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International Advanced School
on
Space Weather
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Effect of Cosmic Rays

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Space weather Operational Airline Risks Service (SOARS)

Effect of Cosmic Rays

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University College London

ICTP, 5 May 2006

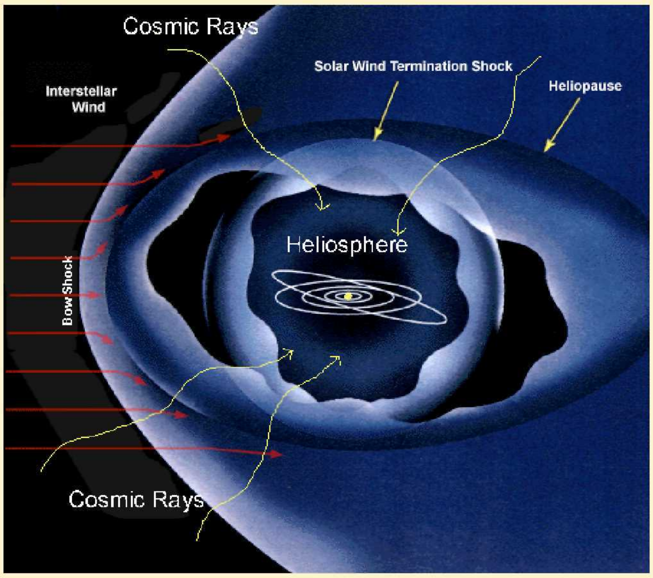
Space weather Operational Airline Risks Service (SOARS)

Overview

- Recap on the origins of cosmic radiation
- Radiation environment in near-Earth space
- Affects on electronics
- Radiation environment at altitude
- Biological effects
- Monitoring the dose at altitude
- Legislation on cosmic ray exposure
- Measurement and calculation of dose
- Compliance with legislation
- Epidemiology and risks

Sources of Cosmic Radiation

- The cosmic radiation incident on the Earth has two sources: Galactic Cosmic Radiation and the Sun.
- Galactic Cosmic Radiation (CGR) originates from highly energetic astrophysical processes, e.g. supernovae. The CGR flux of is reasonably isotropic.
- The cosmic radiation from the Sun is typically less energetic and originates from solar flares and coronal mass ejections (CMEs).



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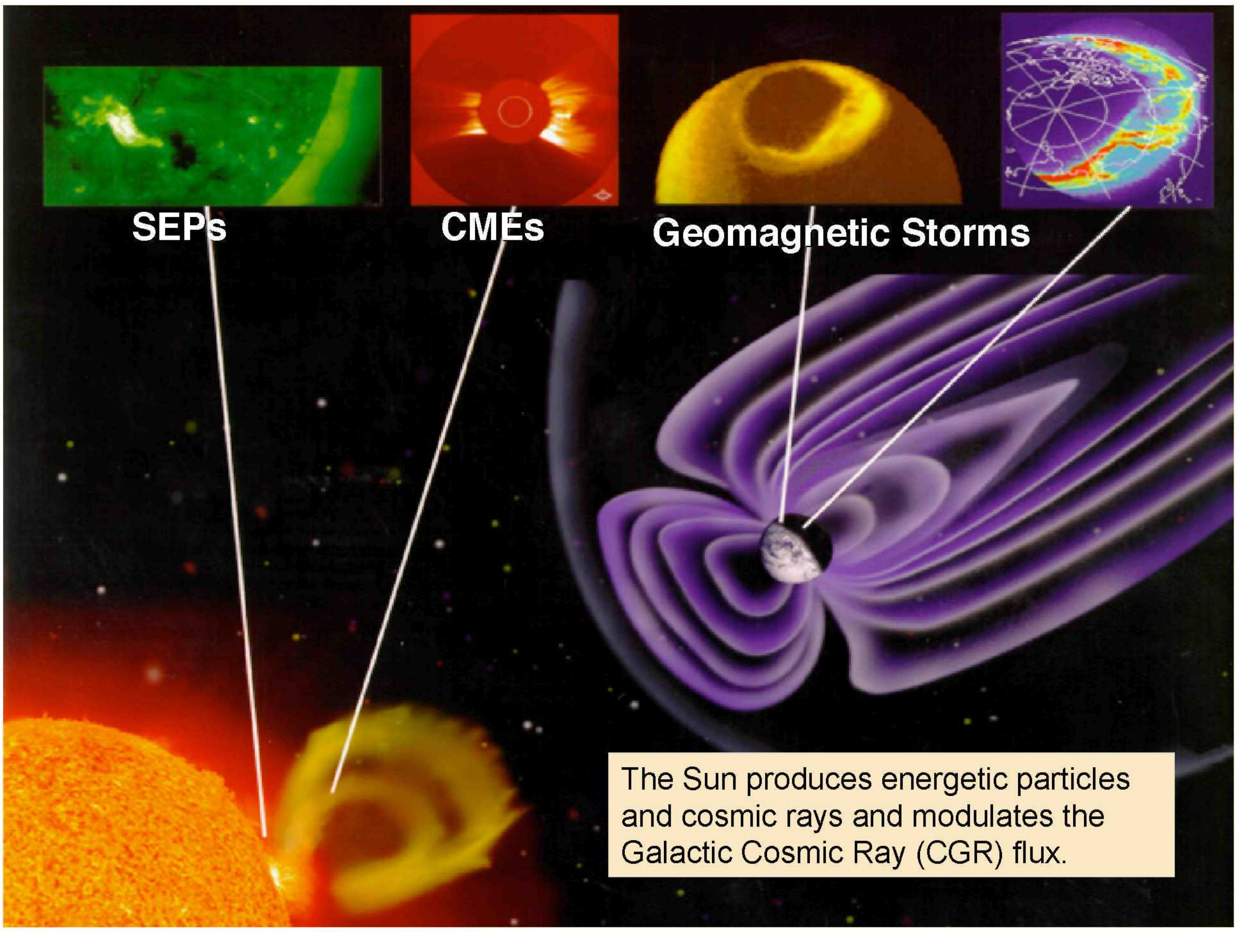
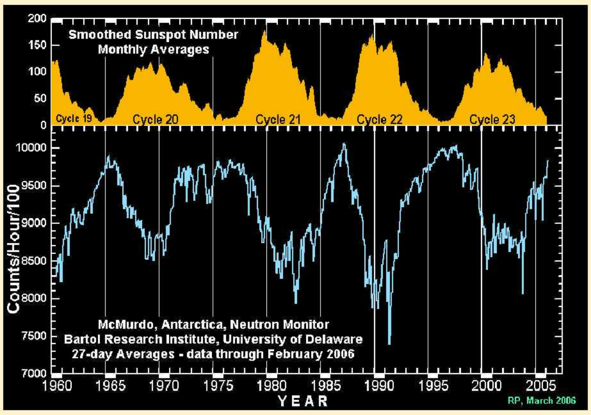


GCR flux is modified by solar activity

The background cosmic rays flux is most intense at solar minimum when the Sun's influence on the heliosphere is at its weakest.

The flux is thus in anti-phase to the solar cycle.



The material carried in a coronal mass ejection (CME) can mask the galactic cosmic ray flux for many days – a Forbush Decrease

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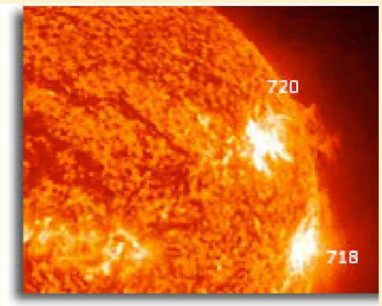
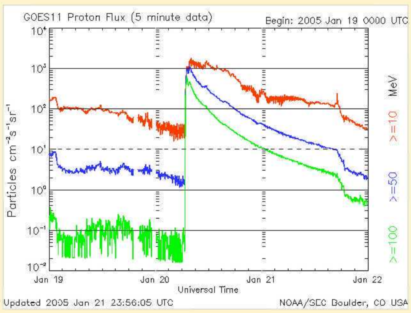
Radiation Storms…

Radiation storms can quickly follow the onset of a large solar flare. Highest energy protons (>100 MeV) travel fastest (up to a third the speed of light!).

As of May 2005, there had been 85 (>10 MeV) radiation storms during the current solar cycle.





Jan 2005: X7 flare began at 20/0636 UT and peaked at 20/0701 UT.
The Intense >100 MeV radiation storm peaked at 20/0710 UT.
This storm was short-lived but did exceed the FAA Solar Radiation Alert at Flight Altitudes for about 1.5 hours.

