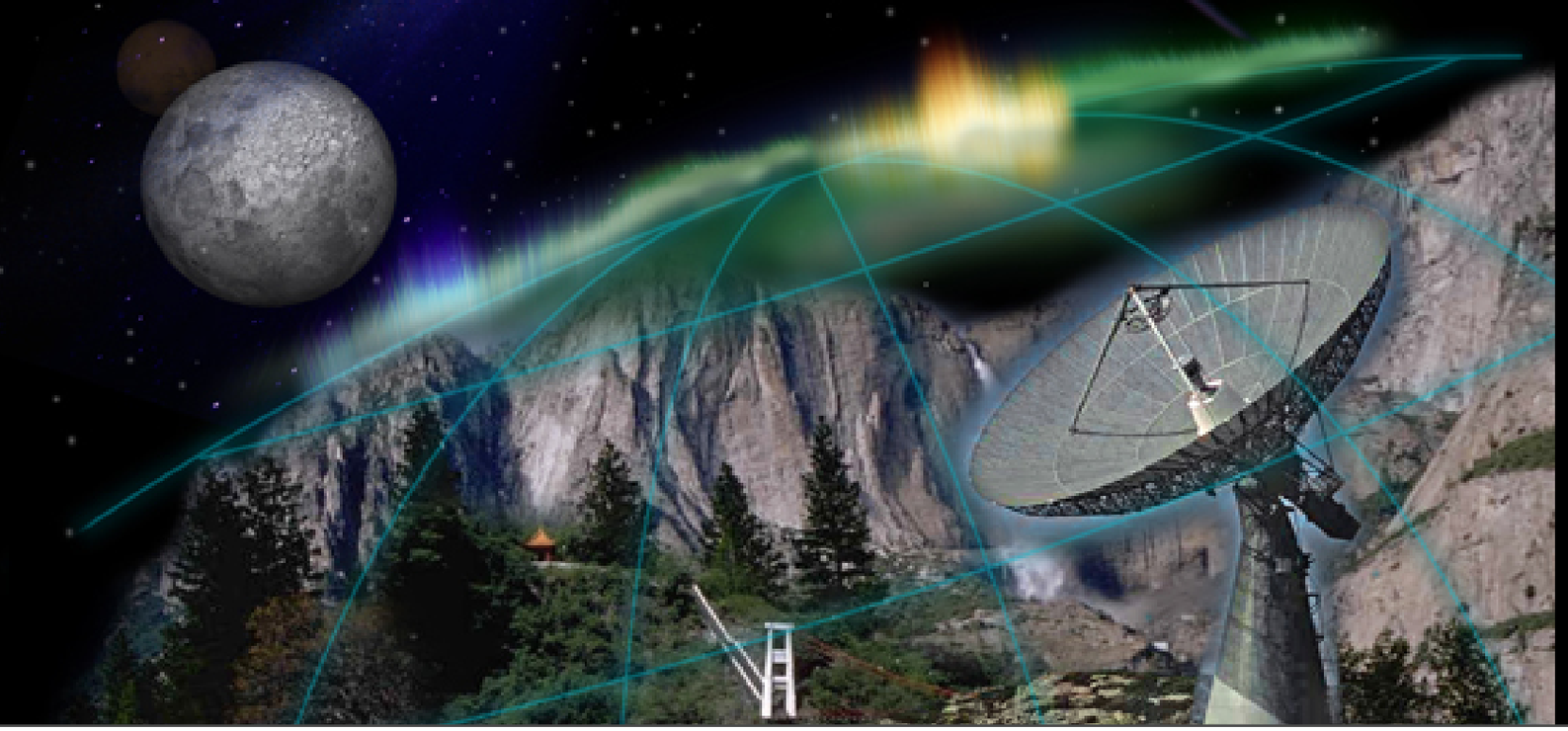
The Stormy Sun
From Kristian Birkeland to Space Weather Hazards

Pål Brekke
Norwegian Space Centre

Not every kind of storm
shows up on weather radar...



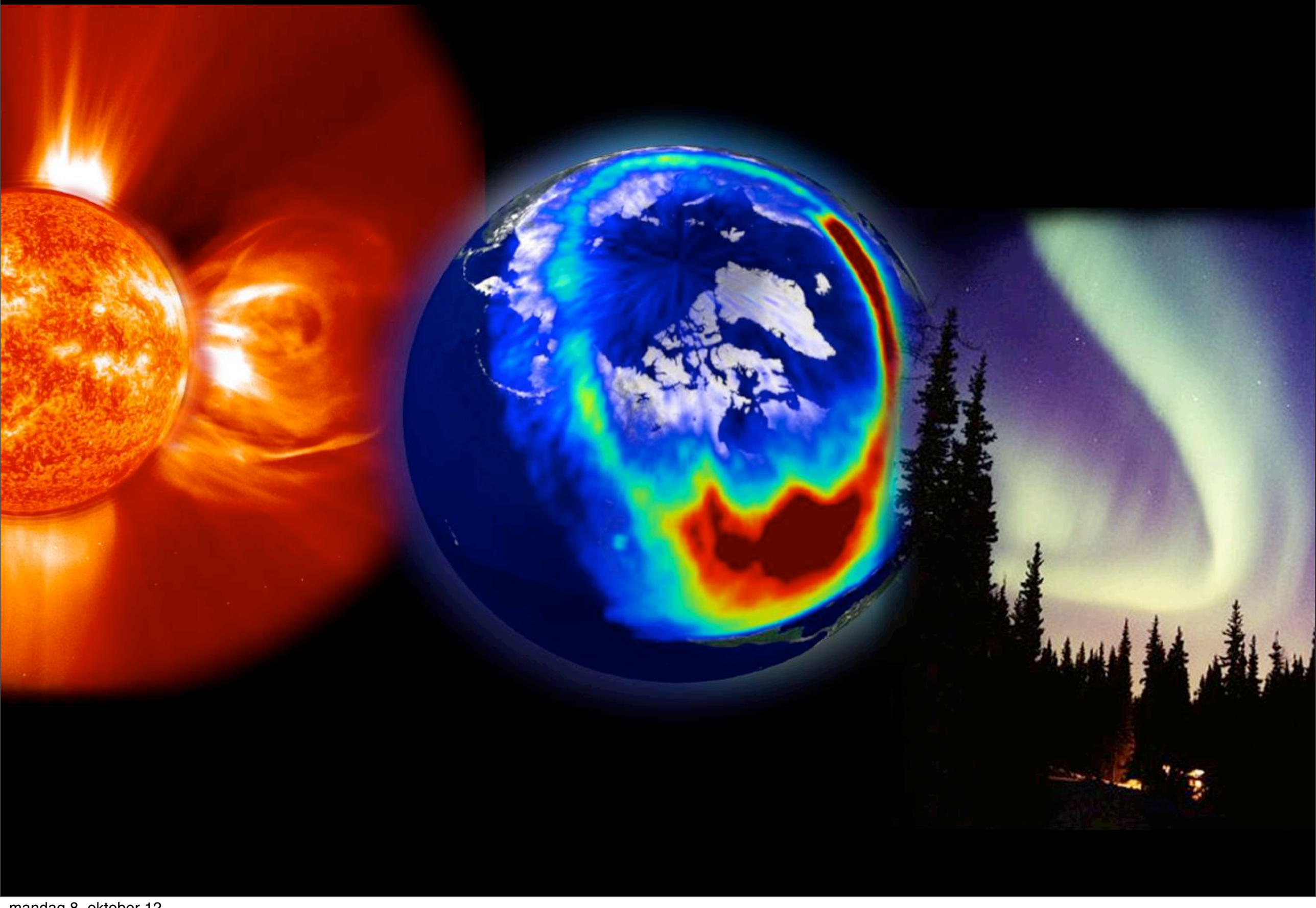
Norsk Romsenter
NORWEGIAN SPACE CENTRE

The Northern Lights

The aurora is a manifestation of something violent happening in our atmosphere where sometimes 1500 Gigawatts of electricity is generated. This is almost double the energy production in Europe!

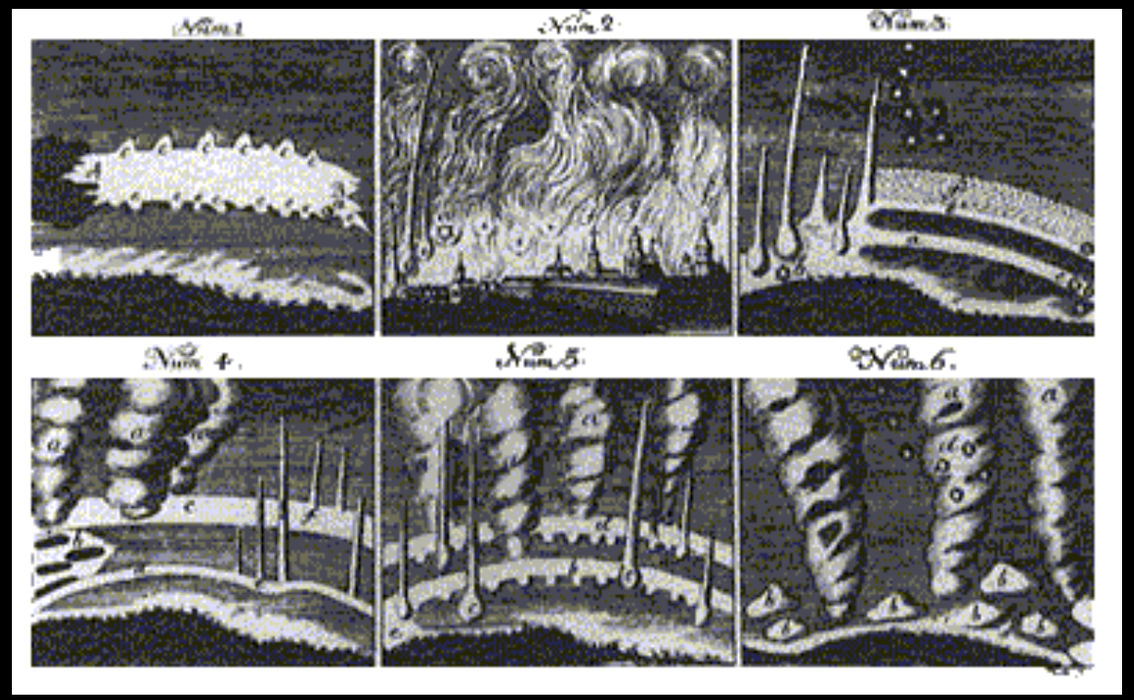
Pål Brekke

The Sun - The Aurora Engine



Early Aurora Science

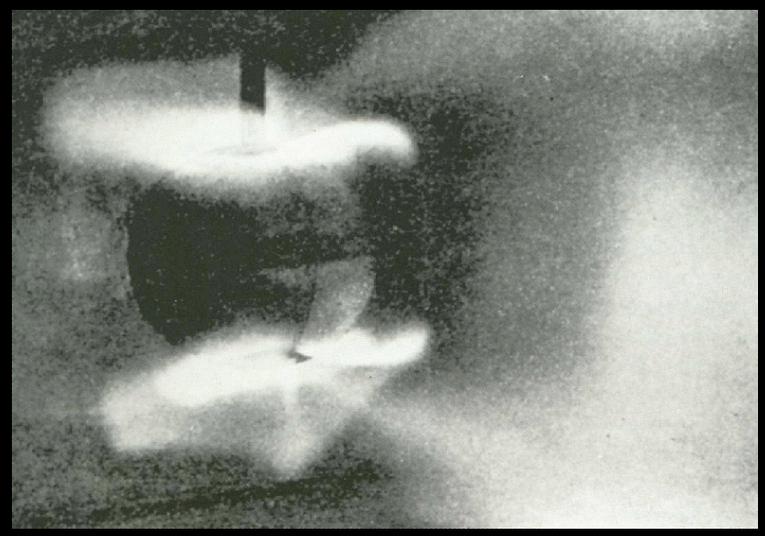
The strong aurora on 6 March 1716 could be observed in large parts of Europe and gave birth to more modern science.



- Sir Edmund Halley published the first detailed description of the aurora in 1716.
  - He expressed that at an age of 60 years he had give up on experiencing this amazing phenomenon.
  - Argued that the top of the aurora arc did not point towards the North pole, but towards the magnetic pole
  - "Auroral rays are due to the particles, which are affected by the magnetic field; the rays are parallel to Earth's magnetic field”

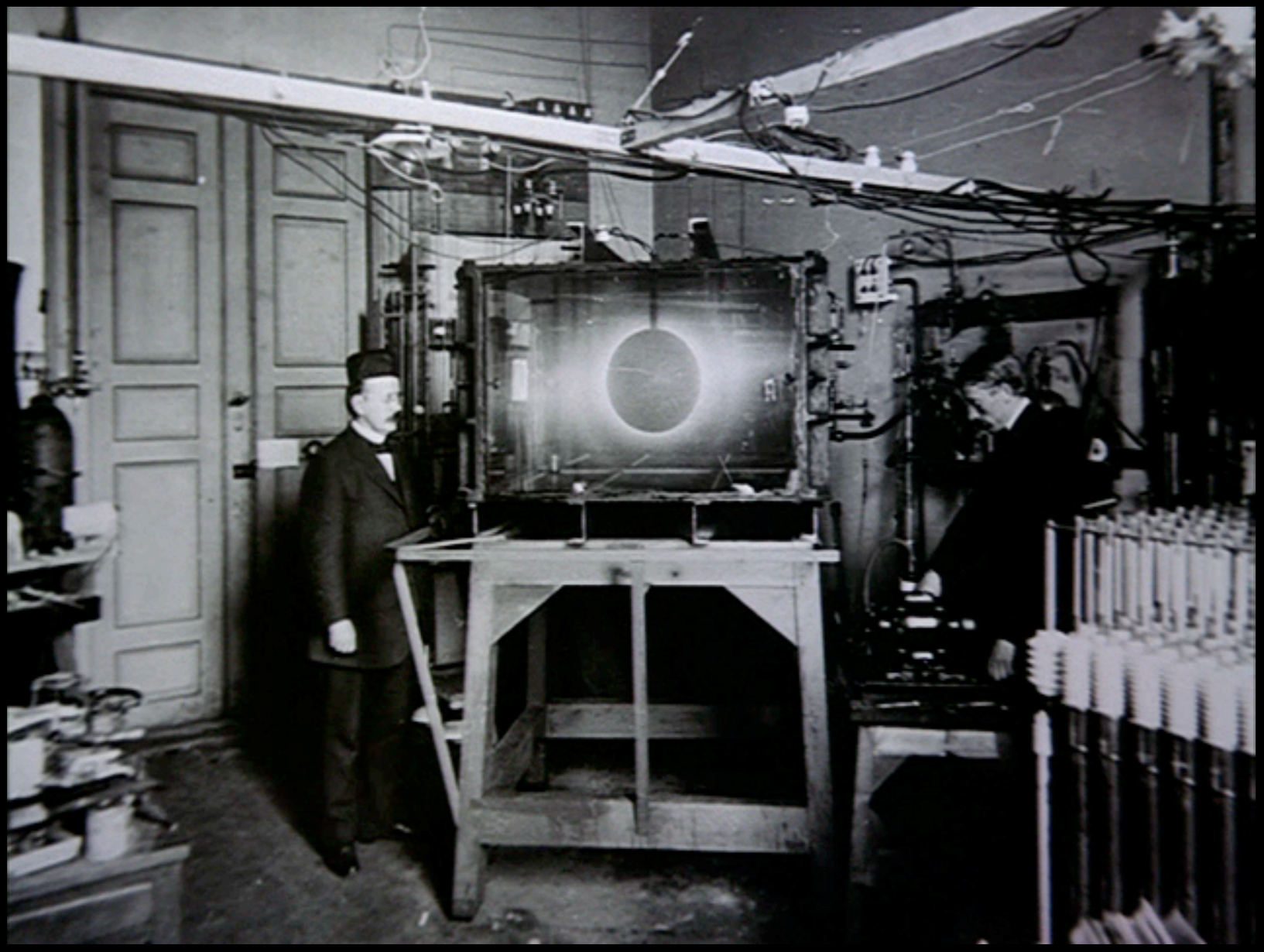
Kristian Birkeland (1867 - 1917)

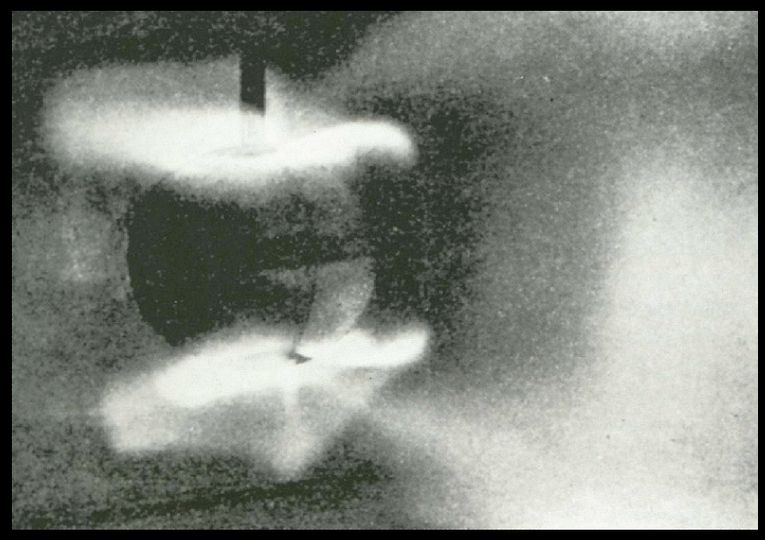
- The first realistic theory of the aurora: Electrical charged particles travelling with large velocities from sunspots. These were captured by the Earths magnetic fields and channelled down towards the polar regions.
- He supported his theory by creating artificial aurora in his laboratory in 1896.



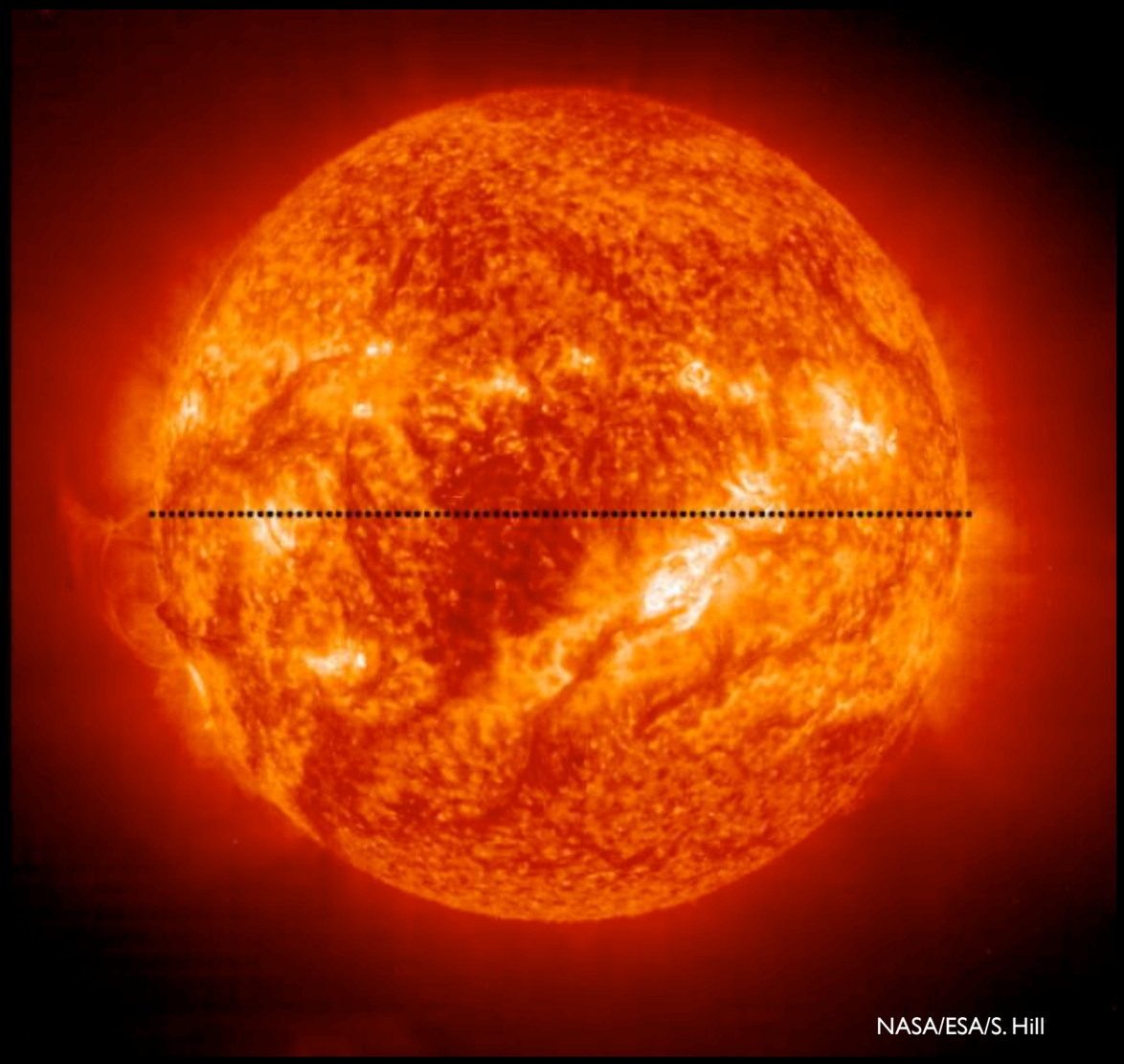
Kristian Birkeland (1867 - 1917)

- The first realistic theory of the aurora: Electrical charged particles travelling with large velocities from sunspots. These were captured by the Earths magnetic fields and channelled down towards the polar regions.
- He supported his theory by creating artificial aurora in his laboratory in 1896.





The Sun



NASA/ESA/S. Hill

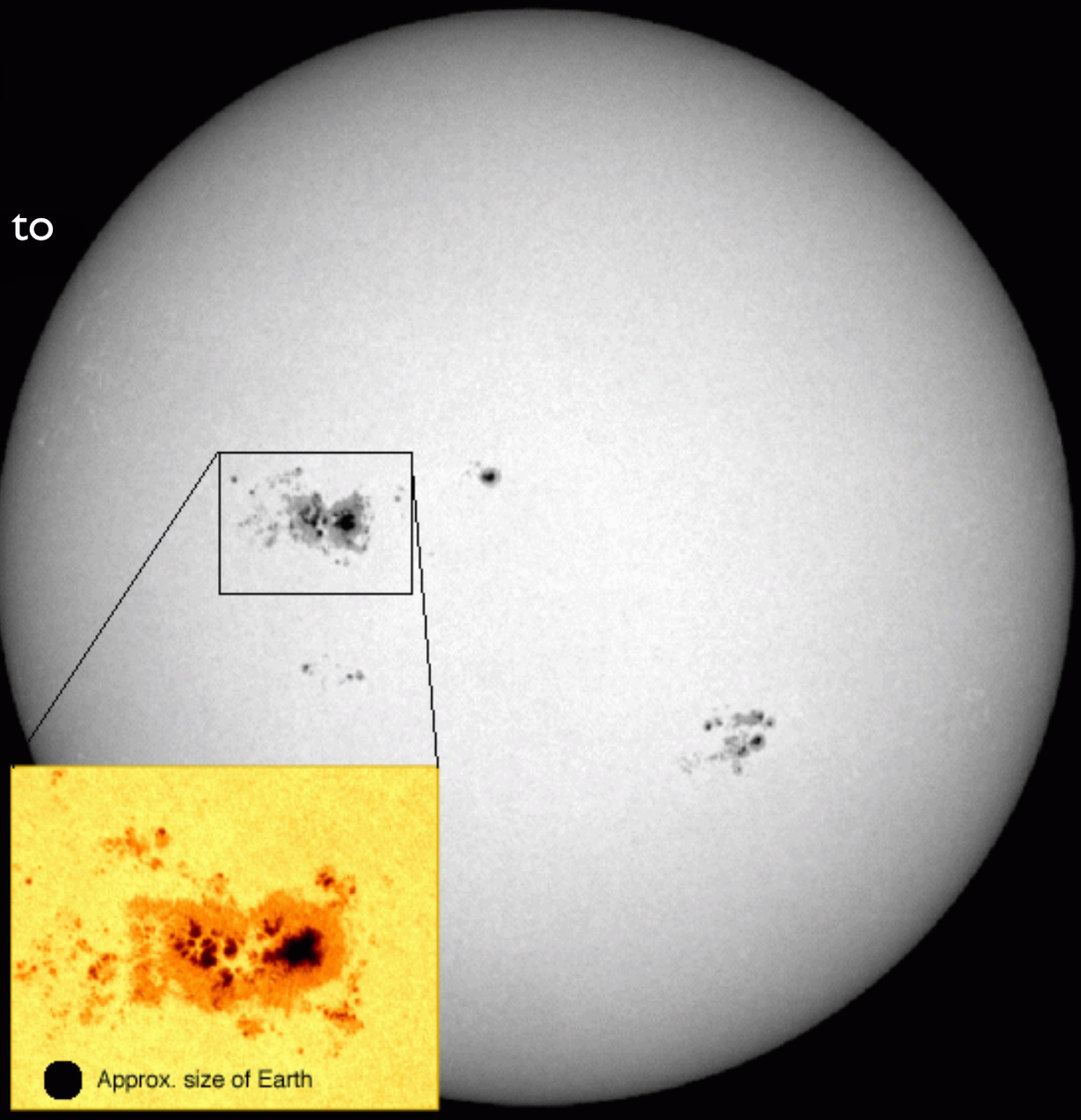
- The Sun is 333,400 times massive than the Earth.
- The Sun contain 99.86% of the total mass in the solar system
- The diameter is 109 times the Earth – The Sun can room 1.3 million Earths
- Consist of 78% Hydrogen and 20% Helium and 2% other elements.

SUNSPOTS

Dark features on the solar surface

Casued by strong magnetic fields emerging from the solar interior.

The strong magnetic fields blocks some of the energy to emerge from these regions.



NASA

NASA/ESA/S. Hill

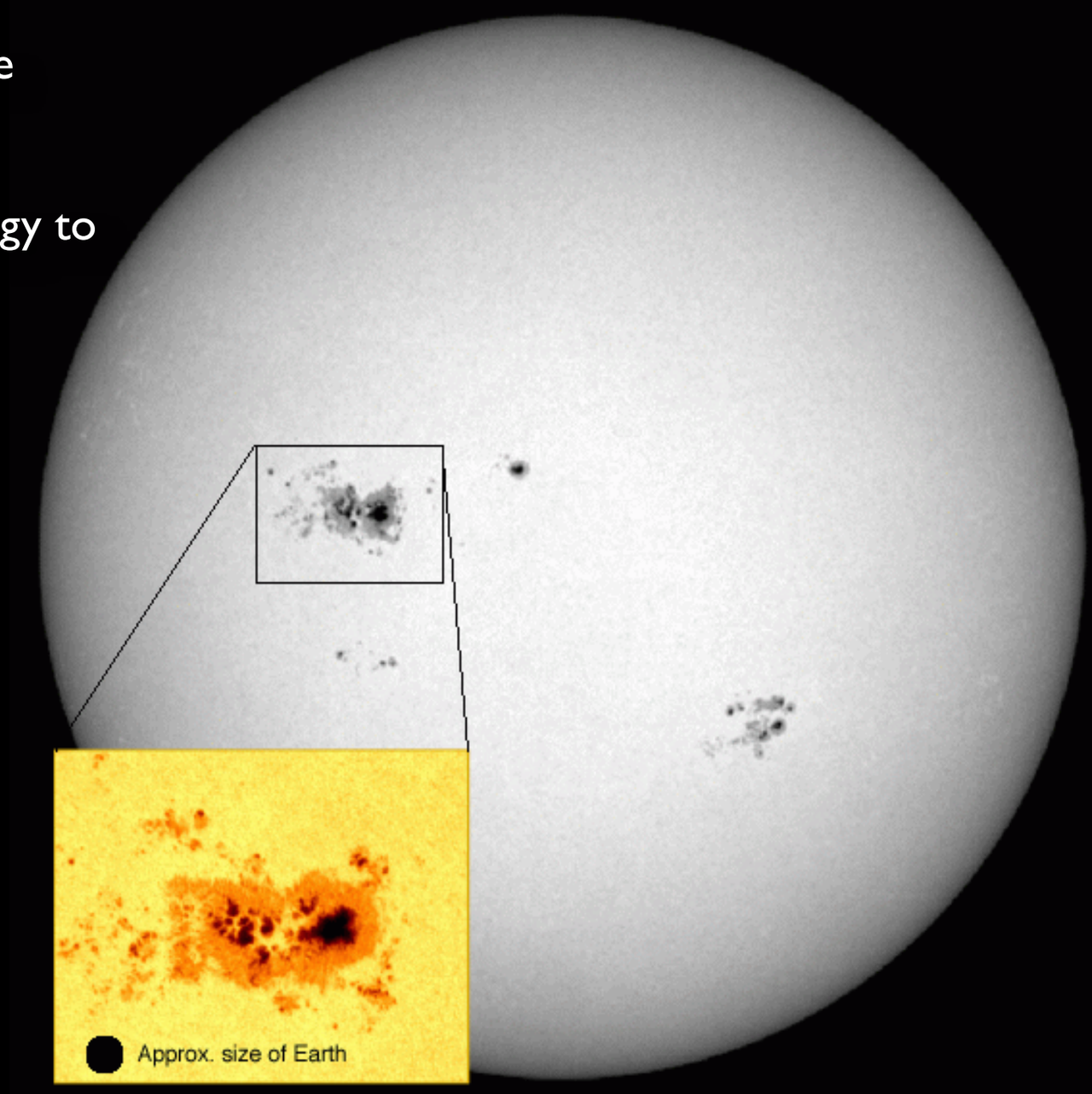
SUNSPOTS

Dark features on the solar surface

Casued by strong magnetic fields emerging from the solar interior.

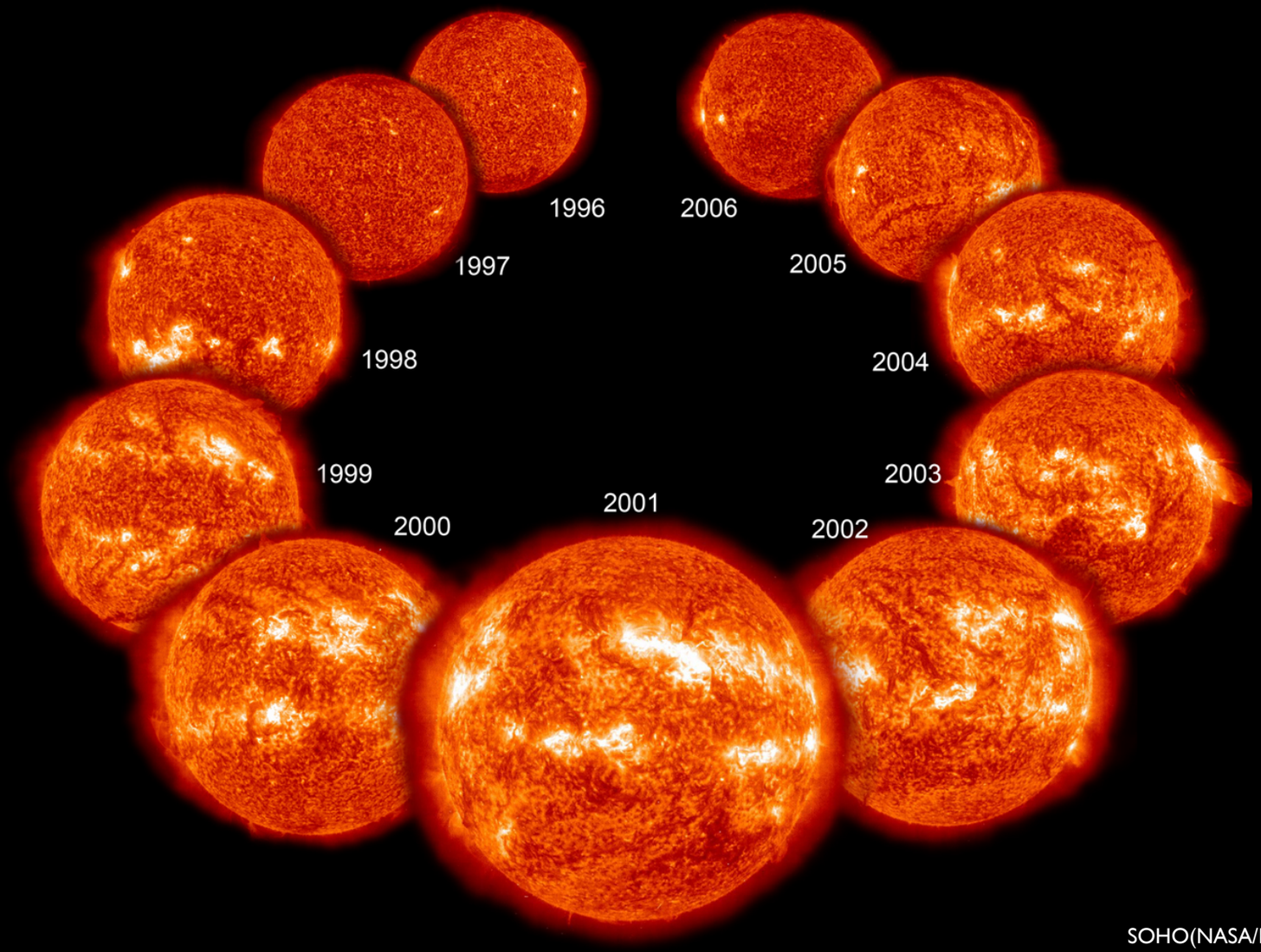
The strong magnetic fields blocks some of the energy to emerge from these regions.

NASA



NASA/ESA/S. Hill

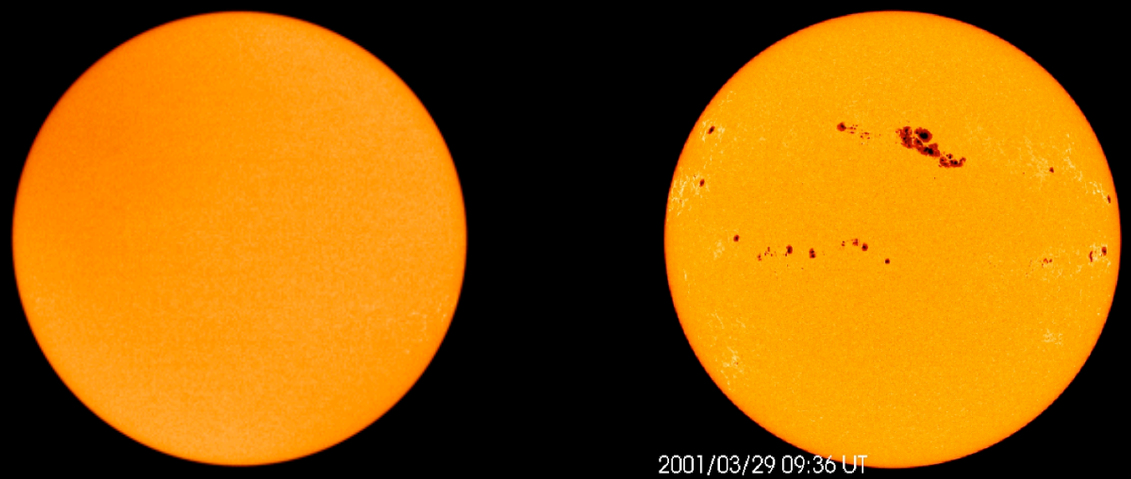
Solar Cycle



SOHO(NASA/ESA/S. Hill)

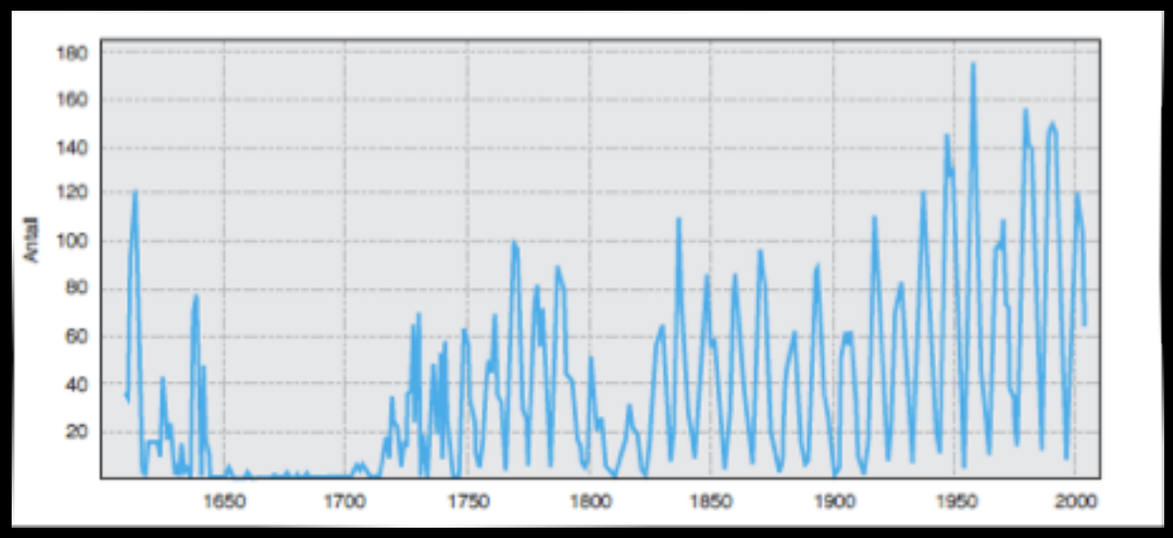
Seen from the Earth with the naked eye the Sun appears to be quite static and calm, yellow disk on the sky. However, the Sun is a very variable and stormy star and contributes with much more than just heat and light. It is the source of the fascinating auroras and it can affect our technology-based society. It also affects the climate since the amount of energy is varying. That is why it is so important to increase our knowledge about the Sun – our life supporting star.

