Effects on Technology

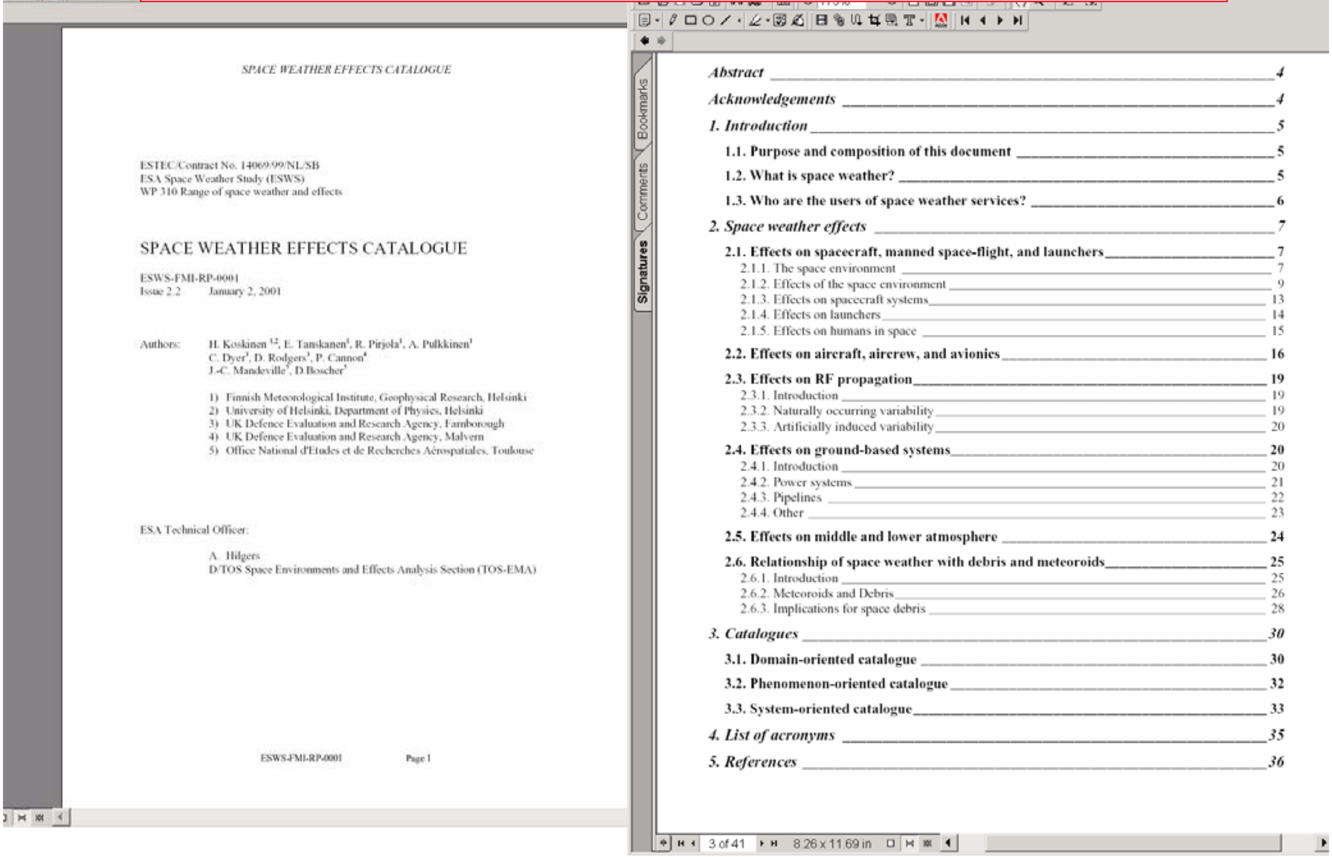
Éamonn Daly

ESA Space Environments and Effects Analysis Section
Noordwijk
The Netherlands

Outline

- Review Effects
- Focus on :
  - Spacecraft Effects
  - Effects to man
  - Aircraft and Aircrew
- Parameters, assessment techniques, requirements

Koskinen et al. produced an excellent compendium recently



SPACE WEATHER EFFECTS CATALOGUE

ESTEC/Contract No. 14069/99/NL/SB
ESA Space Weather Study (ESWS)
WP 310 Range of space weather and effects

SPACE WEATHER EFFECTS CATALOGUE

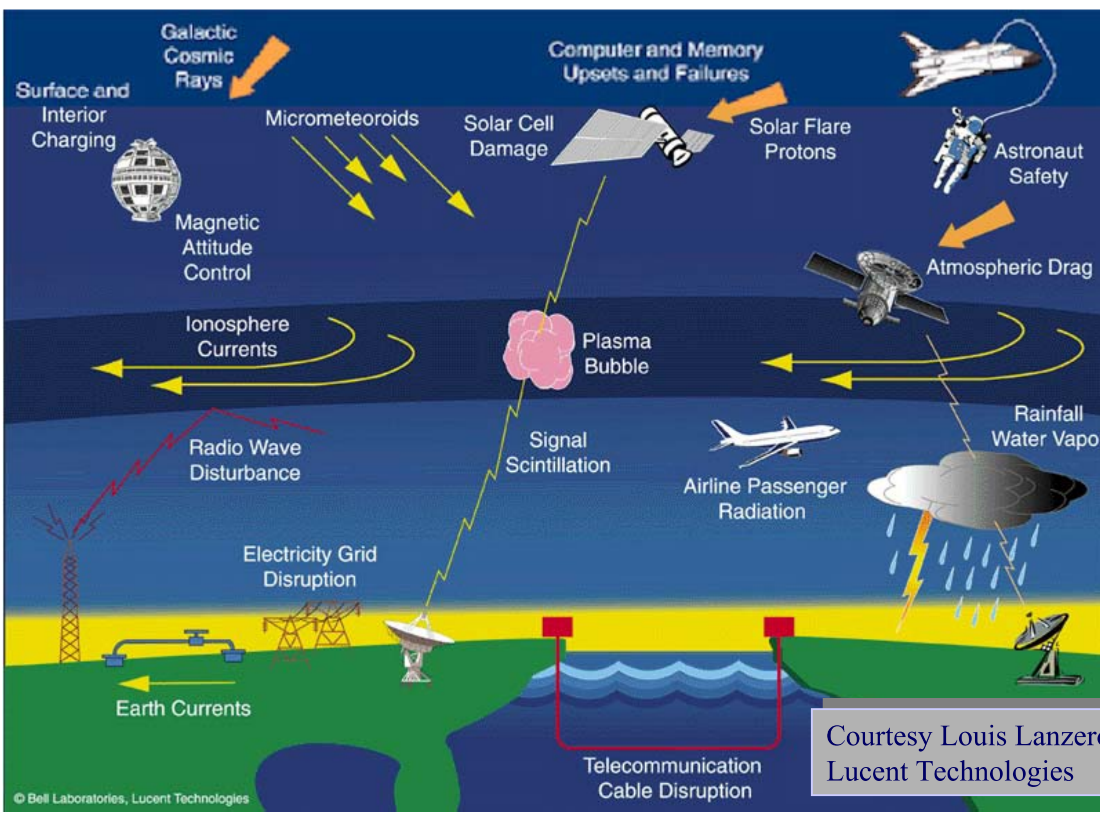
ESWS-FMI-RP-0001
Issue 2.2 January 2, 2001

Authors: H. Koskinen [1,2], E. Tanskanen[1], R. Pirjola[1], A. Pulkkinen[1]
C. Dyer[3], D. Rodgers[3], P. Cannon[4]
J.-C. Mandeville[5], D. Boscher[5]

1) Finnish Meteorological Institute, Geophysical Research, Helsinki
2) University of Helsinki, Department of Physics, Helsinki
3) UK Defence Evaluation and Research Agency, Farnborough
4) UK Defence Evaluation and Research Agency, Malvern
5) Office National d'Etudes et de Recherches Aérospatiales, Toulouse

ESA Technical Officer:
A. Hilgers
D/TOS Space Environments and Effects Analysis Section (TOS-EMA)

ESWS-FMI-RP-0001 Page 1

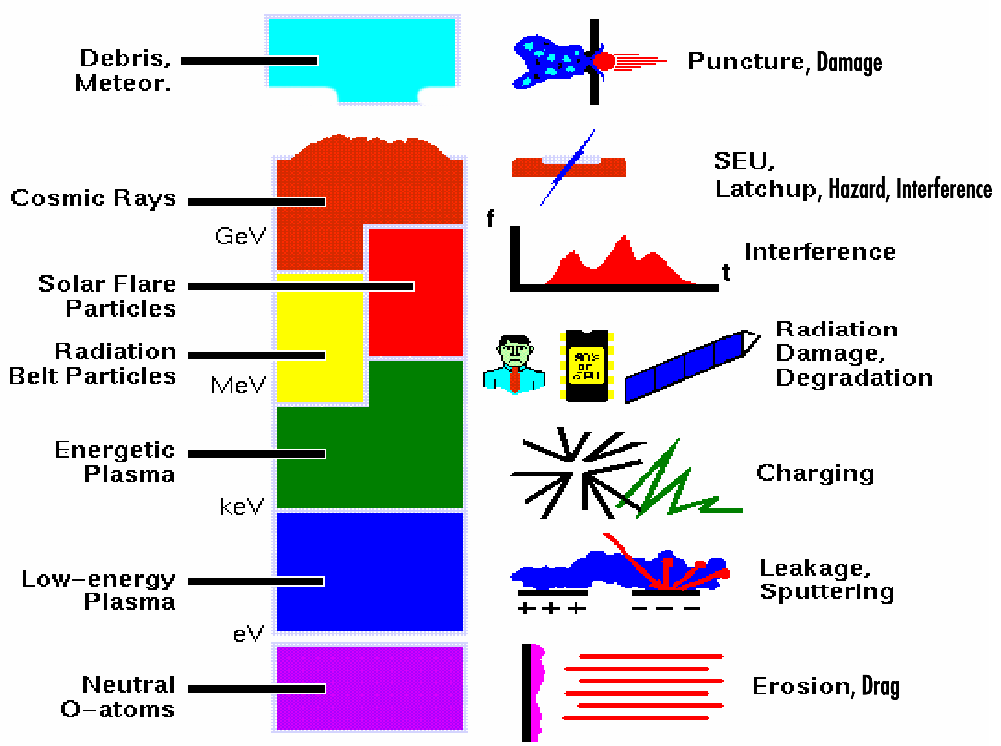


Courtesy Louis Lanzerotti, Lucent Technologies

Effects

- Satellites affected by radiation, plasma, atmosphere, particulates;
- Astronauts - ISS, future exploration missions;
- Radiation hazards to air crew and avionics;
- Ground power outages from currents induced in lines;
- Disruption to communications relying on the ionosphere;
- Disruption of navigation satellite signals (GPS - Galileo);
- Prospecting;
- Climate;
- see **www.esa.int/spaceweather**

Effects to Satellites:



Spacecraft Effects

Radiation Effects are caused by:

