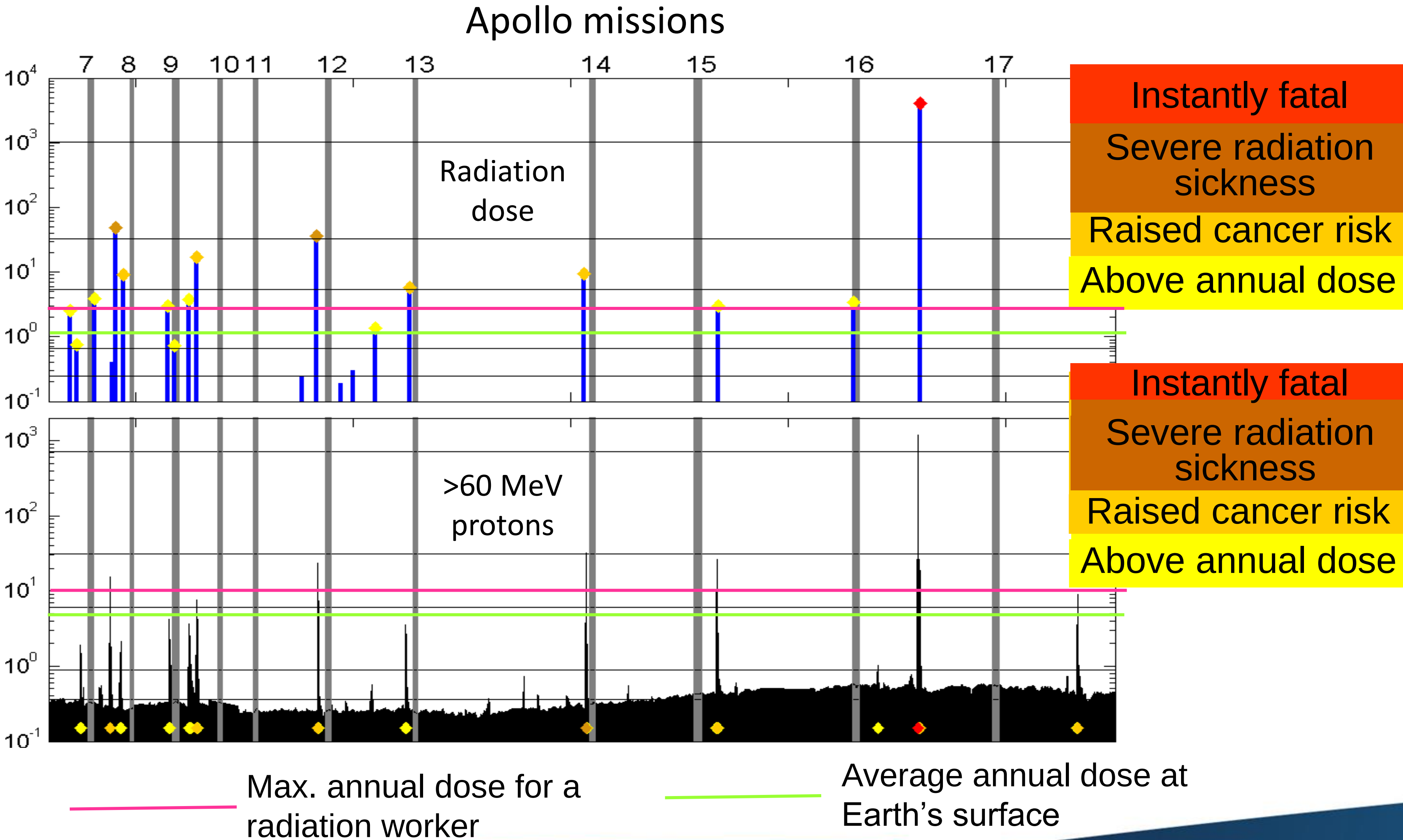
46.5% of all unintentional events





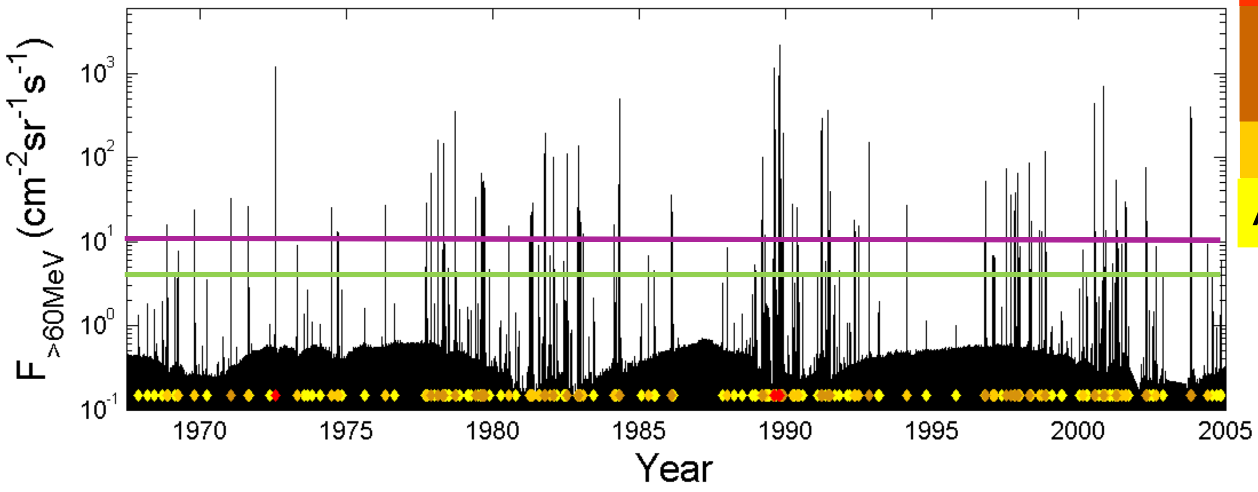


Astronaut Survival



Astronaut Survival

SEPs since Apollo



Instantly fatal

Severe radiation sickness

Raised cancer risk

Above annual dose

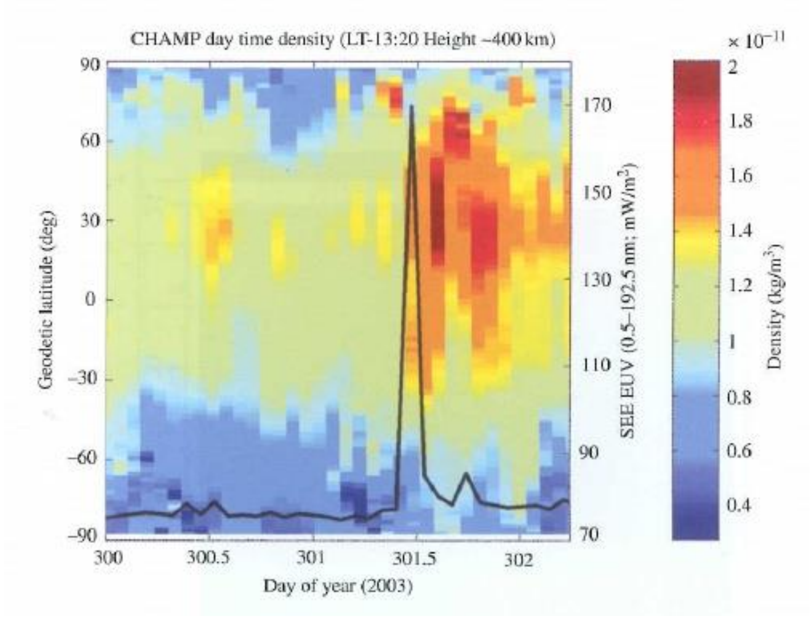
Average annual dose at Earth's surface

Max. annual dose for a radiation worker

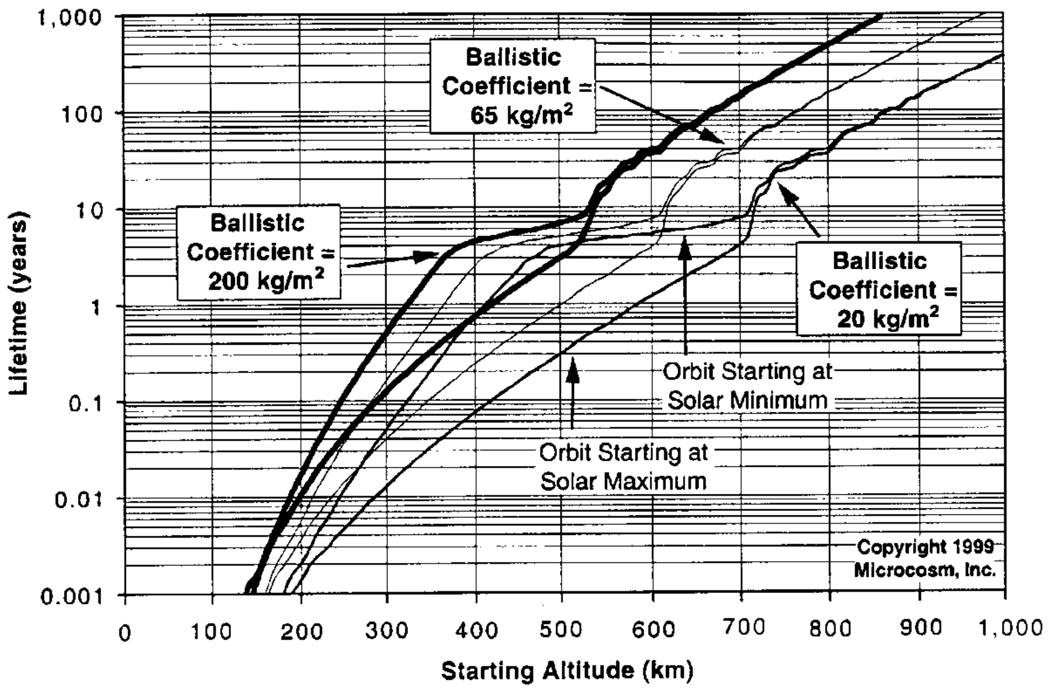
Satellite Lifetime

