Observations of the dynamics of the radiative environment in polar orbit in the period 11/2000-11/2001

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Abstract— The ICARE instrument has been developed for monitoring the space radiation environment and measuring the associated effects on a variety of electronic components. This instrument is currently operated on board the argentine satellite SAC-C launched in November 2000 in a sun-synchronous polar orbit. This paper describes the first year of results from this mission.

I. INTRODUCTION

Electronic components are very sensitive to the space environment, and in orbit measurements of their actual behaviour is the only way to correctly assess any improvement made in the risk estimation methods. The usual environment models themselves may not be completely suitable for the design of new space systems in which margins are reduced. Moreover, the environment inputs have a direct impact on the risk estimation calculations, so it is of prime interest in this context to be able to achieve simultaneously an in orbit measurement of the cause (the environment) and the effects on the devices (single events, dose drifts). Some years ago, CNES decided to develop such an instrument able to address the two types of measurements, with the double goal of contributing to the improvement of the models and knowledge of the radiation environments and the associated effects on components. Versions of this instrument were or will be flown on the MIR and ISS space station and on the technological satellite STENTOR is geosynchronous orbit. Through a collaboration with the Argentine Space Agency (CONAE), the ICARE instrument was also flown on the argentine satellite SAC-C placed in a polar, sunsynchronous orbit in November 2000.

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II. THE INSTRUMENT

A. Overall description

The ICARE instrument was designed with the goal of associating a set of particle fluxes measurements with the associated effects on electronic components.

Figure 1 gives an overview of the instrument. The colour code used for depicting the various sub-systems is :

- yellow : particle detectors
- orange : acquisition electronics
- green : processing and bus interface
- red : power supply
- blue : removable component test module

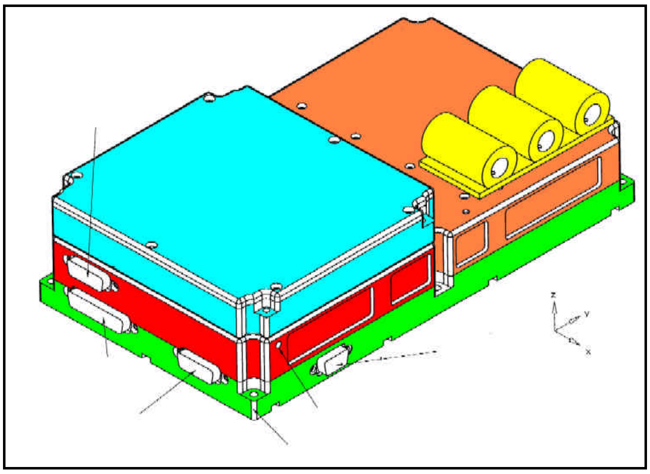

Fig. 1 : View of the ICARE instrument

The base block of the instrument is made of the detectors, the acquisition chains, the processing unit (CPU), the bus interface unit and the power supply converter. The component test board is realised as an independent module, which is not necessary for the instrument to function, and can be changed from one mission to another. This module dialogues with the base block through an RS422 link. The CPU receives telemetry and can send commands. The structure of the processing unit allows for connecting any peripheral sub-experiment using the same protocol.

The bus interface unit is a MIL 1553 controller. The structure of the 1553 network on SAC-C provides for

GPS time stamps available from other instruments. The CPU gathers the detector and component test data, reads the GPS time on the bus, dates the data packet and sends it on the 1553 bus.

The power conversion unit delivers the secondary voltages (+5V, +/-5V, -12V) necessary for biasing the electronics from a floating 20 to 50 V primary bus voltage. The high voltages used for biasing the particle detectors are generated with a second conversion stage form the +12V line.

The instrument draws a power of 2.5 W (including 1 for the optional component test module), weights 2.4 kg (including 500 g for the optional component test module), and has a size of 71 x 281 x 155 mm.