SUNSPOT CYCLE

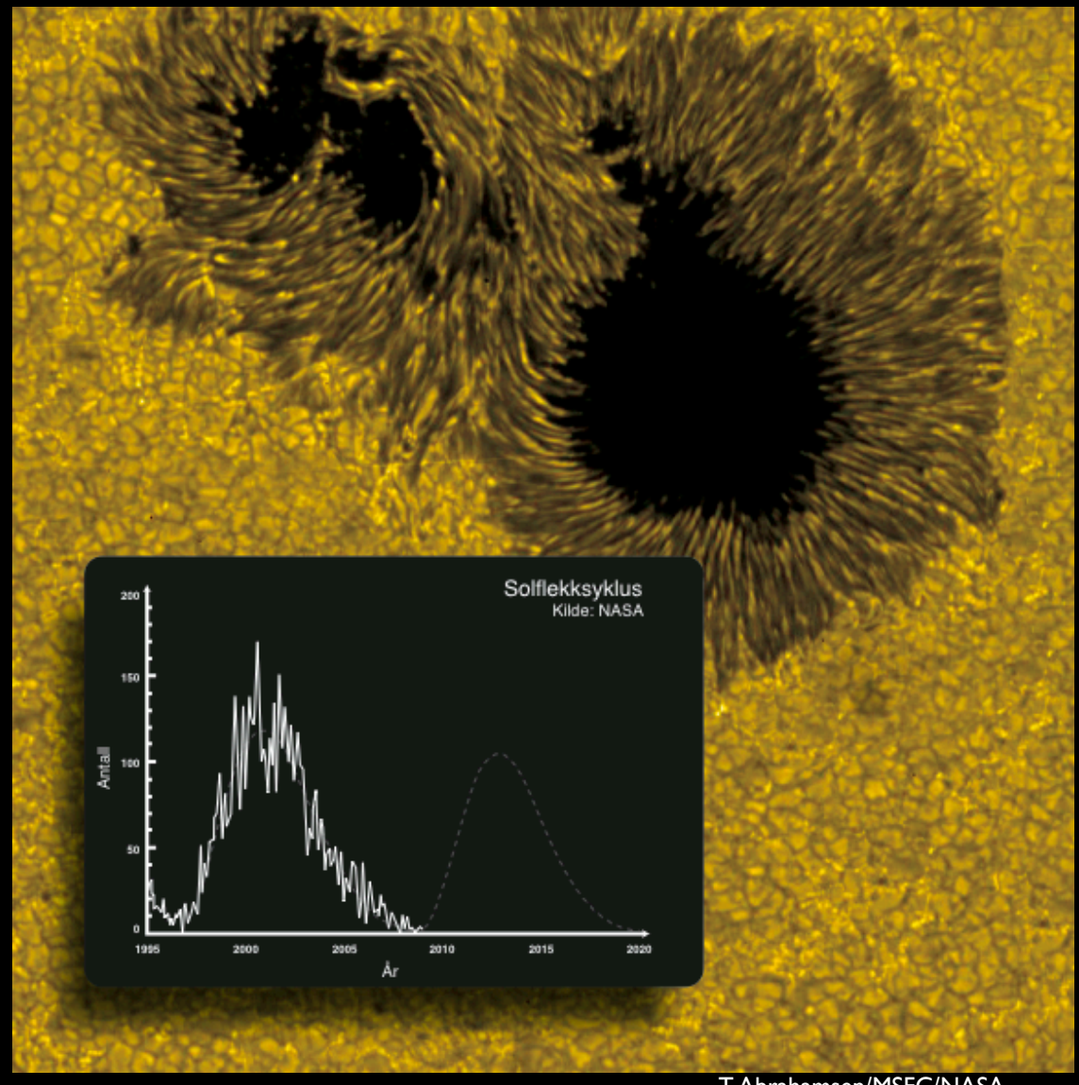


2001/03/29 09:36 UT

SOHO(NASA/ESA)



T.Abrahamsen/ARS

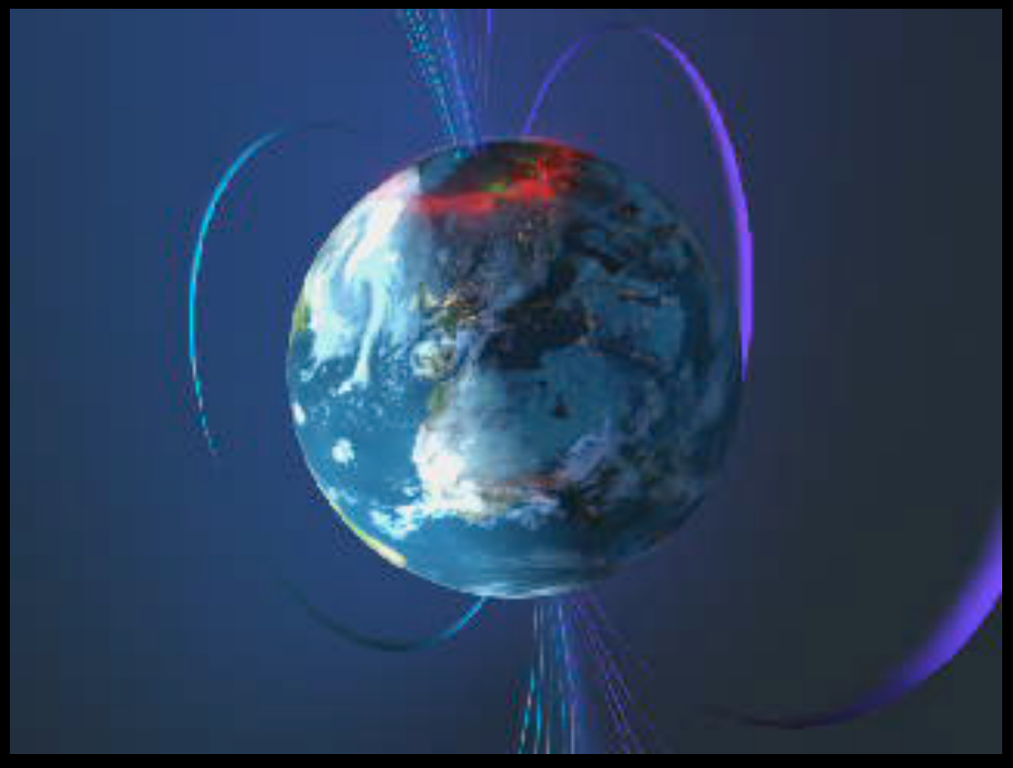


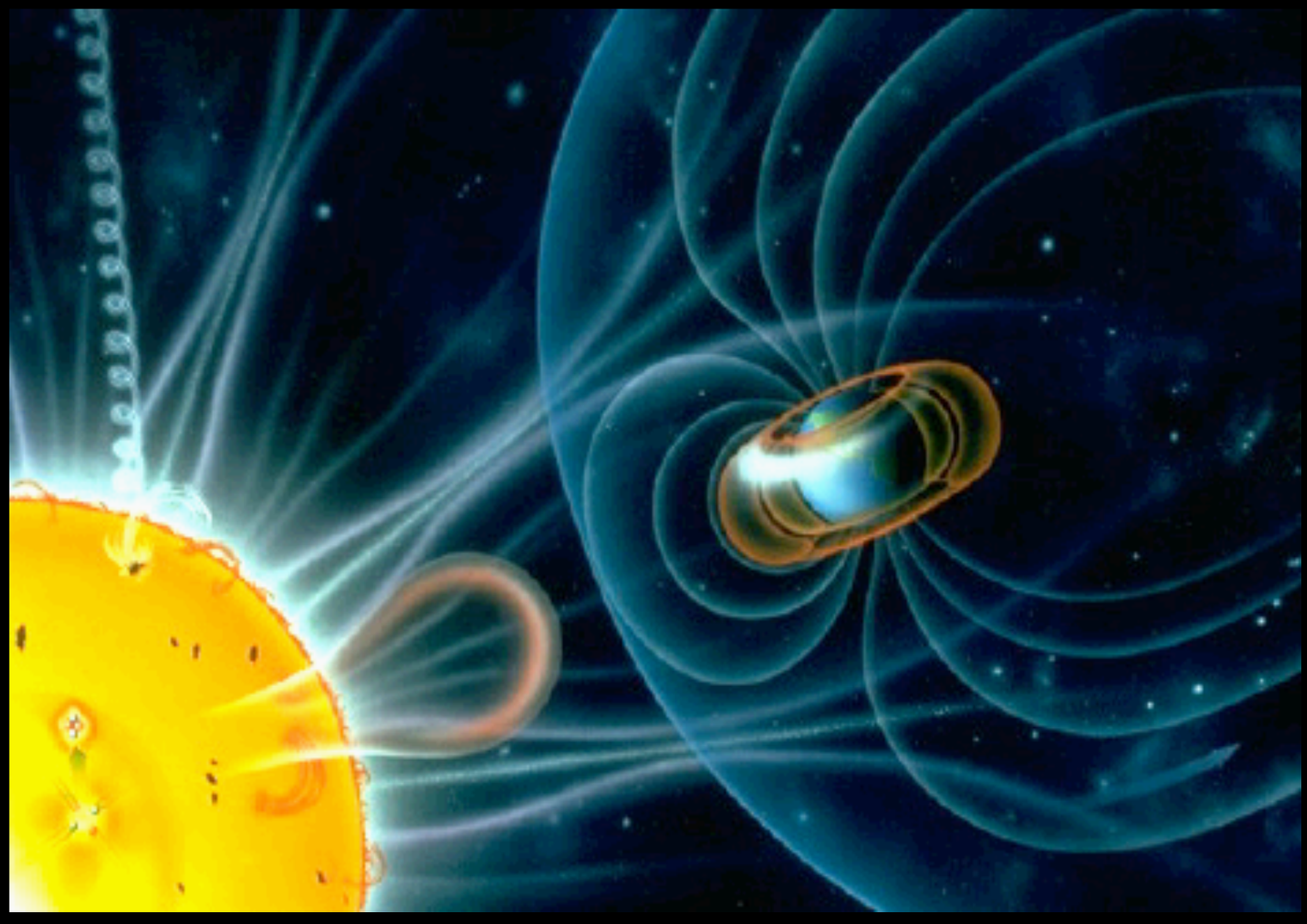
T.Abrahamsen/MSFC/NASA

Every 11-year the Sun goes through a period we call “solar maximum”, where there are many large sunspots. About five years later the Sun will enter “solar minimum” where we se few or no spots. By keeping track of number of sunspots we can follow the pulse of the Sun and how the magnetic forces and number of storms are changing. We have a good record of sunspots from 1610 when Galileo used his telescope.

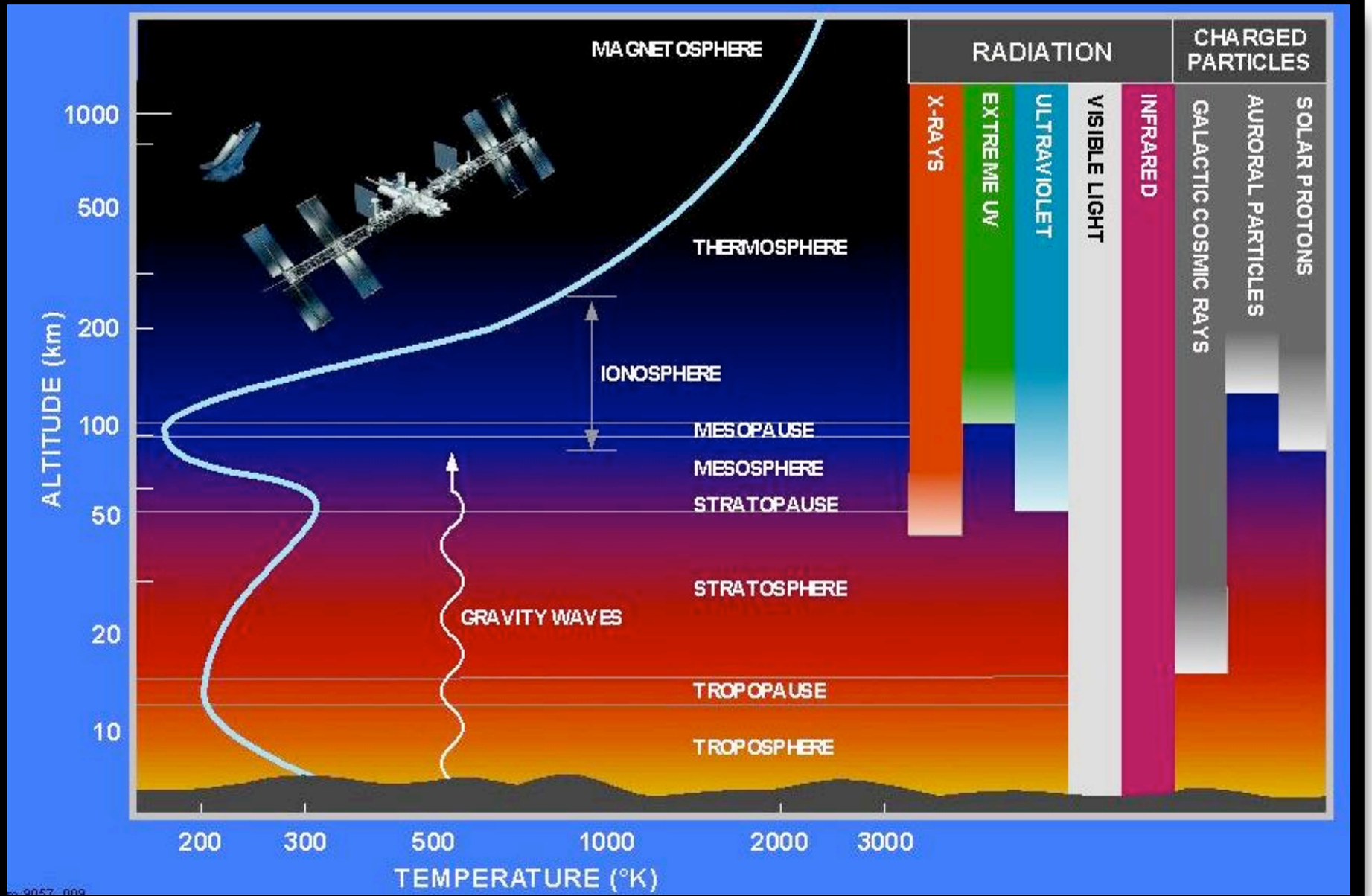
The Solar Wind

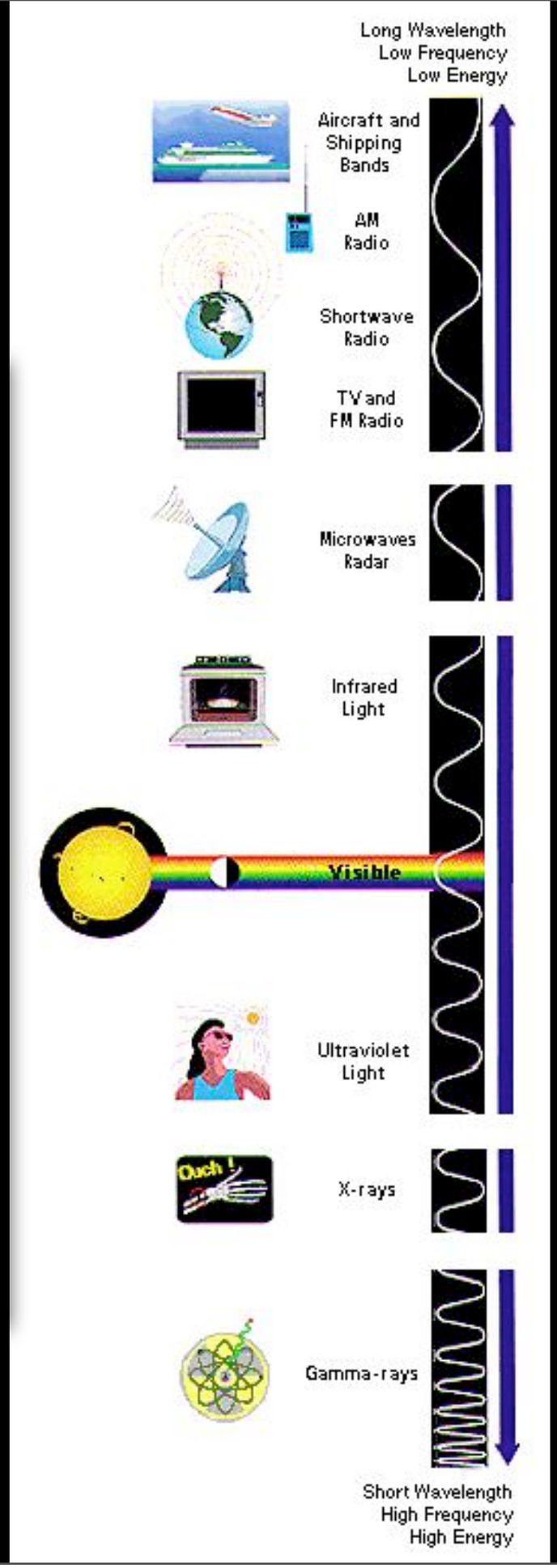
- A constant stream of particles flows from the Sun's corona, with a temperature of about a million degrees and with a velocity of about 1.5 million km/h.
- Gusts in the solar wind will buffet our magnetosphere and lead to a geomagnetic storm.





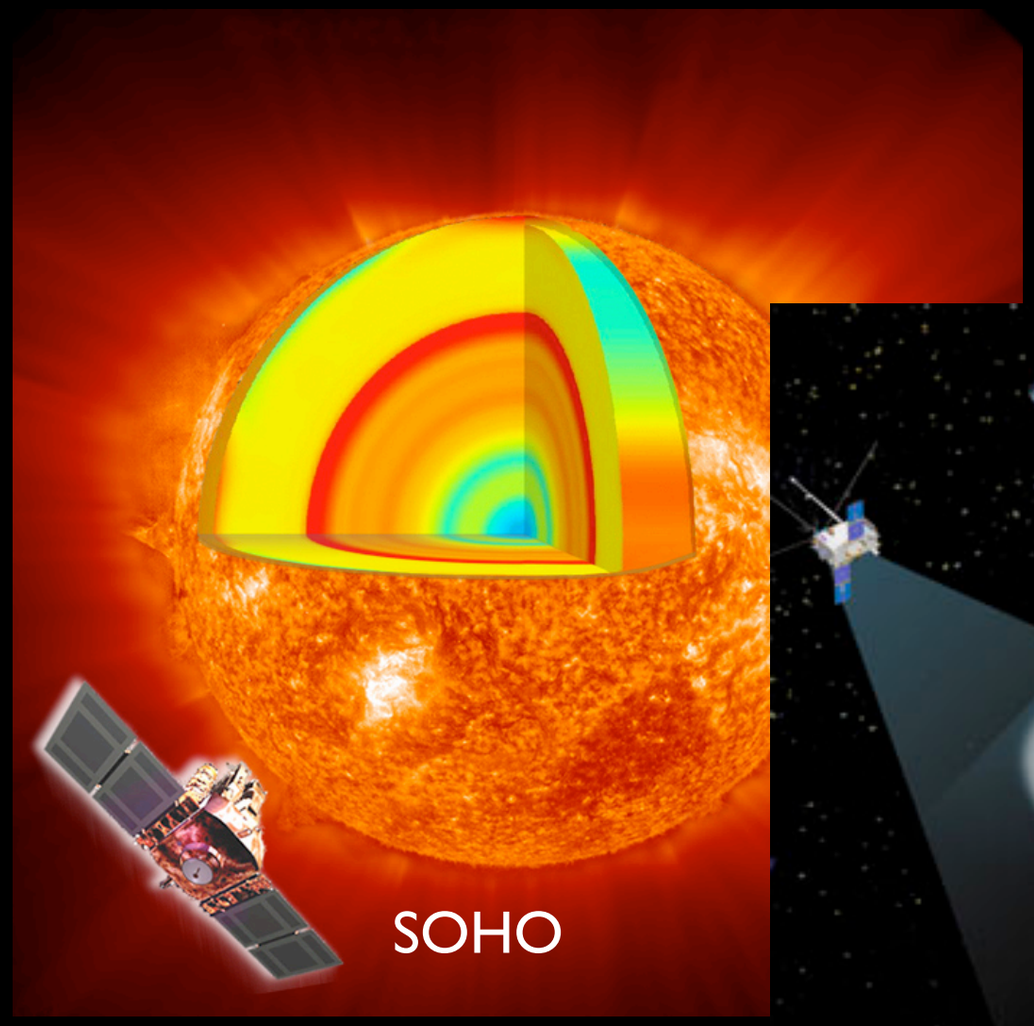
Electromagnetic radiation

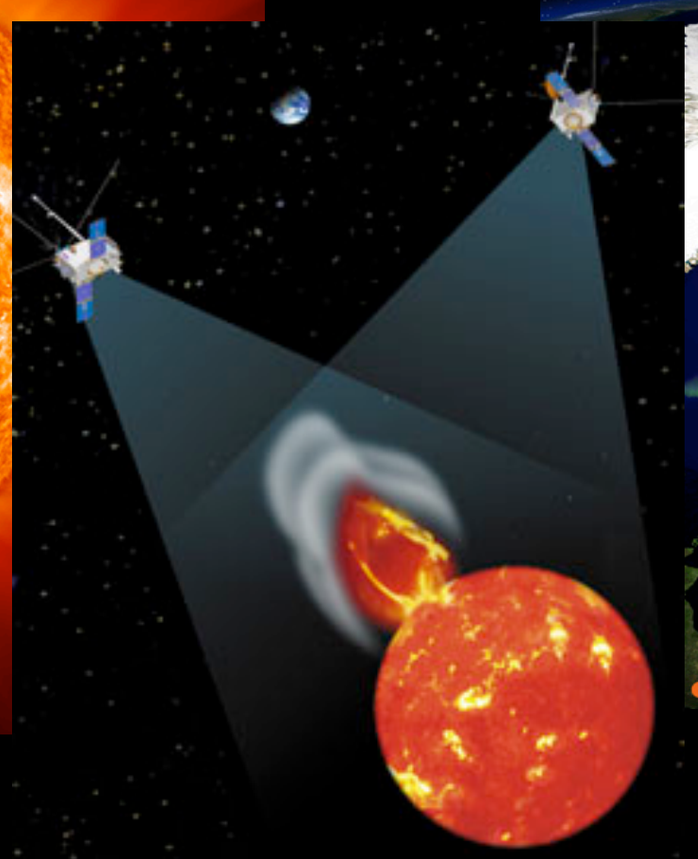


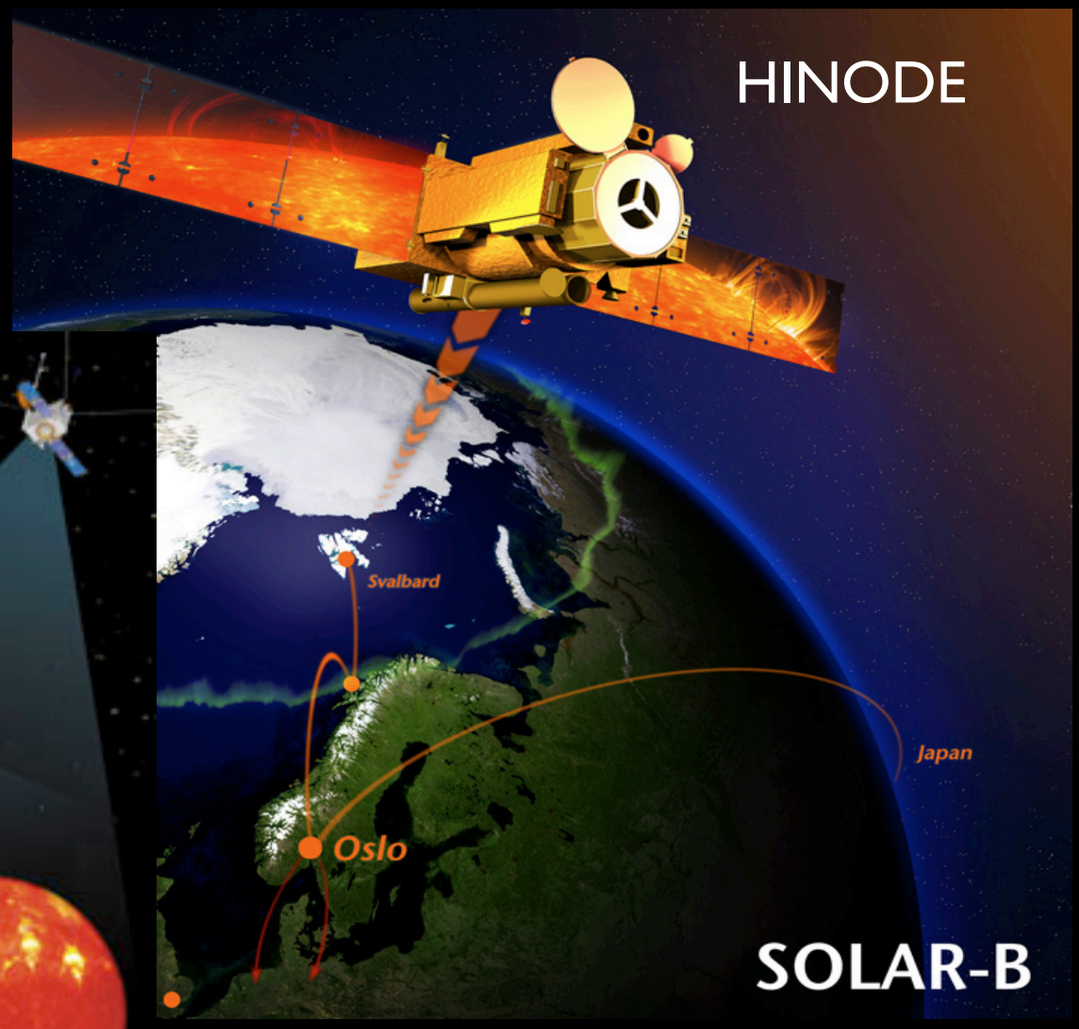


Modern space observatories

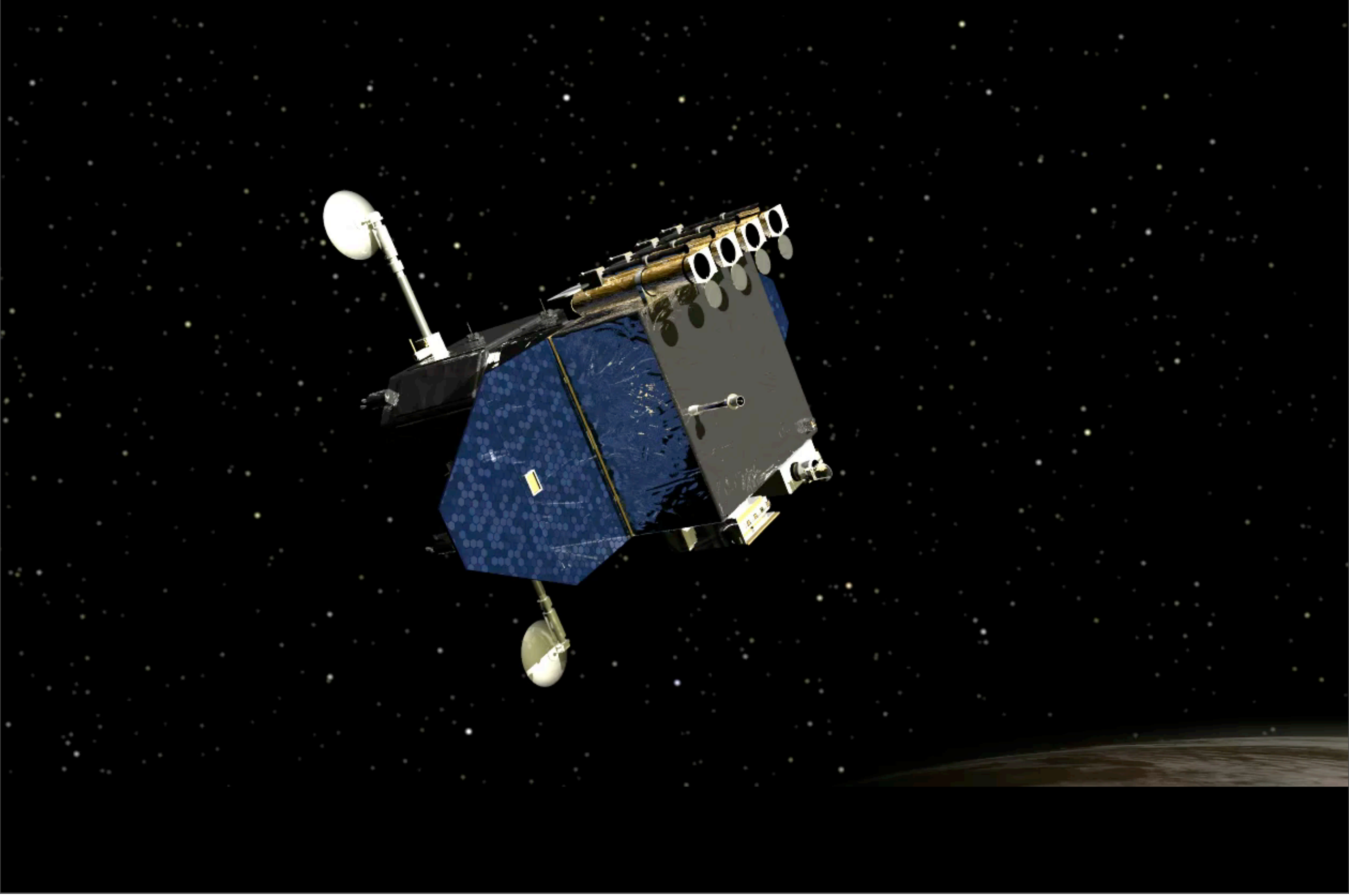
Today, new satellites are monitoring the Sun 24 hours every day. They provide space weather forecasts and warn about solar storms that may hit Earth just like the weather forecasts we see on TV every day about the weather.







