

SPACE SCIENCE AND MICROSATELLITES - A CASE STUDY :
OBSERVATIONS OF THE NEAR-EARTH RADIATION
ENVIRONMENT USING THE COSMIC-RAY EFFECTS AND
DOSIMETRY (CREDO) PAYLOAD ON-BOARD UoSAT-3¹

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The University of Surrey's technology demonstration microsatellite: *UoSAT-3*, launched in January 1990, carries on-board a Cosmic-Ray Effects and Dosimetry (CREDO) payload for characterising the low-Earth orbit (LEO) radiation environment. Measurements made with this payload are correlated with radiation effects observed in the spacecraft's microelectronics, in particular, the occurrence of single event upsets (SEUs) in solid-state memory devices. The CREDO payload consists of two sub-systems, the Cosmic Particle Experiment (CPE) and the Total-Dose Experiment (TDE). The CPE houses an array of large-area PIN diode detectors, connected to a pulse-height analysis network. Particles incident on the detector are counted and logged according to their linear-energy transfer (LET). Results are integrated over five minute intervals and the data are stored in the PACSAT Communications Experiment (PCE) memory. The TDE consists of specially manufactured p-channel MOSFETs which are monitored for changes in threshold voltage due to accumulated radiation dose. During the first year's operation, CREDO has provided measurements of the cosmic-ray background, the trapped particle population of the South Atlantic Anomaly (SAA), and has observed a number of large solar proton events - most recently, the major events of June 1991. This paper reviews the results obtained so far and comments on the suitability of microsatellites for this kind of small-scale space science mission.

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INTRODUCTION

Traditional space missions have become synonymous with major programmes, often running into tens or hundreds of millions of dollars and requiring timescales of many years if not decades.

Such enterprises are only within the grasp of major industrial bodies or government agencies, effectively limiting access to the space environment to either the very rich or the most committed of nations. An example of such an approach is the NASA 'Great Observatories' programme, of which the *Hubble Space Telescope* (HST) and *Gamma-Ray Observatory* (GRO) are the first missions to attain orbit.

While there is a need for such 'big science' missions, we believe that there is still a role to be played by more modest spacecraft, and in any case, the initial problems with the HST have served warning of the dangers of overly concentrating resources in a single mission. In the pioneering years of space exploration, spacecraft had to be of modest proportion simply because of the limitations of the launch vehicles of the day. Nevertheless, many very important scientific discoveries were made by relatively small spacecraft carrying perhaps a single payload - one only has to think of the first successful US satellite, *Explorer 1*, and its radiation detectors which enabled James Van Allen to deduce the presence of natural belts of radiation around the Earth. Certainly, all UK scientific spacecraft to-date have fitted into this category of relatively modest spacecraft, and yet they have made important contributions in the fields of astronomy and astro-physics.

THE ADVENT OF MICROSATELLITES

In recent years, progress in the field of microelectronics has led to the possibility of physically small, yet highly sophisticated spacecraft - the so called 'microsatellites' - re-kindling interest in the possibility of using such spacecraft to carry out missions where bulky scientific or communications equipment is not required.

By adopting a design philosophy which puts the emphasis on sophisticated electronics, rather than mechanical systems, and by taking a realistic 'cost-effective' approach to design, procurement and manufacture, it has been possible to construct spacecraft in time-scales and within budgets which have yet to be achieved by traditional aerospace industries ^[1].

A prime example of such an approach is the UoSAT Spacecraft Programme, undertaken by the UoSAT Spacecraft Engineering Research Unit based at the *Centre for Satellite Engineering Research*, University of Surrey (UK), which, over the past decade, has designed, constructed and operated in orbit, five relatively small low-cost (under \$1 million) yet highly sophisticated satellites. In particular, the *UoSAT-2* satellite, launched in 1984 by NASA (alongside the US *Landsat-5* remote-sensing satellite) on a Delta launch-vehicle, illustrates the speed at which a microsatellite can be designed and built, proceeding from paper design to orbiting spacecraft in less than six months!

Nor does such speed imply a reckless approach as far as reliability is concerned. *UoSAT-2* is still fully operational after more than seven years in orbit, and shows every sign of continuing for many years to come. Its earlier sister satellite, *UoSAT-1*, launched in 1981 by NASA (alongside the *Solar Mesosphere Explorer* satellite) on a Delta launch-vehicle, remained operational right up to the point of its re-entry into the Earth's atmosphere in October 1989.

The UoSAT Programme is directed specifically towards the development of cost-effective space techniques, with particular emphasis on space engineering research and the provision of low-cost proof-of-concept / technology demonstration platforms, especially in the fields of low-Earth Orbit (LEO) communications, medium to high resolution Earth-imaging, small-scale space-science and advanced semiconductor device evaluation.

Being based in a University, another major function of the Programme is space education, both at university graduate level through teaching on an MSc course in *Satellite and Telecommunications Engineering* held at Surrey, and more widely at school, college and even individual level through the 'Satellites in Education' Programme and amateur radio.

Modular Microsatellite Bus

As part of its research activity, the Unit has developed a modular microsatellite bus, which was first used for the *UoSAT-3* and *UoSAT-4* missions, launched together on 22nd January 1990 by Arianespace (alongside the French *SPOT-2* remote-sensing satellite) as part of the first use of the Ariane Structure for Auxillary Payloads (ASAP) which has been developed specifically to provide a launching system for small microsatellite-type spacecraft. The UoSAT modular bus has since been used on the *UoSAT-5* mission, launched with the European Space Agency's *ERS-1* remote-sensing satellite on 17th July 1991, and has been adopted by the Korean Advanced Institute of Science and Technology for their *KITSAT-A* satellite, which will be launched in 1992, as well as by the French for the *Cerise* mission.

The bus is designed to provide all the 'housekeeping' needs of the spacecraft in terms of communications, telemetry and telecommand, on-board computing and data storage, attitude determination and control and power supplies, and it is intended that the various payloads can simply 'plug-in'. By adopting a modular approach, the spacecraft can be configured to meet the needs of a particular payload and mission, with the minimum of re-work from one spacecraft to the next. Indeed, the flexibility of such a system has already been demonstrated, as the original bus was developed for the *UoSAT-C* mission which was slated for a Delta launch. When this opportunity was lost, the *UoSAT-C* spacecraft was rapidly re-engineered into the *UoSAT-3* and *-4* satellites for launch on an entirely different vehicle (Ariane) with very different constraints in terms of mass and volume. The modularity of the *UoSAT-C* bus design enabled the satellite to be effectively split into two smaller satellites with very few changes.

Microsatellite Design Phillosopy

The underlying phillosphy behind the UoSAT microsatellite bus is best summarised by the design 'ground-rules' which have been formulated to minimise the overall cost of the mission, whilst still maintaining an acceptable level of reliability:

..