B. Detectors and acquisition chains

There are three particle detectors tuned for low, medium and high ΔE measurements.

Low ΔE	500 µm Si single mode
Medium ΔE	150 µm Si 6 mm Si/Li coincidence
High ΔE	500 µm Si 500 µm Si coincidence

Five 256 channel spectra are generated (single and coincident). Considering the settings of the thresholds and gains on each acquisition chain, and the ground and flight calibration data, the theoretical expected energy ranges are those summarised below.

Elctrons : 300 keV to 6 MeV
Protons 8 to 30 MeV
Ions 1 to 100 MeV/mg/cm²

The pulses generated through the detectors are pre-amplified, amplified, compared to a threshold, and digitalised using an 8-bit flash ADC. The gains of the pre-amplifier and the amplifier, and the comparison threshold are programmable using telecommands. This versatility provides for adapting the cutoff noise level and allows to easily tune the detection window during calibration and in-flight operations.

The signals from the five detectors are processed through simple logic for generating the coincident spectra. The resulting five channels are :

- channel “E” (“electrons”) : direct signal from the 500 µm low DE detector
- channel “Ps” (“proton single”) : direct signal from the 150 µm medium DE detector
- channel “Pc” (“proton coincidence”) : direct signal from the 6 mm medium DE detector but conditioned to a coincident pulse on the 150 µm medium DE detector within a 1 µs window
- channel “Is” (“ion single”) : direct signal from the first 500 µm high DE detector
- channel “Ic” (“ion concidence”) : direct signal from the second 500 µm high DE detector but conditioned to a coincident pulse on the first 500 µm high DE detector within a 1 µs window

The resulting signals in the five channels are then processed through :

- a digitalisation using a flash 8-bit A/D converter allowing for a maximum conversion rate of 300000 counts / s
- a global counting of all counts above the threshold using five rapid counters allowing for a maximum count rate of 1 million counts / s

The five digitalised spectra are then converted into histograms over the acquisition period using an Actel 1280 FPGA. The resulting functions implemented for each of the five channels are :

- a 256 linear channels pulse height multi-channel analyser
- a rapid counter of the total number of counts over the acquisition period

The acquisition period or cycle can be set from 4 s to 512 s using telecommands. The resulting telemetry corresponding to the emission of the five spectra, the content of the rapid counters and ancillary information such as GPS time, temperature from two sensors (one in the core electronics, the other on the detectors), and check list of all the current parameters on the instrument (mode, gains, threshold, acquisition time,…) is sized to 2.4 ko / cycle. The component module emits its results in an asynchronous way either when its buffer is full or at programmable forced dump periods.

C. Functioning modes and telecommands

The instrument is equipped with a buffering capability of 52 acquisition cycles. This allows a minimum data storage autonomy for cases when the satellite bus would not be able to pick up the data packets.

The instrument has three modes :

- idle : the instrument is biased and functioning but no data is emitted on the bus
- normal acquisition mode : this is the nominal mode in which spectra are generated for each acquisition cycle
- sleep mode : the spectra are generated but not emitted on the bus until warning flag values are exceeded.

The warning flag system is composed of a programmable table of parameters which represent each a group of channels. If the sum of counts on at least one group of channels exceeds the pre-set value, the instrument automatically switches from sleep to acquisition mode for a duration of 10 days. In both normal acquisition mode or sleep mode, a binary warning flag signal is set to 1 when warning flag levels are exceeded and presented on a connector pin for possible use by the host spacecraft.

The main telecommands available are :

- mode selection
- acquisition cycle and integration time setting (4 to 512 s)
- voltage bias of each of the five detectors
- pre-amplifier gains, amplifier gains and detection thresholds on each of the five acquisition chains
- dump period of the component test module
- ON/OFF of each detector
- ON/OFF of the component test module

III. The Mission

ICARE flows on the argentine Earth observation satellite SAC-C (730 km, 98°) through a collaboration between CNES and the argentine space agency CONAE. Other participants to the payload are JPL and DSRI (MMP : magnetic mapping payload), and Italy through two GPS devices. NASA and particularly the Goddard Spaceflight Center played a key role in the development and launch phases of the project, SAC-C being basically a collaboration between CONAE and NASA.