- Drag: $a = -0.5\rho(C_D A/m)v^2$
- Ballistic coefficient: $m/(C_D A)$
- LEO velocity = ~7.5 km/s at <1000 km altitude

Halloween storm

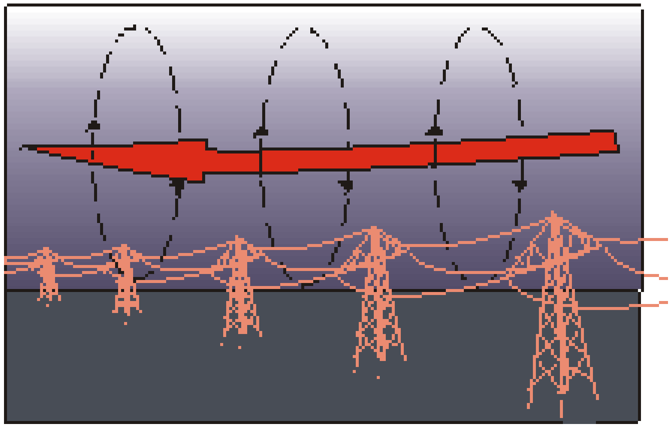


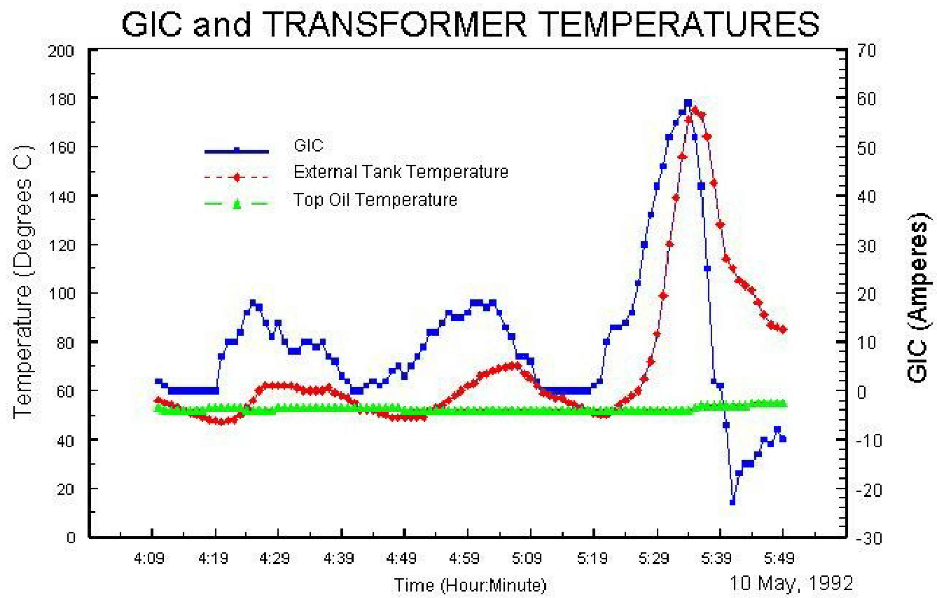
minimum <= solar cycle => maximum



GICs

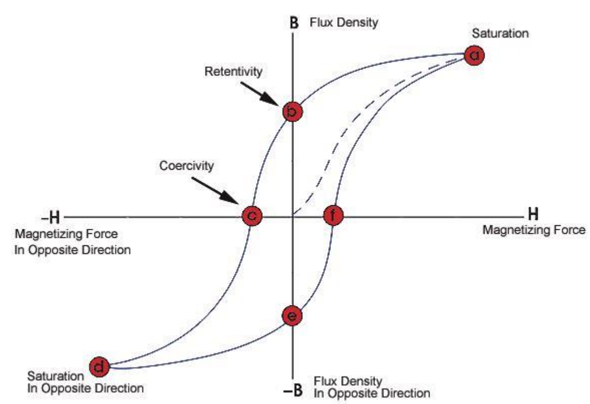
- Geomagnetically induced currents (GICs)





$$\oint_C \mathbf{B} \cdot d\boldsymbol{\ell} = \mu_0 I_{\text{enc}}$$ Ampere's Law