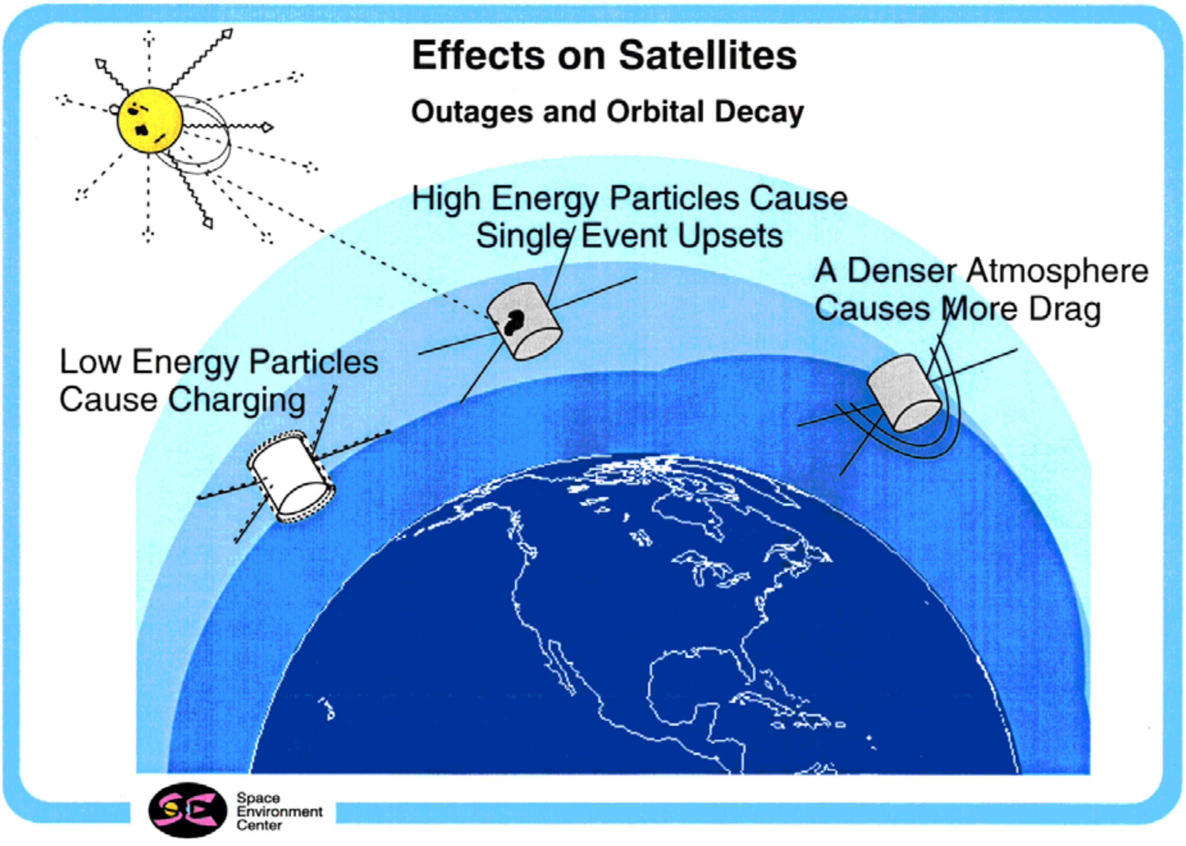
- Total integrated ionising or non-ionising DOSE (is energy absorbed/unit mass; an integral of the flux and the energy loss rate)
  - a problem for electronics, solar cells, materials, man
- Single Event Effects, including Single Event upset (non-permanent error in a bit), single event transients (likewise for "analogue" circuits); latch-up (destructive);
  - a problem for electronics and man

Plasma Effects due to:

- Electrostatic charging resulting in electrostatic discharge and EM pulses;
  - a problem for electronics
- Plasma interactions with "exposed active" systems – solar cell interconnects; electric propulsion; payloads; tethers

Neutrals Cause:

- Drag, depending on atmospheric density
- Erosion of surfaces – the residual Oxygen is non-molecular and corrosive
- Contamination



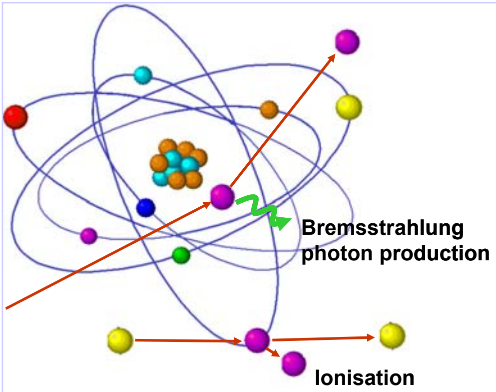
Radiation

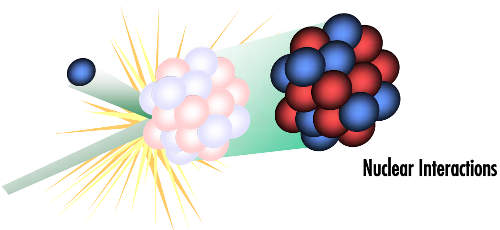
- The principal particles:
  - *Protons* 0.1-300MeV {radiation belts, solar particle events, cosmic rays}
  - *Ions* 0.1-300MeV {cosmic rays, solar particle events, (radiation belts)}
  - *Electrons* 0.01 - 10MeV {radiation belts, (other planets) ((solar))}
- The main interaction is ionisation but other processes can be important sometimes

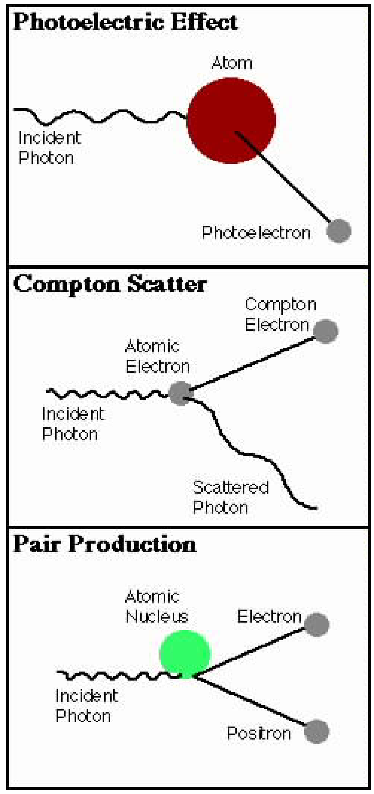
Main Radiation Effects

Effect	Assessment Parameter	Main Interaction
Component Degradation	Ionizing Dose	Ionization
Solar Cell Degradation	Non-ionizing dose	Displacements
SEU	Rate	Ionization
Radiation Background	Rate	Ionization
Optoelectronic Degradation	Non-ionizing dose	Displacements
Astronaut Hazards	Dose Equivalent	Ionization
Internal Charging	Fields	Ionization

Radiation Interactions and Secondary Radiation







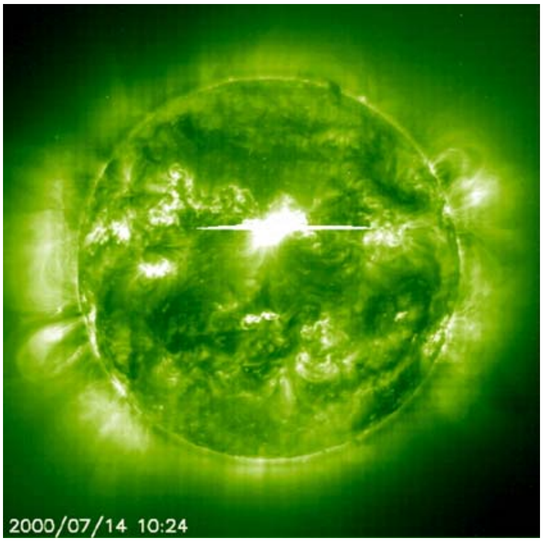
Secondary Radiation

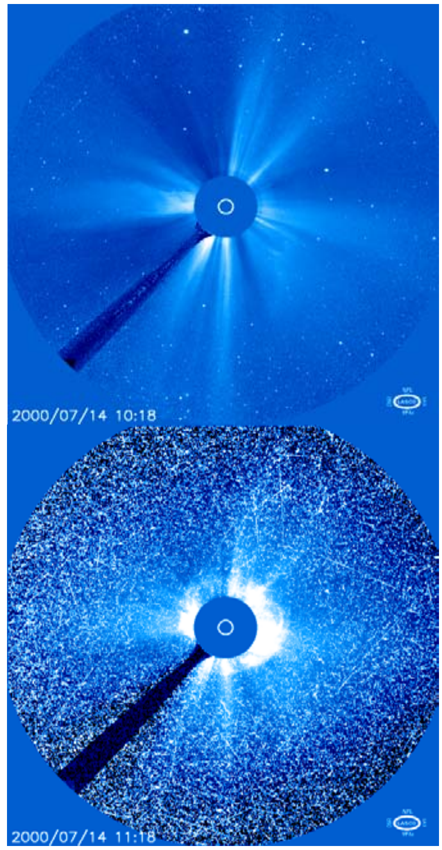
- Effect can be produced by a secondary radiation

Source (primary)	Secondary	Physical Process	Where it is important
Electron	Photon	Bremsstrahlung	Dose, Background
	Secondary electrons	Delta rays	Dose, Background
Photon*	Electrons	Photoelectic ejection Compton scatter Pair production	Dose, Background
Ions	Secondary electrons	("delta rays")	Dose, Background
	Low energy ions	Spallation	SEU, Displacements, Dose
	Pions + exotic	Nuclear interaction	Background
	Nuclear γ-rays	Deexcitation	Background
	Neutrons	Nuclear interaction	Astronauts, Background