SAC-C was launched from Vanderberg Air Force Base with a Boeing Delta-II rocket on 21 November 2000 and inaugurated the first twin Delta-II launch with its prime companion EO-1. EO-1 and SAC-C were very accurately deployed in an Earth observation constellation with Landsat-7 and Terra satellites.

The ICARE telemetry is downloaded to the SAC-C ground station in Cordoba, Argentina, and mirrored and processed at CNES Toulouse. The data are available in near real time, generally the day after the measurements are made.

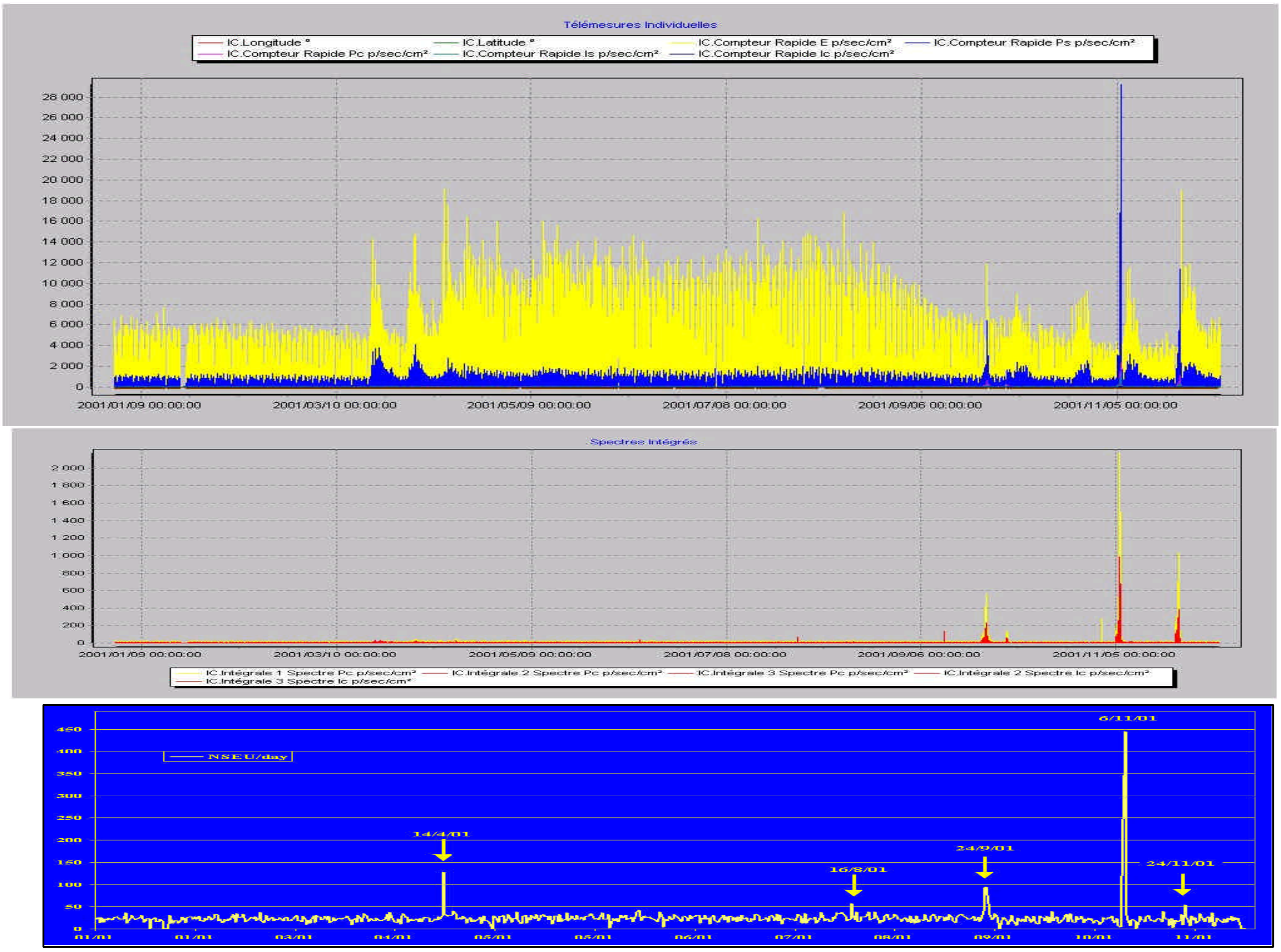

Fig. 2 : total number of counts versus time from 1 January to 10 December 2001. Above, yellow : E, blue : Ps. Middle : yellow : Pc, red : Is, violet : Ic. Below : total number of SEU counts on test devices.

IV. Results from the First Year of Operations

A. Overall results

Figure 2 shows the overall results for year 2001. The active periods of spring and autumn of 2001 are visible on the graphs. It can be noted that the