Experience of Using Micro/Nano-Satellite Technology as a Cost-Effective Means of Radiation Belt Monitoring

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Outline

- Background – Surrey's Micro-Satellites
- The Cosmic-Ray Experiment (CRE) Payloads
  - *KITSAT-1* (1992), *PoSAT-1* (1993) & *AMSAT-OSCAR-40* (2000)
- The Miniaturized CEDEX Payloads
  - *TiungSat-1* (2000) & Giove-A (2005)
- Nano-Satellite Swarms
- Conclusions

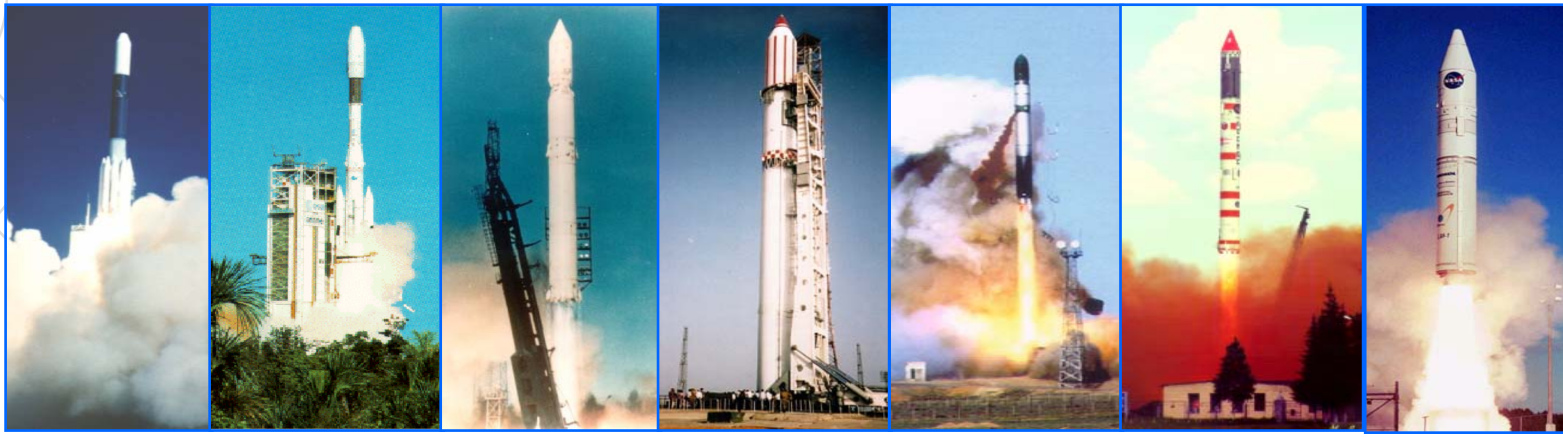
Small Satellites

ENVISAT - ESA

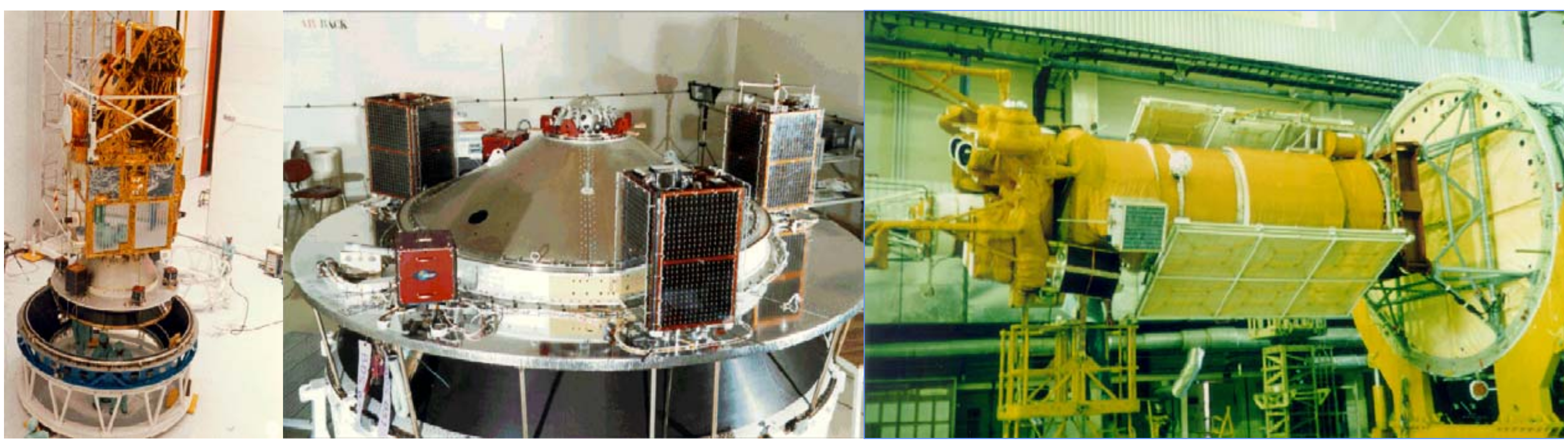
	Mass	*Cost*	*Time*
Large	1000kg+	$500M+	15yrs+
Small	500kg	$100M	5yrs
Mini	250kg	$20M	3yrs
Micro	100kg	$10M	1.5yrs
Nano	10kg	$1M	~1 yr
Pico	<1kg	>$100k	<1yr

Small Satellites

- Launches: Delta, Ariane, Tsyklon, Zenit, Dnepr, Cosmos, Athena

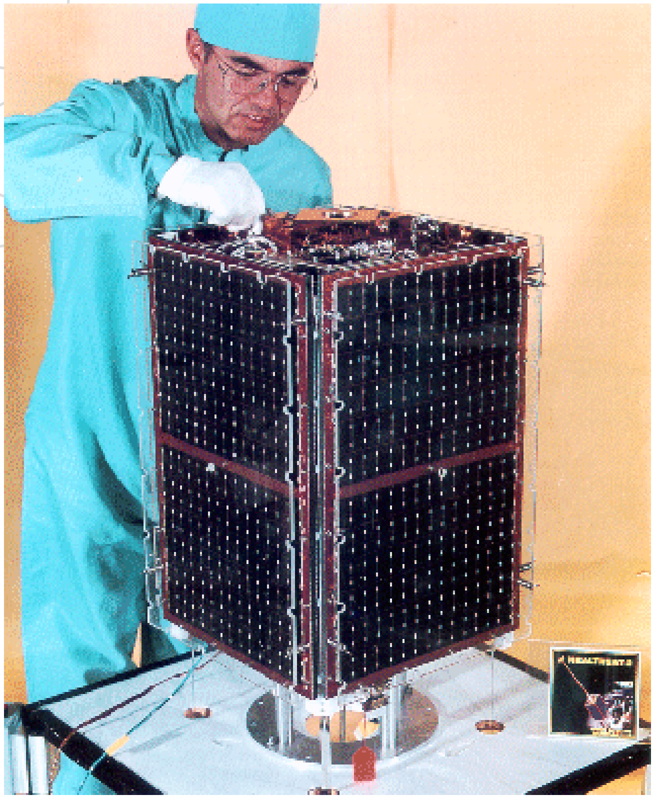


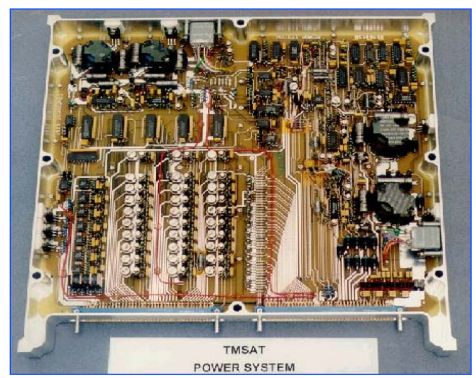
DELTA ARIANE TSYKLON ZENIT SS18/Dnepr COSMOS ATHENA

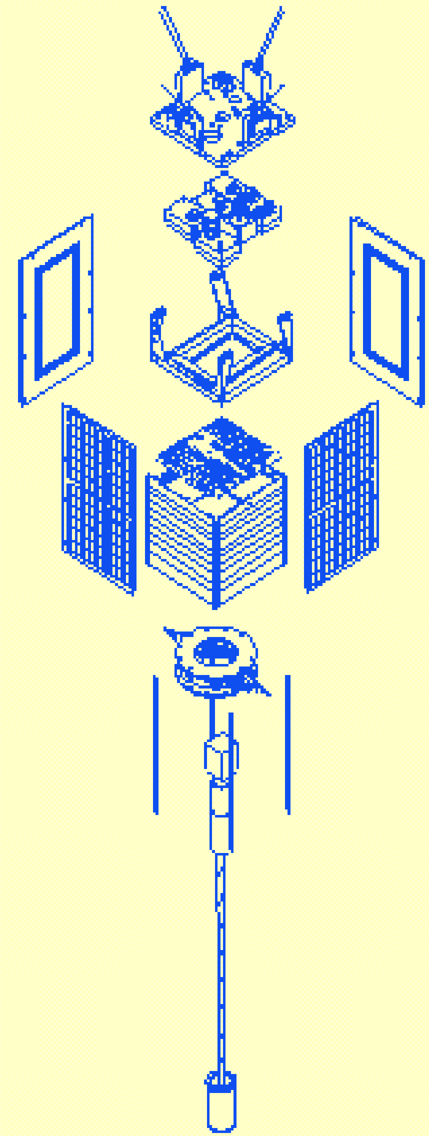


Surrey’s Satellites

- Micro-Satellite Modular, Multi-Mission Bus



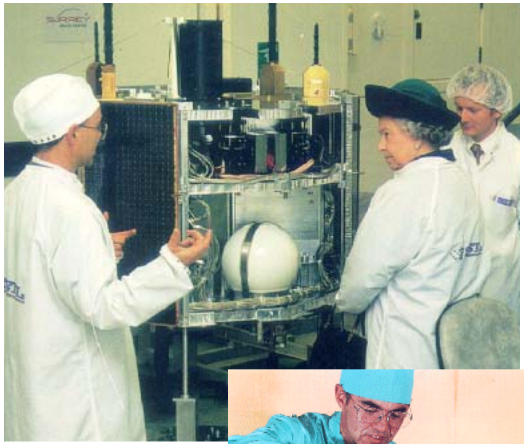


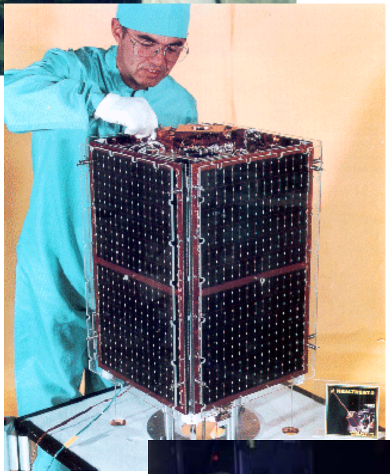


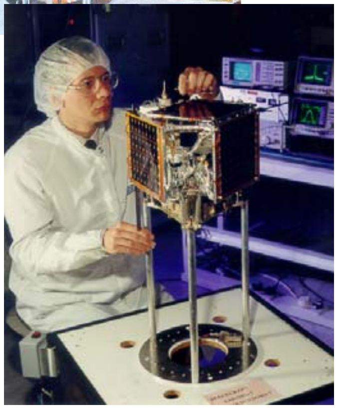
“The ‘PC’ of Space”

Winner of the Queen’s Award for Technological Achievement

Surrey's Satellites







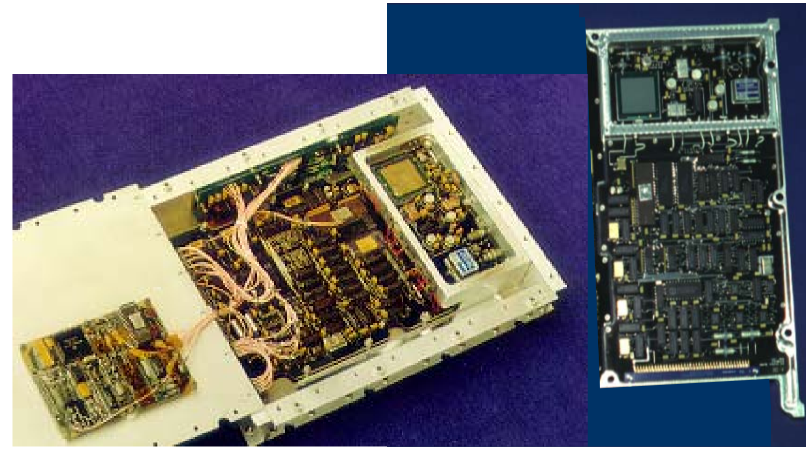
- Surrey's satellites make extensive use of state-of-the-art COTS micro-electronics to achieve complex functionality within tight volume, mass and financial constraints.
- Each new generation of spacecraft has comprised bus sub-systems and payloads of increasing sophistication, utilising the many benefits of COTS devices:
  - ✓ low cost, ready availability,
  - ✓ high performance, low power,
  - ✓ high packing density.
- The effect of the ionising radiation environment on these technologies has been a key research objective.

