Consequences of Space Weather on Near Earth Environment

EFFECTS

Atmospheric

- Modifications on ozone
  - Increased UV amounts on the surface
    - Cancer,
    - Immune system problems,
    - Catarakts etc.
- Upper Atmospheric Heating
  - Auroral Heating
  - Joule Heating
  - Magnetospheric Heating
  - Solar energetic particle Heating
  - Cosmic Ray Heating
- Modifications on upper atmospheric wind systems
- Ionospheric TEC Modifications
- Modifications on Climate

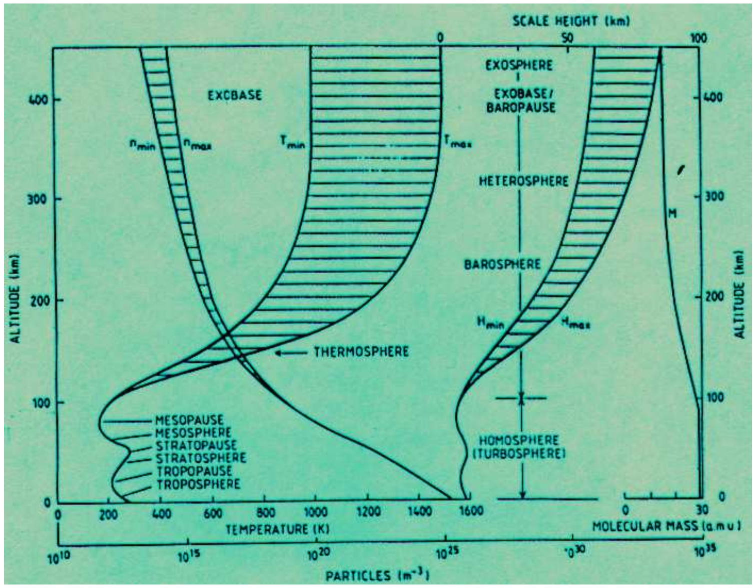
Technological systems

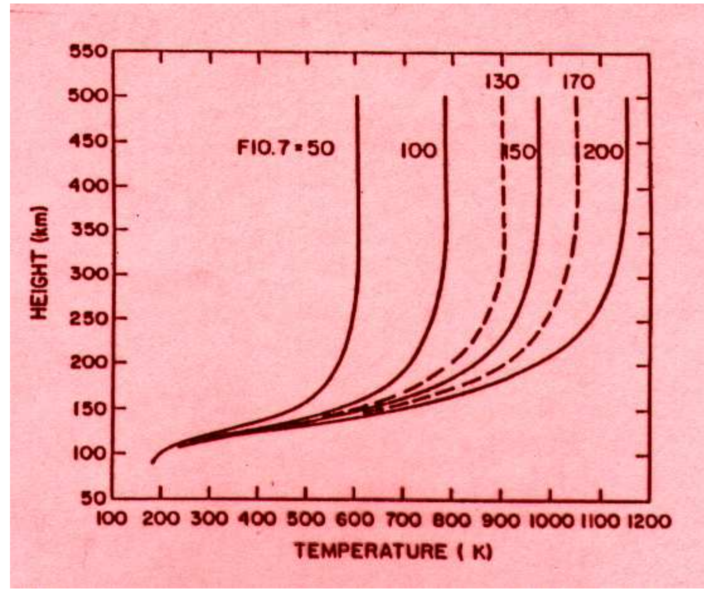
- Satellite technology
  - Spacecraft charging
  - Astronauts
- Communication
  - Navigation
- Electrical Systems
  - Power lines
  - Pipelines
- Earth's global circuit
  - Ionospheric currents
- Radars
  - Radar Range
- Ionospheric Radio Propagation
  - Absorption, Reflection
- GPS Systems

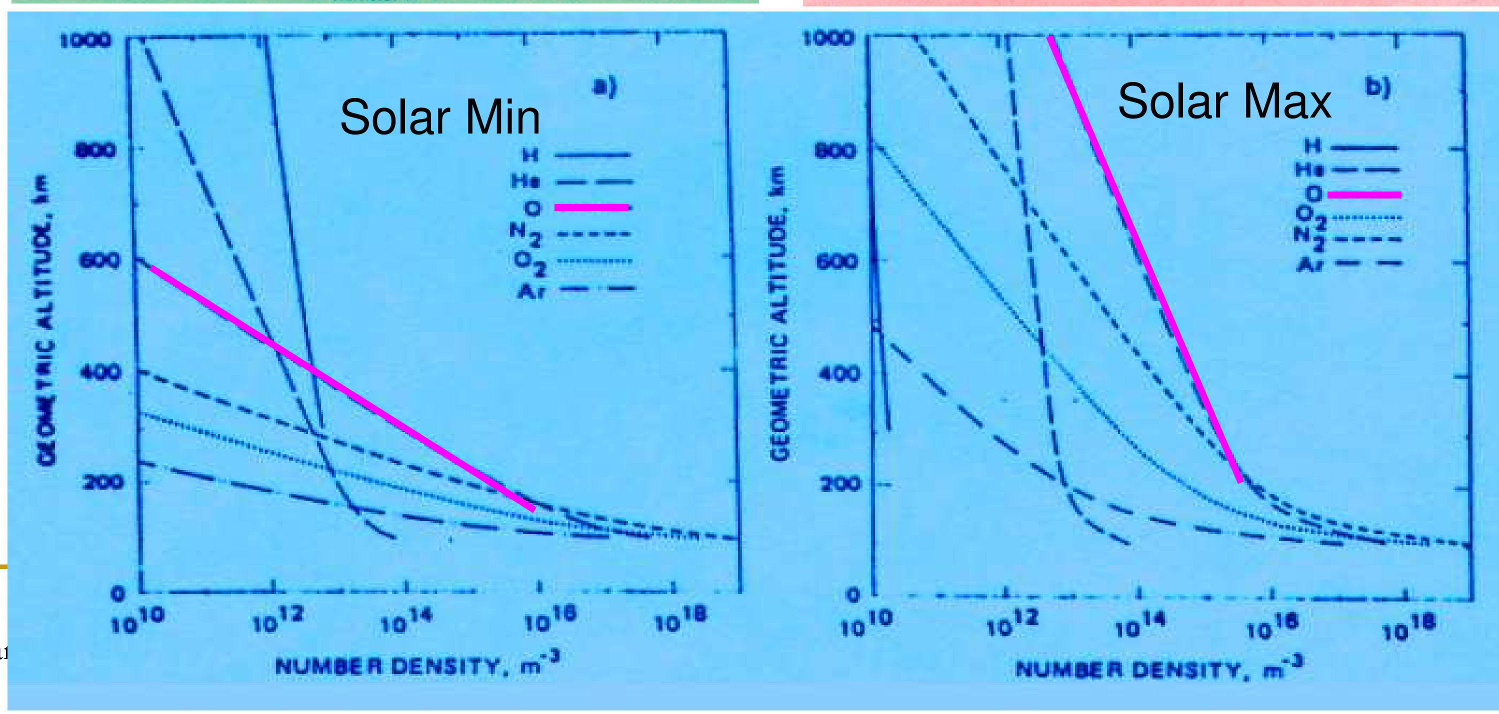
Effects from

- Solar wind particles
- Radiation

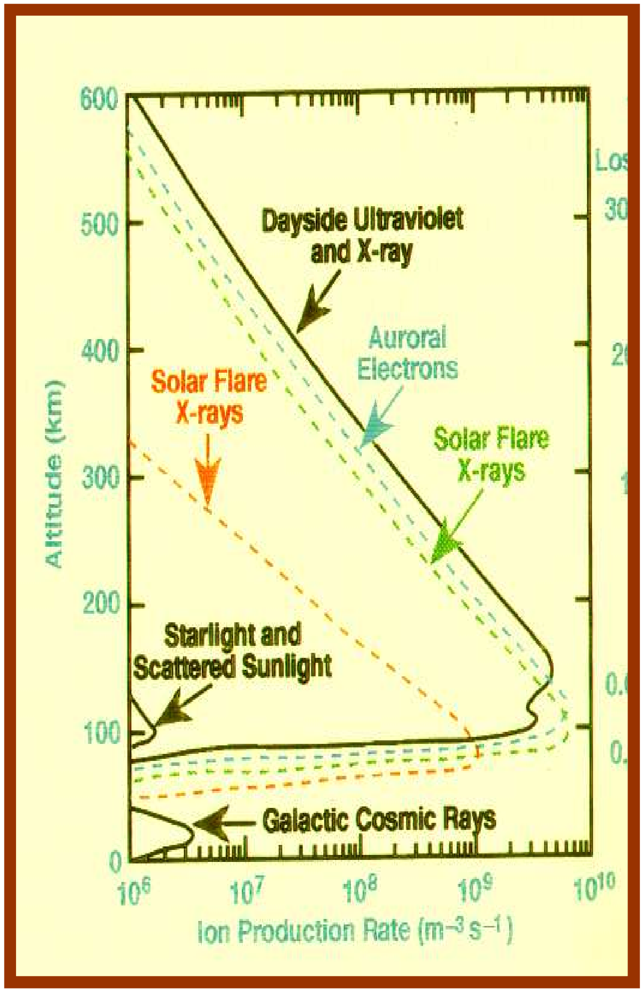
Thermospheric Temperature and Composition and Solar Activity







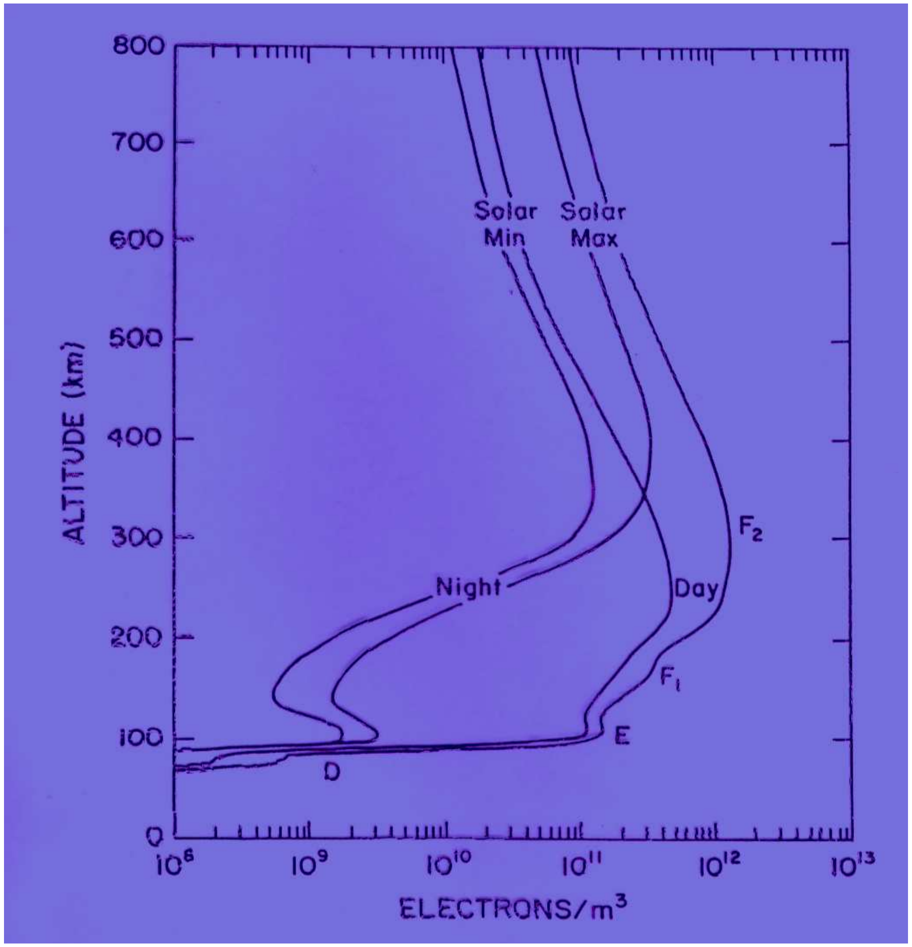
Ionosphere and Solar Activity

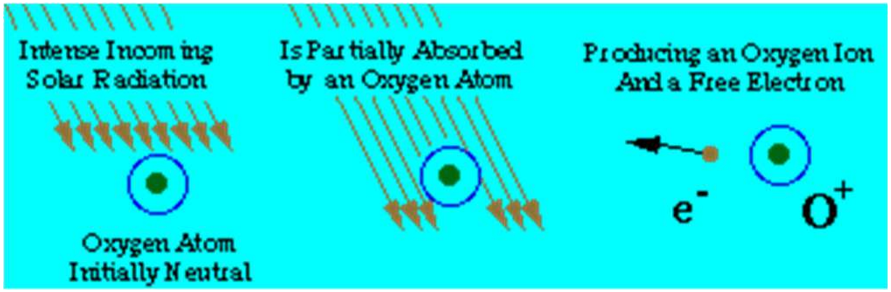


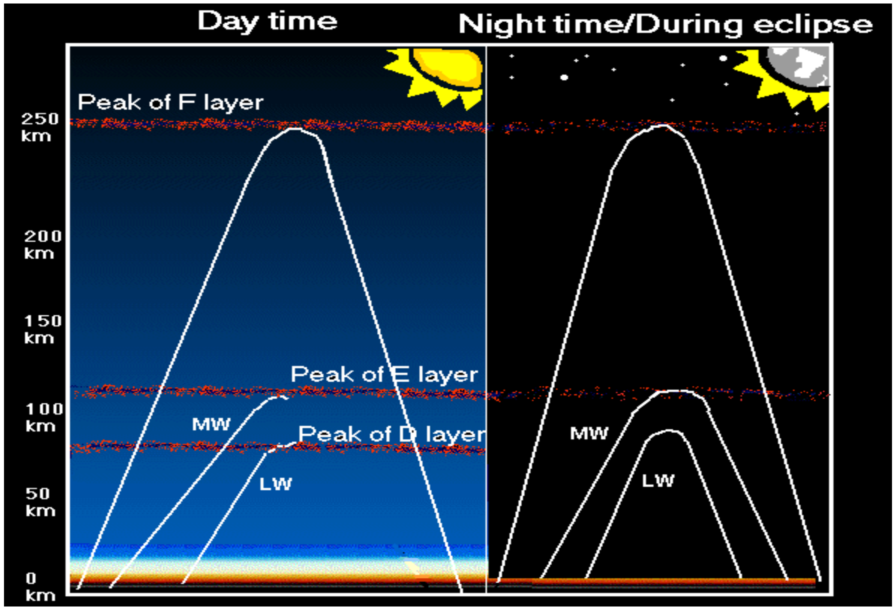
Ionization levels in the ionosphere during solar maximums

Ionization due to
- Solar Flares
- Auroral Particles

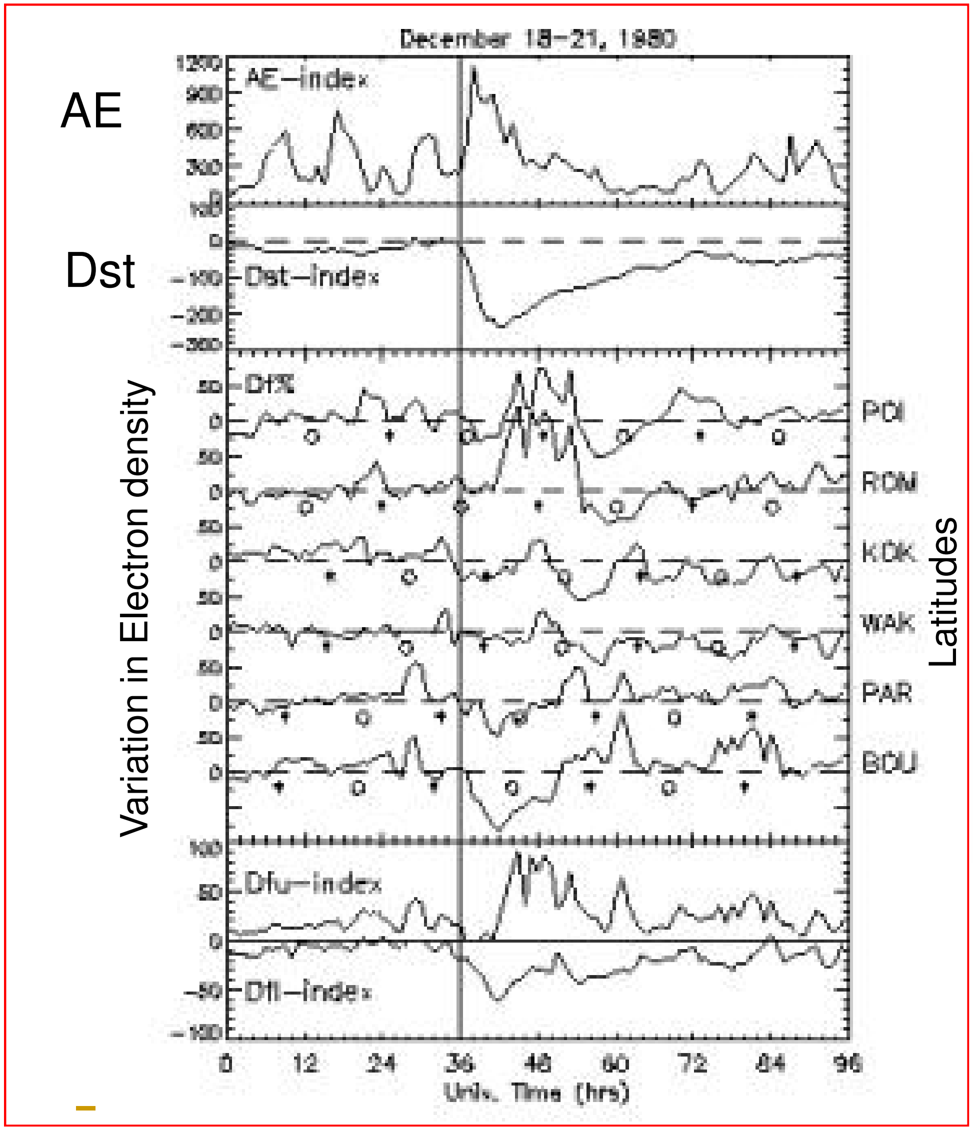
Ionosphere: Communications



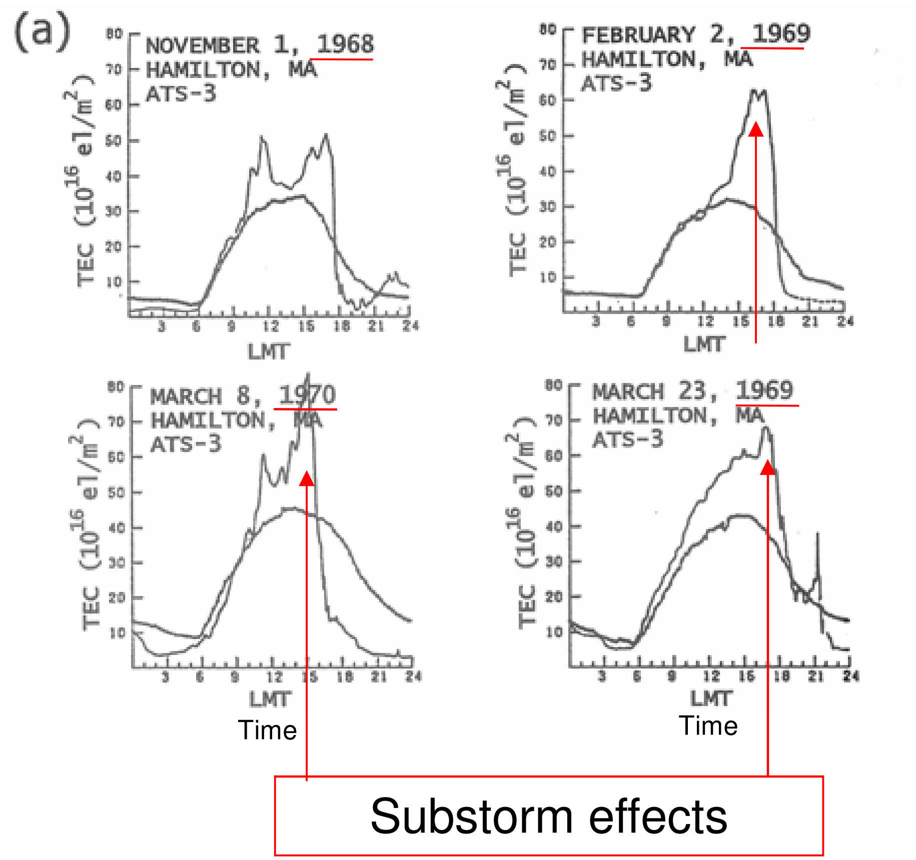




Ionospheric Storms: Increases in electron density

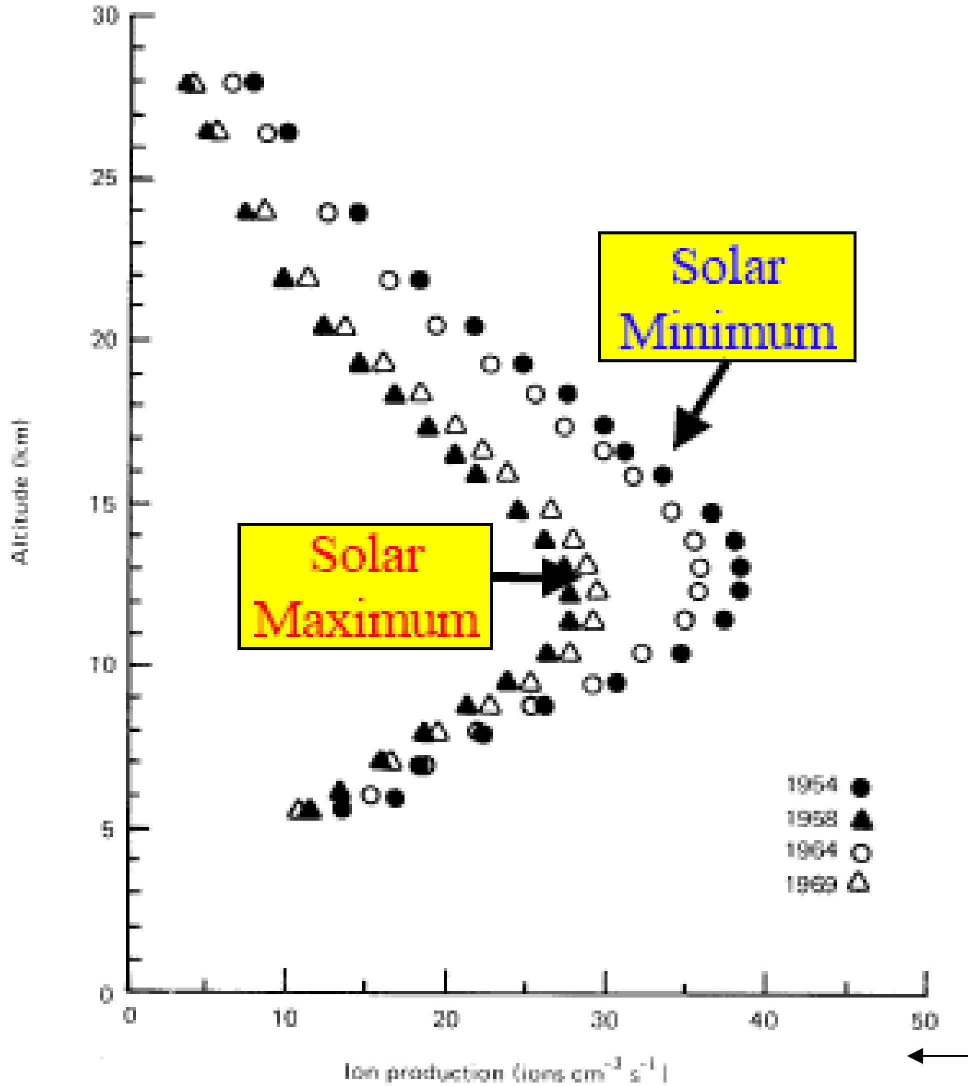


Daily Variations of Total Electron Density (TEC) during Different Storms



- TEC observations during magnetospheric substorms
- Mendillo, 2007, Reviews of Geophysics

