CNES activities related to space weather issues

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Abstract— In the frame of its research and technology program, the CNES (National Centre for Space Studies, France) in close partnership with ONERA (National Office for Studies and Research in Aeronautics, France) and other laboratories and companies, has developed instruments and sponsored studies which have a common interest with the space weather issues and may be considered as a part of the European assets in this field. This paper describes the past and on-going activities and some reflections for future developments in this domain. It also describes some original developments made at ONERA-DESP in which CNES contributed through a long term support.

I. INTRODUCTION

Space weather programs mainly focus on forecasting and nowcasting the orbital environment conditions, main issues are real time or near real time measurement, calculation and interpolation of the characteristics of the space medium. The same assets, instruments, simulation engines, and basic knowledge of the involved physics are needed in the connected field of specification models and risk estimations. A number of activities have been led by CNES and ONERA in this later field. A formal partnership has been set up between the two organisms for close collaboration and joint activities.

This paper describes the existing assets and current status of activities in the fields of flight experiments (radiation monitors, dosimetry, effects on electronic components, micrometeroids) and modelling tools.

II. FLIGHT EXPERIMENTS

A. Radiation environment monitors

The origin of CNES radiation monitors comes from an instrument, the Epic Radiation Monitor (ERM) developed by the CESR (Toulouse, France) as an ancillary instrument for the main X-ray telescope of the ESA XMM mission. The ERM is a monitor devoted to the measurement of ionising particle fluxes, and gives a warning flag that may be used by the prime payload for circumvention measures during the crossing of the radiation belts. CNES sponsored the development by Alcatel Space Industries (ASPI) of the satellite bus interface of the instrument, and a component test board was included in the electronics (see paragraph C.).

The ERM was further on miniaturised in one single box and redesigned by ASPI to fit smaller allocation resources from the carrier satellite. The resulting instrument, COMRAD, will be flown on the French experimental telecommunication satellite STENTOR to be launched in geosynchronous orbit in 2002.

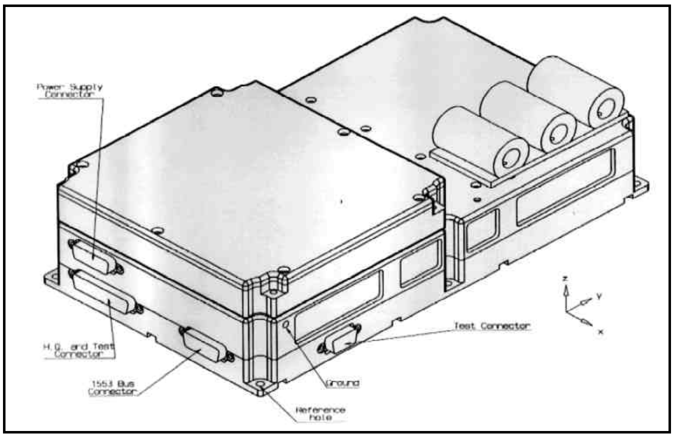

Fig 1 : View of the ICARE instrument.

A third, low cost version based on commercial components, equipped with a new detector head proposed by ONERA-DESP, was developed for the needs of two other missions. The first one was the extension of the collaboration between CNES and RKK ENERGIA (see paragraph C.) and lead to the

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implementation, on the space station MIR, of two monitors one inside, one outside the station, under the experiment name of SPICA. The same version is also flown under the name of ICARE on the argentine satellite SAC-C (730 km, 98°) through a collaboration between CNES and the Argentine Space Agency CONAE. An improved version of SPICA (see B. and C.) is currently flown on the International Space Station under the name of SPICA-S and as a part of a collaboration with RKK ENERGIA on their technology pallet SCORPION.