recent solar flares in September and November appear to be have a larger content in high ΔE particles than those that took place at the beginning of April. The shape of the global counts on channels E and Ps show a clear distinction between states in the radiation belts : during all the summer of 2001, the electron fluxes appear to have been much higher as usual (nearly a factor of 2) following the solar particle event and geomagnetic storm of 11 April.

The levels in the proton belt have also risen but this effect is less visible on the graph. A detailed analysis made at ONERA/DESP has shown evidence for an injection and trapping event similar to the one observed by CRRES in 1991. An enhancement of 10 MeV proton fluxes has been observed and is depicted in Figure 3.

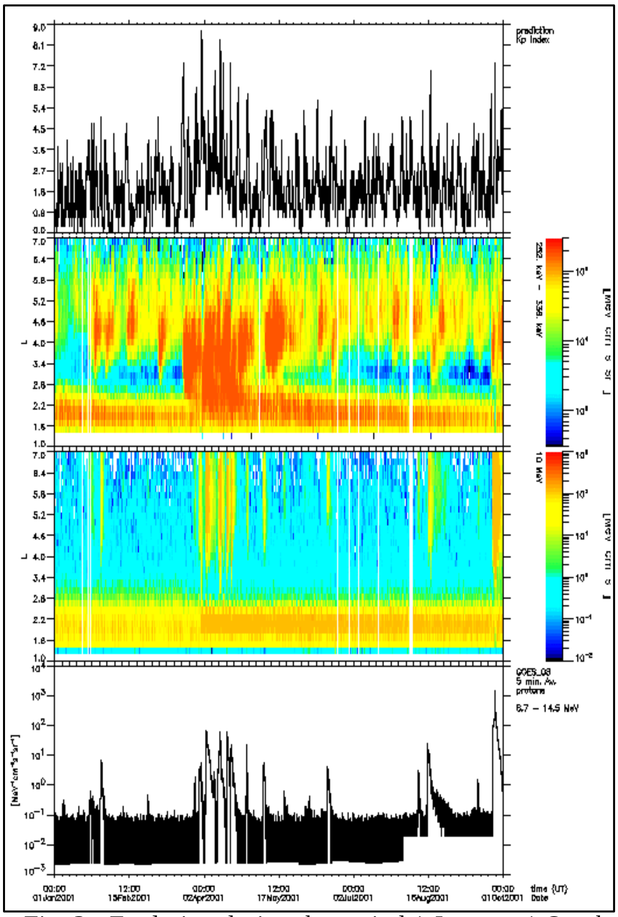

Fig. 3 - Evolution during the period 1 January-1 October 2001 of : top) Kp, 2nd panel) 300keV electrons, 3rd panel) 10MeV protons, bottom) 10MeV protons seen by GOES-8.