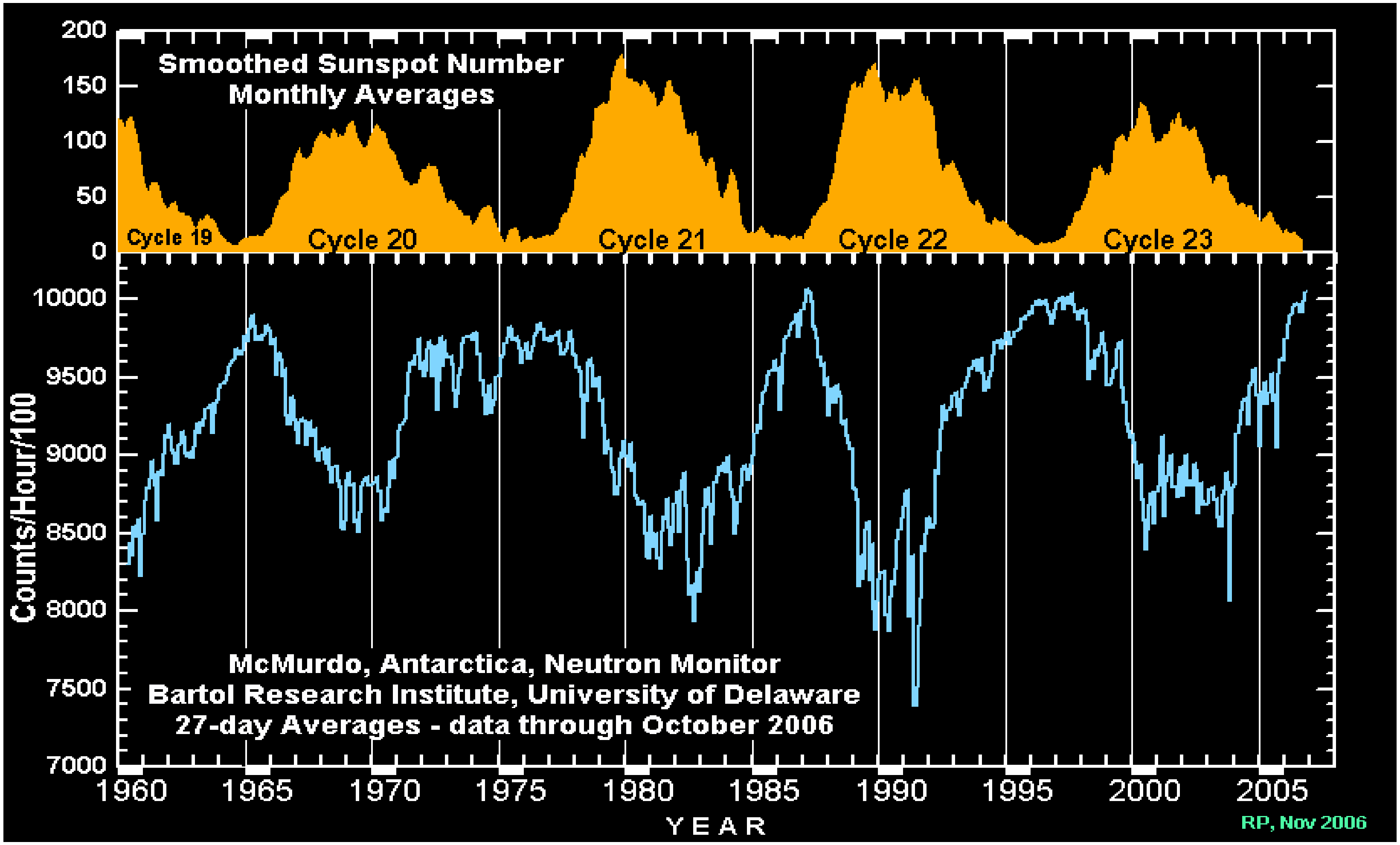
Ionization due to Cosmic Ray flux



- When solar activity is minimum, it is the Cosmic rays that cause the ionization the atmosphere

← Ion production rate over Thule

COSMIC RAYS AND THE SOLAR CYCLE



- Solar activity rises and falls with a period of about 11 years.
- The number of sunspots indicates the level of solar activity.
- Emissions of matter and electromagnetic fields from the Sun increase during high solar activity, making it harder for Galactic cosmic rays to reach Earth.
- Cosmic ray intensity is lower when solar activity is high.

Cosmic Rays and Cloudiness

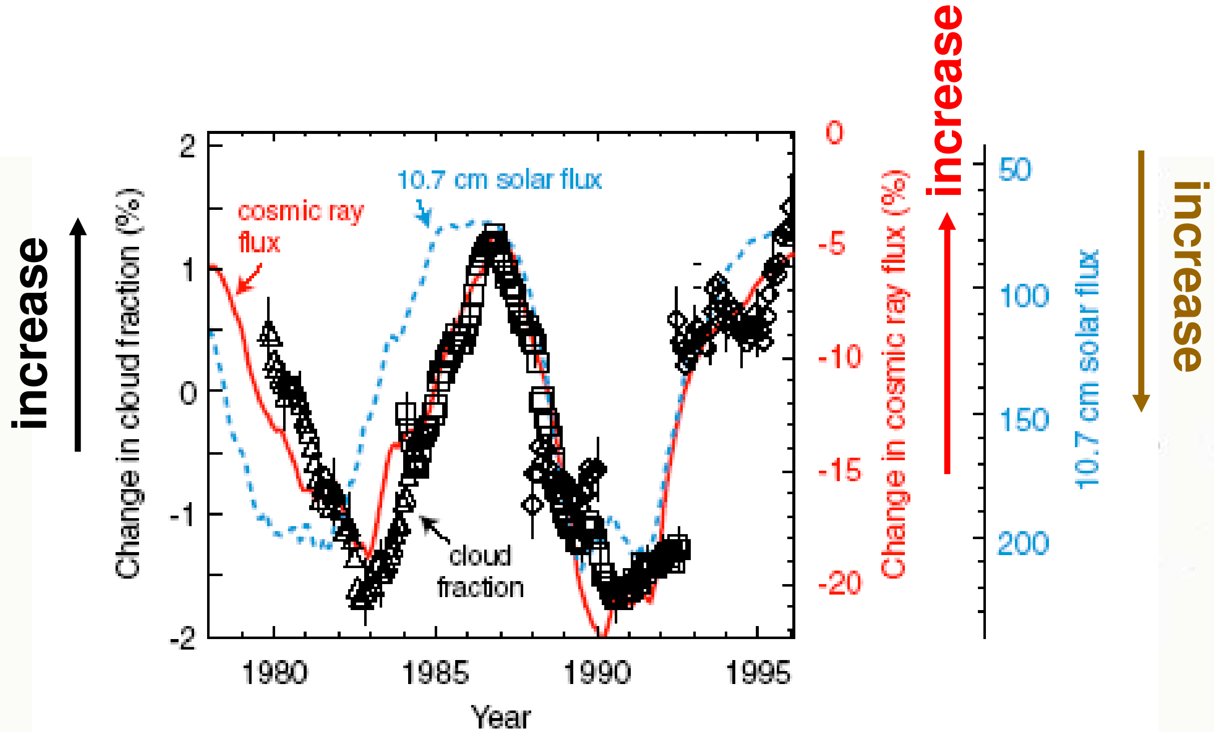
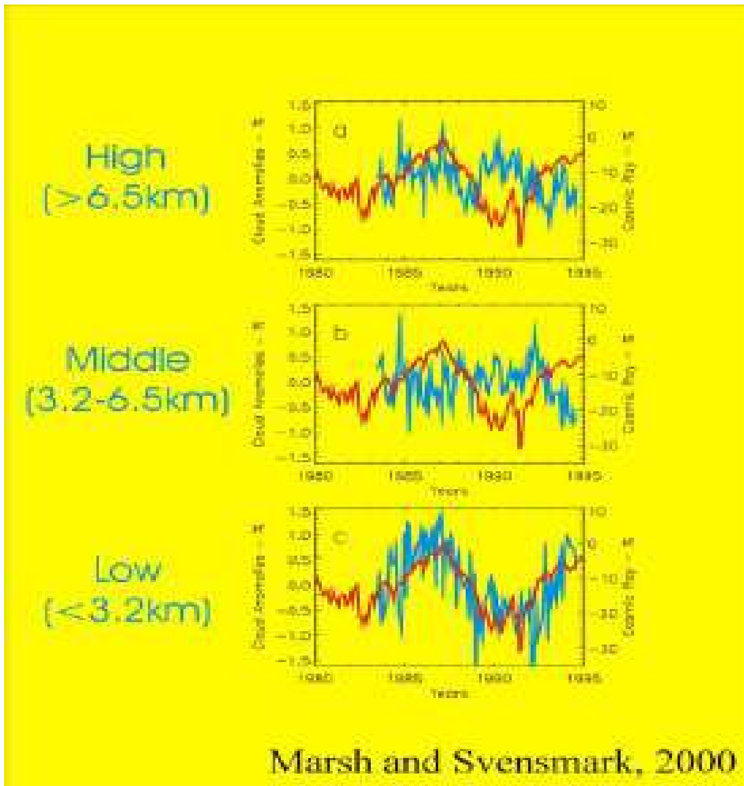
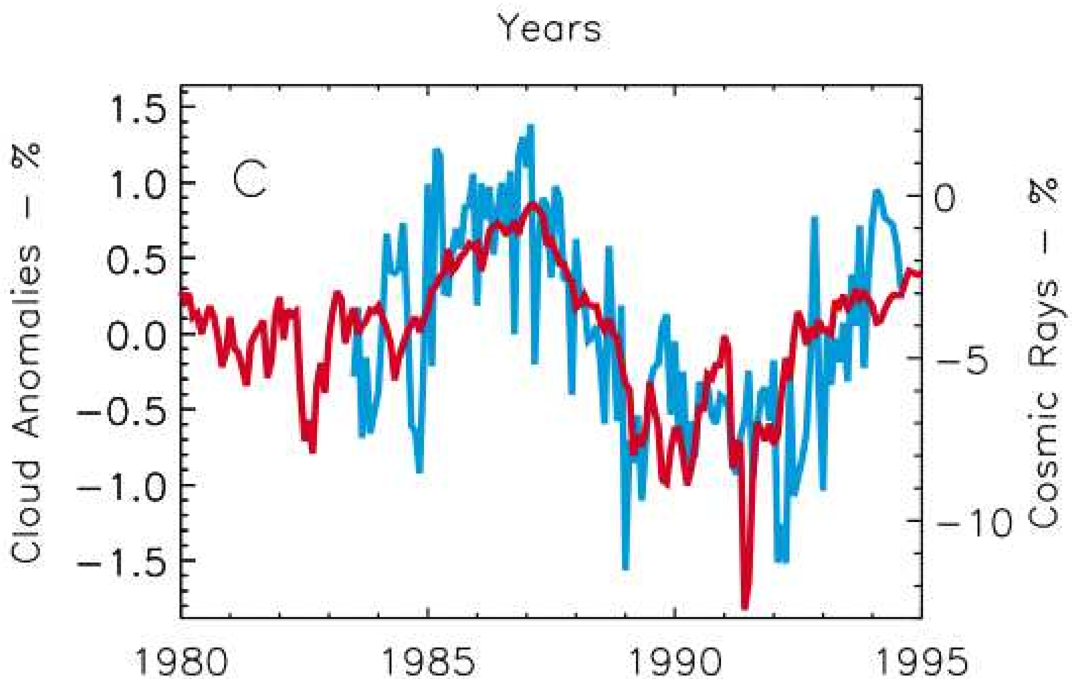


Figure 2. Composite figure showing changes in the Earth's cloud cover from four satellite cloud data sets together with cosmic rays fluxes from Climax (*solid curve*, normalized to May 1965), and 10.7 cm solar flux (*broken curve*, in units of 10^{-22} W m^{-2} Hz^{-1}). Triangles are the Nimbus7 data, squares are the ISCCP_C2 and ISCCP_D2 data, diamonds are the DMSP data. All the displayed data have been smoothed using a 12 months running mean. The Nimbus7 and the DMSP data are total cloud cover for the Southern Hemisphere over oceans, and the ISCCP data have been derived from geostationary satellites over oceans with the tropics excluded.

Cosmic Ray and Cloud Types

Cosmic Ray Intensity at Huancayo)





GCR → 2 % absolute change in low cloud cover over a solar cycle corresponds to a Change in net cloud forcing of ~ 1.2 W/m^2

Maunder Minimum

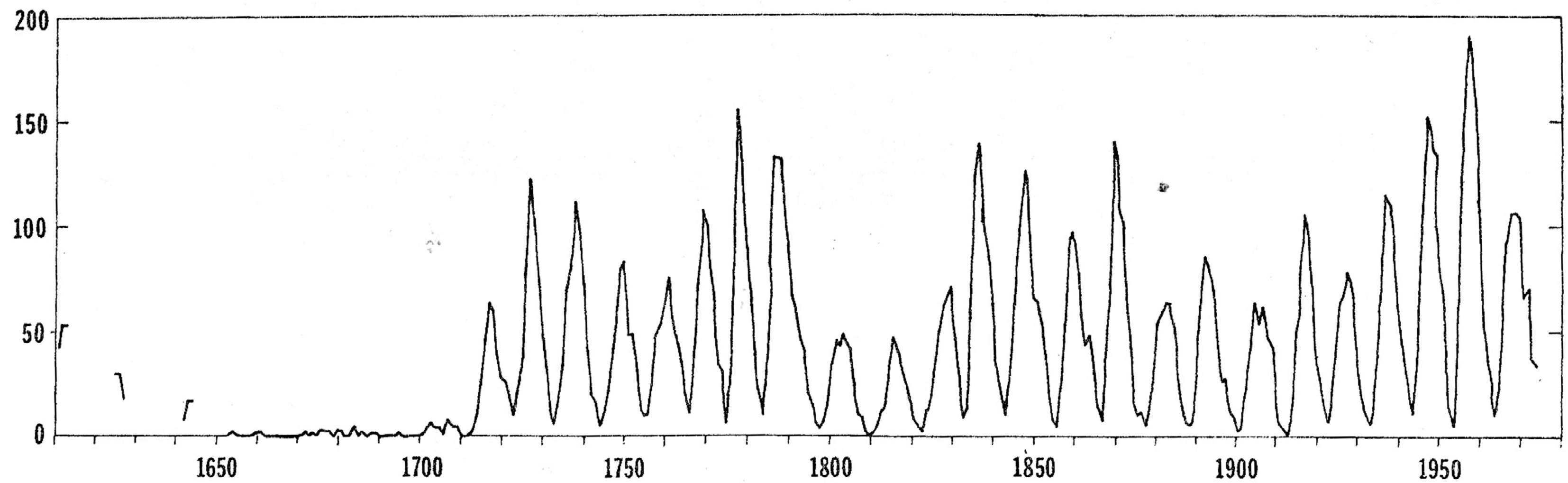


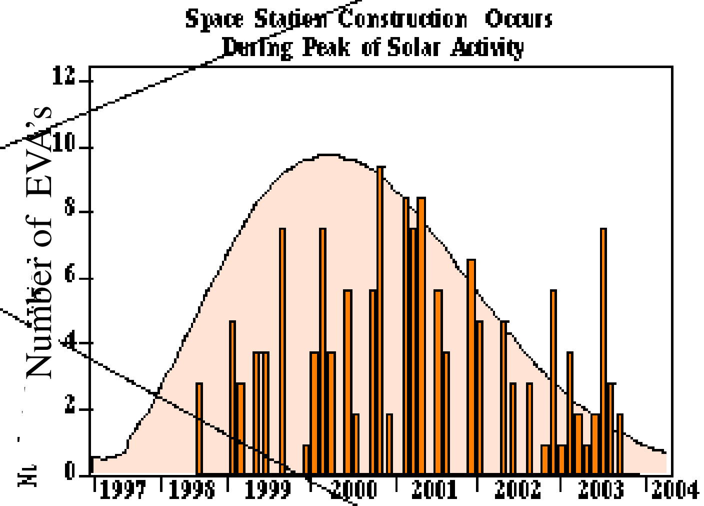
Figure 3. Annual mean sunspot number, AD 1610-1975, from Waldmeier (1) and Eddy (14), based on controlled observation from 1853 and reconstructed from less complete observations in earlier periods. Period from 1645-1715 is the Maunder Minimum.

Space Weather Effects on Technology

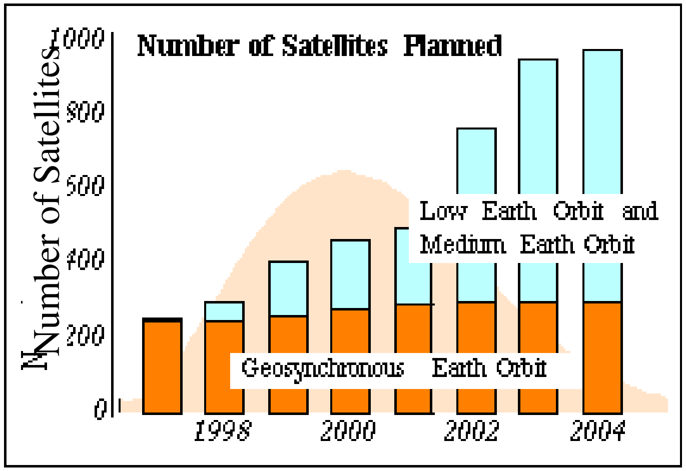
Who is Affected by Space Weather?