Radiation Environment Payloads

Radiation Environment Monitors

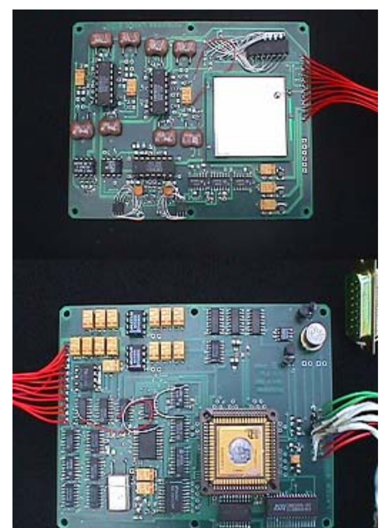
- Surrey has designed, built and operated several successful miniature PIN-diode based radiation environment monitors: the CRE and CEDEX Payloads.
  - ✓ 1992, 1993: *KITSAT-1*, *PoSAT-1:* Surrey's Cosmic-Ray Experiment (CRE) payload (incorporating a TDE).
  - ✓ 1997: A variant of this also flies in Highly Elliptical Orbit on *AMSAT-OSCAR-40*.
  - ✓ 2000: *TiungSAT-1:* Surrey's Cosmic-Ray Energy Deposition Experiment (CEDEX) particle telescope.
  - ✓ 2005: *Giove-A*: CEDEX (Mk. II)

All payloads measure cosmic-ray LET spectra. The CRE's also measure total ionising radiation dose.



AO-40 CRE (SSC/SSTL)

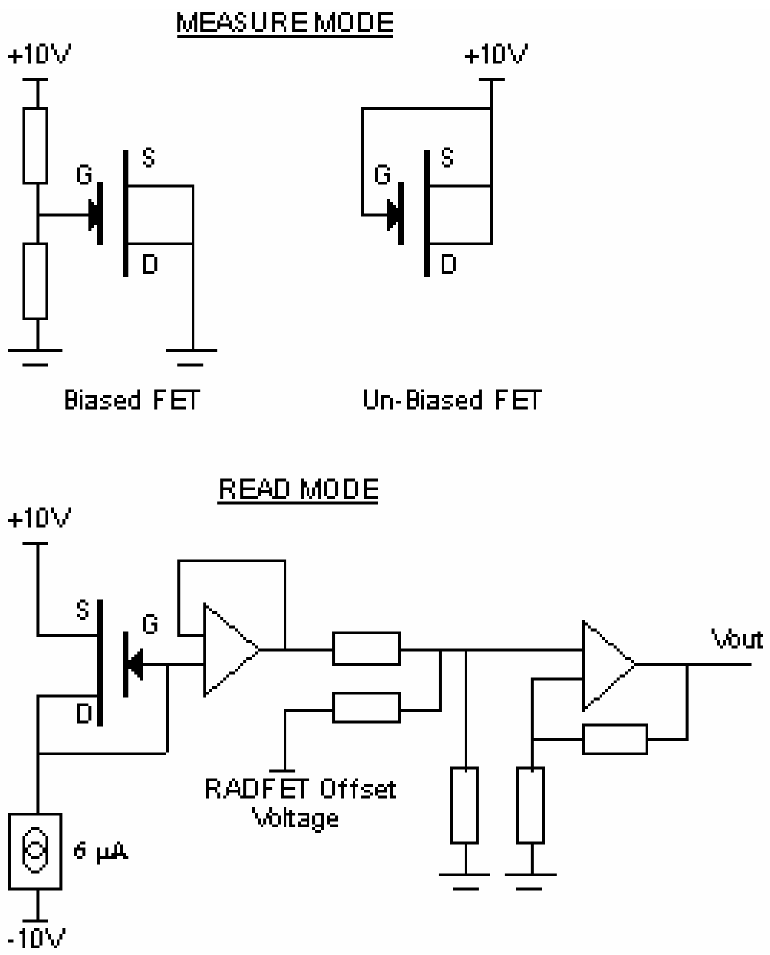
KITSAT-1 & PoSAT-1 CRE (SSC/SSTL)



TiungSAT CEDEX (SSC/SSTL)

The CRE Payloads

- The CRE contains a Total Dose Experiment (TDE) sub-system.
- Exposure to ionising radiation creates electron-hole pairs in the gate SiO_2 of the RADFET sensors.
- The electrons are swept out by the gate bias, but the “holes” accumulate, giving a net positive charge.
- This charge changes the gate threshold voltage V_{th}, which is used as a proxy for accumulated dose.
- The RADFETs are permanently biased (even when the CRE is switched off) to record all accumulated dose.



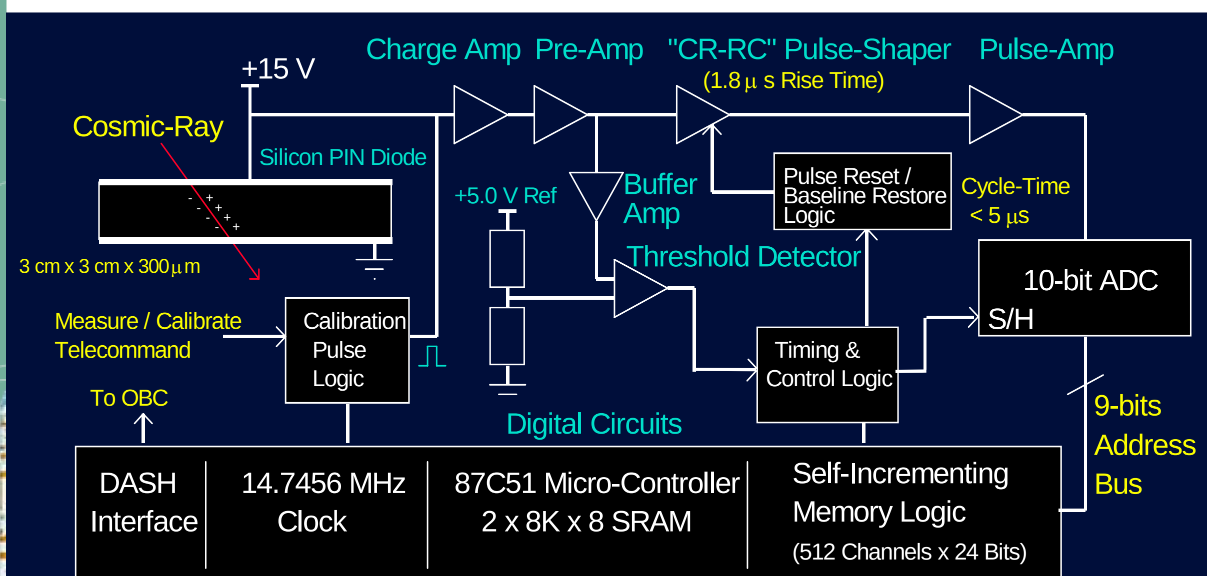
TDE Principle of Operation

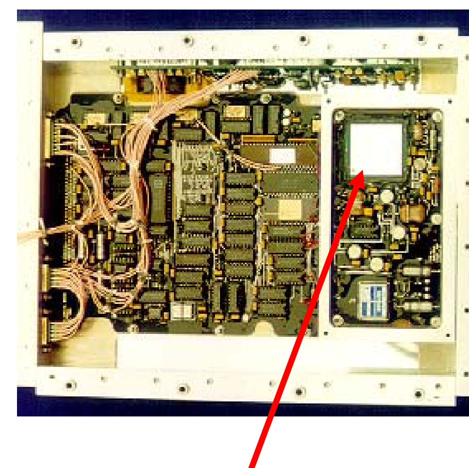
The CRE Payloads

- Results: Sun-Synchronous LEO
  - ✓ The *PoSAT-1* CRE RADFET data showed a uniform accumulation of dose of between 0.7 and 0.9 rad(Si) day^{-1} at 790 km in 1993.
  - ✓ The *UoSAT-5* TDE showed dose-rates of between 0.93 and 1.10 rad(Si) day^{-1} at 770 km over the period 1991-93.
  - ✓ The *UoSAT-3* CREDO payload showed similar dose-rates of between 1.0-1.3 rad(Si) day^{-1} at 795 km over the period 1990-93.
  - ✓ These data (**0.7-1.3 rad(Si) day^{-1}**) were at the lower bound of expectations based on SHIELDOSE modelling.
- Results: “High” LEO (1,320 km, 66^{o} inclination orbit)
  - ✓ The *KITSAT-1* CRE showed dose-rates of **4-6 rad(Si) day^{-1}** in 1993, which was a factor 1.5 times lower than expected.

The CRE Payloads

- The CRE detects protons and heavy ions passing through a 3 cm x 3 cm x 300 μm deep silicon PIN diode.
- These create electron-hole pairs, and the resulting charge is proportional to the total energy deposited by the particle, which is itself related to the particle's linear energy transfer (LET).
- This charge is measured, and a running total is kept of the number of particle events in each of 512 LET channels.
- Instrument has a resolution of 0.05 pC (~1 MeV deposited) and a LET range of ~64-8400 MeV cm^2 g^{-1} (~0.2–26 pC)
- Pulse processing time <5μs.

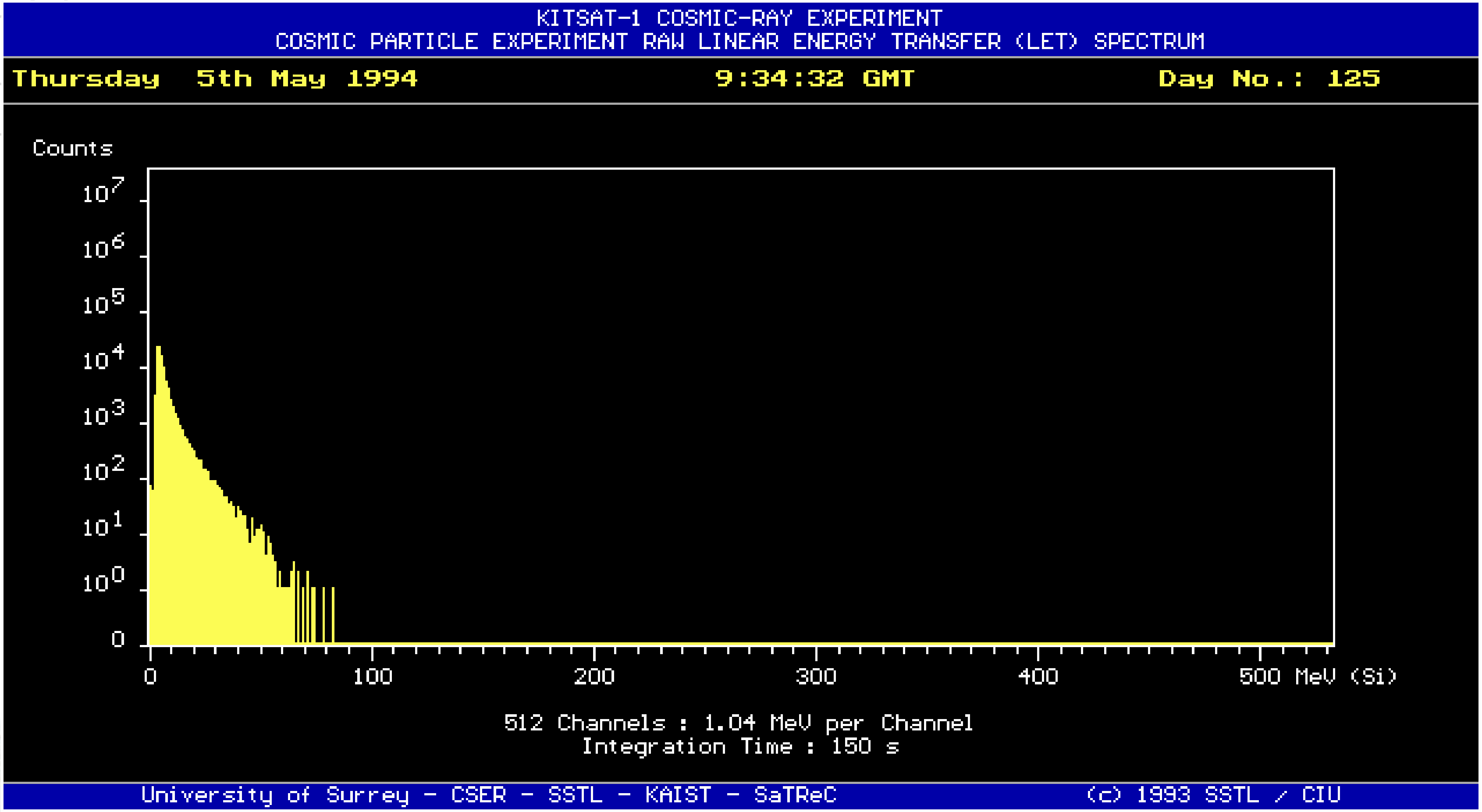




3 cm x 3 cm PIN Diode Detector

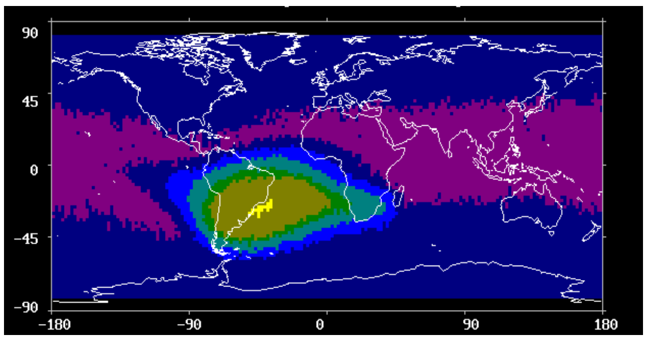
The CRE Payloads

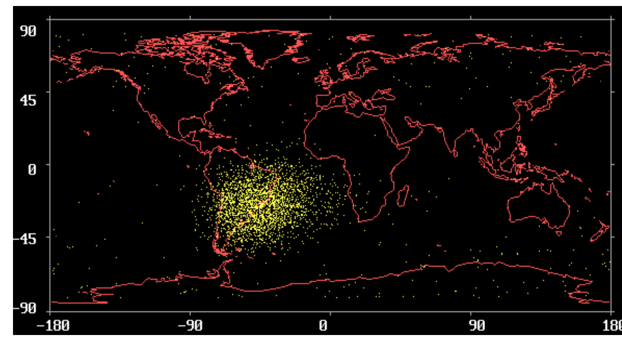
- Typical CRE LET spectrum measured by the *KITSAT-1* CRE (South Atlantic Anomaly at 1320 km altitude)