- a) Keep it simple and examine thoroughly the task and environment of the sub-system and specify components/techniques that will accommodate the task with a suitable, realistic margin of safety. Do not simply go for the highest rated/quality approach as this will generally increase costs dramatically, unless the function strictly requires it.

b) Essential bus modules should use standard, proven designs and hardware wherever possible. Avoid indeterminate software development appearing in critical paths, even at the expense of apparent reduced flexibility and greater hardware count.

c) Redundant paths may use less proven designs or technologies, providing that they are not associated with single-point failure nodes.

d) Use flexible design to provide redundancy via alternative technologies - rather than by duplication - wherever practicable.

e) Use easily defined, simple interfaces between sub-systems wherever possible. Sub-systems should run independently of other systems, even if that entails duplicate hardware (unless there is an overwhelming advantage to be gained).

f) Design essential systems around established, industrial, high-grade, volume production components and attempt to procure 'hi-rel' or 'mil-spec' screened versions. If a component has been in volume production, it is highly likely that any 'bugs' have been removed. Non-essential systems may use more exotic technologies (and thus prove them for the next generation design).

.. "

These design rules, which have under-pinned all the UoSAT spacecraft, have lead to the development of a commercial satellite bus, which is marketed by the University's spin-off company: *Surrey Satellite Technology Ltd.* (SSTL). The SSTL 'Microbus' has been selected for a number of payloads to be launched in the 1990's, by both emerging and well-established space nations.

Limitations of Microsatellites

Microsatellites are obviously not useful for all space-science applications. They are extremely limited in terms of the mass and volume of the payload they can support - usually to just a few kilogrammes, and a few thousand cm³. Having relatively little area for solar panels, the electrical power budget is usually extremely tight, and payloads should preferably consume no more than a few watts. Many scientific payloads need precise pointing control and this has yet to be demonstrated on a microsatellite mission - although studies at Surrey show that it is feasible - even under the constraints of having few moving parts.

However, for those payloads that can operate within these constraints, the advantages in terms of cost and reduced time-scales are overwhelming.

As an example of the use of such a microsatellite bus for space science research, the incorporation of the Royal Aerospace Establishment (RAE) - now Defence Research Agency: Aerospace Division (DRA) - Cosmic-Ray Effects and Dosimetry (CREDO) payload into the *UoSAT-3* satellite will now be described.

THE 'CREDO' PAYLOAD ON UoSAT-3

CREDO was built by AEA Technology, Harwell, UK, under contract to RAE and was incorporated into the *UoSAT-3* satellite by engineers at Surrey. CREDO is a development of an earlier payload: the Cosmic Radiation Effects and Activation Monitor (CREAM), designed in 1985/86 to be flown on the Space Shuttle^[2].

Delays in the Shuttle Programme lead to the development of a version of the instrument for use on the Concorde supersonic transport to investigate the upper-atmosphere radiation environment^[3,4], as well as the CREDO variant for use on free-flying spacecraft such as UoSAT. Flights on a number of future missions encompassing a variety of orbits are now under consideration, including a flight on the RAE *Space Technology Research Vehicle* (STRV)^[5] microsatellite, which is due to be launched into Geostationary Transfer Orbit (GTO) by Ariane in 1993. The incorporation of CREDO into the *UoSAT-3* satellite provided an early opportunity to gain information on the in-orbit performance of the instrument, as well as being particularly useful for monitoring the LEO polar orbit so favoured by remote-sensing spacecraft. This is particularly timely in view of the large investment which will be made in large remote-sensing polar-platforms over the coming decade.

Although there exists a number of models of the radiation environment at these altitudes (such as the *CREME* code of Adams^[6]), there has been little opportunity to validate the codes against flight-data - particularly with respect to gaining simultaneous measurements of the radiation environment and its effect on spacecraft systems, such as single-event upsets (SEUs) in semiconductor memories. Indeed as *UoSAT-3*'s other major payload is the PACSAT Communications Experiment (PCE), which contains over 4 megabytes of semiconductor RAM, there is an unique opportunity to tie-up measurements of the radiation environment with observations of SEU activity in a large memory.

CREDO is an ideal payload for a microsatellite mission. It is relatively compact, fitting neatly into a single standard UoSAT module box (330 mm × 330 mm × 26 mm - see Figure II), although it is a little on the heavy side with a mass of 2.2 kg (a substantial proportion of which is due to the detector shielding). The instrument has almost a 4 *Pi* steradian view and therefore has no special pointing requirements. From an electrical point of view, it is a low-power payload, consuming less than 500 mW from a regulated +5V and +10V/-10V power supply, and therefore continuous operation can be easily supported by the satellite's power system (in-fact this is necessary to ensure the correct biasing of the RADFET sensors). However, it is extremely sensitive to power supply 'noise' and requires substantial filters to isolate its sensitive electronics from the albeit low-level 'hash' produced by the digital systems on-board the spacecraft. In fact, the filtration has proved inadequate to completely remove spurious signals from the most sensitive channels of the instrument (i.e. the Low-Area Detector and Channel 0 of the High-Area Detector).

CREDO consists of two experiment sub-systems, the Total-Dose Experiment (TDE) and the Cosmic Particle Experiment (CPE).

Total-Dose Experiment (TDE)

The purpose of the TDE is to measure the total accumulated ionising radiation dose at various locations on-board the spacecraft. It consists of seven pairs of specially modified p-channel power MOSFETs called RADFETs which have a specially grown gate-oxide of around 0.5 microns thickness.

When exposed to ionising radiation, electron-hole pairs are created in the oxide layer, and being relatively mobile in silicon dioxide, the electrons tend to be swept out, leaving behind the trapped positively charged holes.

Thus, as the device accumulates an increasing dose of ionising radiation, so the gate-oxide becomes increasingly charged, leading to a measurable shift in threshold voltage. For these particular devices, an exposure of a kilorad total-dose will lead to approximately a one volt shift in threshold voltage.

The RADFET pairs (manufactured by REM Ltd. of Oxford, UK) are fabricated on a single die and housed in a standard 14-pin DIL package. In operation, one of the FETs is held un-biased, with the source, drain and gate grounded. The other FET is held biased to 10 volts. During exposure, the passage of an ionising particle through the device leads to the formation of a dense column of electron-hole pairs - i.e. a plasma. In the biased FET, the electric field present tends to sweep the relatively mobile electrons out into the external circuit, leaving the essentially immobile holes behind. Whereas, in the un-biased FET, there is considerable re-combination of electrons and holes, leading to much less charging of the oxide. To 'read' the device, the FETs are momentarily biased with a constant current source (6 microamps), and the resulting threshold voltage is measured. This voltage is a function of temperature as well as accumulated dose, however, by taking a differential measurement between the biased and un-biased FET, it is possible to largely compensate for the temperature effect. Figure III shows a graph of the differential voltage shift between a biased and un-biased RADFET in the CREDO payload itself. The change in voltage is approximately proportional to accumulated dose, and when properly calibrated, is consistent with a dose-rate of somewhat less than one rad per day. This is in line with expectations from computer models of the environment run for the *UoSAT-3* orbit.