$$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$$ Faraday's Law



GICs

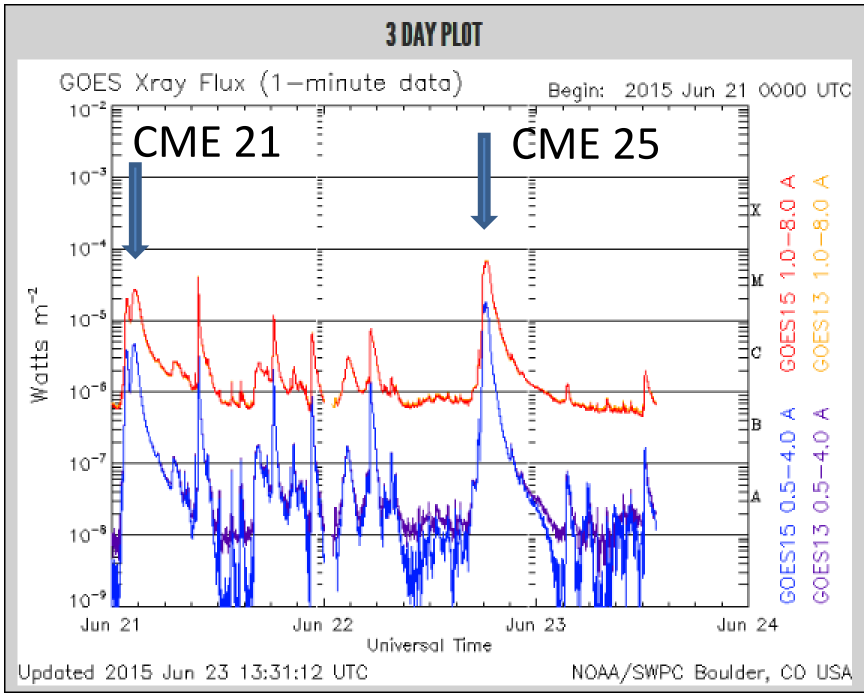
- Transformer replacement cost: ~$10 - 13 million
- Transformer replacement time: 12 - 18 months
- March 1989, Quebec power grid collapses within 90s (cost ~Can $2 billion)
- October 2003 (Halloween storm), ESKOM lost 15X 400 KV transformers

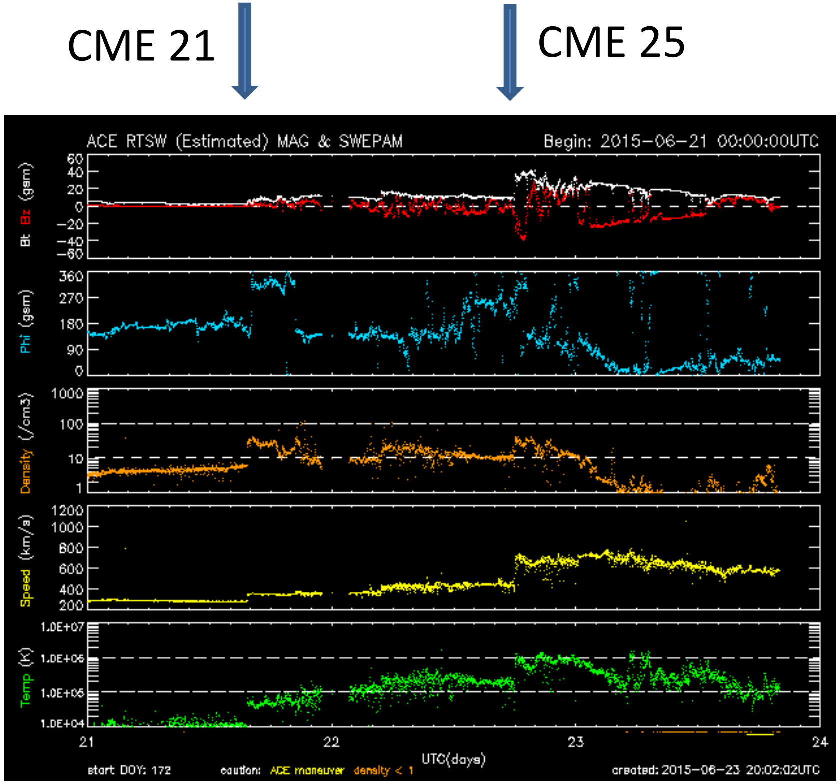
ESKOM, Ruacana,
29 October 2003

(Photos CT Gaunt)

GICs

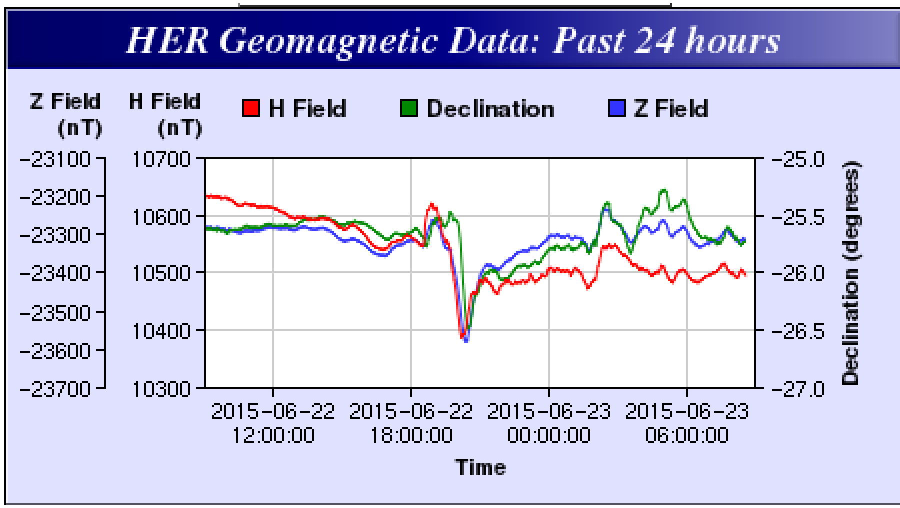
- 21 - 23 June 2015: Biggest space weather storm of solar cycle 24 (?)