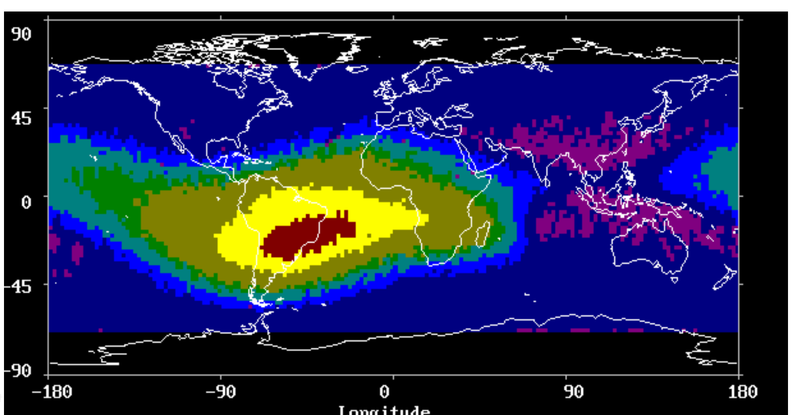
The CRE Payloads

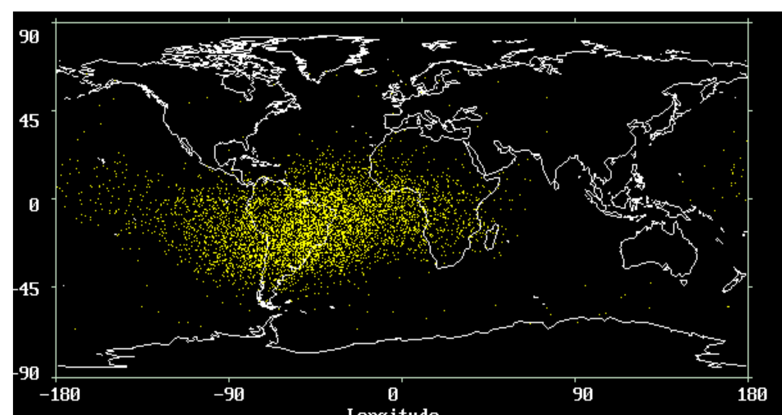
- Results: Correlation of the Environment with SEEs
  - ✓ The *PoSAT-1* CRE Channel 2 (Proton) data showed excellent correlation with recorded single-event upset (SEU) activity in the spacecraft's computer memory systems (790 km).





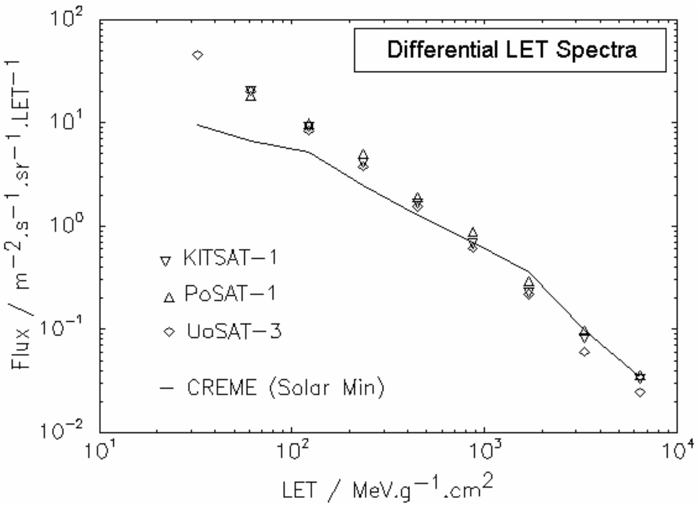
  - ✓ *KITSAT-1* showed a similar correlation at 1320 km altitude.

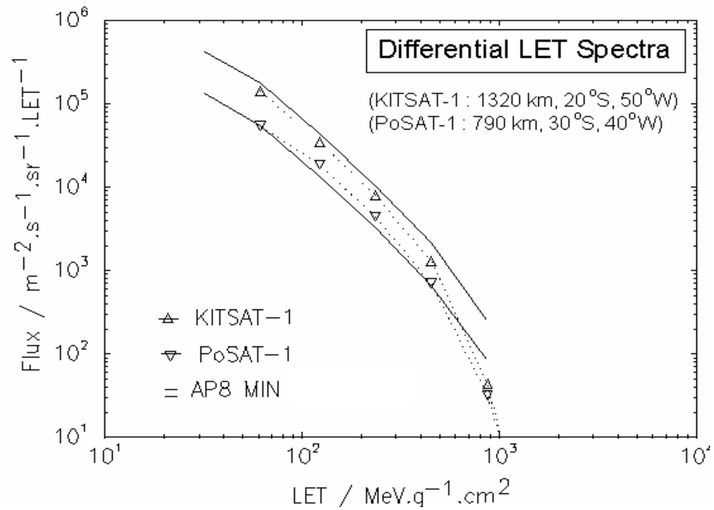




The CRE Payloads

- Results: Comparison with Standard Models
  - ✓ The *PoSAT-1* and KITSAT-1 CRE data have been compared to the CREME cosmic-ray and the AP8 proton environment models.

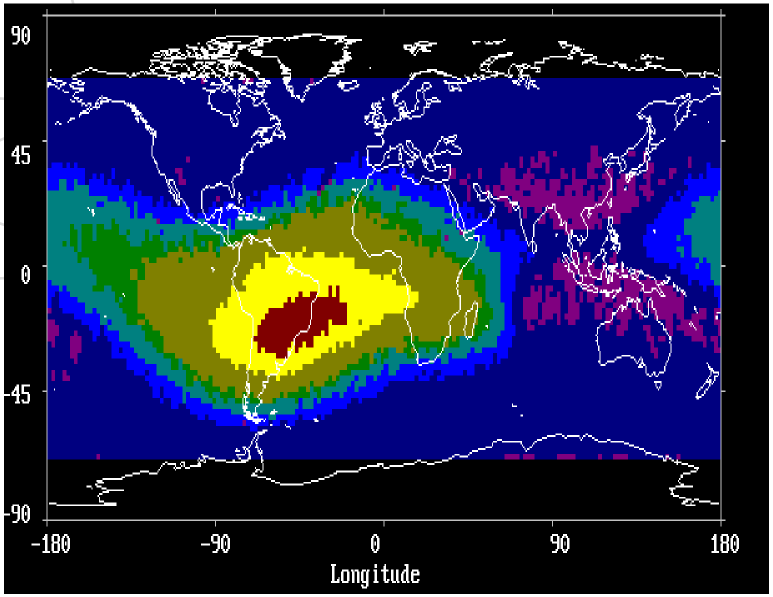


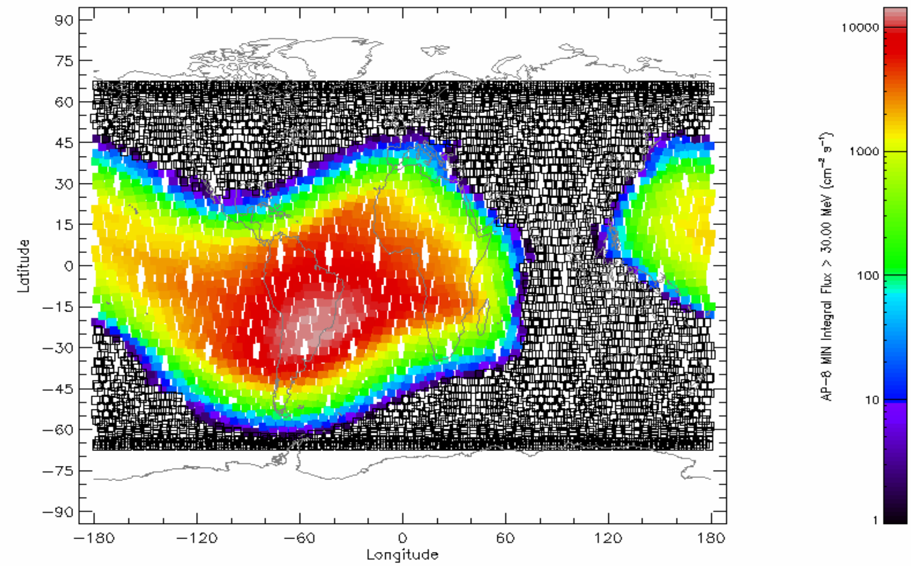


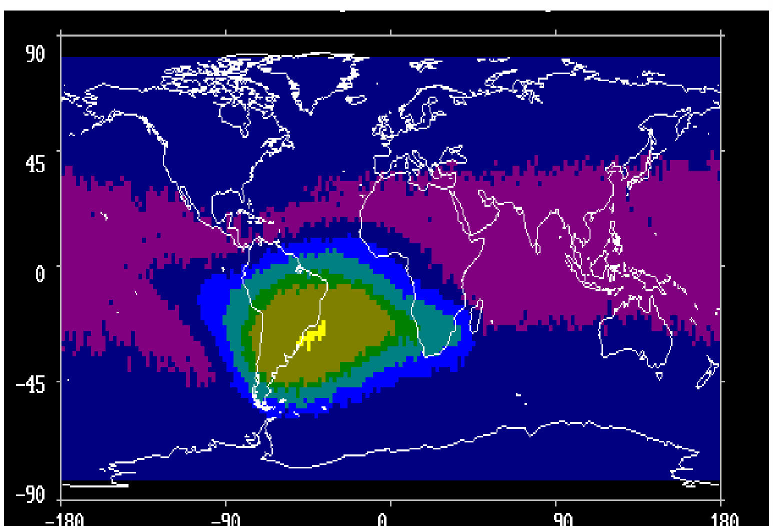
  - ✓ The cosmic-ray data from the two CRE payloads (and the *UoSAT-3* CREDO payload) are consistent, and fit with the CREME model at high LET.
  - ✓ The AP8 model seems to over-predict the proton environment for *KITSAT-1* – also consistent with the observed RADFET dose-rate data.