The upper panel in Figure 3 shows the planetary magnetic index Kp, which gives a good idea of the magnetic storms influencing the radiation belts. On the second upper panel, we plotted omnidirectional flux of around 300 keV electrons in a L versus time plot. On this panel, we can notice the effects of the magnetic storms in the outer belt region. In particular, the March-April period shows an increase in the inner belt, which is followed by a slow decline.

The third upper panel shows 10 MeV protons. Solar energetic particle events are seen for L greater than 4, giving vertical lines on the plot as solar protons penetrate easily the magnetosphere. Though the 31st March 2001 is not a large solar particle event, it gives the raise to an increase of the 10 MeV proton belt in the L= 2-2.4 range, certainly because it was associated with a very intense storm (Kp = 9).

The bottom panel shows the 10 MeV solar protons as seen by the NOAA/GOES-8 geosynchronous satellite for comparison. After the March 2001 event, the 10 MeV proton radiation belt was modified as it can also be seen on the mappings in Figure 4.

A similar event was observed on board the CRRES satellite after the March 1991 event [3].

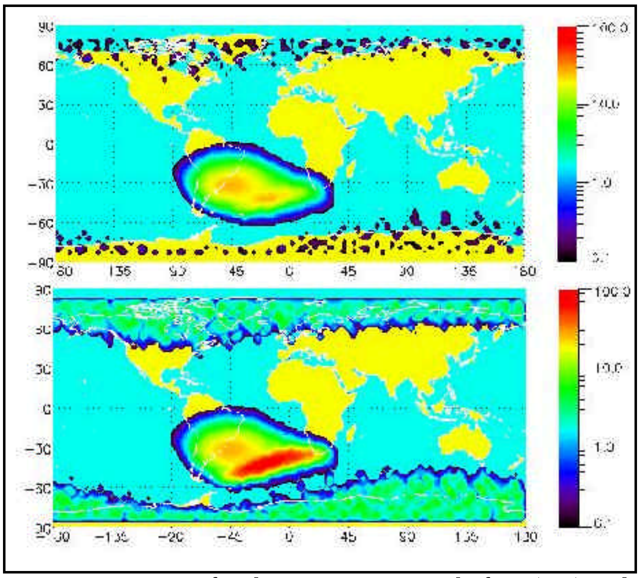

Fig. 4 - Mappings for the 10 MeV proton before (top) and after (bottom) the 31st March 2001 event.

B. Effects on electronic components

However, the exposure time is still too short and no drift has been observed to date.

The basic design of the component experiment sub-system was derived from the previously used EXEQ design [1]. Evolutions from EXEQ include changing of the core microprocessor to an ADSP2101 signal processor, changing and increasing the number of memory types under test, using some memories assembled in 3D stacks (KM44V16004), and adding a parametric measurement function for testing the total dose offset current, voltage drift of operational amplifiers and stand-by currents.

Memory types range from 1Mbits SRAMs to 64Mbits DRAMs (see Table 1).

All the devices are regular commercial components in plastic packages. Linear circuits tested for dose drift are amplifiers in CMOS (LMC662 from National, MAX492 from Maxim) and bipolar technologies (LM258 from Motorola). For these devices the offset voltage or current, the most sensitive parameters, are monitored. Concerning the memories, the stand-by current of one IBM DRAM and one Samsung SRAM are measured.

The system includes also a self-test function of the ADSP2101 digital signal processor (functionality, registers and internal RAM).

device	function	manufacturer	count
SMJ416400	DRAM 4M4	T.I. (5V)	2
KM44V16004	DRAM 16M4	Samsung/stack (3.3V)	2 x 4
HM5165405	DRAM 16M4	Hitachi (3.3V)	4
0165805	DRAM 8M8	IBM (3.3V)	2
HM628512	SRAM 512K8	Hitachi (5V)	6
KM684000	SRAM 512K8	Samsung (3.3V)	6
HM65656	SRAM 32K8	Temic (5V)	1

Table 1 - Memories on board ICARE.