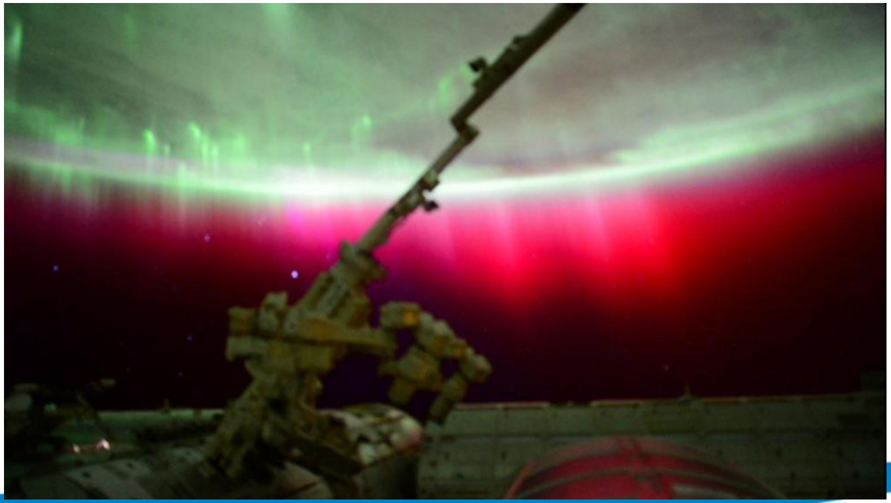


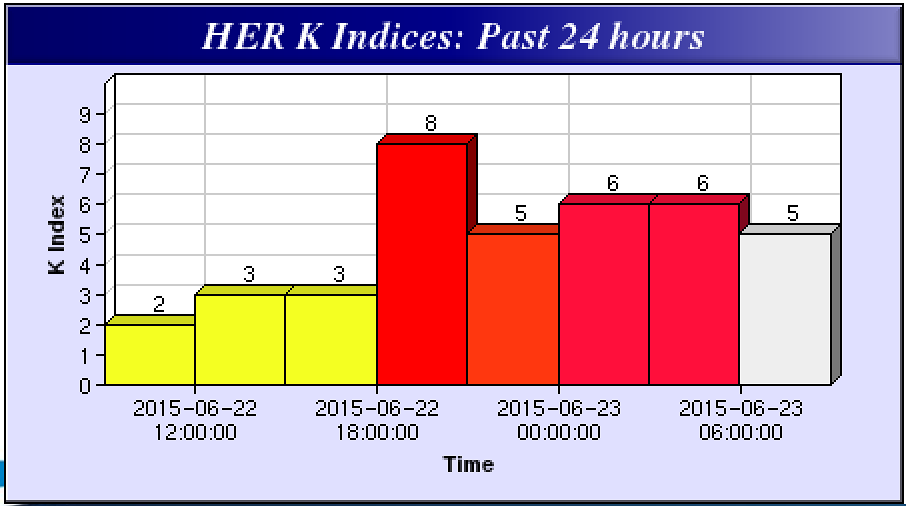
GICs

SANAE



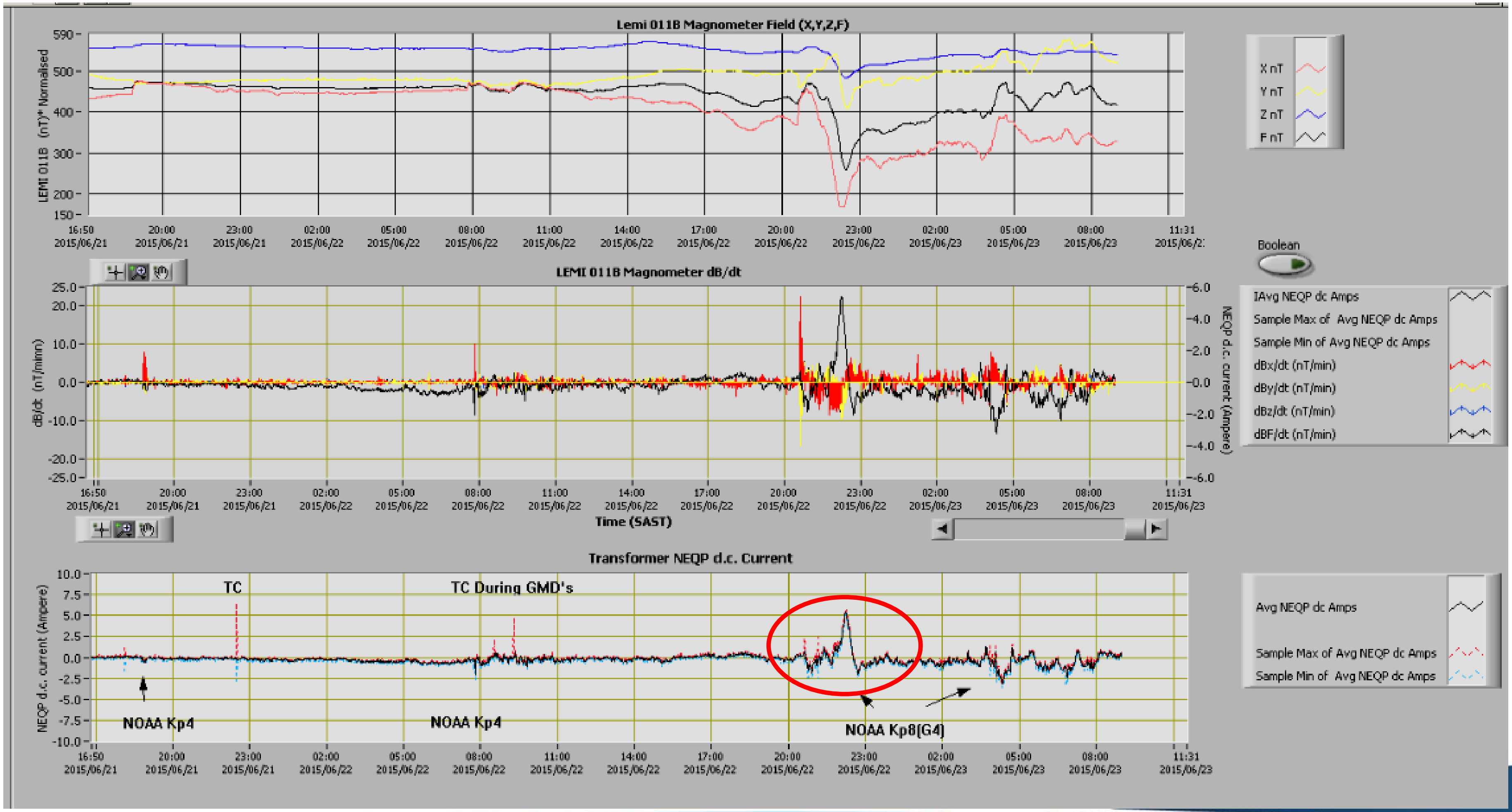
ISS





GICs

- ESKOM Matimba: 5A x 400 KV = 2 MW dissipation into transformer



Eskom Solar Storm Resilience Team – Nick Kruger (research solar monitor)

Satellite navigation

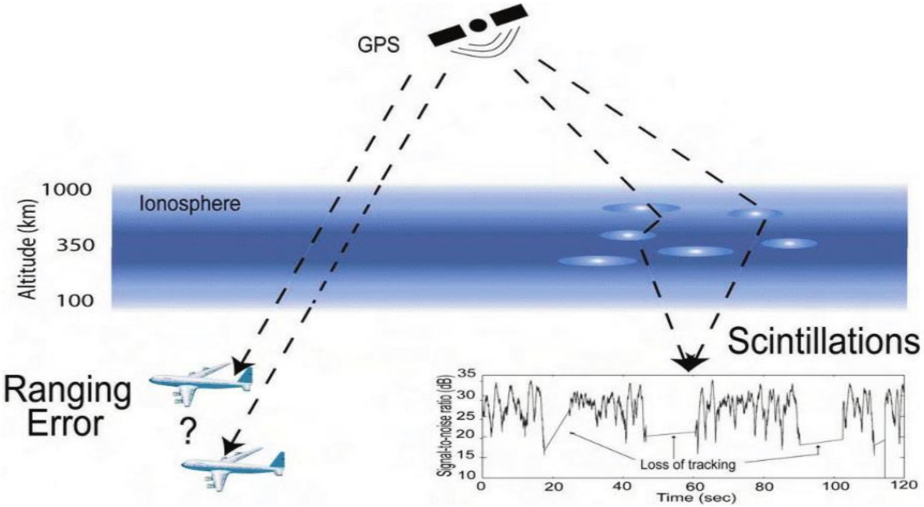
- GPS constellation of 24 (+6 spare) satellites
- Build cost = $12 billion
- Operating cost = $2 million per day
- GPS horizontal accuracy (quiet/storm)= ~10/30m
- GPS vertical accuracy (quite/storm) = ~17/50m