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Radiation Environment

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- **Cosmic rays**
  - Continuous flux of very energetic protons and heavy ions
- **Solar particles**
  - Energetic protons and heavy ions produced sporadically at high intensities
- **Atmospheric & spacecraft secondaries generated by nuclear reactions of the above**
- **Radiation belt protons**
- **Nuclear weapons and reactors.**
- **Radioactivity in packaging.**

Spectra of large solar particle events cf cosmic rays

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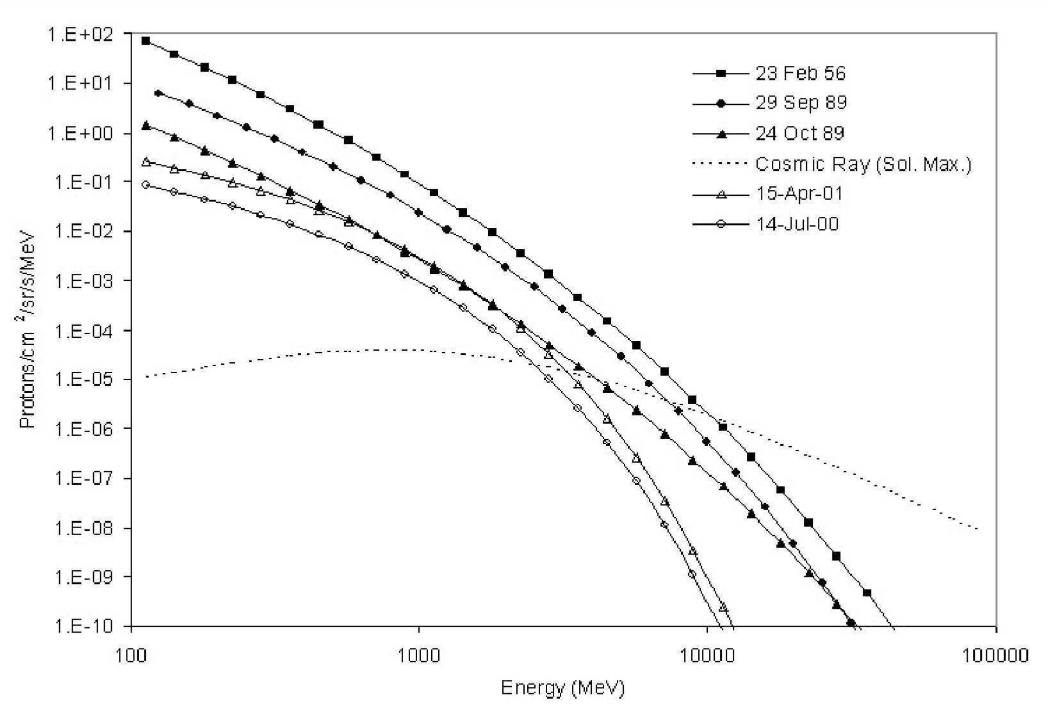

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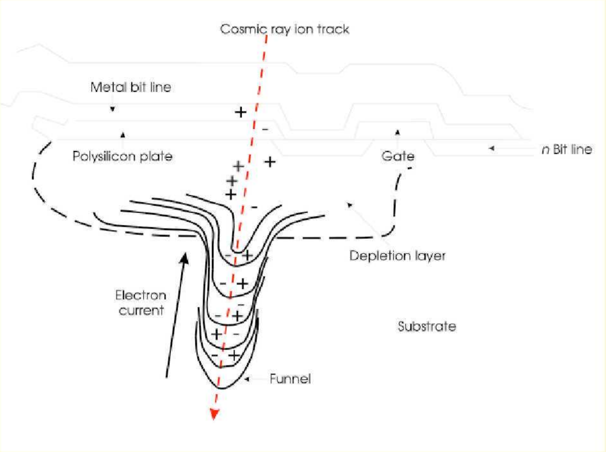
Single Event Effects (SEEs)

- Single Event Effects result from charge depositions of individual particles and include:
  - Upsets (bit-flips)
  - Transients
  - Functional Interrupts
  - Latch-up
  - Burnout
  - Gate rupture
  - Dielectric failure
  - DNA rupture



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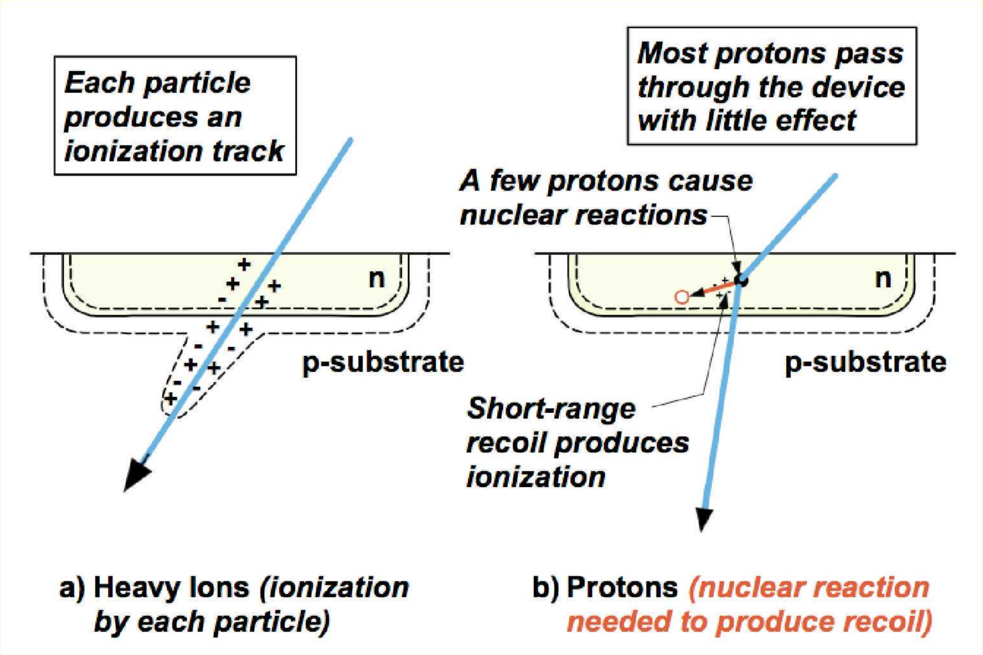
Mechanisms for Heavy Ion and Proton SEUs



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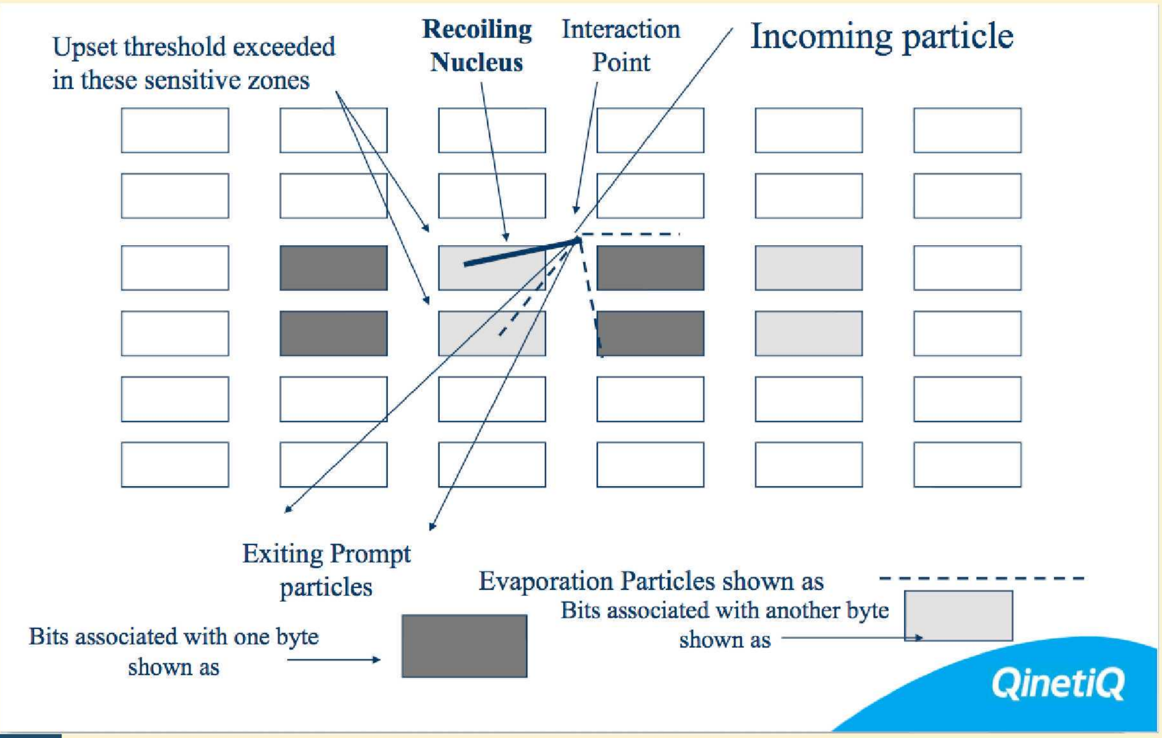
Single Event Effects (SEEs)

- **Disturbance of an active electronic device caused by a single energetic particle:**
  - Upset (SEU) – change in logic state, simplest example is a memory cell in RAM
  - Latch-up (SEL) – sharp increase in current resulting from turning on parasitic *pnpn*
  - Damage or burnout (SEB) of power transistor or other high voltage device
  - Functional interrupt (SEFI) – malfunctions in more complex parts sometimes as lockup, hard error, etc
- **Shielding cannot stop high energy protons or GCRs and good practice is to assume that SEEs <u>will</u> occur and design accordingly:**
  - Use error-detecting and correcting (EDAC) coding schemes on memory systems to protect against SEUs (e.g. Hamming, Reed-Solomon, etc.);
  - Use fast-acting over-current sensing power switches to give a degree of protection against damage from SEL.