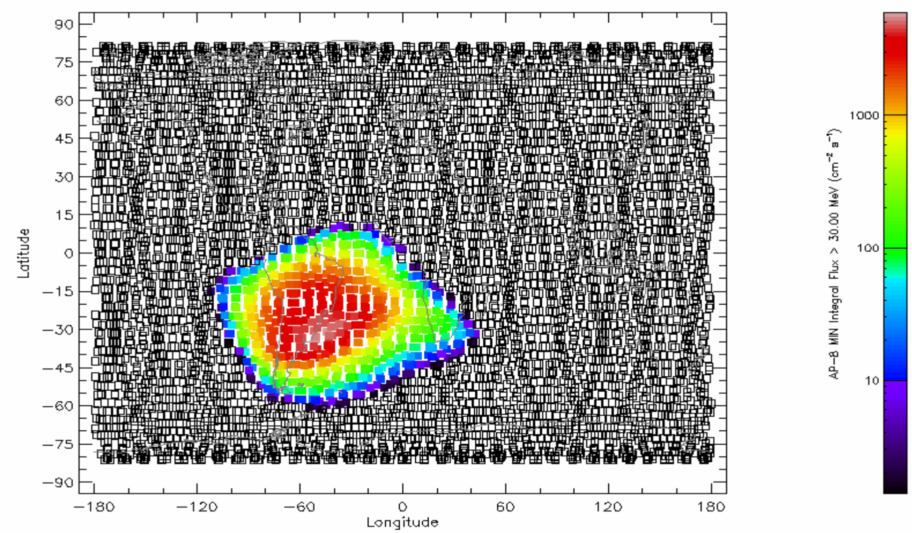
The CRE Payloads

Comparison with SPENVIS



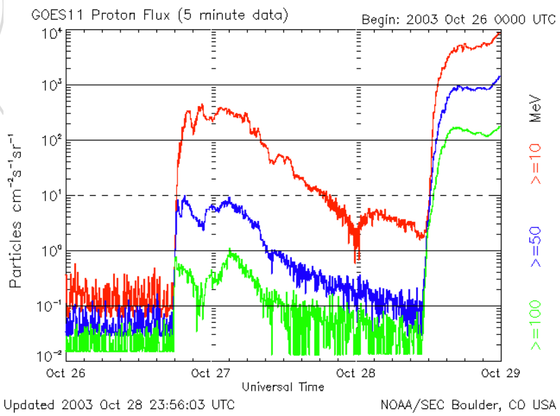


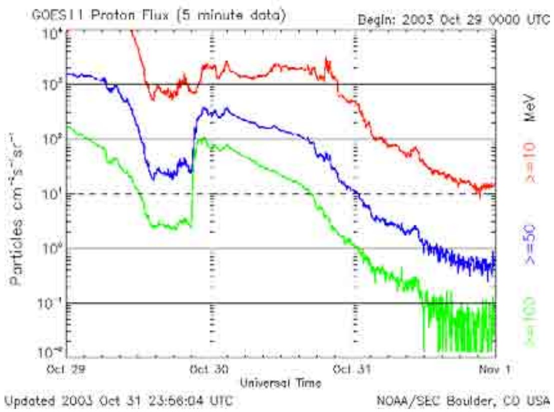


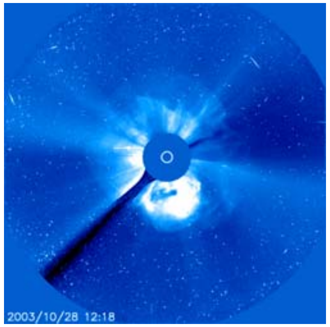


The CRE Payloads

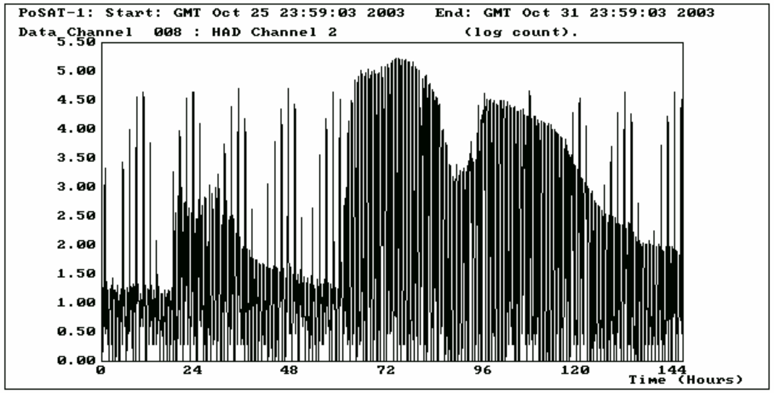
- Results: Solar Particle Events (SPEs)
  - ✓ The *PoSAT-1* CRE data have shown several major SPEs since 1993 including, for example, the SPE of 28th October 2003:



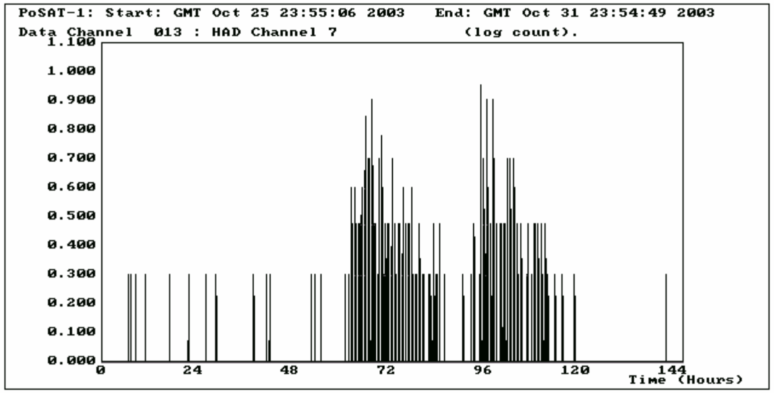




SOHO Image: CME 28/10/03 © NASA



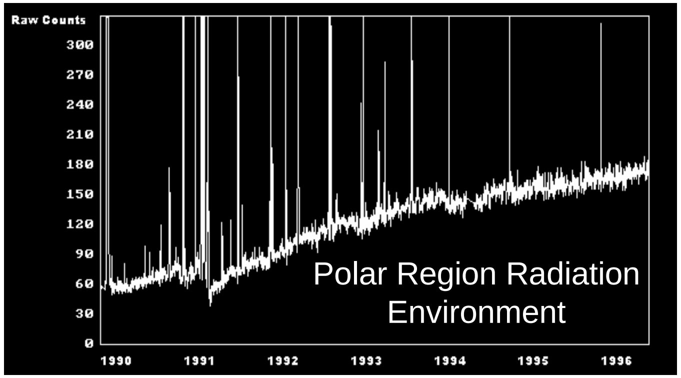
PoSAT-1 CRE >30MeV Proton Flux 26th – 31st October 2003

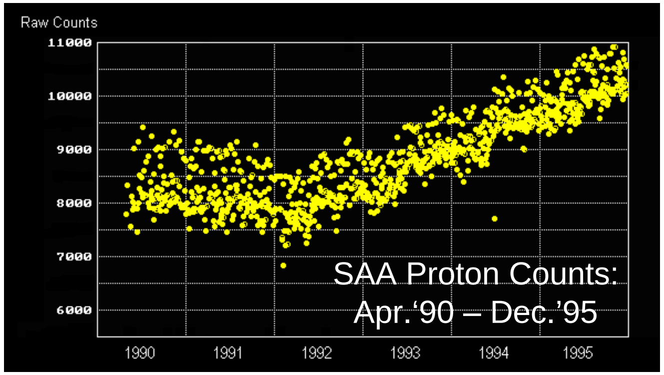


PoSAT-1 CRE Heavy Ion Flux 26th – 31st October 2003

The CRE Payloads

- Results: Long Term Monitoring of the LEO Environment
  - ✓ Together, the *PoSAT-1* CRE and *UoSAT-3* CREDO payloads have tracked the long term changes in the LEO radiation environment over a complete solar cycle.

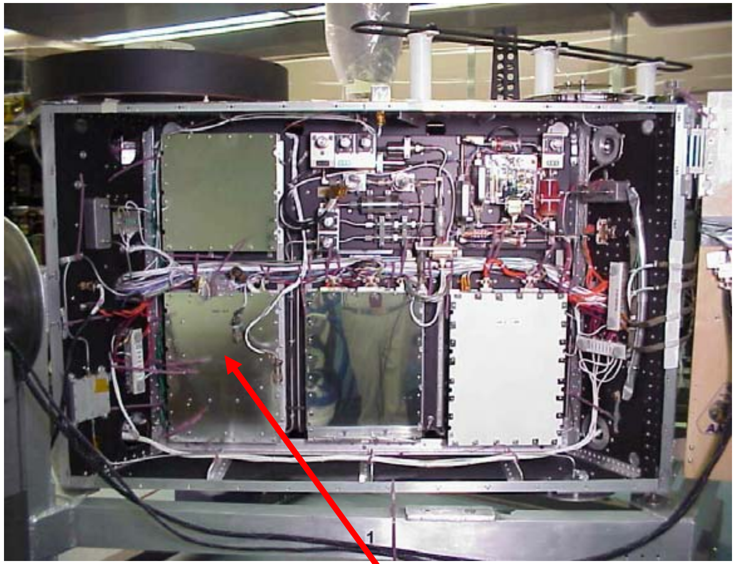




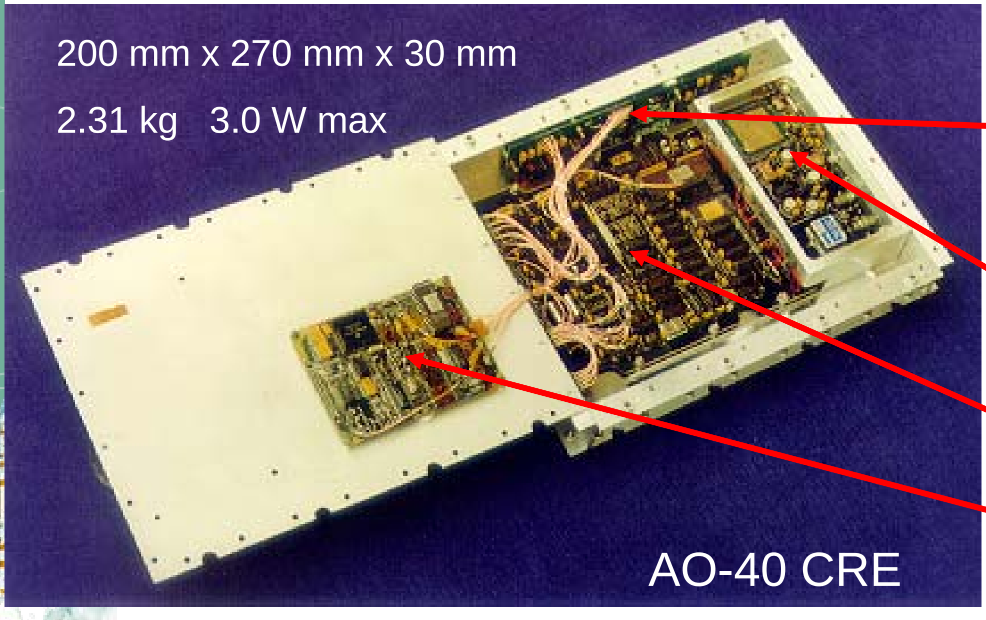
- Monitoring HEO:
  - ✓ An opportunity to monitor the radiation environment in highly-elliptical Earth-orbit (HEO) arose in the mid-90's when AMSAT proposed the *Phase 3D* satellite mission.
  - ✓ Surrey provided a modified CRE payload, which was subsequently launched on-board *AMSAT-OSCAR-40* in November 2000 by ARIANE 5.

The CRE Payloads

- In order to produce a radiation monitoring payload as rapidly as possible, the *PoSAT-1* CRE design was re-packaged and two extra PCBs were added to provide the data and power interface to the *AMSAT-OSCAR-40* bus.
- The payload was delivered in 1997.



AO-40 CRE Payload



10V Power Switches and DC-DC Converters (+5V, -10V)