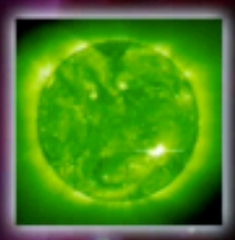
Solar Dynamics Observatory



Solar Dynamics Observatory

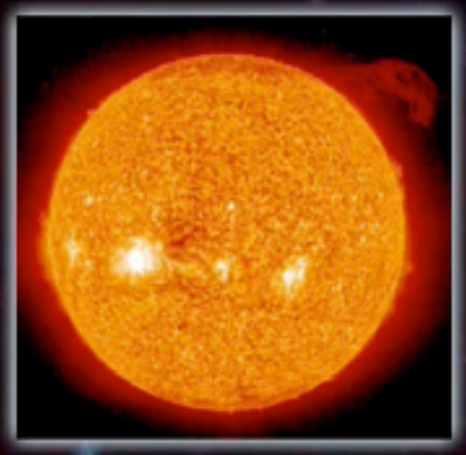
Relative Image Resolution

480 Standard Definition TV

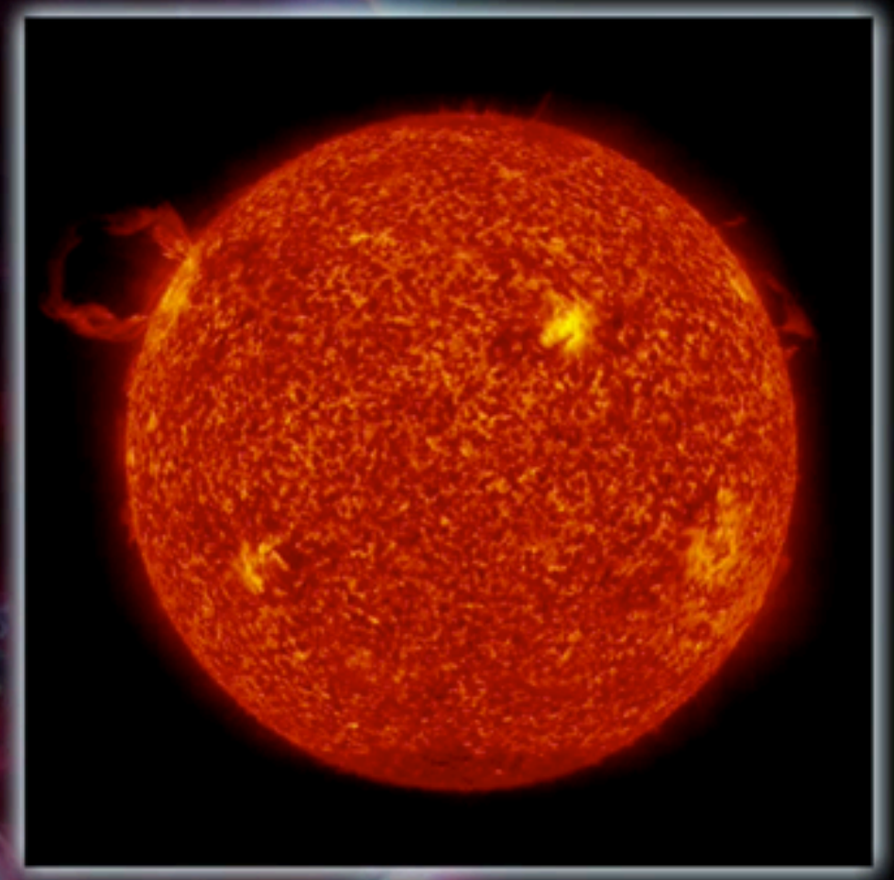


SOHO

1080 High Definition TV



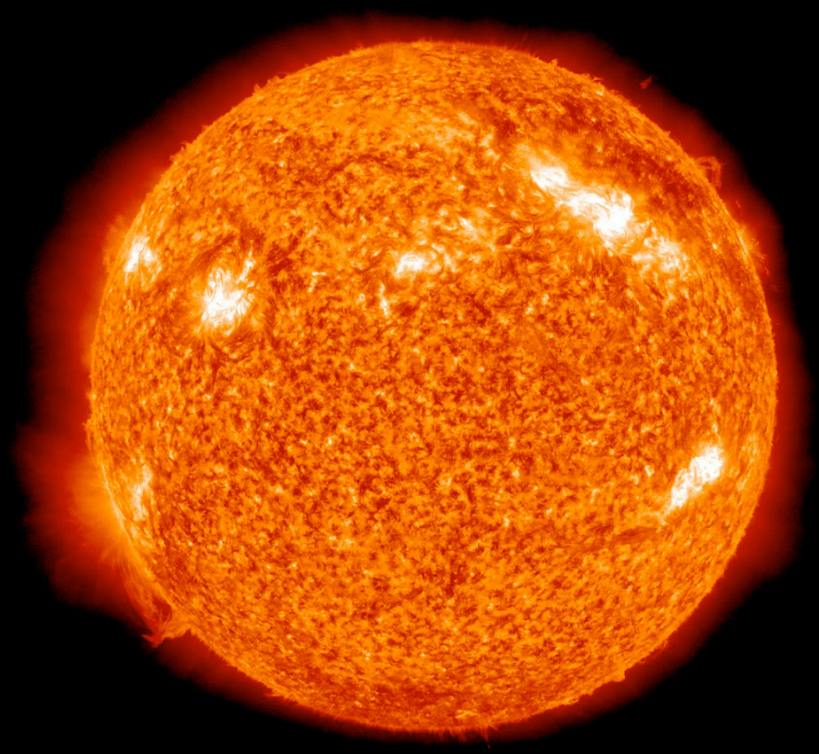
STEREO

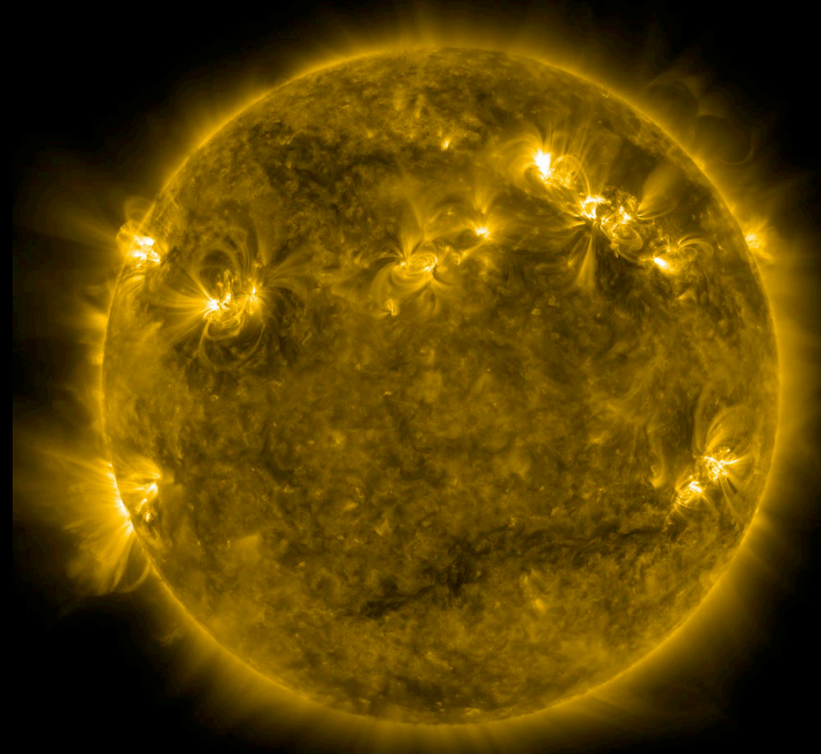


SDO

00:01:50 -00:00:00

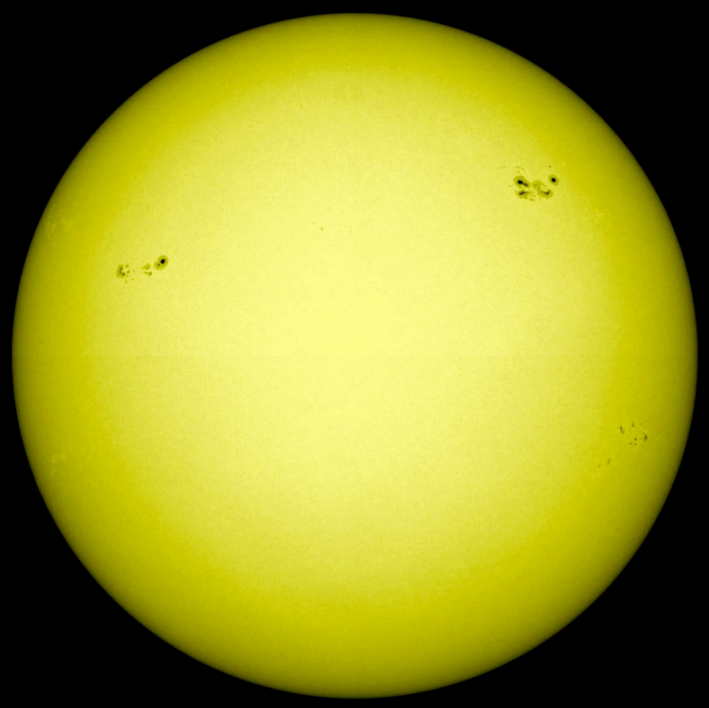
The Sun from Space





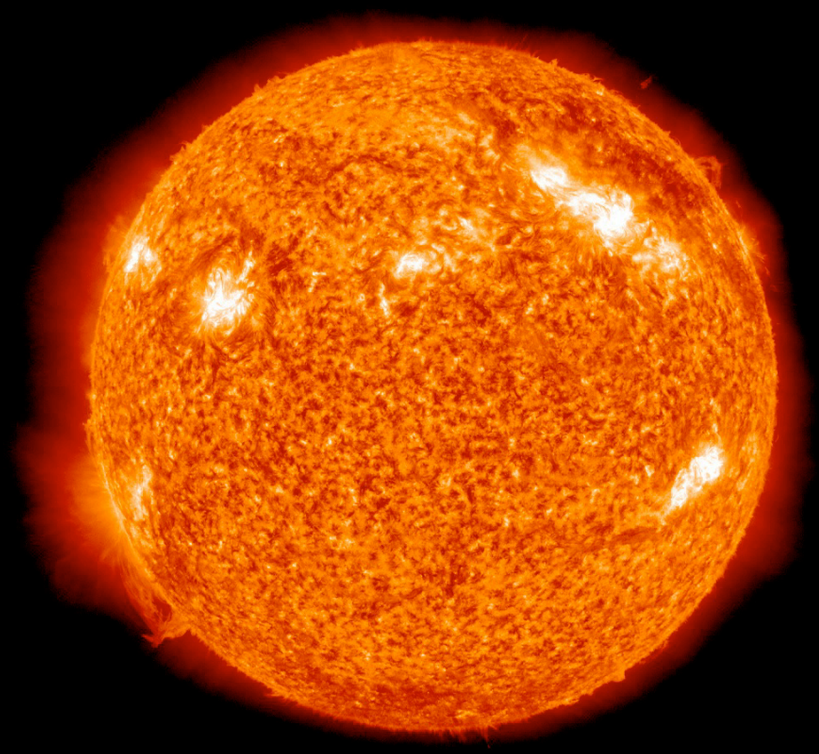
Visible light EUV X-ray

The Sun from Space



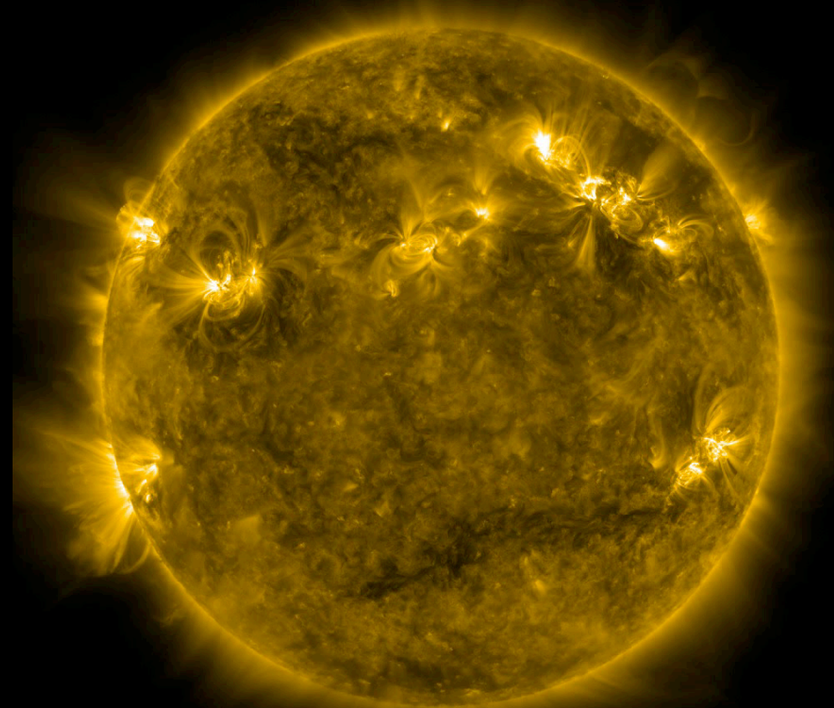
O/AIA 4500 2011-03-06 05:00:08 UT

Visible light



SDO/AIA 304 2011-03-06 05:06:09 UT

EUV

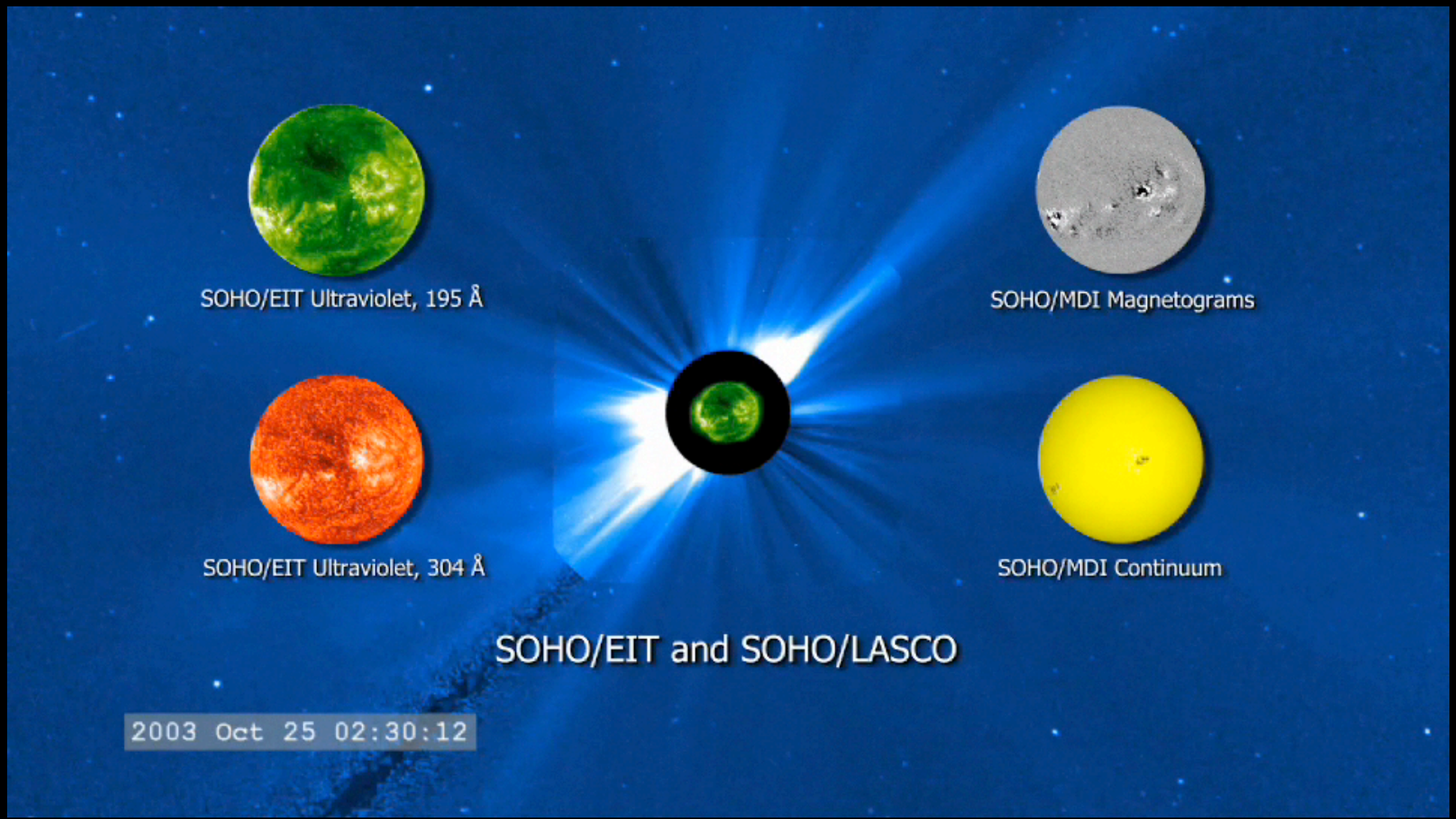


SDO/AIA 171 2011-03-06 05:06:13 UT

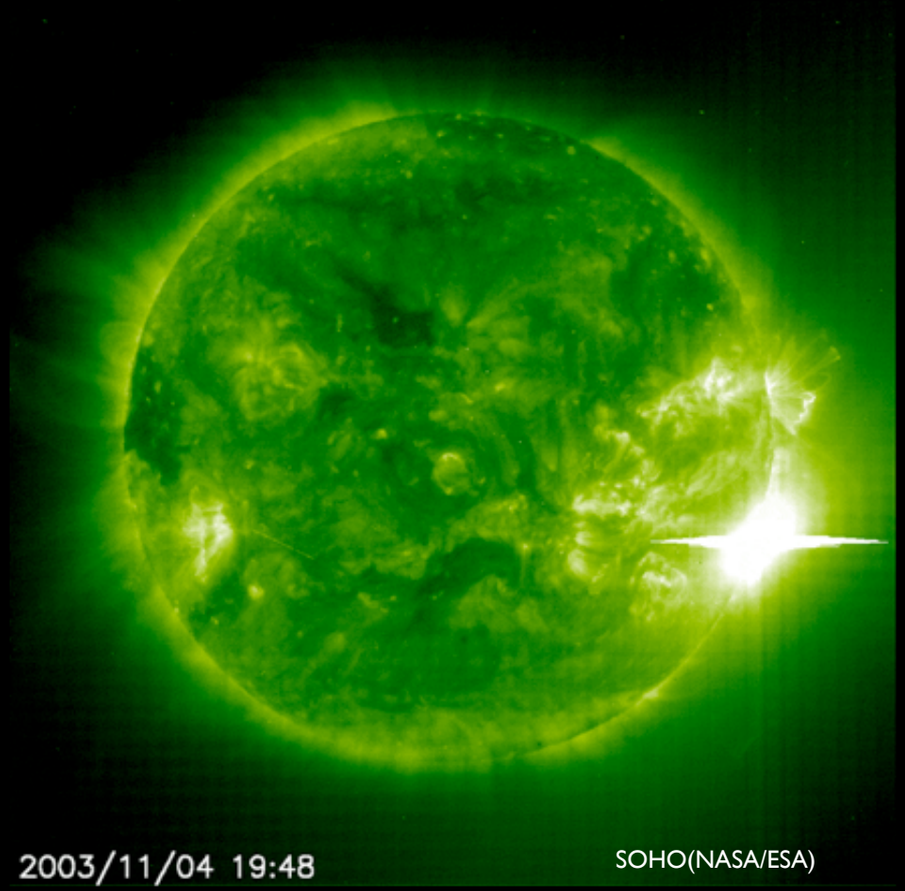
X-ray

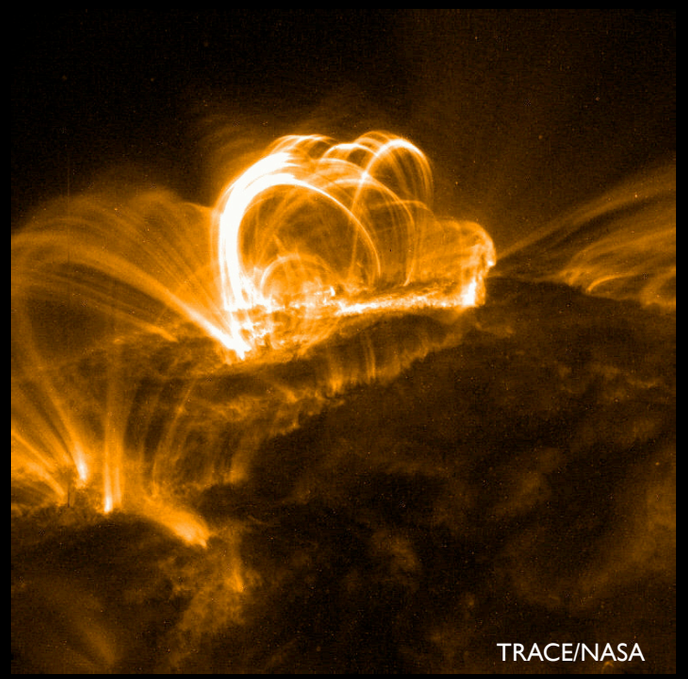
The dynamic Sun

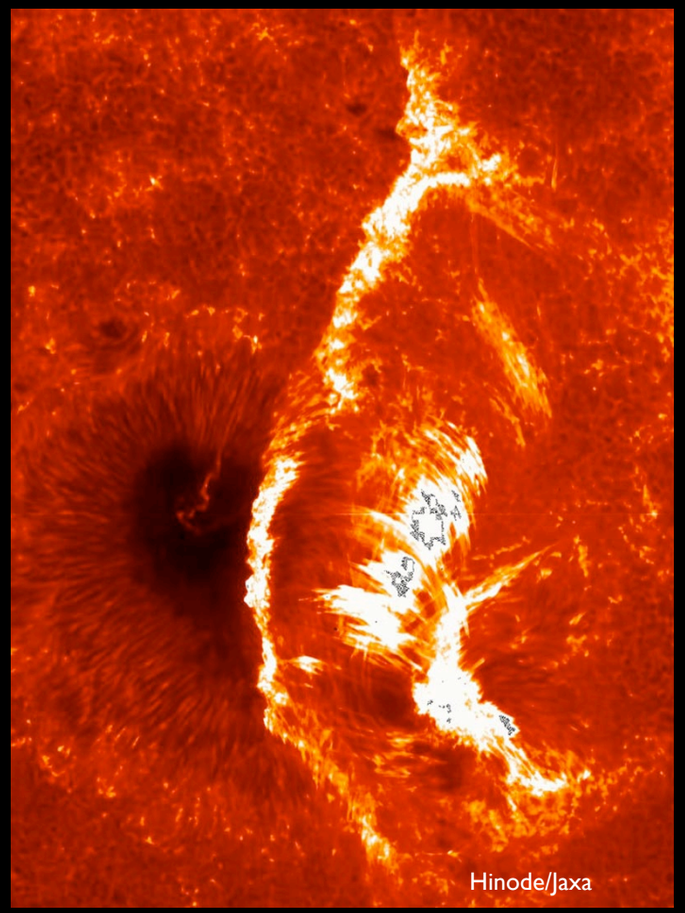
The dynamic Sun



EXPLOSIONS ON THE SUN



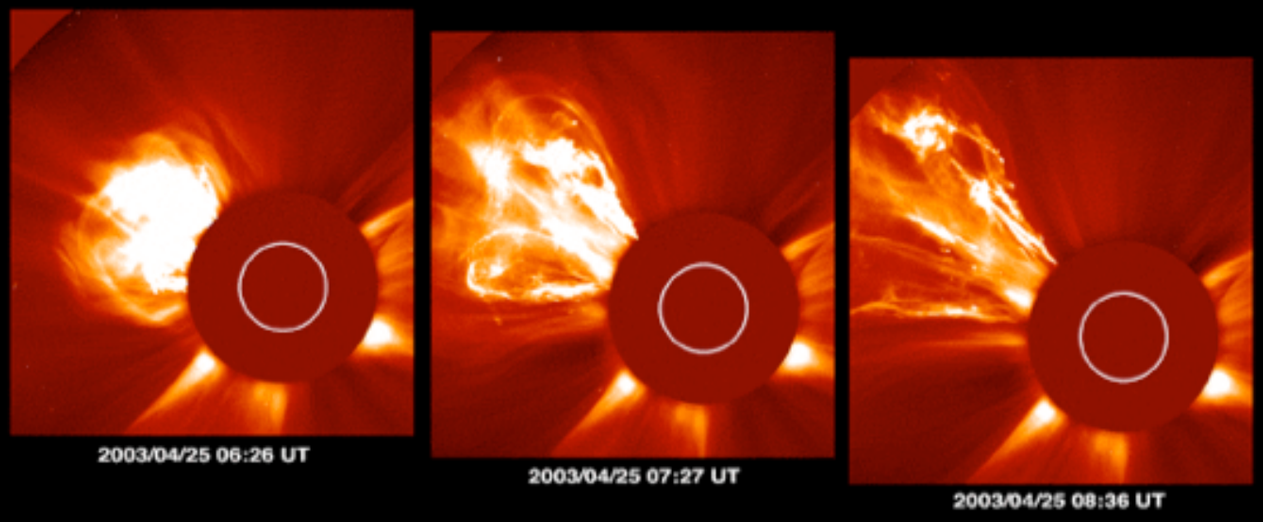




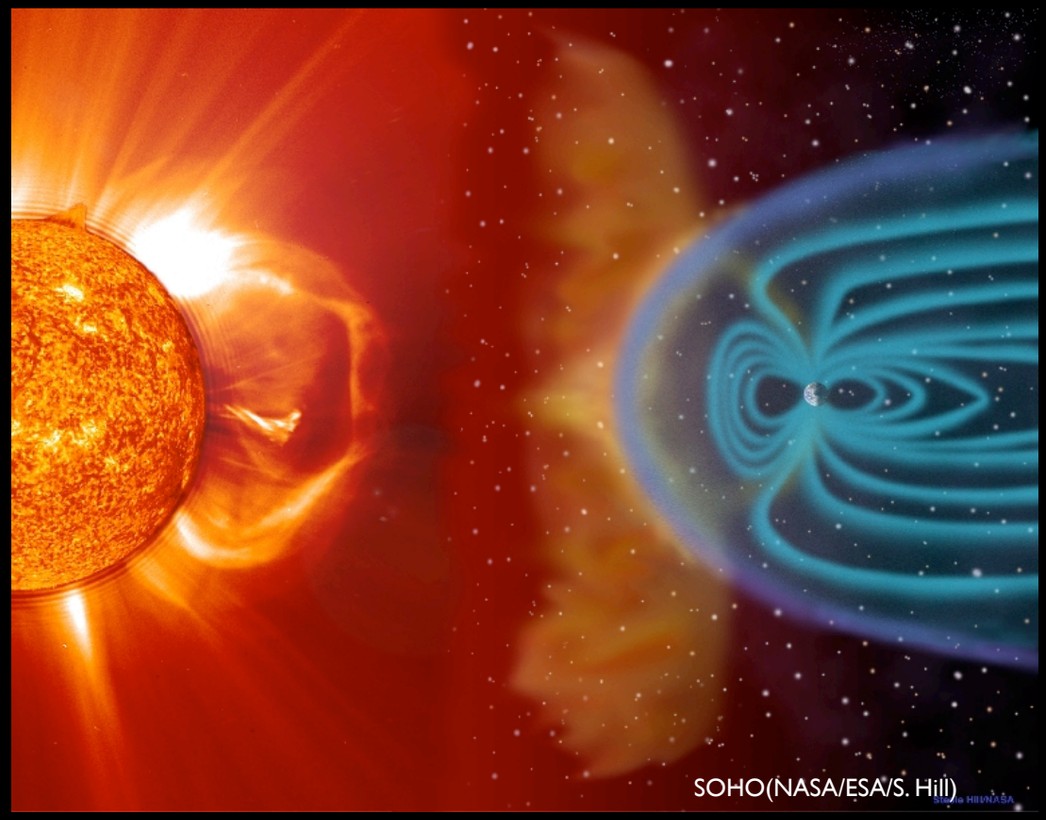
The magnetic field in large active regions on the Sun often gets unstable. This can result in violent explosions in the solar atmosphere – called “flares”. A flare can release in seconds energy corresponding to several billion megatons of TNT. During such explosions the gas is heated to 20 million degrees.

This super heated gas will emit large amount of UV radiation and X-rays. The radiation travels with the speed of light and hits the Earths atmosphere 8 minutes 20 seconds later. Luckily, this hazardous radiation is blocked by gases in our protective atmosphere such as ozone. As will be described later such explosions can affect radio communication and satellite communication.

GAS ERUPTIONS - CORONAL MASS EJECTIONS (CME)



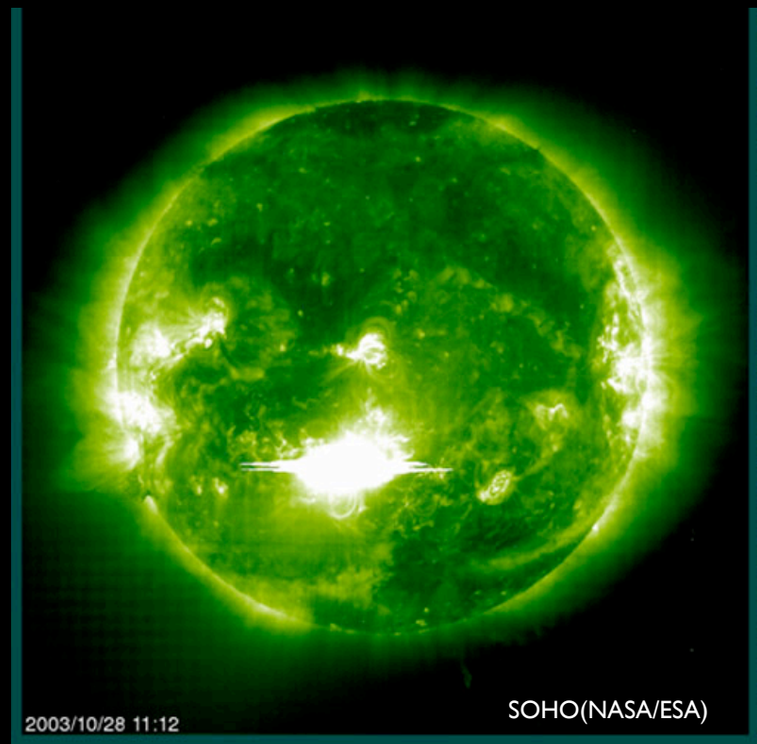
SOHO(NASA/ESA/S. Hill)



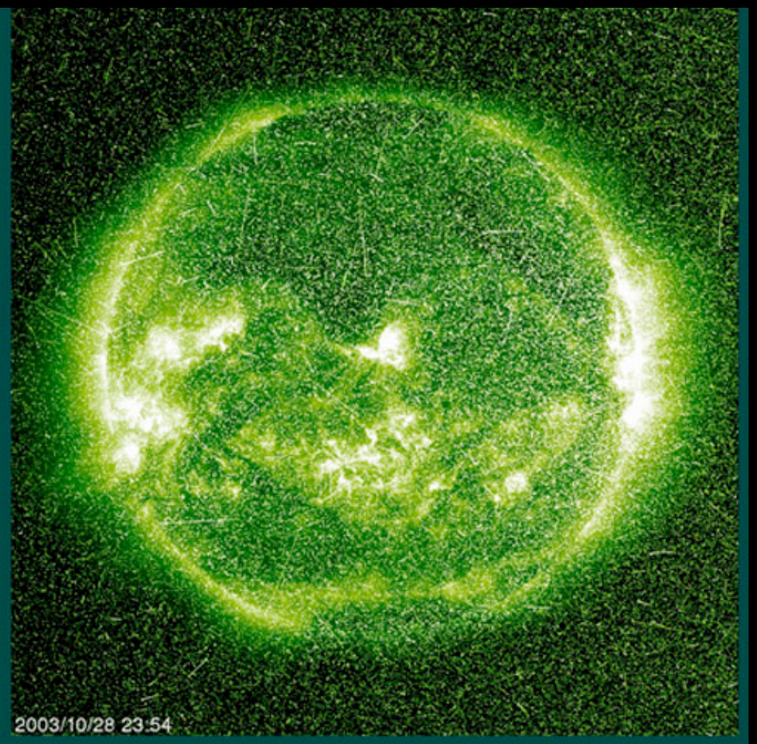
Sometimes large prominences can erupt and large amount of gas and magnetic fields are ejected out in space. The largest eruptions eject several billion tons of particles corresponding to 100,000 large battleships. Such eruptions are called Coronal Mass Ejections or CMEs for short. The bubble of gas will expand out in space and can reach velocities up to 8 million km/h. Still it would take almost 20 hours before it reach the Earth. Usually the solar wind spends three days on this journey.

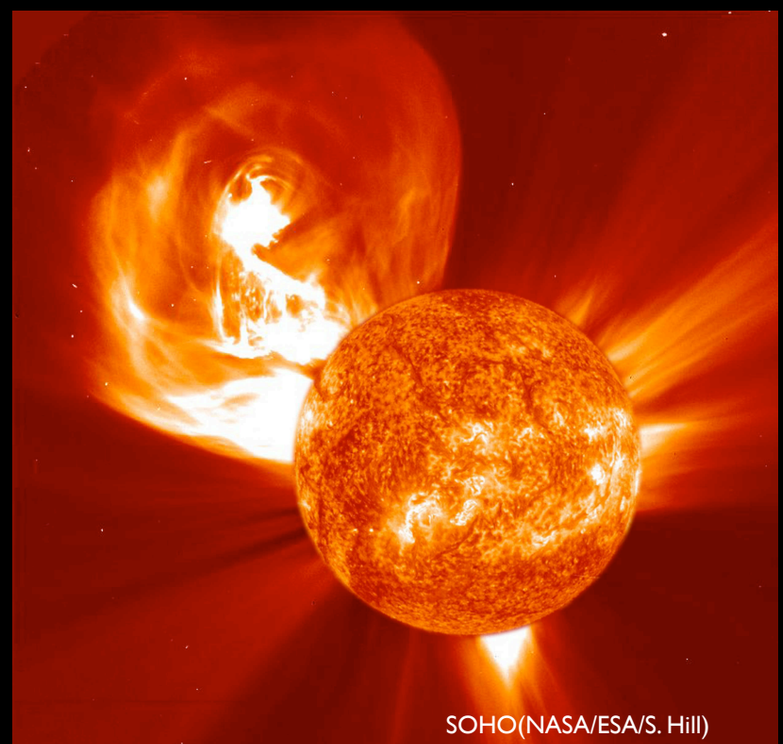
If such an eruption is directed towards the Earth the particles will be deflected by our magnetosphere. The cloud of gas will push and shake the Earths magnetic field and generate a kind of “storm” which we call geomagnetic storms.

PARTICLE SHOWERS FROM THE SUN



SOHO(NASA/ESA)



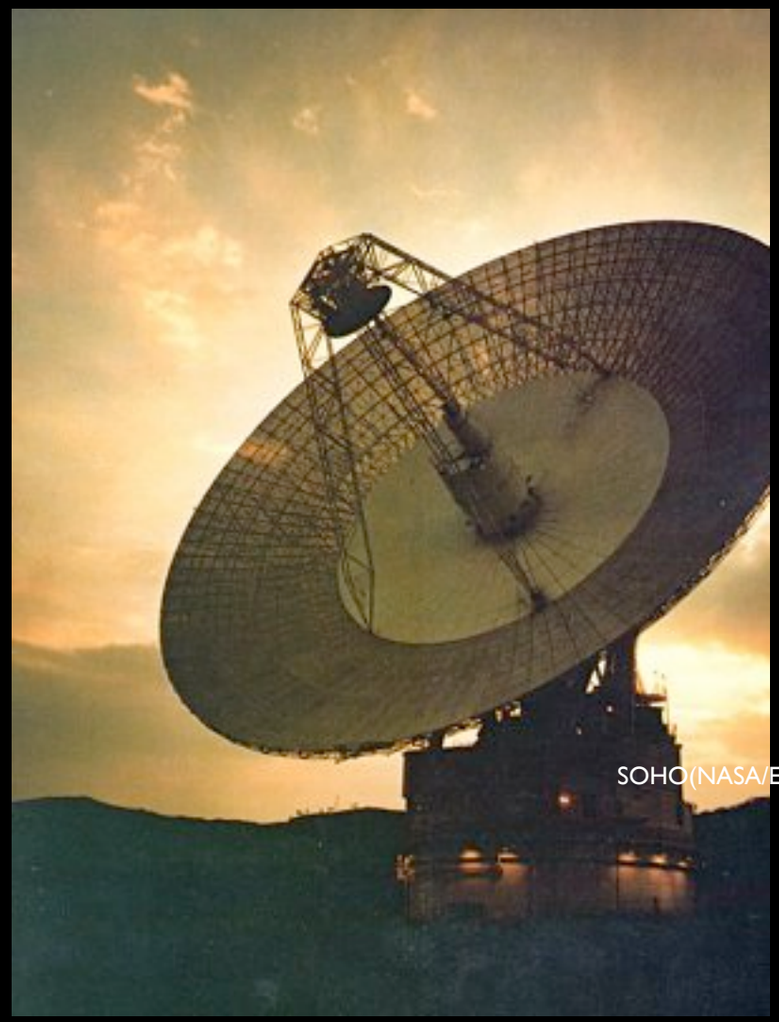


SOHO(NASA/ESA/S. Hill)

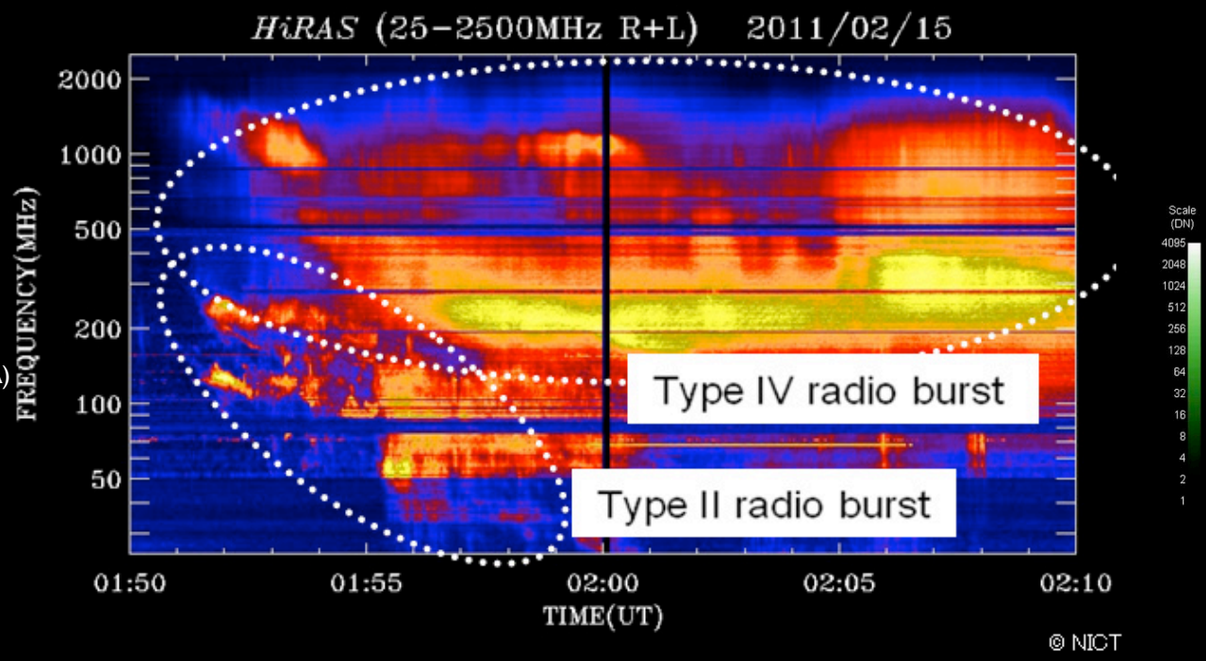
A few times explosions or eruptions will accelerate large amount of particles that travel at almost the speed of light. Such showers of particles consist mostly of protons and it takes less then an hour to reach Earth.

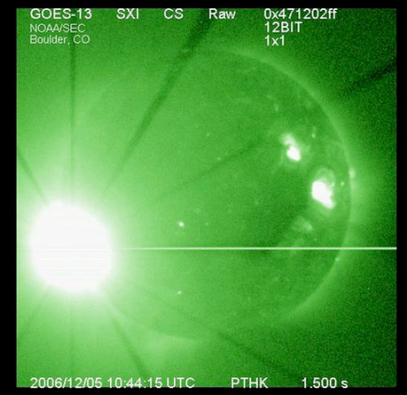
The protons have such high speed and energy that they can penetrate satellites and space ships. Thus, they can damage vital electronic equipment. They can also destroy the quality of images and scientific data from those satellites that are surveying the Sun as shown in the picture above. The particles “blind” the digital cameras and we see a large amount of noise in the images.

RADIO-BURST



SOHO(NASA/ESA)





A few times eruptions on the Sun will generate strong burst of radio waves - often with the same frequencies as communications systems we use on Earth as well as the GPS frequency.