*Secondary

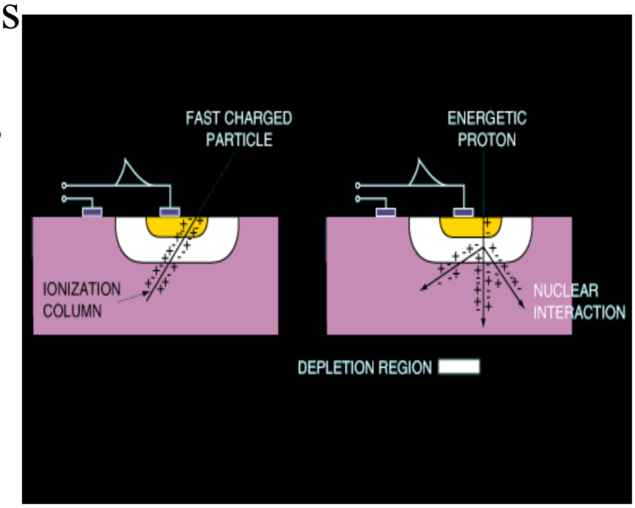
SOHO Image "snowing" on 14 July 2000



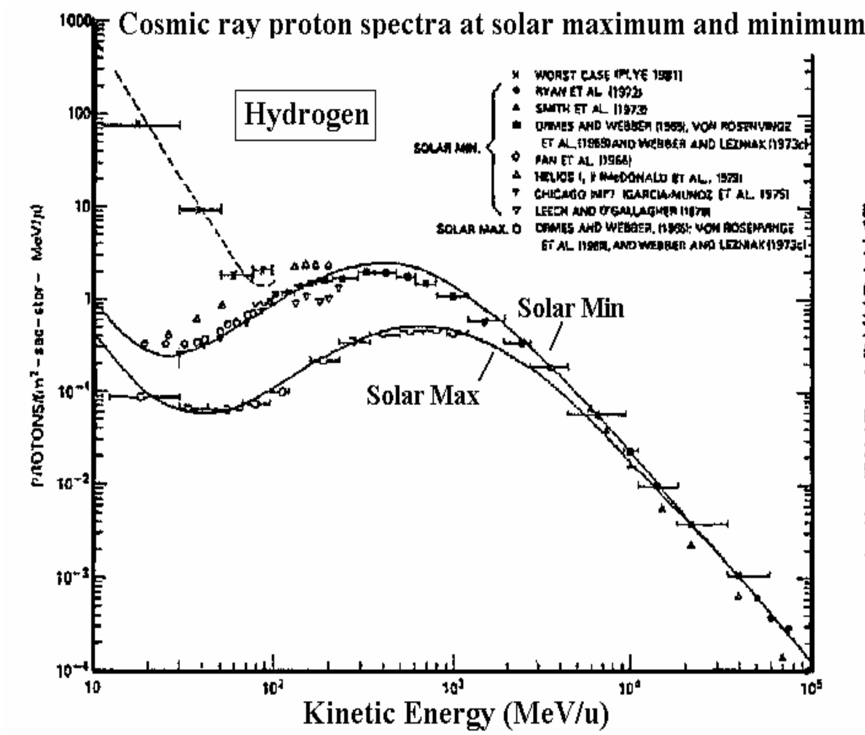


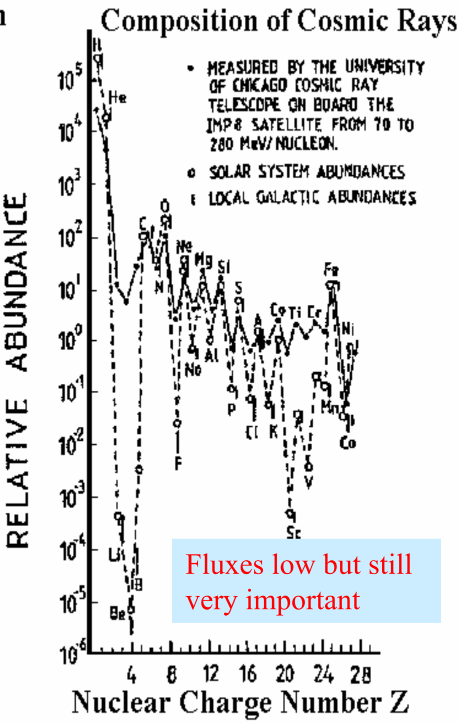
"Single-event" effects

- a particle crosses ("hits") a (small) sensitive target
- the energy deposited causes a noticeable effect:
  - ionisation free charge causes a bit to "flip"
  - pixels of a CCD are "lit up" by creation of free charge
  - DNA is damaged

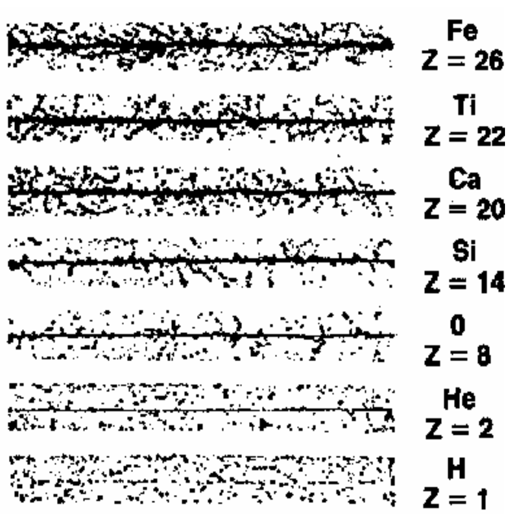


Cosmic Ray Fluxes and Composition

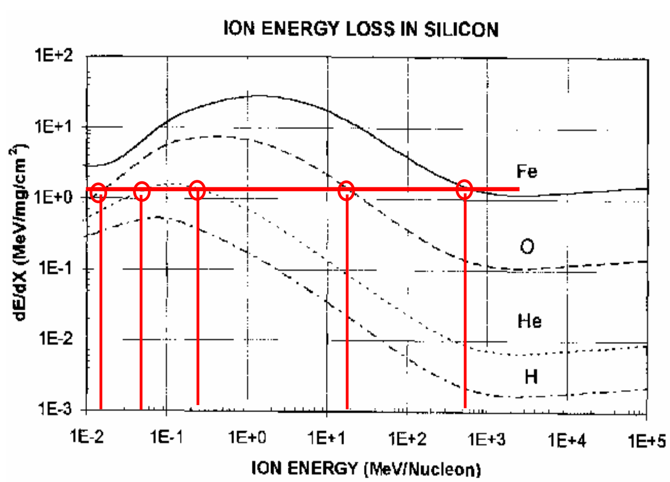




Ions can be highly ionising

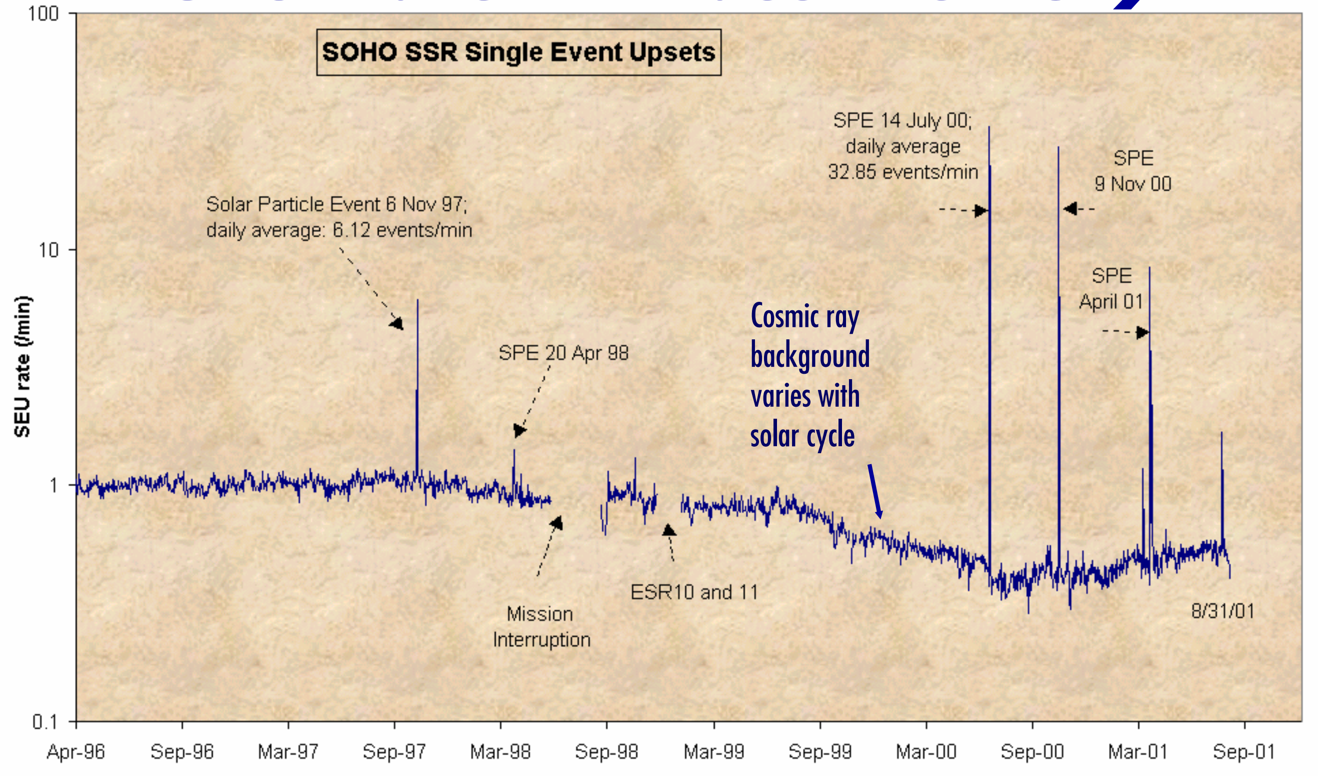


Cosmic ray ion tracks in a photographic emulsion.