A total of 18291 events (see Table 2). were recorded on the memories of the equipment from November the 30th 2000 through December the 17th 2001 . Nine errors have been recorded and attributed to the DSP.

Device	SEU count	SEU/day.dev	SEU/day.bit
SMJ416400	1098	1.46	8.7E-08
HM628512	2497	1.10	2.6E-07
0165805	82	0.11	1.6E-09
KM44V16004	3966	1.30	1.9E-08
HM5165405	1296	0.86	5.1E-08
KM684000	9311	4.10	9.7E-07
HM65656	41	0.11	4.1E-07

Table 2 - SEU results per device type

These events are only bit flip errors (statistics presented in table 2). As can be seen, the number of recorded events is homogeneous among the parts from the same type (+10 / -10 %) except for the HM62656 and 0165805 because of the low event counts.

The Samsung 4Mbit SRAM appears to be the most sensitive device. Compared to the Hitachi 4Mbit from the same type and generation, almost four times more events are detected. This trend is also observed when looking at the ground test data. As a matter of fact, the different bias levels for these two devices increases the sensitivity gap between these two devices.

A mapping of the events is presented in Figure 5. Most of the events (almost 80%) occur in the South Anomaly Atlantic (SAA). Considering the time spend in this zone (only 5%), it is obvious that protons are the main contributors to induce events.

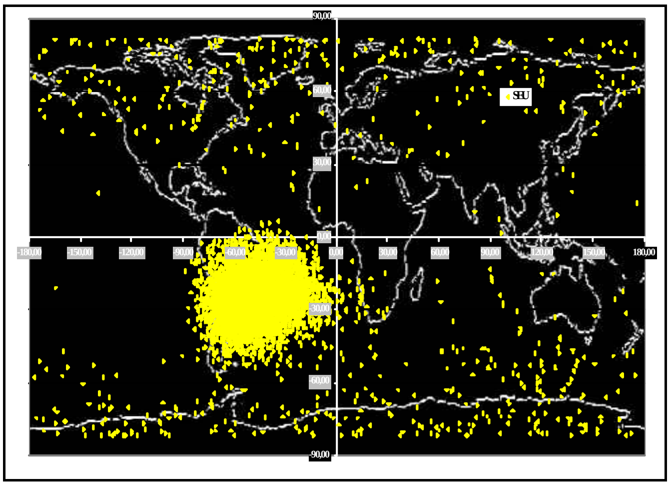

Fig. 5 : Cartography of cumulated upsets on ICARE test board from November 2000 to May 2001 (7416 upsets)

Solar proton events have occurred during the mission and their impact on the SAC-C orbit observed. On Figure 6 is presented the SEU rate per day for the November 2000 - December 2001 period.

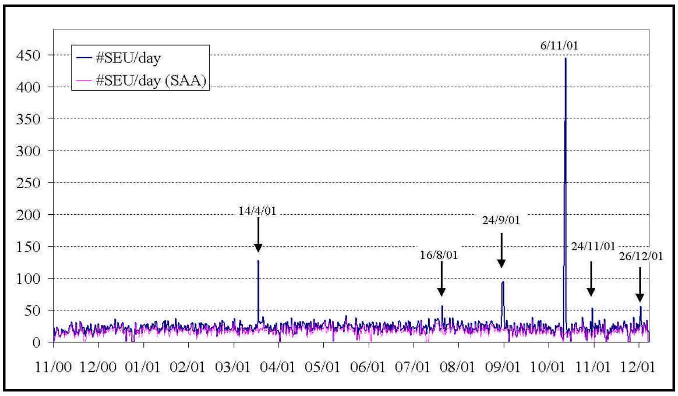

Fig. 6 - Event rate for all parts as a function of time for the November 2000 - December 2001 period.