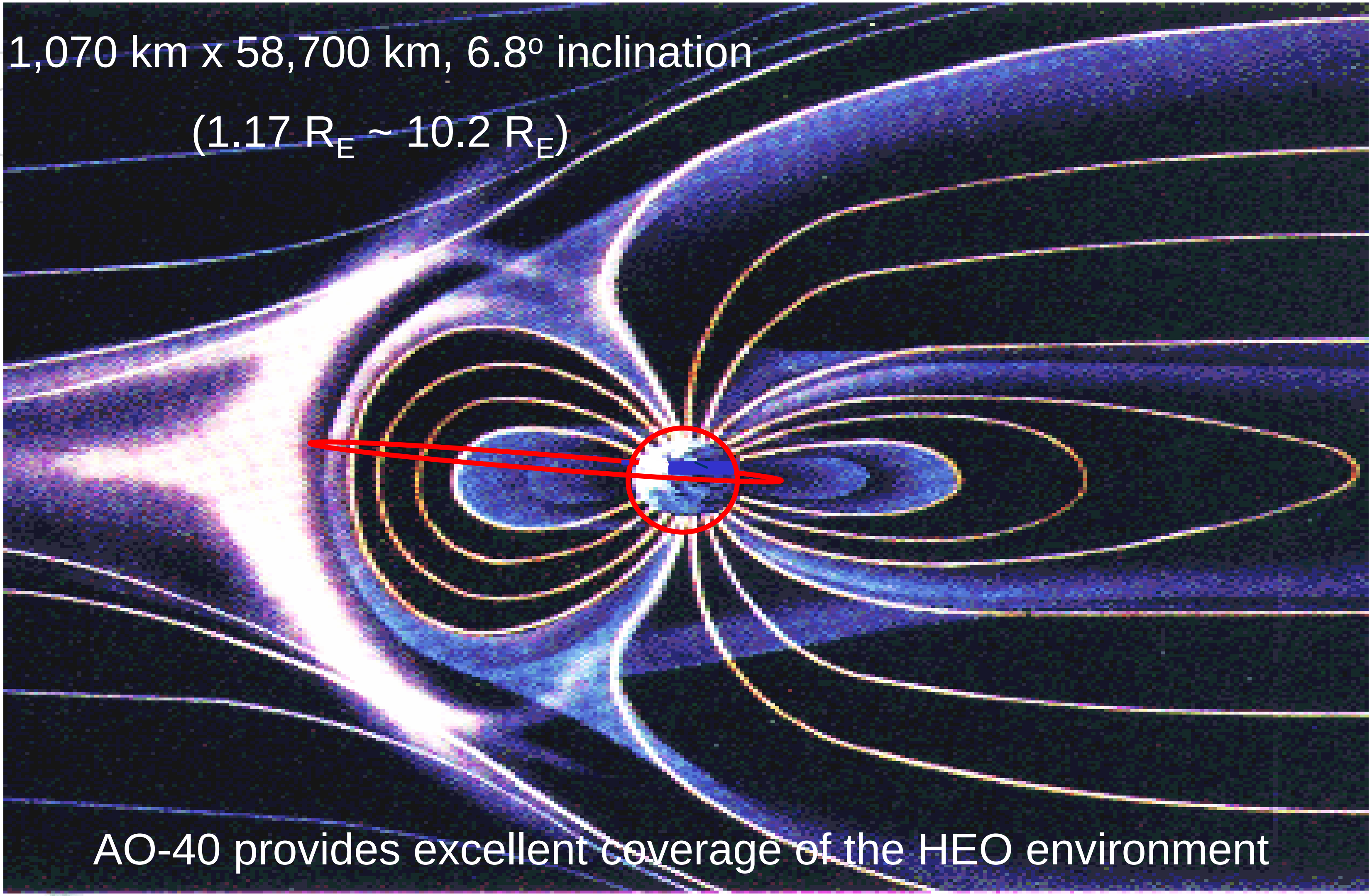
CRE Analogue Front-End

CRE Digital Processing Board

CAN Data Bus Interface

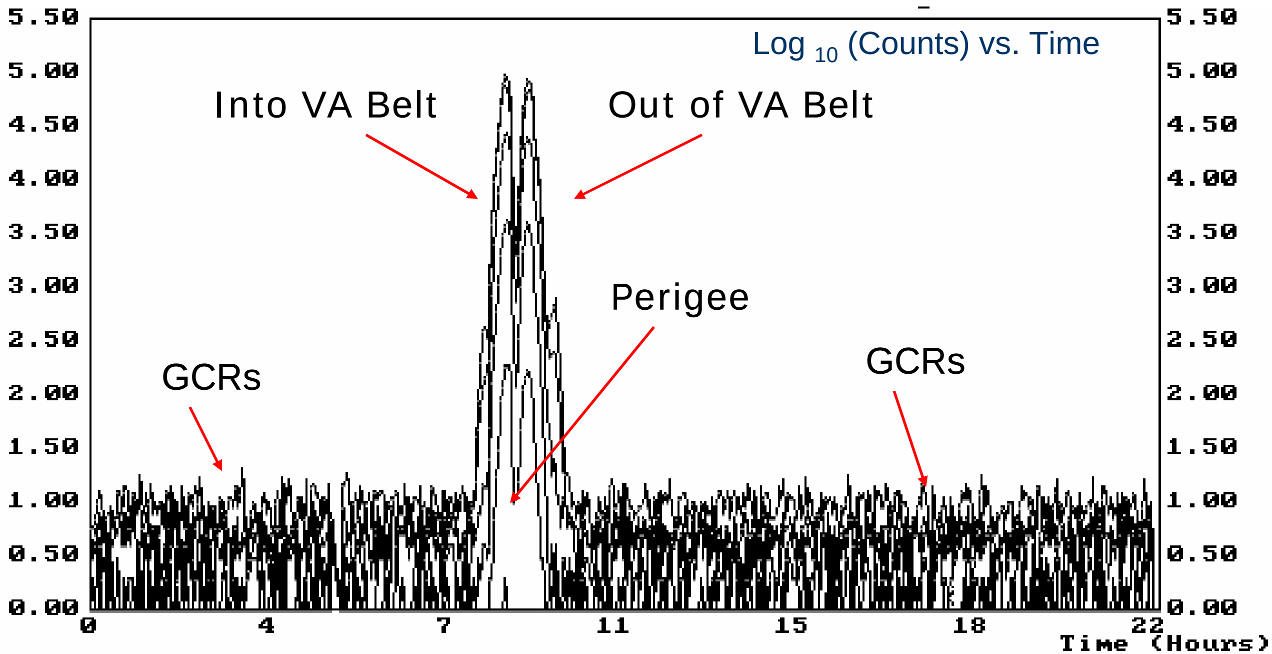
The CRE Payloads

- *AMSAT-OSCAR-40* Final Orbit



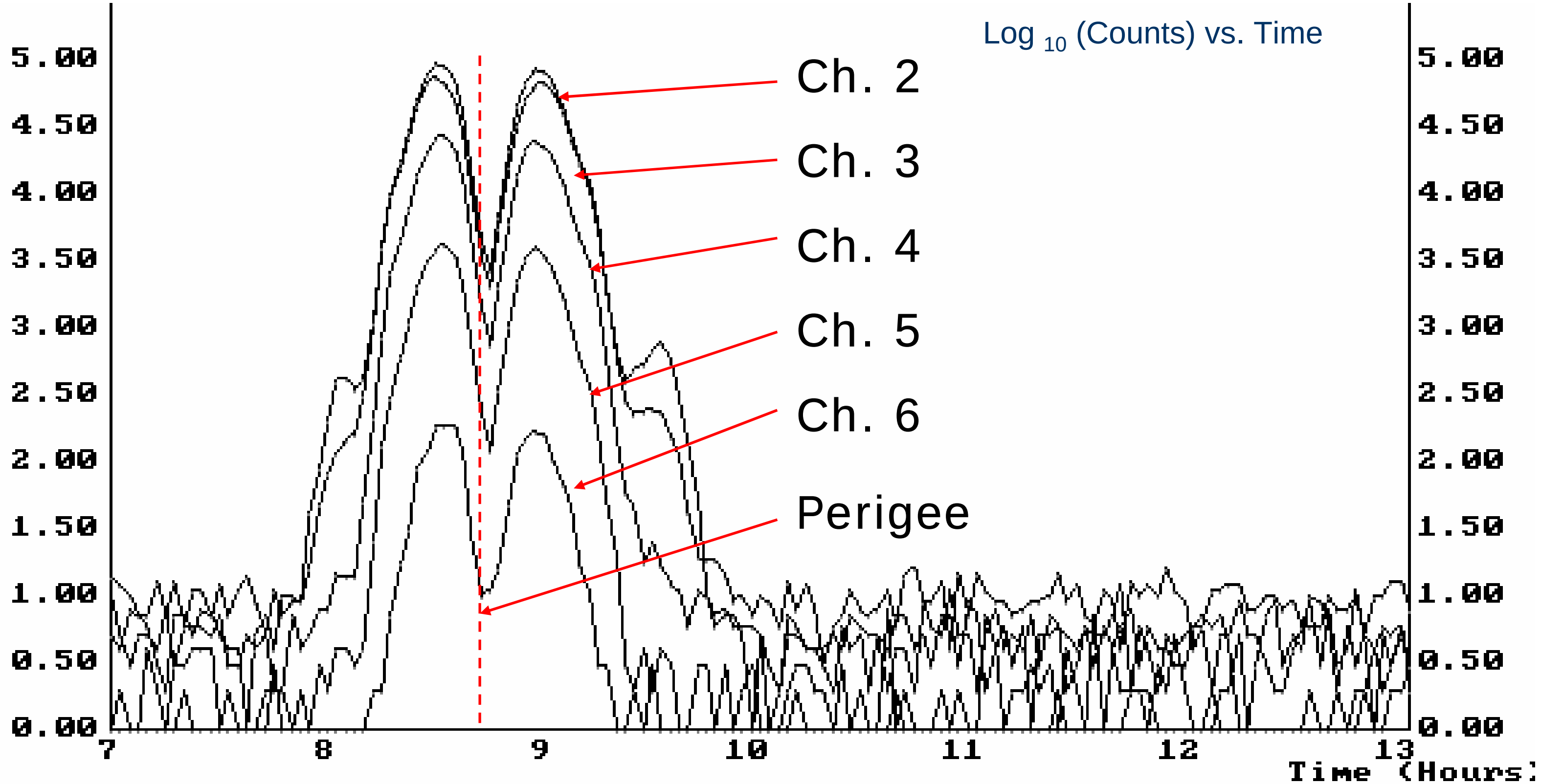
The CRE Payloads

- Due to problems with the spacecraft (the kick-motor exploded!), the first *AO-40* CRE data set was acquired on 15th December 2001 – over a year after launch.
- The graph shows 22 hours of flight data - $\log_{10}$ (particle count) per 150 s period vs. time - including a passage through the inner Van Allen belt.
- In the heart of the inner belt, CEDEX's 3 cm x 3 cm square PIN diode detector was detecting ~1,000 proton hits per second.



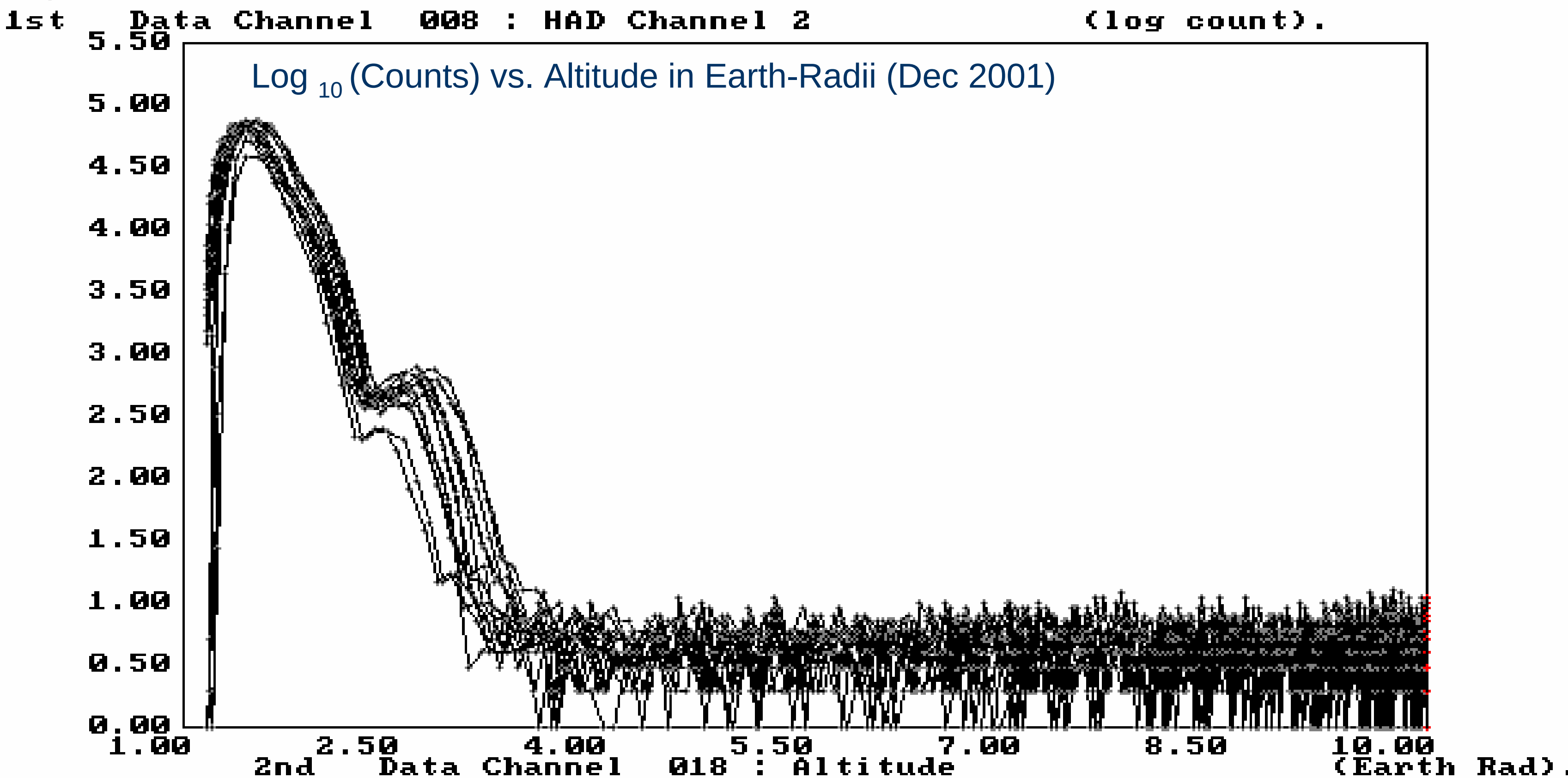
The CRE Payloads

- The Proton Channels (2-6) clearly show entrance to, and exit from, the inner Van Allen Belt an hour or so before and after perigee passage.
- Note: the outer VA Belt is not detected, showing that the instrument is not contaminated by electron strikes.