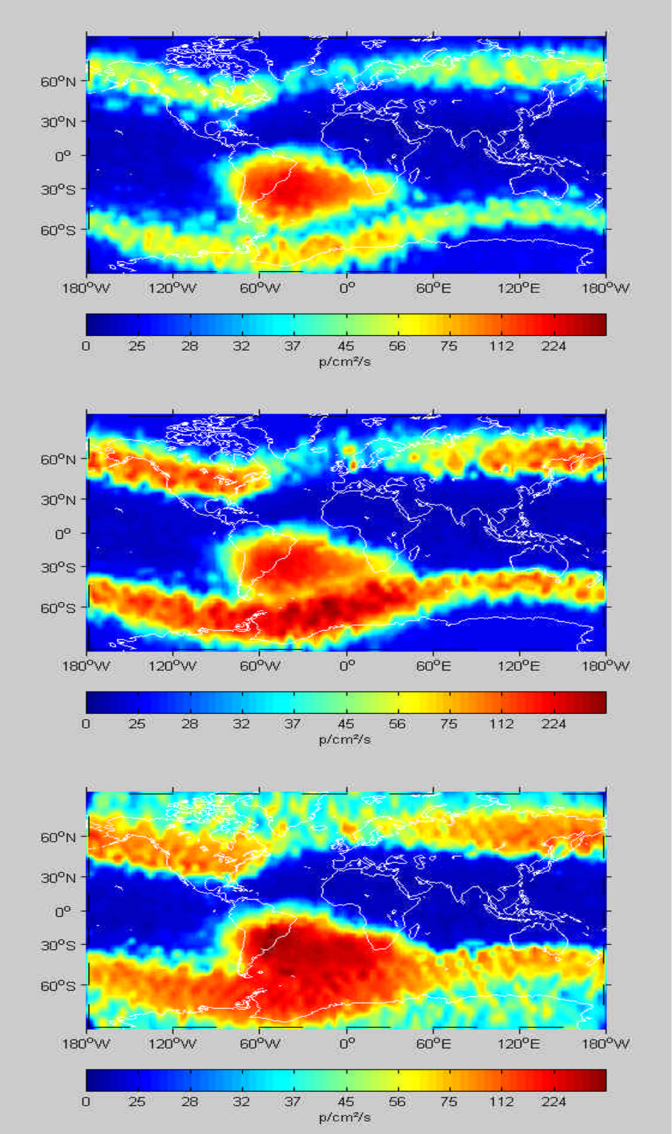

Fig 2 : ICARE, sum of all channels on the low ΔE detector (electrons and protons). From top to bottom : quiet situation on 15 march 2001, magnetic storm effects on 25 march, and solar proton event effects on 11 april.

The characteristics of the various detectors are summarised in Table 1. 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 corresponding theoretical expected energy ranges are :
Electrons : 300 keV to 6 MeV
Protons 8 to 30 MeV
Ions 1 to 100 MeV/mg/cm²

Instrument	Low ΔE	Medium ΔE	High ΔE
COMRAD	500 µm Si single mode	500 µm Si 500 µm Si coincidence	500 µm Si 500 µm Si coincidence
ICARE	500 µm Si single mode	150 µm Si 6 mm Si/Li coincidence	500 µm Si 500 µm Si coincidence
SPICA	500 µm Si single mode	150 µm Si 6 mm Si/Li coincidence	500 µm Si 500 µm Si coincidence
SPICA-S	500 µm Si single mode	150 µm Si 6 mm Si/Li coincidence	500 µm Si 500 µm Si coincidence

Table 1 : Characteristics of the detectors

As an example of results, Figure 2 depicts geographical graphs of the low ΔE detector counts for three conditions in spring 2001 as seen by ICARE in polar orbit.

Figures 3 and 4 are summary charts showing the time frames of the missions and the positions of the orbits for the experiments described in paragraphs A, B, C.

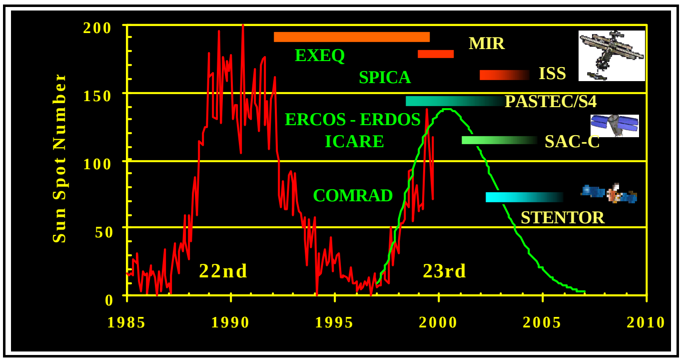

Fig 3 : History of main missions from § A. B. and C.

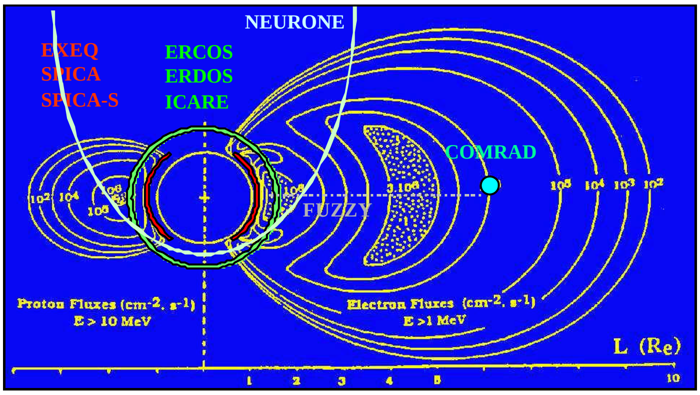

Fig 4 : Orbits (indicative) of main missions from § A. B. and C.