- More than 25 space walks a year
- $9 Billion/year in GPS sales by 2000
- $30 Billion of additional satellites

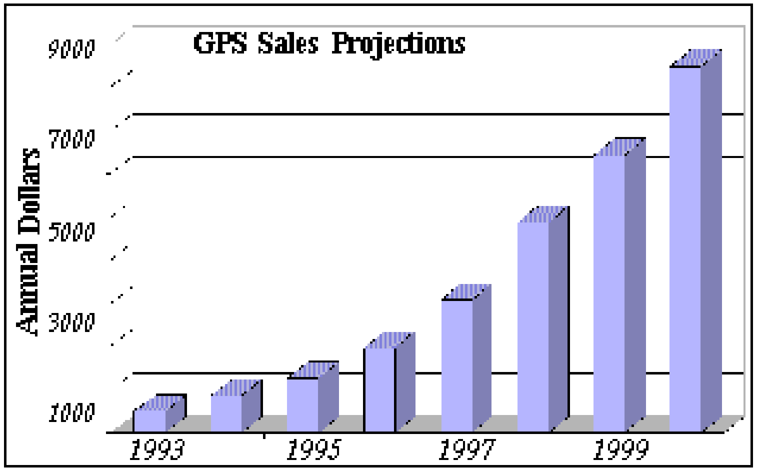
Astronauts



Communications

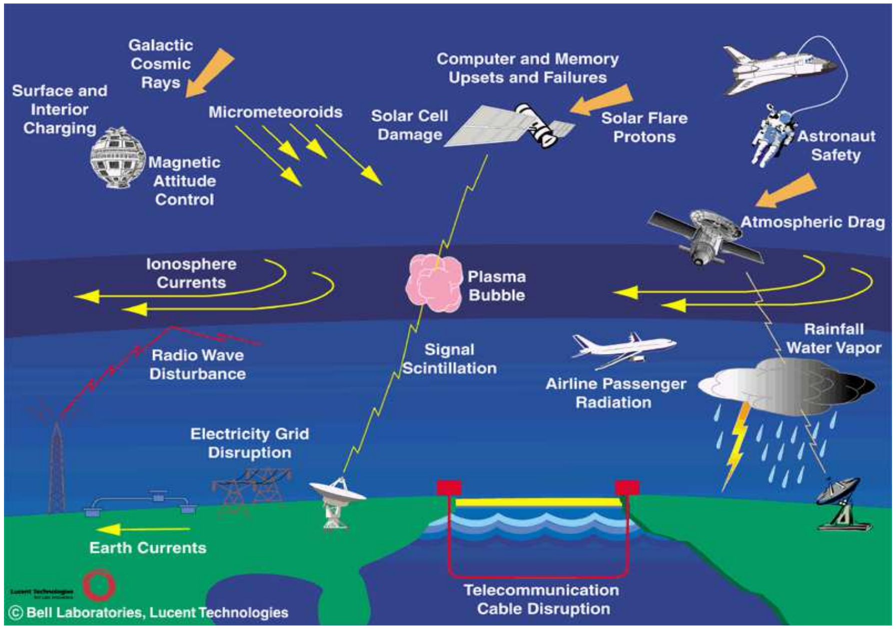


Navigation



Space Weather Can Affect

- COMMUNICATIONS
- NAVIGATION SYSTEMS
  ELECTRICAL POWER GRIDS
- SPACECRAFT ELECTRONICS
- SPACECRAFT OPERATIONS
  SATELLITE LIFETIMES (i.e. drag)
- SPACE POWER SYSTEMS
- MANNED SPACE MISSIONS
  MINERAL SURVEYS
  PIPELINES AND CABLES
  MANUFACTURING OF PRECISION EQUIPMENT



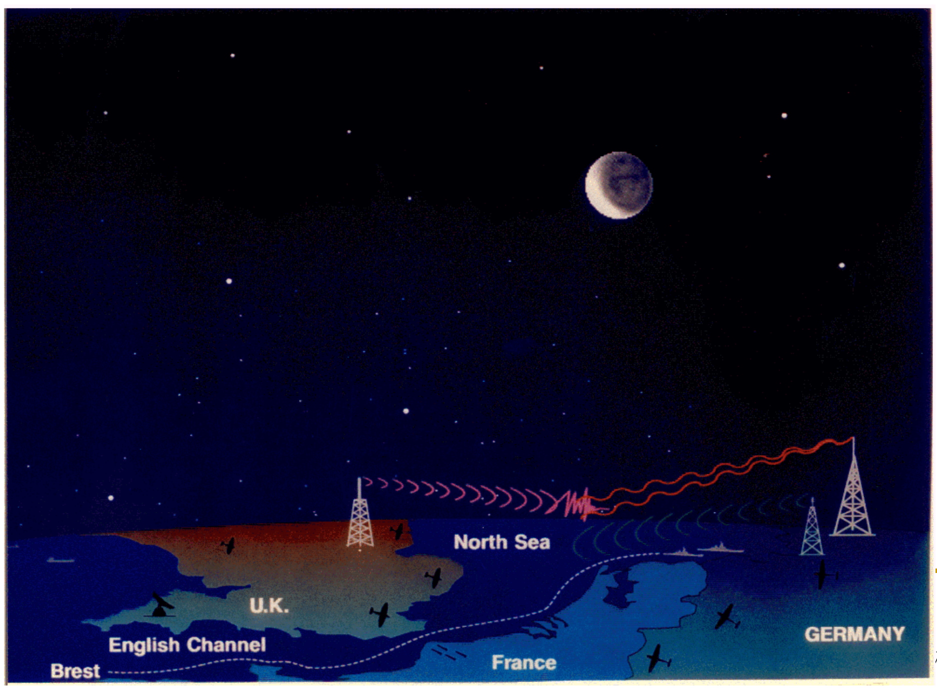
Space Weather...

It was actually there long time back !..
we just did not notice

LOCATION: ENGLISH CHANNEL

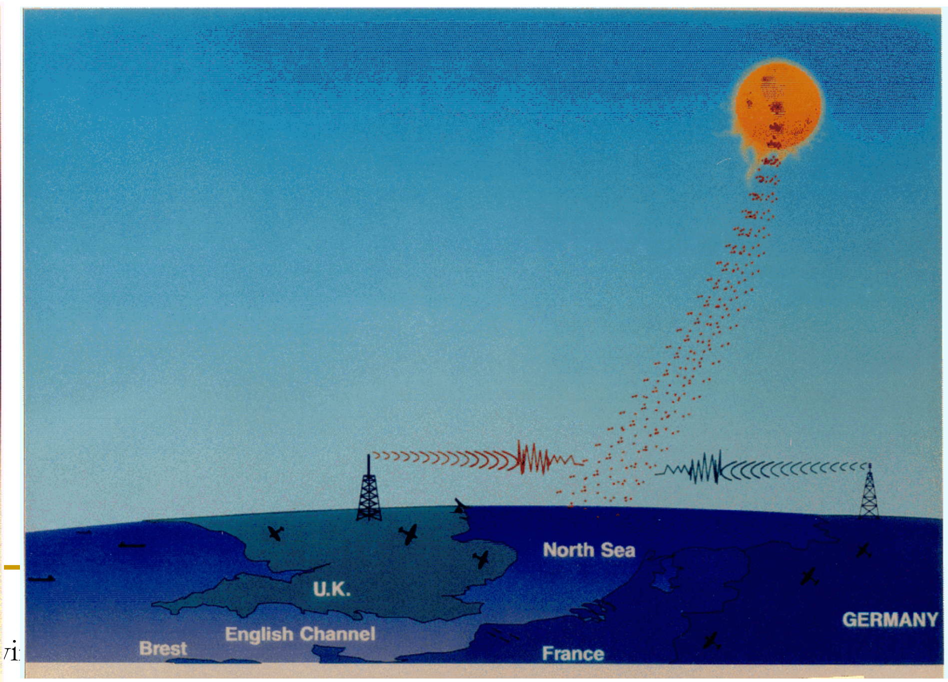
DATE: 12 FEBRUARY 1942

Incident: Jam in British Radar



LOCATION: ENGLAND
DATES: 27 and 28 FEBRUARY 1942

Incident:
Solar radio emissions jam radars



Radiation effect on airplane flights and aircrew

Effects on Spacecraft & Aircraft

Radiation effect on spacecraft systems and instruments

Spacecraft anomalies: from -------- **easily recovered**
to -------- **total mission failure**

-- **engineering** (operation fault, mechanism failure and ageing)
-- ***space weather can not tolerate any kind of engineering faults***

Surface charging	|	Photonics noise
Deep dielectric charging	|	Total dose effects
Single Event Upset (SEU)	|	Material degradation
Solar radio frequency interference	|	Spacecraft drag

Space Weather Impacts on Aviation

Space Weather Impacts on Aviation

Solar Flare Radio Blackouts: disturbances of the ionosphere caused by X-ray emissions from the Sun. HF radio degradation or blackouts are possible at middle and low latitudes.

Solar Radiation Storms: elevated levels of radiation that occur when the numbers of energetic particles increase. Typical effects from solar radiation storms include degradation of satellite tracking and power systems, radiation hazards to humans in flight at high altitudes or high latitudes. HF radio blackouts at high latitudes and induced positional errors to GPS are also possible.

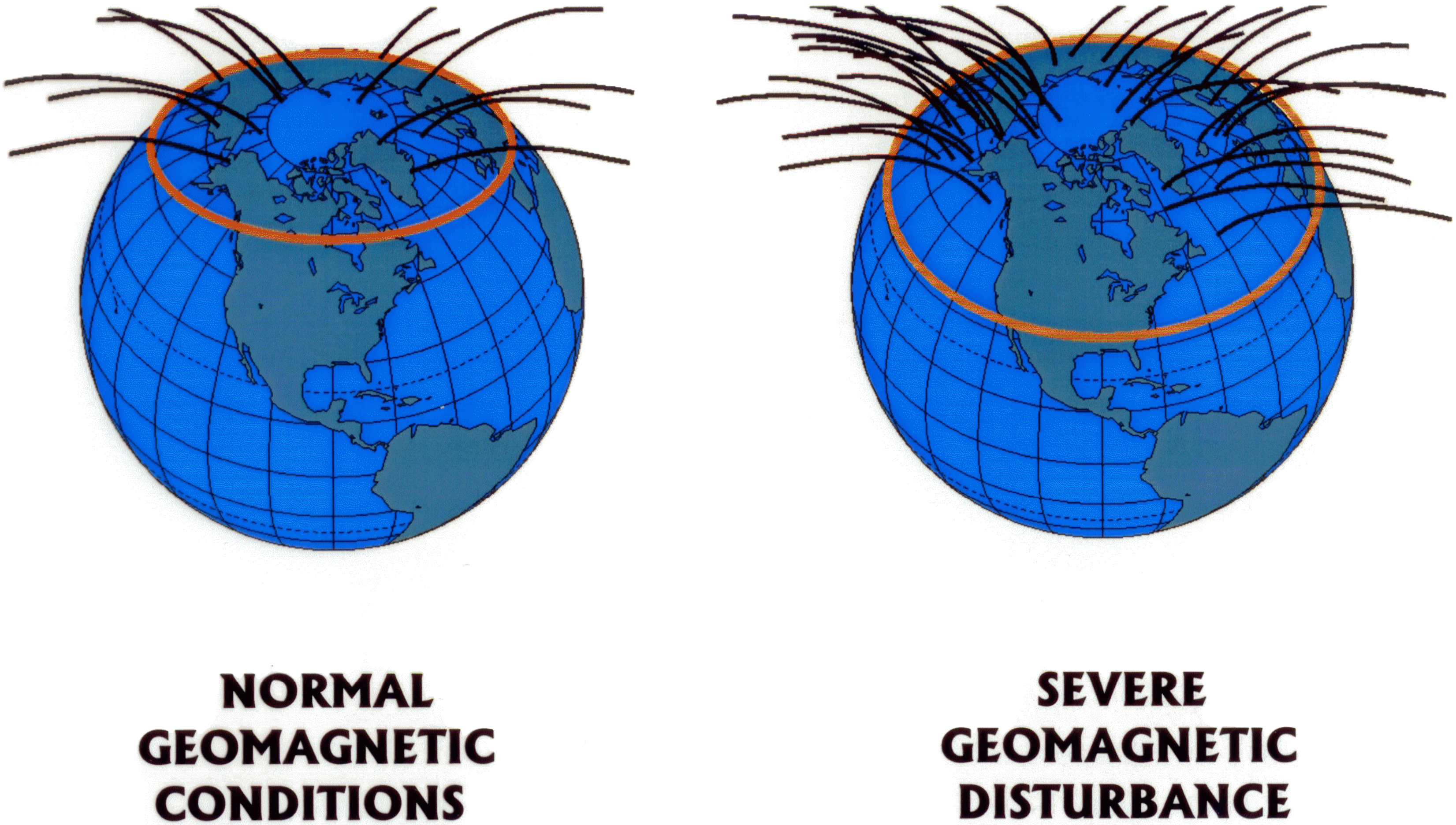
Geomagnetic Storms: disturbances in the geomagnetic field caused by gusts in the solar wind that blows by Earth. Typical effects from geomagnetic storms include degradation of HF radio transmissions, satellite navigation degradation, and disruption of low frequency radio navigation systems. Geomagnetic storms can also disrupt electrical power grids and ATC facilities and other national air space components are susceptible to these power outages. Geomagnetic storms also weaken the ability of the Earth's magnetic field to deflect incoming charged particles.

Box 2. Summary of space weather impacts on aviation.

Radiation Sources

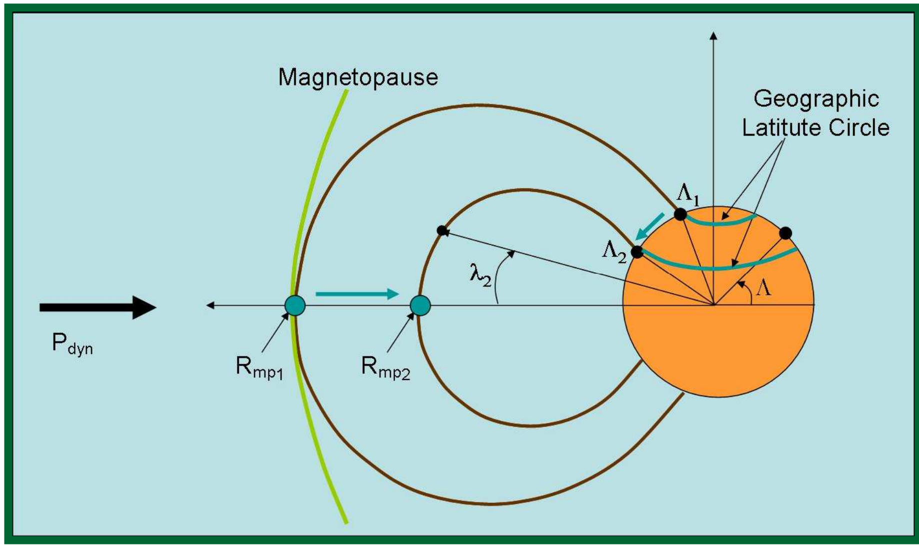
- In flight, there are two principal sources of natural radiation to consider:
    - Galactic Cosmic Rays (GCR) which are always present, and
    - Solar Energetic Particle (SEP) events, sometimes called Solar Cosmic Ray (SCR) events, which occur sporadically.

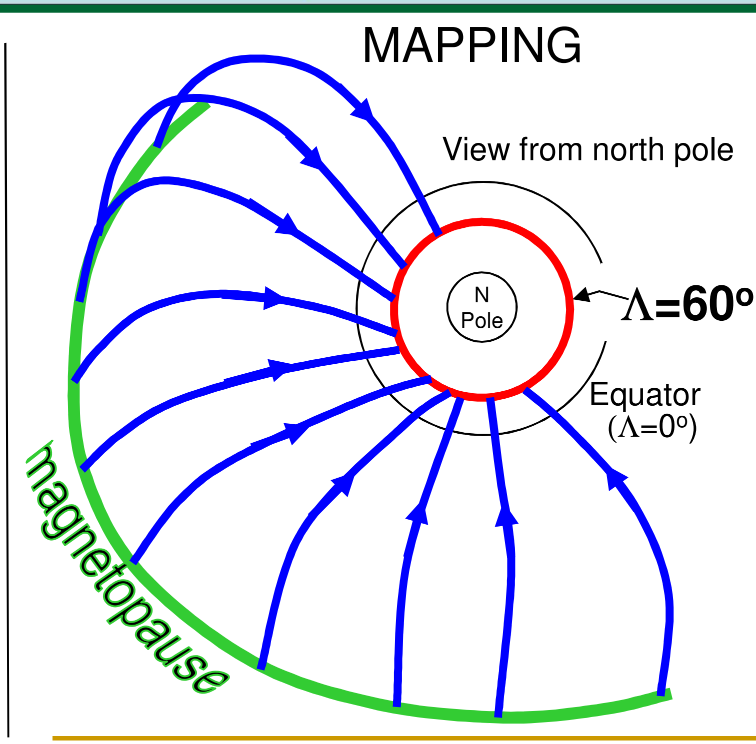
Earth's Polar Regions

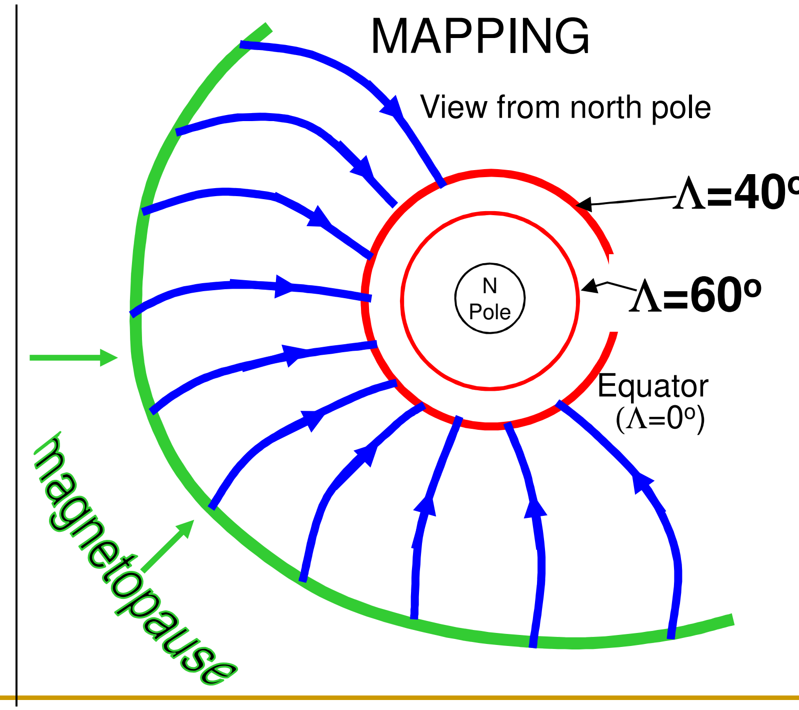


Conceptual view of solar proton access to the northern polar regions during
(left) quiescent conditions and
(right) disturbed conditions when the auroral oval is displaced equatorward.

Field Line Mapping

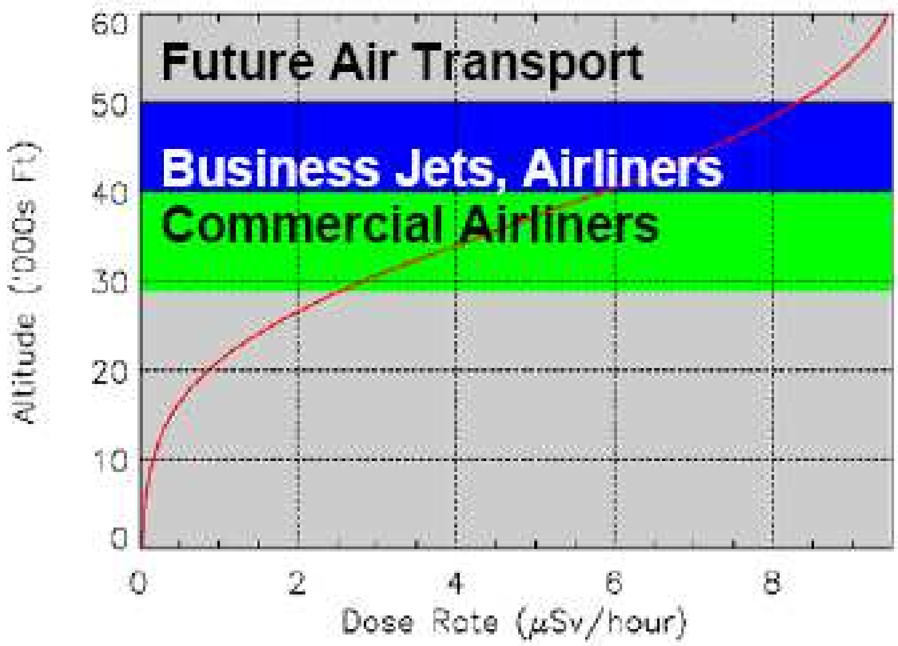






Hazards to Humans: Cosmic Radiation

- Start interacting with atmosphere at about 130 000 ft
- Secondary particles move deeper in the denser atmosphere
- Radiation dose from this particle shower reaches maximum at about 20 km
- Decreases towards sea level
- Dose rates incrfeases with increasing latitude until reaching 50 deg latitude where it stays constant



Change in dose rate due to cosmic Radiation as a function of altitude and aircraft type

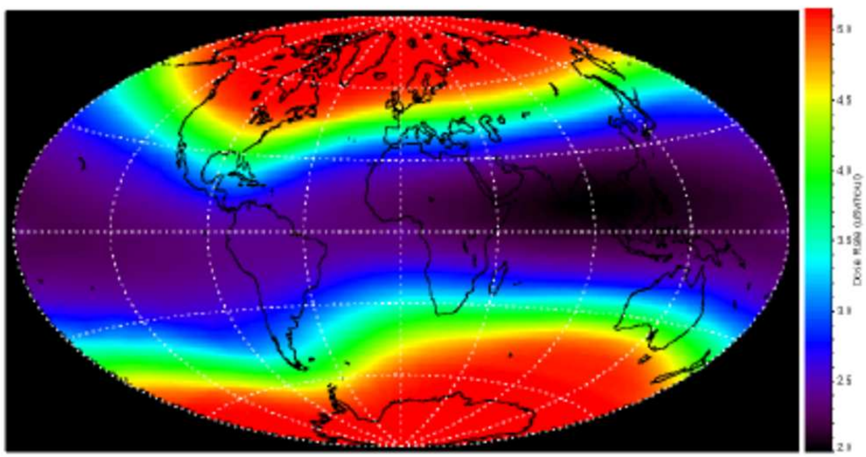


Figure 3. Projected global dose rate at 35,000 ft (Image courtesy SolarMetrics Limited).