The CRE Payloads

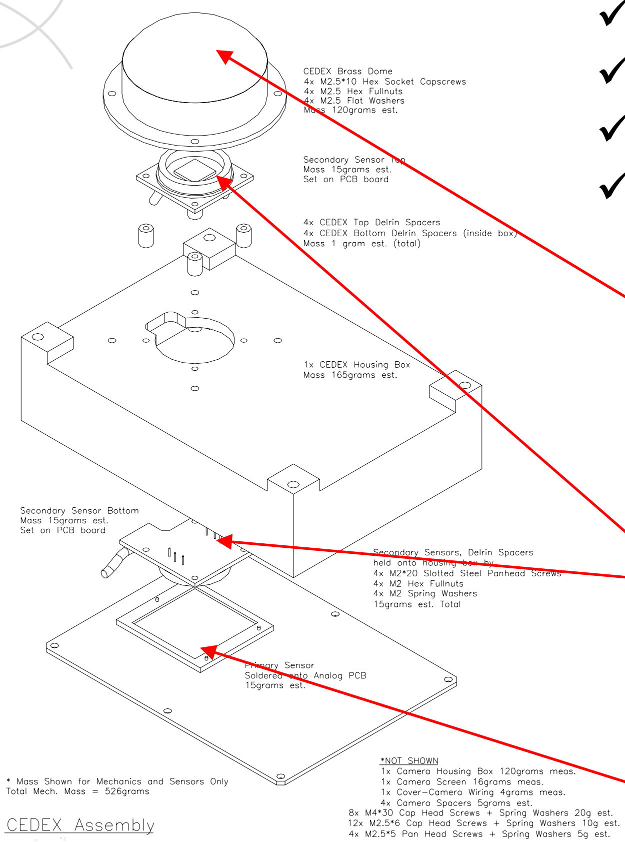
- The complete data set acquired between 15th and 25th December 2001 show the extent of the inner belt peaking at 1.7 R_E (as expected).
- They also show a “third belt” with a peak at ~3 R_E.



The CEDEX Payloads

- A miniaturised (sub-kg) particle "telescope" version of the CRE – CEDEX – was flown on *TiungSat-1* in 2000 into 650 km, 64º orbit.

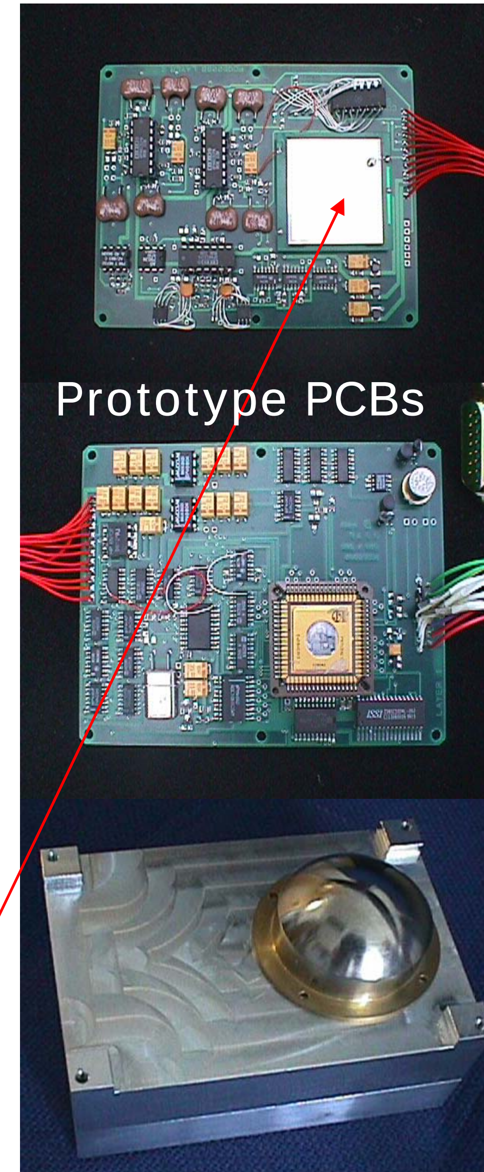
✓130 x 80 x 60 mm
✓800 g (incl. box/dome)
✓2W at 5V
✓CAN Bus Interface
✓Internal Charge Cal.



Brass Dome Electron and Low Energy Particle Shield

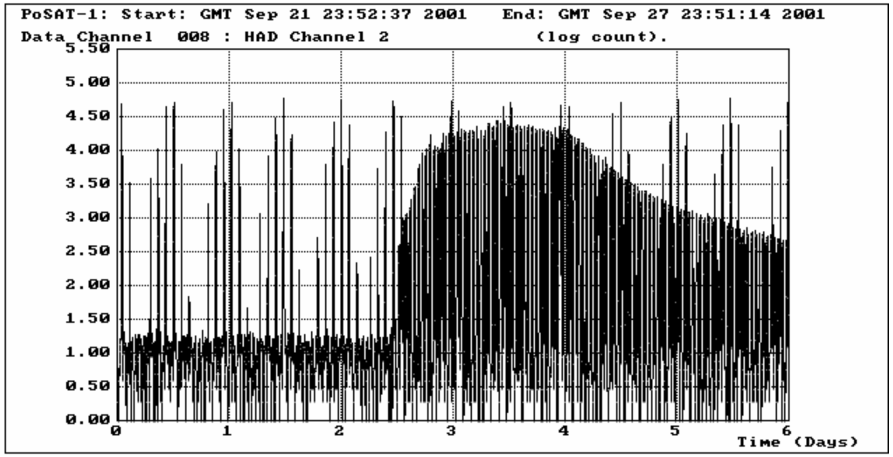
Telescope (60º FoV) PIN Diode Detectors

Main 3 cm x 3 cm PIN Diode Detector

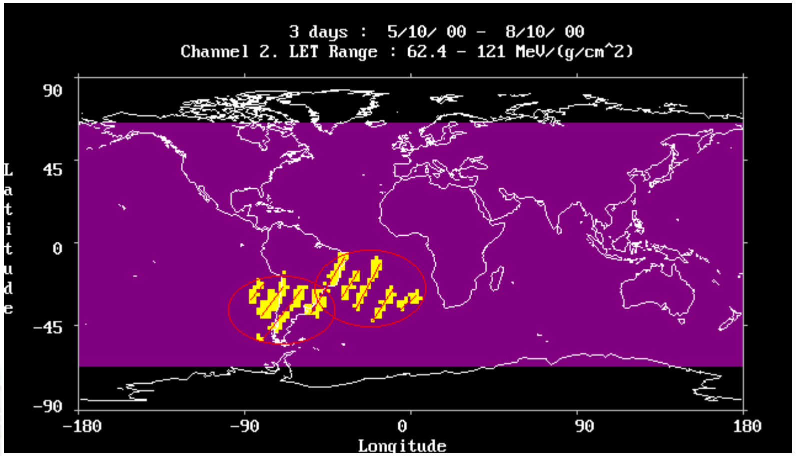


The CEDEX Payloads

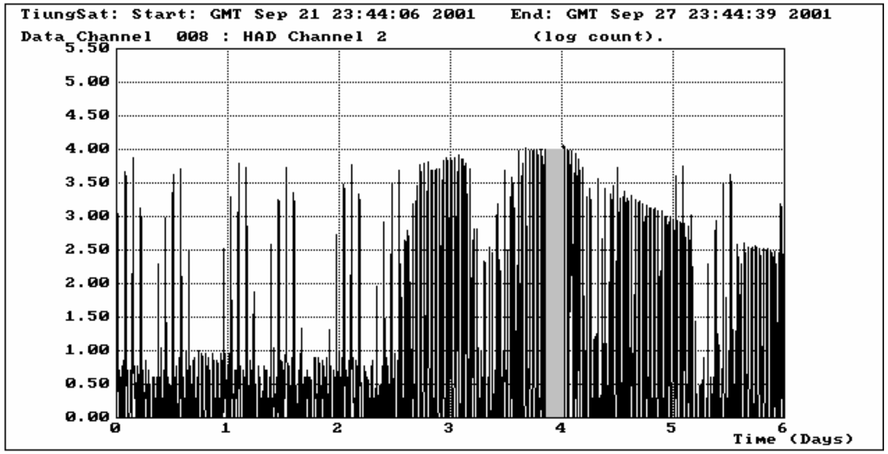
- The *TiungSAT-1* CEDEX payload provides similar results to the *PoSAT-1* CRE instrument, and allows LEO environment trend analysis to continue.
- The particle telescope has provided some data on the proton anisotropy in the SAA.



800 km, 98° Inclination Sun-Synchronous Orbit – Launched in 1993
Log_{10} 30 MeV Proton Flux: 22nd – 27th September 2001



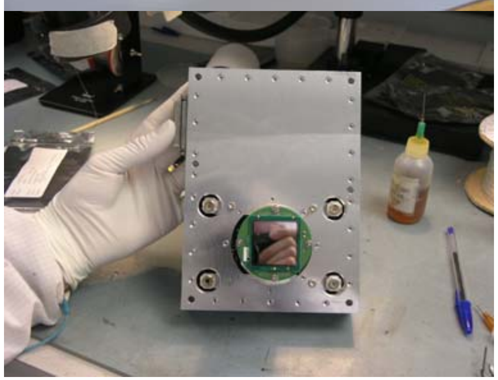
SAA Proton Anisotropy (CEDEX Coincident Channels)

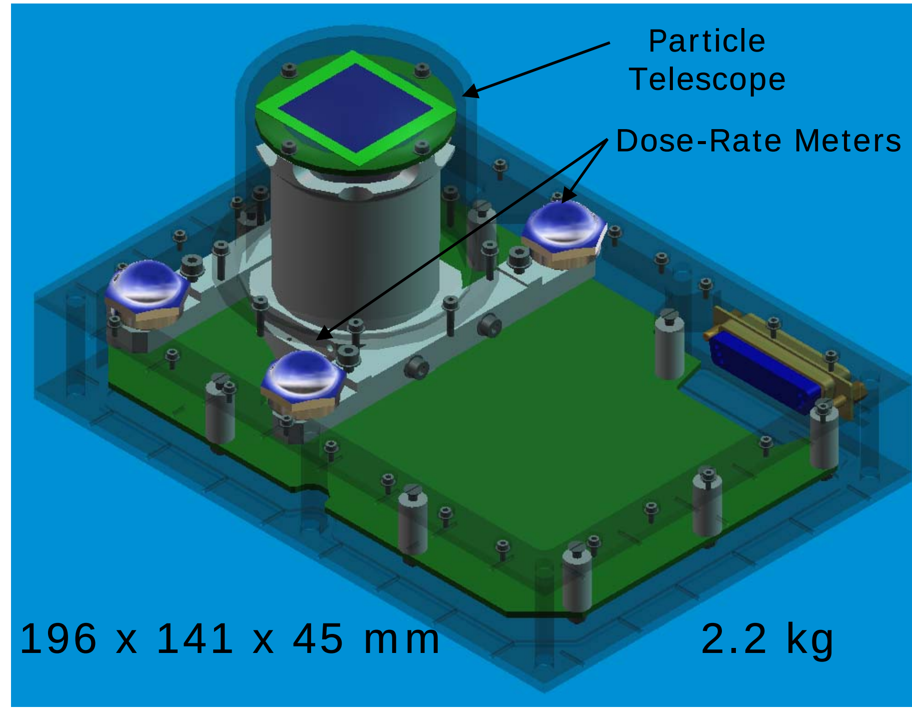


650 km, 64° Inclination Low-Earth Orbit – Launched in 2000
Log_{10} 30 MeV Proton Flux: 22nd – 27th September 2001