B. Dosimetry

Two experiments, ERDOS and SPICA-S, include active dosimeters. ERDOS is part of the technology payload (PASTEC) of the French Earth observation satellite SPOT-4. The dosimeters used were five RadFETs from the LAAS laboratory (France) cased in five different shielding thickness. SPICA-S is equipped with second generation LAAS (France) RadFETs, NMRC (Ireland) RadFET dosimeters provided by ESTEC through a collaboration with CNES on SPICA-S, and novel optically stimulated luminescence (OSL) dosimeters from the University of Montpellier (France).

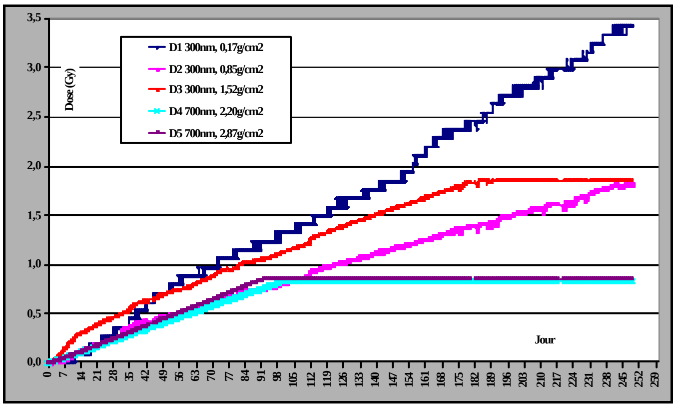

Fig 5 : ERDOS dosimetry results, polar orbit.

The OSL dosimeters have been developed for years in Montpellier and adapted to dose measurement in space with CNES sponsorship. The luminescent materials provide for a wide measurement dynamics (from 0.01 to 1 Mrad). The dosimeter is read by a photodiode, and is erasable using a light emitting diode. This system provides a non-saturating dosimeter usable in a wide range of orbital conditions.

C. Effects on electronic components

A number of experiments have been flown for assessing the actual upset rate observed in a space on a variety of memory and microprocessor devices from various origins and technologies, including commercial circuits. These experiments are ERCOS-II, EXEQ I to IV, MPTB, STRV, EVALCOMP, ICARE, COMRAD, SPICA, SPICA-S which are described below.

The latest experiments, ICARE, COMRAD, SPICA, SPICA-S include also the measurement of parametric drifts of some components (a DRAM and CMOS, bipolar and BiCMOS operational amplifiers). For the missions already in orbit (ICARE, SPICA, SPICA-S) the exposure time has been, or is still, too short and no drift has been observed to date.

ERCOS-II is part of SPOT-4 technology payload and flies on an heliosynchronous orbit (800 km, 98°) since 1Q 1998. It is a follow-on of ERCOS-I that was flown on MIR during one week in 1988. ERCOS-II is made of 11 1-Mbit Micron SRAMs. The figure below gives an overview in the L-time space of the upset counts for year 2000. The major solar event of 14 July 2000 is clearly visible on the graphic. These results have not been published yet.

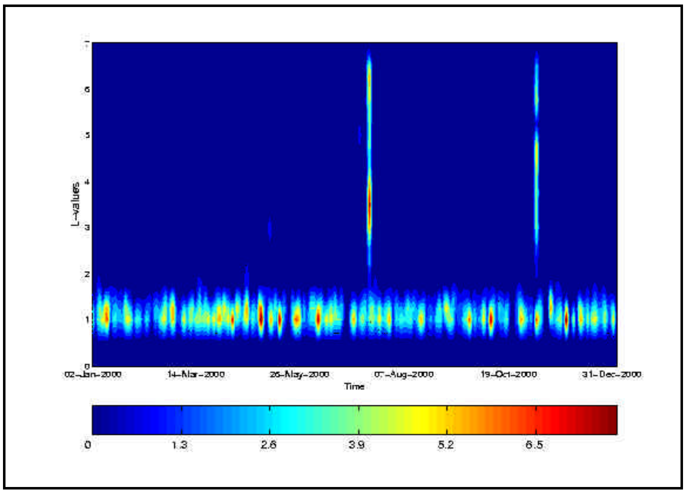

Fig 6 : L, time representation of ERCOS-II upsets for year 2000. July and November 2000 events are visible.

EXEQ I to IV is a series of experiments developed by ONERA-DESP with CNES sponsorship, and have been operated from 1992 to 2000 on the MIR space station through a long term collaboration with RKK ENERGIA (Russia). It consisted of a test bench left on the station, and a modular component test board that was changed four times during the lifetime of the experiments. SRAMs from 256 kbit to 4 Mbit and DRAMs from 16 to 64 Mbit have been monitored. An example of the results is shown in the figure below.