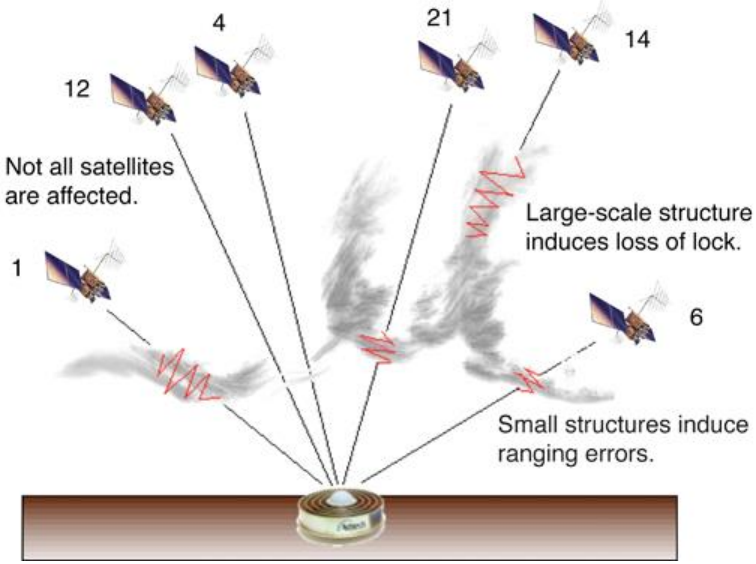
NAVSTAR - USA
GLONASS - Russia
Galileo - Europe

GPS-related global revenue:
2003 - $13 billion
2008 - $21.5 billion
2017 - $757 billion

Satellite navigation

- **Scintillations:**
- Ionospheric electron density variations
- Refractive index variations
- Ray path is perturbed – position and time affected
- 3 - 4 airplane crashes p.a. due to controlled flight into the ground





Vulnerability

- <u>1997-2012</u>:
- Global population increased by 20%
- Global electricity consumption increased by 60%
- Global satellite industry revenue increased by 320% ($190 billion in 2012)
- Over 1000 satellites operated by 50 countries (USA 25% worth $250 billion)
- Space weather annual cost: ~$5-10 billion (only USA, 5% of world population)

- <u>Extreme geomagnetic storm</u> (Kp = 9, estimate 1 per 100-200 years):
- 10% of world population affected for 0.5 – 24 months
- 10% of all satellites (temporarily?) inoperable (hours – days)
- Cost $1-2 trillion per annum (USA only)
- Power blackout cost: ~$4-10 billion per day (USA only)
- Airline diversion: ~$10-100 thousand per aircraft (~100,000 flights daily)
- Airline radiation dose: up to 20 mSv in one flight

Vulnerability

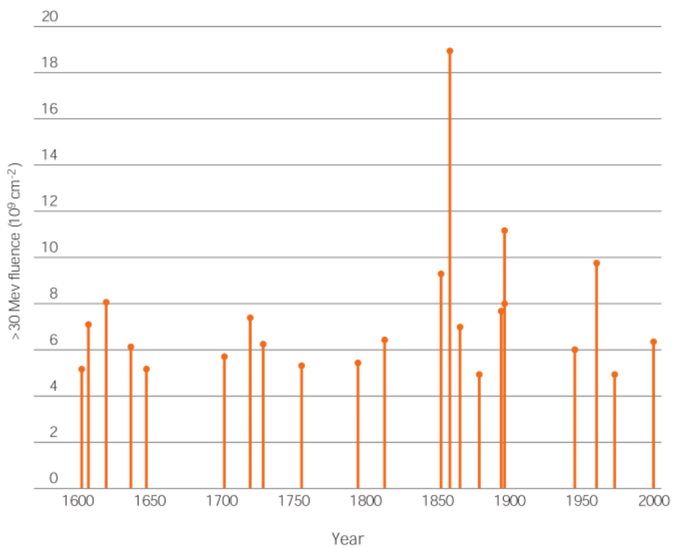
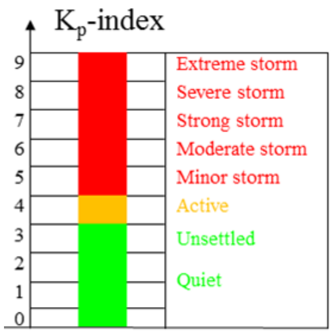


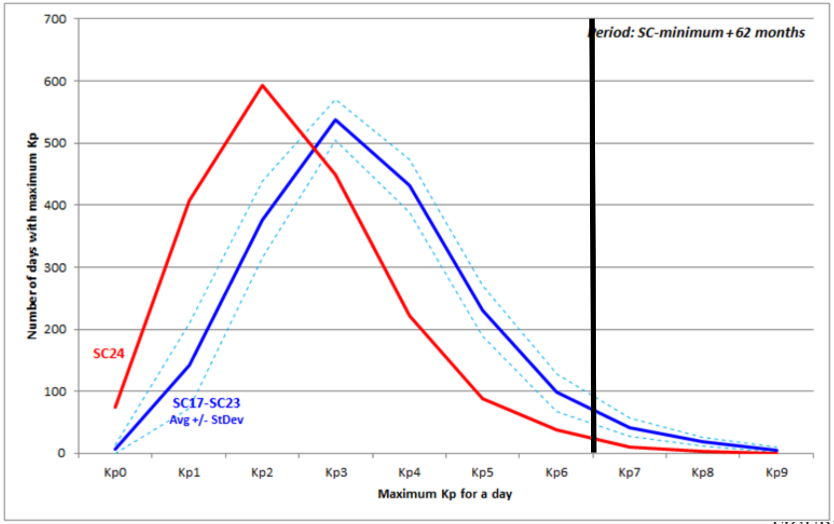
Figure 3. **Timeline of major radiation storms from 1600 to 2010.** The vertical lines are estimates of storm strength (in billions of solar particles per square centimetre) reaching Earth. Data before 1970 estimated from ice core data and recent data from space measurements. The largest peak is again due to the Carrington Event of 1859.