Diagrammatic representation of a single byte multiple-bit upset



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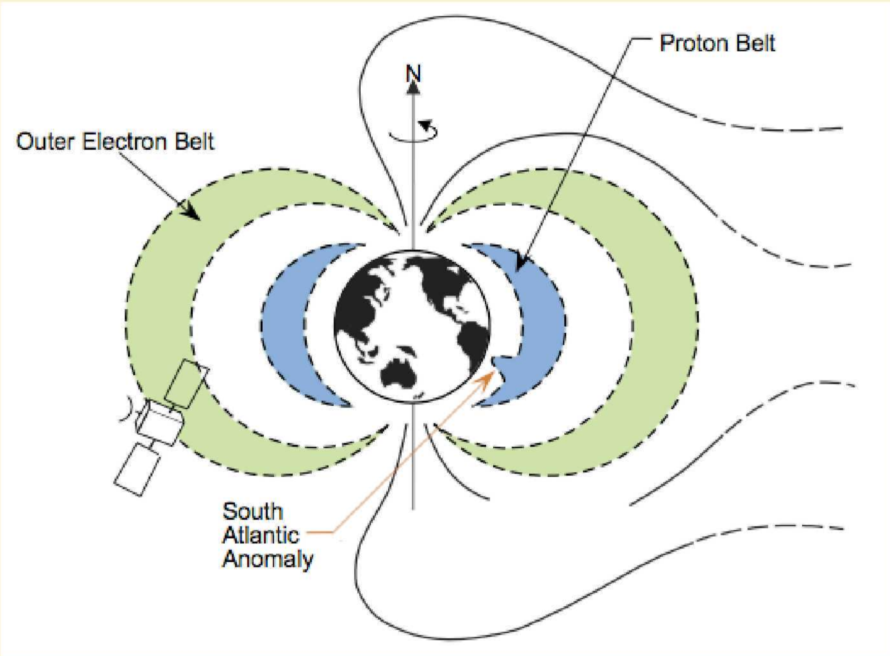
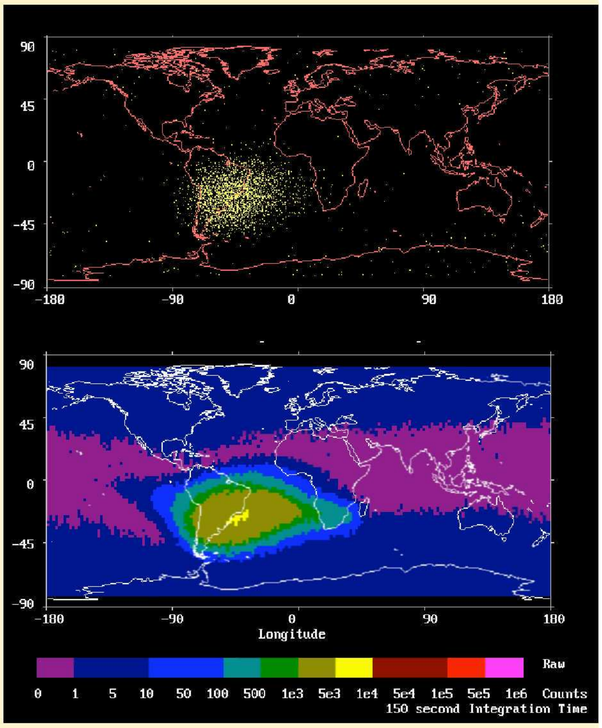
Trapped Radiation Belts around the Earth



p+ energies are ~10-100's MeV, with up to 2×10^5 p^+ cm^{-2} s^{-1} (>10MeV).
e– energies are ~few MeV, with up to 3×10^6 e^- cm^{-2} s^{-1} (>1 MeV).

Location of SEEs

- The near-Earth radiation environment is dominated by the geomagnetic field
- Charged particles are trapped in the Van Allen Radiation Belts
- The proton belt encountered in LEO in the South Atlantic Anomaly (SAA) is due to the tilt and offset of the geomagnetic dipole with respect to the Earth's rotation axis.
- The SAA is a major source of of SEE activity.



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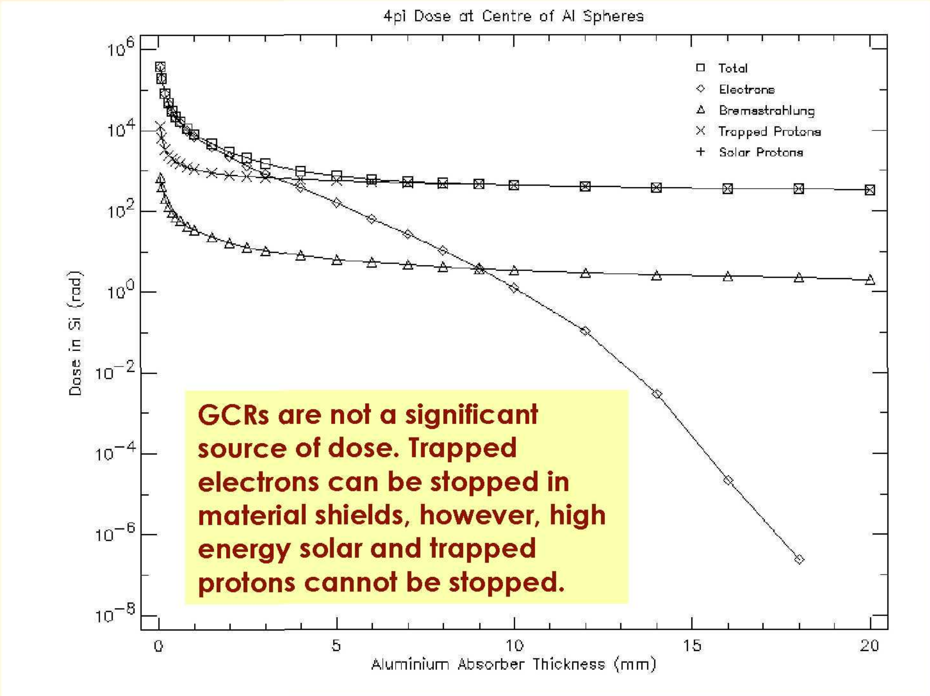
Total Dose Effects



Annual Dose - 800 km Sun-Synchronous Orbit (at solar max)

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SEEs in Space

- Problem first predicted in 1962 as a limit to scaling.
- Observed in space with increasing frequency since 1975.
- Major problem realized in 1984 when TDRS-1 attitude control memory showed several upsets per day (several hundred during major solar particle event) requiring expensive ground control.
- Latch-up failure of ERS-1 PRARE instrument after 5 days of operation in July 1991.
- PCs on Shuttle and MIR required frequent reboot, typically every nine hours.
- Remains a major source of anomalies in space systems, e.g. NASA Microwave Anisotropy Probe on 5 Nov 2001.

Upset Rates in 1 Gbyte of SRAM

Event	Neutron Flux /(cm^2-sec)	Upset Rate (/hr)	MTBU (sec)
1GV - 17km			
23-Feb-56	2893	1164	3.1
29-Sep-89	487	196	18.4
19-Oct-89	39.1	15.7	229
22-Oct-89	70.4	28.3	127
24-Oct-89	79.7	32.1	112
GCR (Sol. Max)	9.3	3.6	1003
1GV - 12km			
23-Feb-56	1113	493	7.3
29-Sep-89	191	84.7	42.5
19-Oct-89	16.1	7.1	504
22-Oct-89	28.2	12.5	288
24-Oct-89	31.5	13.9	258
GCR (Sol. Max)	5.8	2.5	1468

(Cross-section of 5×10^{-14} cm^2 per bit)

Radiation at Altitude

- Look at how cosmic radiation varies at aircraft altitudes
- Describe the PIPSS project undertaken to measure the cosmic radiation and look for the influence of solar activity
- Legislation and how airlines comply
- Brief overview SOARS project
- Epidemiology and risks

Based on work from PIPSS project to monitor cosmic radiation on aircraft and from an ESA Space Weather Pilot Project, SOARS, that is investigating the effects of space weather on the aviation industry.