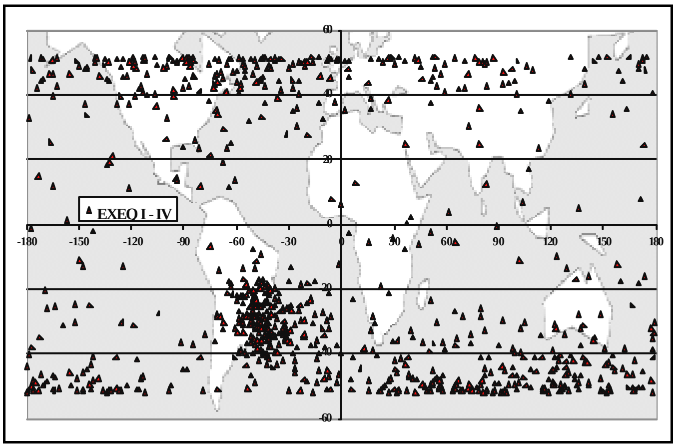

Fig 7 : Geographical representation of EXEQ-I to IV cumulated upsets.

Experiment	ERDOS	ERCOS	EXEQ 1-4	NEURONE	FUZZY	SPICA	ICARE	SPICA-S	COMRAD
Carrier	SPOT-4	SPOT-4	MIR	MPTB	STRV 1d	MIR	SAC-C	ISS	STENTOR
Orbit	SSO	SSO	LEO	HEO	GTO	LEO	SSO	LEO	GEO
Spectra						X	X	X	X
Dosimetry	X							X	
Dose drifts						X	X	X	X
Single events		1 M	256 k 16 M	256 k	256 k	4 M 64 M	4 M 64 M	4 M 64 M	4 M 64 M
System		micro controller	micro processor	artificial neural network	fuzzy controller	signal processor	signal processor	signal processor	signal processor

Table 2 : Summary table for environment and component effects flight experiments

A contribution in the American MPTB payload (Microelectronics and Photonics Test Bed) was also made through a collaboration between CNES and NRL, with the TIMA laboratory as a principal investigator and ONERA-DESP and CEA as a co-Is. Two “NEURONE” boards are flown on MPTB. These boards implement a process of SPOT image recognition developed by CEA along with upset rate measurements on two SRAM memory types. MPTB orbit is highly elliptical, it crosses the radiation belts and reaches zones far out of the magnetosphere. Amazingly, the artificial neural networks, tuned for a given level of performance in image recognition, exhibited an improvement in recognition efficiency after the solar event of 14 July 2000. Examples of upset counts in the L, time space for the two SRAMs are showed in the figure below for the period of the event of July 2000.

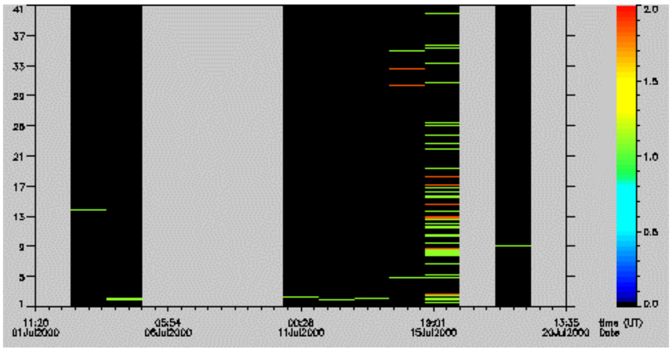

Fig 8 : L, time representation of MPTB SRAM upsets for the days before and after the 14 July 2000 solar flare.

The same CNES – TIMA – DESP collaboration was implemented again through a CNES – NASA/GSFC collaboration on the ETB (Electronics Test Bed) on STRV 1c/d. The principle of the “FUZZY” boards was the same as the NEURONE board, except that the processor was now a fuzzy controller and the application a Mars robot piloting program developed in fuzzy logic by the Max Planck Institute (Germany). Due to the failure of STRV 1c/d in its early days in orbit, no result could be drawn from this experiment.

The EVALCOMP test board (8 16-Mbit Texas Instruments DRAMs) was developed by ASPI under CNES sponsorship and included as a secondary payload in the XMM Epic Radiation Monitor (ERM). Due to some operating problems with the main instruments, the board has been temporarily shut down but can be now reactivated again.

The COMRAD, ICARE, SPICA and SPICA-S all include a component test board derived from the principles developed originally for EXEQ. The boards slightly differ in the composition of the devices tested. Missions and orbits for these instruments have been described in paragraph A. The board on SPICA-S includes Hitachi SRAMs provided by ESA/ESTEC.