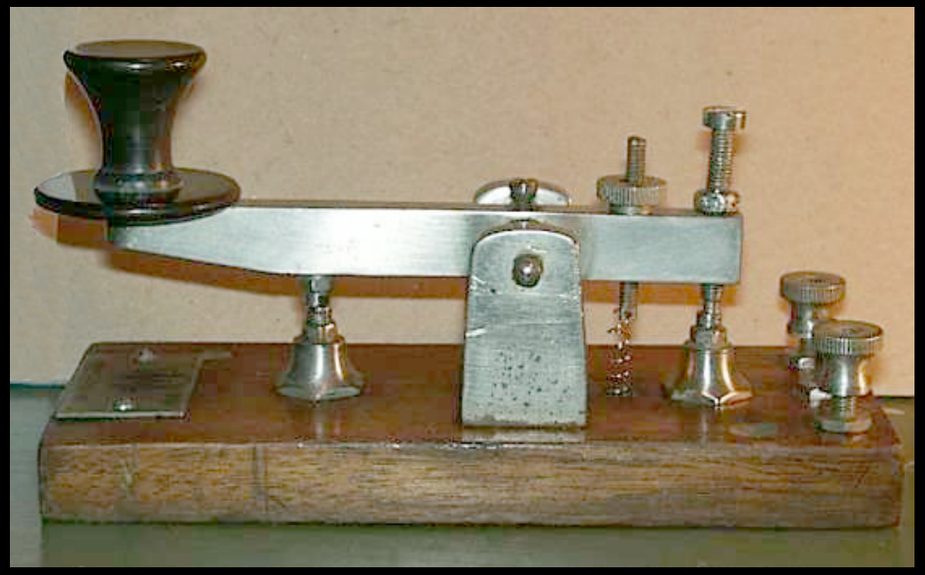
Space Weather

From the book «Our Explosive Sun» (P. Brekke)

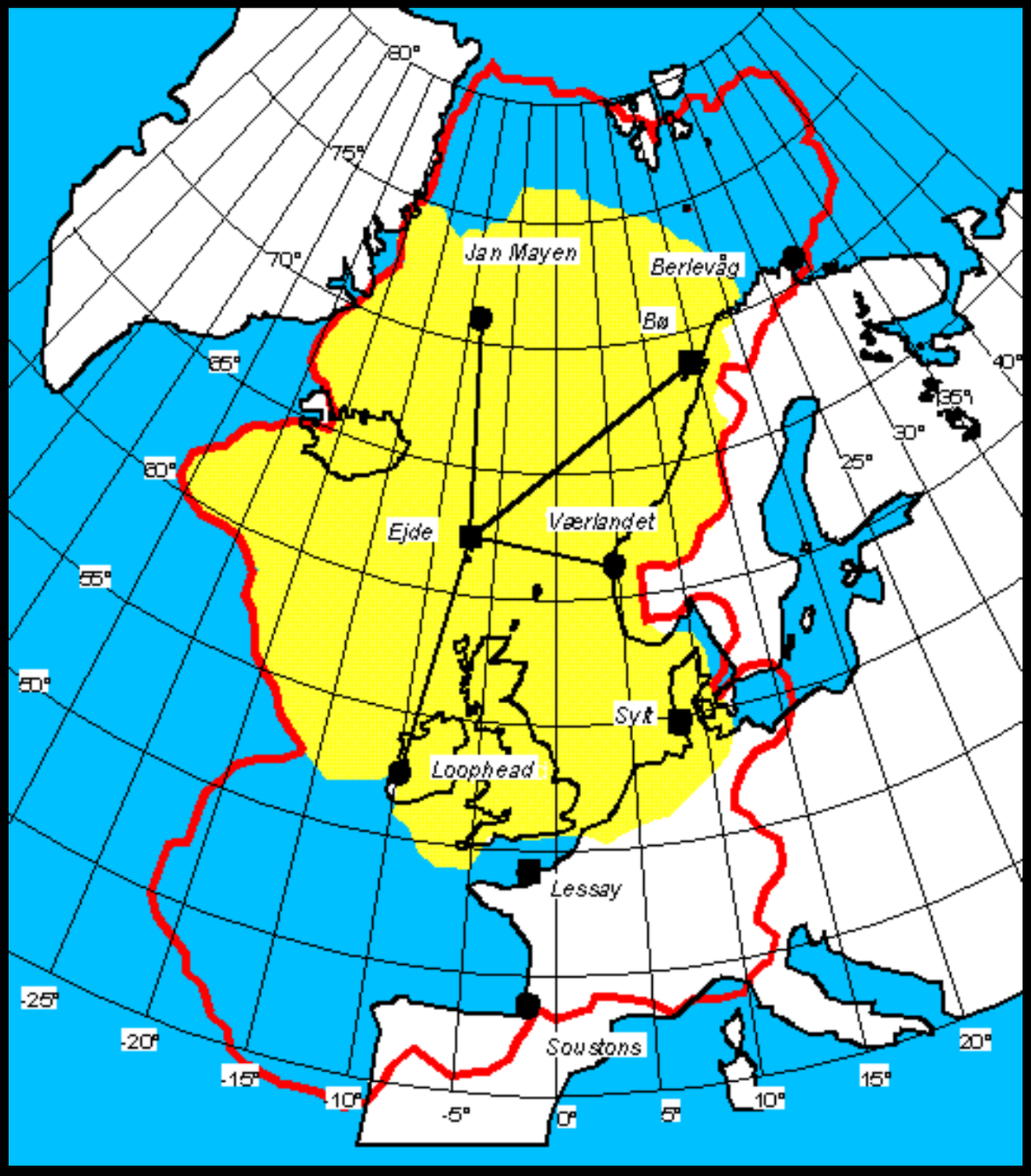
Early effects from Space Weather

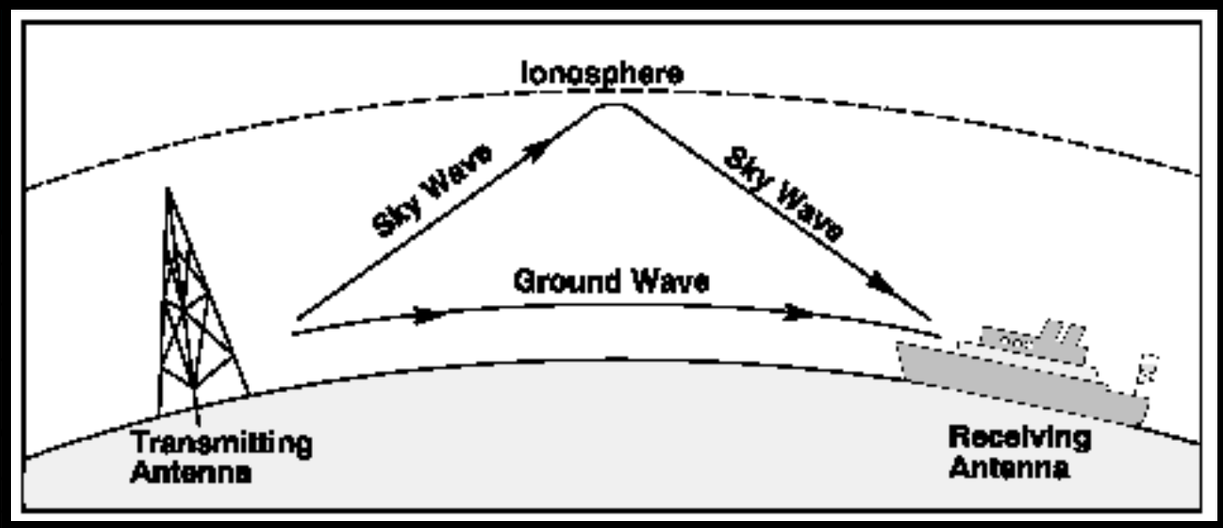
The first reported effects came from the telegraf operators.

- 17 november 1848: "Telegraph line between Piza og Firenze knocked out"
- September 1851: Telegraf system in New England disrupted.
- Sparks and fires reported due to strong induced currents.
- In Bosten (1859) they managed to rune the telegraph system without batteries or power.



Navigation systems - LORAN C





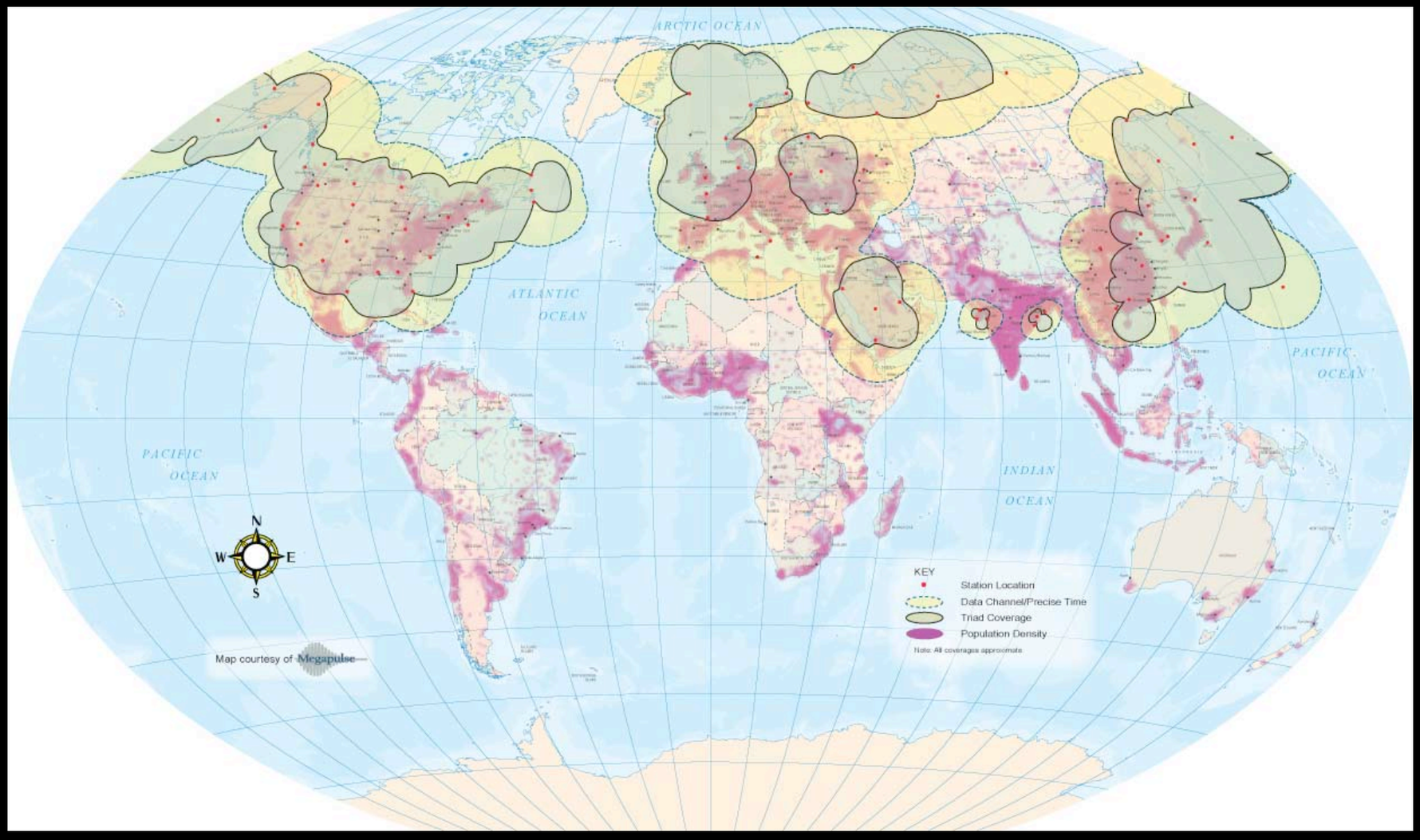
Feil i posisjonering fra 1-12 km

Image Credit: M. A. Shea, Geophysics Directorate, Philips Laboratory

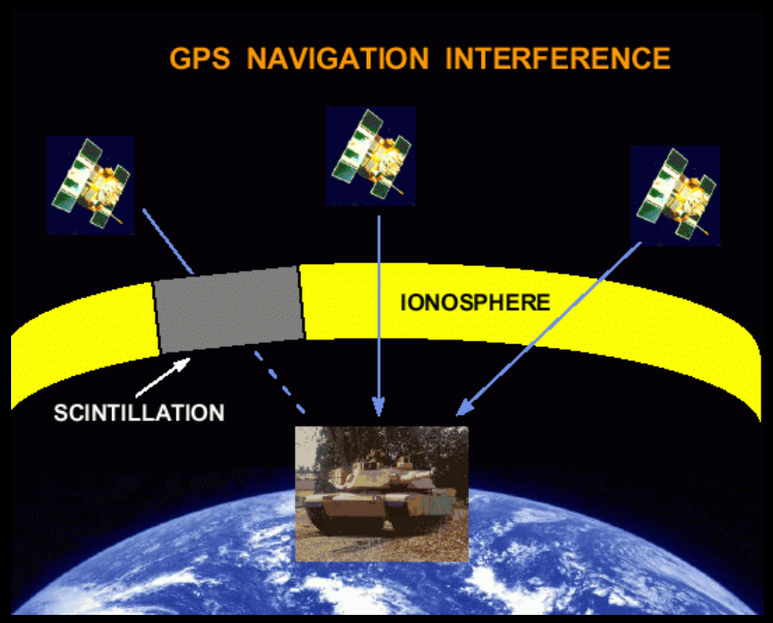
Degradation of LORAN C

- X-rays/Flares - affects the dayside of the Earth (sunlit side)
- Proton showers - affects the dayside of the Earth (sunlit side)
- Geomagnetic storms - day and night + globally

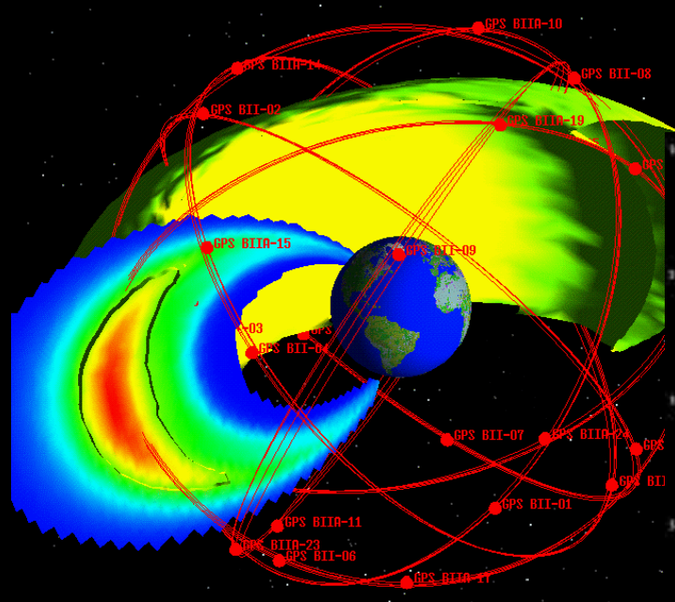
Normal accuracy is about 0.2 km. During solar storms it can be degraded to about 5 km.
Loran C can be useless for several ours in some cases.

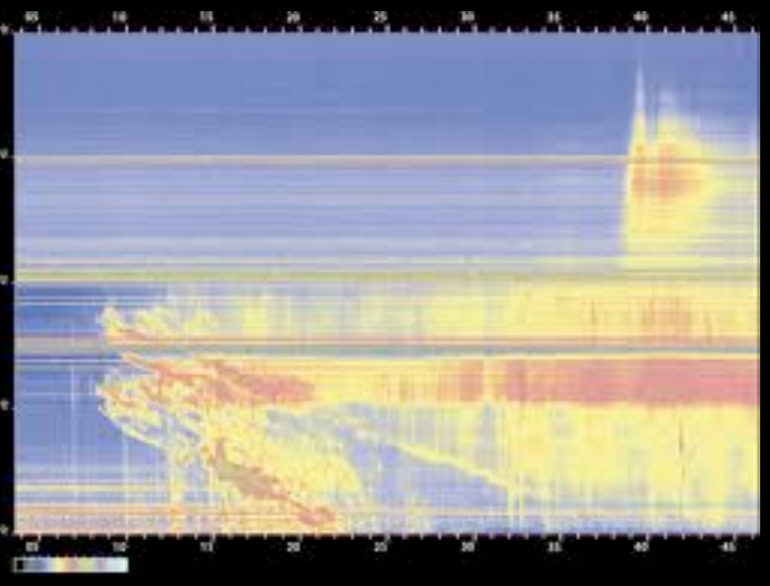


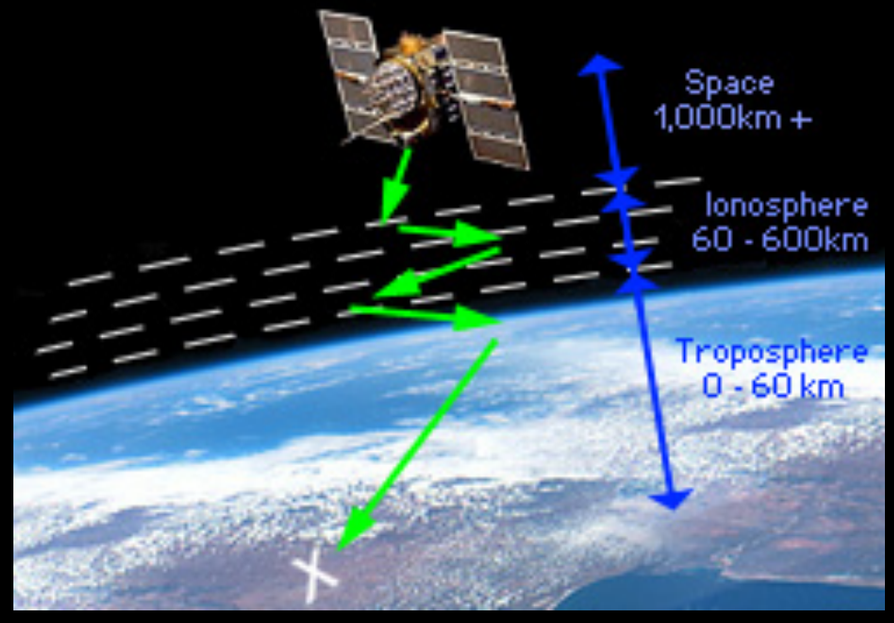
Navigation systems (GPS)



- Turbulence in the ionosphere causes scintillation in the satellite signal and can disrupt the reception.
- Total amount of electrons (TEC) along the path of the signal can introduce errors up to 100 meters.
- Radio bursts can «jam» the signals.

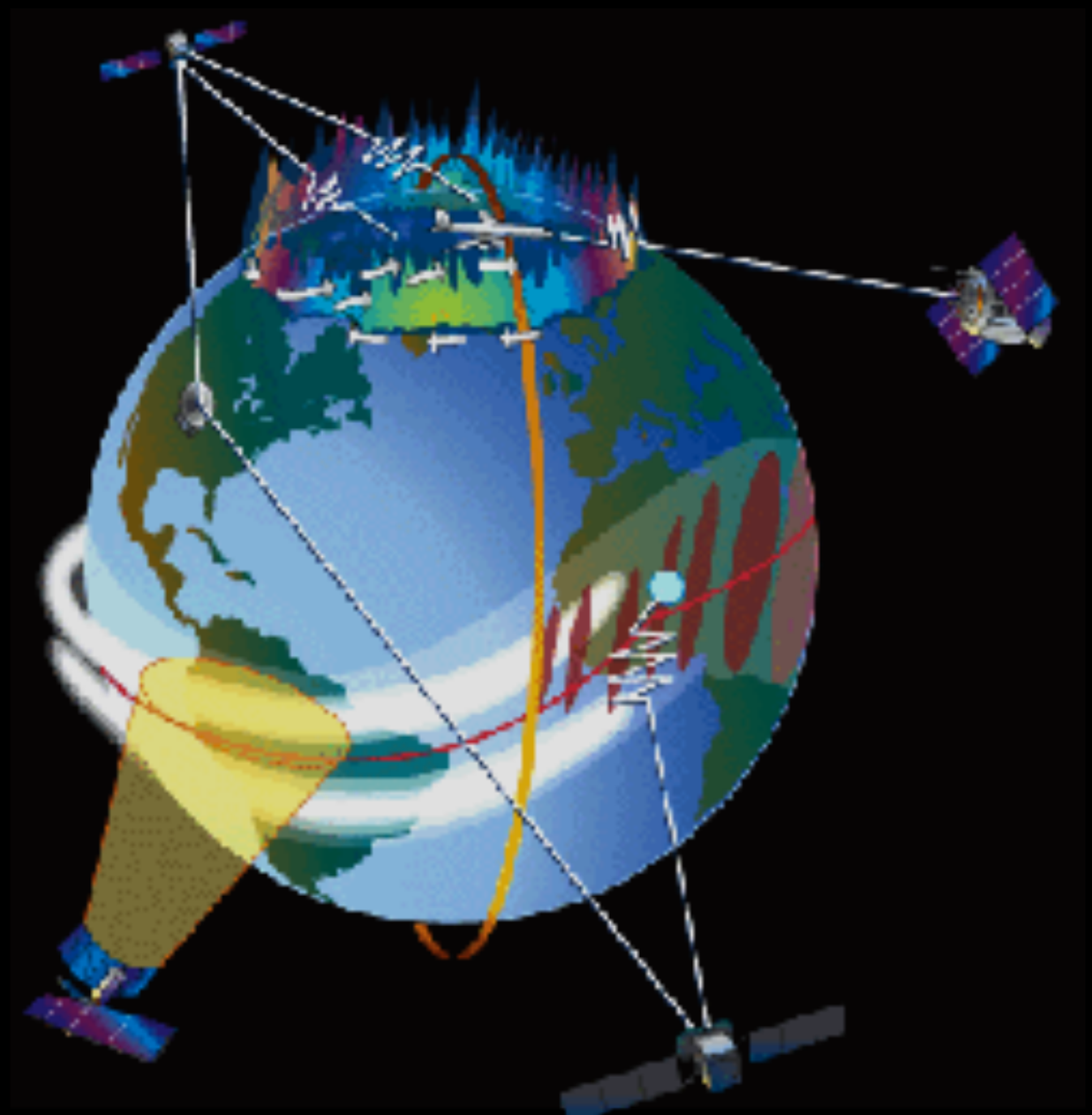






GPS problens in the High North

- Ionospheric disturbances are most severe along the equator and polar regions.



Some don´t care about GPS accuracy

For others it is critical

- Errors in GPS based systems can be a serious problem.

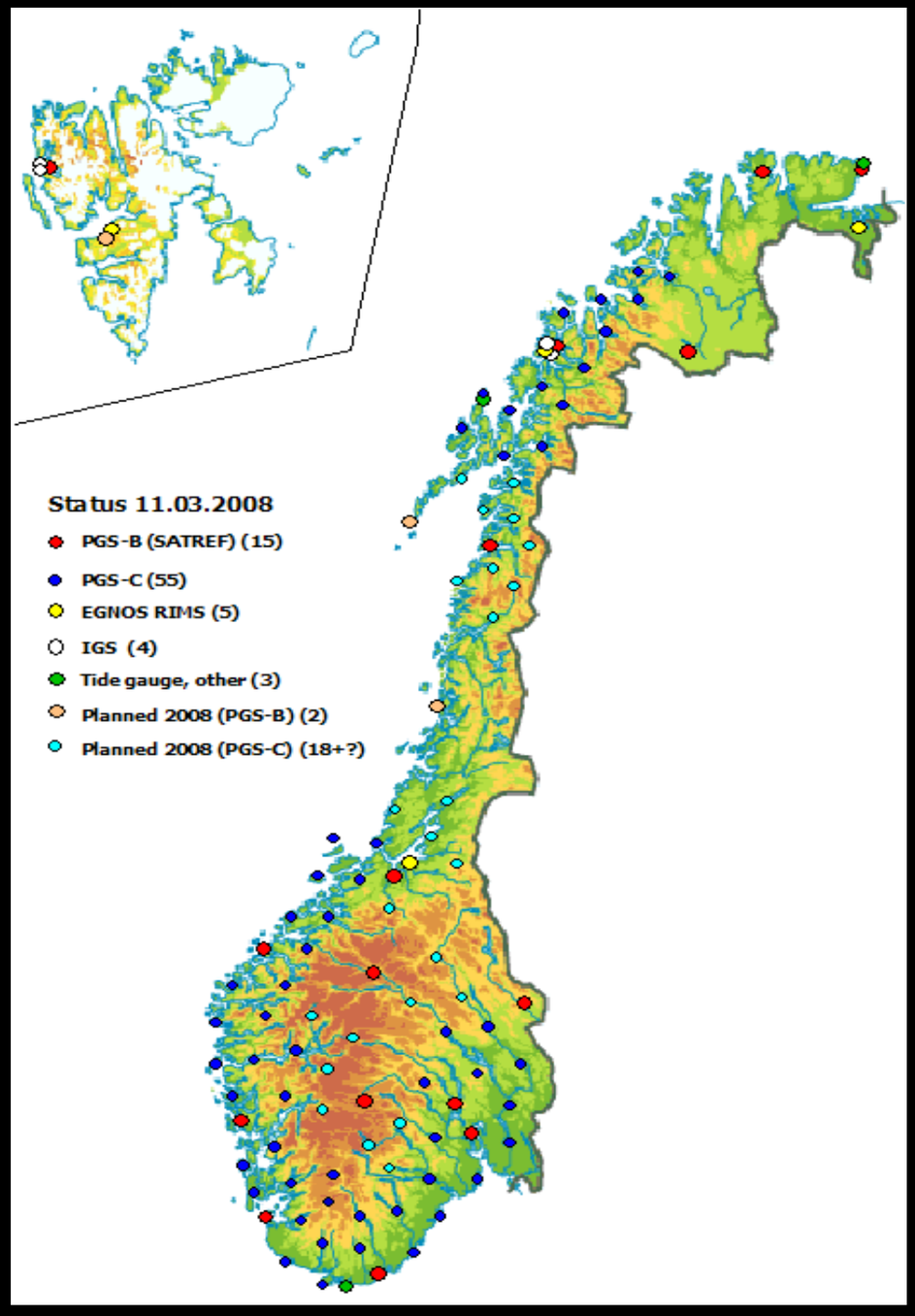
High precision positioning problematic

- Kongsberg Seatex - world leading within dynamical positioning. They experiences often disruption outside the coast of Brasil. This causes interuption of the operation.

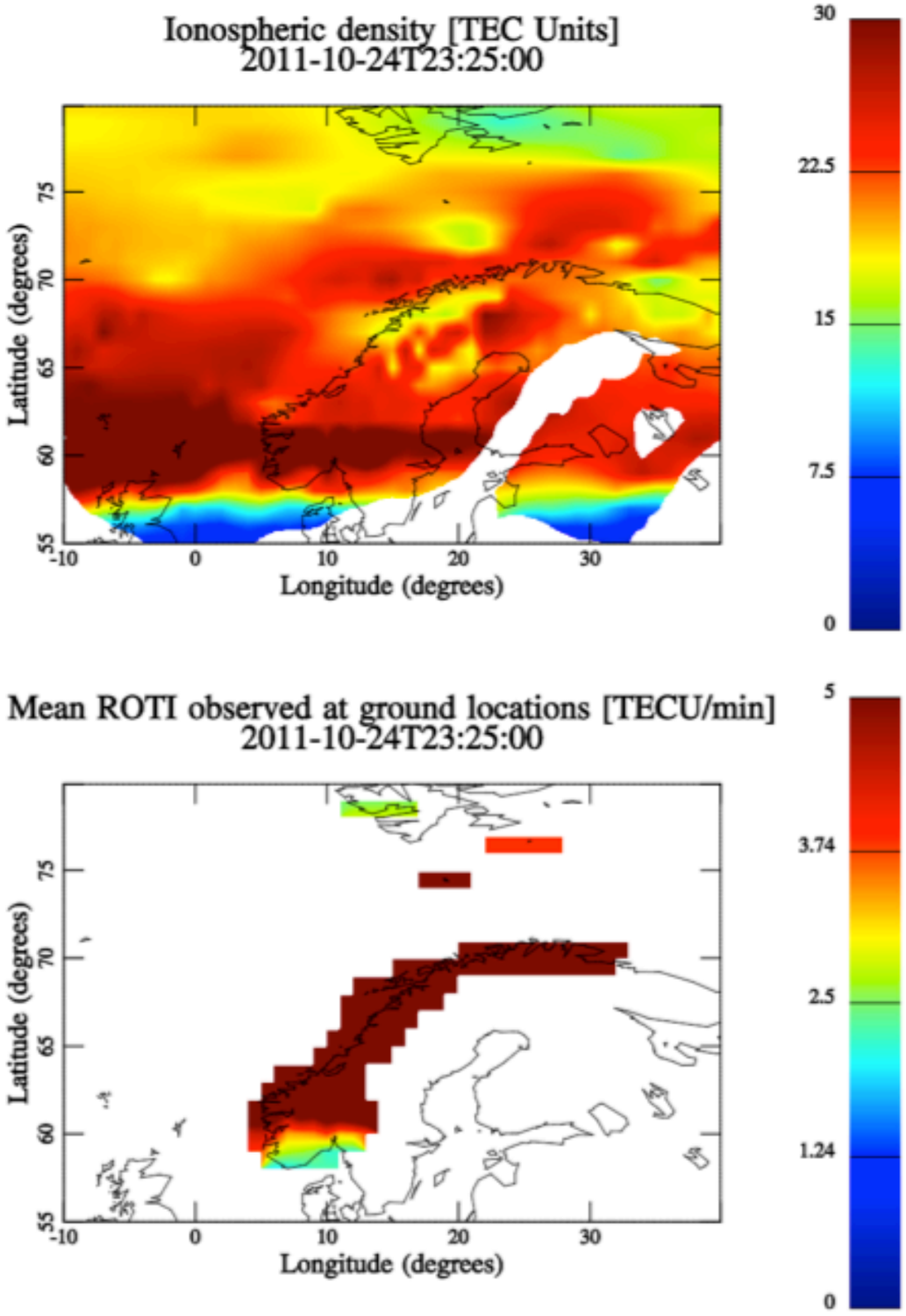
Corrections of GPS positions

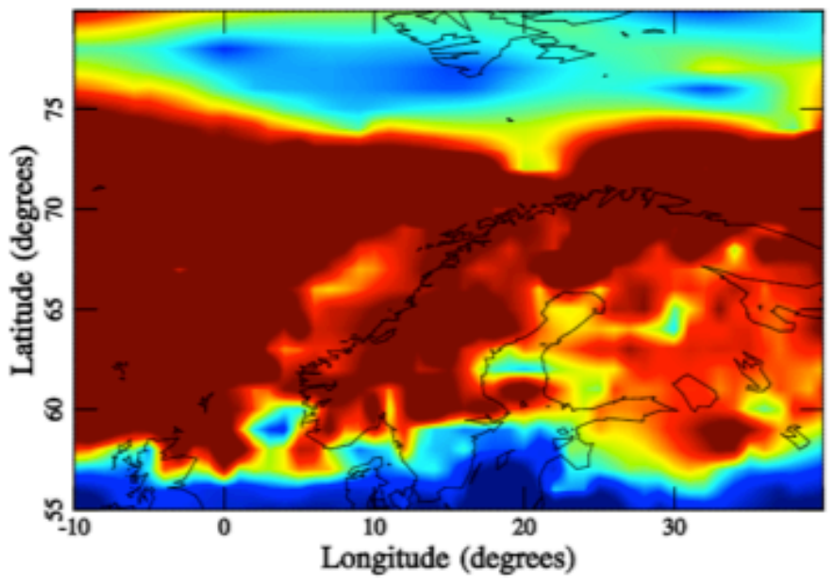
- In Norway the Norwegian Mapping Authority has the national responibility for providing corrections to GPS users.
- They monitor the Sun and have developed an ionospheric modeld that improve these corrections and warn their customers.

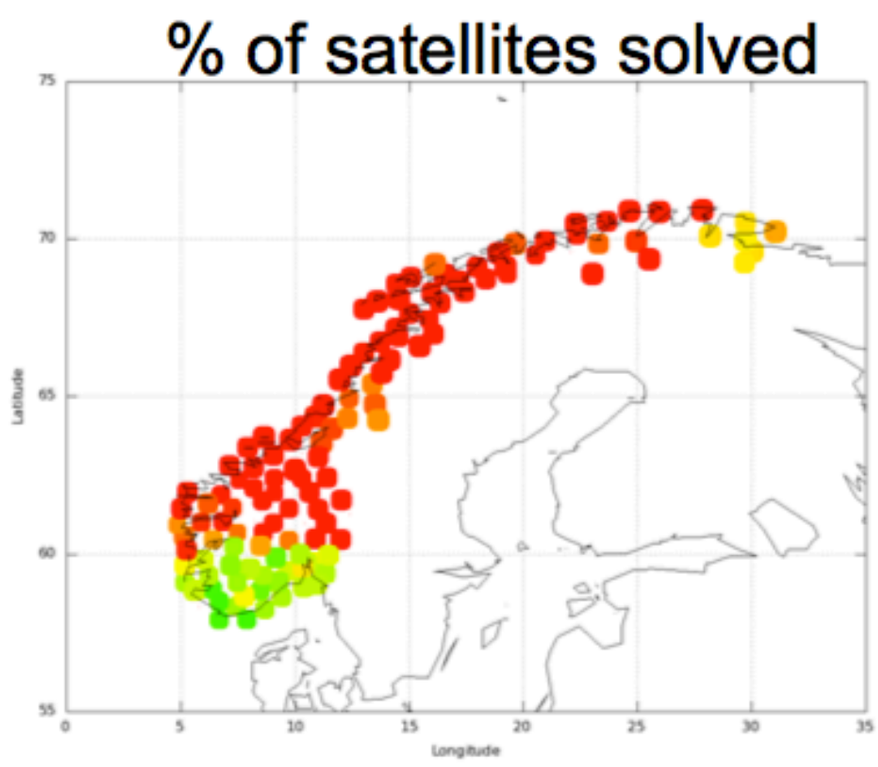
SATREF Control Centre



Recent solar storm - affected GPS

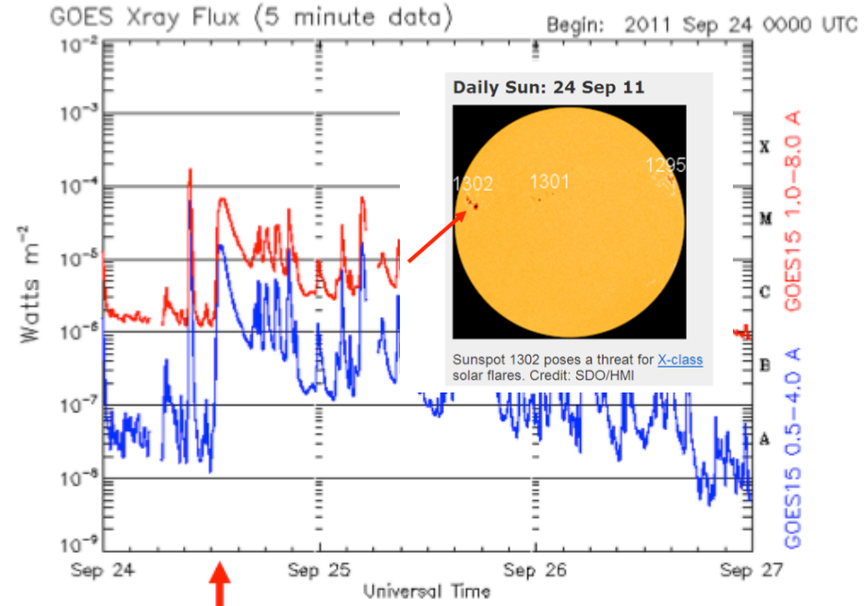


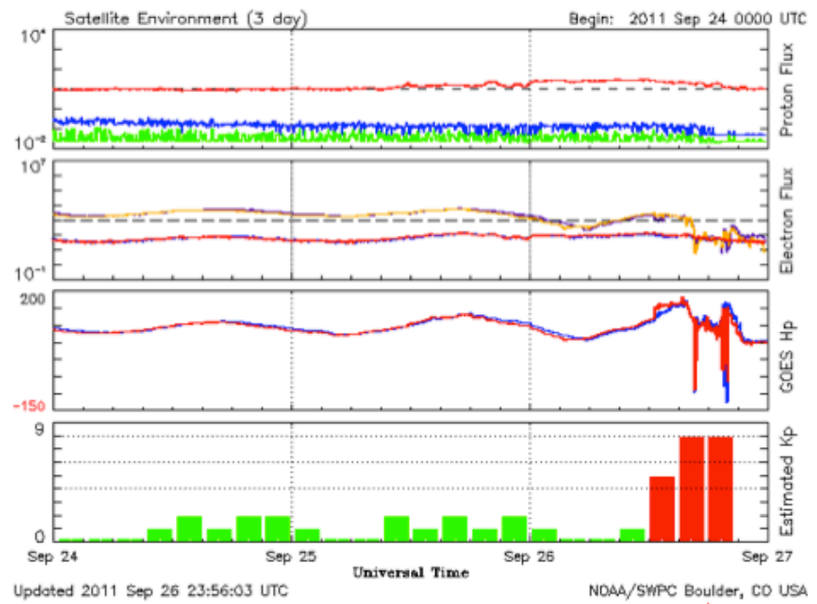




Radioburst «jammed» the GPS system

- 24 September 2011 - a radioburst affected the GPS network on the day-side of Earth.