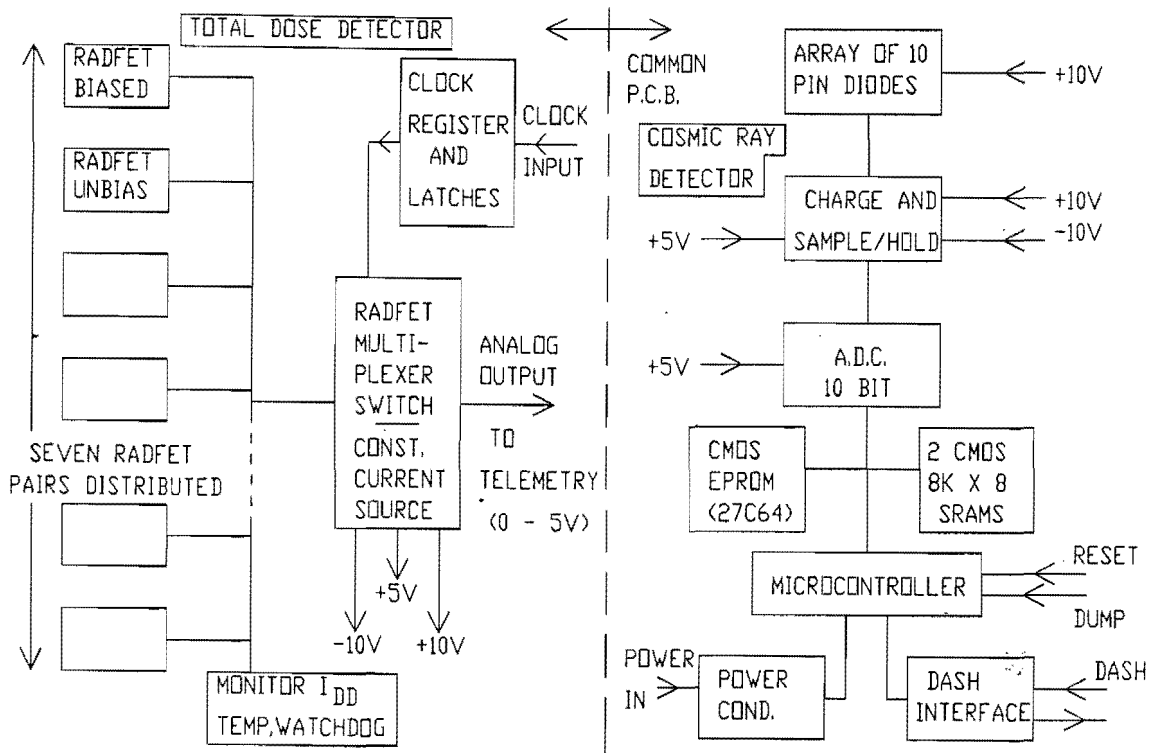
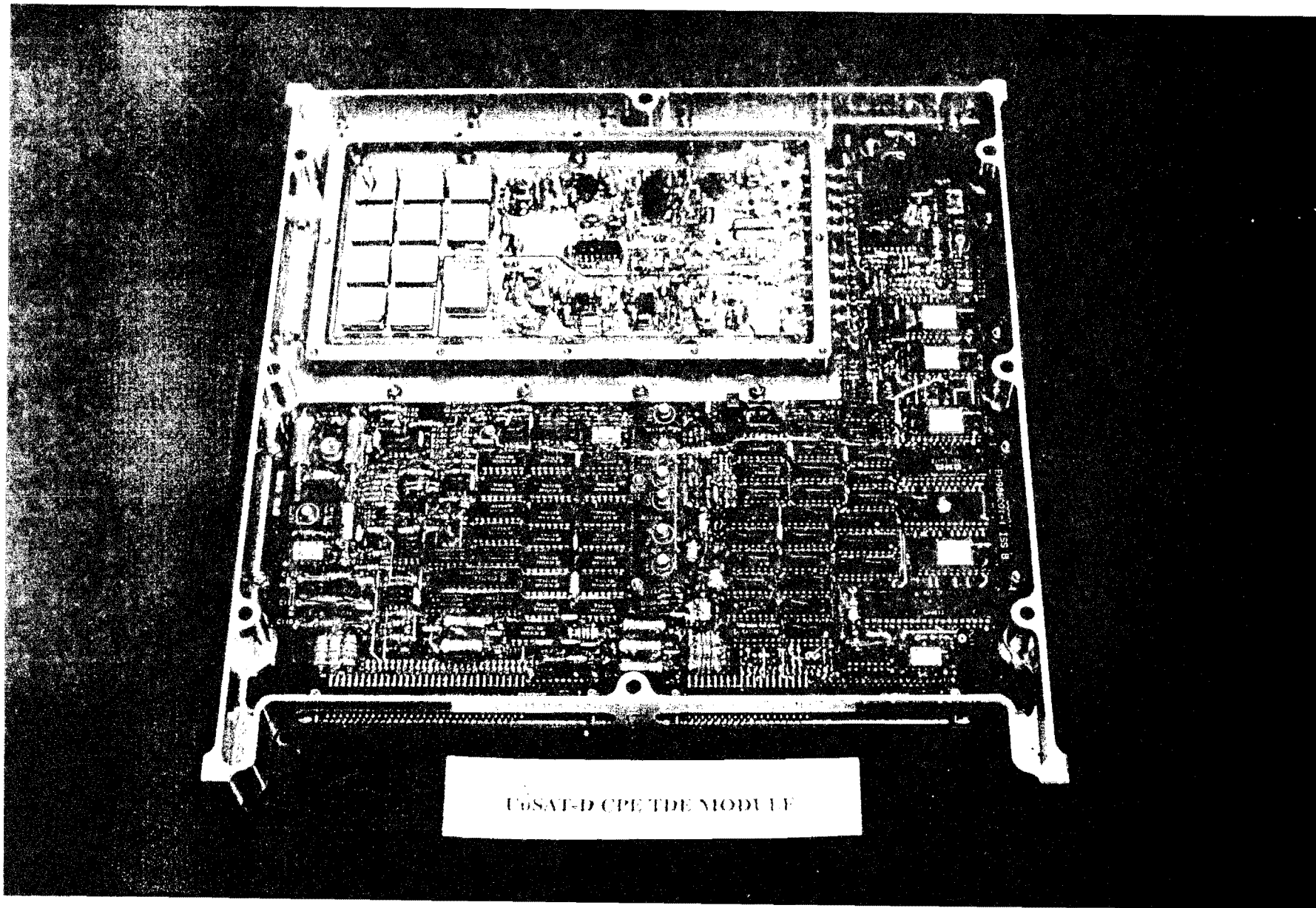