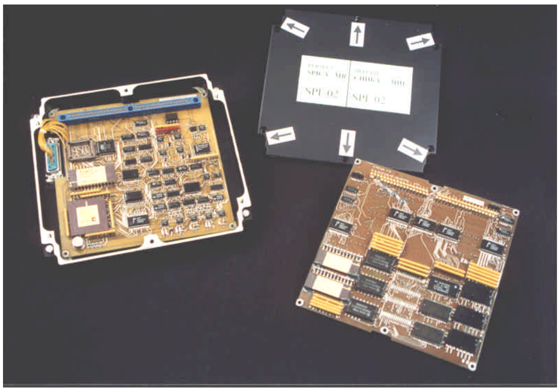

Fig 9 : standard component test board

The figures below show some results from the ICARE mission.

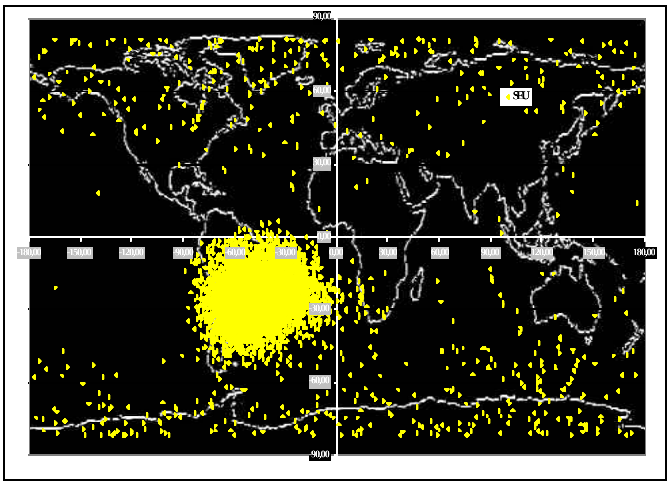

Fig 10 : Cartography of cumulated upsets on ICARE test board from November 2000 to May 2001 (7416 upsets)

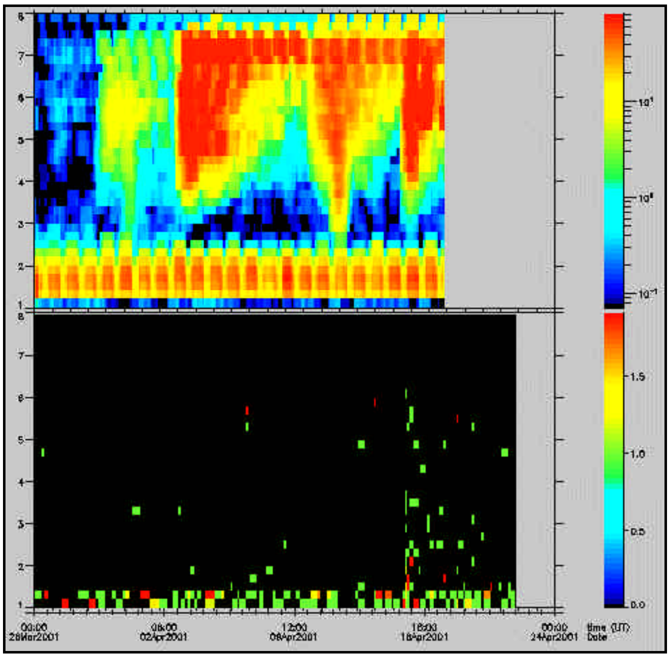

Fig 11 : ICARE : L-time charts comparing 10 MeV proton counts with upsets observed on the memories.

Apart from these dedicated experiments, upset rates on operational satellites or equipment have been monitored. The data from the on board computer memory and mass memory of the CNES experimental satellite S80/T have been extensively studied through a collaboration with the University of Surrey (United Kingdom) during the 90's. S80/T is based on a UoSAT platform and orbits the Earth on the same orbit as TOPEX/POSEIDON (1300 km, 66°).

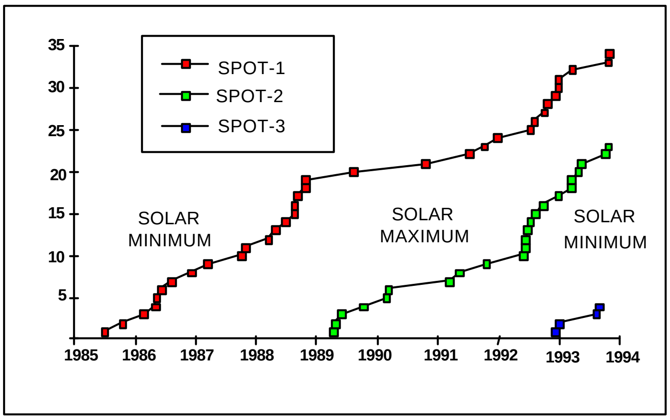

Fig 12 : Number of upsets versus time for the SPOT-1,2,3 on-board computer memories (period 1986 – 1994). These memories are only sensitive to heavy ions (LET threshold 40 MeV mg-1 cm²)

Data from the on board computers of SPOT 1, 2 and 3 satellites have also been recorded and interpreted since 1986. Other instruments such as the are also used as alternative sources for upset data. The figure above shows the upset rate on SPOT OBCs from 1986 to 1994. The memories used being only heavy-ion sensitive, the variation in upset rates is attributed to the modulation of cosmic rays intensity along the solar cycle.