The CEDEX Payloads

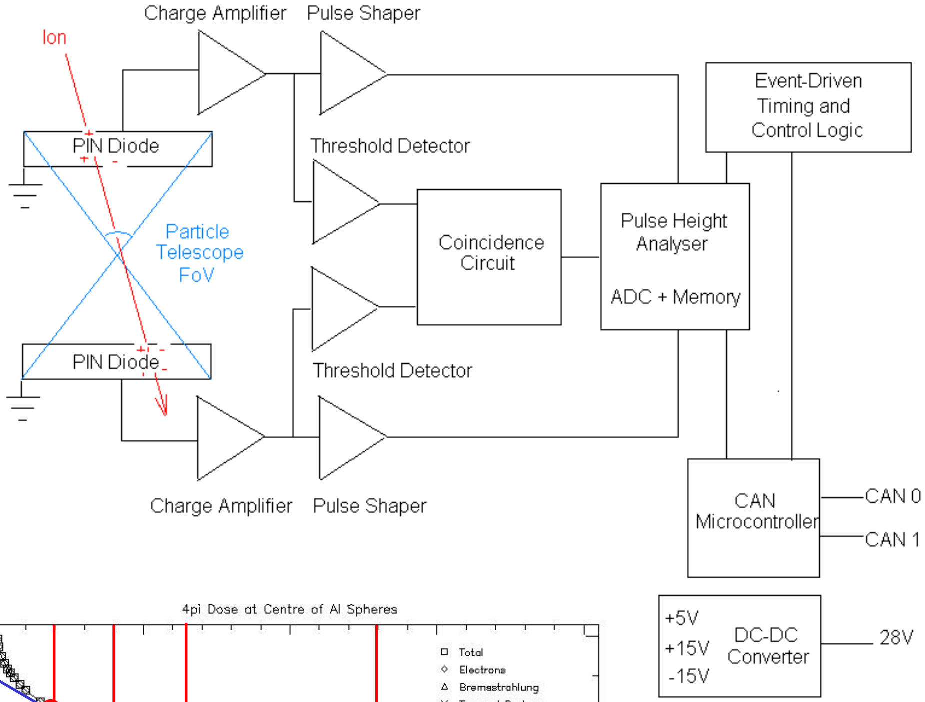
CEDEX Space Radiation Environment Monitor (Giove-A 2005)

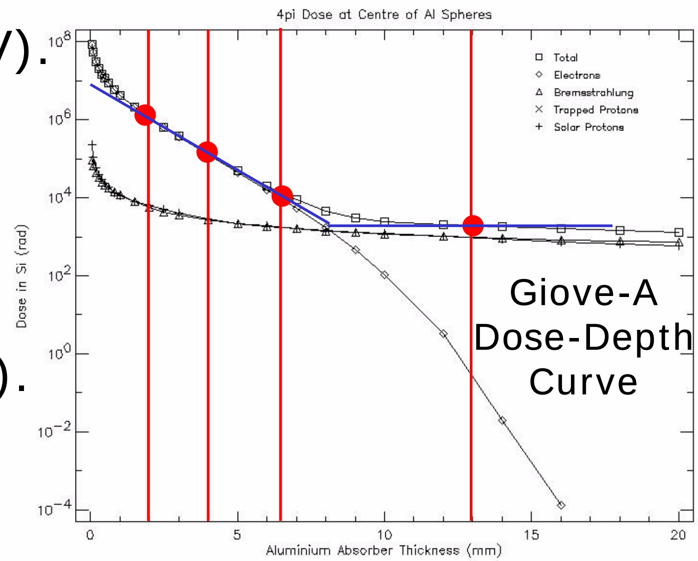




The CEDEX Payloads

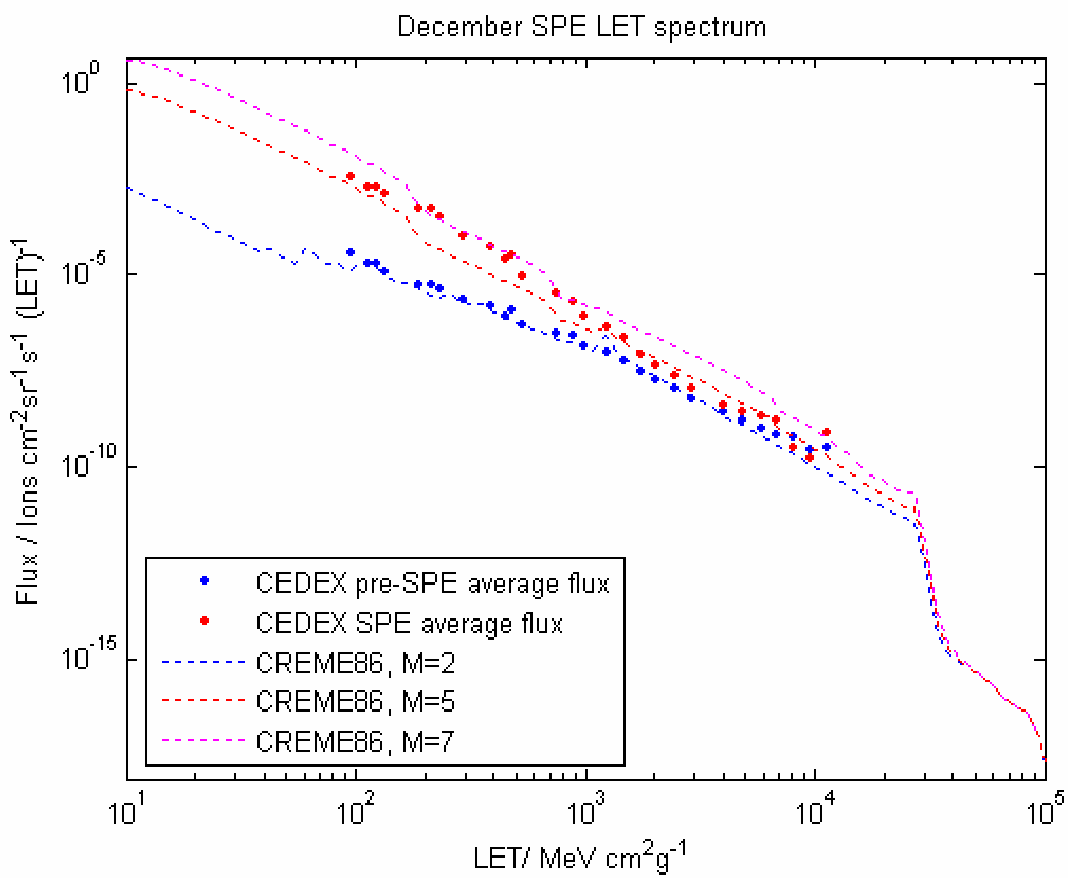
- Primary Functions
  - ✓ Monitor high-energy proton fluxes (~45-50 MeV).
  - ✓ Provide a LET spectrum for the cosmic-ray environment (512 channels: 32-10,000 MeV cm^2 g^{-1}).
  - ✓ Monitor high particle fluxes (e.g. solar particle events).
  - ✓ Gain particle direction information (44^o-60^o FoV).
- Secondary Functions
  - ✓ Experimental dose-rate monitoring at different shielding depths (2&4mm Al; 2&4mm Cu).
  - ✓ Characterise dose-depth curve.





The CEDEX Payloads

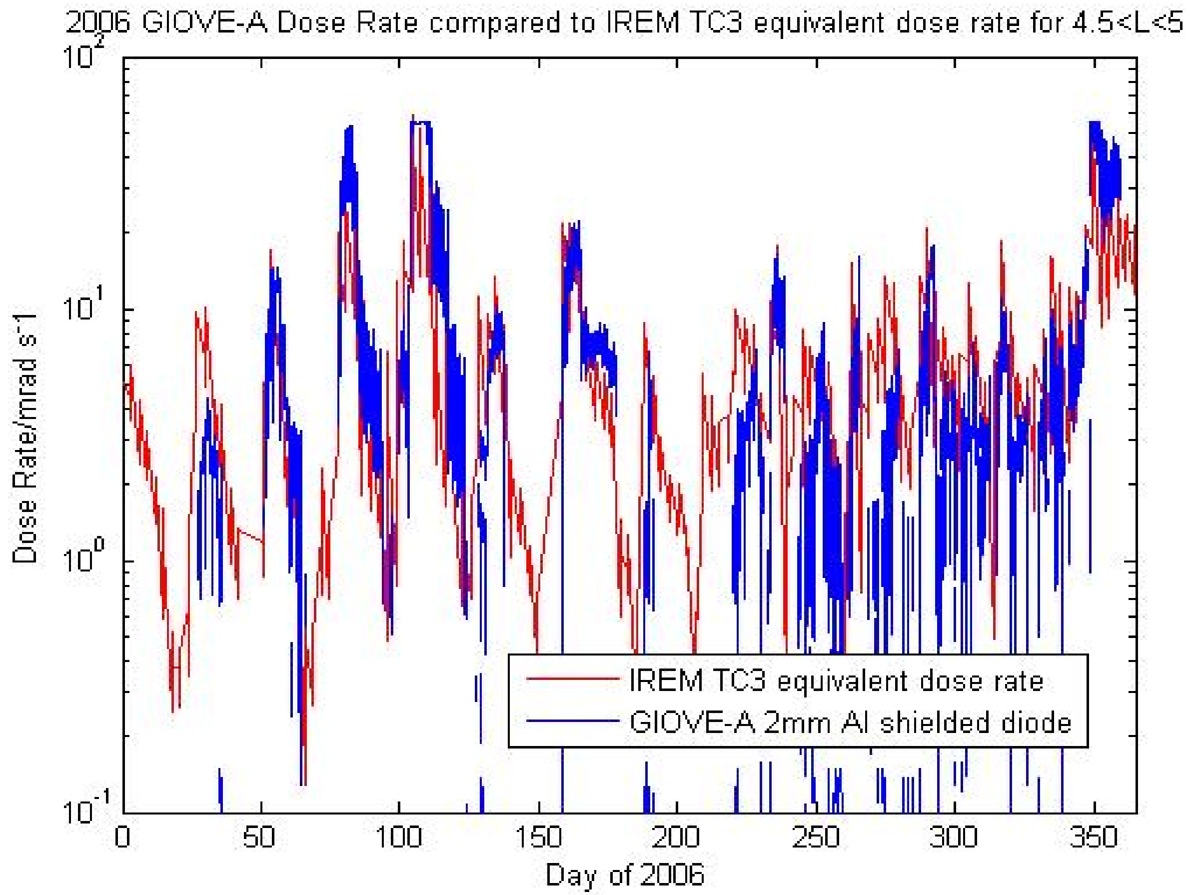
- CEDEX LET spectrum a good match to CREME86 quiet time model predictions;
- SPEs of December 2006 enhanced low LET spectrum significantly to match CREME86 flare time models.



CEDEX measured Heavy Ion LET Spectrum for January to December 2006 and during SPEs compared to CREME86

The CEDEX Payloads

- INTEGRAL/IREM fluxes combined with instrument model;
- IREM data shows a fair match to Giove-A CEDEX dose rates



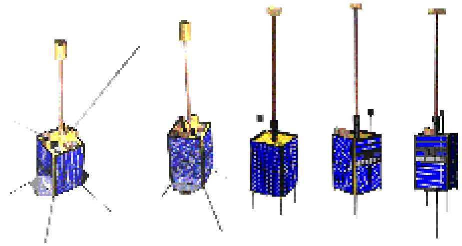
2mm Al shielded flight Dose Rate compared to Dose Rates expected from INTEGRAL/IREM fluxes

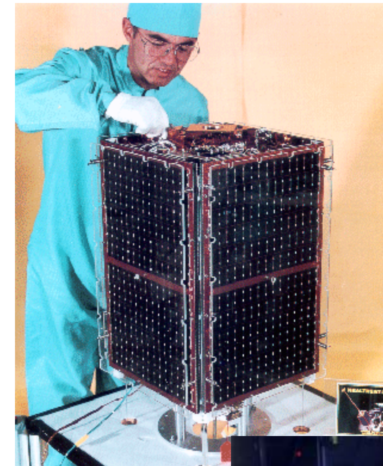
Nano-Satellite Swarms

1979-91

UoSAT
Micro-satellites

50-65 kg

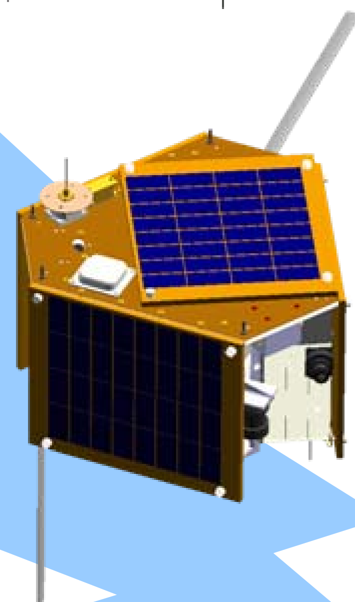




1995-2000

SNAP
Nano-satellite

6.5 kg

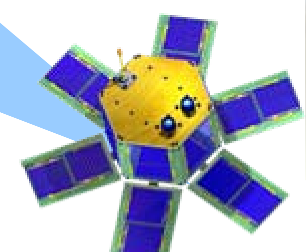


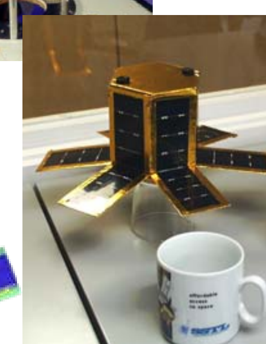
Surrey is studying the concept of “swarms” of tiny satellites for Space Science