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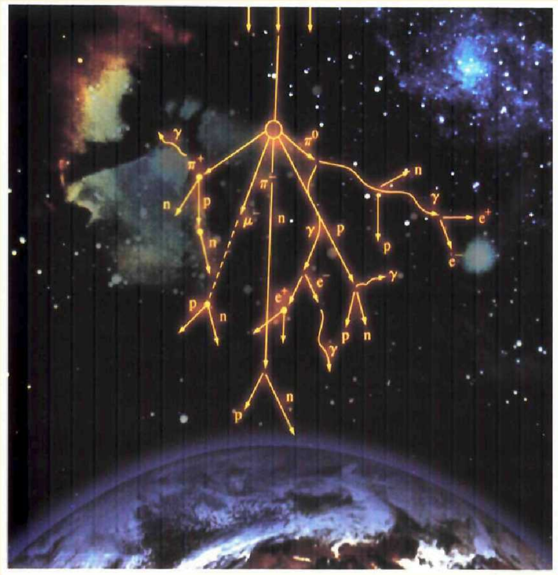
Cosmic Rays cascade



Neutrons, created by cosmic ray interactions with the O_2 and N_2 in the air, peak at ~60,000 ft. At 30,000 ft the neutrons are about 1/3 the peak flux, and on the ground, ~1/400 of the peak flux. The peak flux is ~4 neutron/cm²/sec. Other particles such as secondary protons and pions are also created, but for SEU the neutrons are the most important.

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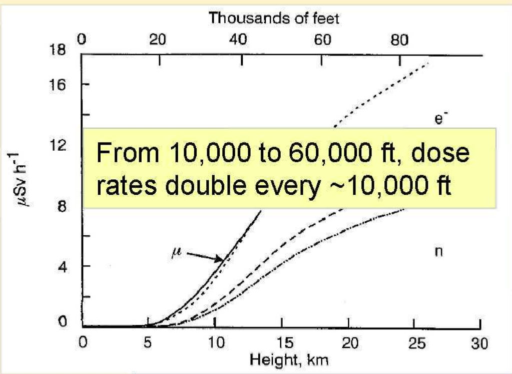
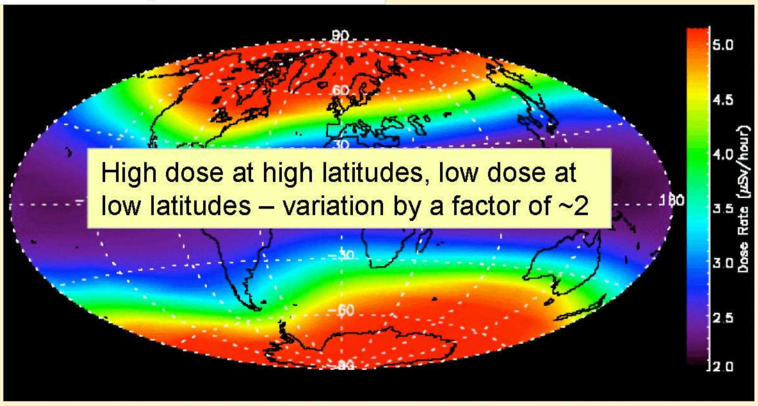
Variation in Dose Rate



- The Earth's magnetic field acts as a shield and the atmosphere provides an additional barrier to cosmic rays .
- As a consequence, the dose rate is dependant on altitude and location
- The background flux is modulated by the solar cycle and by coronal mass ejections.
- Intense solar flares can add to the dose rate for short intervals



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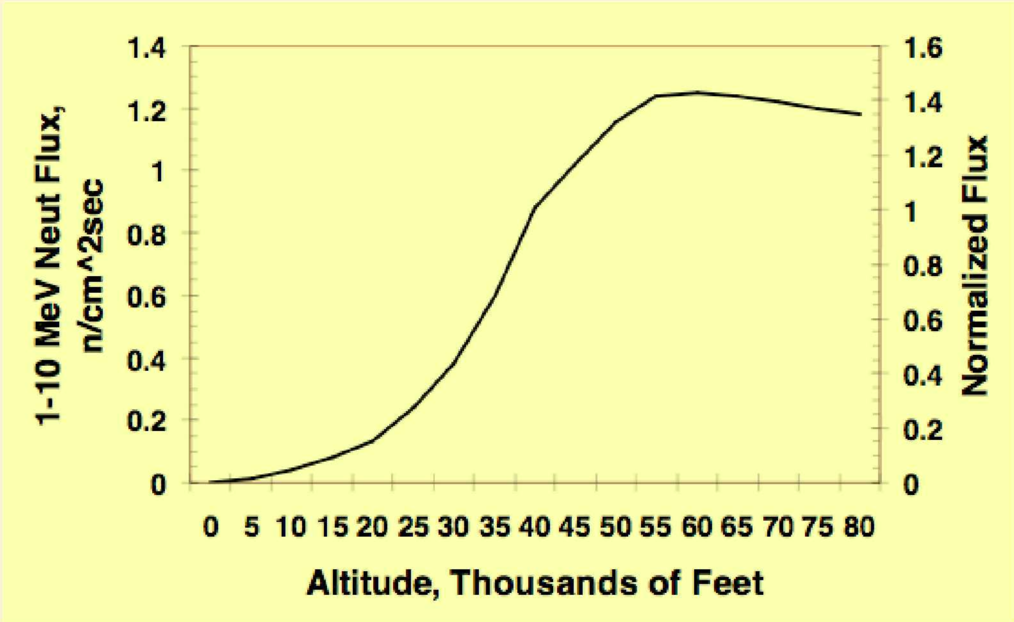
Variation with Altitude



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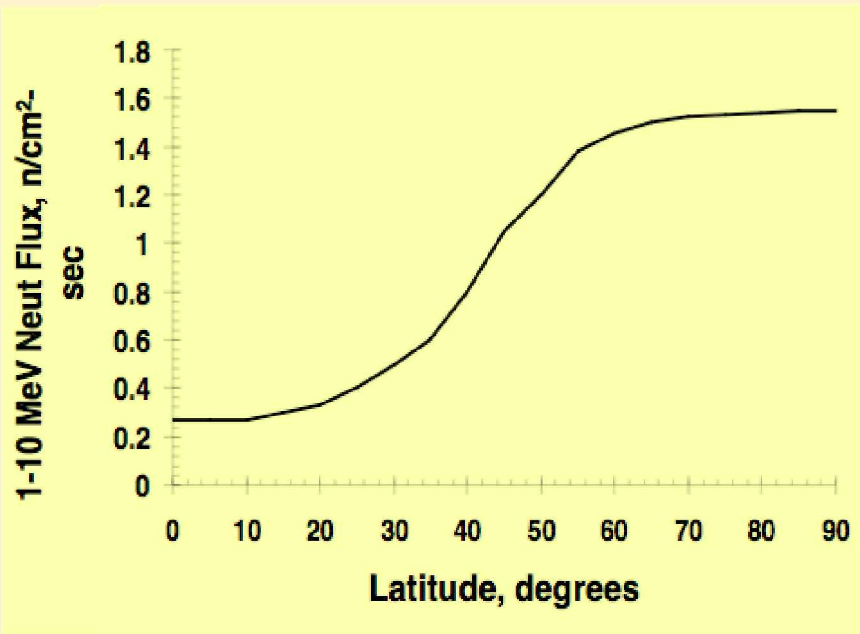
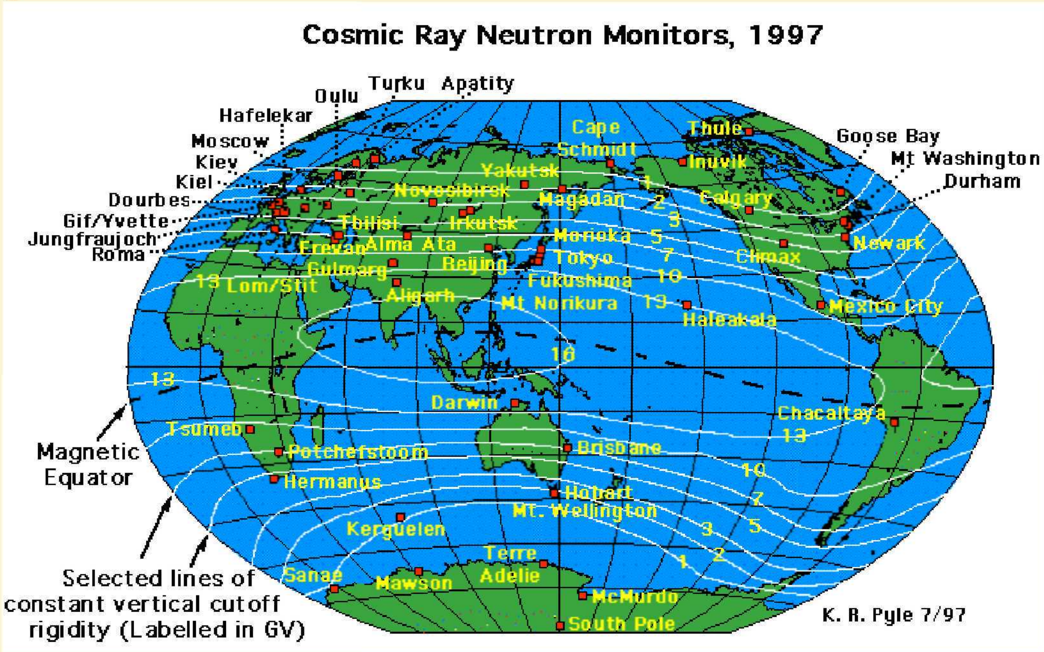
Variation with Latitude



Rigidity Cutoff



Rigidity is the resistance to bending in the magnetic field and penetration is easiest at the magnetic poles.