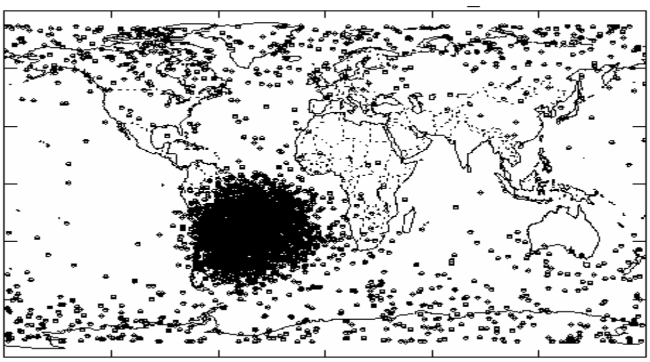


Note that $dE/dx \propto nz^2Z/mv^2$

SEU Rate in Mass Memory



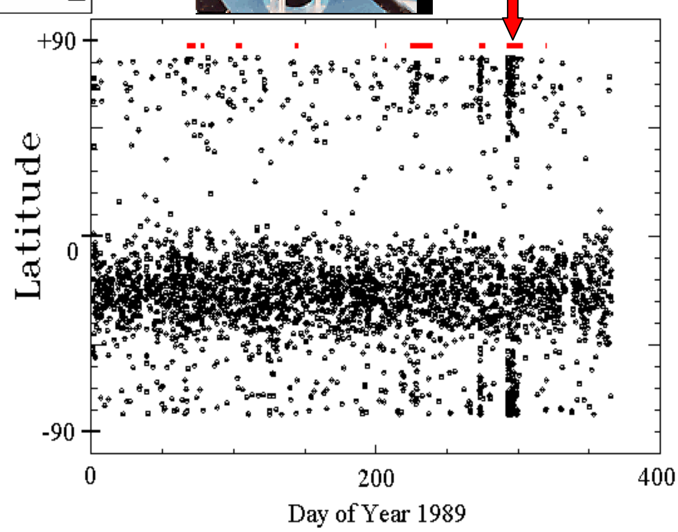
UoSAT SEU's



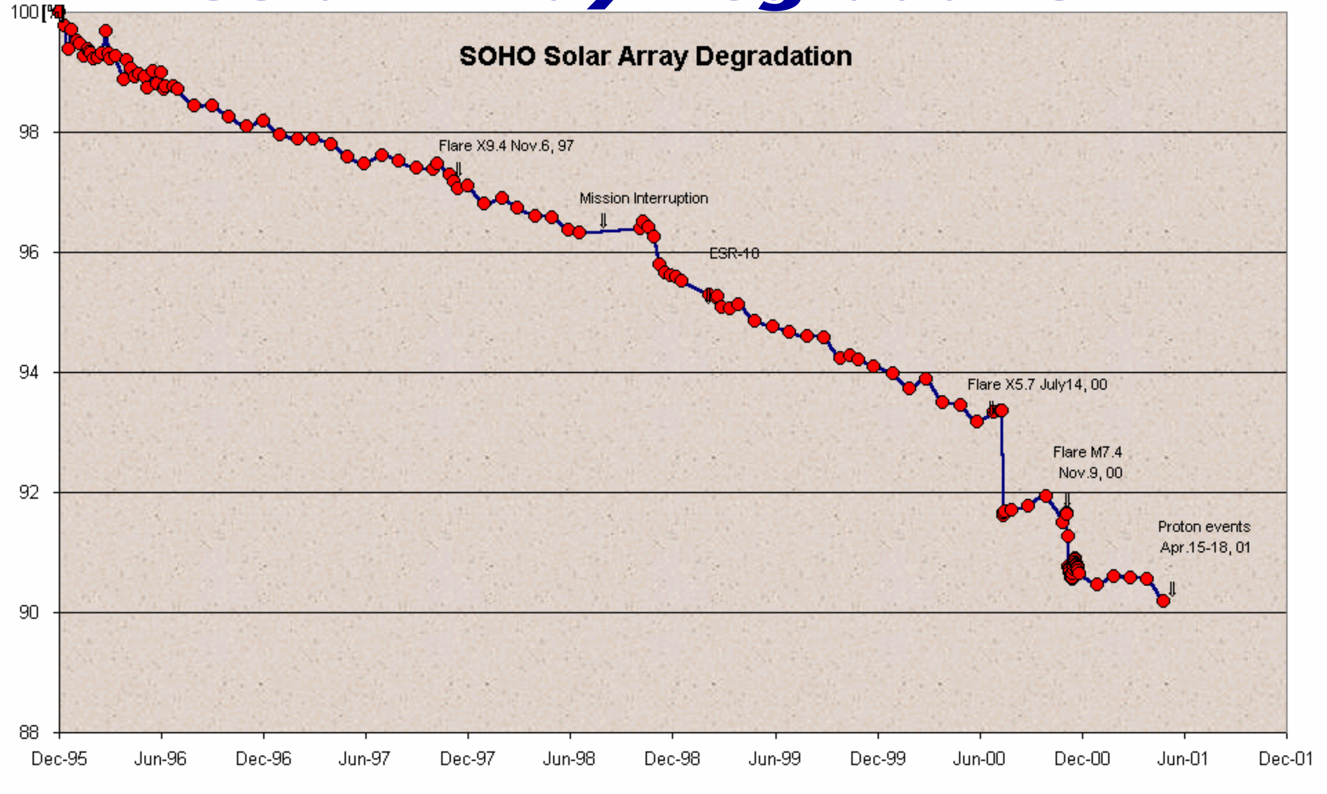
Oct '89

Mapped

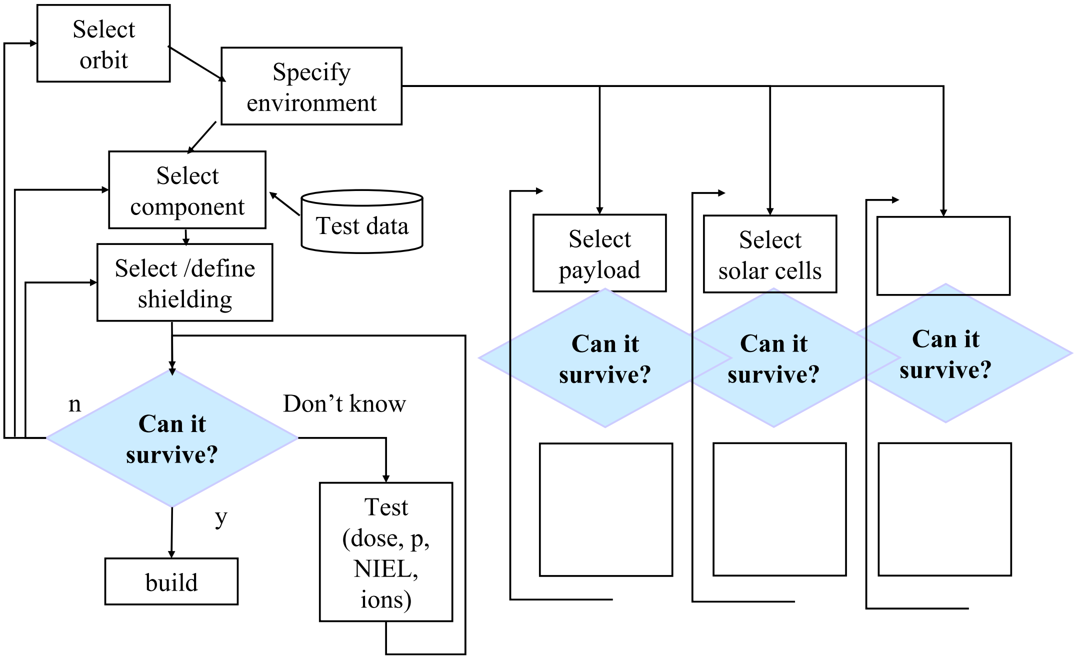
Time behaviour



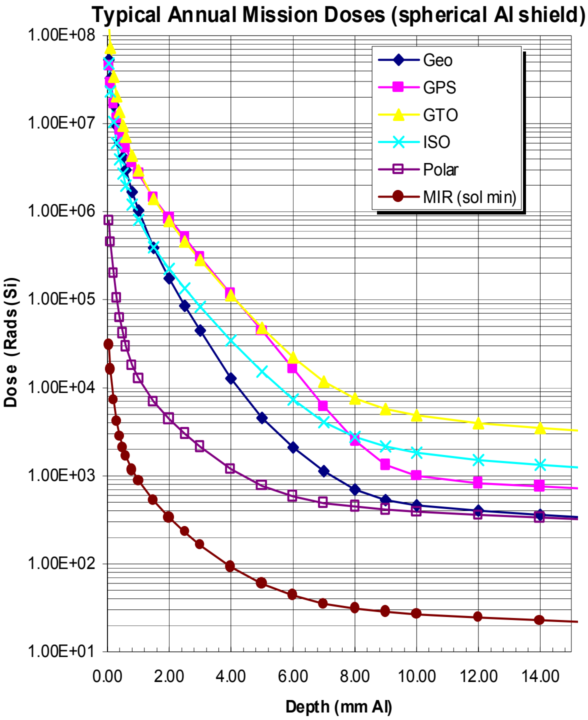
Solar Array Degradation



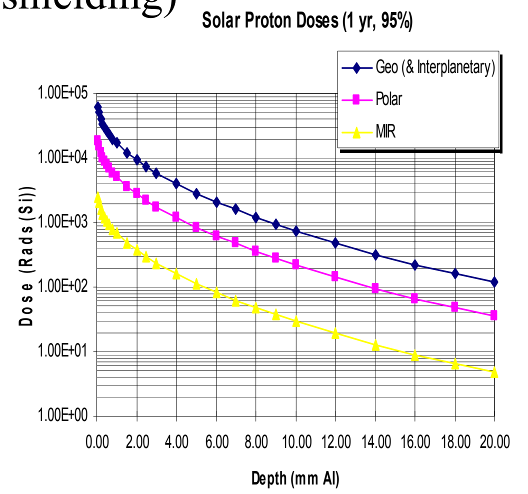
Basic Radiation Assessment Process



Annual Dose vs. depth for various missions

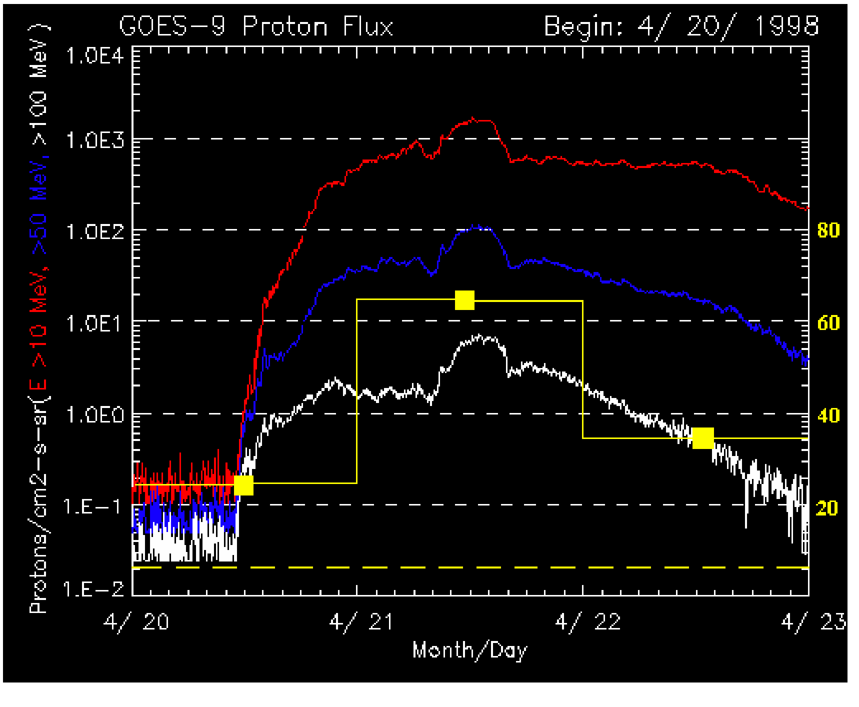


Dose vs depth for solar protons on various missions (accounts for geomagnetic shielding)



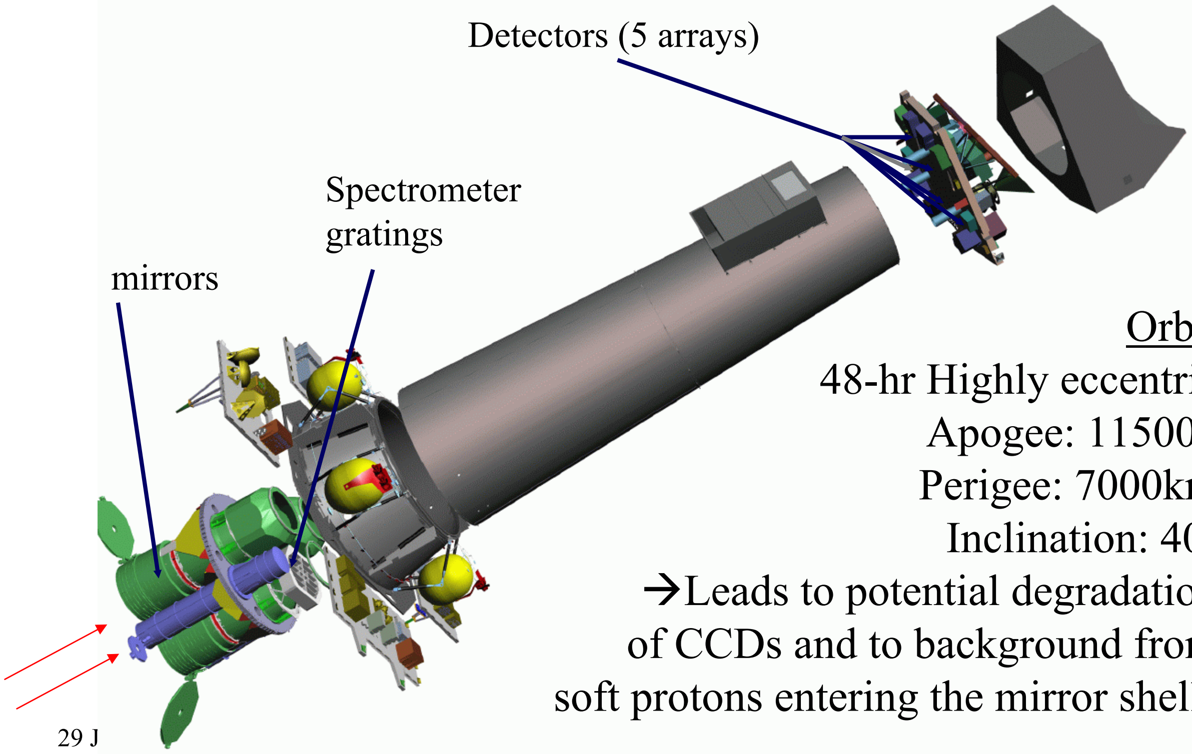
Note that Mrad doses can be reached

ISO Star Tracker



- Error rate increases in small solar event
- provided software can cope, this phenomenon should not lead to problems
- but there are several cases of attitude stabilisation loss