Hazards to Humans: Cosmic Radiation

- Dose rate at about 12 km in mid-latitudes (23,5-66,5deg) is typically up to about 6microSieverts (μSv) per hour.
- Near equator, 3μSv/hr
- 1 Sievert is a measure of potential harm from ionizing radiation
- 1Sv=1 joule/kg
- Typically London to Los Angeles flight in a commercial airplane accumulaes about 6,5 μSv/hr.
- Solar cycle can cause +/- 20% variations in dose from solar minimum to solar maximum.

SPEs and radiation dose

- SPEs increases the radiation dose at airplane altitudes
- Solar flares emits with energies up to 10's of MeV (unit of energy)
- Only protons with energies up to 300 MeV can produce radiation effects on aircraft altitudes
- On average 3 events over a solar cycle with suffiecient intensity and energies to produce significant effects in the atmosphere

- SPE event of 1956
- Radiation dose received at 12 km on the transatlantic flight would havebeen approximately 10 μSv.
- Such events are rare:once every 100 years
- Smaller more typical events in Sept and Oct 1989 indicate 2mSv fora similar flight

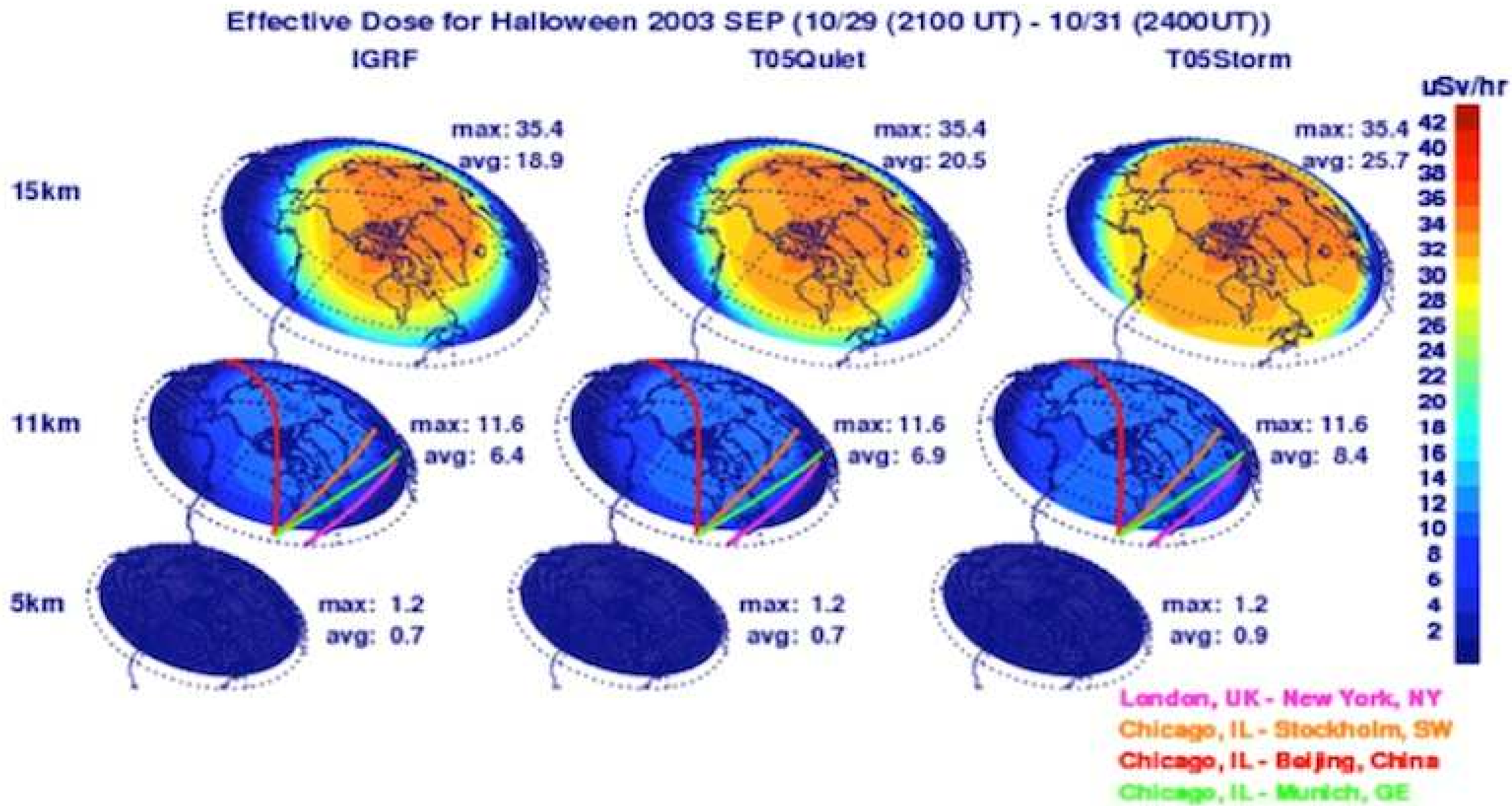
Dose Equivalent Rate (micro-sieverts per hour (μSv/h)

	Solar Minimum (10/86)		Solar Maximum (7/89)	
Altitude (x1000 ft)	35 degrees North Latitude	70 degrees North Latitude	35 degrees North Latitude	70 degrees North Latitude
0	0.0401	0.0412	0.0374	0.0380
10	0.190	0.207	0.173	0.181
20	0.985	1.14	0.875	0.953
30	3.25	4.06	2.85	3.24
40	6.78	9.02	5.88	6.99
50	9.71	13.8	8.36	10.3
60	11.1	17.1	9.49	12.3
70	11.4	19.2	9.68	13.3
80	11.2	20.6	9.44	13.8

- The table gives estimates of the radiation dose equivalent at the times of a recent solar minimum (10/86) and solar maximum (7/89) for representative high and low latitude locations at 90 degrees west longitude as a function of altitude.

- These values were obtained through the use of the CARI-6 program developed by the Civil Aeromedical Institute of the Federal Aviation Administration.

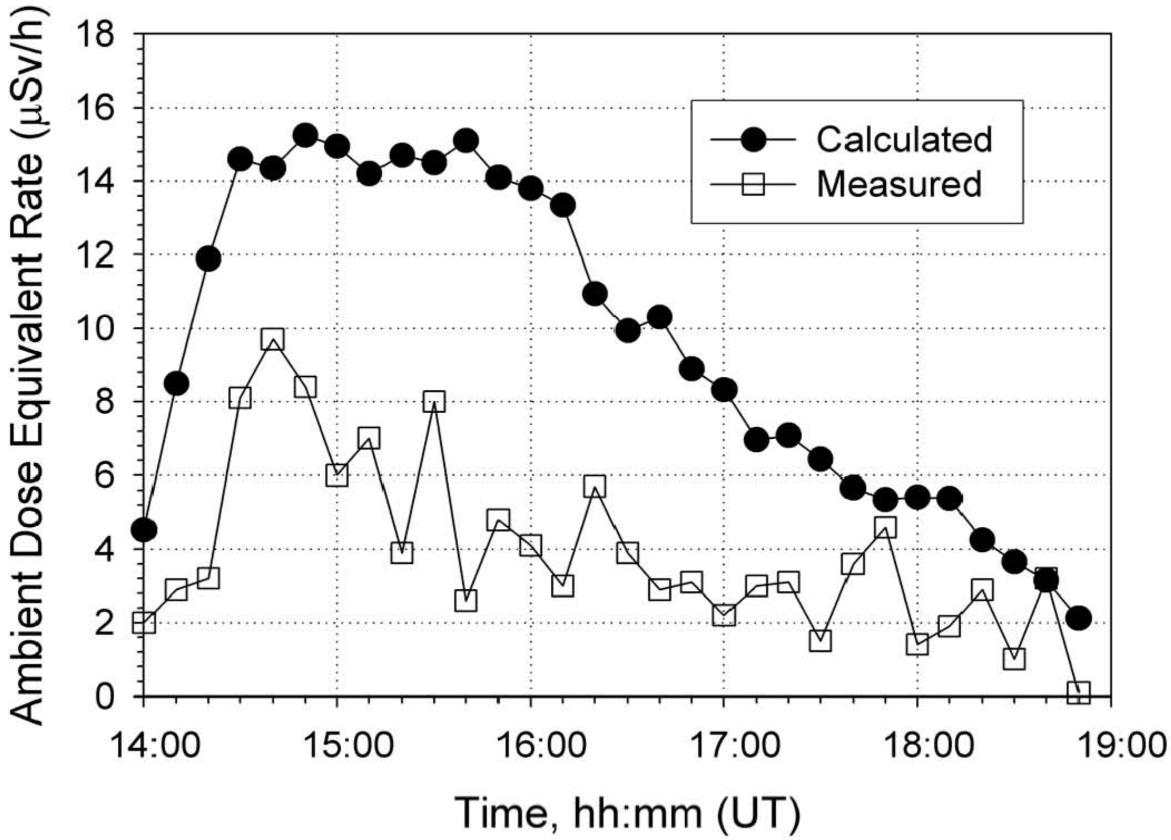
High altitude flights and radiation dose



- The image shows global snapshots of atmospheric effective dose rates over the northern hemisphere polar region for a Halloween 2003 SEP event.
- The effective dose rates are shown at three altitudes and for three different magnetic field models used in the cutoff rigidity simulations.
- Geomagnetic effects have a large influence of SEP radiation exposure, especially along the north Atlantic corridor region, and their neglect can underestimate the predicted radiation exposure by over a factor of two.

Radiation Dose and Airplane Flights

Radiation Dose that the flight is subjected to



Calculated and measured ambient dose equivalent rates from solar cosmic radiation on 15 April 2001.

Measurements (Spurný and Dachev, 2001) were made using an MDU spectrometer on an A310-300 flight from PRK to JFK.

From prag to newyork

ESTEC/ESA

Polar Flights

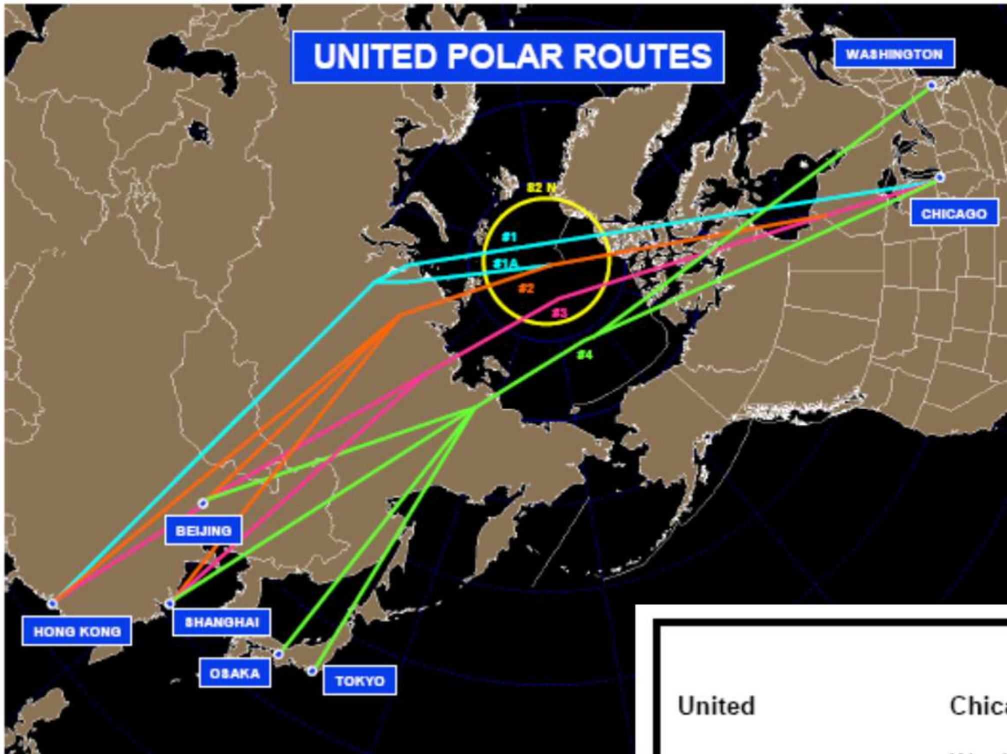


Figure 1. Polar Routes used by United Airlines (

Airlines Flying North Polar Routes

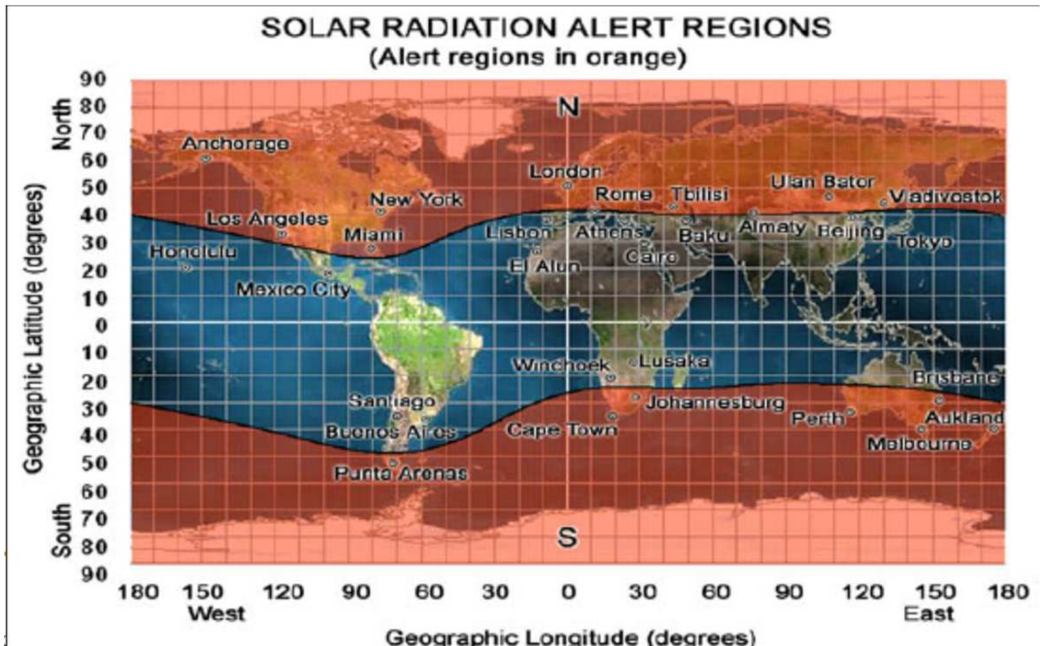
United	Chicago:	Hong Kong, Beijing, Tokyo, Shanghai, Osaka
	Washington (IAD):	Tokyo
Continental	Newark:	Hong Kong, Beijing, Tokyo
Air China	New York (JFK):	Beijing
Cathay Pacific	New York (JFK):	Hong Kong
Singapore	Newark:	Singapore
Air Canada	Toronto:	Hong Kong, Beijing, Shanghai, Seoul, Tokyo
Northwest	Detroit:	Tokyo
Thai	New York (JFK):	Bangkok
American	Chicago:	Shanghai
Korean	Seoul:	from New York (JFK), Washington (IAD), Chicago (ORD), Atlanta (ATL), Toronto (YYZ)

Expected to Fly Polar: Asiana, Japan, All Nippon

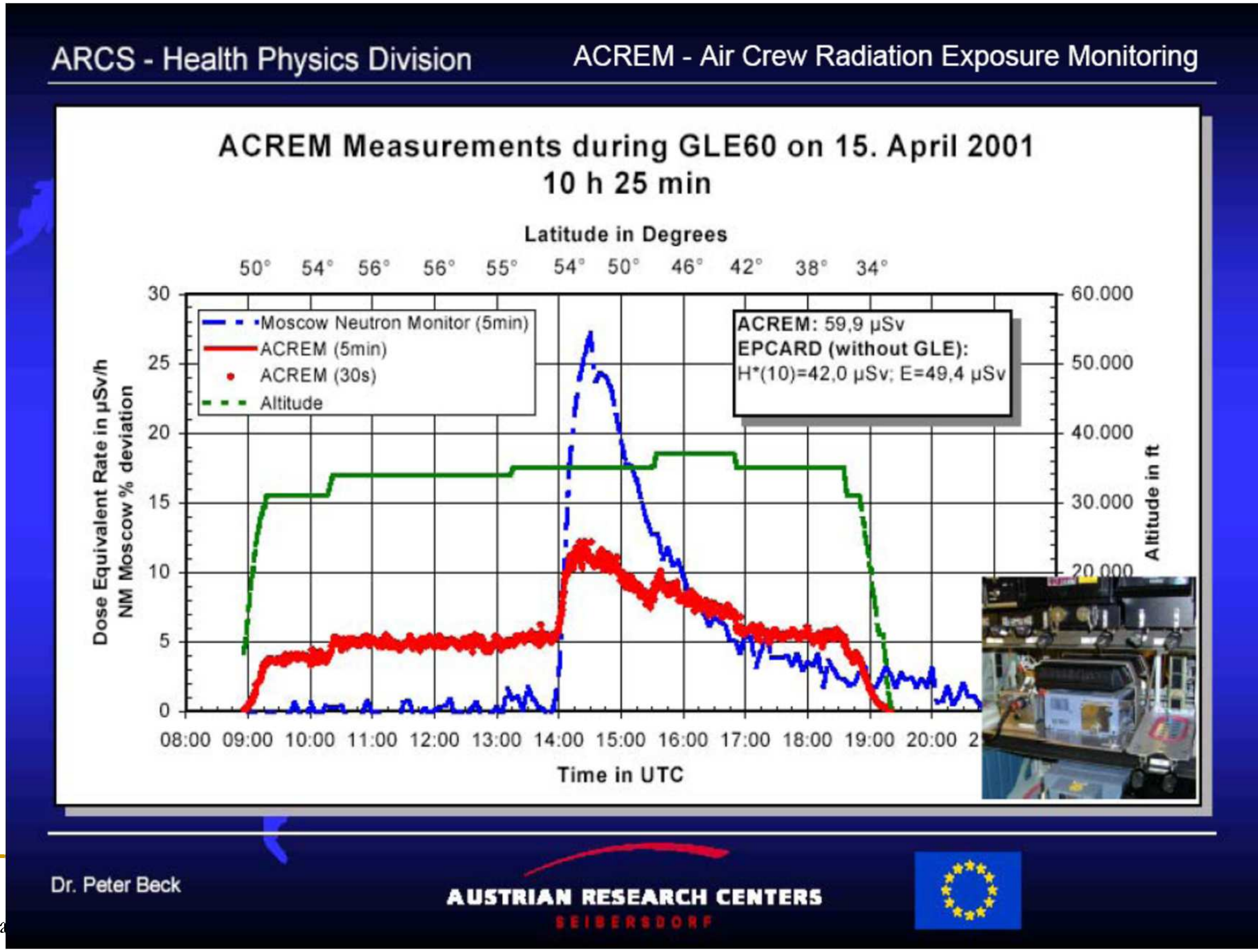
Box 1. Airlines flying north polar routes (Source: Dave Rome, NAVCANADA).