UK National Risk Register 2015

Event probability

- Space weather is mostly mild but occasionally stormy
- Kp > 6 for 5% of days in solar cycle, then (in the USA):
  - 59% of satellites experience “latch-up” or failure
  - 20 - 60% increase in insurance claims (on electrical failures)
  - 10 - 40% increase in power grid “disturbances”
  - 4% of all power grid “disturbances” attributed to space weather GICs





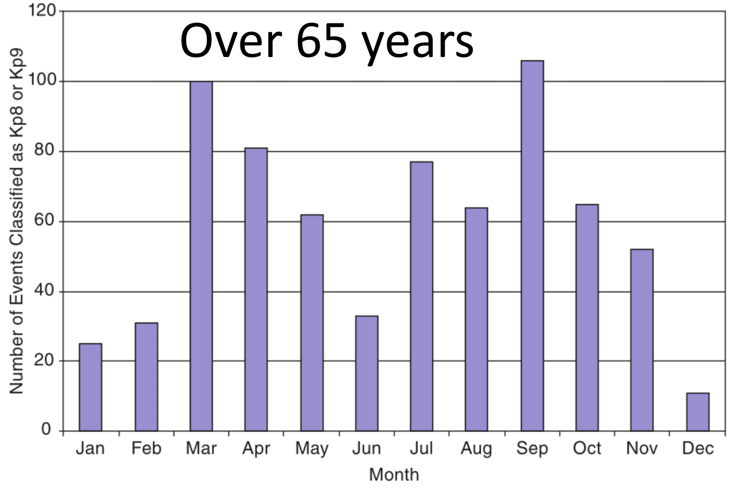


FIGURE 2.3 Incidence of Kp8/Kp9 events by month, 1932-2007, based on an analysis of 222,072 observations. SOURCE: Data from World Data Center for Geomagnetism.

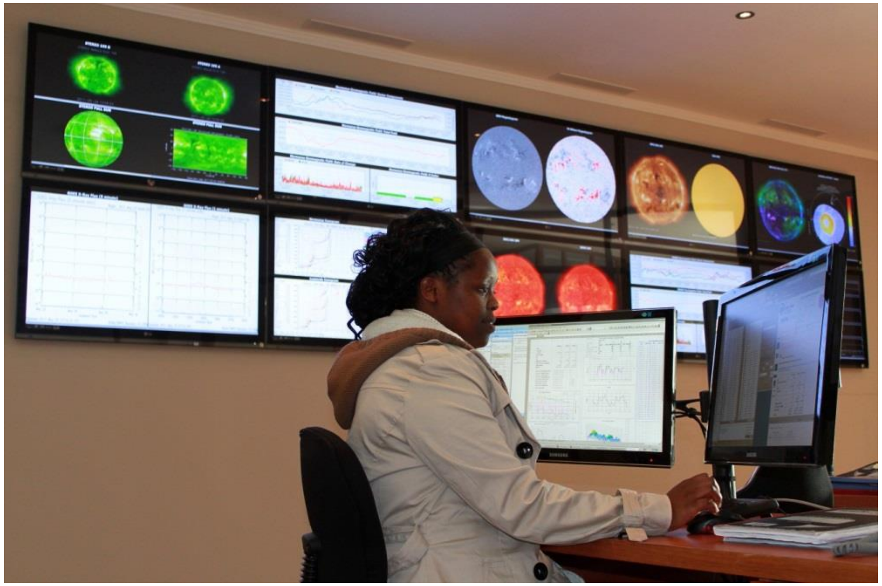
Mitigation

ESA space weather prediction EU cost-benefit analysis 2006 – 15 years

Benefit Level (order of magnitude)	**Industry Sector**		
	Main Industry	Relevant SWSs	Dominant Sub-Sector Beneficiaries
1,000M€	Ground-based industry	Geomagnetically Induced Current (GIC): f, n, p Geomagnetic field perturbations: f, n.	Powerline generation and distribution companies
	Ionospheric	Polar cap absorption and Solar energetic particle events, Ionospheric scintillation: f, n, p. Total Electron Count (TEC): f, n, p Radiation affecting airline crew and passengers: f.	Airlines
100M€	Space industry	Hazardous environment for spacecraft: f, n, p. Atmospheric drag for LEO spacecraft: f, n, p. Solar energetic particle events affecting launch: f. Hazardous environment in Space: f, n.	Satellite operators
	Research and education	Geomagnetic field perturbations: p	None
1M€	Tourism	Auroral intensity: f	Hotels, the only sector considered.

Mitigation

- Regional Warning Centre for Africa operating under International Space Environmental Service (ISES) since 2007.
- SANSA Space Weather Centre was officially opened on 10 December 2010 by Minister of Science and Technology.