D. Micrometeroids and debris

Meteroids and spacecraft debris smaller than 1 mm represents a non-negligible risk for orbiting vehicles due to their kinetic energy. This small size objects cannot be observed using ground-based classical radar or optical devices.

1-Passive detectors

Knowledge of the space "debris" environment can be deduced from observing material which has stayed in space. Observation of the number and the size of impacts provides information on the particle flux. Furthermore, analysis of the residue inside the craters makes it possible in certain cases to determine the origin of the incident particle. CNES participated in analyzing the thermal blankets from the FRECOPA trays and clamp parts on LDEF (Long Duration Exposure Facility). Other appraisals were done on the solar panel of the Hubble Space Telescope which was brought back to Earth.

In the same line of thought, sensors have been designed to trap the incident particles. Blocks of absorbent materials are made from aerogel (silica gel) or from stacking thin aluminum sheets (mutilayer). These systems trap particles of a size less than approximately 500 µm. Cartridges like the one shown on the next figure were on-board LDEF and the MIR station. Similar experiments are foreseen by CNES on ISS.

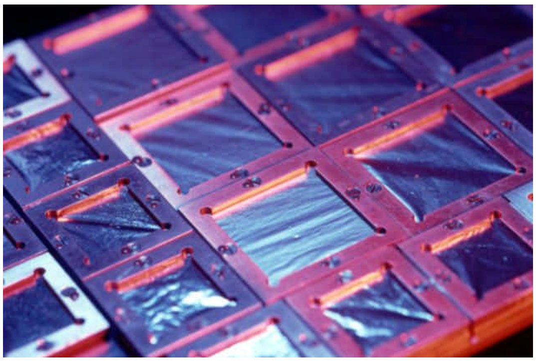

Fig 13 : Cartridges of passive detectors

2-MOS sensors

The MOS sensors are based upon the monitoring of the discharge of a parallel-plate capacitor using a thin dielectric. When a high velocity particle impacts the exposed plate with enough energy, it can cause the dielectric to breakdown and results in a discharge of the capacitor. The event is measured by monitoring the shape of the discharge. After discharge, the sensor is recharged to the nominal value within a short time. The device is best suited to the detection of particles with diameter ranging from 0.5 µm to 100 µm. One example is shown on the next figure.

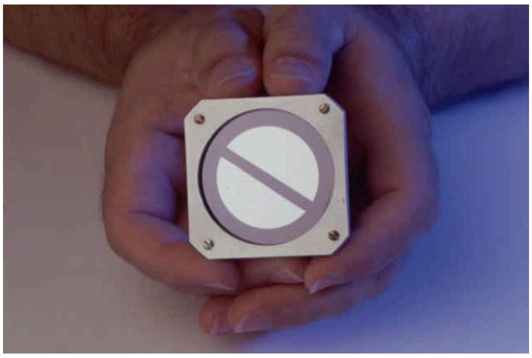

Fig 14 : MOS active micrometeroid and debris sensor

Prototypes were developed and tested. The engineering model has been manufactured (2000) and 4 flight models will be produced in 2001 for in-flight experiments on FBM (Franco-Brazilian Micro satellite) to be launched in 2002 and on the ISS (International Space Station) in 2003.

However these sensors are not able to measure simultaneously the mass and velocity of the particles. This can be solved by coupling a MOS sensor with a PVDF one.

3-PVDF sensors

These sensors use the electrical properties of PVDF (polyvinidylene fluoride) film.

The PVDF film is electrically polarized permanently when manufactured and does not require an external source of polarization. Local depolarization occurs when impacted by a particle moving at high speed. These sensors provide only an information on the date of impacts.

Therefore a PVDF film is generally coupled with a MOS sensor or another PVDF film.

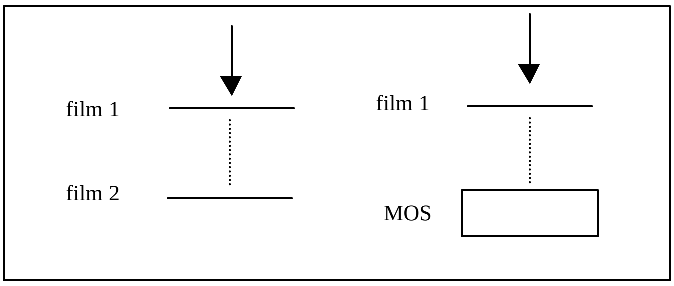

Fig 15 : arrangement of PVDF and MOS sensors

A laboratory prototype sensor was produced. A flight experiment (MOS+PVDF) is envisaged on the third French microsatellite (PICARD), scheduled for launching in 2005.