Airlines avoid polar routes during Radiation Storms due to both exposure and communications concerns

- Polar regions which are subjected to radiation dose is shown in orange



Measurements during GLE60 Flight on April 15, 2001
ACREM-Air Crew Radiation Exposure Monitoring



Times scales and Alerts

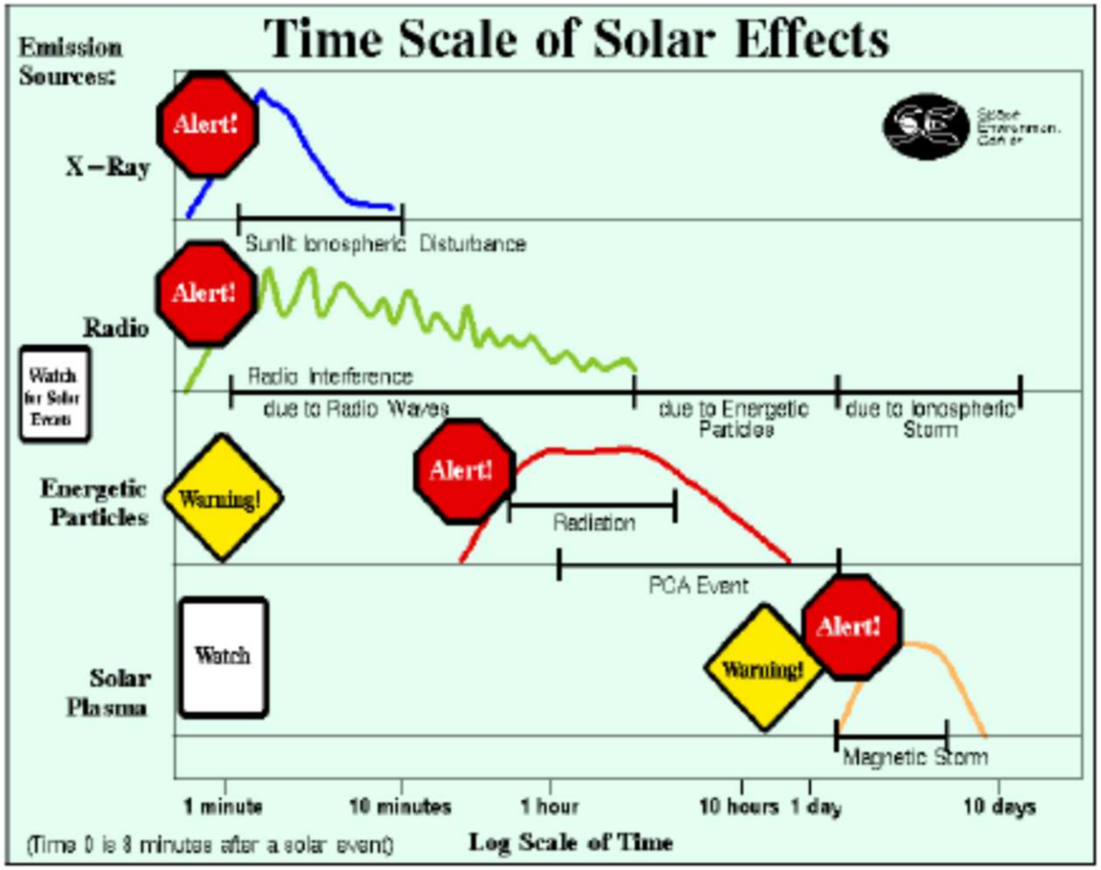
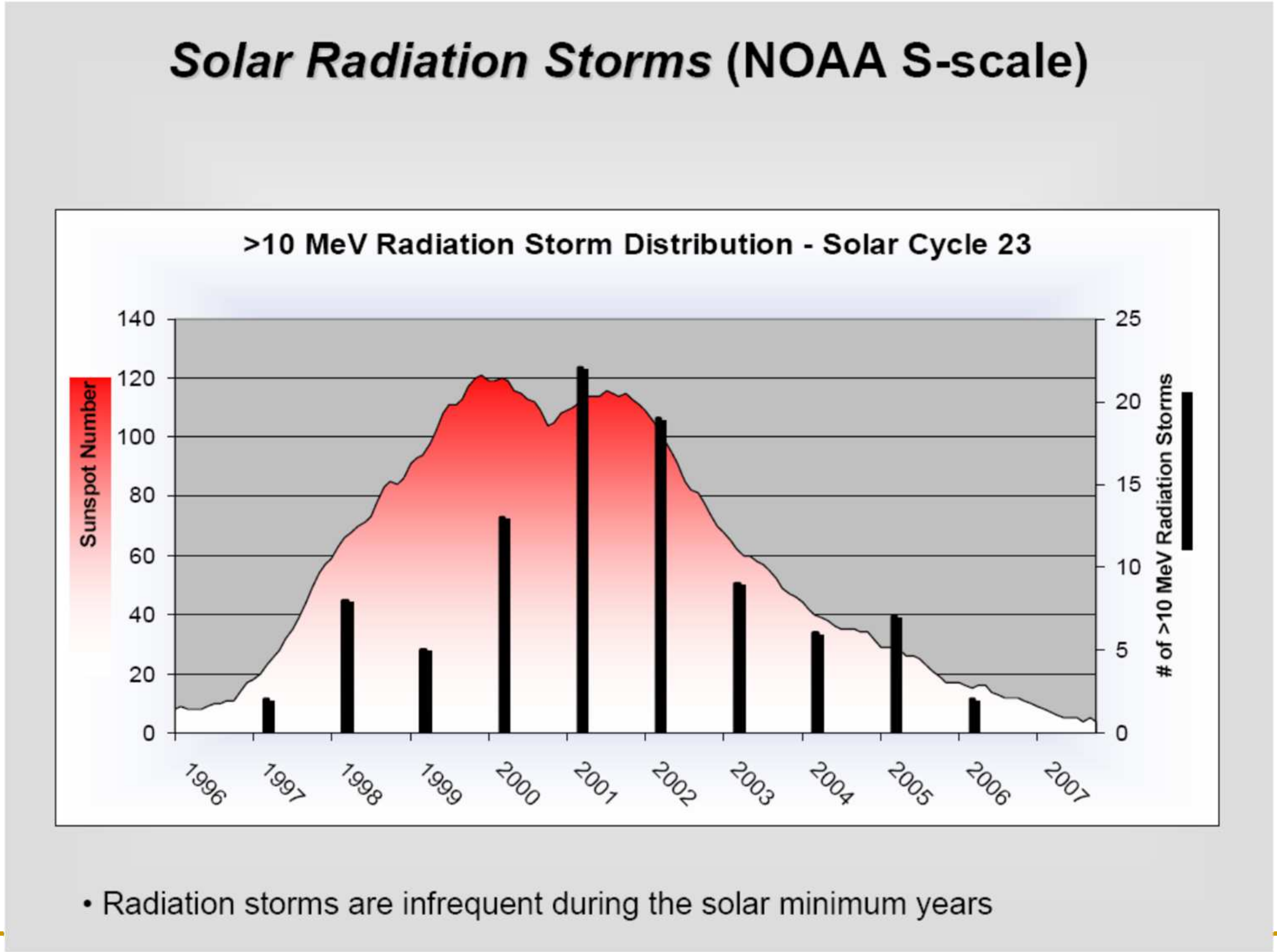
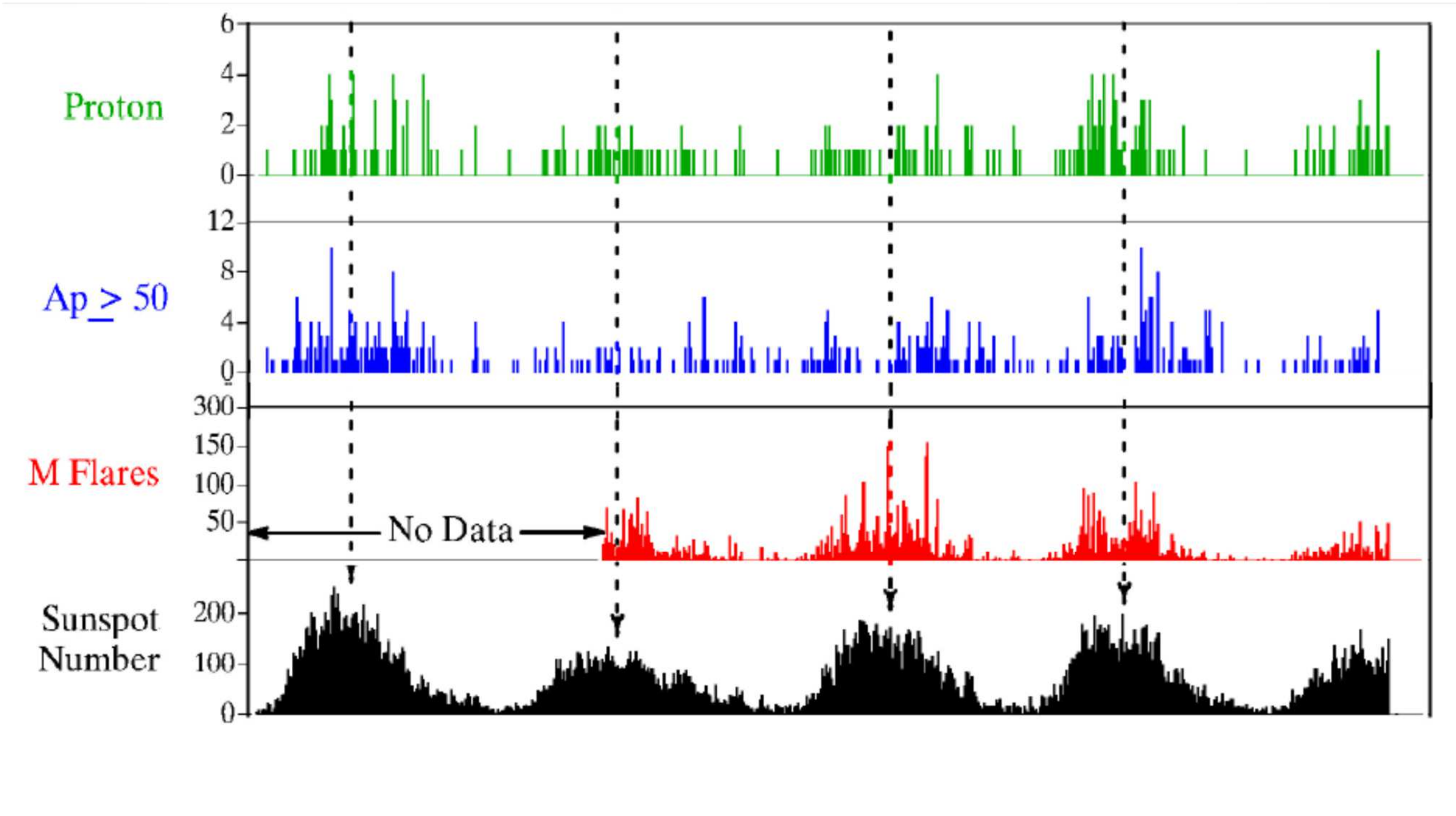


Figure 2. The time scales of solar effects (source: NOAA SEC). Eight minutes after a flare and/or a CME erupts from the Sun, the first blast of Extreme Ultraviolet (EUV) and X-ray light increases the ionospheric density, which can impact HF communication loss. 10 minutes to several hours later, energetic particles arrive. One to four days later, the CME passes and energizes the magnetosphere and ionosphere, affecting navigation systems and radio communications.

Sunspot number-Number of >10MeV Radiation storms Relationship



Sunspot number, Flare, Ap and Proton Event Relationship



Radiation Belts and Energetic Particle Flux

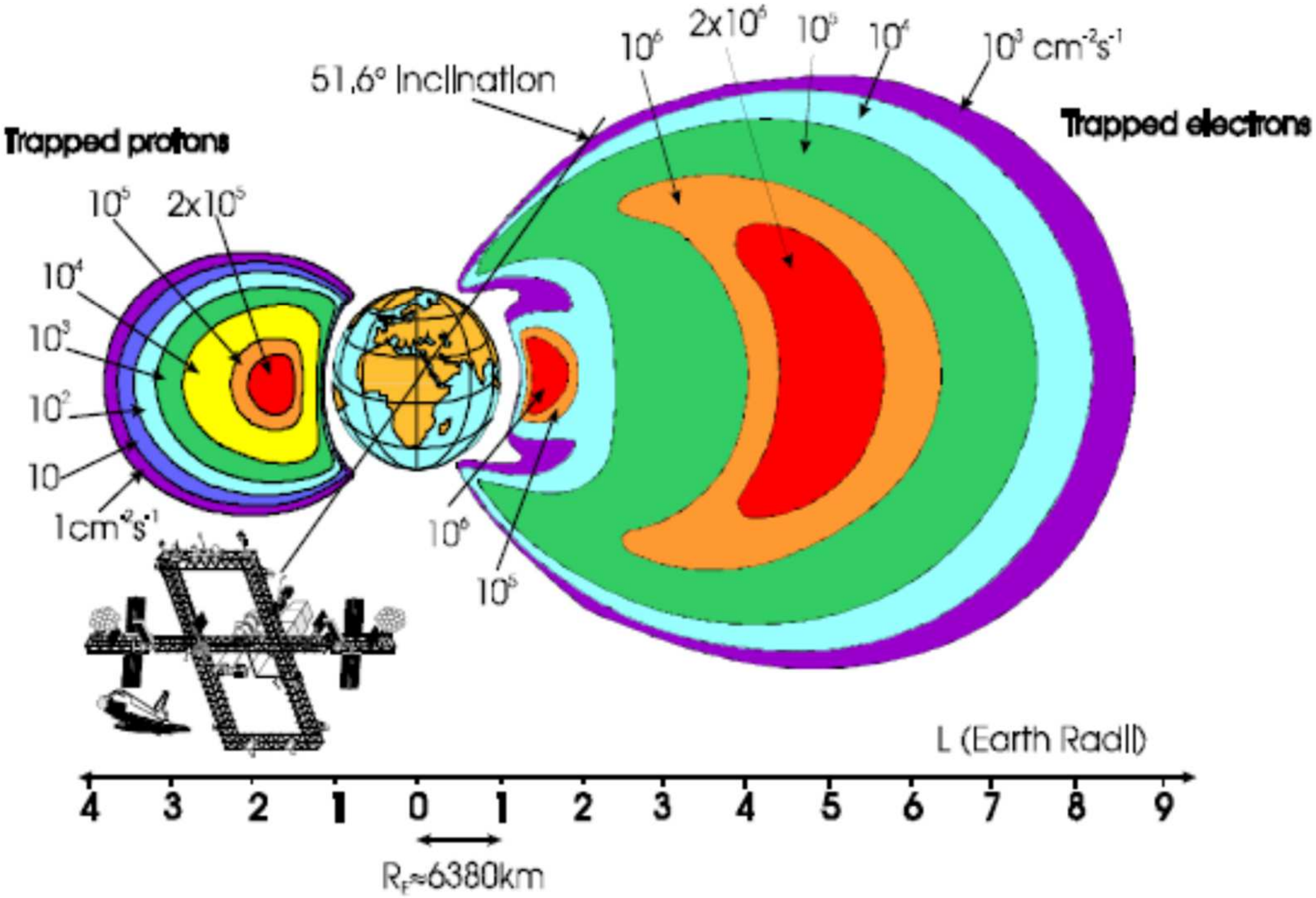


Fig. 1. Artist's impression of the radiation belts.

Altitude Distribution of Neutron Flux

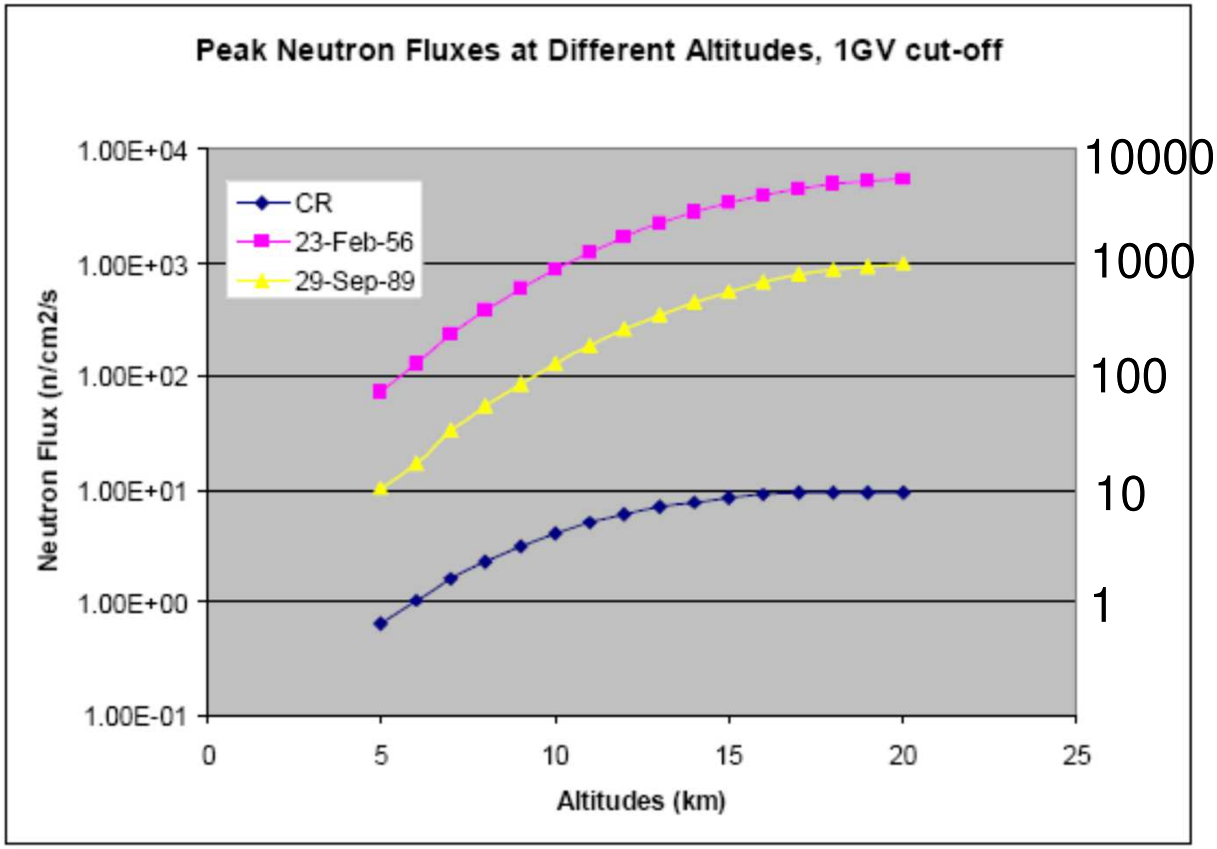
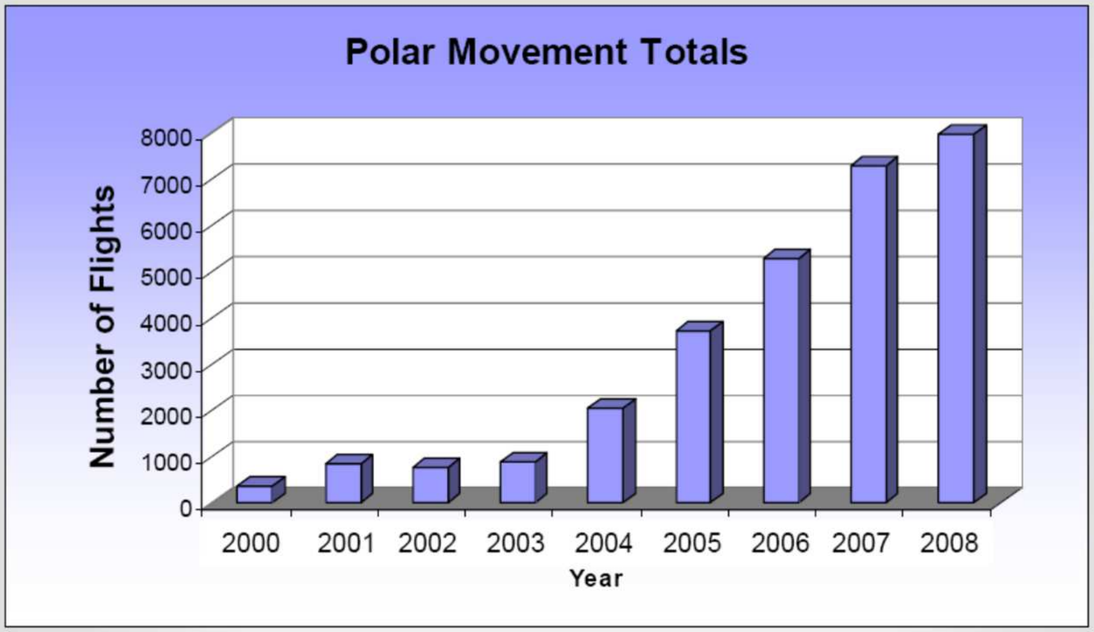


Fig.3. The calculated altitude profiles of the peak neutron fluxes at 1 GV show large increases for the solar particle events of 23 Feb 1956 and 29 September 1989 compared with cosmic ray fluxes. The solar particle fluxes also increase much more rapidly with altitude.

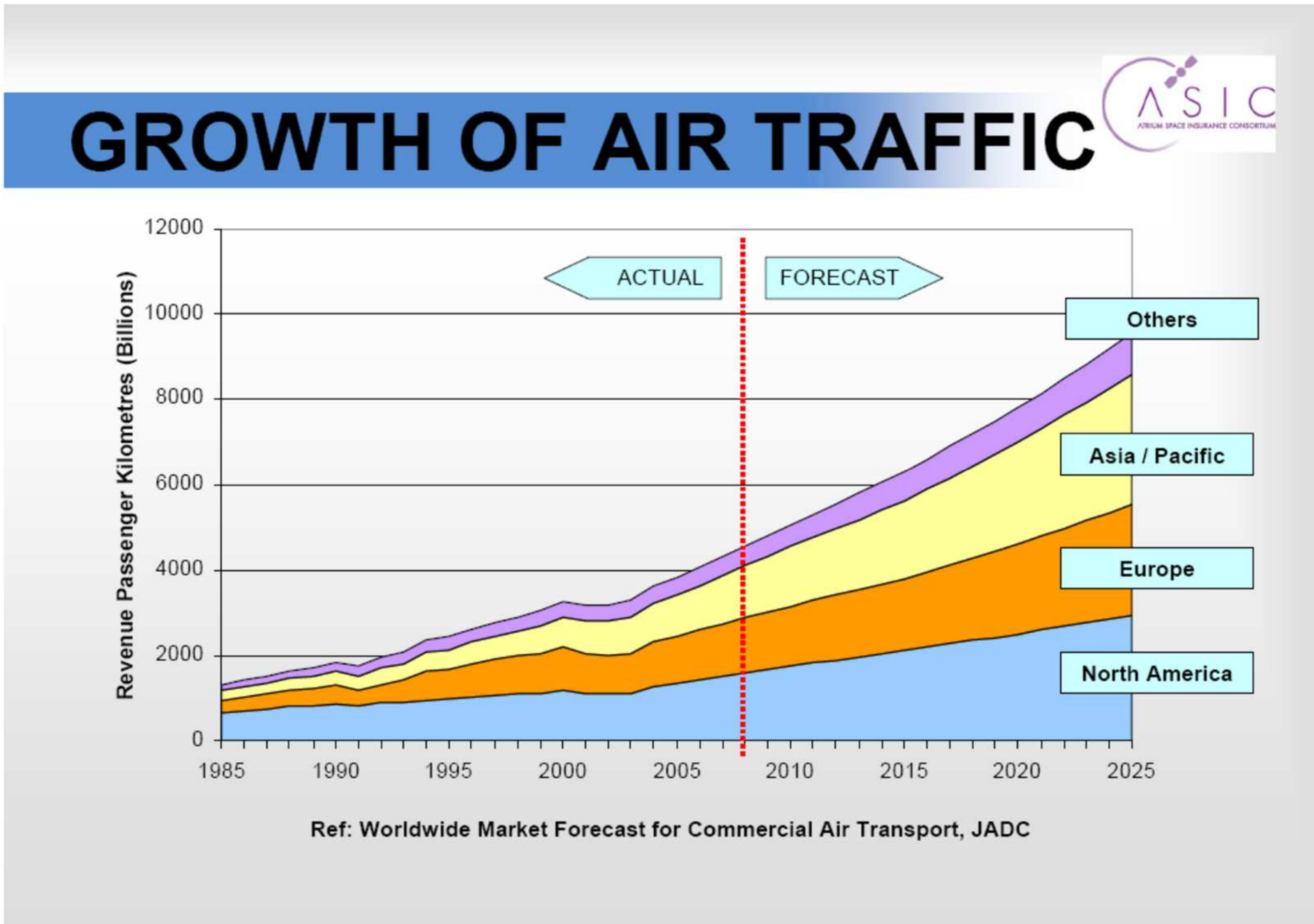
Increased Polar Flights and Passenger Information

Cross Polar Aviation



Polar Route Passenger Movement				
	2004	2009	2014	2019
Capacity	228,000	384,000	972,000	1,768,000
Avg. Annual Growth Rate		13.9%	20.4%	12.7%

Growth of Air Traffic



Polar warnings

***ALERT**: Solar Radiation Alert at Flight Altitudes Conditions Began: 2003 Oct 28 2113 UTC*

*Comment: **Satellite measurements indicate unusually high levels of ionizing radiation, coming from the sun. This may lead to excessive radiation doses to air travelers at Corrected Geomagnetic Latitudes above 35 degrees north, or south.***

(Federal Aviation Administration)

Warnings/Rules/Laws/Directives

- **"Eurocontrol Studying Effects Of Solar Events On GNSS Signals."**
  Inside GNSS
- (7/1) , "Eurocontrol, Europe's air traffic control agency, is studying the effect of solar events on civil aviation applications and developing ways to maintain air safety when GNSS signals are affected." This is a "key" issue, according to the article, for the Single European Sky ATM Research (SESAR) program which will update Europe's air traffic control system. "Eurocontrol has contacted with French engineering consultants Egis Avia to study the effect of ionospheric disturbances on GNSS-based applications for different phases of flight, then develop and test mitigation techniques."
  - *Inside GNSS*

http://mailview.custombriefings.com/mailview.aspx?m=2010070201aiaa&r=2913954-cede&l=020-9e7&t=c>

Directive 96/29/Euratom – Ionizing Radiation

- Establishes uniform basic safety standards to protect the health of workers and the general public against the dangers of ionising radiation.
- Article 42 of the Directive imposes requirements relating to the assessment and limitation of air crew members' exposure to cosmic radiation.