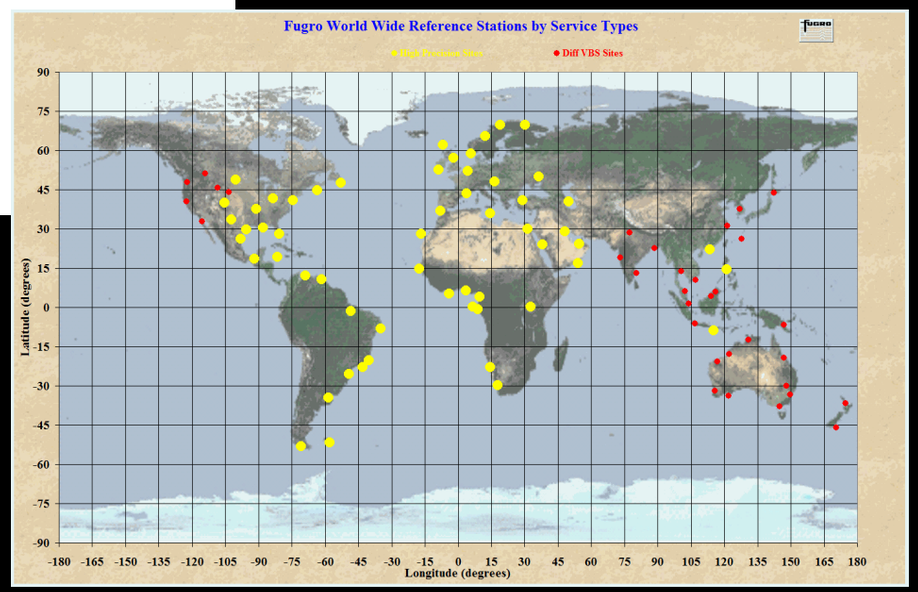
X-Ray burst

Energetic Events

Date	Time Begin	Time Max	Time Half Max	X-ray Class	X-ray Integ Flux	Optical Information Imp/ Brtns	Optical Information Location Lat CMD	Rgn #	Peak Radio Flux 245	Peak Radio Flux 2695	Sweep Freq Intensity II	Sweep Freq Intensity IV
21 Sep	1204	1223	1245	M1.8	0.034			1302				
22 Sep	0953	1000	1009	M1.1	0.008			1302				
22 Sep	1029	1101	1144	X1.4	0.450			1302		970	2	
23 Sep	0147	0159	0210	M1.6	0.016	1N	N25W63	1295				
23 Sep	2154	2215	2234	M1.6	0.030	SF	N23W73	1295	190	210		
23 Sep	2348	2356	0004	M1.9	0.013	SF	N11E52	1302	170	220	3	
24 Sep	0921	0940	0948	X1.9	0.110	2B	N12E60	1302	33000	660	2	3
24 Sep	1233	1320	1410	M7.1	0.290			1302	4800	12000		
24 Sep	1719	1725	1731	M3.1	0.016			1302				

X-Ray burst

Two days later the solar wind from the same flare reaches earth

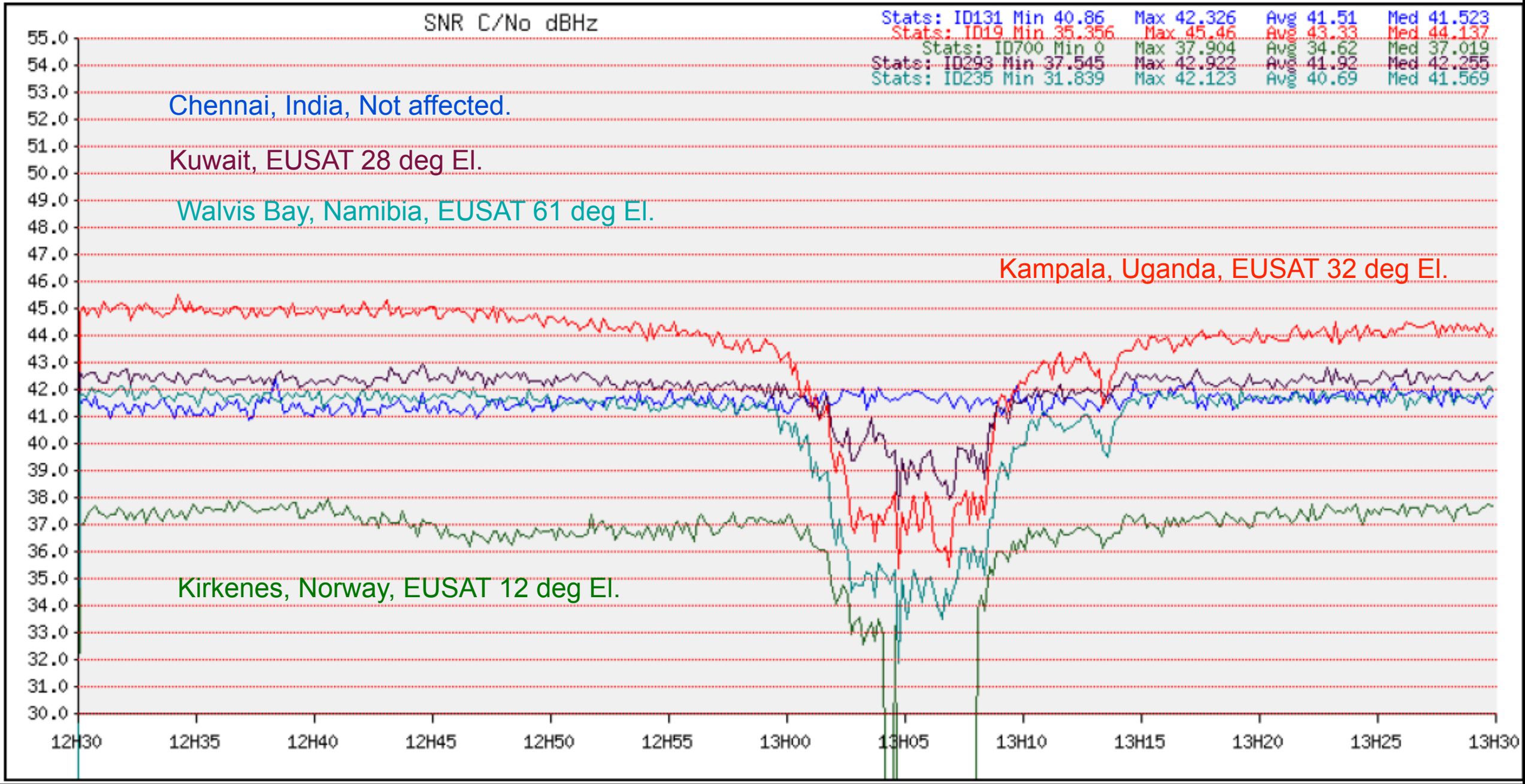


Fugro L-Band tracking EAME 24 Sept

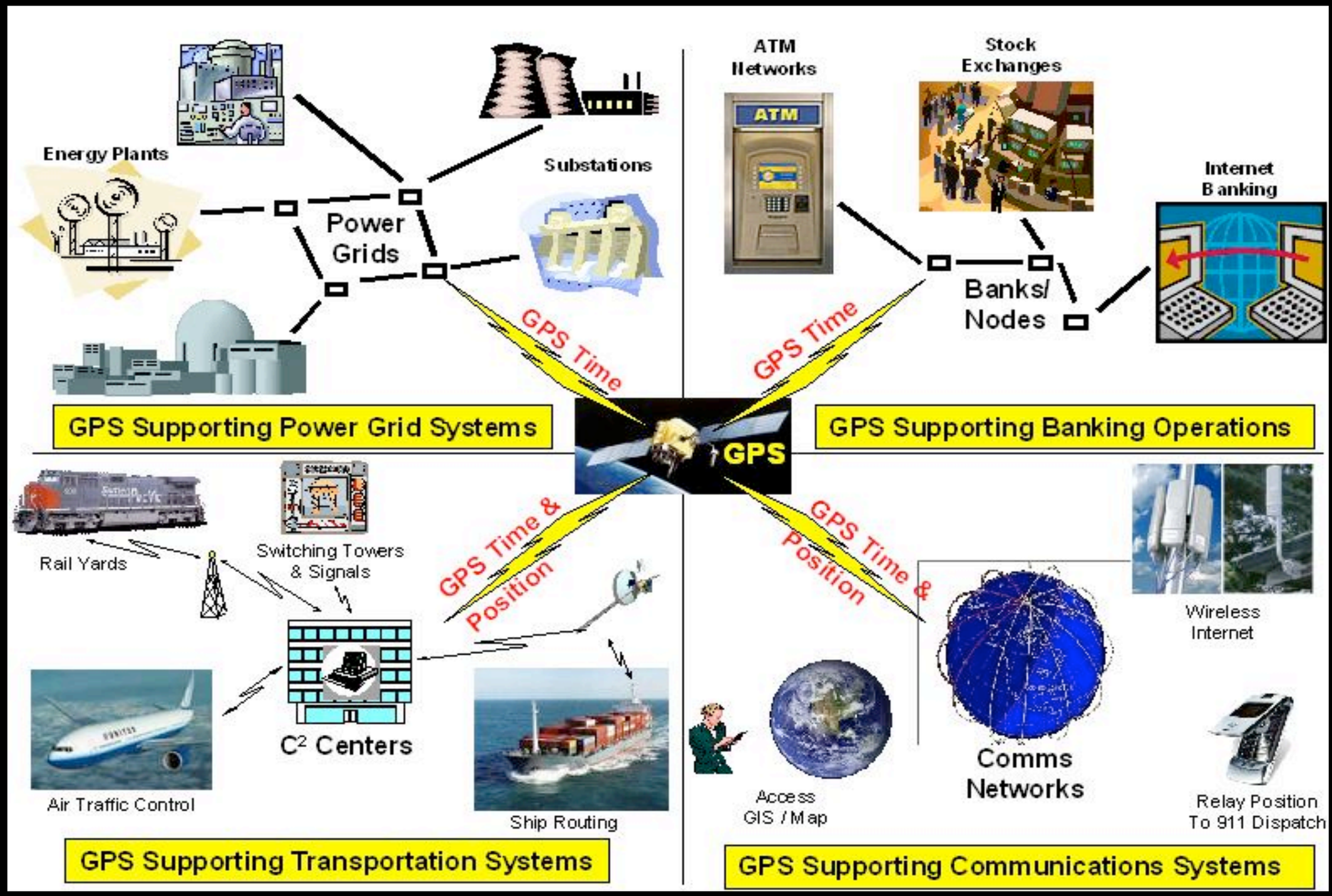
www.fugro.no

Reference Stations 131-Chennai (APSAT)
19-Kampala (EUSAT) 700-Kirkenes (EUSAT) 293-Kuwait (EUSAT)
235-Walvis Bay (EUSAT)

From 2011-09-24 12:30:00 to 2011-09-24 13:30:00

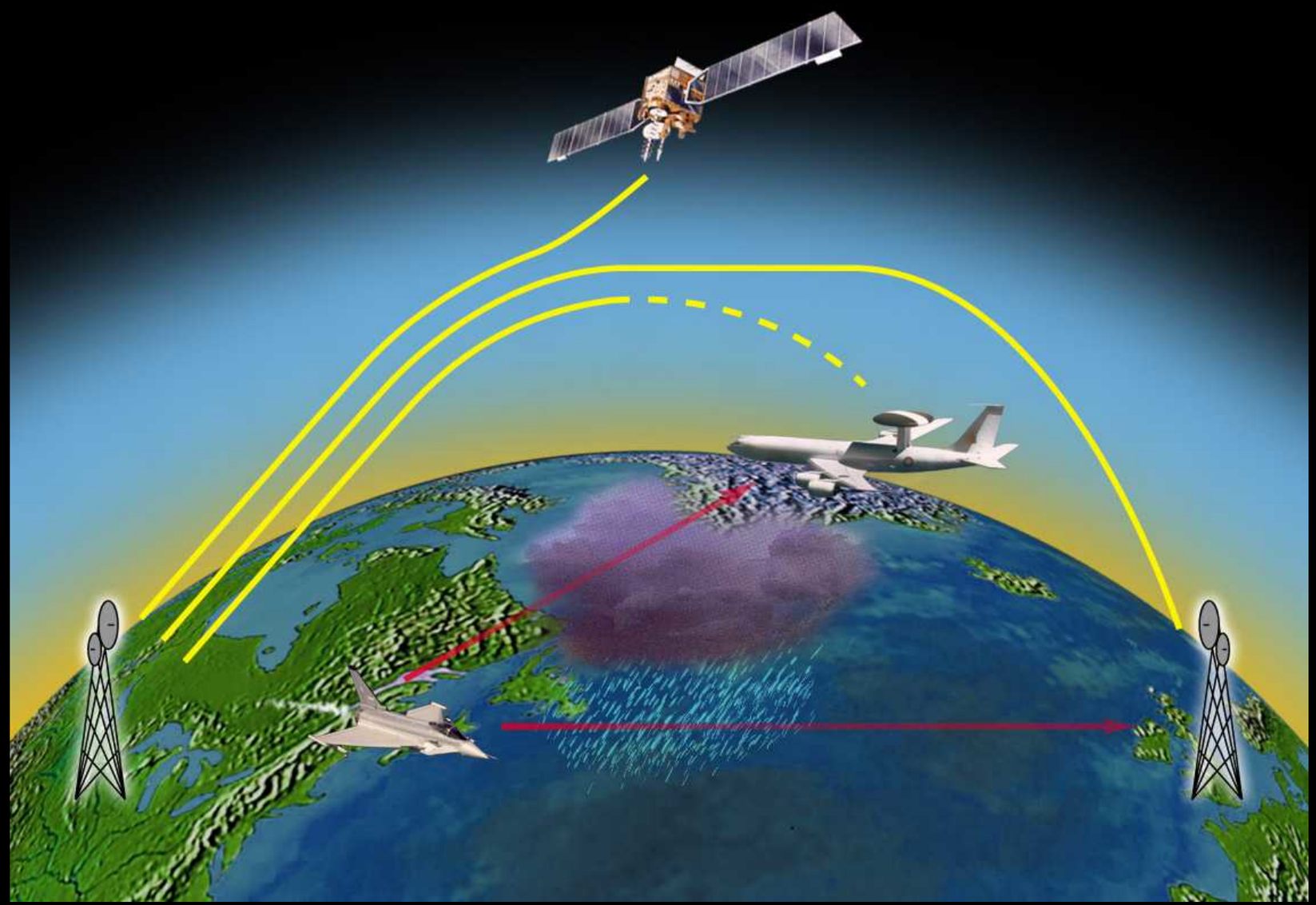


Extent of GPS Dependencies

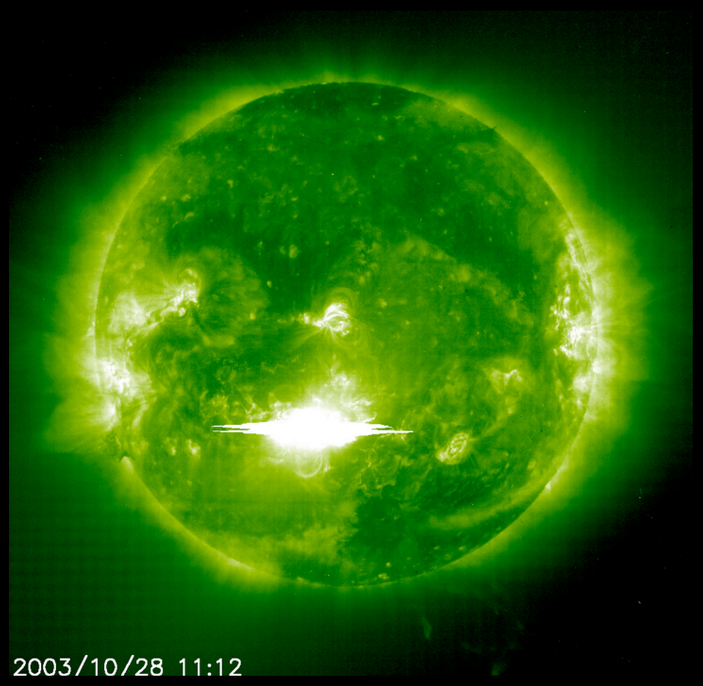


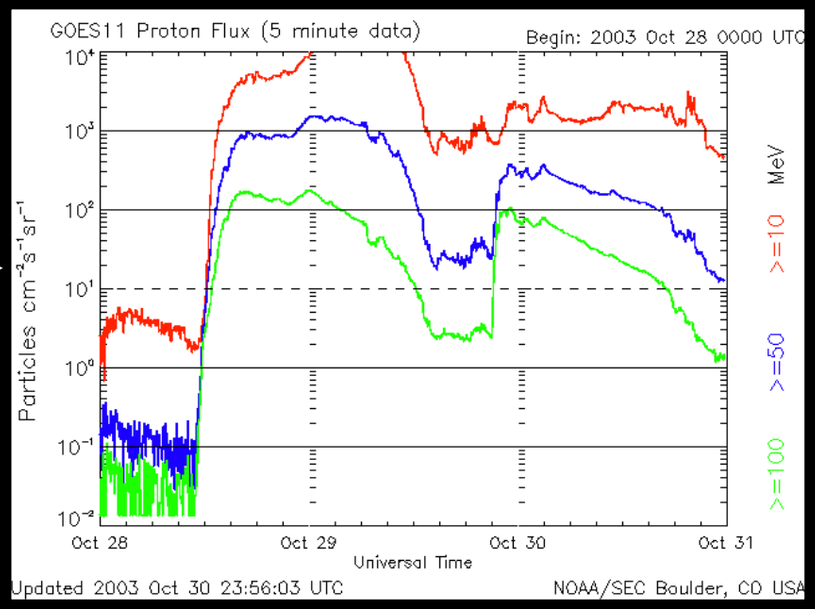
K. VanDyke, DOT

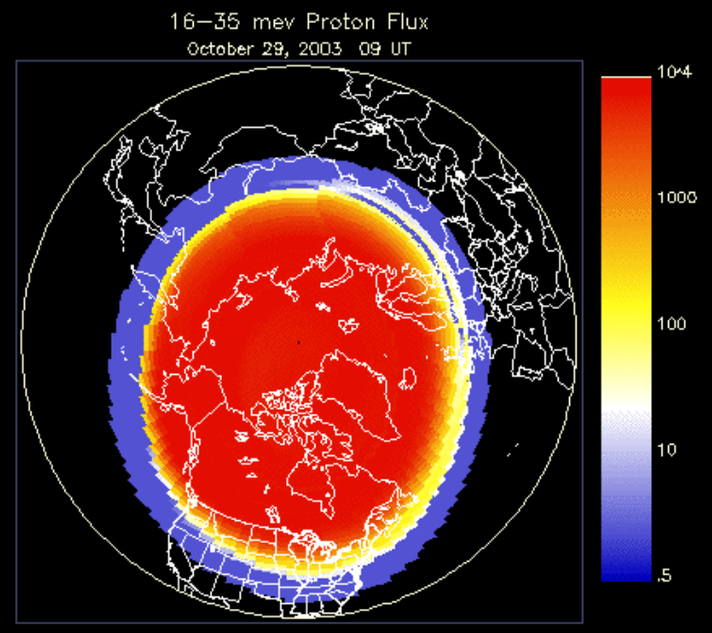
Radiocommunication i polar regions difficult



Radiation Storms = degraded comm







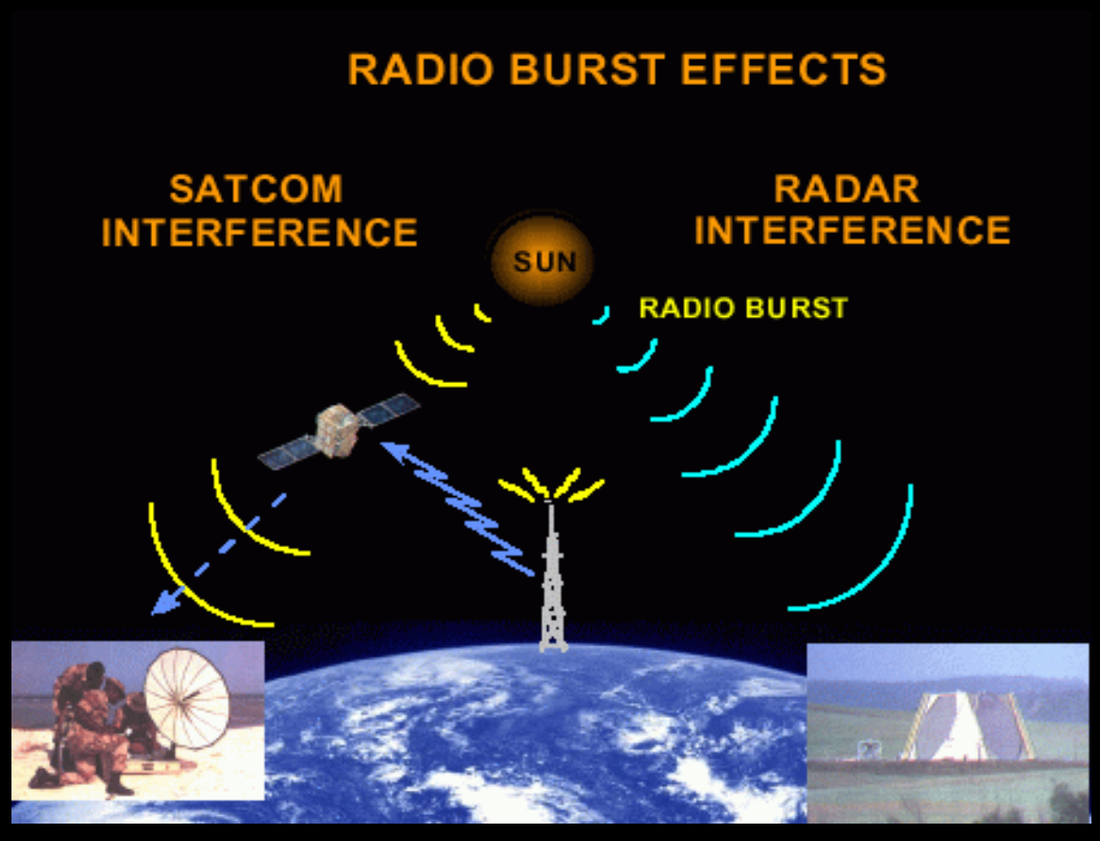
Radiation storms cause extended periods (hours to days) of HF communication blackout at higher latitudes

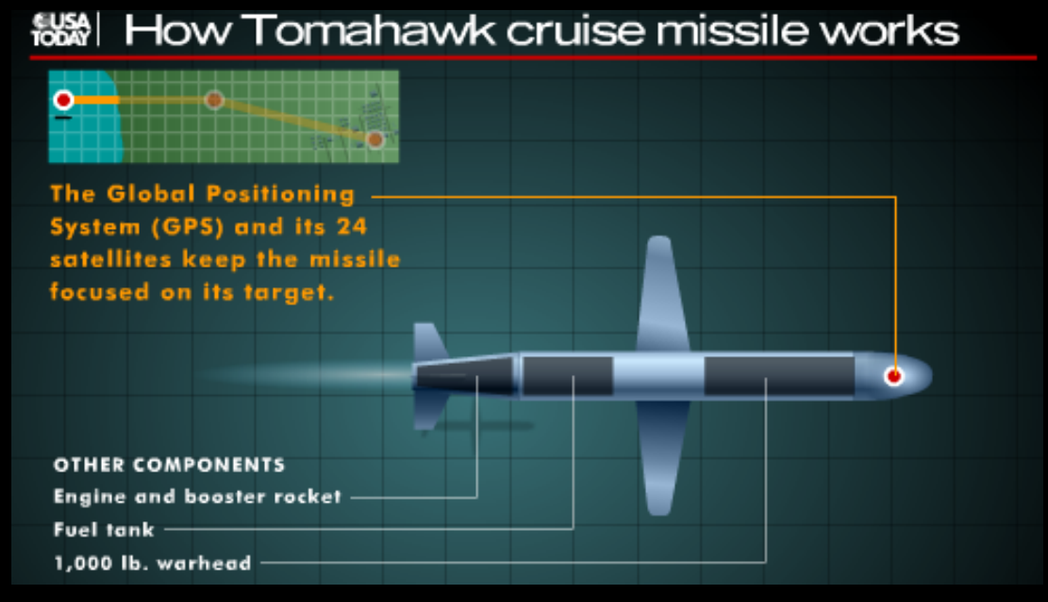
Conditions are usually worse on daylight side

A geomagnetic storm occurring at the same time as a radiation storm can increase the hazard at lower latitudes

Effects on military systems

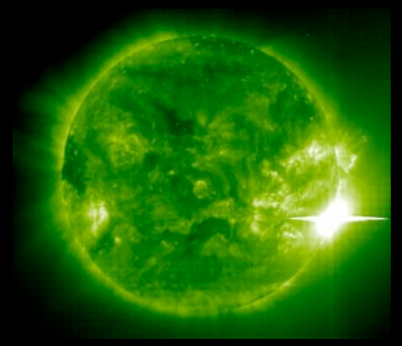
- HF satelite communication (SATCOM) can be disrupted for several hours during strong flares.
- Some weapon systems use GPS for navigation.
- Military satellite systems
- Early warning systems
- Search and rescue





Effects on cell-phones

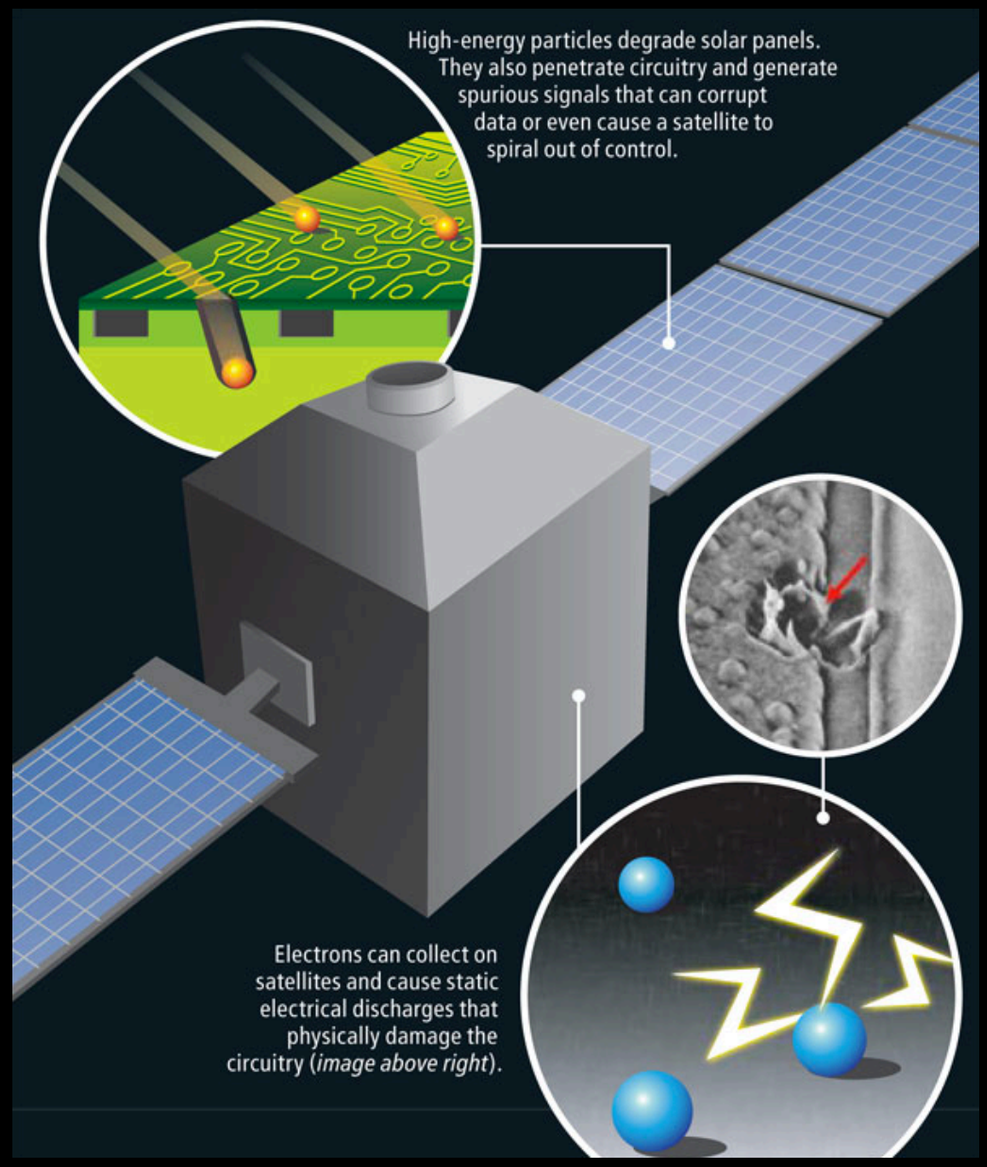
- Radioburst from the Sun can interupt cell phone calls.
  - If your base station is in the direction of the Sun (evening/morning) due to interference.
  - Can lead to “dropped calls”
  - In areas where teh signal is already weak - this can cause more problems.

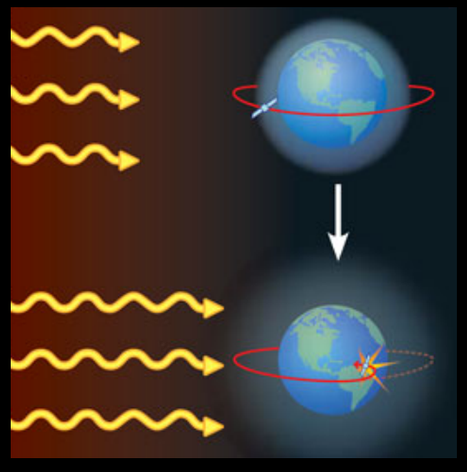


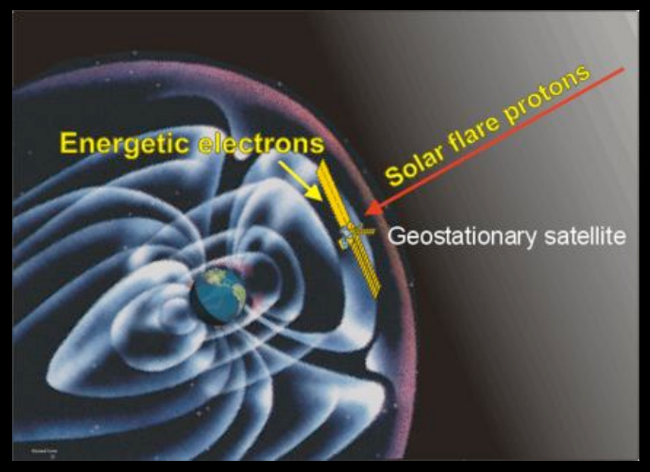
Effects on Satellites

Examples:

- Surface charging
- Single Evente Upset (from high energy particles)
- Increased drag
- Interference and scintillasjon of the signal
- Space debris
- Orientation problems
- Nosie on the star trackers/navigation systems.
- Degradation of material/solar cells
- Hits by micro meteorites



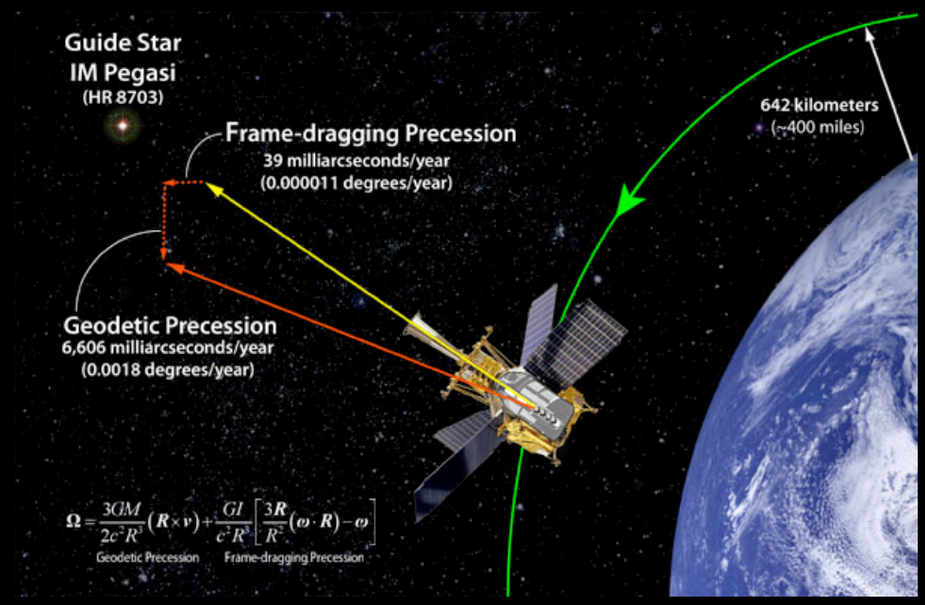


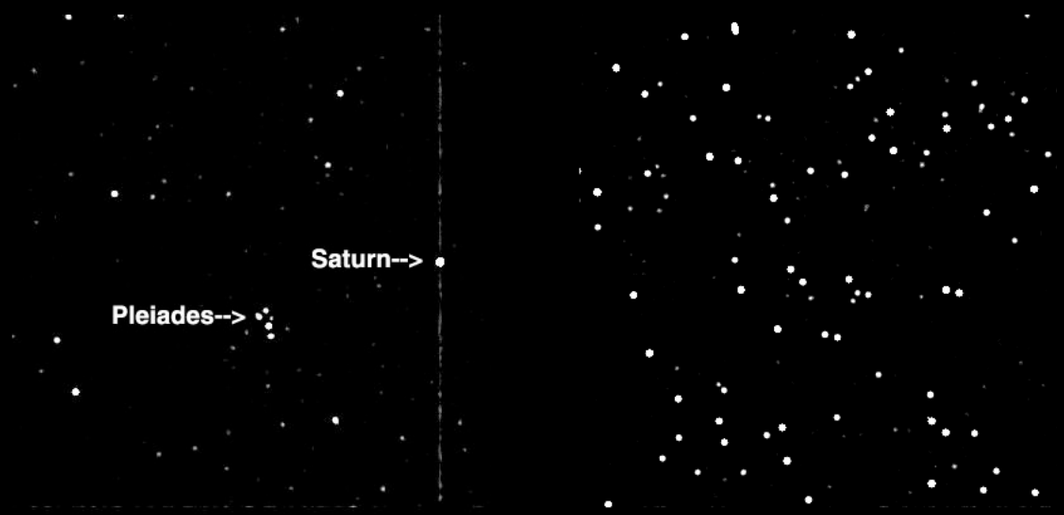


Orientation problems

Some satellites use star trackers to «lock» into stars for navigation, others use the Earths magnetic field.

Star trackers can easily be «tricked» by false stars created by high energy protons hitting the CCD camera.





Før protonskur

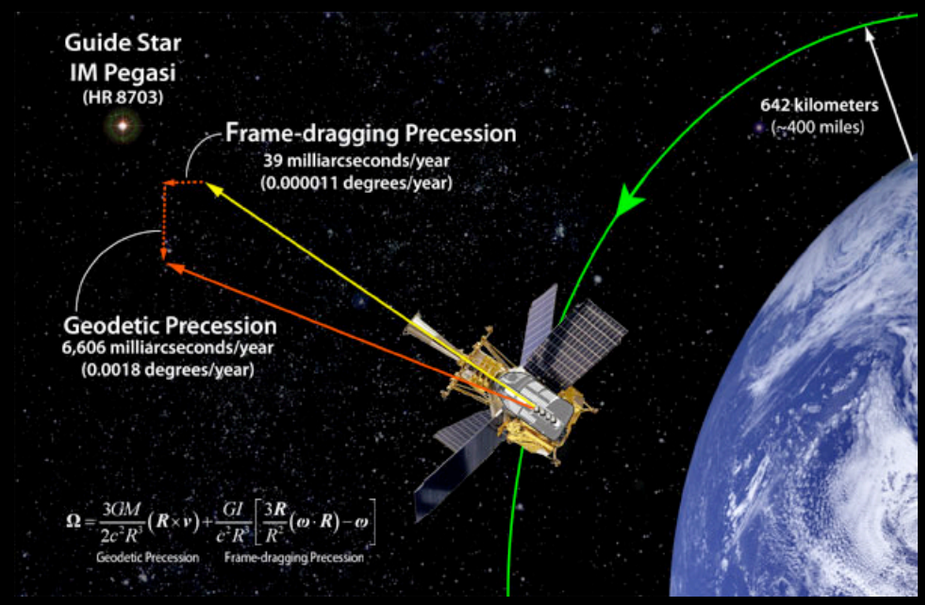
Etter protonskur

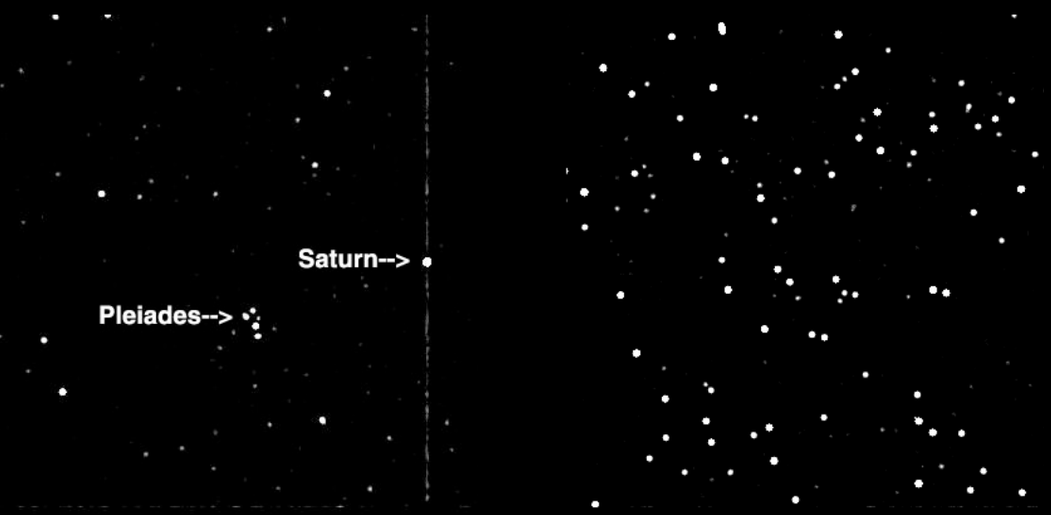
Magnetic navigation can be affected by dynamics in the Earths magnetic field.

Orientation problems

Some satellites use star trackers to «lock» into stars for navigation, others use the Earths magnetic field.

Star trackers can easily be «tricked» by false stars created by high energy protons hitting the CCD camera.