XMM: Radiation Damage to Detectors

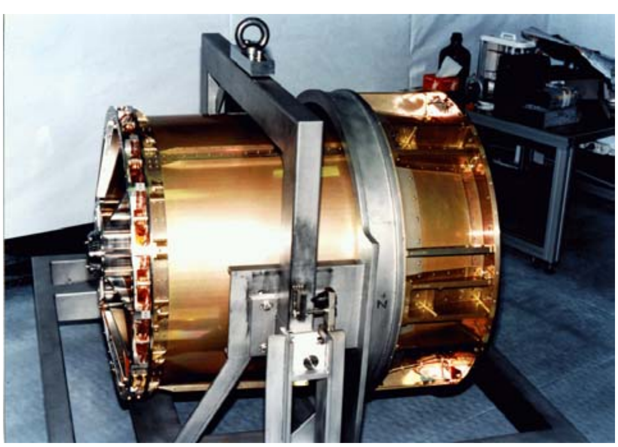


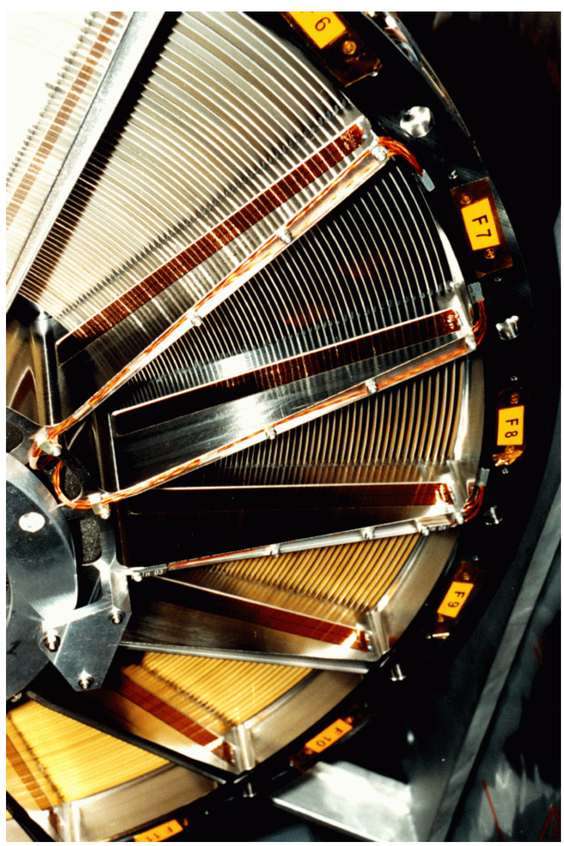
Orbit

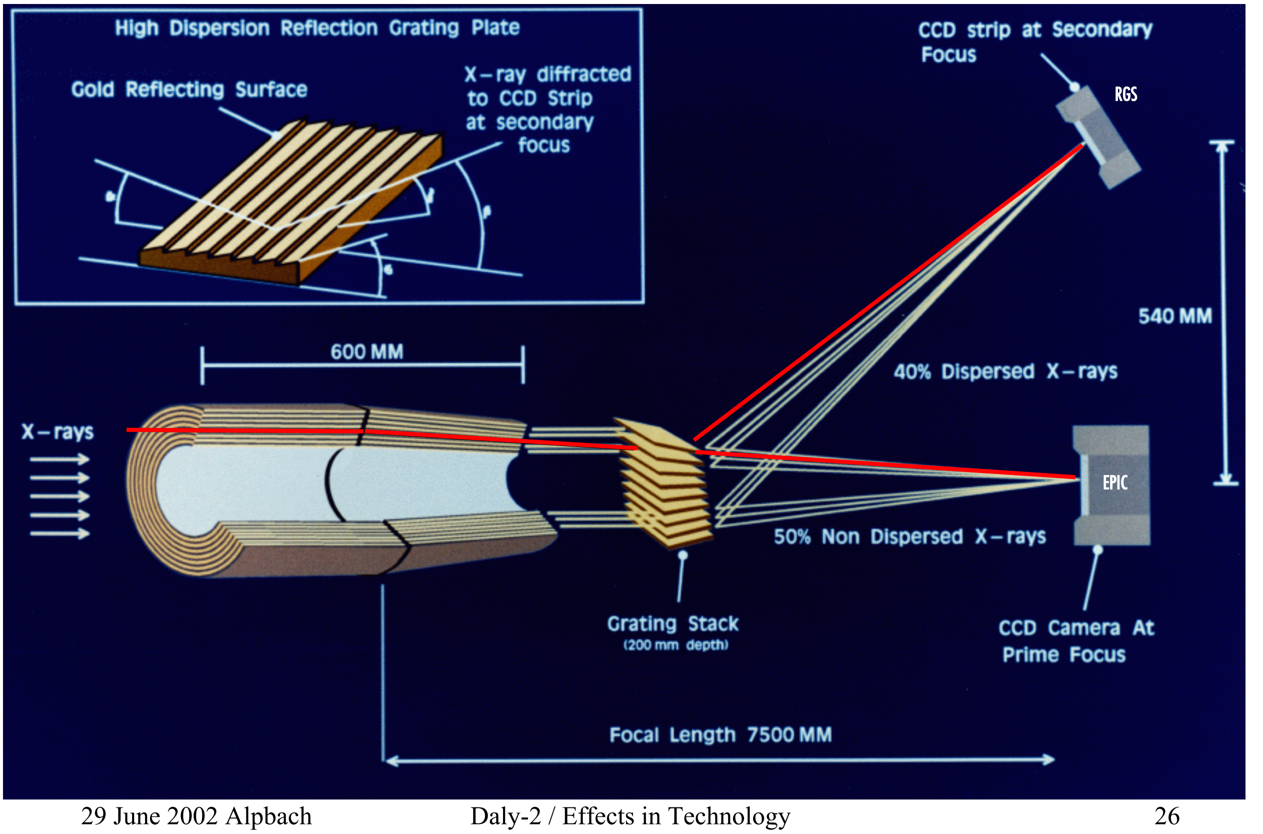
48-hr Highly eccentric
Apogee: 115000
Perigee: 7000km
Inclination: 40°
→Leads to potential degradation of CCDs and to background from soft protons entering the mirror shells

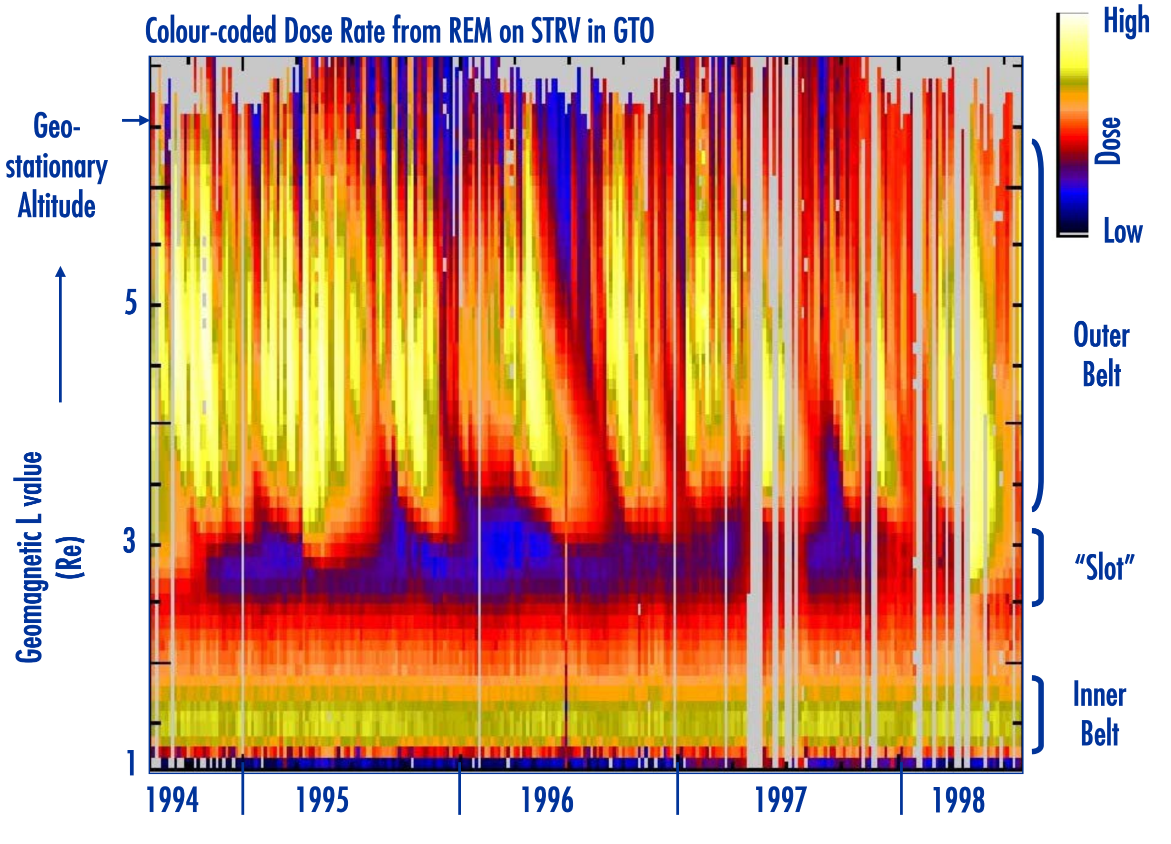
Mirror Module of XMM:

- 58 shells with mm-sized gaps






High Dispersion Reflection Grating Plate
Gold Reflecting Surface
X-ray diffracted to CCD Strip at secondary focus
CCD strip at Secondary Focus
RGS
540 MM
40% Dispersed X-rays
600 MM
X-rays
EPIC
50% Non Dispersed X-rays
Grating Stack
(200 mm depth)
CCD Camera At Prime Focus
Focal Length 7500 MM

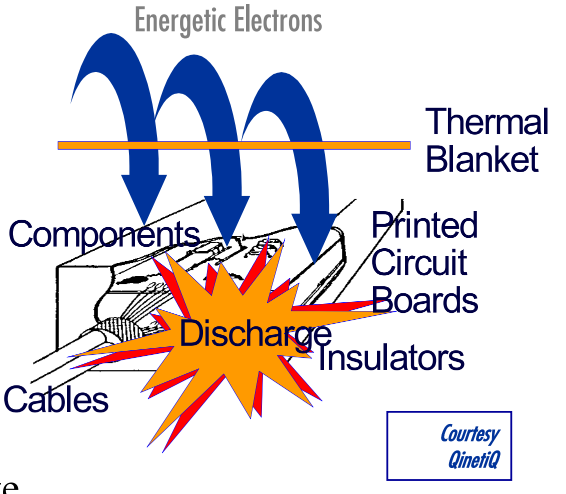

Colour-coded Dose Rate from REM on STRV in GTO
High
Dose
Low
Geo-stationary Altitude
Geomagnetic L value (Re)
5
3
1
Outer Belt
"Slot"
Inner Belt
1994
1995
1996
1997
1998

Charging-related anomalies

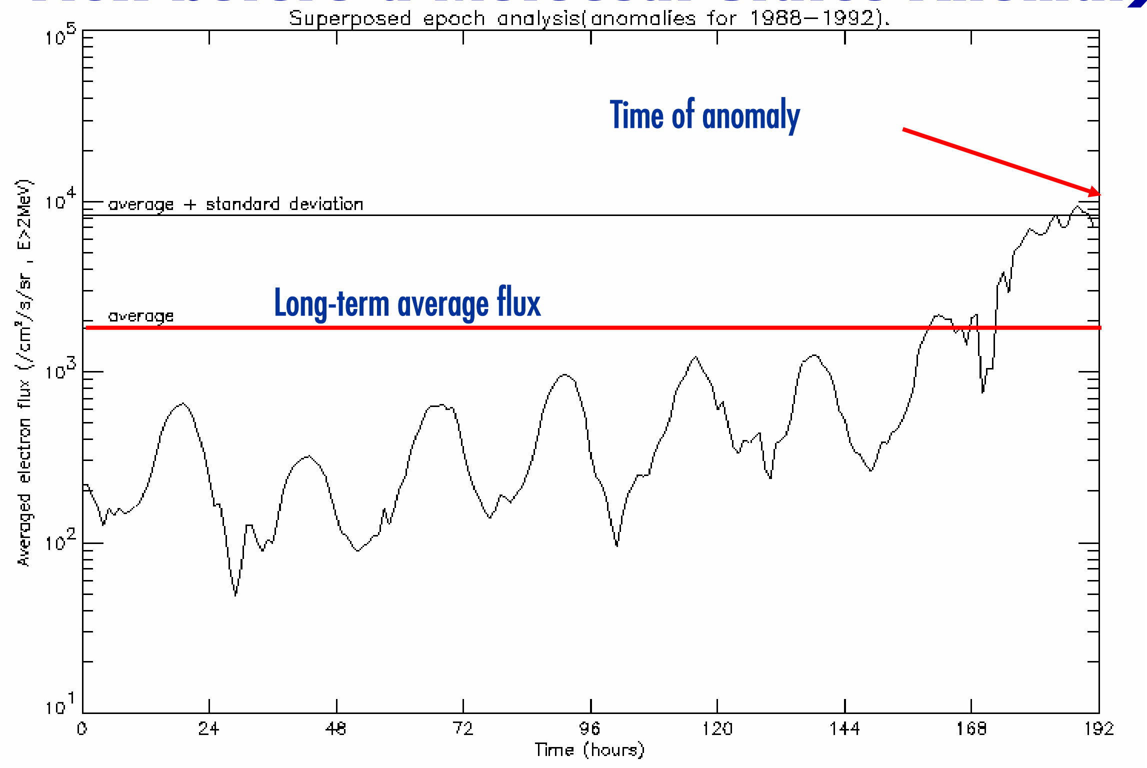
- Often caused by hot plasma causing electrostatic charging of outer surfaces
  - Potential differences lead to discharges
- Also caused by energetic electrons getting inside materials and stopping
  - High electric fields lead to breakdown discharges