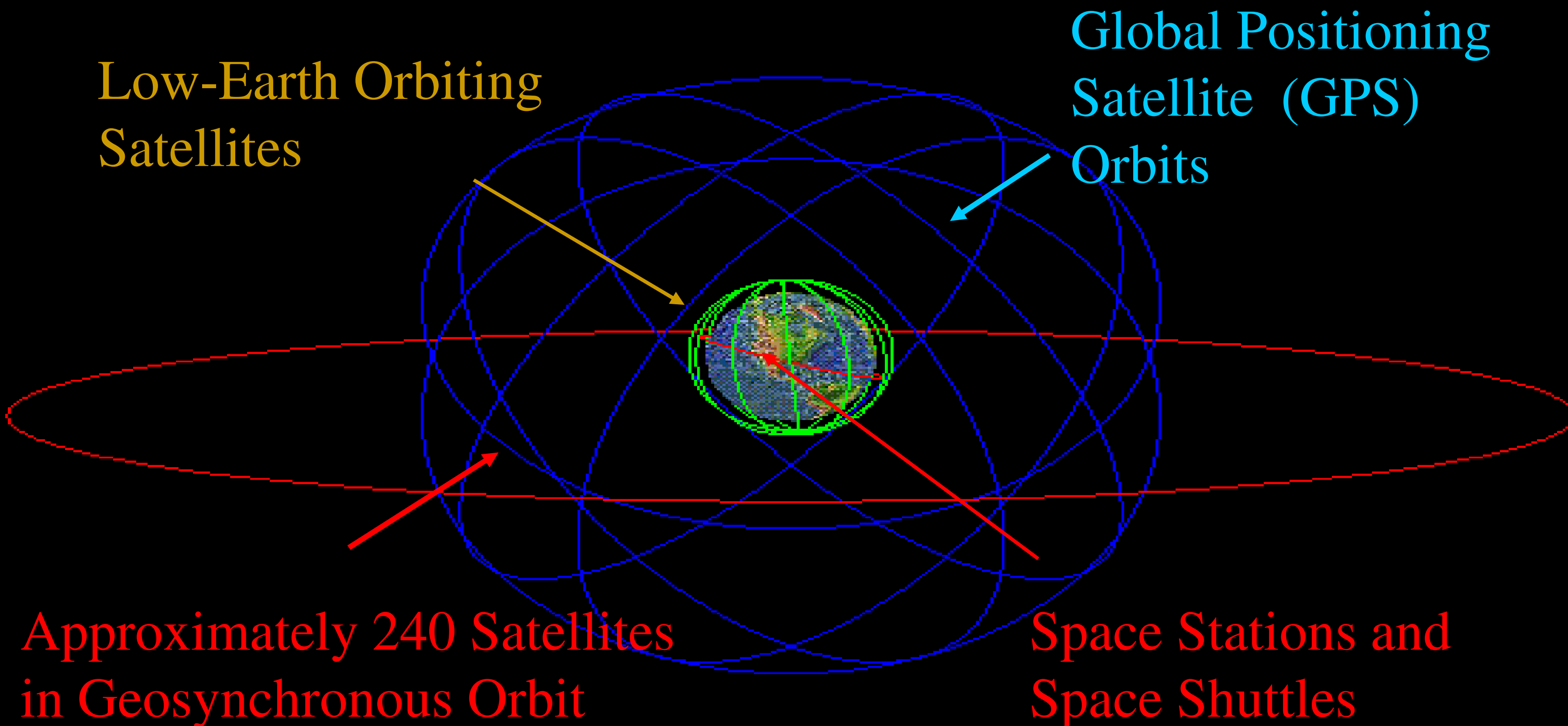
Protection?

- IPRP (International Commision for Radiological Protection)
- Recommended dose limit for aircrew is a 5-year average does of 20 miliSv per year
- No more than 50 miliSv in any single year
- For pregnant women→ different thresholds

- The council of the European Union adopted Directive 96/29 Euratom on 13 may 2000
- Article 42 of directive emposes
  - Assesment and limitation of air crew members's exposure to cosmic radiation and the provision of information on the effect of cosmic radiation
- EU adopted an action level of 6 mSv/yr beyond which EU operators must keep a record of an individuals' exposure.
- Below 6mSv exposure monitoring is only a recommendation
- Current flight profiles and annual flight hours generally make this a workable limit when monitored through nuclear power workers.
- In Japan, state regulation recommend that Japanese airlines have to try to keep their air crews below 5 mSv/yr which s the dose limit for other occupatinally exposed workers in Japan.

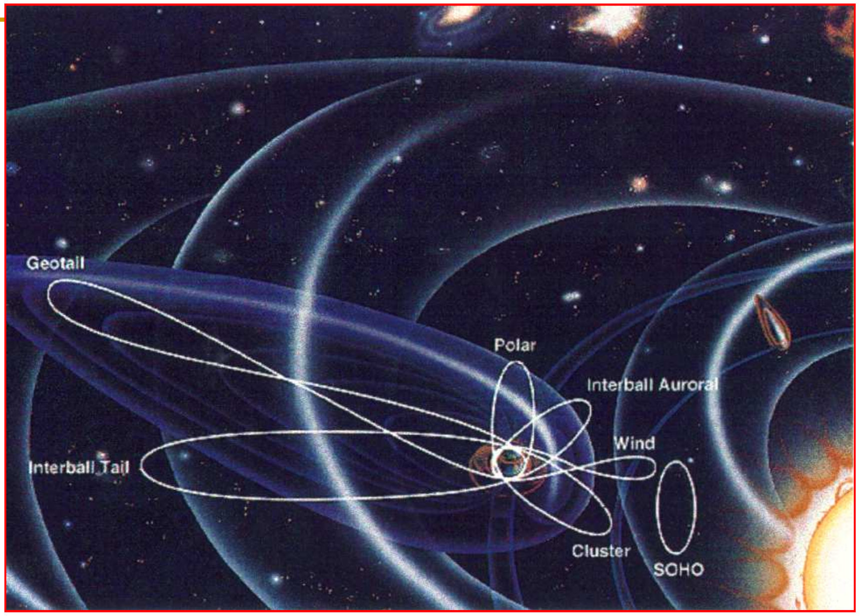
- Radiation dose, airline companies, insurance companies
  - Airlines should develop Codes and Measurement Methods for ***Air*** Crew ***Dose*** Assessments,
  - Occupational ***Insurance*** Association (BG).

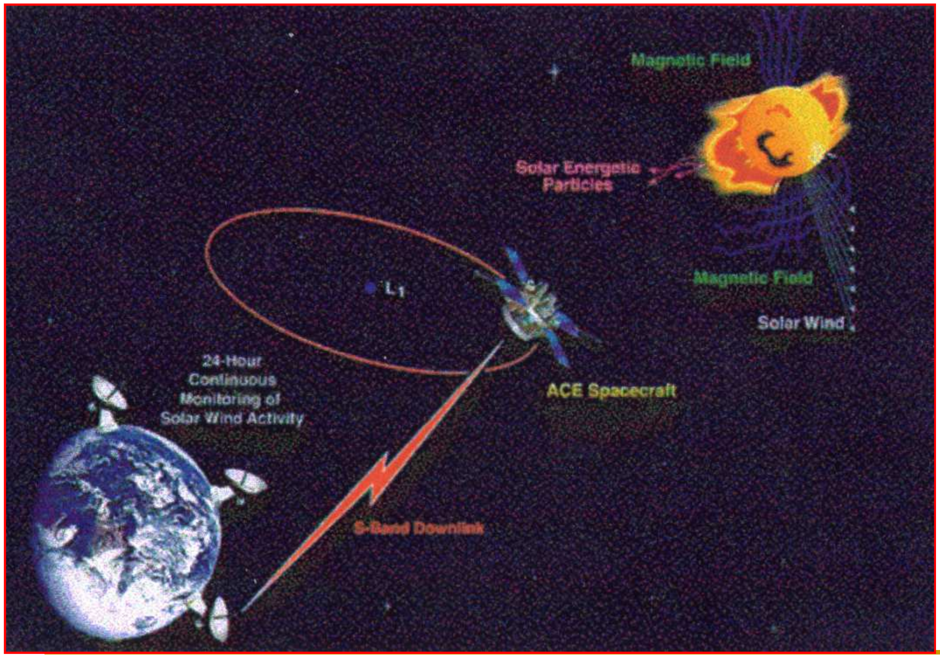
Satellites Encounter the Radiation Belts in Many Different Orbits

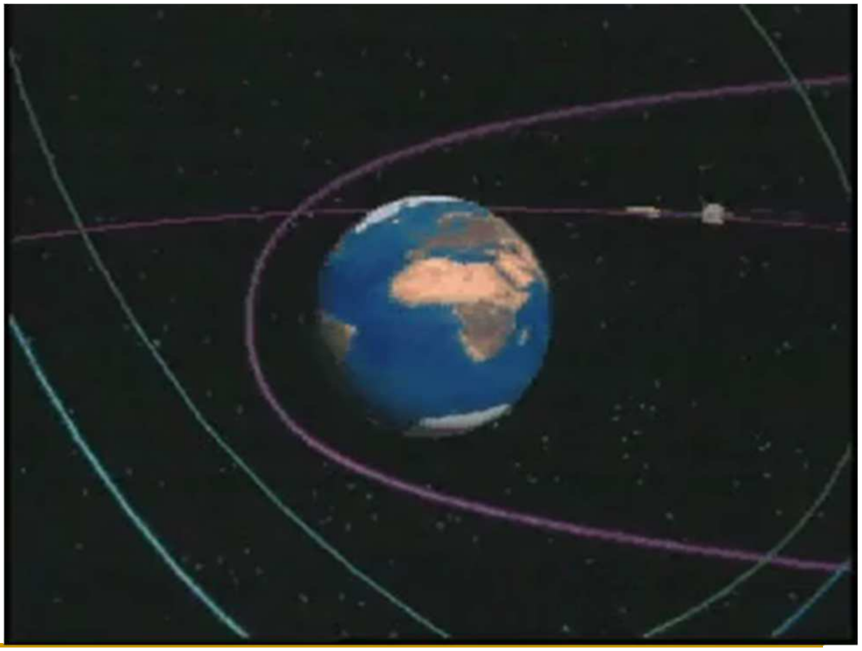


Magnetospheric Satellites

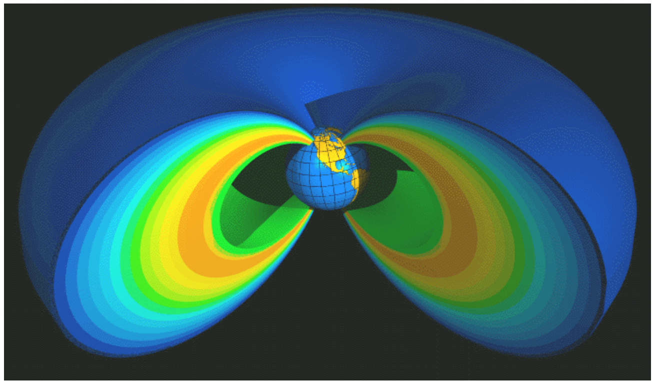
Need care !

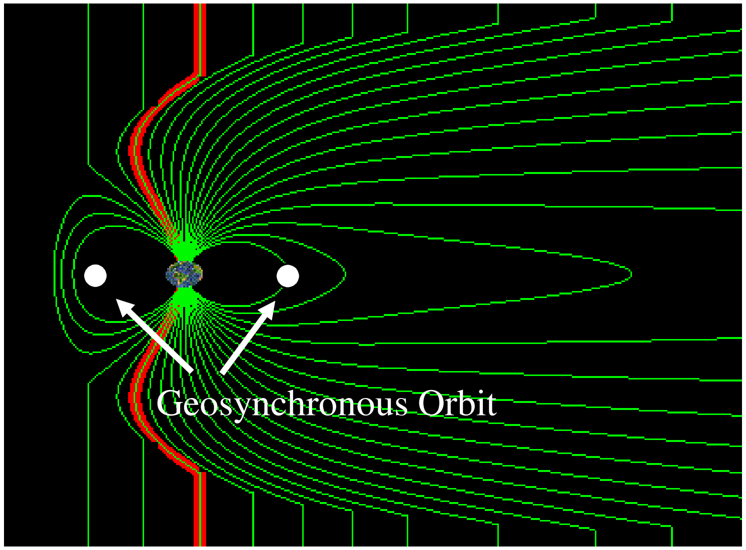






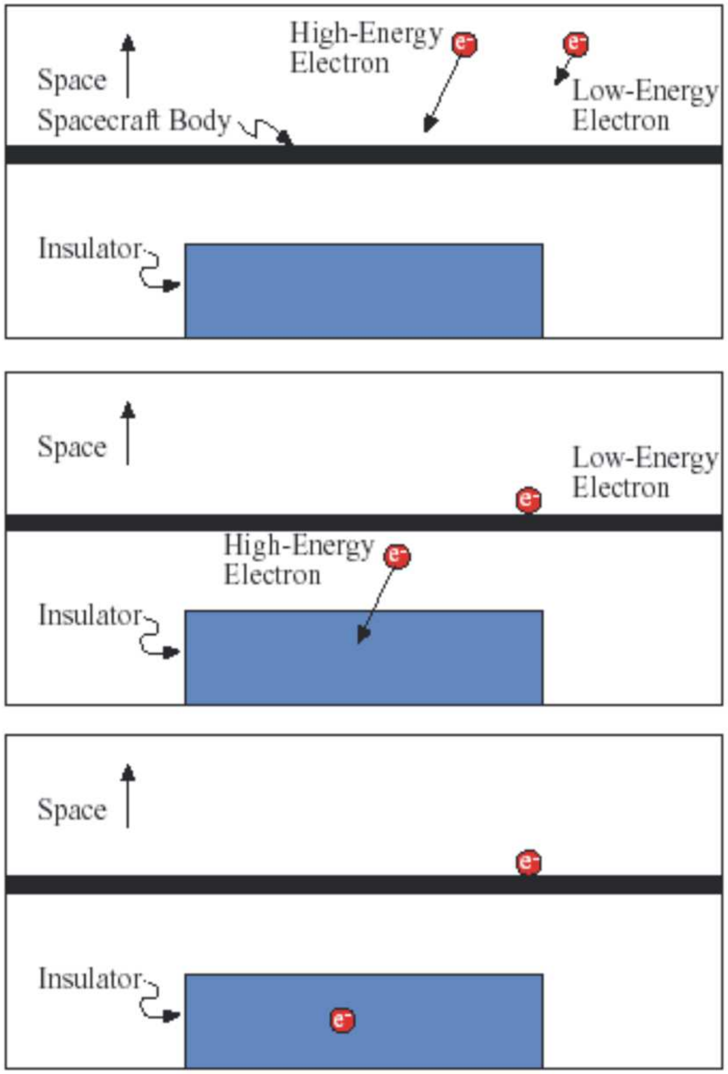
Radiation Belts





- Radiation belt fluxes peak at roughly 4 Earth radii.
- Magnetic field at geosynchronous orbit is stronger near noon than near midnight.
- Charged particles drift around Earth on roughly constant magnetic field surfaces.

SPACECRAFT CHARGING



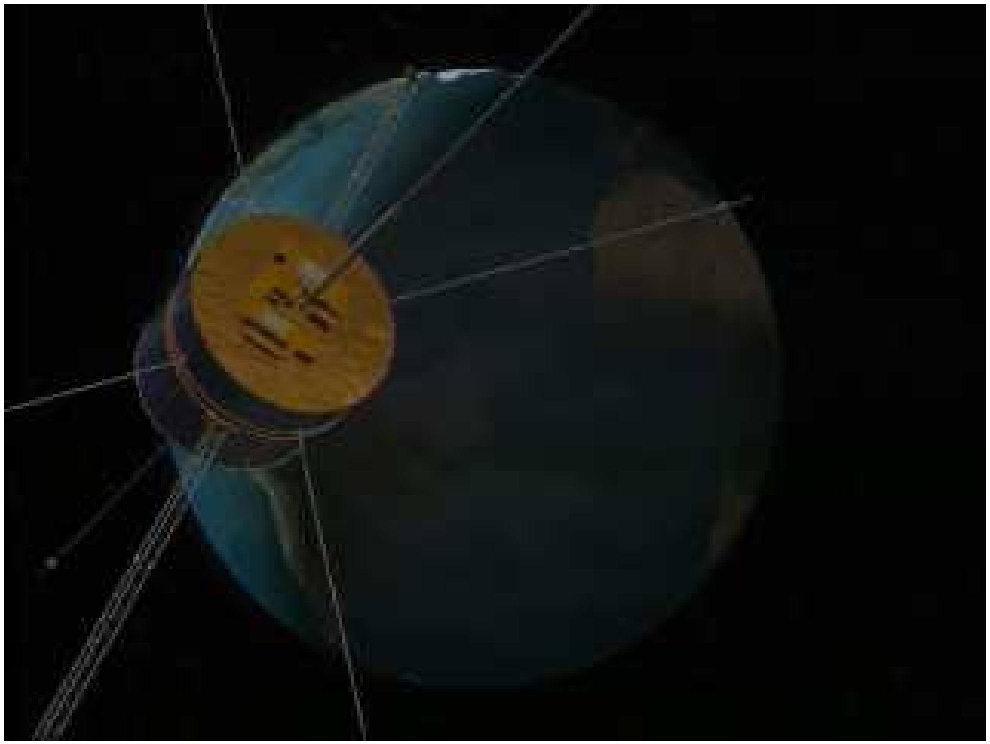
Low-energy electrons "stick" to the spacecraft surface.

High-energy electrons penetrate the satellite and can get embedded in insulating materials.

Electrons can slowly drift out of the material, and therefore long periods (days) of high electron fluxes are associated with deep-dielectric anomalies.

CHARGING ANIMATION HERE !