Figure I : Schematic of the CREDO Payload on UoSAT-3

Figure II. USAT-3 CREDO Payload



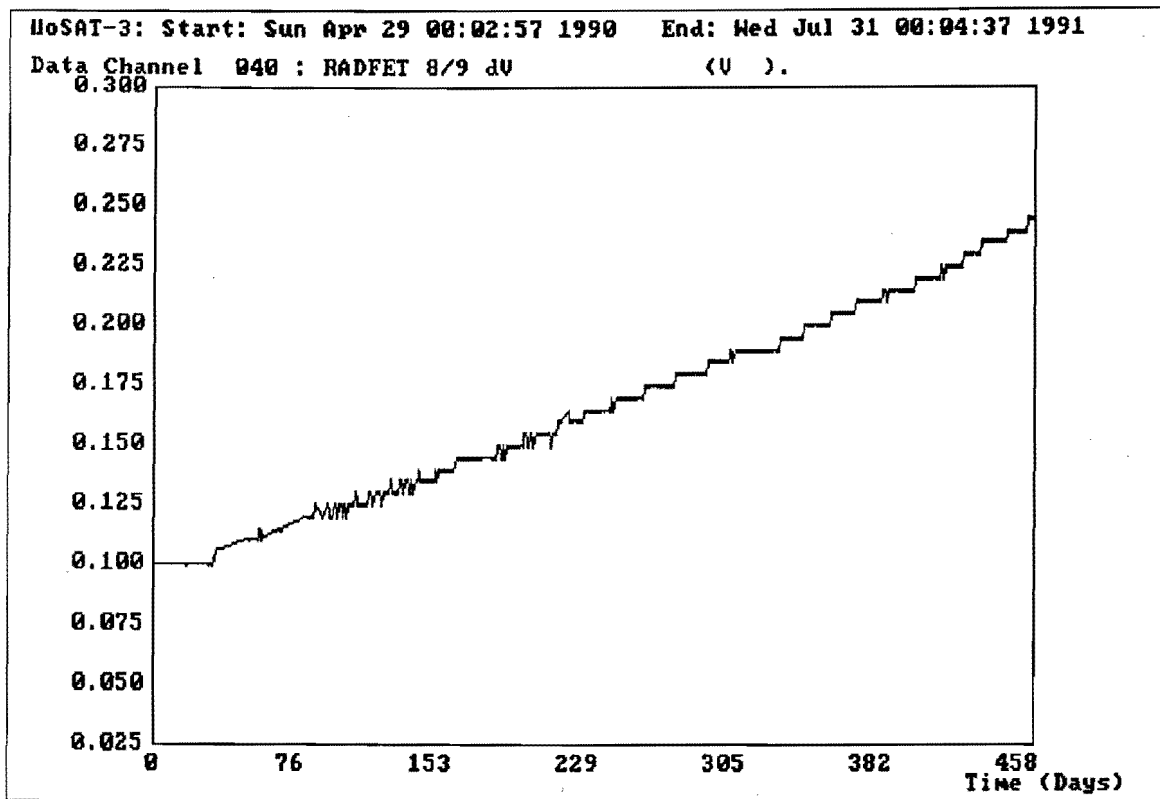


Figure III : Differential Shift in Threshold Voltage for a Normally Biased and Normally Un-Biased RADFET Pair

Interestingly, during this period there were a number of major solar proton events, however, there was no significant change in the dose-rate observed by the RADFET's. This is consistent with the idea that for this particular orbit, the traversals of the South Atlantic Anomaly (SAA) region contributes the bulk of the dose, and further, that this population is virtually unaffected by such solar proton events. This is also supported by data from the CPE part of the payload.

UoSAT-5 also carries a TDE based upon the RAE/AEA Technology design. One difference has been the inclusion of an experimental sensor based upon commercial FET devices on the outside of the spacecraft (the RADFET on the exterior of UoSAT-3 did not survive long enough to return any data). This is already showing a considerable shift in threshold voltage for the biased FET as compared to the un-biased FET, even though it has only been exposed for a matter of days (see Figure IV). Although the sensor has yet to be calibrated against laboratory sources, a preliminary estimate would suggest a dose-rate of the order of 100 kilorad per year on the outside of the spacecraft, showing the effectiveness of the spacecraft structure in shielding the interior. The cycling seen in the graphs is due to the changes in temperature that the sensor undergoes during the course of an orbit, reaching -35°C at the end of eclipse and $+20^{\circ}\text{C}$ at the end of the sunlit portion of the orbit.

Data from the TDE are gathered every 5 minutes by the PCE. The results are stored on-board in a data-file for downloading to the mission control ground-station at Surrey. Usually this is done each working day, although the spacecraft has the capacity to hold many days of data-files before they have to be deleted to make space.