Spacecraft Charging

- Many satellites experience “anomalies” which do not lead to satellite loss
- e.g. ESA satellites Marecs, ECS, and Meteosat in 1980’s-90’s
- ANIK-E1 & E2 failures in 94 & 96
- (Telstar 401 failure on 10th Jan 1997 following CME on 7th - not charging?
- Galaxy4 satellite anomaly led to pager network outage - not charging?)
- For service providers, price of inadequate hardening can be loss of spacecraft and expensive compensation / litigation
- To protect is also expensive as shielding mass is costly

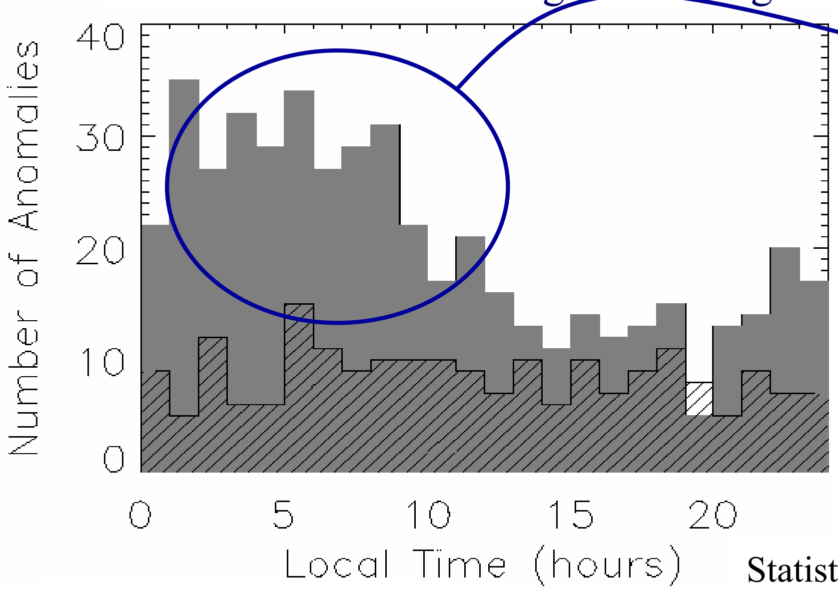


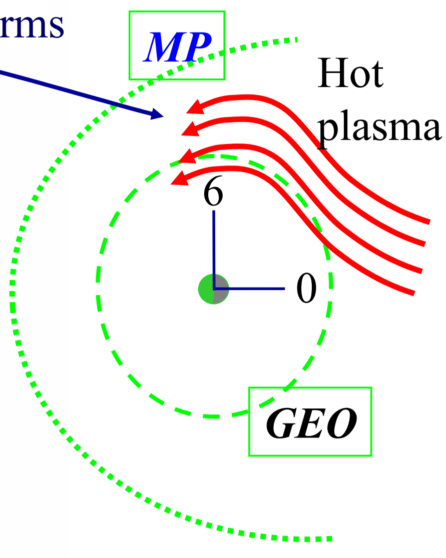
Behaviour of Average Energetic Electron Flux before a Meteosat Status Anomaly



Charging-Induced Anomalies

Anomalies on the morning side during storms

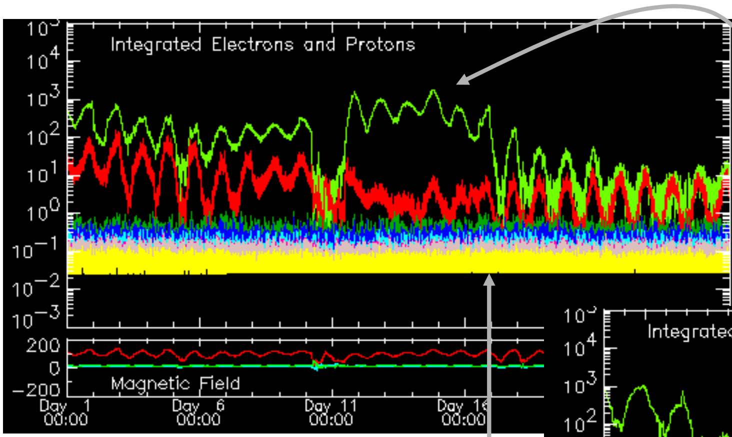




Meteosat Anomalies

Statistical Survey (*Rodgers et al.*) of Meteosat-3 anomalies and their local time distribution

Equator-S Failure

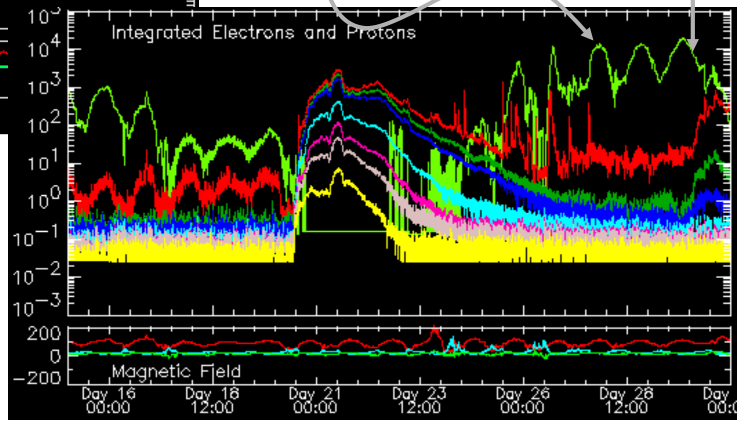


December 97

Primary CPU Fails

Enhanced Hot Electrons

Back-up CPU Fails

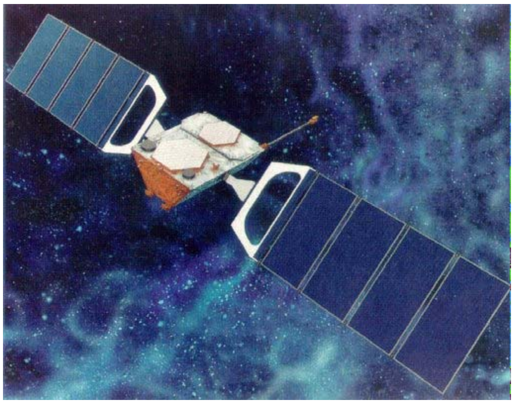


April 98

GOES Energetic Particle Data Courtesy NOAA

Globalstar

(Space Systems Loral's "Big LEO" global mobile communications network)



"Phone satellite operator Globalstar in August 2001 confirmed the failure of three of its 48 operational spacecraft during 2001, probably caused by the maximum of solar activity in 2001. The company said it was able to restore service to one of the satellites, which is now processing calls as usual".

- Globalstar statement: *"Earlier this year [2001], we detected anomalous behavior in three Globalstar satellites and removed them from service. After several months of analysis and testing, the company was successful in restoring service to one of the satellites, which is now processing calls as usual. It has also been determined that the remaining two satellites have failed, and two on-orbit spare satellites are now being manoeuvred into position to replace them, one in September and one in November.*
- *"The cause of the satellite failures has not been determined with certainty, but it appears likely that they were caused by a temporarily severe space environment. These environmental conditions have now passed and are not expected to return for 10 or more years."* http://www.globalstar.com/EditWebNews/208.html

Canadian experiences (800 events over 25 years, courtesy Telesat Canada*)

Anik-E momentum wheel electronics provide an excellent example of an unambiguous space-weather-related failure **.

Conversely, the investigation of the March 1996 Anik-E1 power failure showed that, although initially suspected of being so, it was in fact not related to space weather.

** Evans, J. and Gubby, E. R., "Ground Loop Attitude Control System for the Anik-E Satellites" International Union of Radio Science XXVIth Assembly, University of Toronto 16 August 1999

Anik-A's
- 11 uncommanded mode switches of telemetry encoders.

Anik-B
- One earth sensor mode switch, believed to be caused by optical solar reflector discharge.

Anik-C's
- C1 and C2 had only a few phantom commands (i.e. mode changes, unit turn-on/off);
- C3 had more than 100 such events.

Anik-D's
- D1 had only 3 events (uncommanded mode switches);
- D2 suffered a major service outage on 8 March 1985, when multiple events occurred simultaneously.

Anik-E's
- Many phantom commands, especially RF amplifiers;
- On 20 Jan 1994 both momentum wheel electronic units failed on E2, one failed on E1;
- Several RF amplifier failures.

MSat
- Many phantom commands;
- Very large number of RF amplifier failures.

Nimiq
- A few phantom commands (as of Oct 1999)

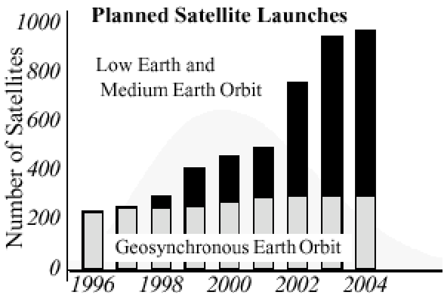
* SPACE ENVIRONMENT EFFECTS AND SATELLITE DESIGN, Robin Gubby & John Evans, JOURNAL OF ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS, 1999

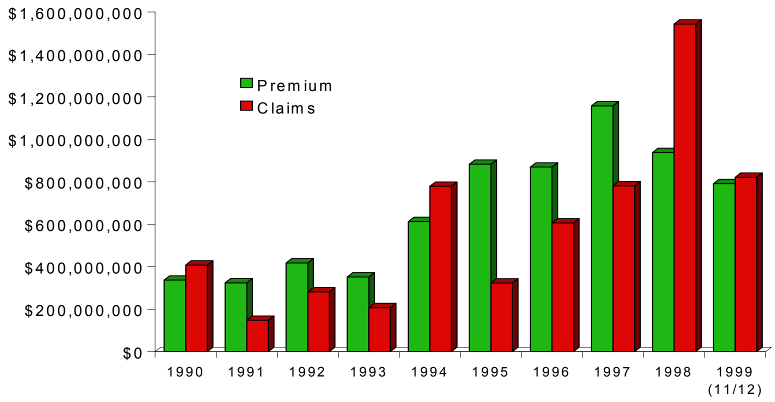
Image Credit: L. J. Lanzerotti, Bell Laboratories, Lecent Technologies, Inc.