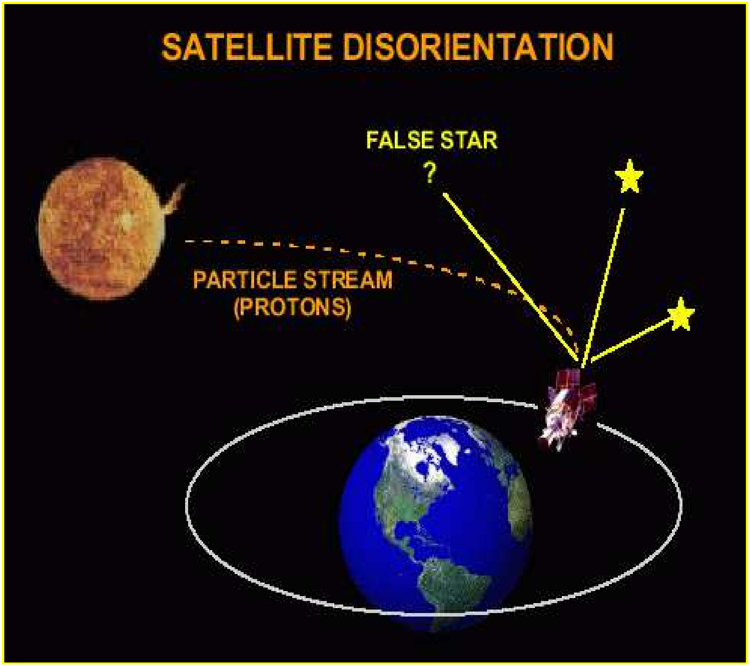
Charging Animation



Animation does not work in PPT

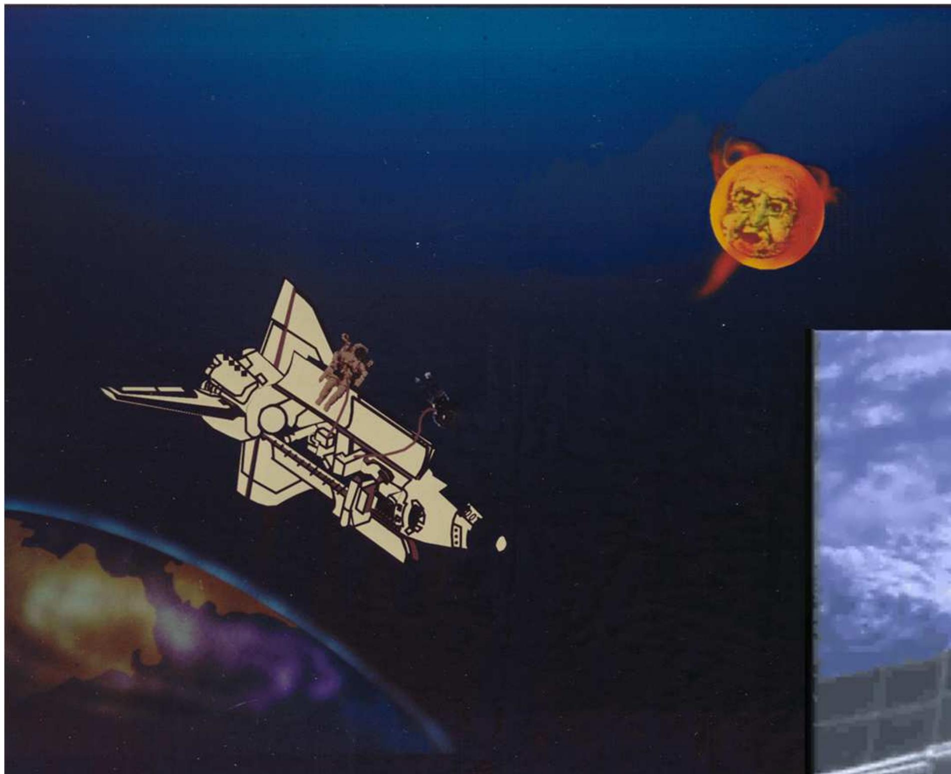
Use WinPlayer to run

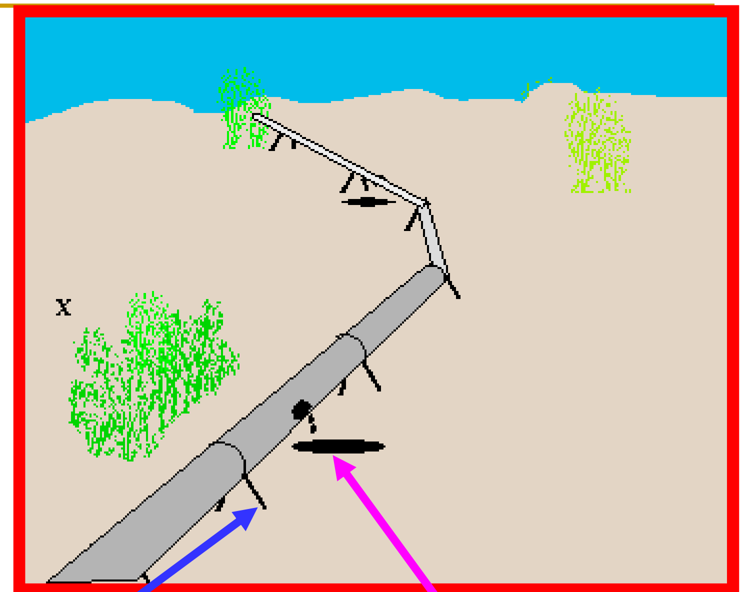
SPACECRAFT CHARGING AND DISORIENTATION



Failure of
ANIK communication satellite

Astronauts and Space walk



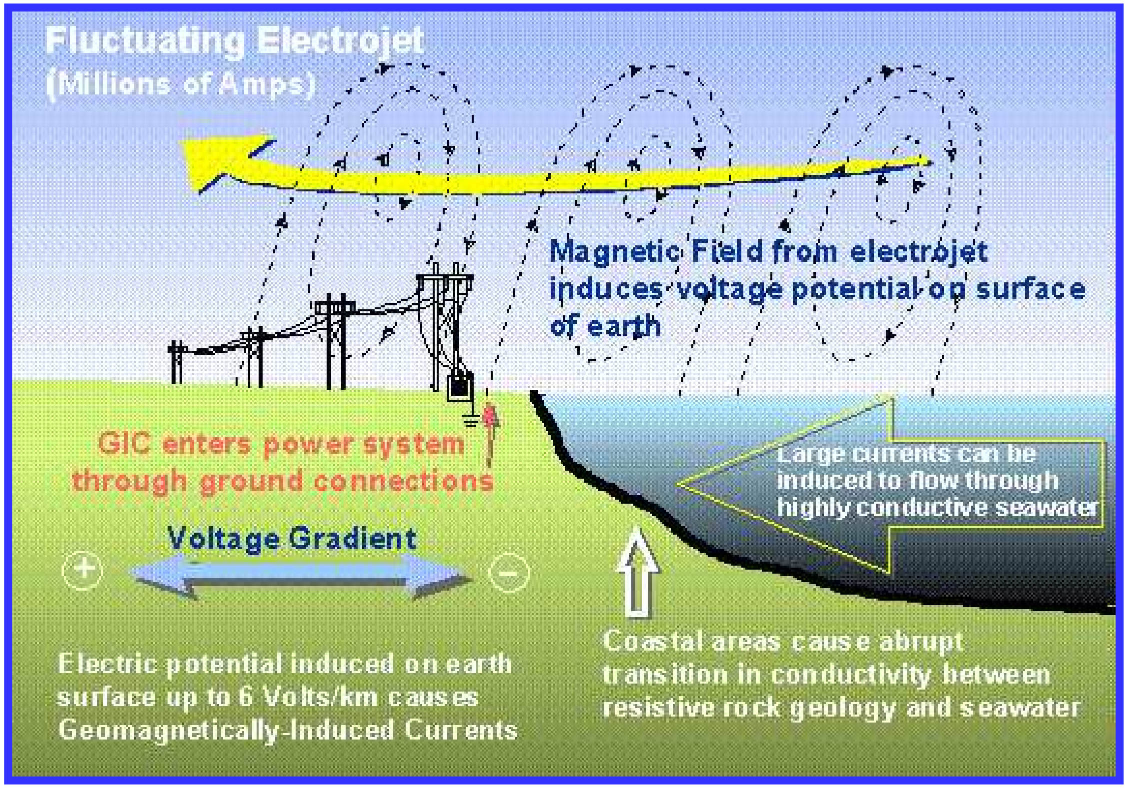


Connection Points to Ground Subjected to GIC

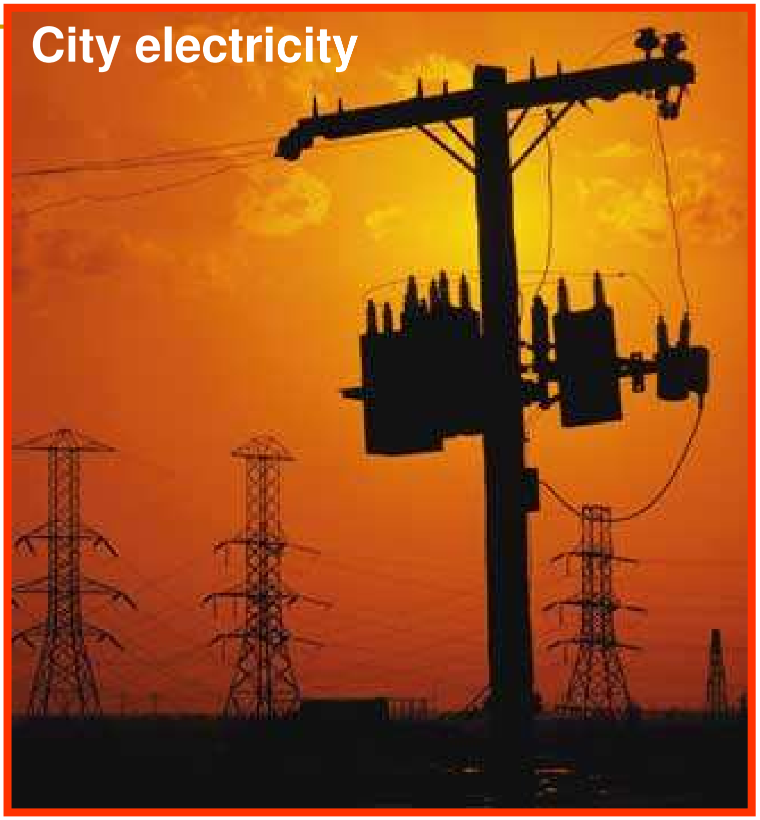
Corrosion and Leakage

PIPE LINES
RAILWAYS
BRIDGES

POWER LINES



Fluctuating Electrojet
(Millions of Amps)
Magnetic Field from electrojet induces voltage potential on surface of earth
GIC enters power system through ground connections
Large currents can be induced to flow through highly conductive seawater
Voltage Gradient
Electric potential induced on earth surface up to 6 Volts/km causes Geomagnetically-Induced Currents
Coastal areas cause abrupt transition in conductivity between resistive rock geology and seawater



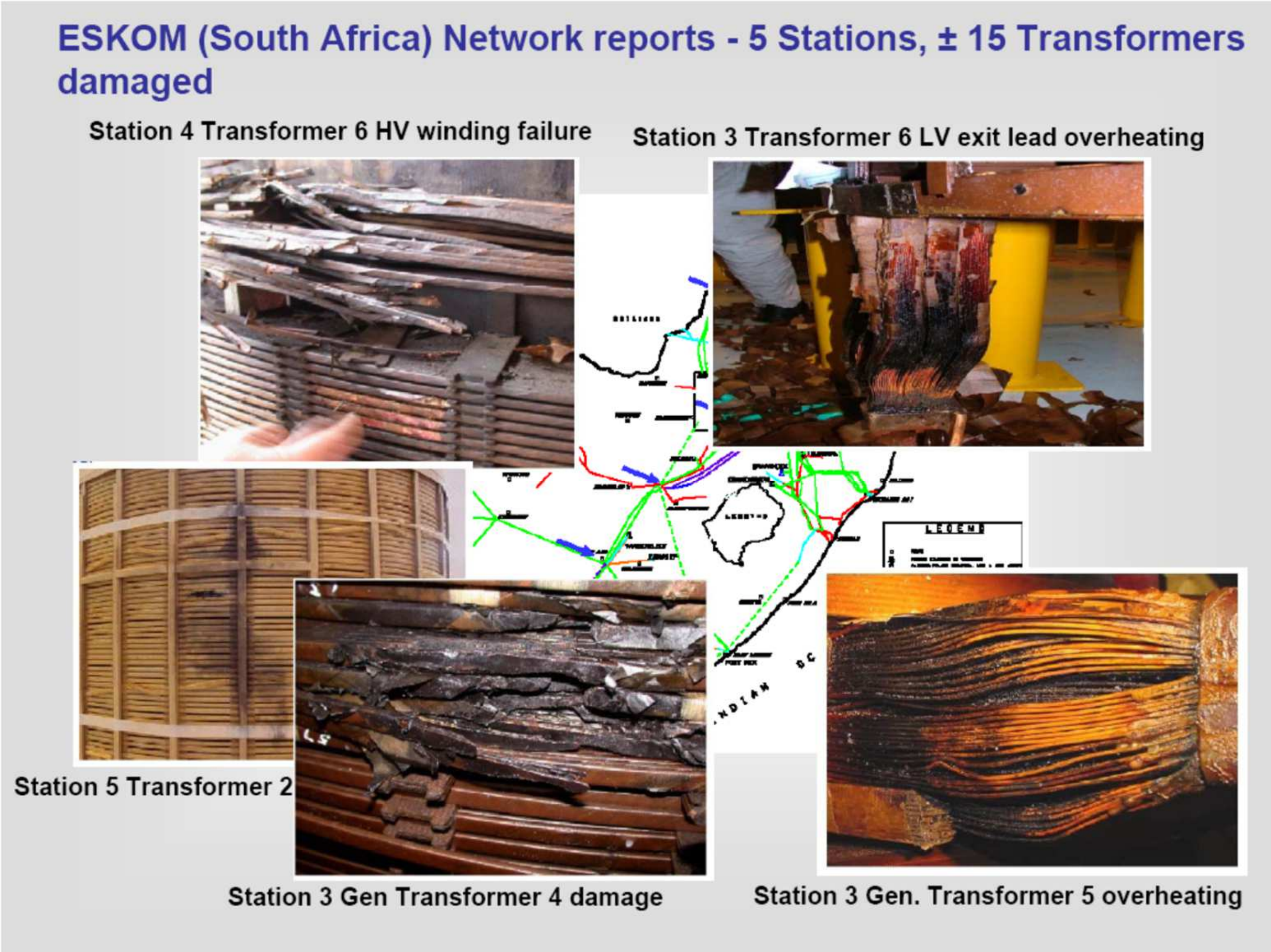
City electricity

TOASTED TRANSFORMER

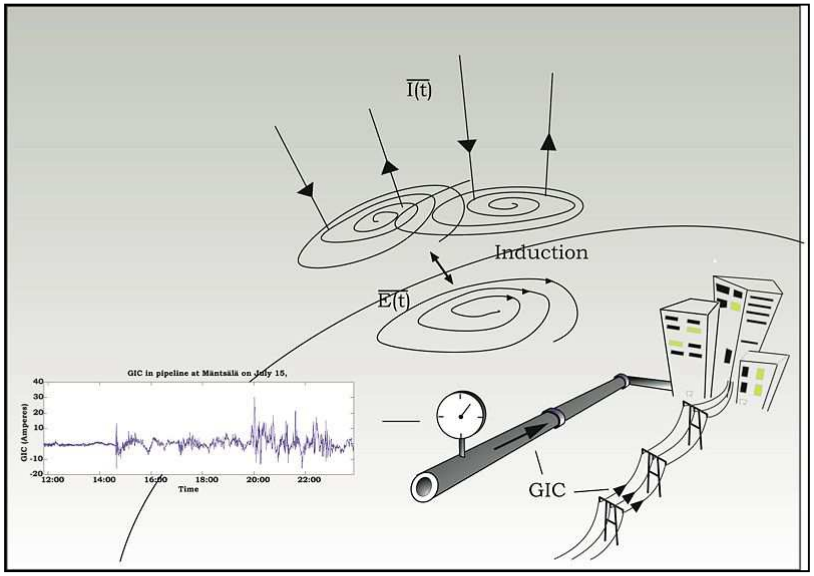
- ***MARCH 1989 MAGNETIC STORM***

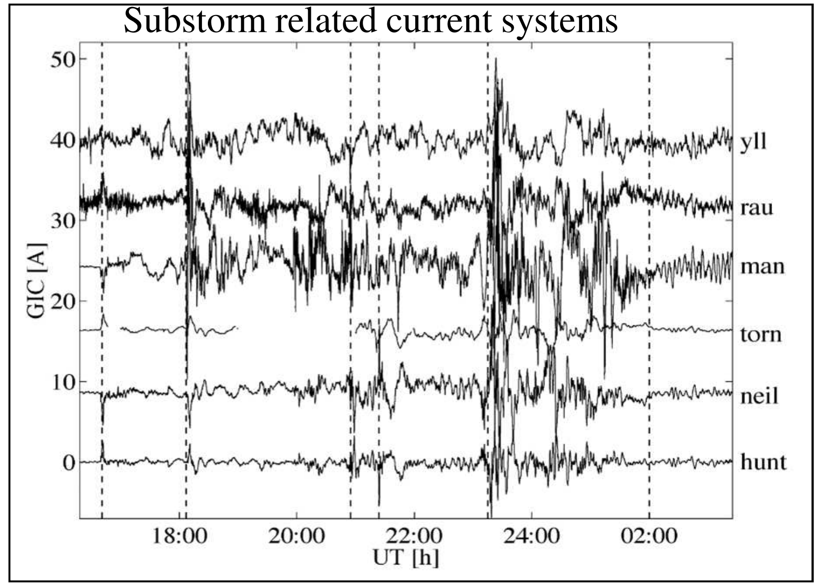
- **$10,000,000 transformer at Salem nuclear plant damaged beyond repair6-week outage waiting for replacementSame storm blacked out Hydro-Quebec power grid -- 6,000,000 people without power for 9 hours**
- Source: J G Kappenman, http://www.mpelectric.com/storms/

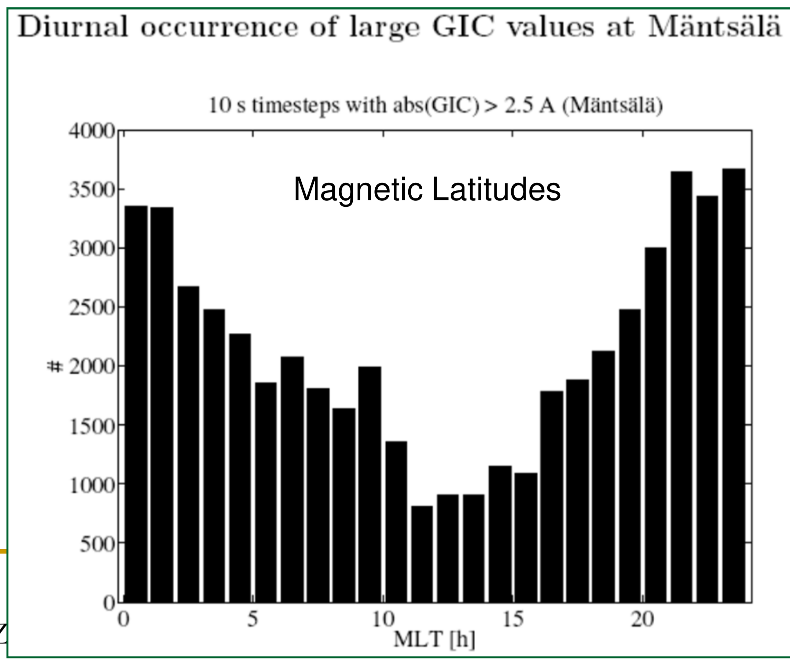
Bursting Transformers at 5 Stations

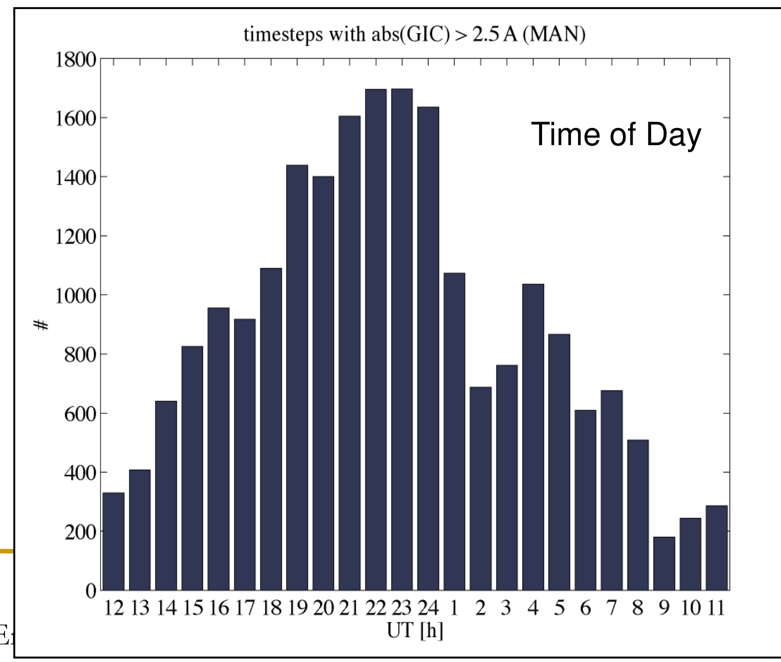


Geomagnetically Induced Currents (GIC)