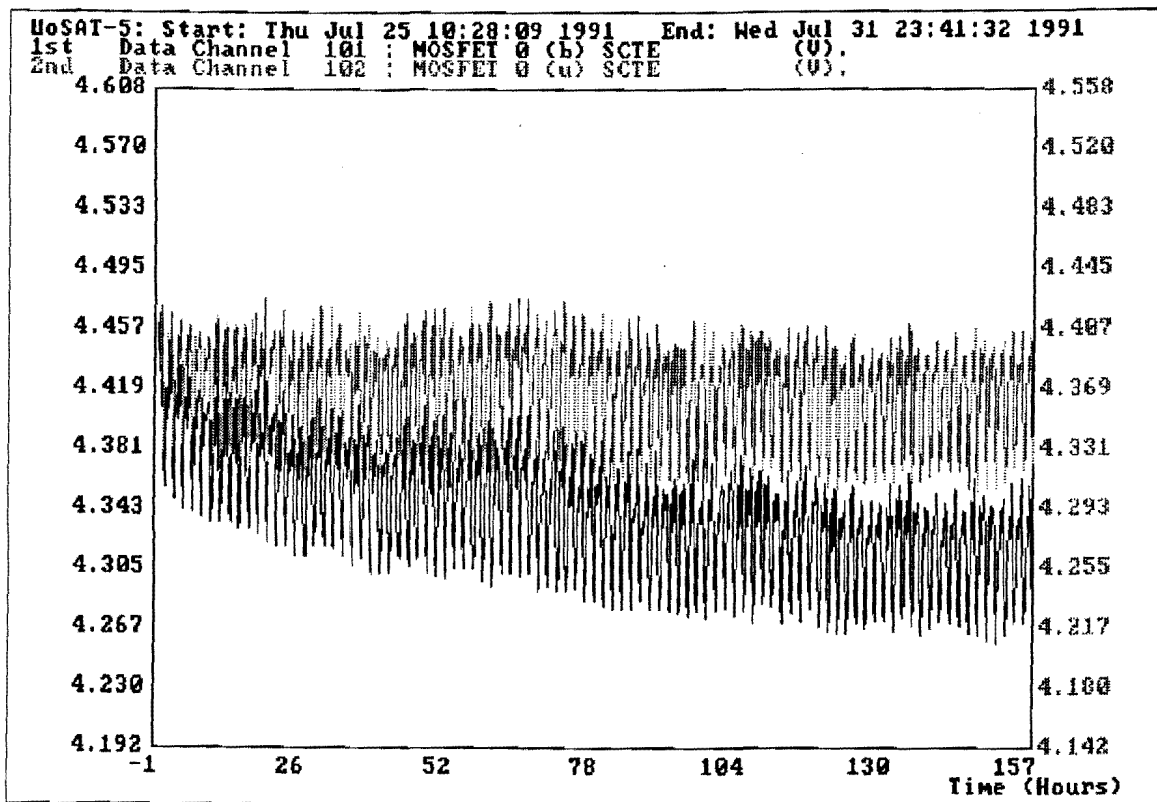


Figure IV : UoSAT-5 Experimental FET Dosimeter - Initial Shift in Threshold Voltage

The Cosmic Particle Experiment (CPE)

The CPE is perhaps the more interesting of the experiments in the CREDO payload. It is based around an array of large-area PIN diodes, which are connected to a charge pulse height analysis network. Ionising particles traversing the diodes give rise to charge pulses which are proportional to the energy they deposit on their way through (i.e. their linear energy transfer - LET).

The diodes are arranged in two detector systems: a Low-Area Detector (LAD) for high count-rate applications and a High-Area Detector (HAD) for good statistics at moderate to low count-rates. The experiment is autonomously controlled by an 80C31 microcontroller.

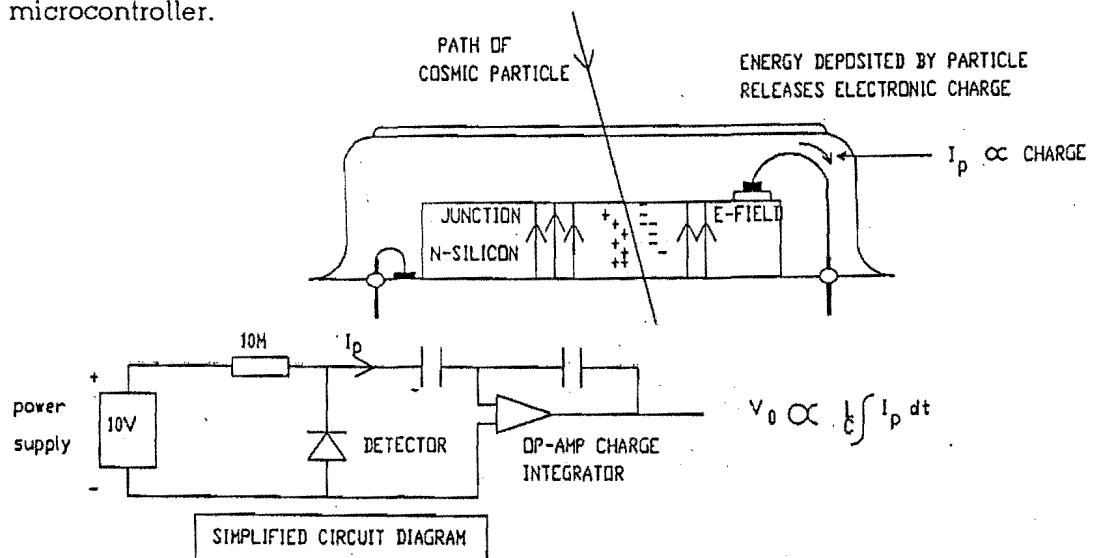


Figure V : Principle of Operation of the CPE PIN Diode Detector

The LAD consists of a single 1 cm², 300 um deep PIN diode with a charge threshold of 0.02 pC (equivalent to a normally incident particle with a LET of 6.4 MeV / (g cm⁻²)), designed to detect particles under high flux conditions - avoiding excessive dead-times. The resulting charge-pulses are counted, but not analysed further. The dead-time of the instrument is software limited to approximately 0.5 ms. As mentioned previously, this detector is very sensitive to electronic noise coupled in on the power lines, and so its results are somewhat degraded.

The HAD consists of a flat array of 10 PIN diodes, connected in parallel to give a 10 cm² detector. This is connected to a 9-way multi-channel analyser with thresholds ranging from 0.1 pC to 20 pC full-scale (corresponding to a LET range of 32.2 MeV / (g cm⁻²) to 6430 MeV / (g cm⁻²)).

In operation, the charge-pulses from the HAD are detected and assigned to 'energy-bins' and the results are integrated over a 300 second period. The dead-time of the instrument is software limited to approximately 1 ms.

Both the LAD and HAD diodes are shielded by an aluminium box to limit the count-rates to around 100,000 counts per integration period (300 s) in the most sensitive channel when passing through the heart of the SAA.

Data from the experiment are communicated over the spacecraft's DASH (Data SHaring) network to the 80C186-based packet communications transponder / OBC, which handles time-stamping and filing of data ready for transmission to the ground-station. The system works autonomously, and data files representing each day's activity are stored on-board (in the 4 Mbyte semiconductor RAMDISK) until they are requested by the operator (usually each working day). Files stored on the spacecraft are protected against SEU by software coding / wash routines, and the downlink is error-controlled by the packet communications protocol to ensure error-free data at the ground-station.

RESULTS

Figure VI shows the predicted electron and proton fluxes incident on the spacecraft using the standard AP8 (Max) and AE8 (Max) models. Figure VII shows actual data from the CPE and it can be seen that there is a good qualitative fit between the observed HAD Channel 1 count-rates and the predicted proton fluxes.