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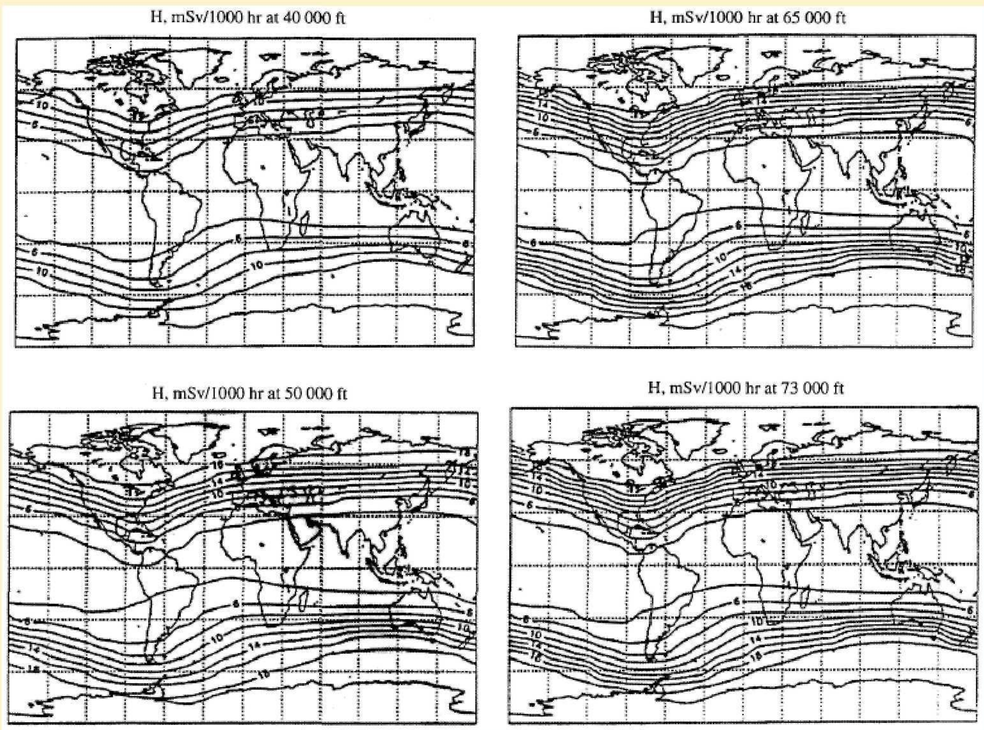
Variation with Position & Altitude



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SEEs at altitude

- QinetiQ Cosmic Radiation Effects & Activation Monitor flown on Concorde between 1988 & 1992, and on SAS Copenhagen-Seattle route in 1993. Measured charge-deposition events in silicon. 5 solar particle increases observed.
- PERFORM computer withdrawn for tests in 1991 following accumulation of errors in SRAM memory.
- More than one upset per flight in 280 64K SRAMs on Boeing E-3 AWACS and NASA ER-2.
- Saab CUTE experiment in 1996 showed upset every 200 flight hours in 4 Mbit SRAM. 2% are multiple-bit upsets.
- Autopilot design altered after faults shown to correlate with altitude and latitude.

Legislation on exposure

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- Since May 2000, European airlines have been required to assess the radiation dose experience by their crewmembers.
- CEC Directive 96/29/Euratom, article 42, requires airlines to assess the maximum annual dose that crewmembers will be exposed to if it is expected to exceed 1 mSV per annum.
  - Directive in response to recommendations of International Commission on Radiological Protection (ICRP) in 1990.
  - Implemented at the national level – led to variations across countries
  - NOTE: Currently the legislation only applies to aircrew, as employees of the airlines
- If the dose is liable to exceed 6 mSv per annum, monitoring of the dose received by individuals must be carried out.
  - Roster should be modified to try to avoid exceeding 6 mSv.
  - For pregnant aircrew, article 10 applies: Once the pregnancy is declared to the operator, the dose should not exceed 1 mSv in the remainder of the pregnancy (ALARA).

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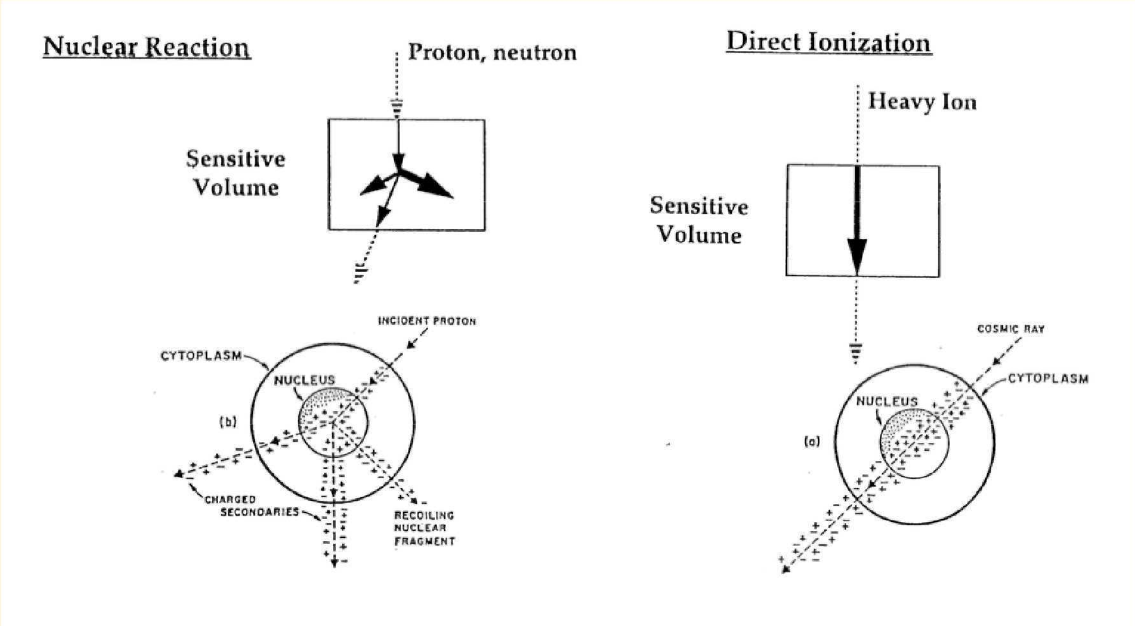
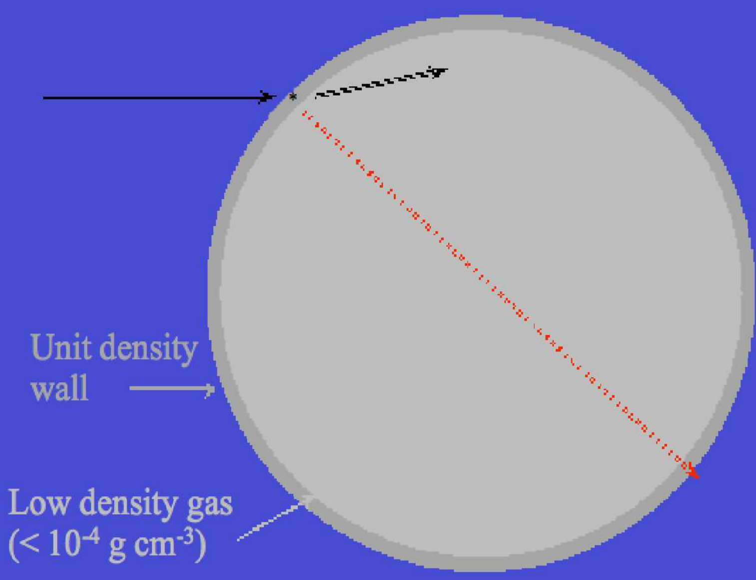
Single Event Effects and Radiobiological Effects



Neutron Interactions in TEPCs

A TEPC is designed to emulate the interaction of a neutron with 1mm? of tissue



Charged particle crosses wall and enters TEPC gas cavity. The low pressure means that the particle loses energy less rapidly than in tissue.

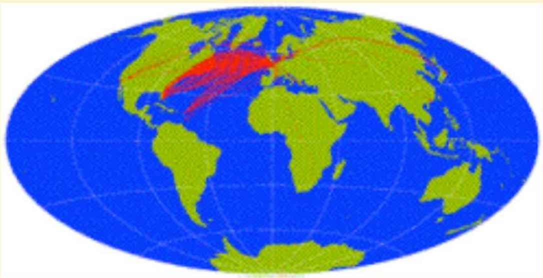
NPL

PIPSS Study

The Hawk TEPCs were carried in the overhead lockers and had batteries and flash memory cards that would allow them to take data for 3-4 weeks.

- Objective of the PIPSS study was to use in-fight measurements, together with observations made by solar and space plasma satellites supported under the PPARC programme, to determine the influence of solar events on the radiation experienced at aircraft altitudes.
- Measurements were made using Tissue Equivalent Proportional Counters (TEPCs) that were flown with Virgin Atlantic Airways.
- The data were analyzed to validate the current radiation dose models.