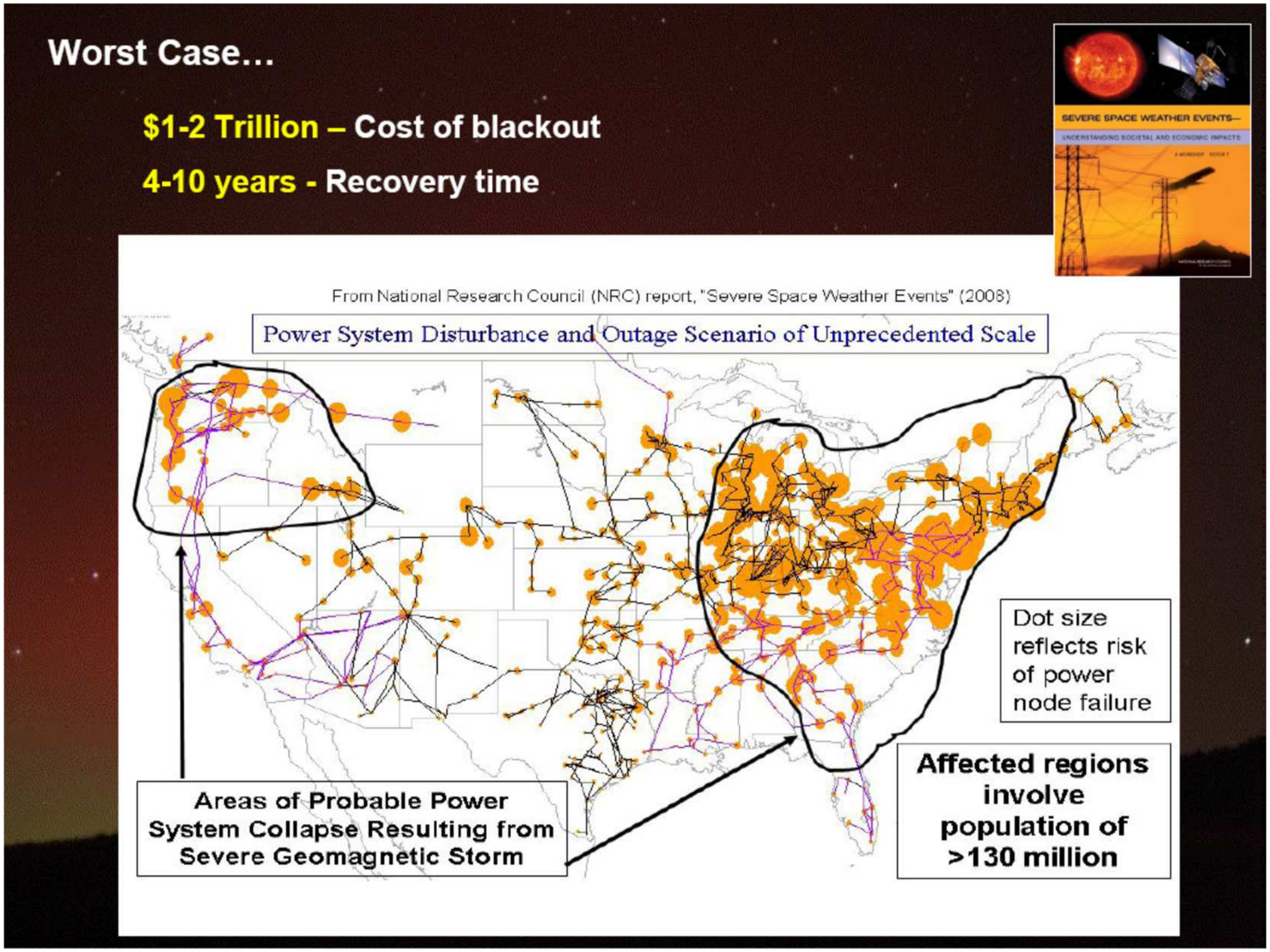






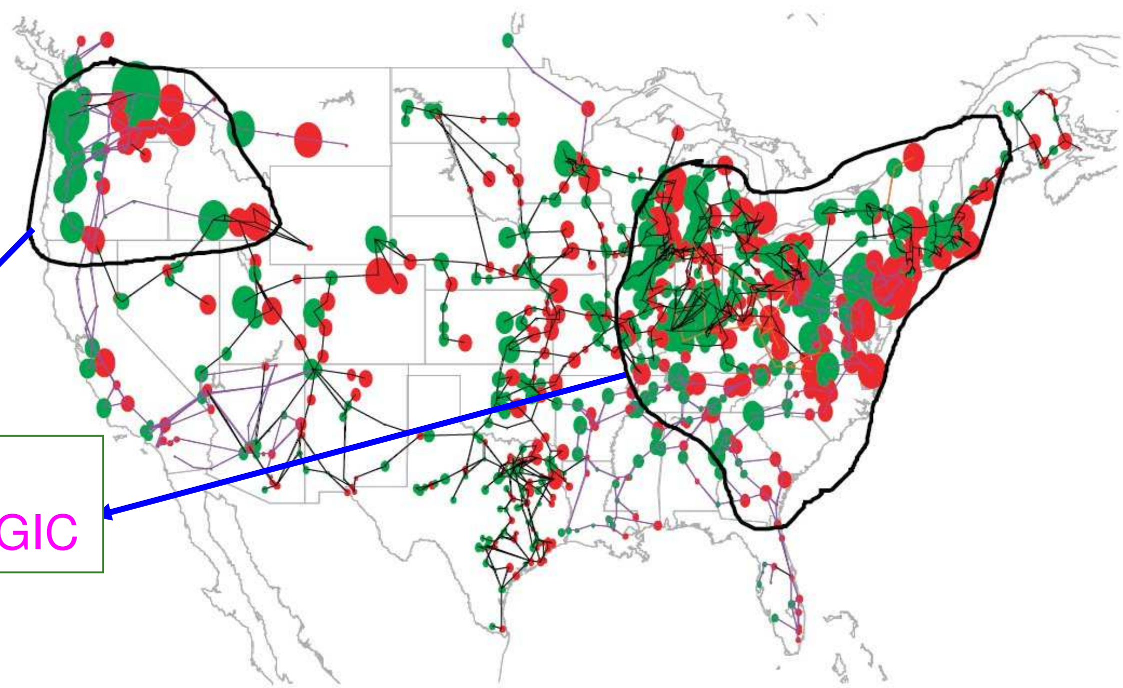


Blackouts …



Worst Case…
$1-2 Trillion – Cost of blackout
4-10 years - Recovery time
SEVERE SPACE WEATHER EVENTS—
From National Research Council (NRC) report, "Severe Space Weather Events" (2008)
Power System Disturbance and Outage Scenario of Unprecedented Scale
Dot size reflects risk of power node failure
Areas of Probable Power System Collapse Resulting from Severe Geomagnetic Storm
Affected regions involve population of >130 million

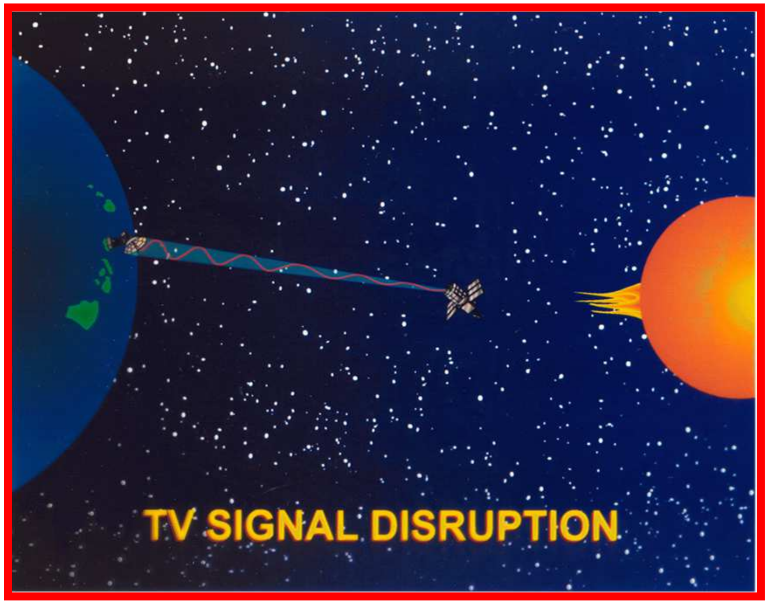
Areas most vulnarable to GIC

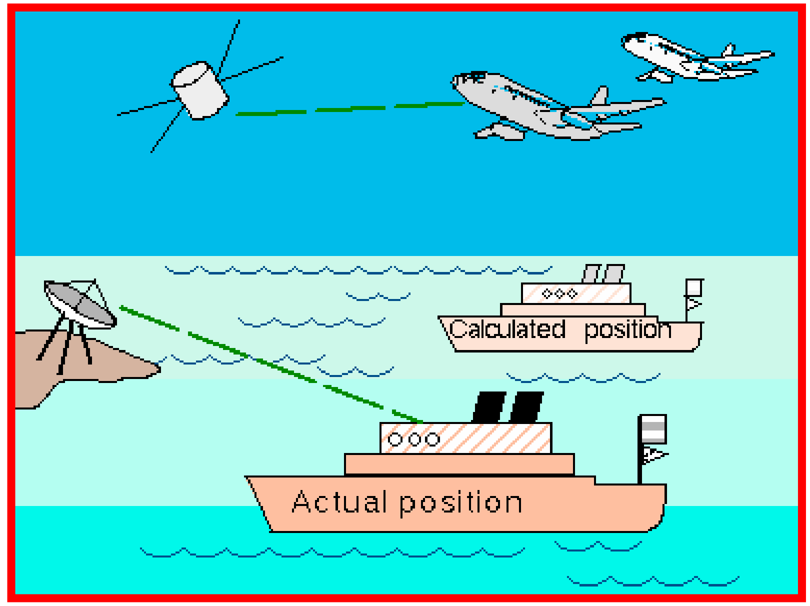


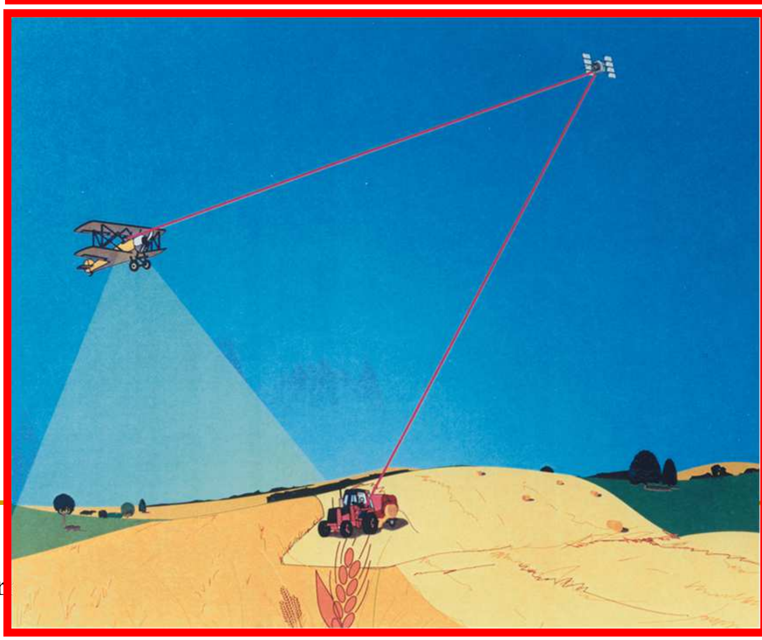
Areas most vulnarable to GIC

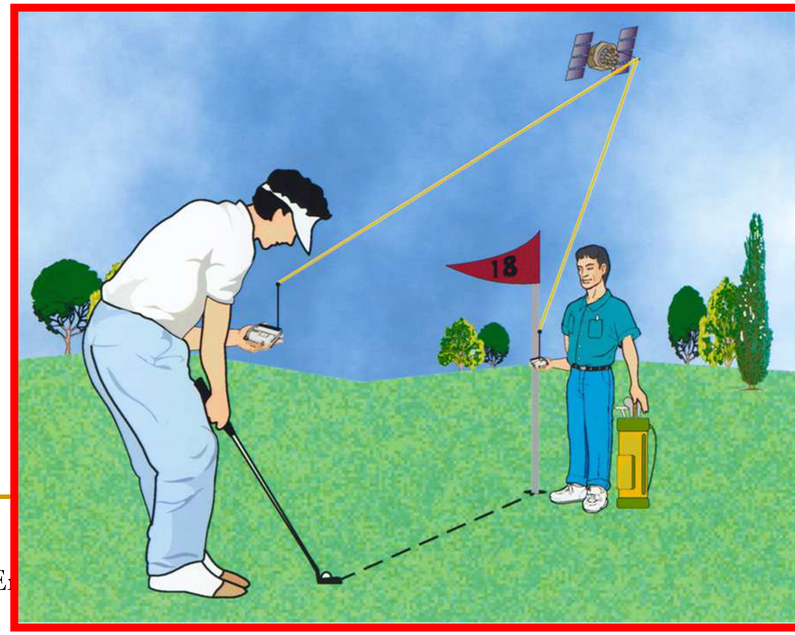
FIGURE 7.1 Scenario showing effects of a 4800 nT/min geomagnetic field disturbance at 50° geomagnetic latitude scenario. The regions outlined are susceptible to system collapse due to the effects of the GIC disturbance; the impacts would be of unprecedented scale and involve populations in excess of 130 million. SOURCE: J. Kappenman, Metatech Corp., "The Future: Solutions or Vulnerabilities?," presentation to the space weather workshop, May 23, 2008.

Target Detection



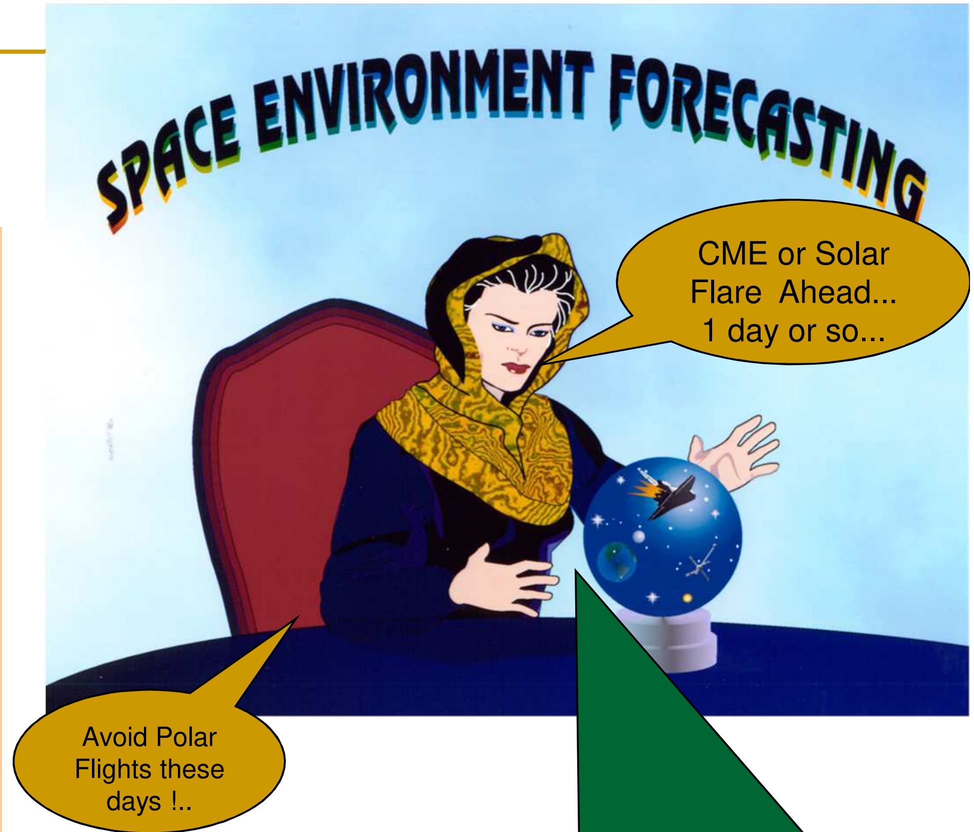


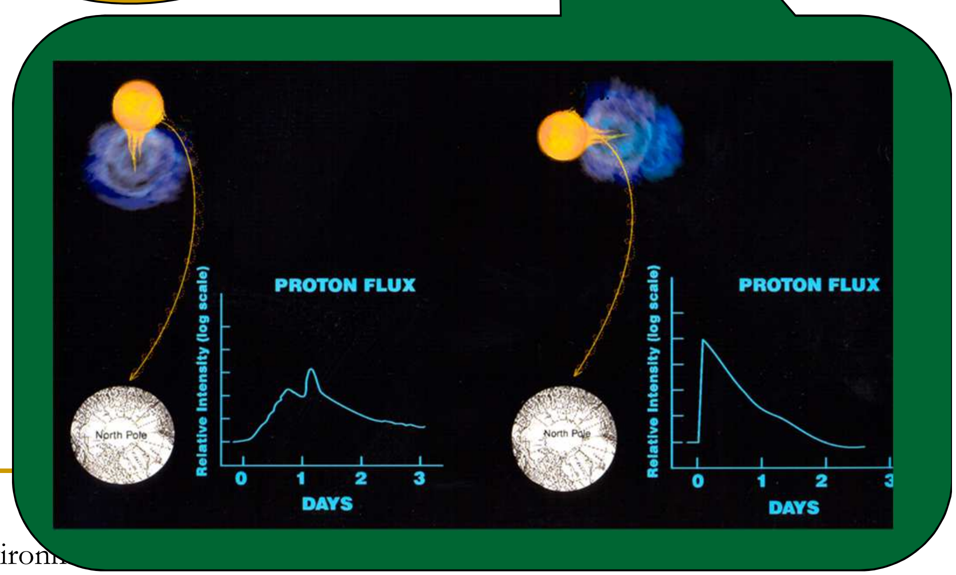




Future ??

- Growing dependence on technology → Growing needs for Space Weather Prediction
- More and Accurate measurements in space
- Building models of space environment
  - are required for better understanding of our space environment in both short and long time scales, including the controversial issues on solar-climate connection and
  - to act timely against the possible hazards coming from the space.





NOAA Space Weather Scale

Geomagnetic Storms

Level	Power Systems	Spacecraft Operations	Other Systems	Average Freq.
G5	Grid systems can collapse and transformers experience damage.	Extensive surface charging, problems with orientation, uplink/downlink and tracking satellites	Pipeline currents reach hundreds of amps, HF radio propagation impossible, satellite navigation degraded, low-frequency radio navigation out, and aurora seen as low as the	4 days per cycle
G4	Possible voltage stability problems, portions of grids collapse and	Experience surface charging and tracking problems, orientation problems need	Induced pipeline currents, HF radio propagation sporadic, satellite navigation degraded, low-frequency radio navigation disrupted, and the aurora seen as low as	60 days per cycle
G3	Voltage corrections required, false alarms triggered on protection devices, and	Surface charging, increased drag, and orientation problems need corrections.	Intermittent satellite navigation and low-frequency radio navigation problems, HF radio intermittent, and the aurora seen as low as mid-latitudes.	130 days per cycle
G2	High-latitude power systems affected.	Corrective actions required; changes in drag affect orbit predictions	HF radio propagation fades at higher latitudes, and the aurora seen as low as 50 degrees.	360 days per cycle
G1	Weak power grid fluctuations	Minor impact on satellite operations	The aurora seen at high latitudes (60 degrees); migratory animals begin to be affected.	900 days per cycle

NOAA Space Weather Scale

Solar Radiation Storms

	Biological	Spacecraft Operations	Other Systems	Ave. Freq.
S5	Unavoidable high radiation hazard to astronauts on EVA); high radiation levels to passengers and crew in commercial jets	Loss of some satellites, memory impacts cause loss of control, serious noise in image data, star-trackers unable to locate sources; permanent damage	no HF (high frequency) communications possible in the polar regions, and position errors make navigation operations extremely difficult.	Fewer than 1 day per cycle
S4	Unavoidable radiation hazard to astronauts on EVA; elevated radiation to passengers in commercial jets at high latitudes.	Memory device problems, noise on imaging systems, star-trackers cause orientation problems, and solar panels degraded.	blackout of HF radio communications through the polar cap and increased navigation errors over several days.	3 days per cycle
S3	Radiation hazard avoidance recommended for astronauts on EVA; commercial jets at high latitudes receive low-level radiation	Likely single-event upsets, noise in imaging systems, permanent damage to exposed components/detectors, and decrease of solar panel currents	degraded HF radio propagation through the polar cap and navigation position errors.	10 days per cycle
S2	None	Infrequent single-event upsets.	small effects on HF propagation through the polar cap and navigation impacted.	25 days per cycle
S1	None	None	minor impacts on HF radio in the polar regions.	50 days per cycle

NOAA Space Weather Scale

Radio Blackouts

Level	HF Radio	Navigation	Ave. Freq.
R5	Complete HF (high frequency) radio blackout on the entire sunlit side of the Earth lasting for a number of hours. No HF radio contact with mariners or en route aviators.	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	Fewer than 1 day per cycle
R4	HF radio communication blackout for one to two hours on most of the sunlit side of Earth. HF radio contact lost during this time for	Outages of low-frequency navigation signals cause increased error in positioning for mariners and general aviators for one to two hours. Minor disruptions of satellite navigation possible on the sunlit side of Earth.	8 days per cycle
R3	Wide area blackout of HF radio communication signals, loss of radio contact for mariners and en route aviators for about an hour on sunlit side of Earth	Low-frequency navigation signals degraded for about an hour, affecting maritime and general aviation positioning.	140 days per cycle
R2	Limited blackout of HF radio communication signals on sunlit side, loss of radio contact for tens of minutes for mariners and en route aviators.	Degradation of low-frequency navigation signals for tens of minutes affecting maritime and general aviation positioning.	300 days per cycle
R1	Weak or minor degradation of HF radio communication signals on sunlit side, occasional loss of radio contact for mariners and en route aviators.	Low-frequency navigation signals degraded for brief intervals affecting maritime and general aviation positioning.	950 days per cycle

Protection?

- Future commercial flights
  - Designed for increased range (i.e. increase in polar route traffic)
  - To utilize the available airspace at higher and higher latitudes
- Increases the doses (8-10 microSv/hr at 42000 ft, 10-12 microSv at 51000 ft
- Quicker flights will reduce doses
  - Will increase cruising speeds
  - Reduce times by %15-20 %
  - But altitudes at 15 000 km
  - Route doses will increase by 30-40%

- At high altitudes, two effects contribute to the dose
  - Increasing number of secondary particles with altitude reaching maximum at 20 km
  - Secondary particle composition: it becomes more and more dominated by multiply-charged ions which have a greater potential to cause larger biological damage.