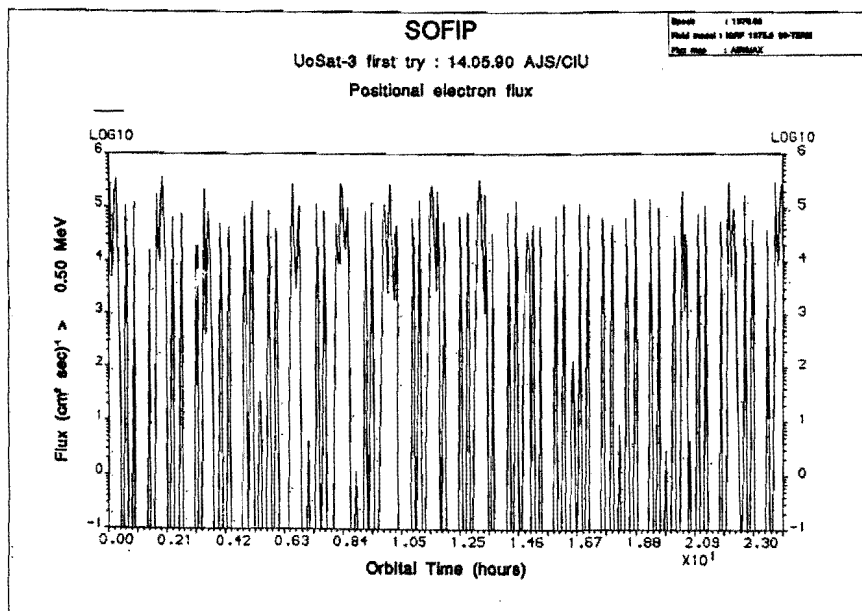


Figure VI (a) : UoSAT-3 Predicted Trapped Electron Flux (AE8 Max Model)

In Figure VI (b) and Figure VII, the large peaks are due to the trapped proton population of the SAA.

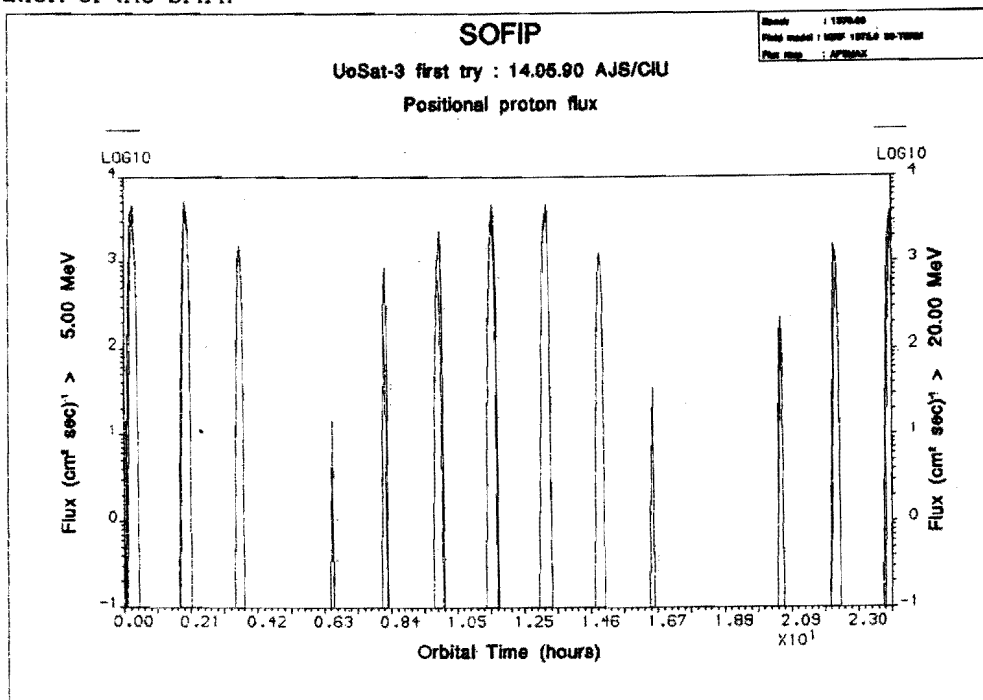


Figure VI (b) : UoSAT-3 Predicted Trapped Proton Flux (AP8 Max Model)

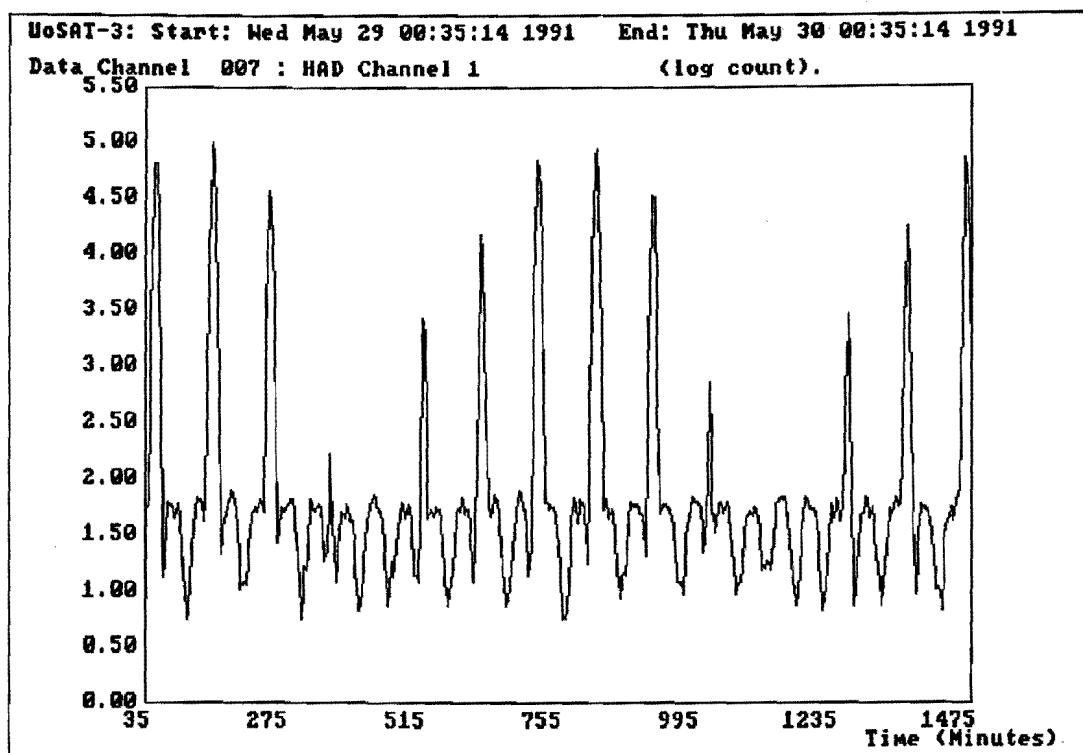


Figure VII : CREDO Flight Data - CPE HAD Channel 1
(32.2 - 62.4 MeV / (g cm⁻²) Normal Incidence LET)

Additionally, the data from the CPE shows a lower level region of activity peaking over the polar regions, and having a minimum over equatorial regions. This is due to the cosmic-ray background, which is strongly modulated by magnetic latitude. Particles with low magnetic rigidity (the quotient: momentum/charge) can only penetrate at high magnetic latitudes, whereas particles with higher rigidities may penetrate at lower magnetic latitudes.