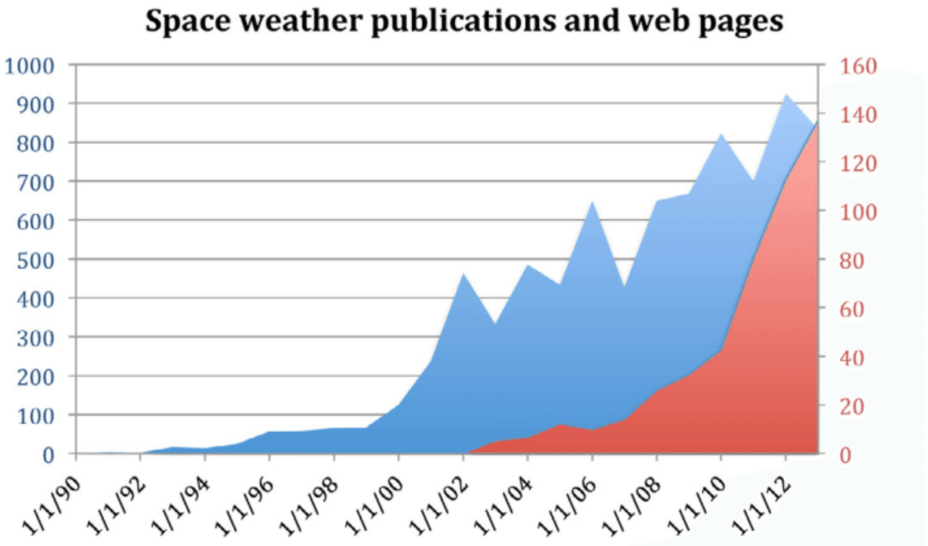
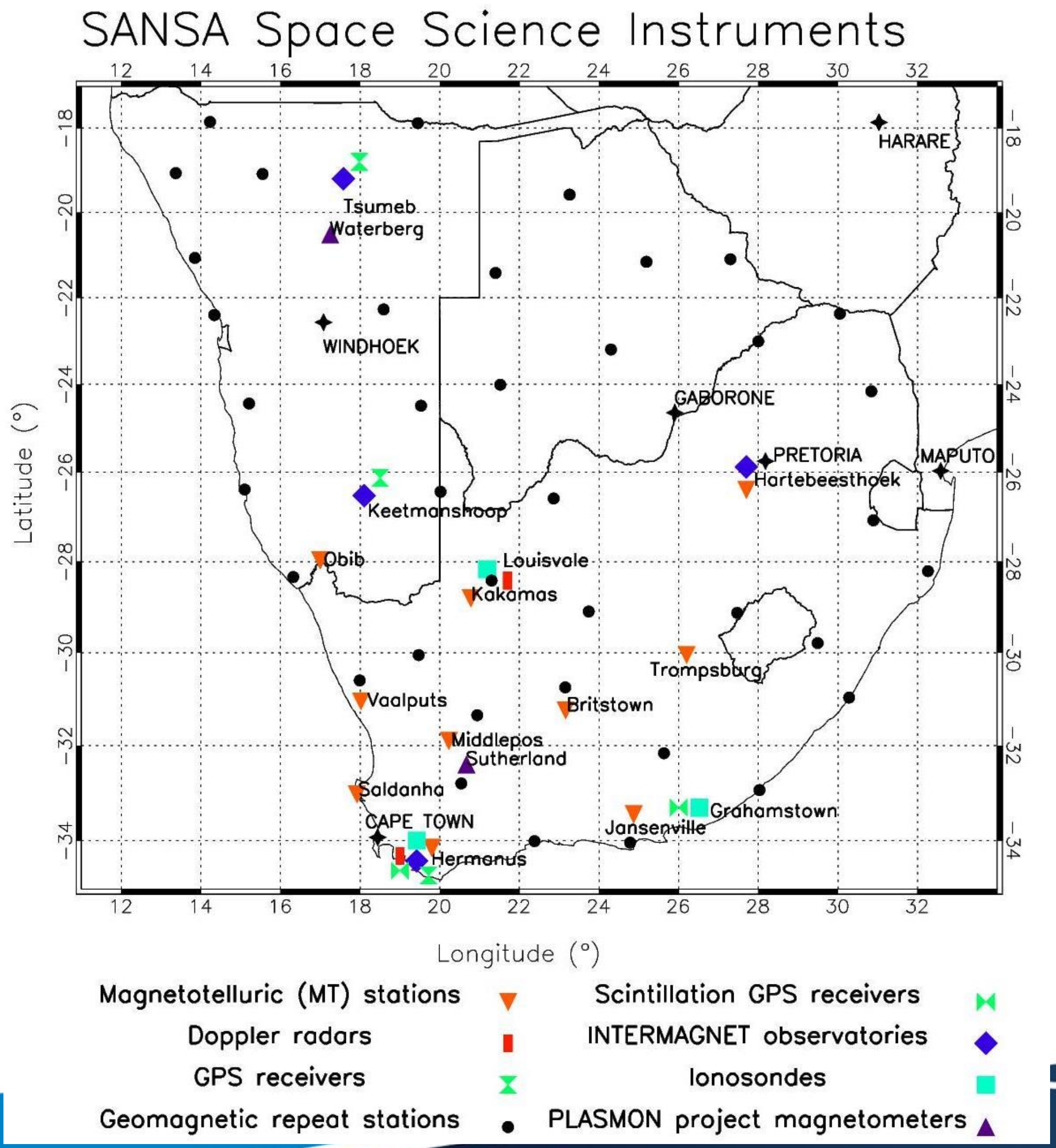


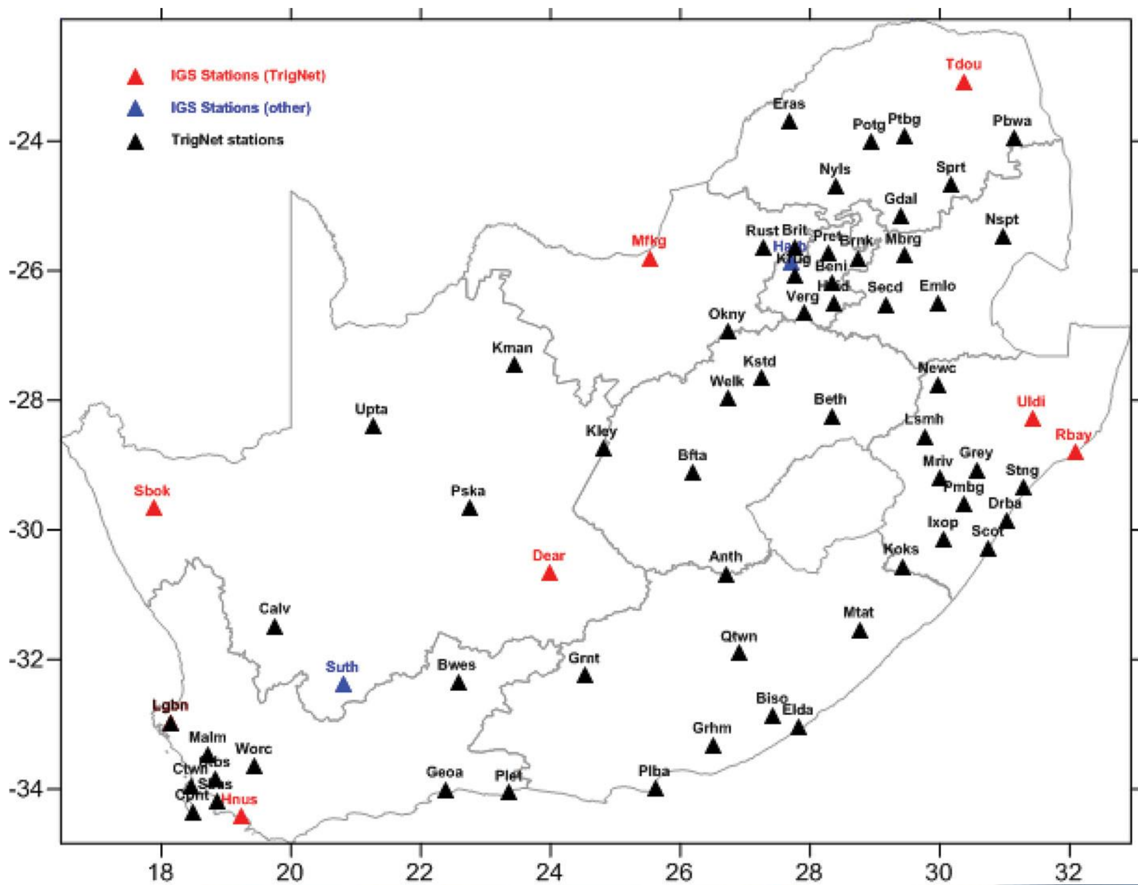
Fig. 1. Number of publications per year with "space weather" in the abstract in NASA/ADS (blue; left axis), and the number of web sites returned by a Google search for "space weather" within calendar years (since 2003) in thousands (red; right axis).