The observing campaign



- The TEPCs were flown on more than a 1000 flights in the northern hemisphere by Virgin Atlantic Airways
- Also flown on over 100 flights in the southern hemisphere by Air New Zealand
- Information about the flight profile had to be associated with the TEPC data post flight
  - Initially by hand
  - Later using engineering logs
- Light-curves from GOES used to identify solar activity

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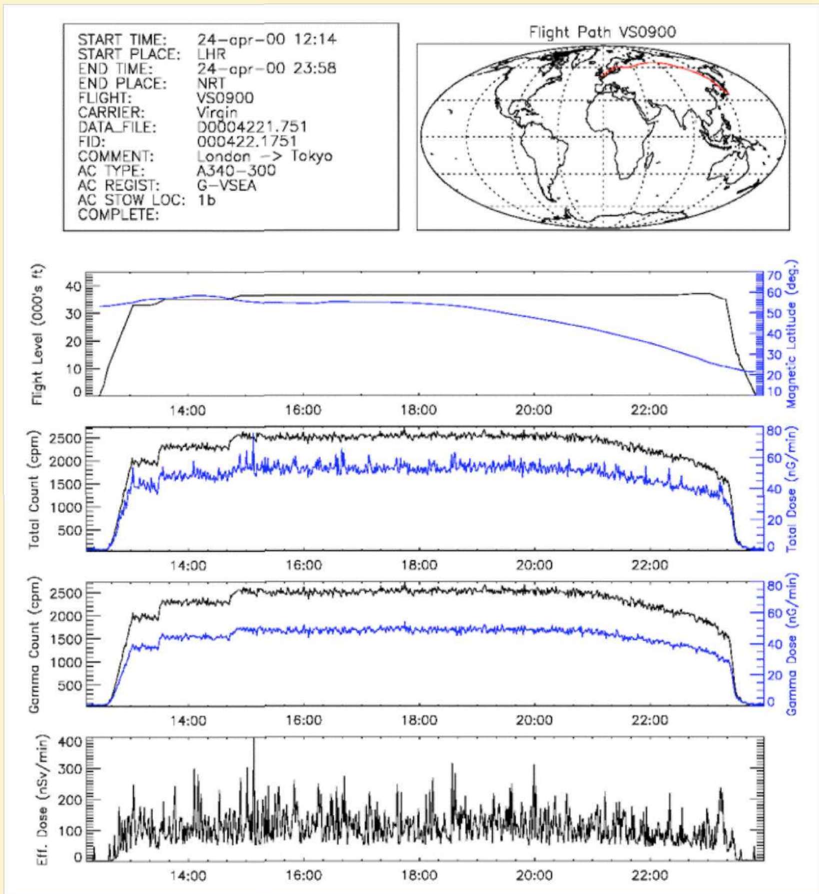

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Typical doses

Route	No. of Flights	Mean Route Dose (µSv)	Std Dev (µSv)
London → Tokyo	4	52.5	3.7
Tokyo → London	3	59.3	2.7
London → Los Angeles	3	51.5	2.7
Los Angeles → London	2	47.9	1.5
London → San Francisco	2	46.8	1.4
San Francisco → London	2	38.0	4.5
London → Shanghai	2	43.4	3.3
Shanghai → London	1	56.8	-
London → Hong Kong	1	42.9	-
Hong Kong → London	1	55.0	-
London → Orlando	2	36.6	1.0
Orlando → London	2	28.9	1.3
London → New York	3	33.8	2.3
New York → London	2	29.8	1.2
London → Miami	2	30.8	4.7
Miami → London	1	27.7	-
London → Boston	6	30.7	3.1
Boston → London	4	25.9	3.2
London → Johannesburg	6	25.6	1.5
Johannesburg → London	5	25.0	3.1
London → Athens	4	11.4	0.9
Athens → London	4	13.0	0.6

The exposure on a trans-atlantic flight is roughly equivalent to a chest X-ray, but the quality of the radiation is different – CR mainly high LET neutrons

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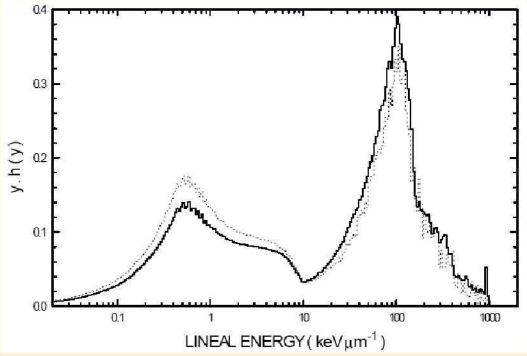
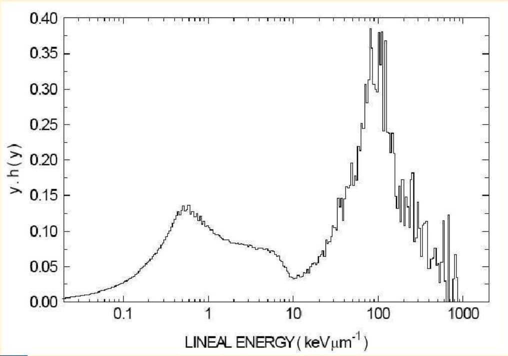
Measurement by TEPC





- The energy deposited in the detector is expressed as lineal energy in KeV/μm assuming a mean cord length inside the cavity
- Top plot compares measured dose for London-Johannesburg (dotted) and the sum of all northern hemisphere routes
- Bottom plot shows measurements on a London Tokyo flight

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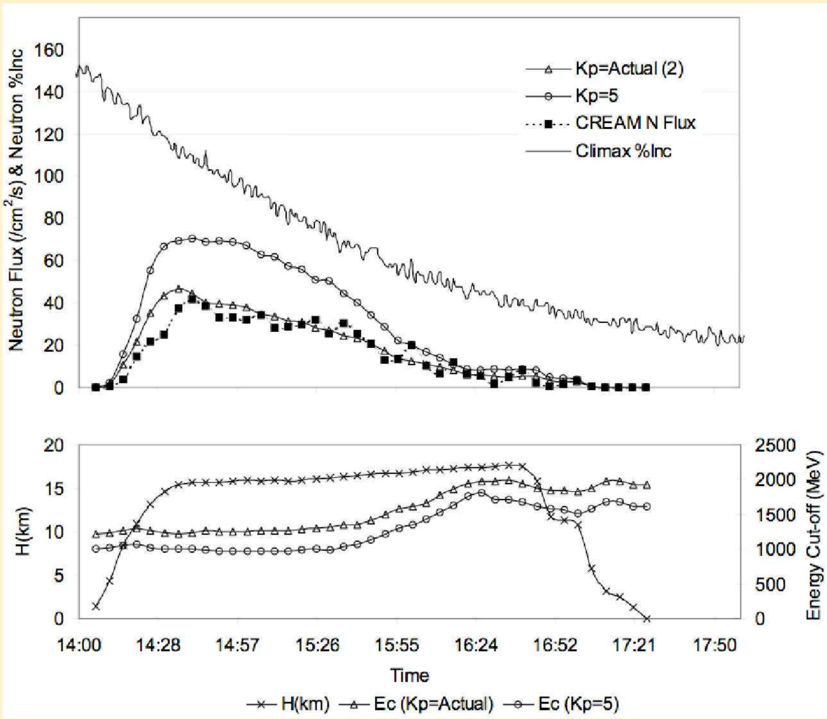
Calculated neutron fluxes for Concorde



Flight JFK–LHR due to 29 Sept 1989 Event for 2 geomagnetic conditions.

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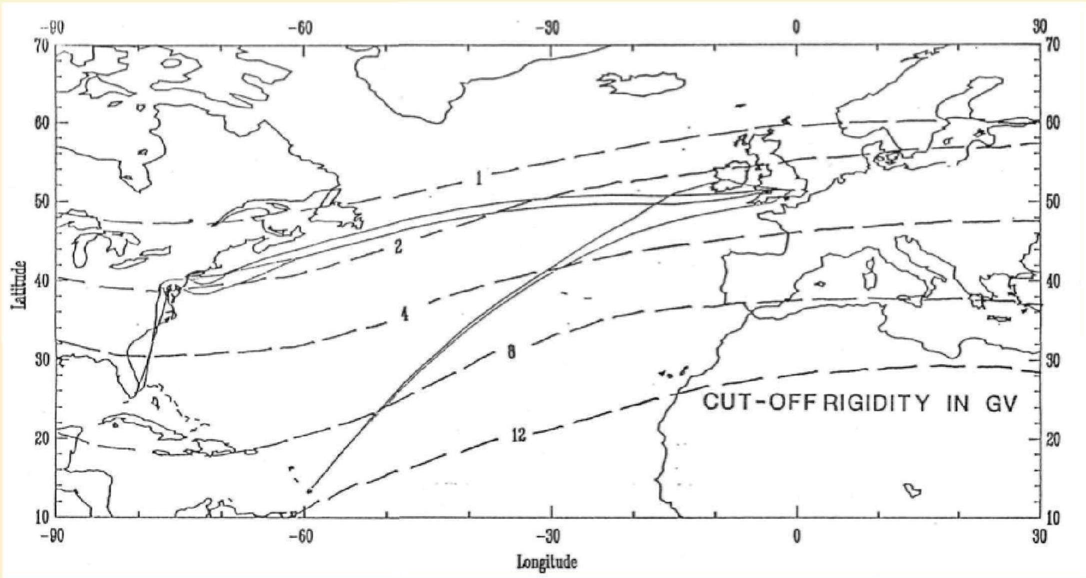
Affects of Rigidity



Concorde routes were actually well protected on routes across the North Atlantic to Washington, etc.