Assets in Space - Satellite Insurance

- Total value of more than 600 satellites currently in orbit is about $50-100 billion
  - 235 of these are insured (value: $20 billion)

- Growing market: 1500 space payloads are expected to be launched the next 10 years
  - potential insured value $80 billion





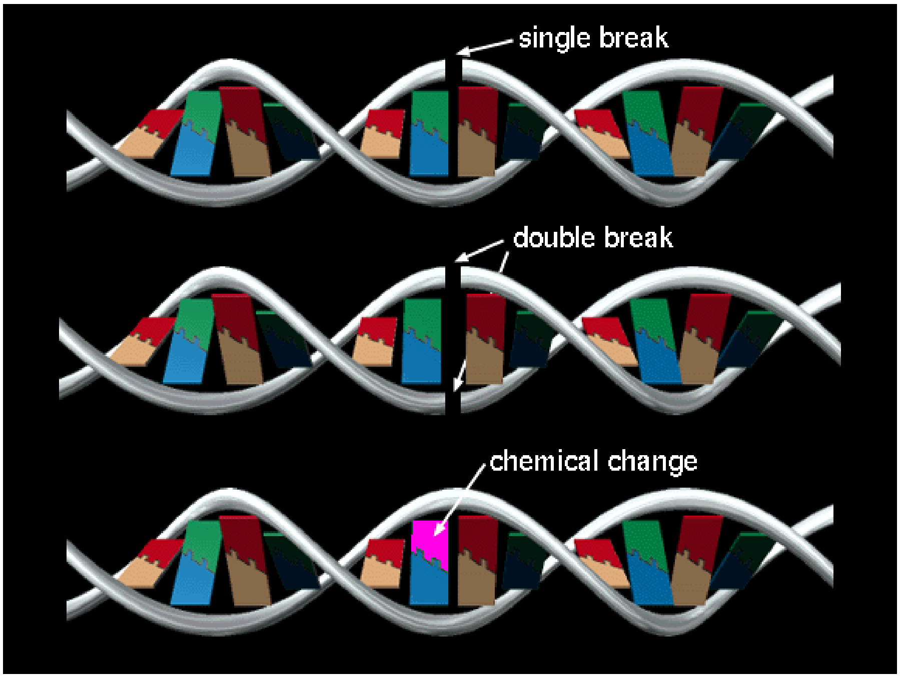
This charts shows total claims, not only space weather related

Estimated $500 million in damages due to space weather last 4 years

Source: USAU

Space environments and effects analysis section

Space Crew Effects



Doses to crew

US/ESA Astronaut limits

Exposure Interval	Blood Forming Organs	Eye	Skin
30 Days	25 rem	100 rem	150 rem
Annual	50 rem	200 rem	300 rem
Career	150 - 400 rem [200 + 7.5(age - 30) for men] 100 - 300 rem [200 + 7.5(age - 38) for women]	400 rem	600 rem

age	man	woman
20	125	65
25	162.5	102.5
30	200	140
35	237.5	177.5
40	275	215
45	312.5	252.5
50	350	290
55	387.5	327.5
60	425	365
65	462.5	402.5

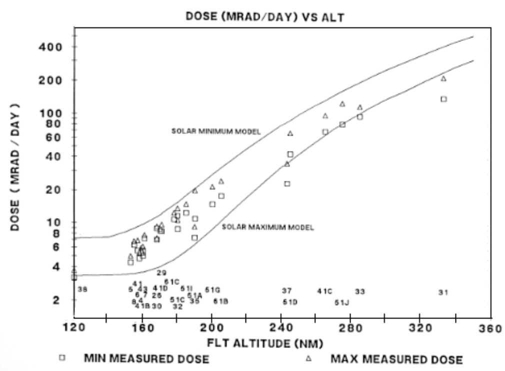


Figure 2. Absorbed dose to crew for 28.5 degree inclination Space Shuttle flights.

- October '89 solar event: Eye: 600-1100 REM; Skin: 800-1700 REM; BFO: 90-113 REM
- Fatality ~400 REM /30d; Rad^n sickness ~100 REM
- Occupational limits 1.5 - 5 REM
- Public limit <1 REM/yr

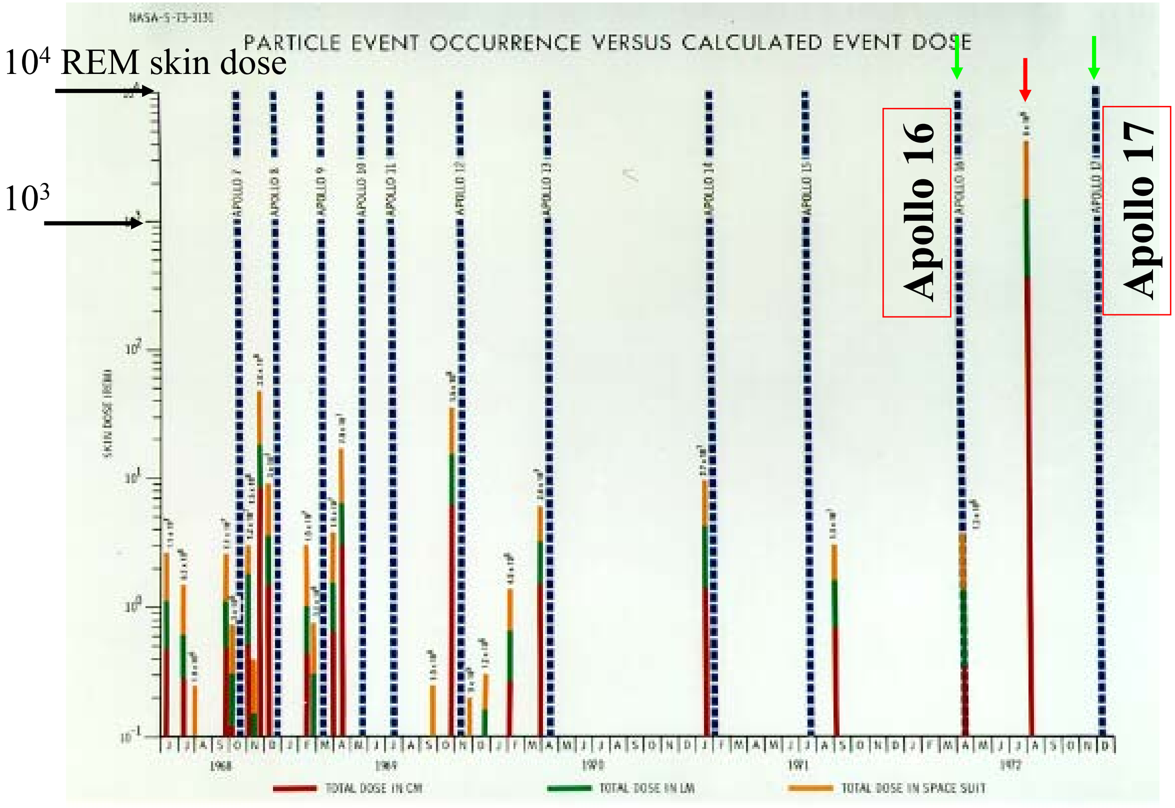
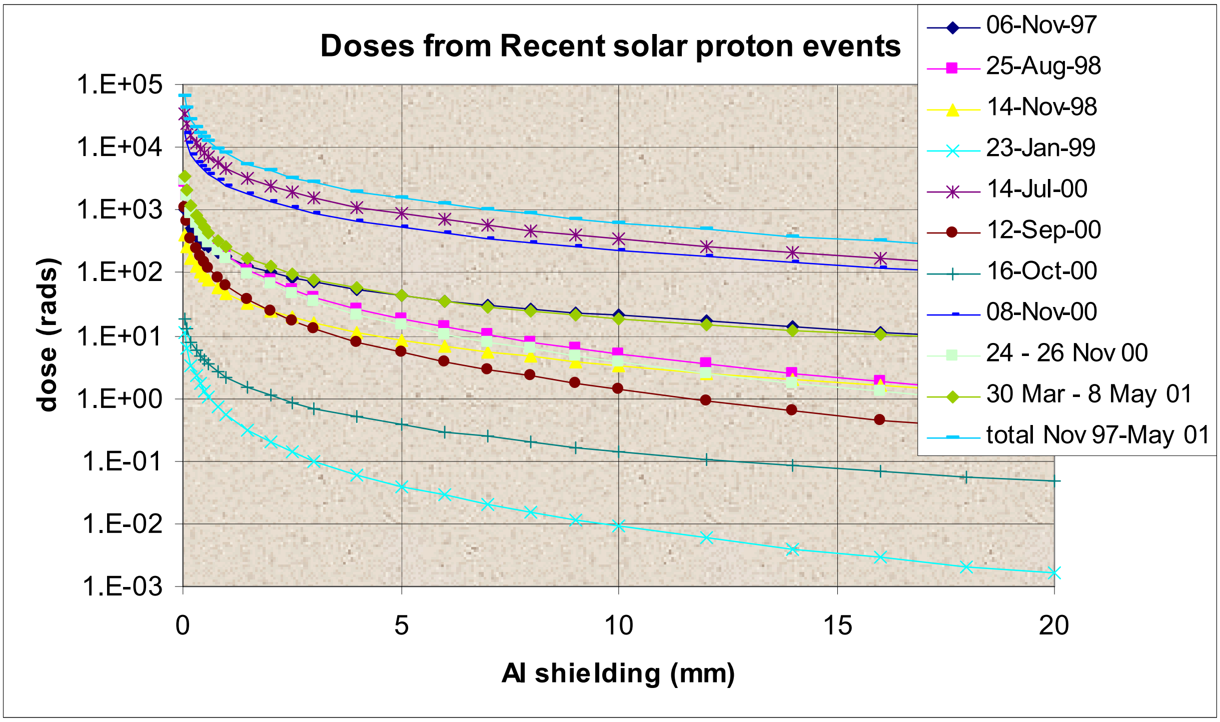
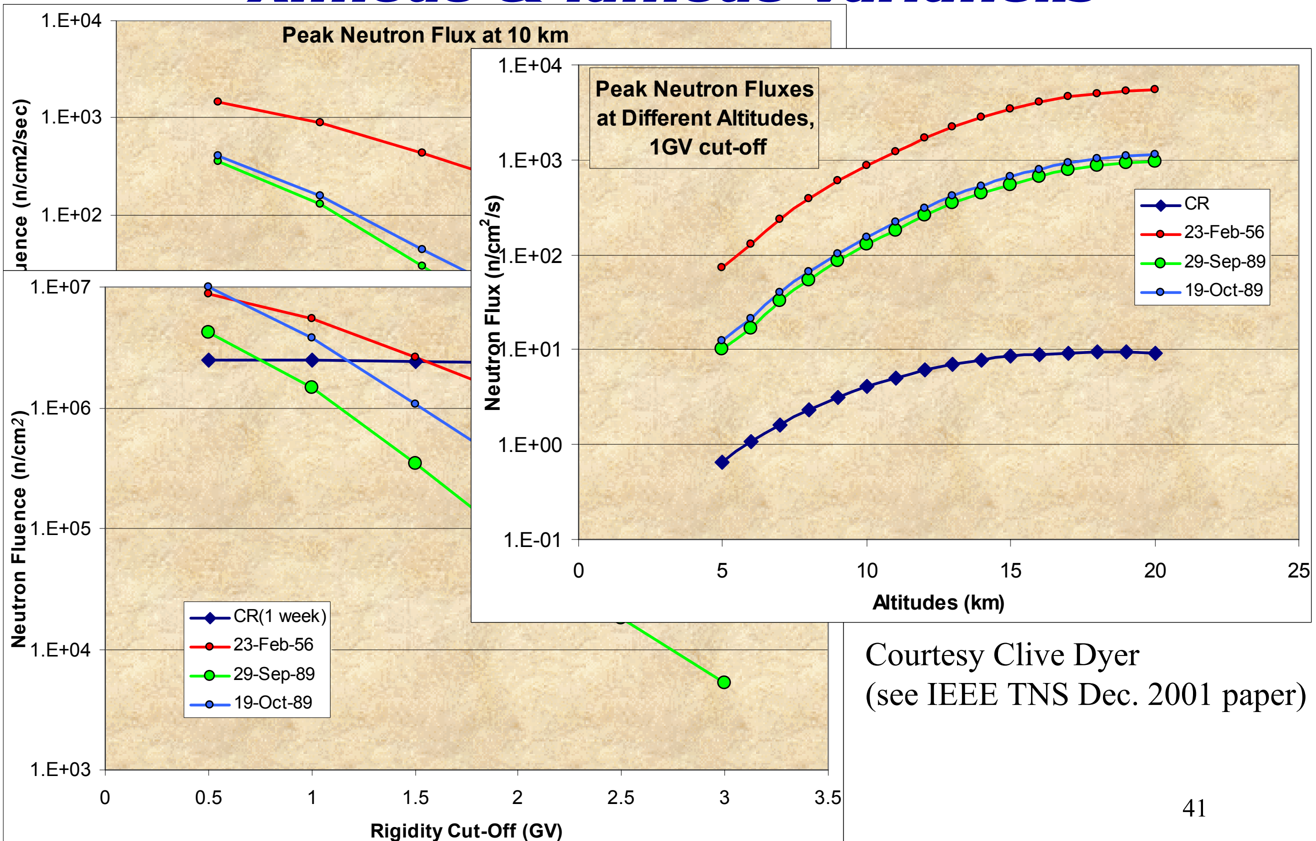