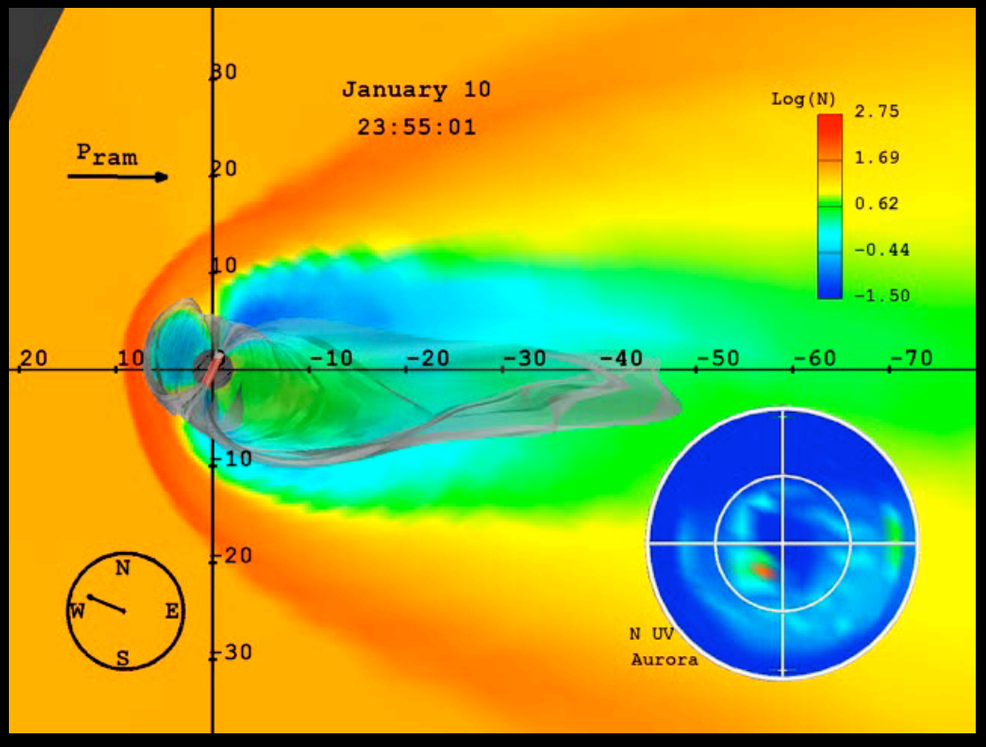




Før protonskur

Etter protonskur

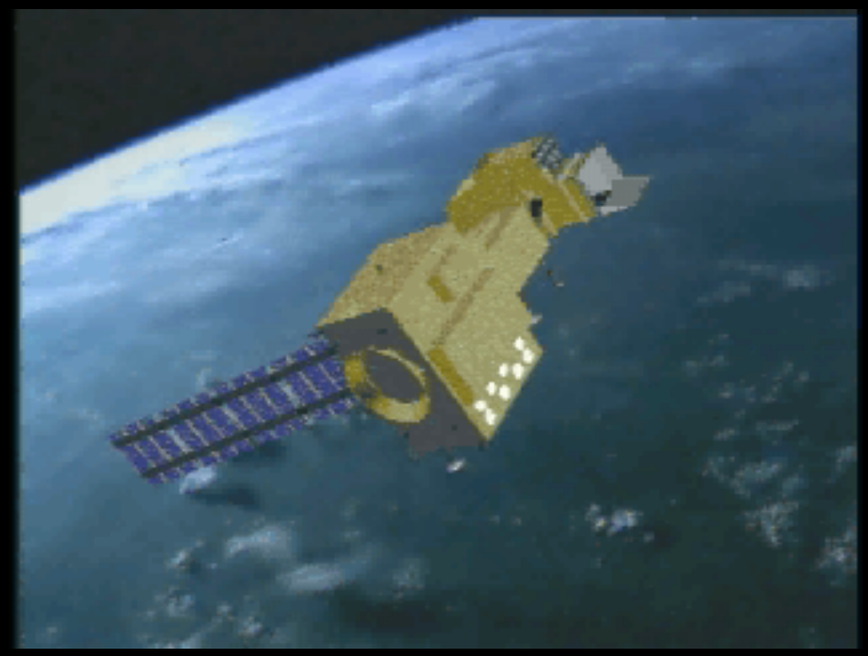
Magnetic navigation can be affected by dynamics in the Earths magnetic field.

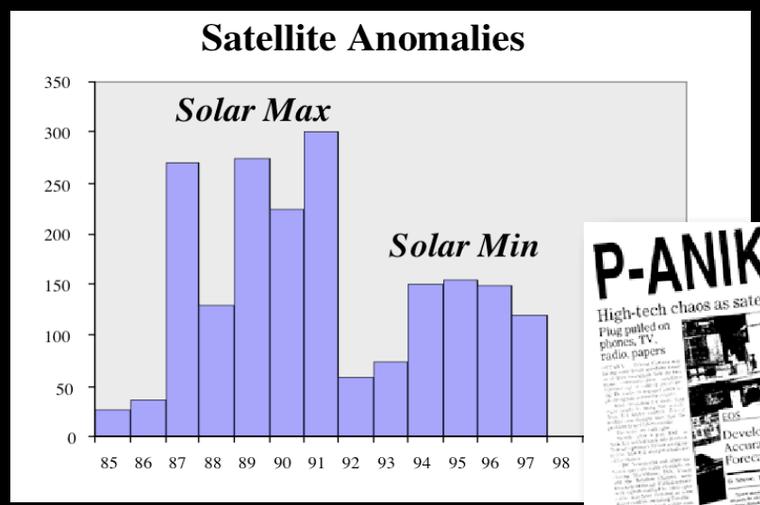


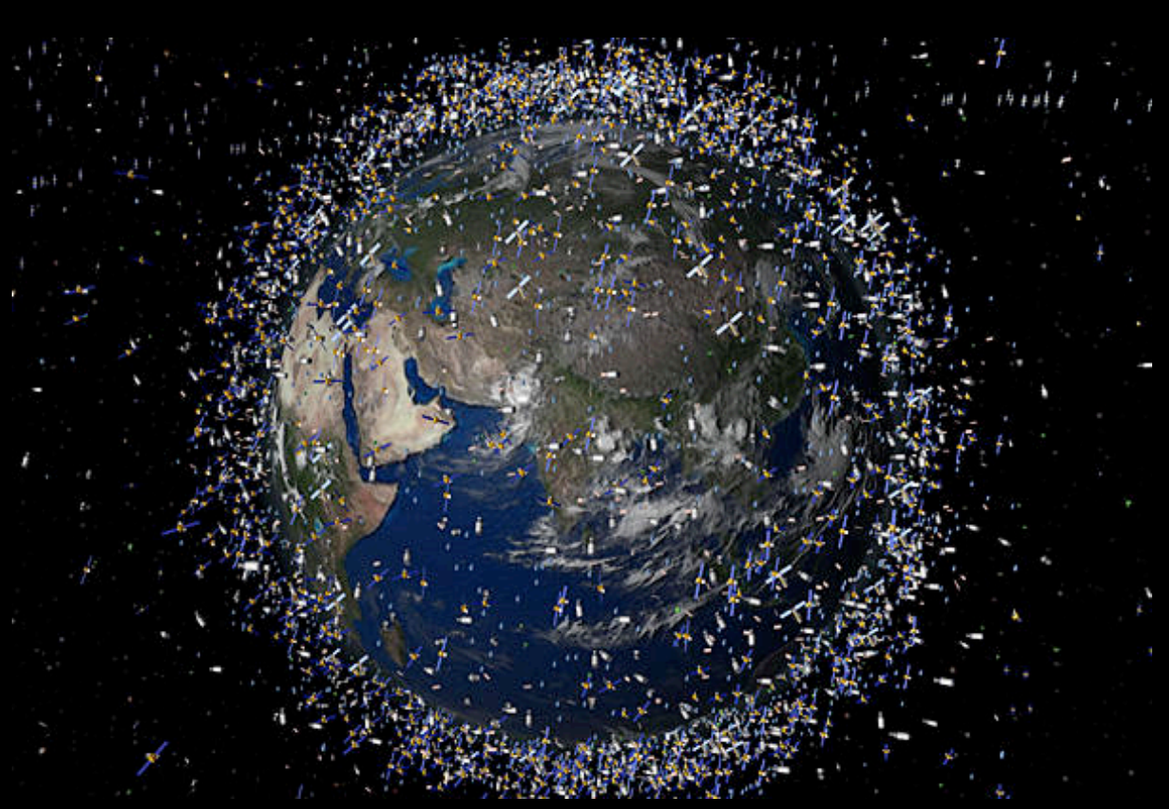
Damage to satellites

Some examples

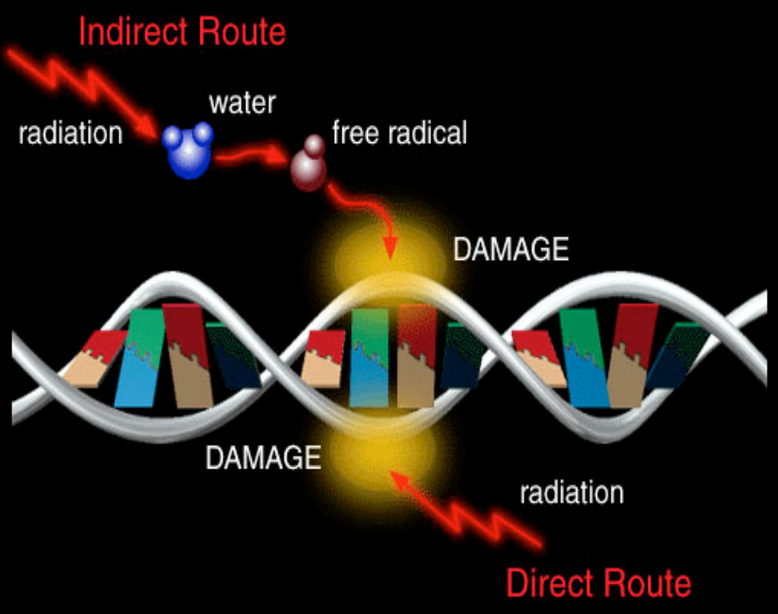
- Telestar 401 (Jan 11 1997)
- Galaxy IV (1998) – cost 250 mill USD
  - 80% of all pagers in USA failed
  - PC-Direct (internet)
  - CBS's radio and TV feeds
  - CNN's Airport Network
- A number of satellites are damaged
- Annual loss can reach $500 millions





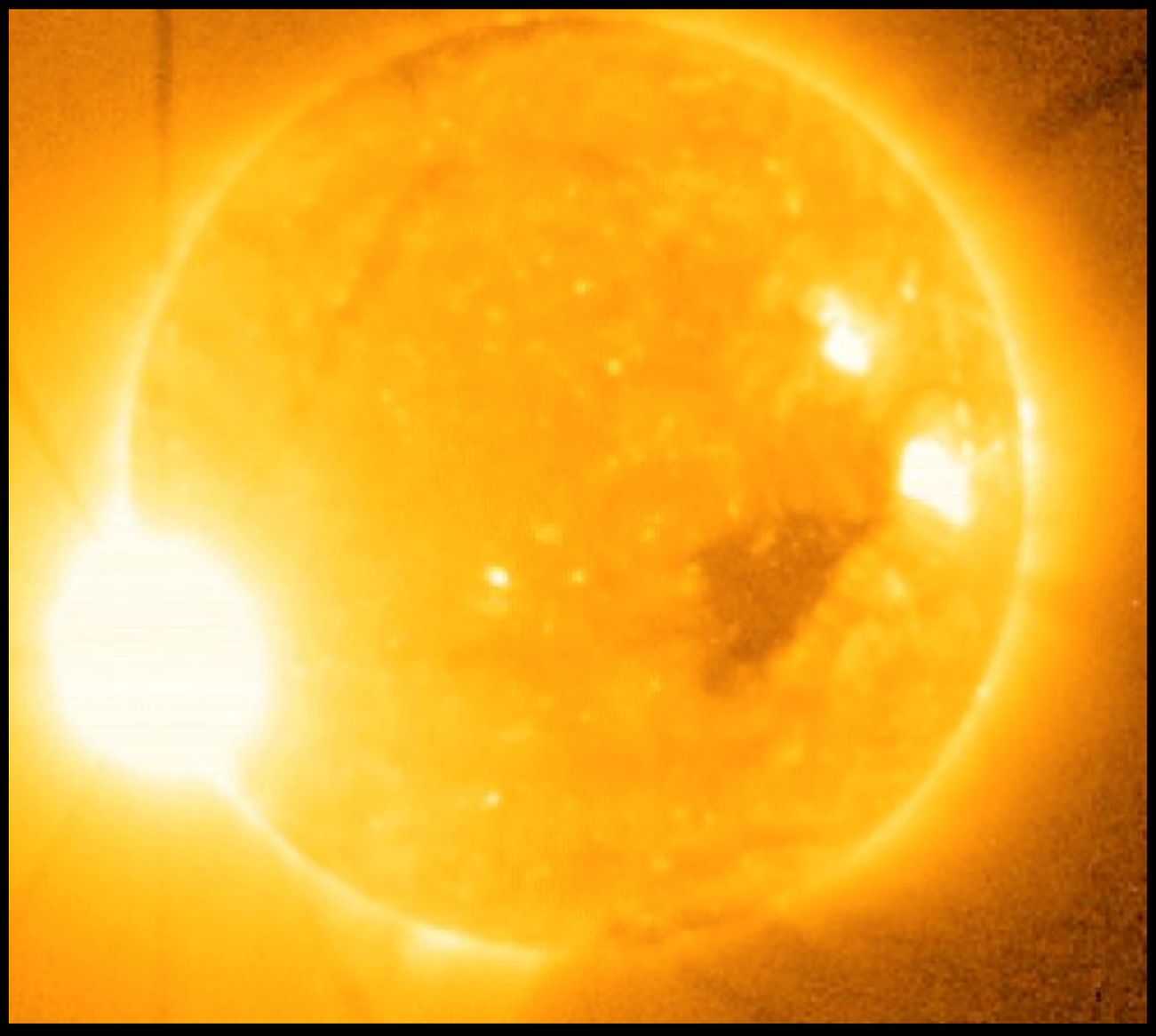


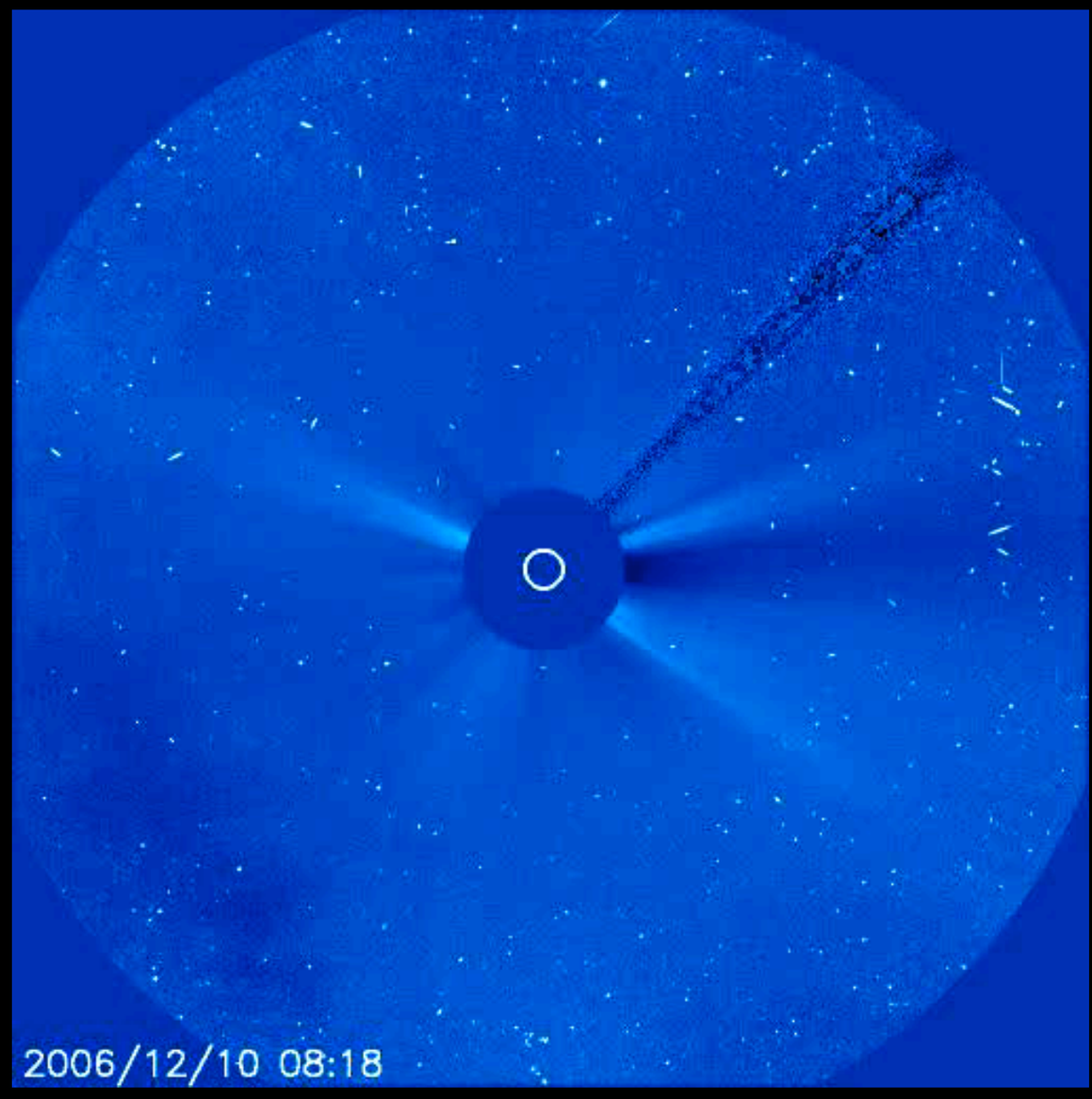
Radiation hazards



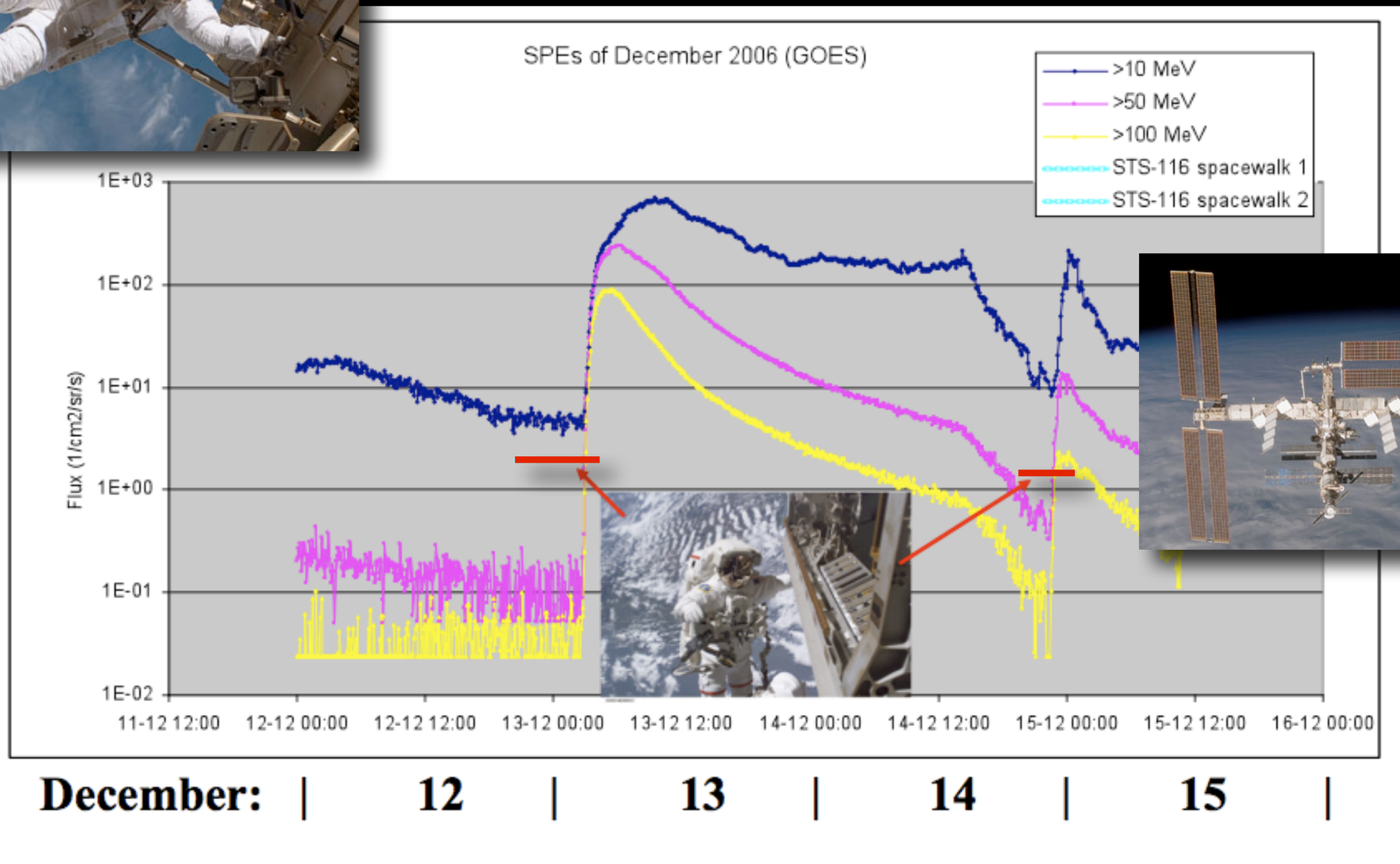
- Humans in space
  - Space Shuttle, International Space Station, missions to the Moon and Mars

Proton shower 14 desember 2006

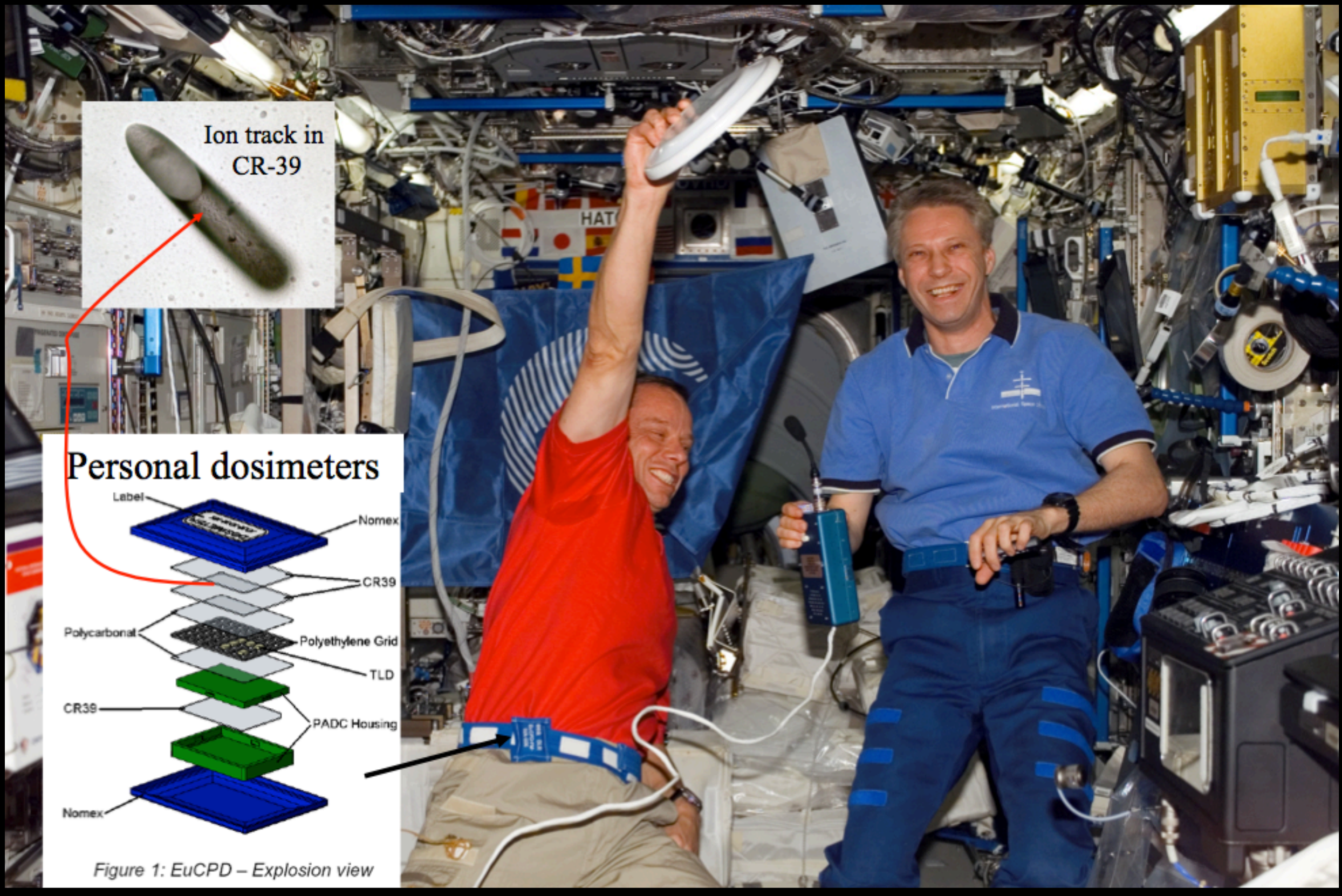




Christer Fuglesang - Proton event

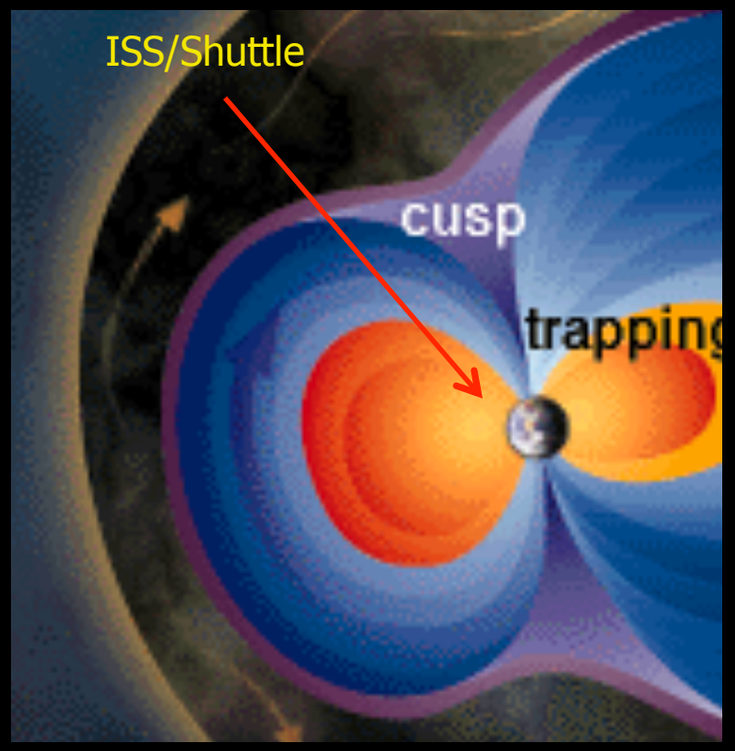


Christer Fuglesang - radiation



The Apollo program - pure luck?

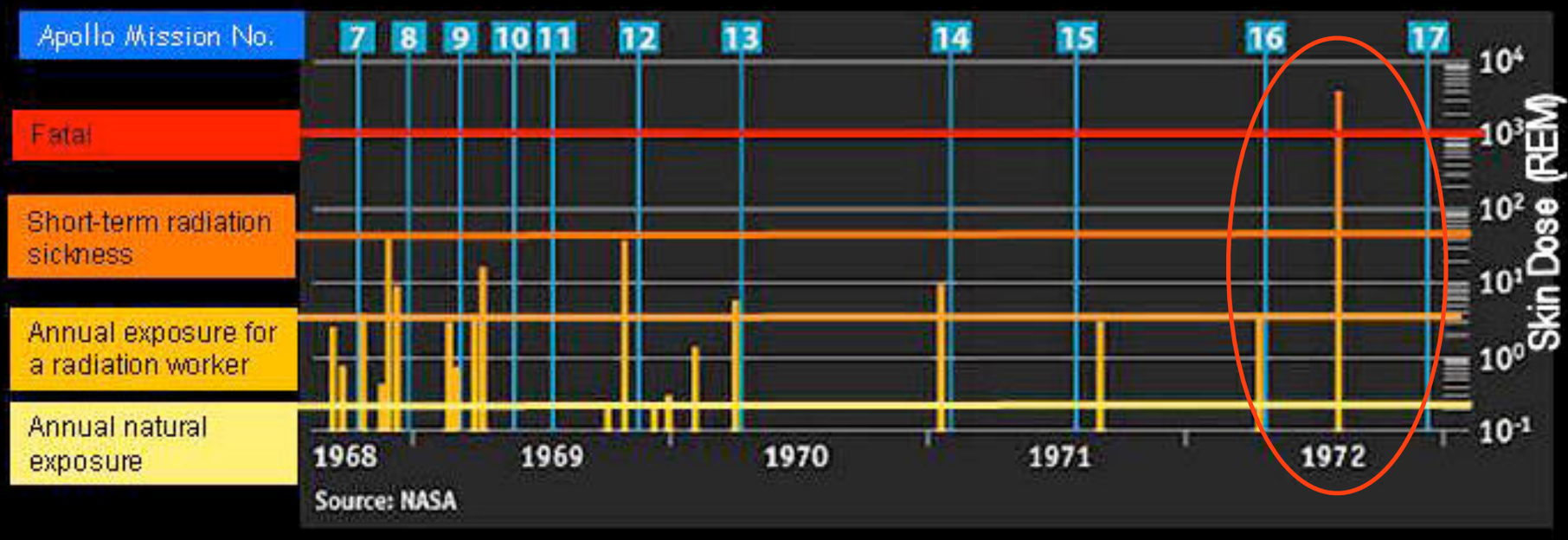
- Humans have limited experience from deep space muíssions. Onlu a few short trips to the Moon with Apollo.
  - ISS og and the space shuttle were protected fairly well by the magnetosphere.

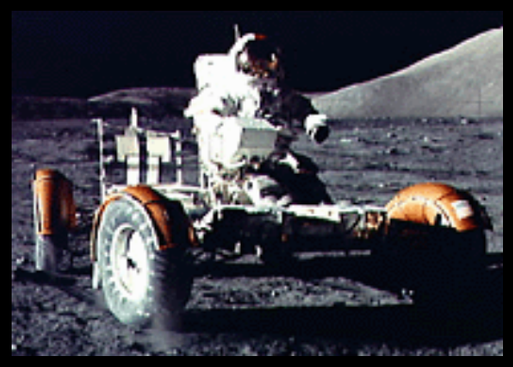


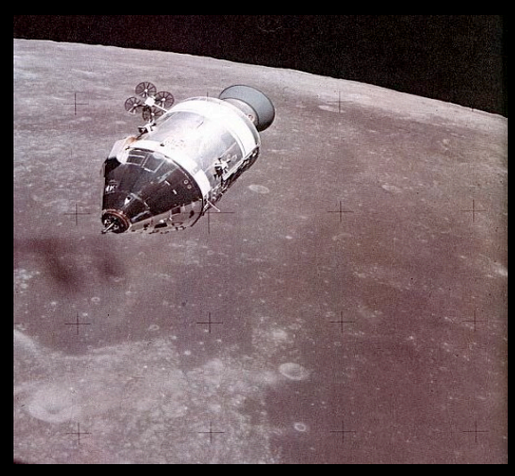
- The Apollo sucess could have been different of the very strong proton shower in August 1972 would have occured during the Apollo 16 or 17. This could have produced a leathal dose for the astronauts.

- The proton showers in october 1989 and in 2003 may have led to a leathal dose on the surface of the Moon.

Proton events during the Apollo program







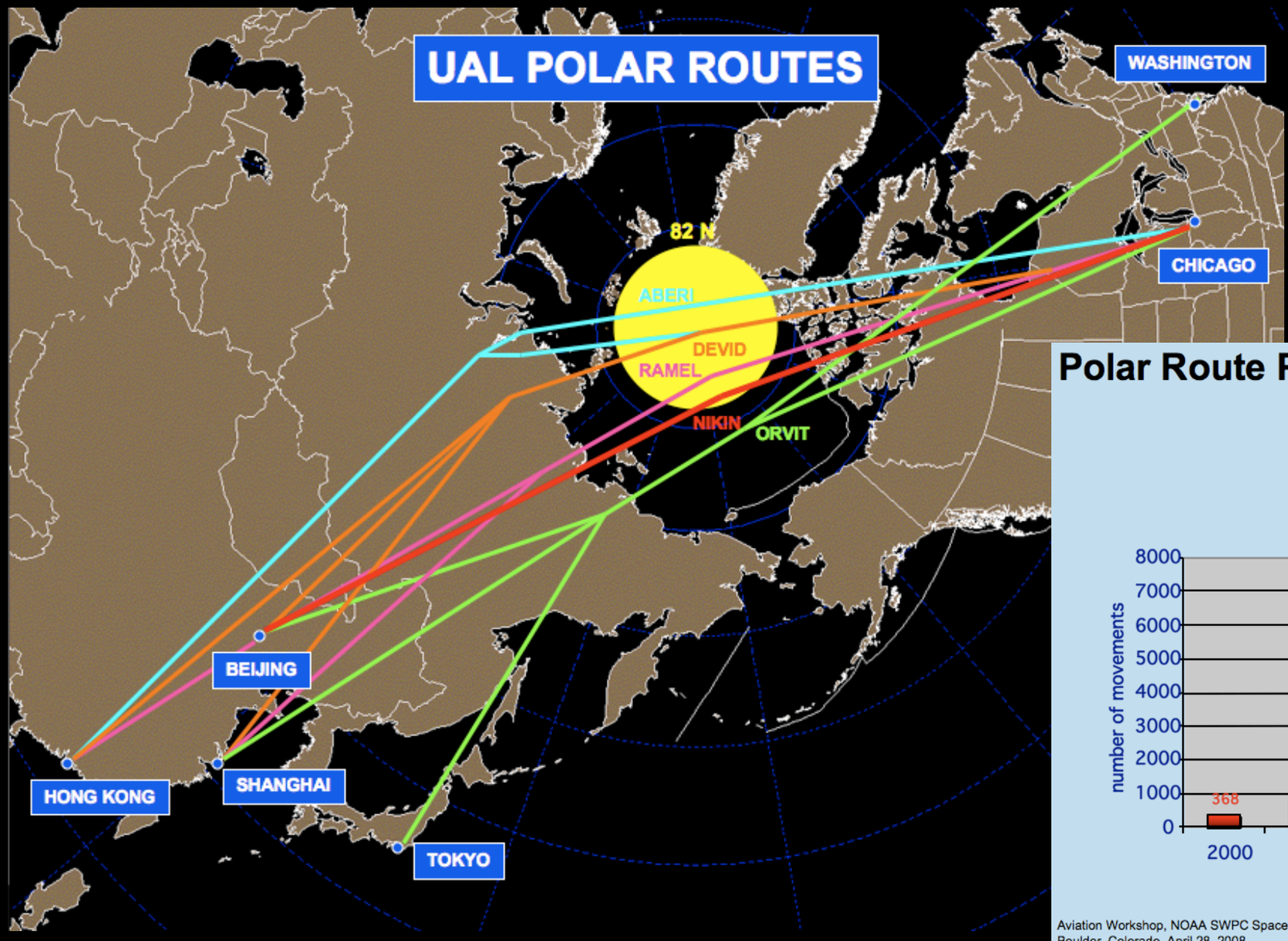
1972 event: 4000 REM in space suit, 1000 REM in Lunar Module

Effects on airplanes

Effects on airplanes

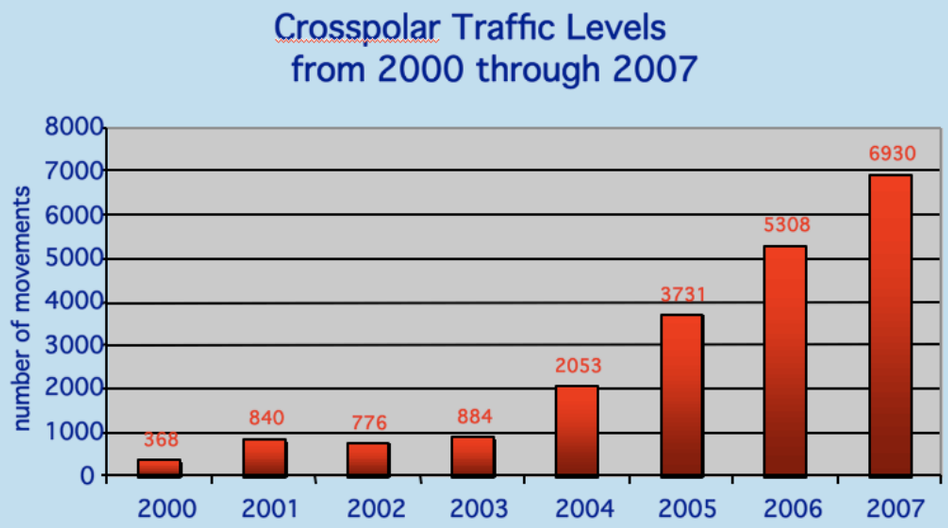
- Disruption of HF communication on polar transatlantic flights
- Energetic particles (affects humans and avionics)
- GPS and navigation
- NextGen, SESAR