2000-2007

PalmSat
Pico-satellite

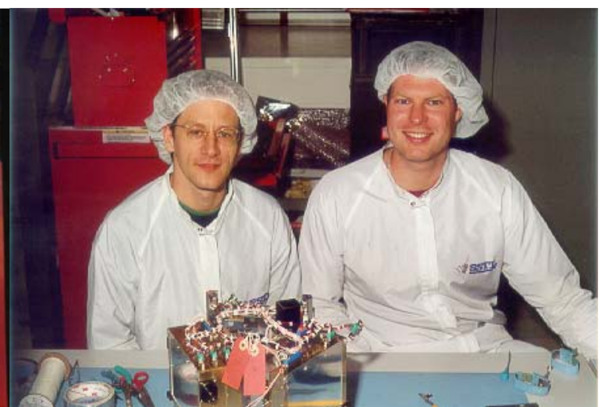
~ 1-2 kg



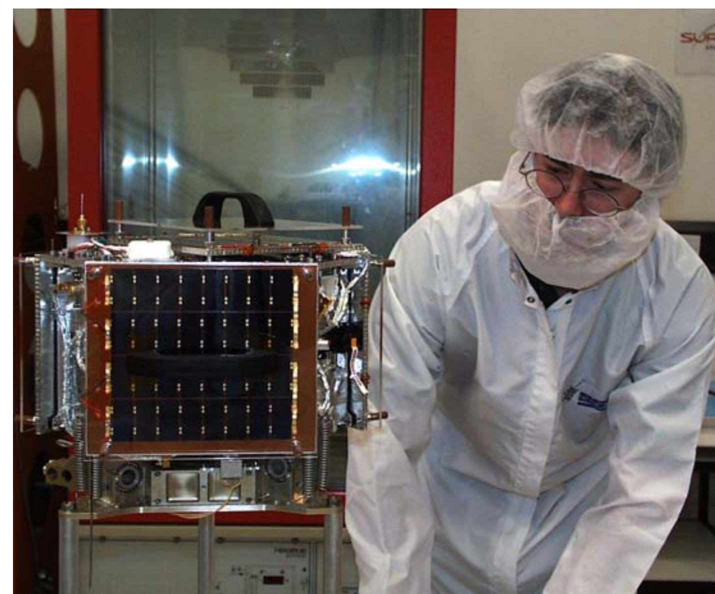


Nano-Satellite Swarms

- SNAP-1 – UK's First Nano-Satellite.
  - 1995 challenge: "design a soccer-ball sized spacecraft"!
  - SNAP-1 design begun in earnest in October 1999, delivered May 2000, launched 28th June 2000.
  - Designed and constructed by SSC staff and students, and SSTL engineers. Funded by SSTL as internal R&D Project.
  - Design-to-orbit – 9 months; cost ≤ $1M.



Jerome Salvignol, Project Manager
Ed Stevens, AIT Manager



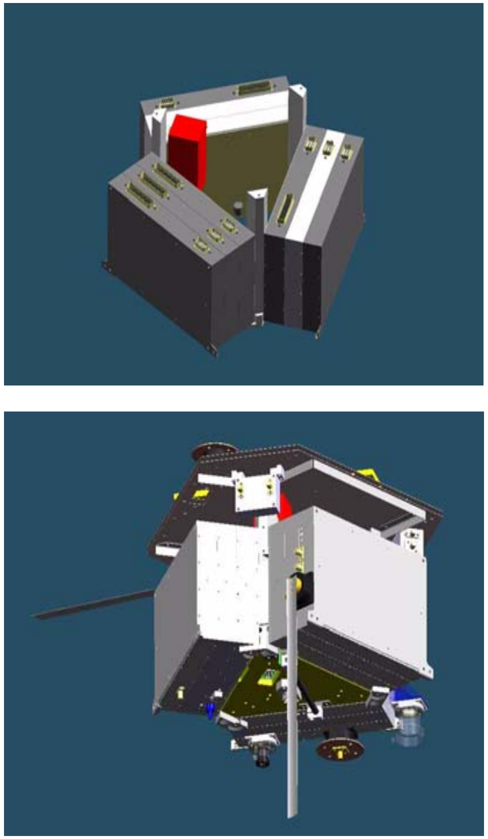
Dr Craig Underwood,
SNAP-1's Chief Architect and Co-Project Manager

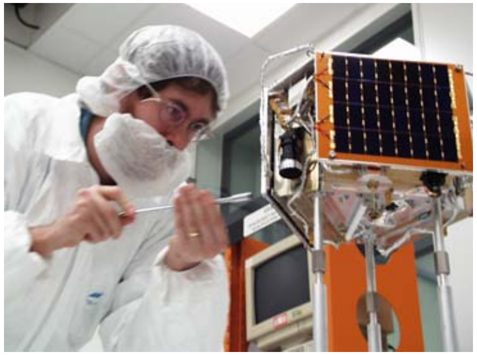
Dr Guy Richardson, SNAP-1's Chief Mechanical Engineer

Nano-Satellite Swarms

- Architecture
  - **6.5 kg mass** – modular, COTS-based design.
- Power
  - 4 GaAs solar panels; advanced NiCd battery.
- Data Handling
  - 3.3V/1.5V 220 MHz SA-1100 32 bit RISC; 4 Mbyte DEDDEC EDAC RAM; FPGA implemented sub-systems.
- RF/TTC
  - VHF U/L at 9600 bps FSK; S-Band D/L at 38.4 kbps BPSK or 76.8 kbps QPSK; internal CAN bus.
- ADCS/GNC
  - 3-axis stabilisation with orbit control via a modified 12 channel “ORION” GPS receiver, a compact 3-axis flux-gate magnetometer, 3 miniature magnetorquer rods and a single miniature pitch-axis momentum wheel.
  - Butane Cold-Gas Thruster (50 mN; ~3.5 m/s DV)
  - UHF Inter-Satellite Link Receiver Payload
  - VHF Spread Spectrum Communication Payload
- Payloads
  - Machine Vision System Payload - four “5th Generation” CMOS video cameras for remote inspection and Earth imaging.

MCAD Model of SNAP-1



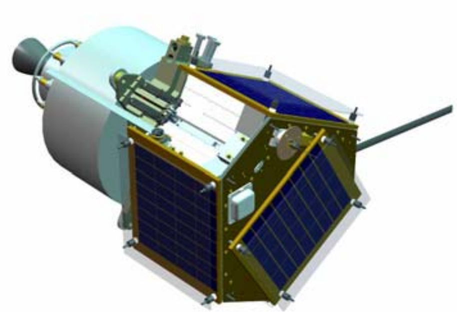


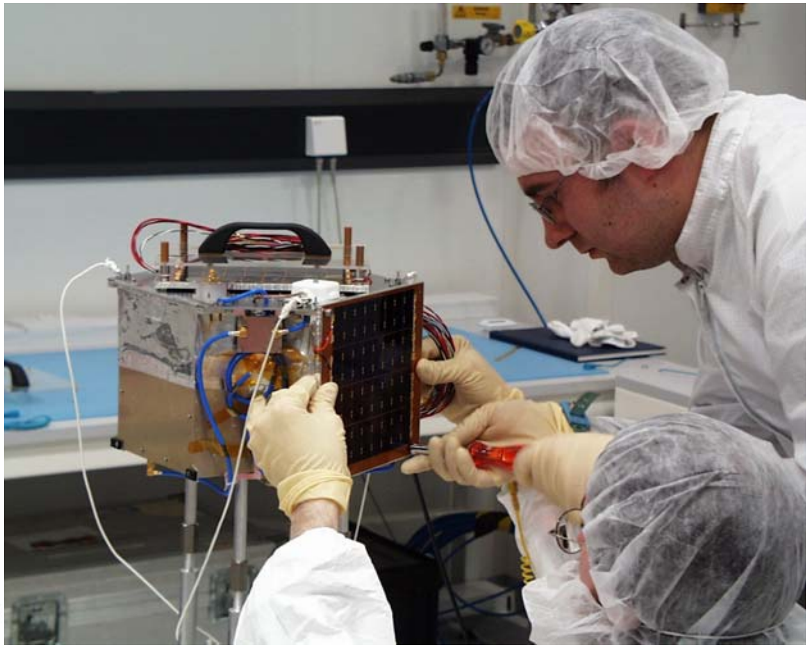
SNAP-1 AIT, April/ May 2000

SURREY SPACE CENTRE

Nano-Satellite Swarms

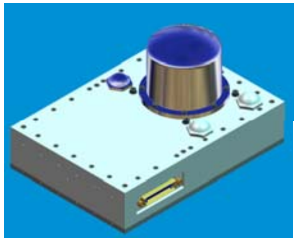
Rapid Off-The-Shelf Nano-Satellite Core





SNAP-1 Under Construction

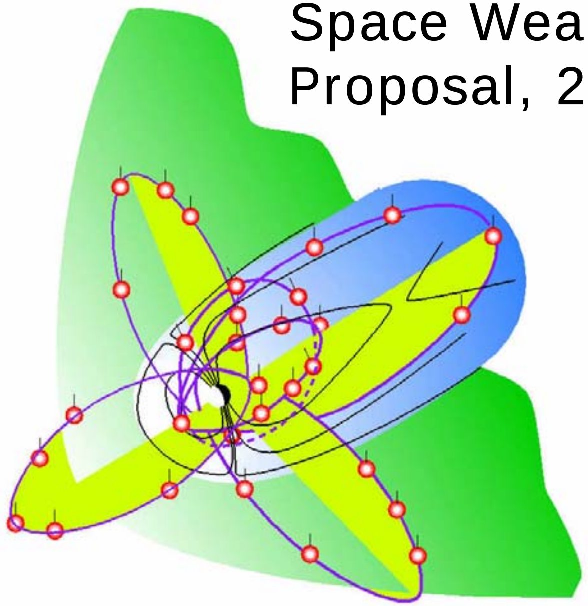
SNAP-1 Orbit Control System



CEDEX “Nano-Tray” Format Payload

Nano-Satellite Swarms

Space Weather Advanced Research Mission Proposal, 2002 (SSTL, Swedish Space Corporation)



Sketch of the full SWARM

Instrument	Mass Kg	Power W	Data Words [a]	Telemetry kbps [b]
Magnetometer	1.95	0.8	96	0.75
Ion Sensor	0.9	1.5	3840	30
Electron Sensor	0.9	1.5	3840	30
Electronics	0.6	5.0	-	-
Total	**4.35**	**8.8**	**7776**	**60.75**

Payload Resources

30 x 25 kg Nano-Satellites

Group	LT	Inclination	GSE lat. @ apo.	Apogee	Perigee
1	1200	0º	0º	$20R_e$	$2.5R_e$
2	1800	0º	0º	$20R_e$	$2.5R_e$
3	0600	0º	0º	$20R_e$	$2.5R_e$
4	0000	0º	0º	$12R_e$	$2.5R_e$
5	0000	0º	0º	$30R_e$	$2.5R_e$
6	0000	~90º	~60º	$15R_e$	$2.5R_e$

Orbit Parameters – 5 Satellites in each group

Even Smaller?

- PalmSat – a (large) coffee-cup sized satellite!
  - <3 kg mass – integrated, COTS-based design.
  - Power – 18 panels of 3 triple-junction solar cells; 6 cell NiMH or Li-ion battery; 3-4W orbit average power;
  - OBC/Bus Controller – 3.3V 20 MHz PIC Micro-Controller; SRAM, FRAM memory.
  - RF/TTC/ISL – Amateur Band U/L & D/L – 9.6 kbs AX.25 packet link; 2.4 GHz SS ISL.
  - ADCS/GNC – Active magnetic + Momentum Wheel; Miniature GPS Receiver.
  - Cosmic Ray Detector Payload – cut down version of CEDEX – credit-card sized.
  - Propulsion – Micro-Resistojet.

All subsystems comprise "credit-card sized" PCBs.

Overall satellite dimensions: approx. 12.5 cm diameter (panels un-deployed) by approx. 15 cm height.

PALMSAT an SSC Student Satellite Project

Conclusions

- The CRE/CEDEX Payloads have provided near-continuous monitoring of the LEO proton/heavy-ion environment over the last 15 years on *KITSAT-1*, *PoSAT-1* and *TiungSAT-1*.
- Results have provided collateral environmental data for SEE analysis of Surrey's spacecraft, and have enabled standard radiation environment models to be evaluated.
- The CEDEX payload is the miniaturized successor to the CRE – modified to operate in the challenging environment of MEO – flight-proven on *Giove-A.*
- CEDEX, and similar miniature monitoring instruments, combined with proven nano-satellite technology (such as SNAP) could provide a cost-effective means of monitoring the radiation belts in detail.
  - Acknowledgements: AMSAT, ASTB-Malaysia, BNSC, DERA (QinetiQ), EPSRC, KAIST, MoD (UK), PoSAT-Consortium, SSTL, Swedish Space Corporation, ESA.


Thank-You!

End

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www.sstl.co.uk

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