Figure 10. Solar proton events during the Apollo Program.

Doses from recent space weather events



Radiation Enhancements in the Atmosphere -Altitude & latitude variations



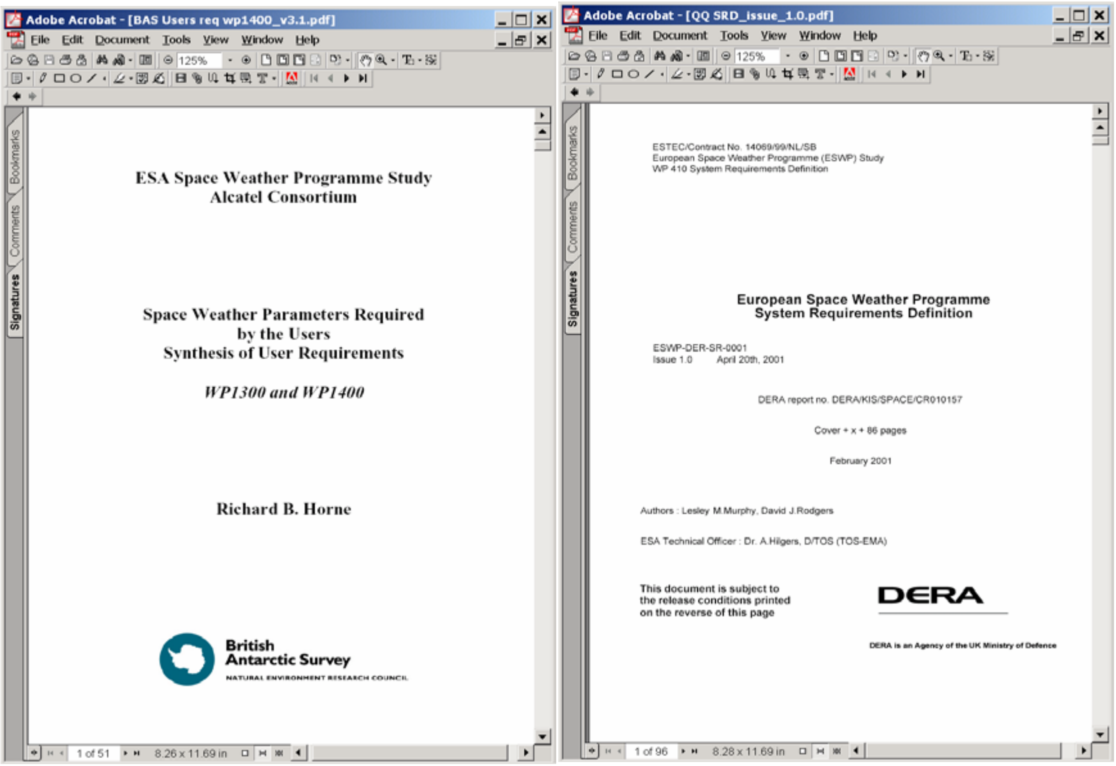
Courtesy Clive Dyer
(see IEEE TNS Dec. 2001 paper)

Measurement and Assessment Requirements

"Top Level"

1. Extracting accurate specifications from a good statistical basis.
2. Forecasting the long term space environment conditions for spacecraft design.
3. A posteriori determination of the condition of the space environment that prevailed at dates requiring in depth analysis or data quality label (e.g. date of spacecraft anomaly or date of scientific data collection).
4. Evaluating in real-time whether the space environment conditions are compatible with planned operations or are requiring specific actions.
5. Forecasting the short to medium term space environment conditions for operation planning.

Good Syntheses of Requirements have already been distributed


Adobe Acrobat - [BAS Users req wp1400_v3.1.pdf]

ESA Space Weather Programme Study
Alcatel Consortium

Space Weather Parameters Required
by the Users
Synthesis of User Requirements

WP1300 and WP1400

Richard B. Horne

British Antarctic Survey
NATURAL ENVIRONMENT RESEARCH COUNCIL

Adobe Acrobat - [QQ SRD_issue_1.0.pdf]

ESTEC/Contract No. 14069/99/NL/SB
European Space Weather Programme (ESWP) Study
WP 410 System Requirements Definition

European Space Weather Programme
System Requirements Definition

ESWP-DER-SR-0001
Issue 1.0 April 20th, 2001

DERA report no. DERA/KIS/SPACE/CR010157

Cover + x + 86 pages

February 2001

Authors : Lesley M.Murphy, David J.Rodgers

ESA Technical Officer : Dr. A.Hilgers, D/TOS (TOS-EMA)

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DERA

DERA is an Agency of the UK Ministry of Defence

Parameters and their Measurement

Effect	Parameter	Derivation	Instrument	Location
Spacecraft:				
Rad Damage	dose	flux	Dosimeter or flux meter (e to 10MeV, p to 200MeV)	Local or mapper
Rad damage sol array	Non-ionising dose	flux	Flux meter (e to 2MeV, p to 10MeV) or NI dose sensitive device	Local or mapper
SEU	Ion fluxes	flux	Spectrometers (ion species + energies to 200 MeV/u)	Local or mapper
Charging (internal)	Internal fields	External electron spectra	Spectrometers (e to 10MeV)	Local
Charging (external)	Charging levels or plasma e and ion spectra		Spectrometers (from eV to 50keV), Langmuir probes, Charging plates	Local
Astronauts	Dose equivalent	Dose from flux or directly; composition of radiation	Tissue equivalent meters; dosimeters, spectrometers	Close to crew Outside vehicle
	Warnings	Solar X-rays, UV /CME launch	imagers	Any
Aircraft:				
Crew	Dose	Neutron flux or dose	Dosimeter or Neutron monitor	Local
Electronics	SEU	Neutron flux	SEU monitors or Neutron monitors	Local

Near Real-Time Data

Component	**Available Measurement**	**Caveat**	**Delay before availability**
Galactic cosmic rays: 100 MeV to 1 GeV	Neutron monitor (ground)	Proxy	1 hour
	Neutron monitors	Proxy Only above ~400 MeV	1 hour
SPE particles: 100 keV to ~100 MeV	GOES ACE	Require model at low altitude	5 min
X, EUV, UV photons	GOES SOHO		5 min

Near Real-Time Data

Component	**Available Measurement**	**Caveat**	**Delay before availability**
Magnetopause boundary location	GOES	Only 2 points at GEO	5 min
	ACE	Input to model	5 min
Plasma: 0.1 to 100 eV	TEC NPOES	Integrated value Only at 830 km altitude	1 hour 1 hour
Plasmasheet and auroral Electron energy spectrum (100 eV to 20 keV)	LANL NPOES Kp A	Only at GEO Only at 830 km Proxy Proxy	1 day 1 hour 1 day 1 day

Near Real-Time Data

Component	Available Measurement	Caveat	Delay before availability
Radiation belts proton energy spectrum 1 MeV to 1 GeV	GOES NPOES	Only at GEO Reduced energy range Only at 830 km	5 min 1 hour
Radiation belts electrons energy spectrum 100 keV to 10 MeV	GOES LANL NPOES Kp A	Only at GEO Only at GEO Only at 830 km Proxy Proxy	5 min 24 hours 1 hour 1 day 1 day
Thermospheric flux	F10.7 Kp	Input to model	Once a day 1 day

Forecast: Precursor

Phenomenon	Tracer	Precursor
Flare	X, UV, Vis, MeV protons	Sunspot Magnetic structure
CME	Vis image	Sunspot
ICME	Radio Interplanetary scintillation	CME
SPE	MeV protons	CME
Substorm	AE, Kp NPOES	
Storm	Kp GOES LANL	IMF Bz <0
Ionospheric and thermospheric change	TEC Radars	EUV from backside IMF Bz <0

Improvements Needed

- Data coverage: Lacking especially:
  - eV to keV electron environment at high altitude
  - Rad environment from 100 keV to 1 MeV at high altitude
  - Thermospheric flux
- Long term continuity:
  - Scientific data disappear after end of mission (Yohko, SOHO, ACE, …Triana).
  - Ground observatories are not eternal either.
- Reliability:
  - Mainly depending of US data & data provision system;
  - Data distribution to Europe is internet based with relatively poor reliability and quality check. Bad access to models.
- Models accuracy:
  - First principle models are not in general intended for operational purpose.
  - Empirical models can be run fast but are still in their infancy and require more data (especially for extreme events).

Engineering solutions

- Design to worst-case is currently more common than use of space weather warnings:
  - uses pessimistic environment assessment and shielding assessment resulting in:
    - mass penalty for over-design
    - use of over-engineered (e.g. hardened) parts
- Risk assessment:
  - based on statistical models of (for now) solar energetic particle fluences
  - is a more rational way to take decisions
- Better understanding of risk of the worst-case can lead to relaxing margins: lowering costs

Practical Application

- For engineering studies of space environments and effects, a popular system is ***Spenvis***
- Space Environment Information System
  - has *help*, links to environment standard, background information, etc.
  - has orbit generation etc.
  - Has all the models needed
  - so all is under one system

Design of Systems

- General principle: know the threat and the system well
- Data handling and similar systems:
  - SEU's , Latch-up,...
  - Effects in linear devices: SEU, SET
  - consider the application and its tolerance to upsets
  - consider the implications at system level
  - error and failure recovery
- Imaging systems
  - AOCS: star trackers: anticipate the response and ensure software can cope
  - Payloads: very sensitive science systems need background removal - necessitates detailed simulation and validation

Operations

- Manned example already well established:
  NASA-JSC system uses NOAA resources
- Science mission instrument shut-off
  e.g. XMM, Integral take action if hazardous conditions are detected
- Launch authorities can delay launches
  (e.g. rapid decision taken for Cluster-II launch on July 16 '00)
- Reliability of forecast is a major obstacle

Conclusions

- Space weather (and space environment) effects to spacecraft are a serious and growing concern – results in a large cost impact
- Hazards to humans in space will become critical beyond low orbit;
- Hazards to aircraft crew important and recognised by EU legislation
- Effects on aircraft electronics may have to be more thoroughly worked on