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SOARS

- The Space weather Operational Airline Risk Service (SOARS) is a space weather pilot project jointly funded by ESA. It has the following objectives:
  - Determine how the aviation industry is affected by space weather
  - Propose a service that could help airlines plan their operations
- Involves only space weather effects relevant to aviation
  - Effects of RF Communications
    - Effects of HF and Satellite voice and data communications
    - Effects on Satellite Navigation (e.g. GPS, WAAS)
  - Monitoring radiation exposure of airline crewmembers
  - Monitoring other effects that could be attributed to space weather, e.g. in avionics
- The risks associated with radiation exposure have been studied as part of the project.

Compliance to Legislation

- Legislation implemented at the national level
  - Implementation has cost implications for the airlines
- Dose assessment is commonly carried out using predictive computer codes – CARI, Sievert, EPCARD, etc.
  - These give reasonable approximations when solar activity is low, but do not properly account for the increased levels of radiation due to large energetic flares
- Significant differences in the way it is implemented
  - In France and Germany, if the dose is expected to exceed 1 Msv per year, assessment has to be carried and the results stored in a central data base – the French must use Sievert
  - In the UK, airlines do the assessment separately – there are differences depending on the route pattern
  - In Sweden, increased exposure of workers to natural hazards during is not considered a problem – still adjusting Swedish vs. EU regulatons…

Note: The radiation has a much higher component of high-LET radiation in aircrew (and astronaut) exposures, as compared with nuclear workers where 93% of exposures are from low-LET radiation.

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Linear Energy Transfer

- LET – linear energy transfer. LET represents the average amount of radiation energy lost when traversing a small distance. It has units of energy divided by the short distance.
  - High-LET radiation: radiation that produces lots of damage over a short distance in tissue or other material is called high-LET radiation. Alpha particles represent high-LET radiation.
  - Low-LET radiation: produces only a small amount of damage when evaluated over a short distance. Gamma and x rays represent low-LET radiations.
- To produce a given amount of damage, it takes a larger absorbed dose of low-LET radiation than for high-LET radiation.
- Biological damage produced by low-LET radiation is usually more efficiently repaired than damage produced by high-LET radiation.

Note: The radiation has a much higher component of high-LET radiation in aircrew (and astronaut) exposures, as compared with nuclear workers where 93% of exposures are from low-LET radiation.

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Exposure of SAS aircrew

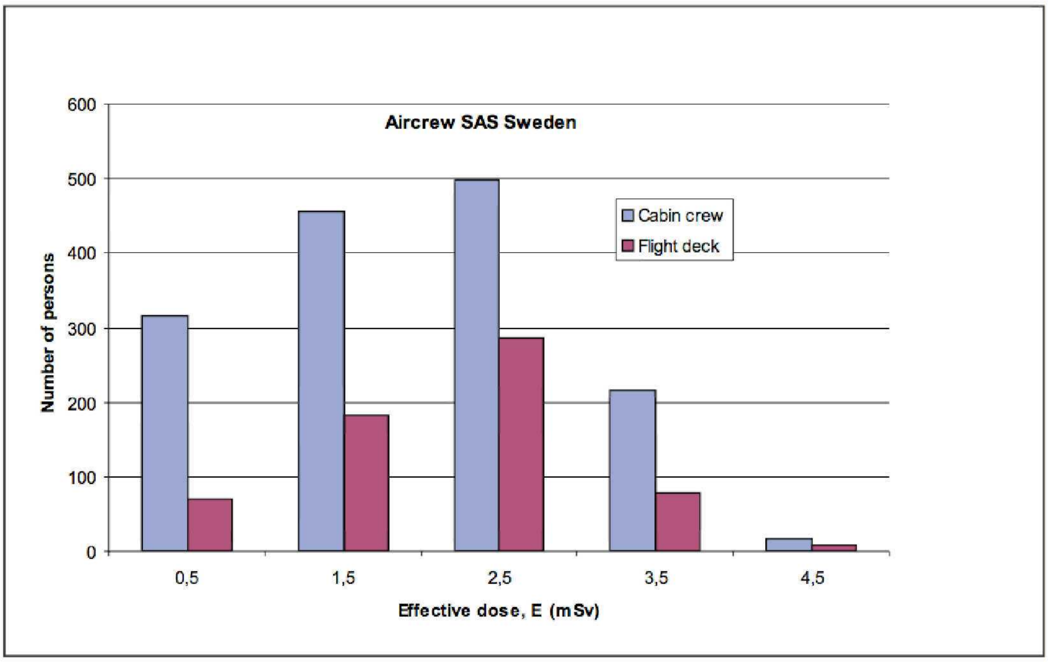


Figure 3. Calculated effective dose to aircrew in the Swedish airline SAS for 2004. The dose is shown separately for cabin crew and crew on flight deck.

Comparison of Swedish Workforces

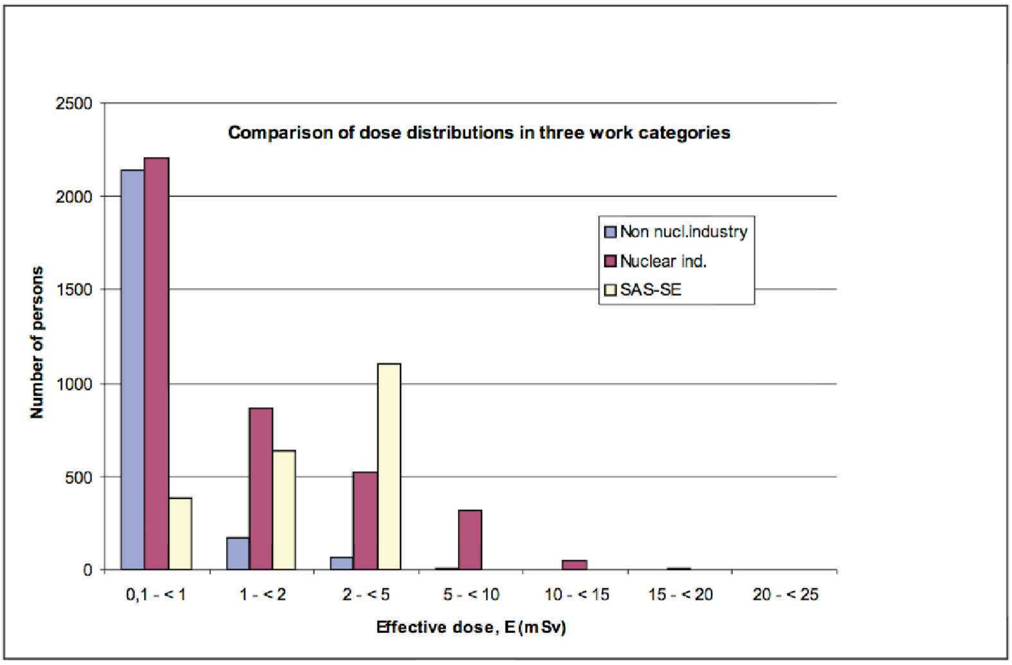
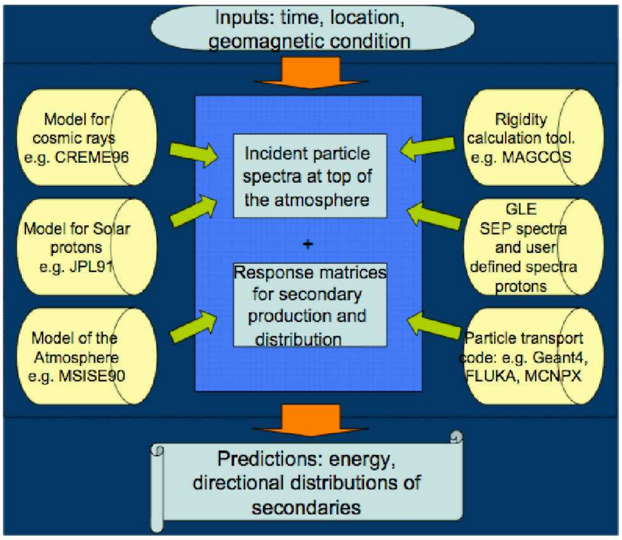


Figure 4. A comparison of the distributions of number of persons in different intervals of effective dose for the non-nuclear industry (2003), the nuclear industry (2004) and the Swedish SAS (2004).