Quiet-Time Cosmic-Ray Environment

It has been possible to examine the quiet-time cosmic-ray background by analysing the HAD count-rates (per 5 minute time-bin and per 10 cm² detector area) for periods when the spacecraft was outside the SAA and when the solar activity level was low. For the purposes of the analysis the SAA was taken to be the area bounded by 10° S to 30° N in latitude, and 120° W to 60° E in longitude. This is somewhat of an overestimate of the size of the SAA, but ensures that the quiet-time data is uncontaminated by the SAA trapped particle population. The recorded times associated with the data were used to reconstruct the position of the spacecraft in terms of altitude, latitude and longitude, and this in turn was input to a model of the magnetosphere based on that of Adams^[7] which extrapolates from a world-wide grid of vertical cut-off rigidities at 20 km altitude derived by Shea and Smart^[8]. Thus, the vertical cut-off rigidity for each location was found. The data were sorted into 1 GV rigidity-bins (i.e. 0-1 GV, 1-2 GV, .. , 14-15 GV) upto a rigidity of 15 GV, and compared to predicted count-rates derived from the CREME code. In order to do this, a full isotropic path-length analysis was done of the diodes assuming a 1 cm² cross-section and a 300 um collection depth. It was found that there was reasonable agreement between the predicted and the observed count-rates, particularly at the high-LET end of the spectrum. However, at the lower-LET end, the observed count-rates greatly exceed the predictions (see Table 1). It is possible that this is due to secondary effects such as nuclear reaction products which are not taken into account by the Adams code as it only considers energy loss by ionisation and particle loss by nuclear interaction. The authors are currently investigating the effects of proton induced nuclear reactions through other computer codes.

Table 1
COSMIC PARTICLE EXPERIMENT COUNT RATES
(Quiet Time GCR Background, Vertical Cut-Off Rigidity : 2-3 GV)

<u>HAD Channel</u>	<u>Threshold Charge</u>	<u>Normal Incidence LET</u>	<u>Counts (per 5 minutes)</u>	
	<i>pC</i>	<i>MeV / (g cm⁻²)</i>	<i>Mean Obs.</i>	<i>Pred.</i>
1	0.10	32.2	46.5 +/- 0.1	11.1
2	0.19	62.4	21.7 +/- 0.1	7.23
3	0.38	121	9.35 +/- 0.05	5.42
4	0.73	234	4.11 +/- 0.03	2.88
5	1.4	453	1.64 +/- 0.02	1.36
6	2.7	881	0.630 +/- 0.014	0.885
7	5.3	1710	0.242 +/- 0.008	0.396
8	10.3	3312	0.064 +/- 0.004	0.103
9	20.0	6430	0.018 +/- 0.002	0.034

Observations of the South Atlantic Anomaly (SAA) Region

The SAA is of great interest for this particular orbit as it is known that the trapped-proton population in this region gives rise to the bulk of the SEU activity seen in the memory devices on-board all the UoSATs^[9,10,11]. A contour map of the SAA has been constructed from a year's observations by CREDO, and the form and position of this map corresponds very closely to that of the AP8 flux model. More recently, a different processing technique has been used to create a colour-contour map of the HAD counts over the entire area of the globe covered by UoSAT-3, resolved on a 2° × 2° grid. The results for 12 'quiet' days and 12 'disturbed' days are shown in Figure VIII. The effect of solar protons mirroring at high magnetic latitudes (low-rigidities) can clearly be seen in the disturbed plot.

The 'banding' seen at these latitudes is an artifact caused by the decay-time of the solar-proton population compared to the orbit period of the satellite. It is clear from these plots that the SAA region is relatively un-affected by such disturbances.