Infrastructure

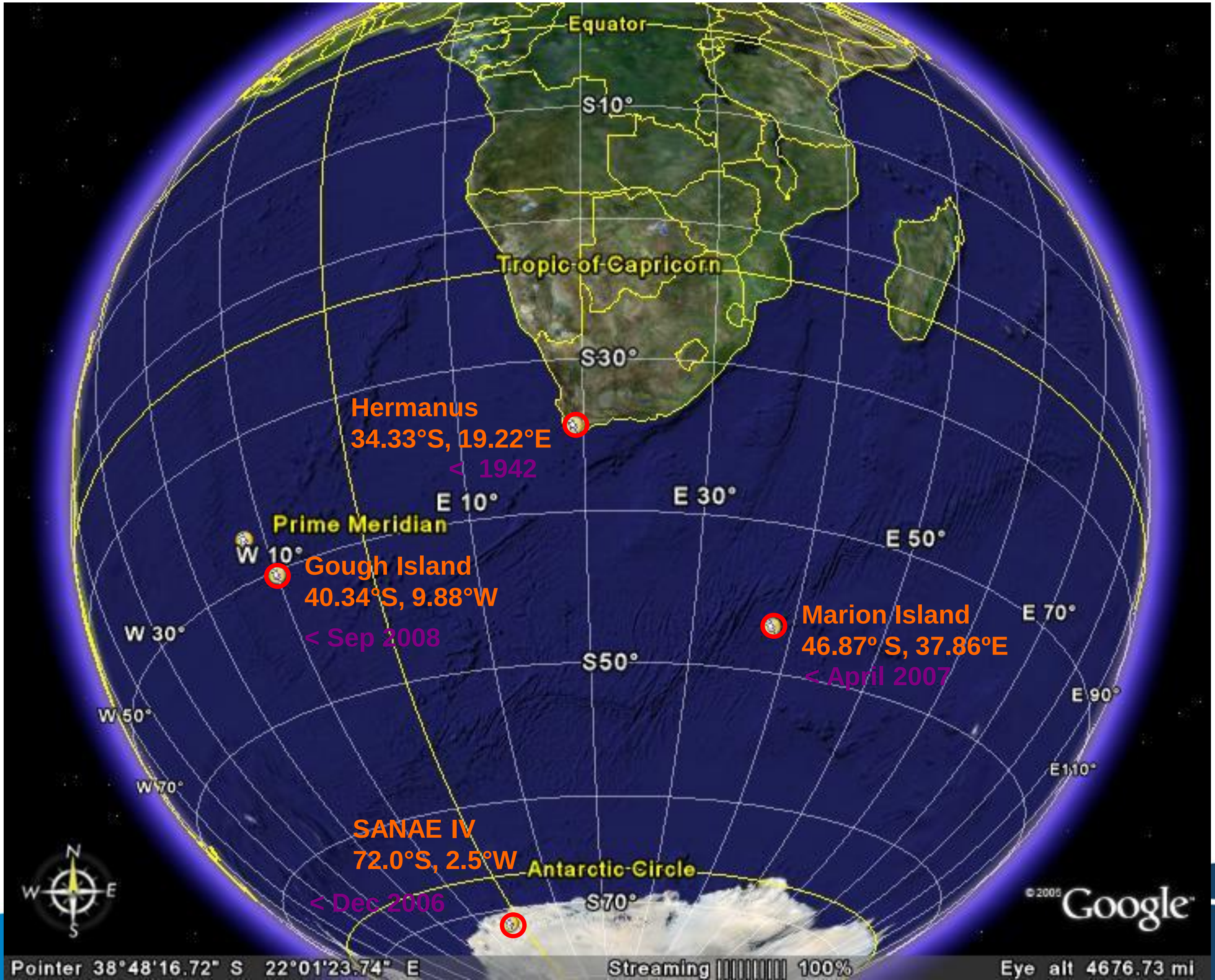


Infrastructure

- 67 TrigNet GPS receivers
- Used to measure Total Electron Content (TEC)

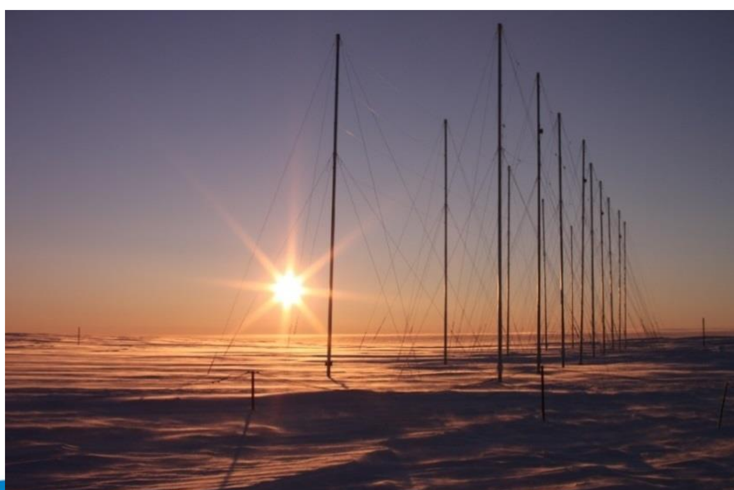


Infrastructure

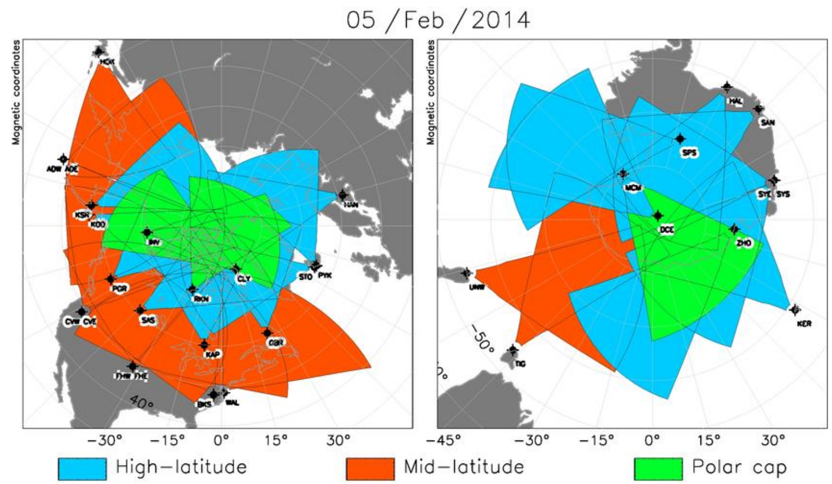


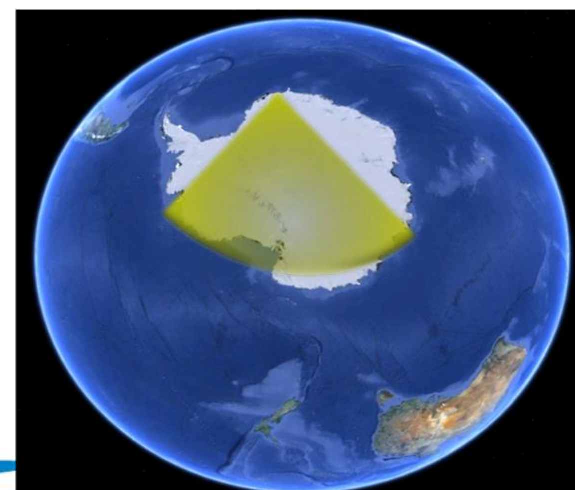
Infrastructure

SANAE since 1960



SuperDARN since 1997





Conclusions

- Space Weather super-storms are rare (1 in 100 - 200 years)
- The Carrington super-storm occurred 156 years ago
- Impacts of a super-storm can be severe

- Space Weather major storms are common (few annually)
- Impacts of a large storm can be expensive

- If nothing goes wrong during a major/super-storm, then our mitigation strategy and investment has worked.

Thank You

in service of humanity

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