Effects on polar routes



M.Stills, United Airlines

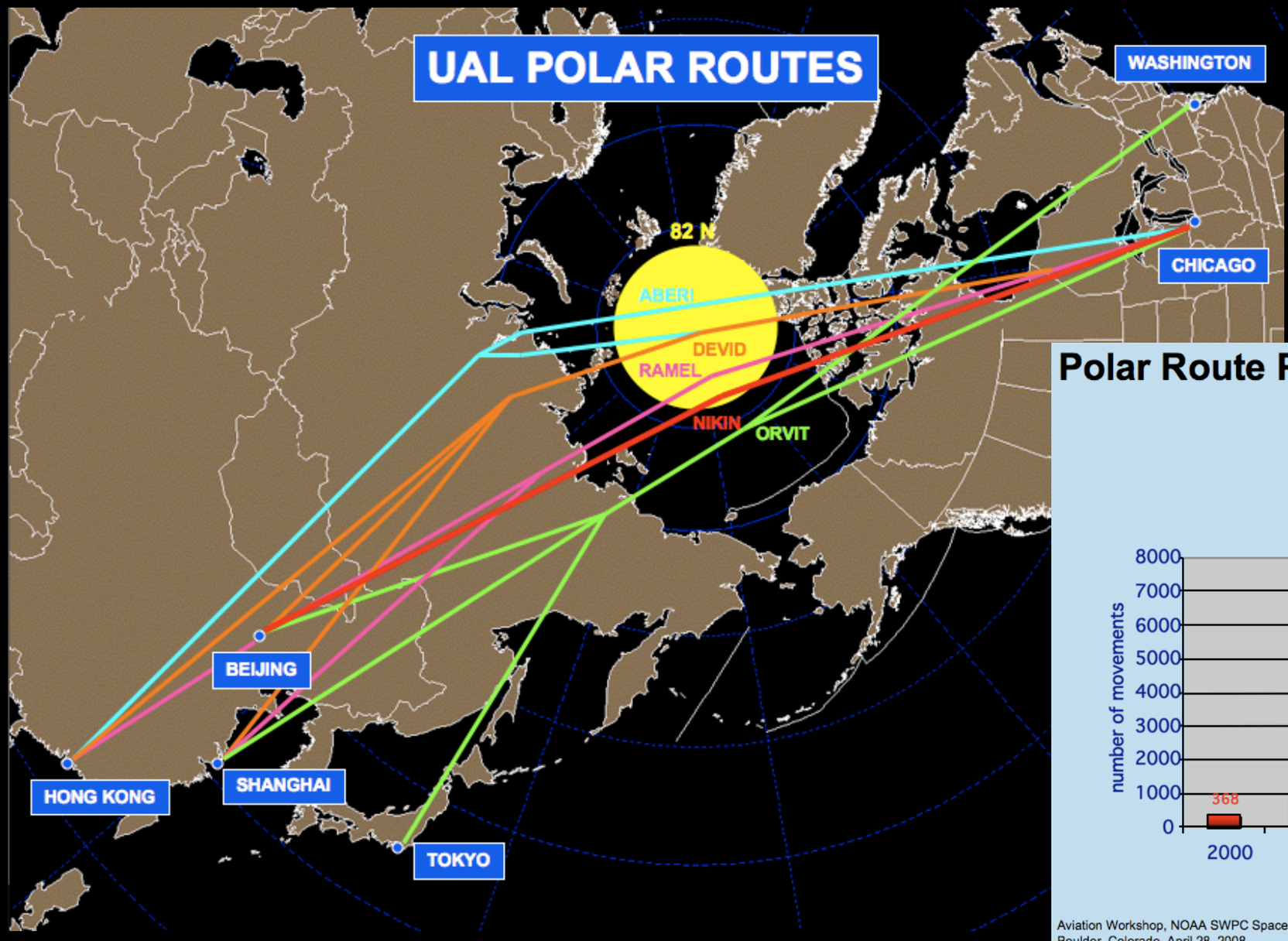
Polar Route Popularity – Some Statistics



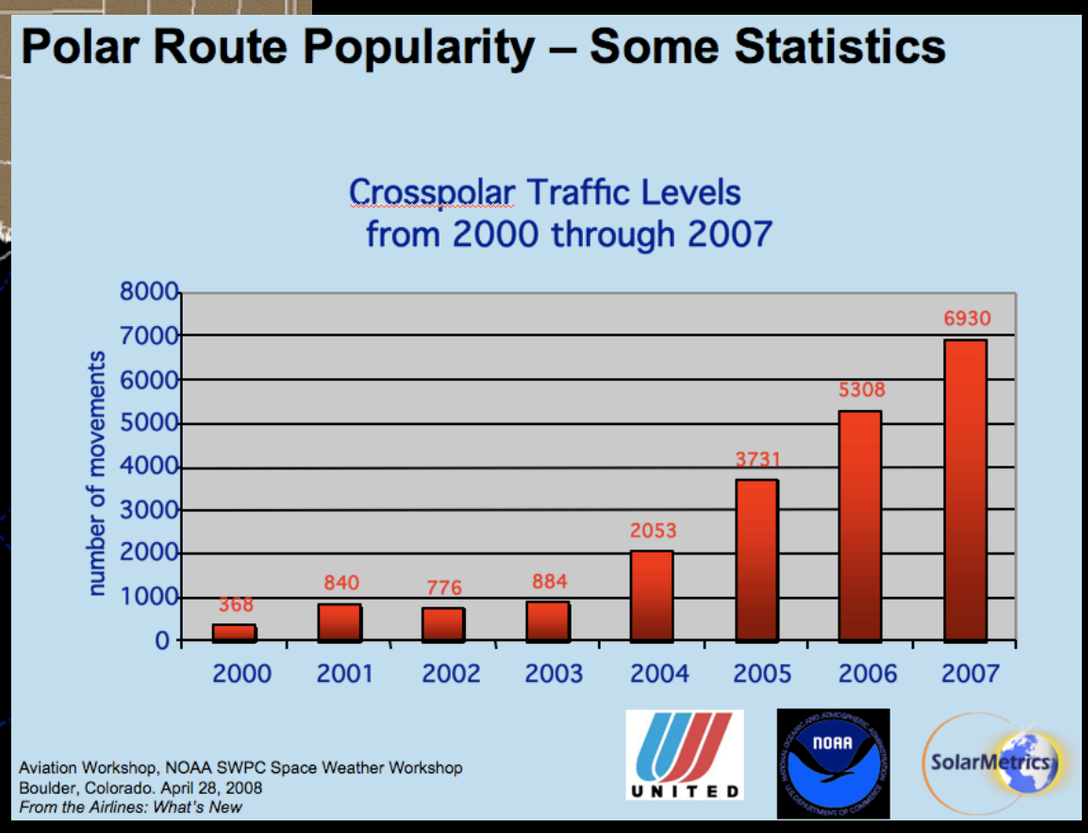
Aviation Workshop, NOAA SWPC Space Weather Workshop
Boulder, Colorado. April 28, 2008
From the Airlines: What's New

Effects on polar routes

- About 8000 flights per year in 2008.
- No satellite communication north of 82nd degree N.
- GPS can get unstable.

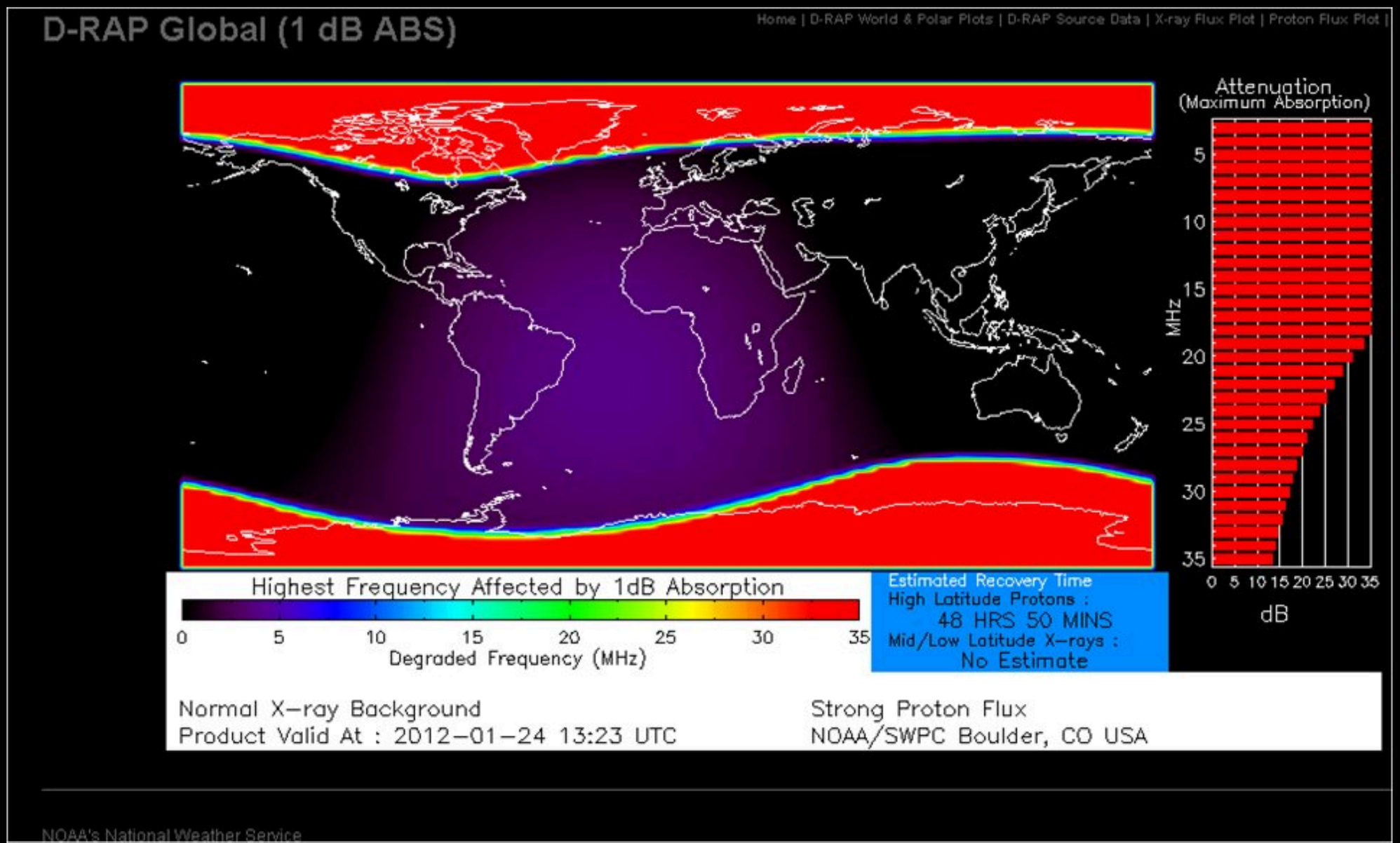


M.Stills, United Airlines



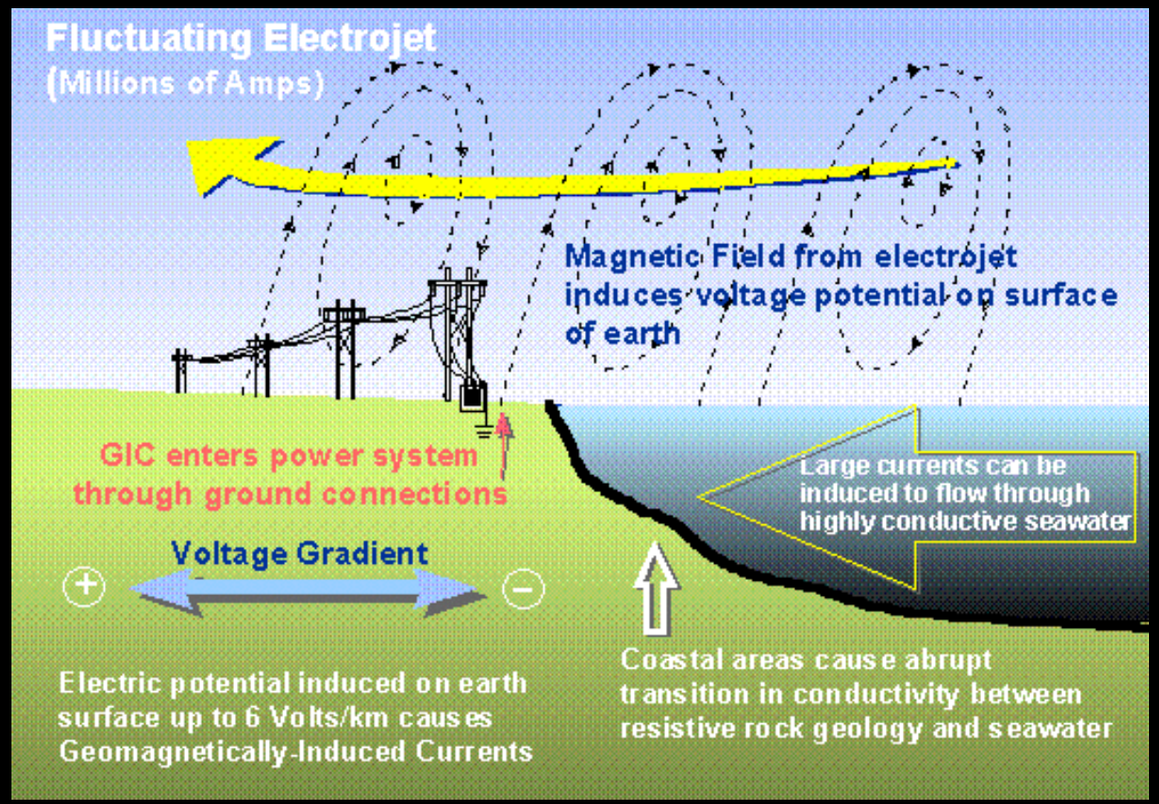
Flights were diverted

- Delte Airlines and United diverted some of their polar flights to avoid radio communication problems and increased radiation doses for the crew.
- The South pole was without radiocommunication for two days (where satellite communication is unavailable).



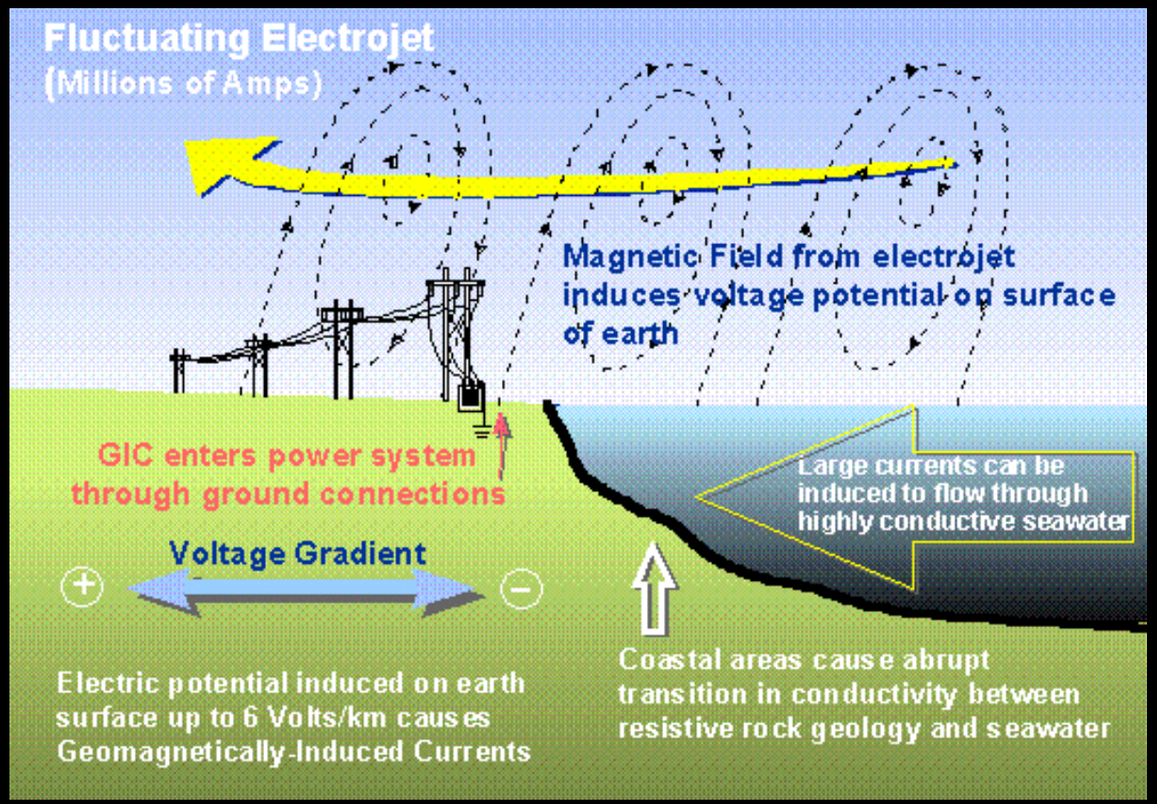
This graphic shows the energetic particles entering the D-region of the ionosphere. SWPC forecasters use this product to show where the energetic particles are entering and to give a visual to what is currently happening here at Earth. The red that can be seen at the poles is where the energetic particles enter and where airliners and spacecraft, should try to avoid.

Disruption of power grids

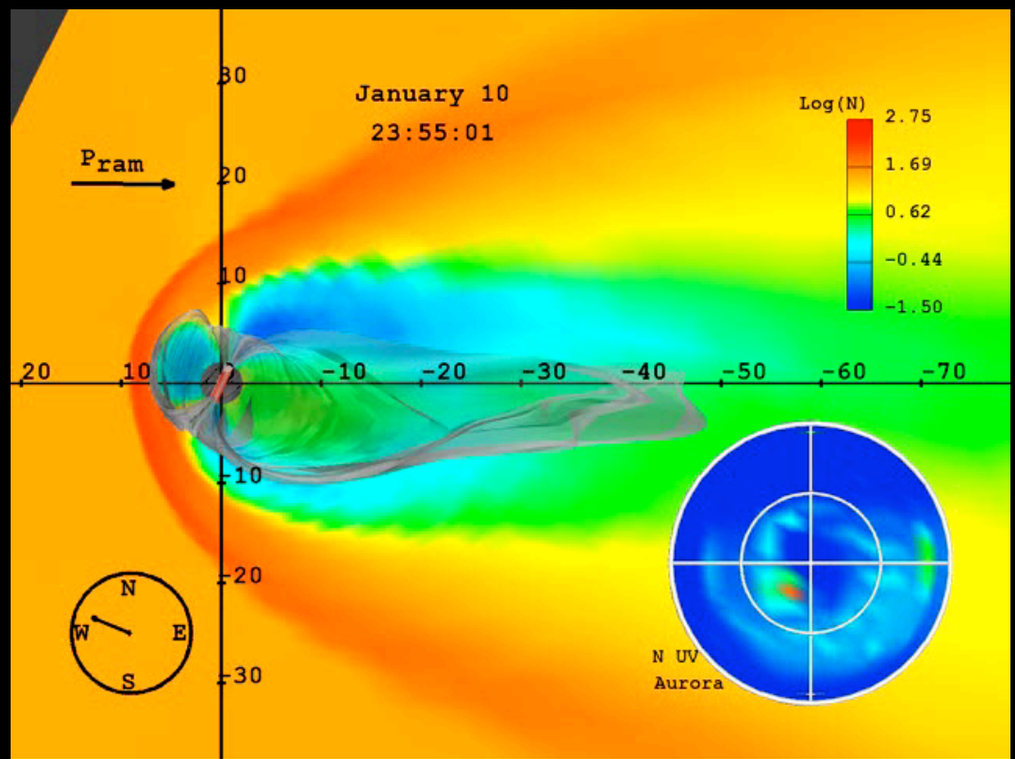


- These currents leaks into all lang conductors:
  - Power grids
  - Oil- and gas pipelines

Disruption of power grids

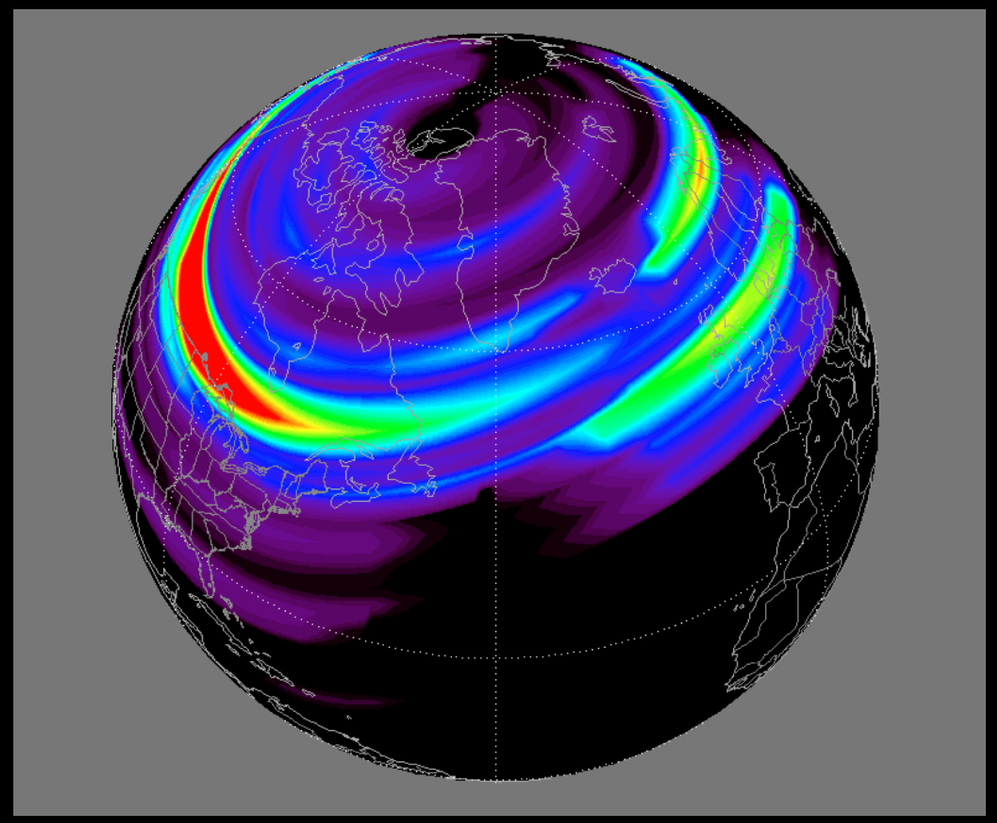


- These currents leaks into all lang conductors:
  - Power grids
  - Oil- and gas pipelines



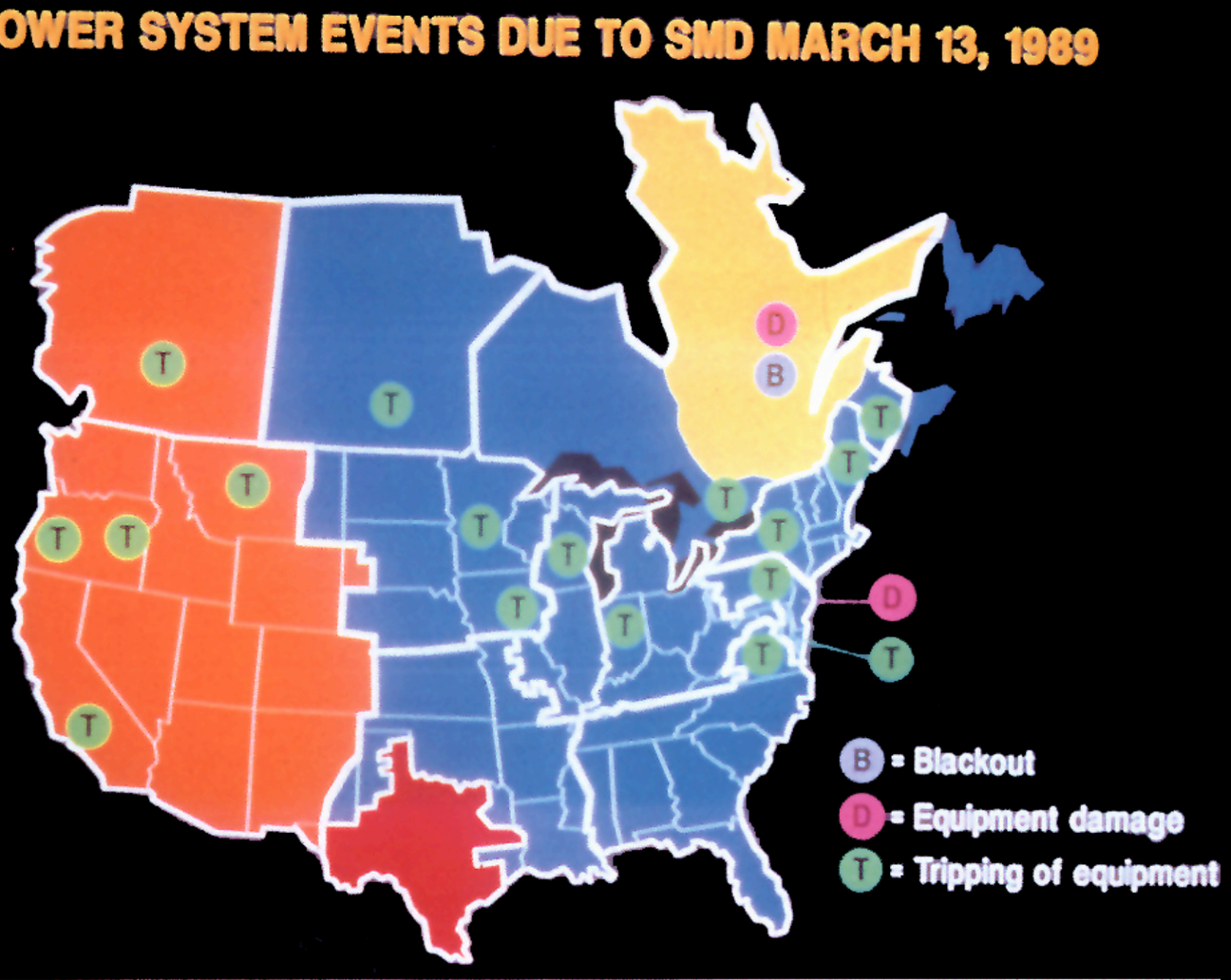
Power failure March 1989

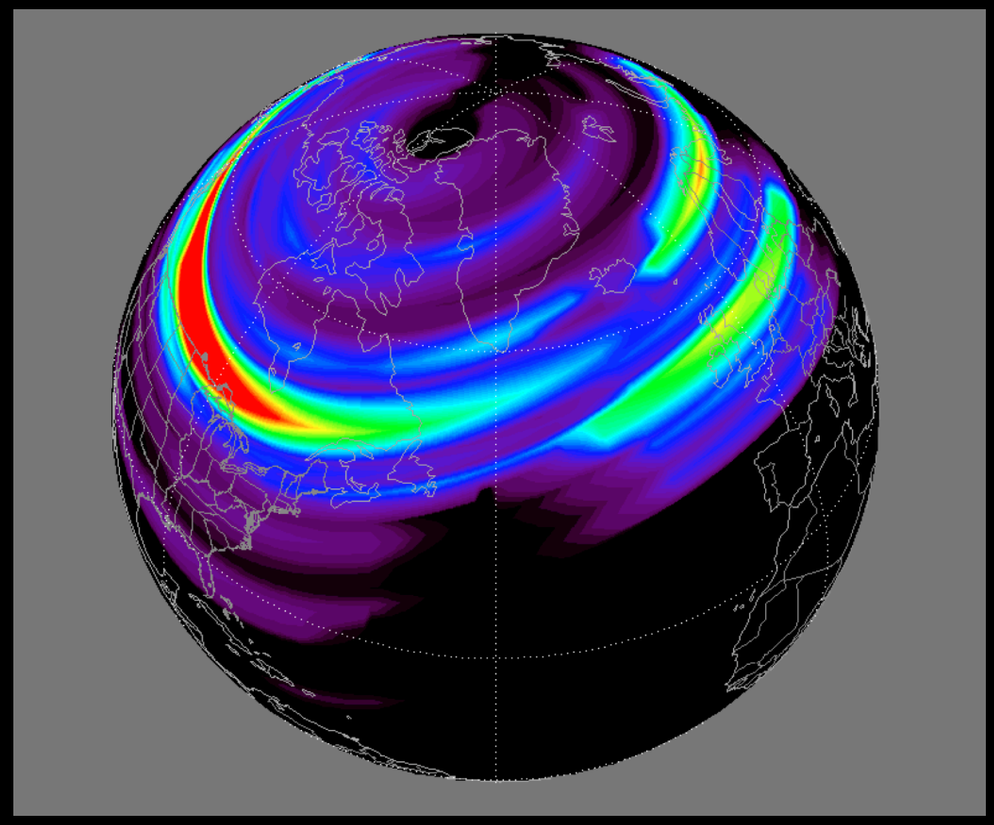
- The entire power grid in Quebec collapsed
- The collapse almoste spread into the NE USA
- Such a collapse would have had en estimated $3-6 billion impact on the US economy.

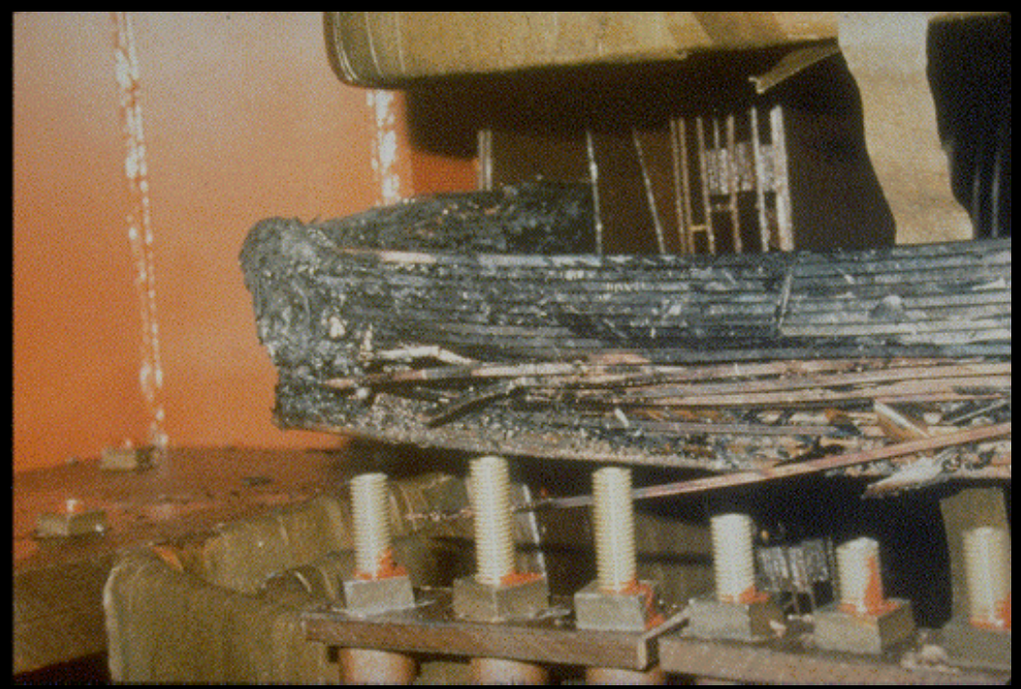


Power failure March 1989

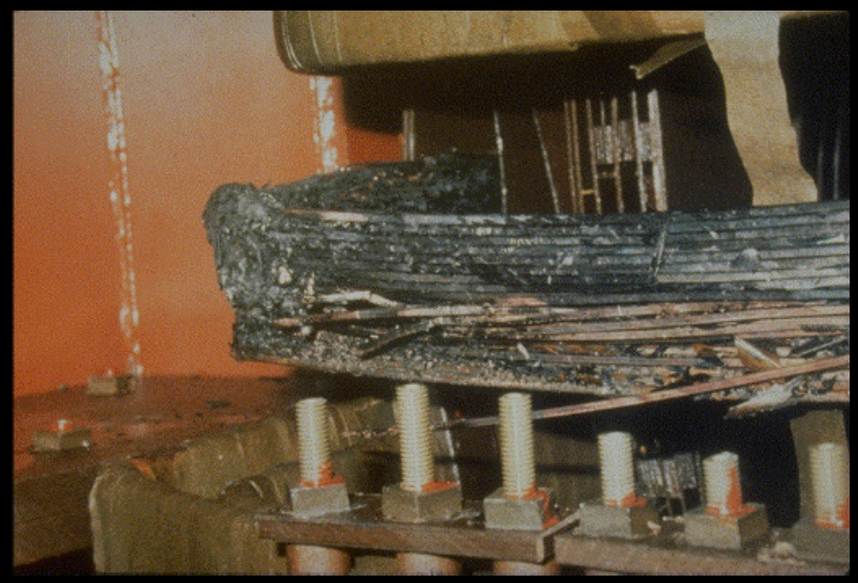
- The entire power grid in Quebec collapsed
- The collapse almoste spread into the NE USA
- Such a collapse would have had en estimated $3-6 billion impact on the US economy.







Damages after the 1989 storm



Damages to a trafo in Delaware, New Jersey in March 1989.

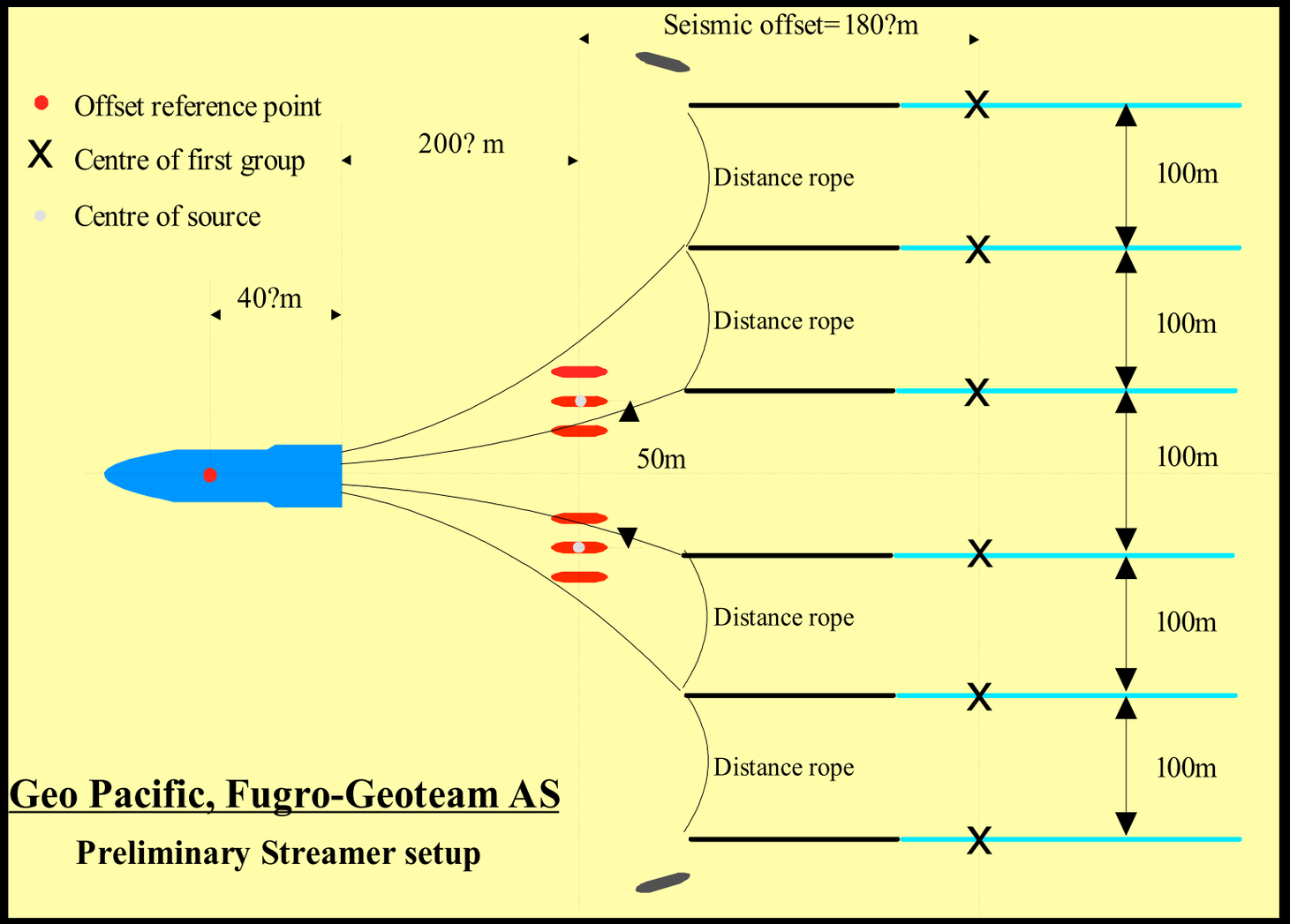
Cost: 10 million USD, repair can take one year.

In this case a used trafo was available and they swapped it in 6 weeks.

Sweden: lost power in six 130 kV distribution lines.

Chicago: Five trafoes in Chicago damaged in April 1994.