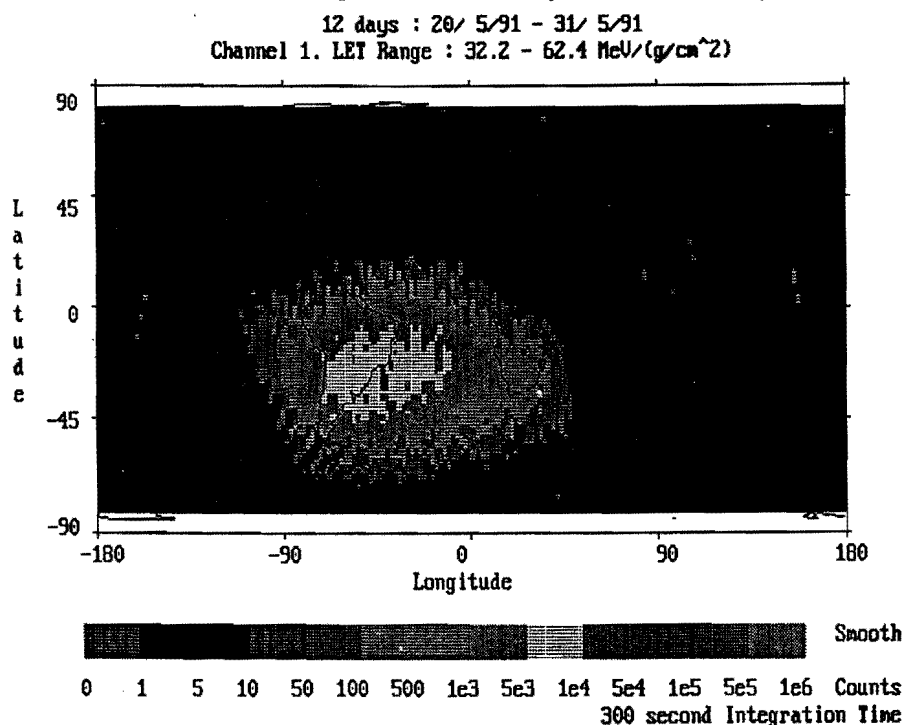


Figure VIII (a) : Map of HAD Channel 1 Activity : 12 'Quiet' Days

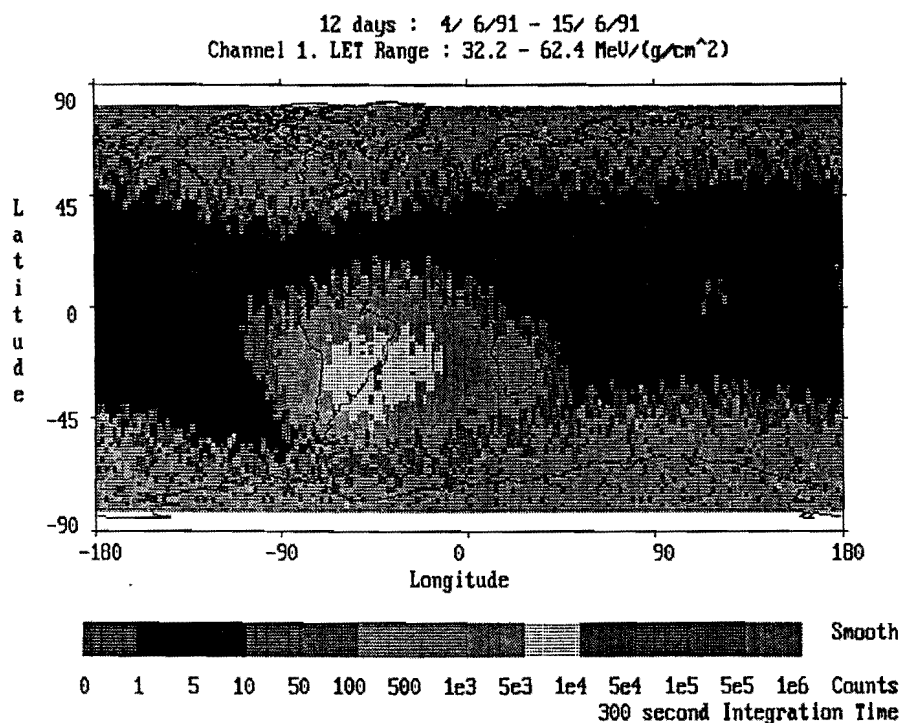


Figure VIII (b) : Map of HAD Channel 1 Activity : 12 'Disturbed' Days

Solar Proton Events

During the first year's operation of CREDO, there have been several periods of intense solar activity leading to the injection of solar protons into the magnetosphere. The most notable of these was the recent major flare activity from 'Region 6659', which caused extensive solar proton events. Figure IX shows the extent of the activity throughout the month of June 1991.

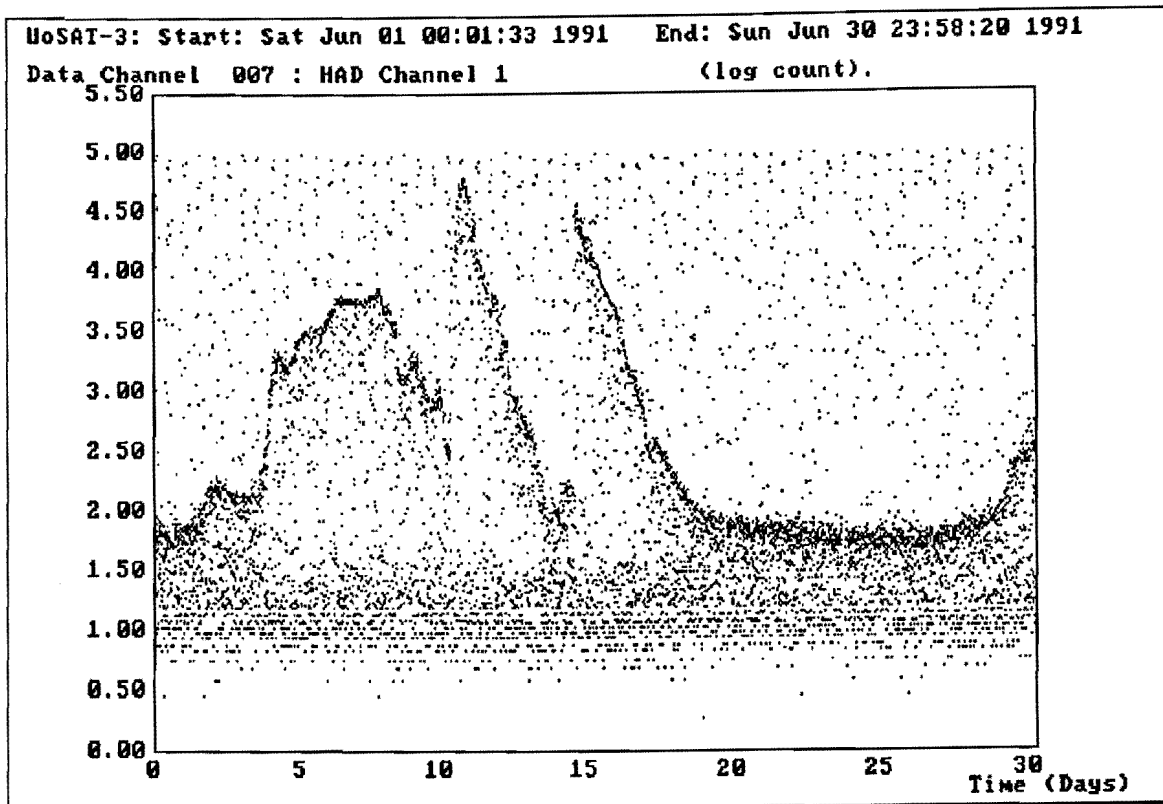


Figure IX : Major Solar Activity Observed by CREDO for June 1991

The count scale of Figure IX is logarithmic, and it can be seen that the polar-region count-rates (upper bound of the envelope) reach as high as 10^5 counts per 5 minutes - comparable to the rate observed in the heart of the SAA. By comparison, the normal 'quiet' time count-rate is less than 10^2 . It can also be seen that the equatorial region count-rate (lower bound of the envelope) remains essentially un-affected, thus, the solar particles are unable to penetrate to high rigidities (13-14 GV).

More detailed analysis shows that during these 'storms', the low-rigidity (less than 6-7 GV) LET spectrum is considerably enhanced over 'quiet' time levels, upto LETs as high as $1000 \text{ MeV} / (\text{g cm}^{-2})$, whilst the high-rigidity spectrum remains unchanged. This unusually high level of solar activity did give rise to increased SEU activity on the UoSAT satellite, and the authors are currently analysing these events to correlate them with flux levels and the 'hardness' of the spectrum.

CONCLUSIONS

It has been shown that, whilst not a panacea, microsattellites can play a useful role in supporting small-scale space-science missions. They are obviously limited in terms of volume, mass and power, but have very real advantages in terms of cost, performance and speed of production - it is possible to design an experiment and get it into orbit before the thesis is due! This opens up the space environment to institutions which would otherwise not have ready access - such as universities.

The UoSAT-3 CREDO payload has been described, and some of the results of the first year's investigations have been presented. It is fair to say that the payload has been a particularly successful one, and it augers well for its inclusion on future space missions - not least on RAE's own microsattelite: STRV to be launched in 1993.

Results from CREDO are being used in the University of Surrey's and DRA's research programme into the effects of space radiation on microelectronic devices, and are being combined with observations of SEU activity on the UoSAT-2, -3 and -5 satellites. Analysis of the results is giving fresh insight into the applicability of the current generation of computer models used to predict radiation effects in space.

ACKNOWLEDGEMENTS

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