4-Optical detectors

Orbital debris of a size between 0.1 mm and 10 cm are difficult to detect from a satellite.

Two major families of instruments may be suitable:

- passive instruments using the radiation emitted or diffused by the object and which detect a flux, observe a shape and deduce the equivalent surface, a distance, a speed. These instruments provide good space coverage making it possible to determine the shape and locate the target. Moreover, as they are passive, these instruments are often less bulky and require less power than active instruments.

- active instruments transmitting a coded light source to the target. This source illuminates the target and makes it possible to measure the shape, distance and speed. Active instruments are suitable for distance measurement (telemetry). However, their range varies from $1/d^3$ to $1/d^4$ (d = distance from the target to the satellite)

Preliminary results show that:

- Detection of orbital debris on a mini-satellite (even a microsatellite) is feasible, as far as a reasonable mass, consumption and interface is concerned (with regard to this, an arbitrary mass less than 40 kg and a 35 W consumption was set).
- The passive instrument corresponds better to our requirements (detect and characterize the maximum number of events). Thus, one expects to detect between 10 and 100 « small debris », size less than 1 mm per year and several hundred large objects (between 1 and 10 mm).

E. Future possibilities

One interesting possibility for the future would be to try to define a basic European "kit" for space weather related instruments. This kit would list the existing assets among the European partners in this field, and try to define various options adapted to the resources available on board the satellite along with possible improvement of the instruments themselves and the definition of a semi-standard and modular data collection and bus interface unit.

In the frame of the Galileo Engineering Model (GEM) study made by CNES to ESA for the GSTB-V2 program, proposition was made to consider for the payload both SREM and ICARE monitors. The goal is to characterise the poorly known and extremely variable MEO environment and provide a common measurement point for cross-calibration of the two complementary instruments.

III. TOOLS AND MODELS

A. Empirical models

A number of works have been performed for trying to build semi-empirical engineering models based on the interpretation of existing orbital measurement. These works have started years ago at ONERA-DESP and are supported and partly sponsored by CNES. To date, the following fields have been studied :

- construction of a semi-empirical model of electron fluxes for geosynchronous orbits based on a set of 15 year measurements from 4 geosynchronous satellites from the Los Alamos National Laboratories (USA), through a collaboration between ONERA and the later institute. This is a statistical model, and the orbital data provide an empirical description at energies up to 2 MeV. The corresponding fluxes are much lower, in this range, than the fluxes estimated using AE8. The longitudinal dependence of electron fluxes described by AE8 is not seen in the flight data and accordingly, does not appear in this model.
- extension of this model to energies up to 7 MeV using AE8 spectral shapes and derivation of an engineering model usable by design engineers.
- on-going construction of an outer belt electron model using data from GEO and GPS satellites.

B. Radiation belts dynamic simulation engine

These works are based on the development of a family of radiation belts models, the Salammbô 3D and 4D codes. They have also started years ago at DESP and are partly supported by CNES. In its last version, Salammbô is a 3D simulation (2D space and time) of particle transport in the magnetosphere. These tools have extensively been used for simulating the earth's radiation belts. They have also been applied to the simulation and understanding of the electron belts of Jupiter.

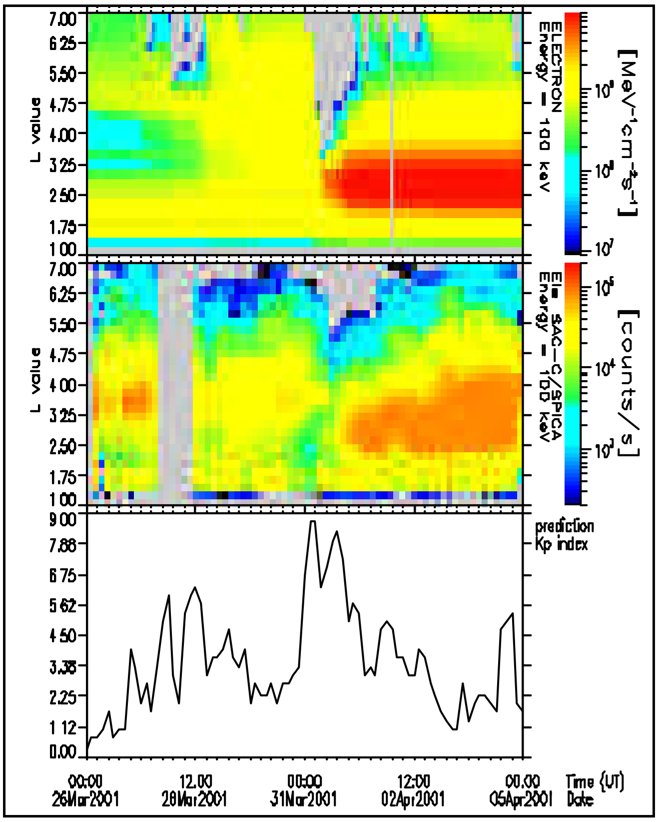

Fig 16 : Comparison between ICARE results and Salammbô simulations for the period 26 March – 5 April 2001. From top to bottom : ICARE measurements, Salammbô simulation, Kp indices versus time.