Geomagnetic surveys - search for oil and gas

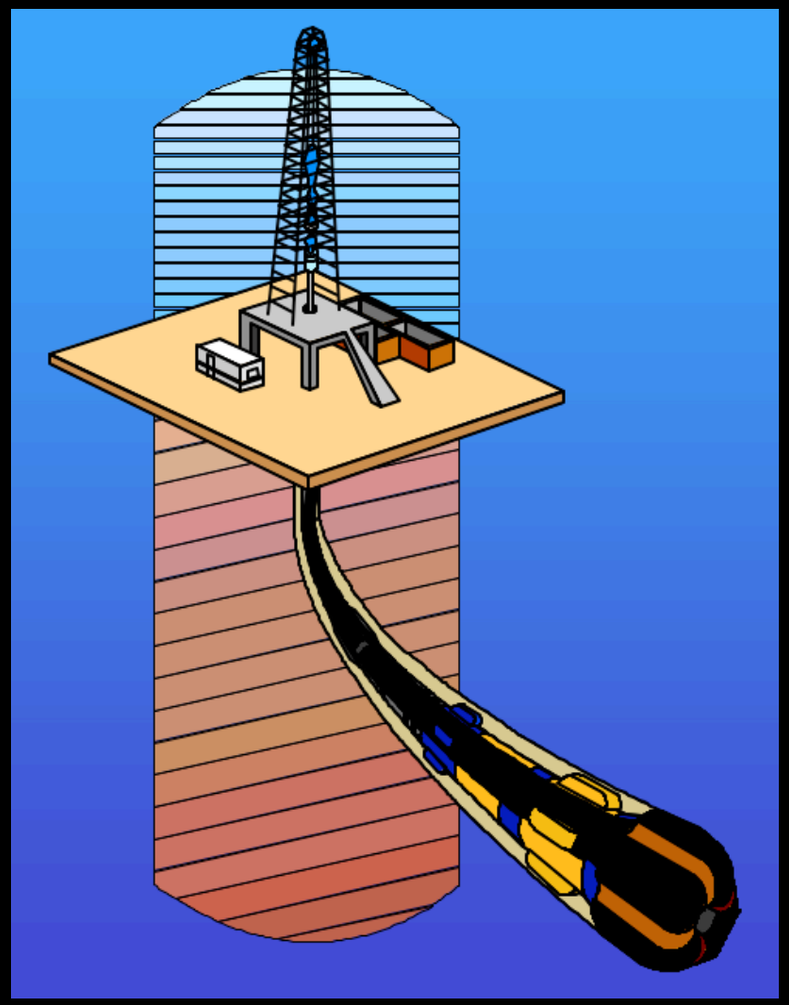


Fugro-Geoteam use ships with sensitive magnetometers on long cables.

Directional drilling

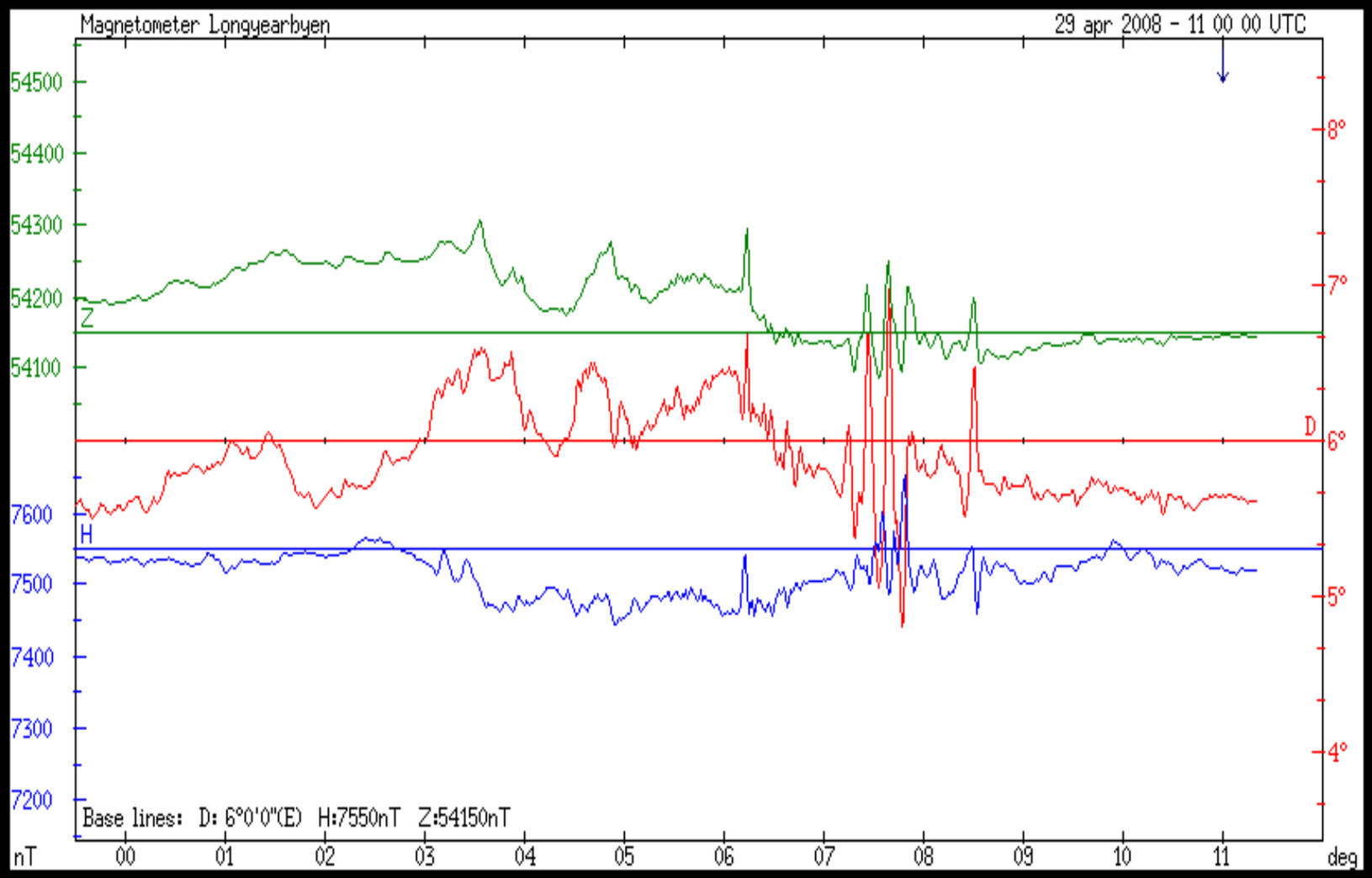
Directional drilling

- Oil industry relies on geomagnetic maps to guide the drill and monitor the well direction.

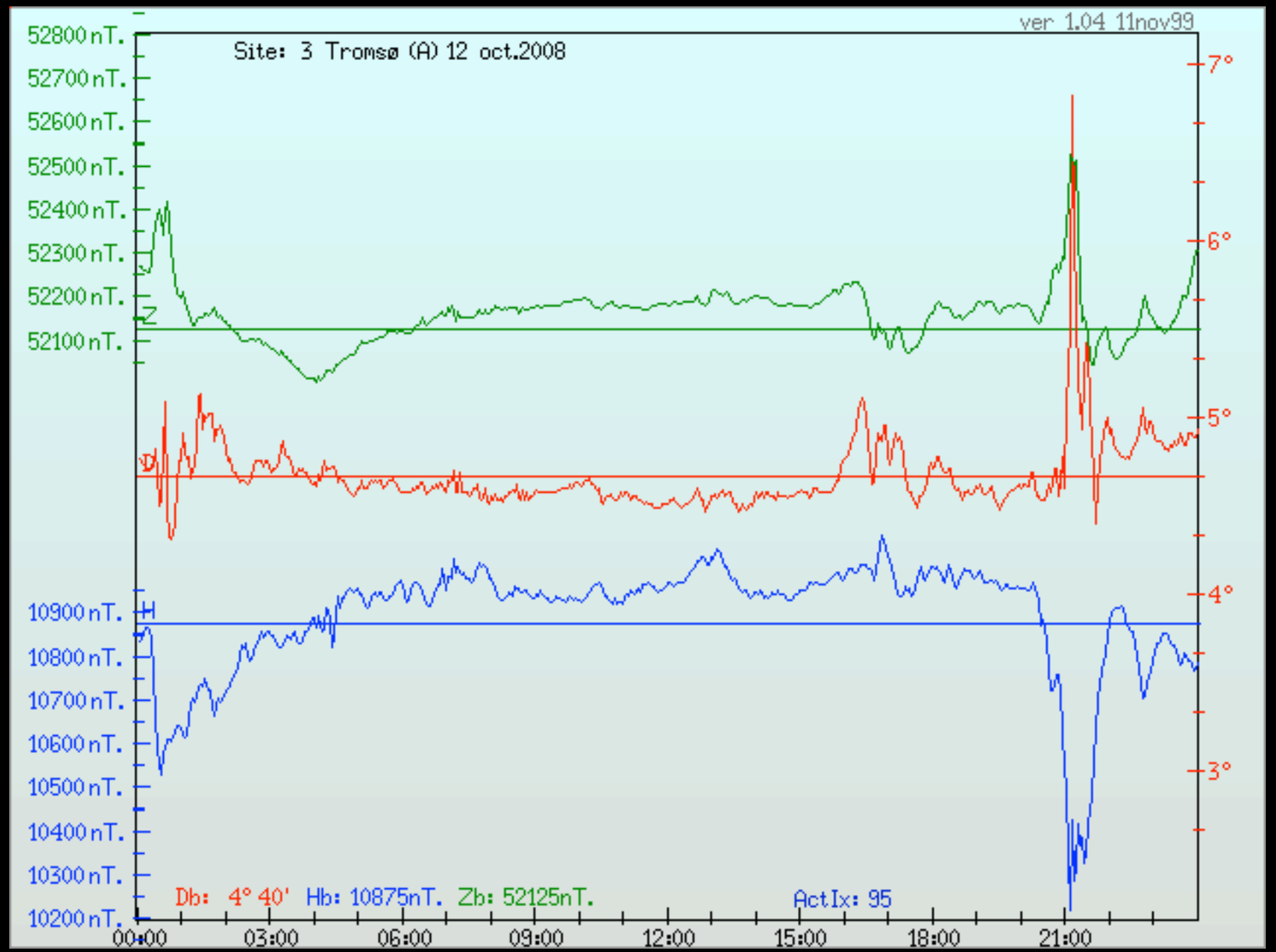


Drilling companies are buying spaceweather data

- UiT delivers “real-time” magnetometer data to the drilling companies to eitehr correct or extend the time they cam operate.



Effects on a compass



Impacts on animals

- The navigational abilities of homing pigeons are affected by geomagnetic storms
- Pigeons and other migratory animals, such as dolphins and whales, have internal biological compasses composed of the mineral magnetite wrapped in bundles of nerve cells.

Impacts on animals

- The navigational abilities of homing pigeons are affected by geomagnetic storms
- Pigeons and other migratory animals, such as dolphins and whales, have internal biological compasses composed of the mineral magnetite wrapped in bundles of nerve cells.

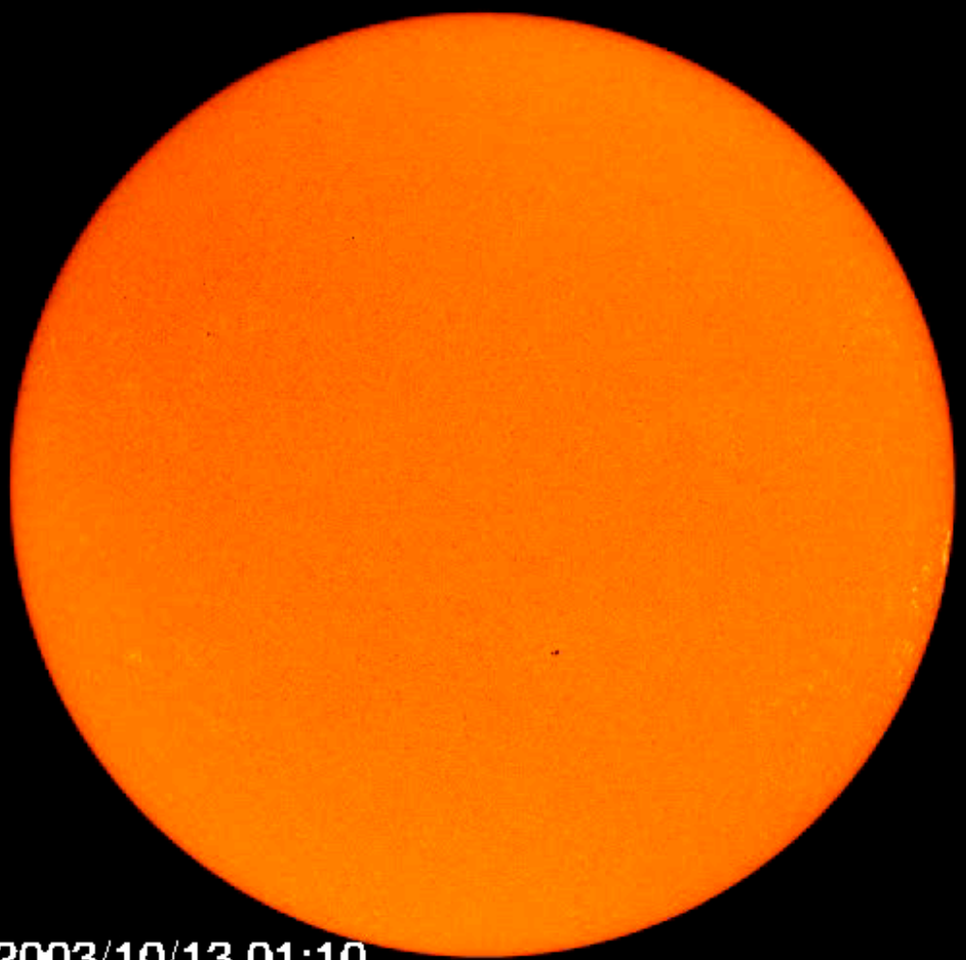
The Halloween-storms

Solar storm 28th October 2003

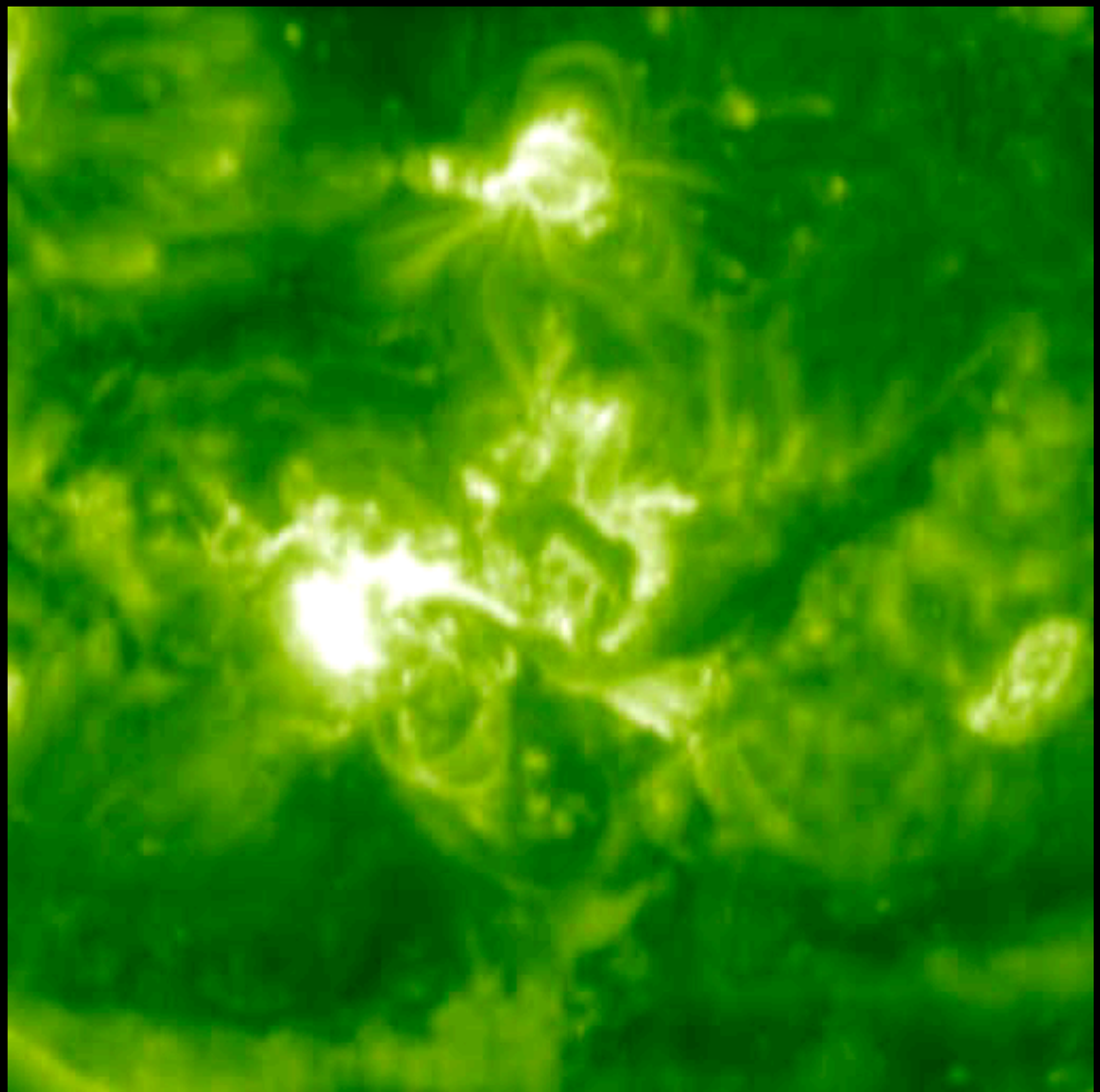
Giant sunspots developed

The Halloween-storms

Giant sunspots developed

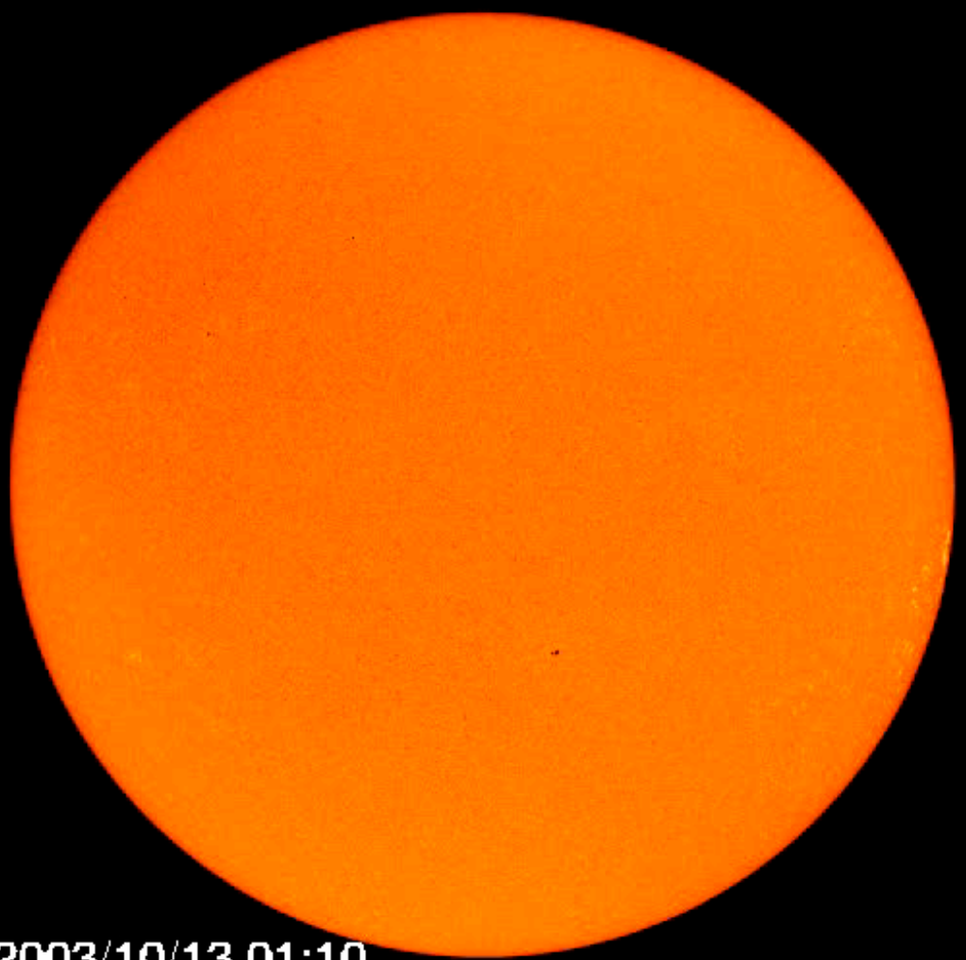


Solar storm 28th October 2003

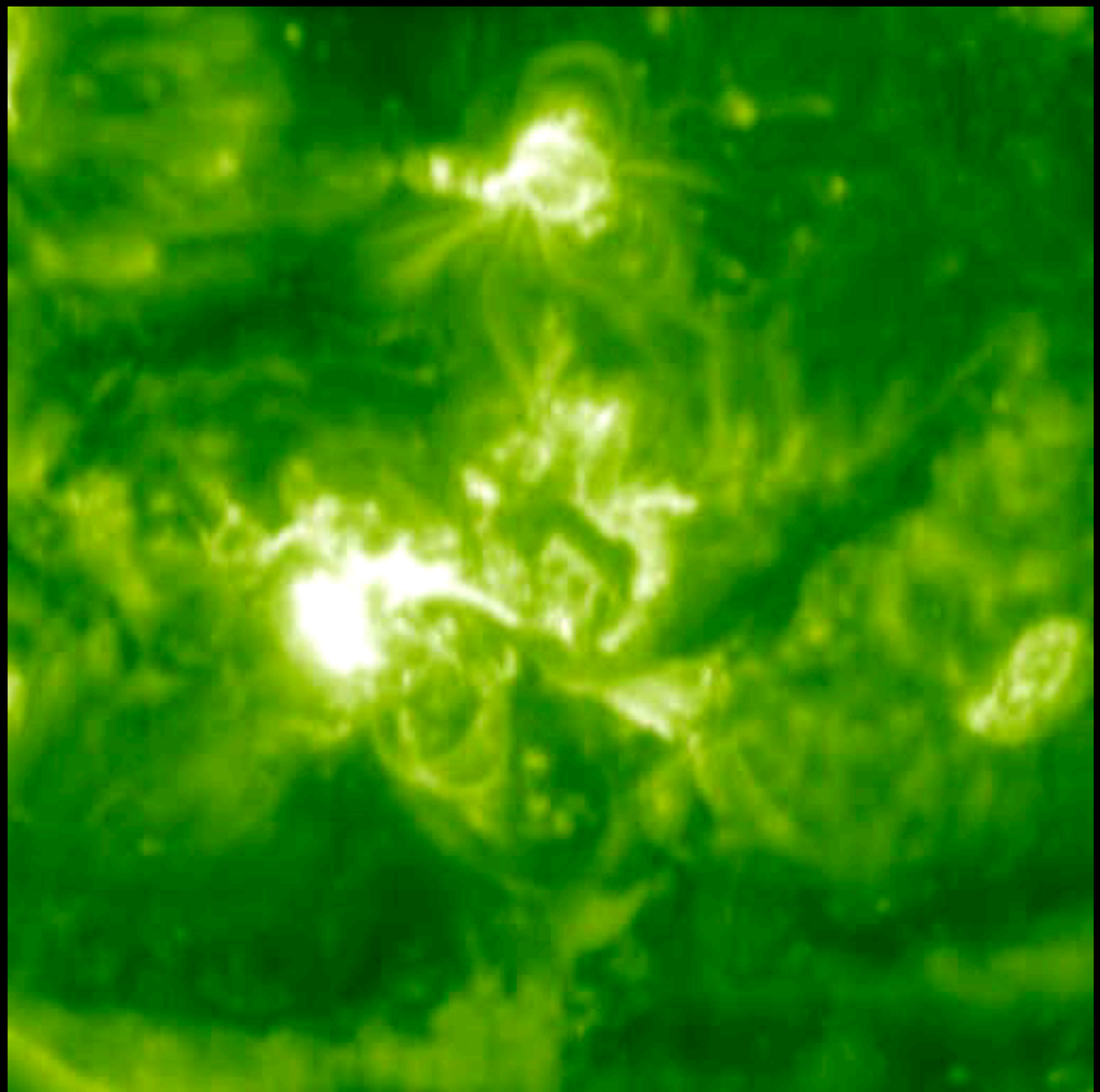


The Halloween-storms

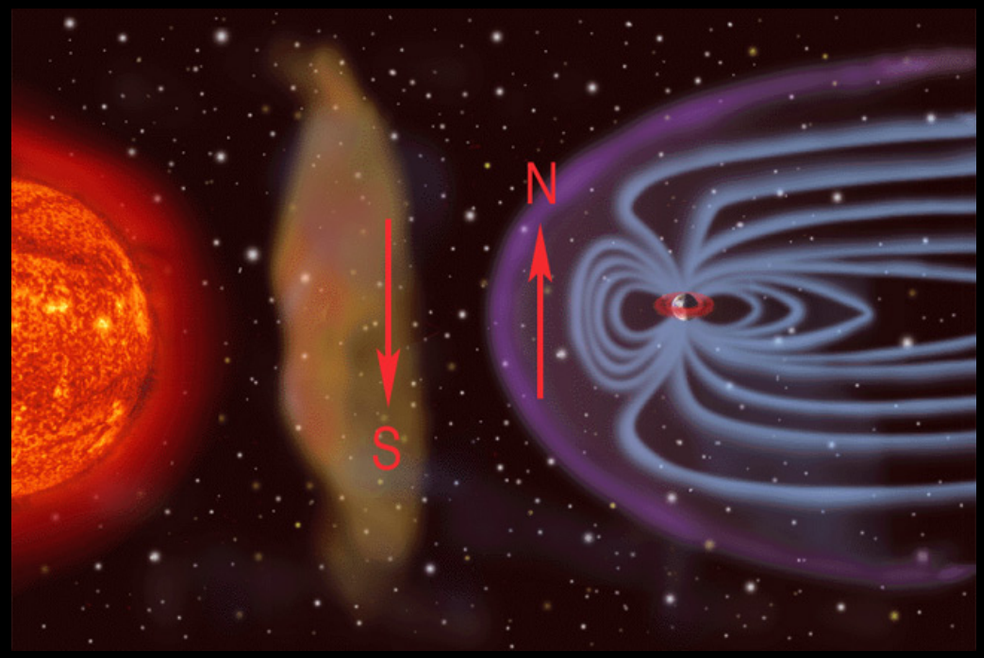
Giant sunspots developed

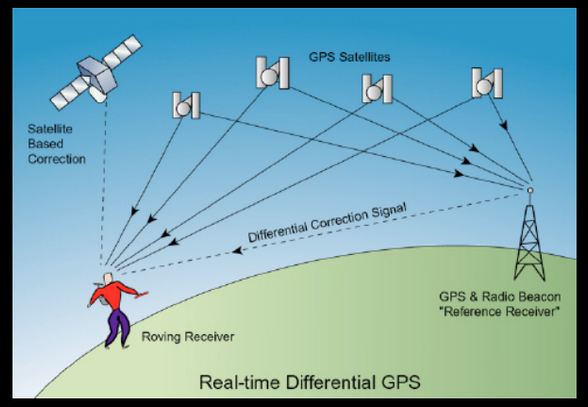


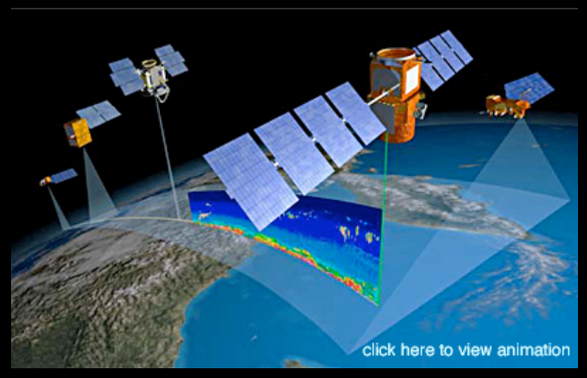
Solar storm 28th October 2003



Effects from the Halloween storms



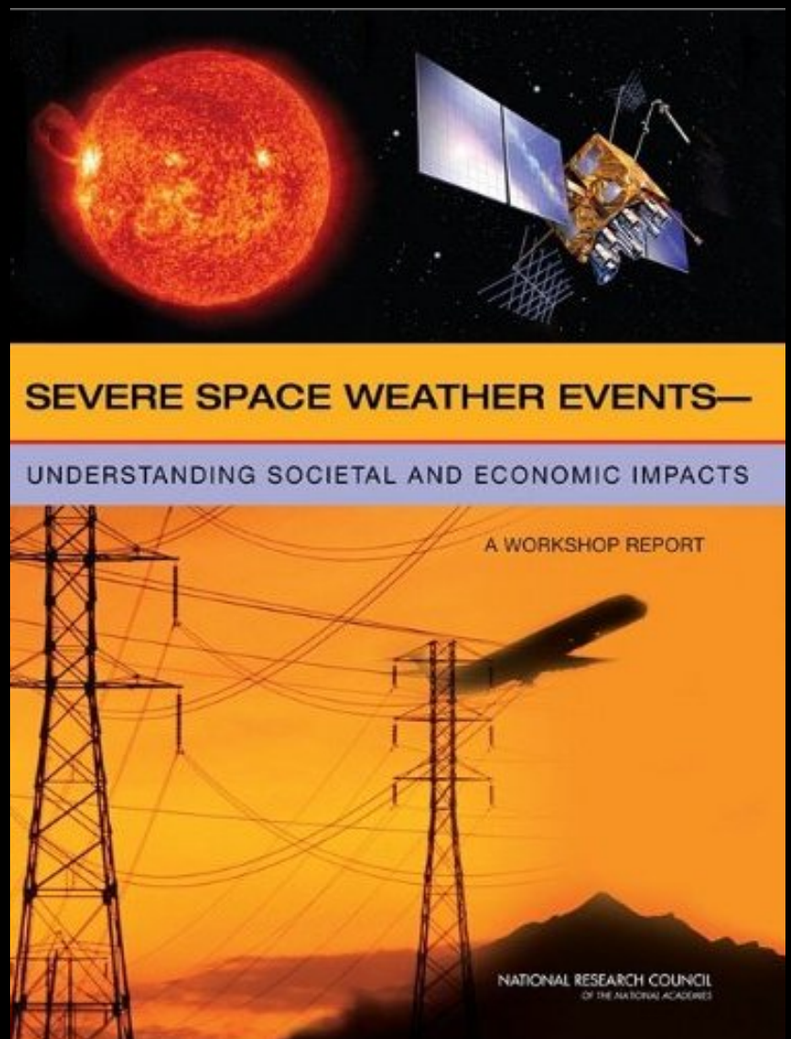




- More than 20 satellites and spacecrafts were affected (not including classified military instruments), Half of NASA satellites affected. One Japanese satellite lost
- Severe HF Radio blackout – affected commercial airlines
- FAA issued a first-ever alert of excessive radiation exposure for air travellers
- Power failure in Sweden
- Climbers in Himalaya experienced problems with satellite phones.
- US Coast Guard to temporarily shut down LORAN navigation system.
- Radiation monitor device on Mars Odyssey knocked out Parts of the Martian atmosphere escaped into space

Space Weather - Why should we care?

- The society is much more dependent on space technology
- Rapidly growing sector:
  - Broadcast TV/Radio,
  - Long distance phone, cell phones, pagers
  - Internet, finance-transactions
  - 350 million ++ users of GPS by 2015
- Change in technology
  - more sensitive payload
  - components with higher performance.
  - light and low cost components
- Humans in space
  - More and longer space flights
- Space wetaher warnings will be even more important for our society in the future.

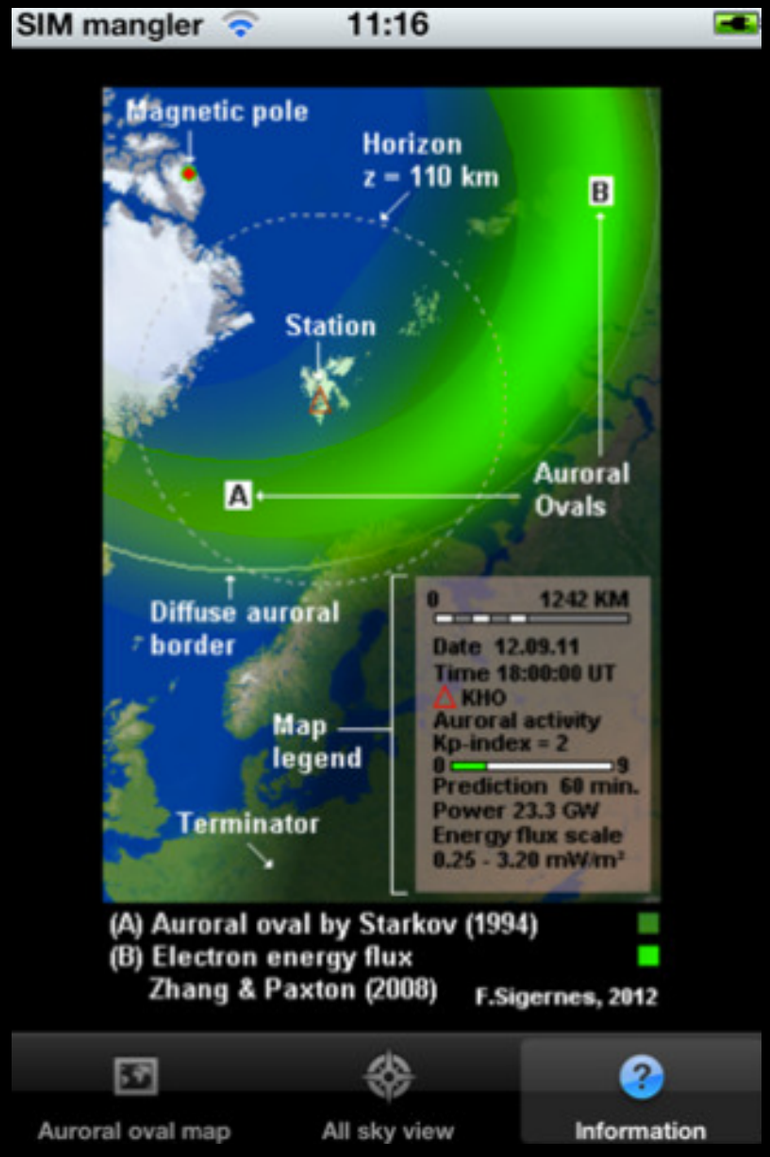


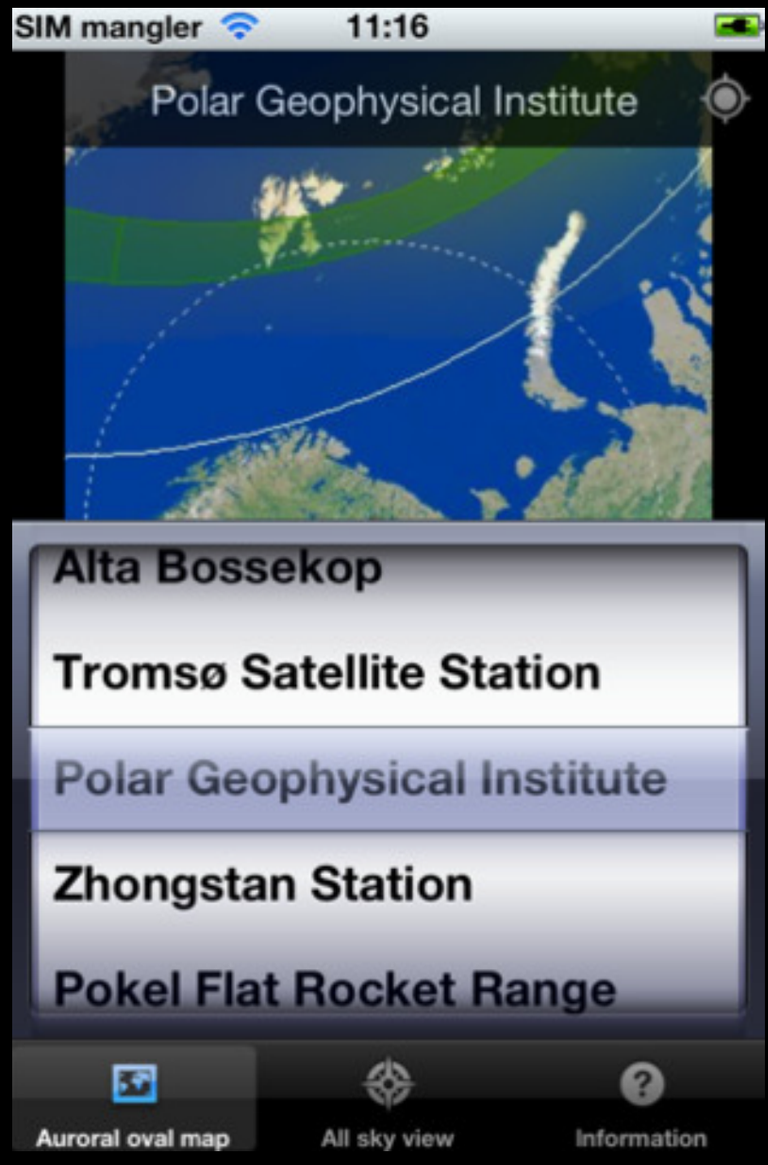
National Academy of Sciences, evaluated the impacts from a «super storm» and concluded that USA would be hit hard.

Damaged could reach 1000 billion USD

It could take 4-10 years to repair all damages.

Auroral Forecast - iPhone/Anroid Apps





Learn more about the Sun and the Aurora

New books

New: Feb 2013