Components of the QinetiQ Atmospheric Radiation Model



- Models of the Cosmic ray radiation:
  - B&O'N model, MSU model, QinetiQ model.
- Solar energetic protons
  - From GLE neutron monitor data plus GOES spacecraft
- Rigidity cut-off code
  - MAGNETOCOSMICS/GEANT4
- Response Matrices of atmosphere to energetic particle
  - Atmosphere Model: MSES90, NRLMSES2001
  - Particle Transport codes: MCNPX, FLUKA, GEANT4

QinetiQ

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(mSv)

Flight	Flight Date Code	Flight Route Code	TEPC H*(10)	TEPC E*	CARI-6 Feb-00 E	CARI 6M E	SIE-VERT E	EPCARD E	EPCARD H*(10)	EPCARD Ratio E/H	TEPC(E) /CARI 02/00	TEPC(H)/ EPCARD (H)	TEPC(E)/ SIEVERT	TEPC(E) /CARI6M
Lon-S/H	17180100	LS1	45.7	53.9	45.2	45.1	50.7	54.89	46.54	1.179	1.192	0.982	1.063	1.195
Lon-S/H	19200200	LS2	41.1	48.2	42.4	41.9	49.9	51.32	43.79	1.172	1.136	0.939	0.965	1.150
											1.164	0.960	1.014	1.172
Lon-JFK	18190100												1.206	1.200
Lon-JFK	27280300												1.107	1.210
JFK-Lon	28280300												1.102	1.209
Lon-JFK	17180400												1.163	1.259
JFK-Lon	18180400												1.106	1.269
Lon-JFK	17180700												0.986	1.090
													1.112	1.206
Lon-LA	29010300												1.076	1.282
Lon-LA	26270300												1.006	1.242
Lon-LA	16170400												1.094	1.290
LA-Lon	17170400												1.063	1.206
Lon-LA	16170700												0.923	1.103
LA-Lon	17170700												0.962	1.107
													1.021	1.205
Lon-JNB	23240300												0.950	1.027
JNB-Lon	24250300												0.876	1.035
Lon-JNB	02030400												1.027	1.047
JNB-Lon	03040400												0.855	1.048
Lon-JNB	05060400												1.002	1.036
JNB-Lon	06070400												1.025	0.977
JNB-Lon	23240400												1.105	1.053
Lon-JNB	26270400												1.111	1.025
											1.033	1.112	0.994	1.031
Lon-Tok	04[illegible]		47.1	55.2	46.9	46.7	55.1	58.24	49.70	1.172	1.177	0.948	1.002	1.182
Tok-Lon	05[illegible]		62.2	74.2	61.1	61.0	62.7	75.99	63.66	1.194	1.215	0.977	1.184	1.217
Lon-Tok	24[illegible]		53.2	63.0	53.2	53.3	55.9	65.67	55.44	1.185	1.184	0.959	1.127	1.182
Tok-Lon	25[illegible]		58.9	70.2	59.6	59.1	63.0	74.36	62.41	1.191	1.177	0.944	1.114	1.187
Lon-Tok	20[illegible]		43.5	51.1	46.2	46.1	53.7	59.22	50.43	1.174	1.106	0.863	0.951	1.108
Tok-Lon	21[illegible]		46.5	55.2	48.5	48.2	52.9	63.22	53.23	1.188	1.139	0.874	1.044	1.146
											1.166	0.927	1.070	1.170

LEGEND
<5%
5% - 10%
10% - 20%
20% - 30%
>30%

Different codes provide reasonable agreement with TEPC measurement for periods of low solar activity, but there are always residual errors of up to 30%. These residuals are not systematic – each code sometimes does better on some routes than others.

The differences may arise because the codes:

• Do not adequately model the Rigidity cutoff – this determines how easily cosmic rays penetrate the Earth's magnetic field

• Do not properly model variations in cosmic ray background. Most codes use proxies calculated as monthly averages – influences resulting from solar activity generally have much shorter time scales than this.

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Trying to improve how CARI works

		Original	Daily	Flight
Jo'burg	Mean	0.9207	0.9224	0.9242
	SD	0.0236	0.0221	0.0218
LA	Mean	0.9142	0.9520	0.9493
	SD	0.0560	0.0157	0.0185
Tokyo	Mean	0.9590	0.9799	0.9807
	SD	0.0366	0.0215	0.0211
New York	Mean	0.9803	0.9924	0.9918
	SD	0.0581	0.0376	0.0417
Hong Kong	Mean	0.9308	0.9474	0.9636
	SD	0.0627	0.0437	0.0187
Athens	Mean	1.0642	1.0674	1.0690
	SD	0.0536	0.0574	0.0487
Shanghai	Mean	0.9725	0.9684	0.9673
	SD	0.0205	0.0115	0.0100

<2%
<4%
<6%
<8%
>8%

We have also been looking at how to improve the accuracy of CARI, e.g. by calculating the Heliocentric Potential (a proxy to the modulated GCR flux) on a daily and flight-by-flight basis.

There are still problems related to how the codes handle particles from flares.

Epidemiology of cosmic radiation

- **Because of the concerns about cancer, several epidemiological studies have been carried out on the effects of cosmic radiation:**
  - Early studies involved too small a sample (few hundred)
  - Two detailed studies published in 2003 involved large number of European aircrews over extended periods :
    - Blettner et al. studied a total of 28,000 male cockpit crew from 9 countries, between 1960 and 1997
    - Zeeb et al. studied more than 44,000 cabin crew from 8 countries, from late 1940s to the late 1990s
  - Only cancer that showed any significant increase in occurrence was melanoma *(recreational activities?)*
  - Boice (2000) suggests that the incidence of cancer caused by exposure to cosmic radiation is too small to be identified by epidemiological studies

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Risks

- **The risks associated with exposure have also been assessed:**
  - **At the average dose of 3 mSv per annum, the annual average risk of fatal cancer is about 1 in 10,000**
  - **Aircrew working for 30 years would incur a lifetime risk of developing radiation-induced fatal cancer of 1 in 190 (i.e. ~0.5% risk)**
  - **The risk incurred would be in addition to the risk in the absence of the occupational exposure. In the general population of the US, about one in four adults (23%) will eventually die of cancer (Landis et al. 1999)**

Note: The radiation has a much higher component of high-LET radiation in aircrew (and astronaut) exposures, as compared with nuclear workers where 93% of exposures are from low-LET radiation.

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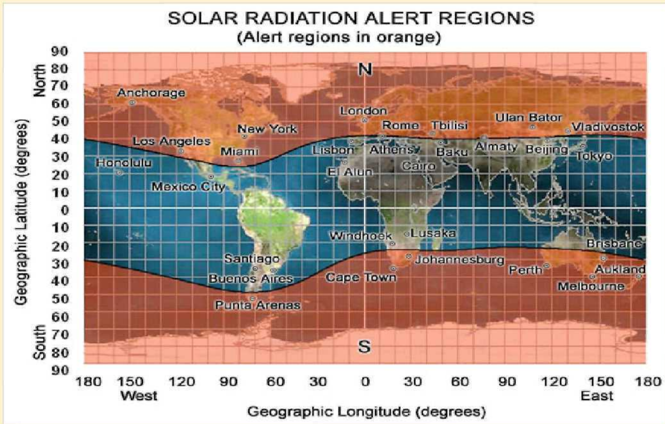
Concerns about Radiation

Radiation Alerts

At time of high solar activity, the US FAA issues Radiation Alerts and instruct it aircraft to fly at lower altitudes – several alerts were issued in Oct-Nov 2003.

Often this is an over-reaction, but aircrew remain concerned about radiation.



USA TODAY – 28 Mar 2005

Cancer fears limit Hong Kong aircrews' New York trips

HONG KONG (AFP) — Airline Cathay Pacific has limited aircrews' flights on the non-stop Hong Kong-New York route after it was found the journey could increase the likelihood of cancer, a report said Sunday.

Staff of the British-owned, Hong Kong-based airline say they have been limited to just two of the ultra long-haul flights per month since it was found the route exposed passengers and crew to high levels of cosmic radiation when they flew over the North Pole.

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Summary

Space weather Operational Airline Risks Service (SOARS)

- Cosmic radiation has affects on man's activity in both space and in the air
- The affects of electronics continue to be felt
  - Design measures can only do so much
  - Shrinking component sizes make them more susceptible
  - Can even be affected at ground level
- Effects of radiation on aircraft an issue, but not as bad as the press makes out

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Summary

Space weather Operational Airline Risks Service (SOARS)

- Exposure to cosmic radiation has become an issue for the European airlines because of recent legislation
- Airlines are required to monitor crew exposure
  - For a typical mix of flights this is not a problem, but it could be for crews dedicated to long distance, high latitude routes
- Epidemiological studies suggest that the increased incidence of cancer is difficult to measure and the risks seem relatively low (although comparison with exposure in other workplaces is not simple)
  - New planes fly higher and the problems will increase
  - Space tourism could add a new dimension to the issue

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