Salammbô can be used as a nowcasting and forecasting engine for predicting the conditions at any location in the magnetosphere from the input of actual measurements, and thus is a first embryo of a space weather prediction model for conditions in the magnetosphere. These same models can be used for calculating average and worst case conditions for periods of time in the order of magnitude of the duration of a space mission, and can consequently be used for deriving engineering models for satellite specification and design.

Possible future applications of the Salammbô models can be to optimise the definition of a radiation belt mapping constellation by determining the minimum set of measurements, satellites and orbits necessary to achieve a complete description of the radiation belt fluxes, the remaining space – time intervals being interpolated using the model.

C. Calibrating the instruments

The sources used for calibrating the instruments were Am241 (alpha particles) and Cf252 sources (alpha particles, fission ions) and 2 MV proton and electron Van de Graaf accelerator at DESP, the joint CNES – DESP heavy ion beam line at IPN (Orsay, France), and the proton accelerators of UCL (Louvain la Neuve, Belgium) and PSI (Villigen, Switzerland). The GEANT-4 code was used by DESP for determining the detection matrix (ΔE versus channel number) of the detectors.

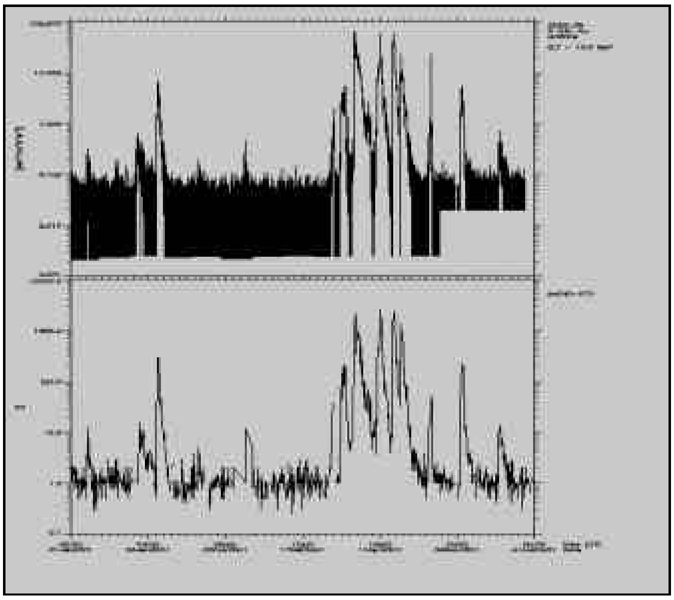

Fig 17 : Comparison between GOES-8 proton counts in channel 6.7-14.5 MeV at L=6 and ICARE results for L between 5 and 7 in channels 40 to 70 of the Ps spectrum

DESP also used the data available from well calibrated detectors such as GOES and LANL instruments, for a flight cross-calibration that results in a fine tuning of the energy channels. The figure below shows a comparison between proton flux variations measured by GOES –8 (L = 6) in the 6.7-14.5 MeV channel, and ICARE flux variations for L values between 5 and 7, and for channels 40 to 70 of the "proton single" (Ps, 150 µm Si) detector.

IV. CONCLUSIONS

A variety of instruments and flight experiments have been developed in various fields connected with the space weather concerns. These experiments can contribute to the study of the space environment and its variability, and also to a better assessment of the effects of the conditions in space on technological devices. As far as usability of technology in space and spacecraft safe operation are considered, the later aspect of the experiments can provide quantified flight figures. Modelling and data analysis studies have been also undertaken to contribute in developing the knowledge and tools necessary for a scientific understanding of the environment phenomena and effects in question.

The last decades of the 20th century have experienced a dramatic evolution in the microelectronics technologies which are now far deep in the submicronic domain. This is an unprecedented fact in the history of techniques, and we may consider that electronics are still in a state of fast evolution, far away from a situation of equilibrium. These technologies have demonstrated without any doubt they sensitivity to space radiation and space weather conditions. Most of the space systems designed in the 90's with these technologies will still be in they orbital life during the next solar cycle. The trend toward new and smaller devices may still continue for some years to an unknown extent. Whether the situation will become critical or not for future systems is still open. In this context, it is very important to secure environment monitoring and continue to observe the behaviour of new technologies in space.