One can see the strong increase in the event rate correlated to 5 solar events also recorded by the particle detectors.

The "extra" SEU detected during these periods are seen for high latitudes, near the polar zone. The event rate in the SAA remains nearly constant, as illustrated in Figure 7. This figure indicates that the increases in the SEU rates are better correlated with 100 MeV protons than with 10 MeV ones which may not able to penetrate the satellite shielding down to the component level.

The fact that the SEU rate in the SAA remained nearly constant before and after the April event which lead to the apparition of a modification of the 10 MeV proton fluxes suggests also that the fluxes at energies of the order of 100 MeV were not significantly modified on the SAC-C orbit.

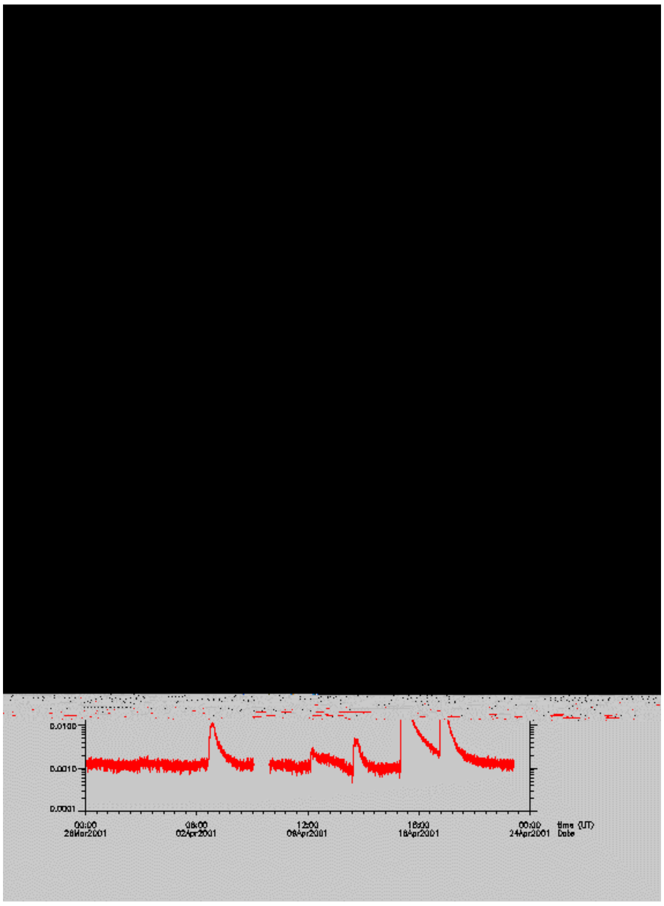

Fig. 7 : 20 March to 20 April 2001. First two upper panels : ICARE : L-time charts comparing 10 MeV proton counts with upsets observed on the memories. Bottom panel : counts on the GOES-8 10 MeV (black) and 100 MeV (red) energy channels.

The interest of SEU measurements, apart from checking risk estimation techniques, is to bring additional information about the environment itself. The ICARE instrument was designed as a trade-off between a reasonably good performance and a small allocation from the host satellite in order to be a candidate for as much missions as possible. The SEU measurements help to extend the investigations to higher energies than the detectors themselves can directly observe.

V. CONCLUSIONS

The ICARE instrument was successfully operated on board the Argentine satellite SAC-C. The effects of many solar and geomagnetic events were observed during the year 2001. A large amount of environment and component effects data has been gathered and is currently processed in full details. Works are still in progress to correlate the proton flux increases, for different energy ranges, with the SEU rate variations. The comparison with other measurements such as GOES measurements in geosynchronous orbit gave much additional perspectives to the interpretations. In this respect, the launch in the end of 2001 of a version of the ESA/ESTEC SREM monitor on the PROBA satellite, placed in an orbit similar to SAC-C, opens the opportunity for widening the field of investigations with two complementary sources of orbital data.

VI. REFERENCES

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