CENTRE NATIONAL D'ÉTUDES SPATIALES

In-orbit anomalies due to radiation. Lessons learnt

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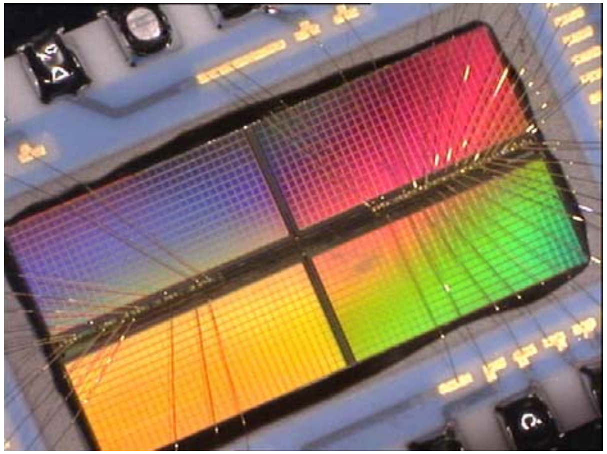
Technical context

- **A problem which is** specific **to space applications**
- **A** major **dimensioning** constraint **for on-board systems**
- **Very** fast evolution **of electronic technologies**

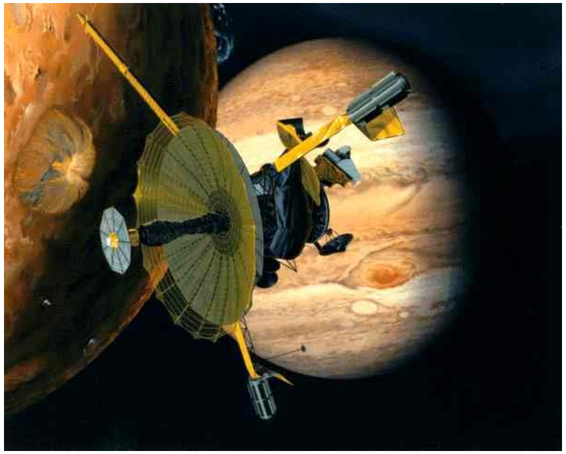
- **Performance often leads to** cutting edge **designs**
- **A strong economic drive toward** margin reductions
- **More** exposed **missions**
- **Smaller satellites (less shielding)**



Dimensions : 0.1 µm²
(or 0.3 µm x 0.3 µm)
for a 1-Gbit DRAM cell

Time : 1 ps
for a 1-GHz processor

Charge : 1 µV
for a 22-bit ADC

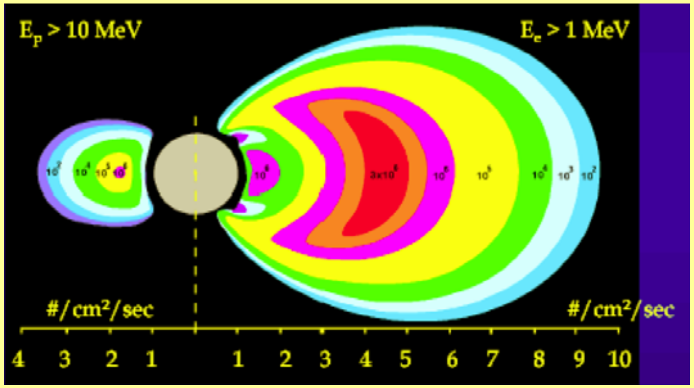


256 Mbit SDRAM : more transistors in a single chip than in a whole 1980's spacecraft designs

(GALILEO Jupiter probe for example)

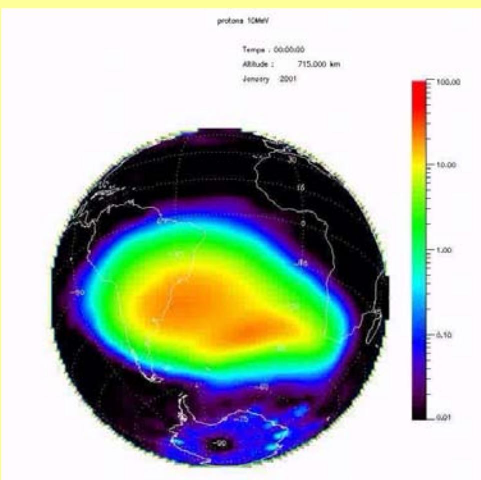
Space environment radiation sources

Radiation belts

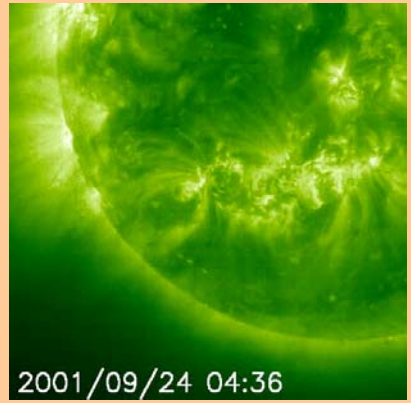


Protons | **Electrons**

keV- 500 MeV | eV ~ 10 MeV

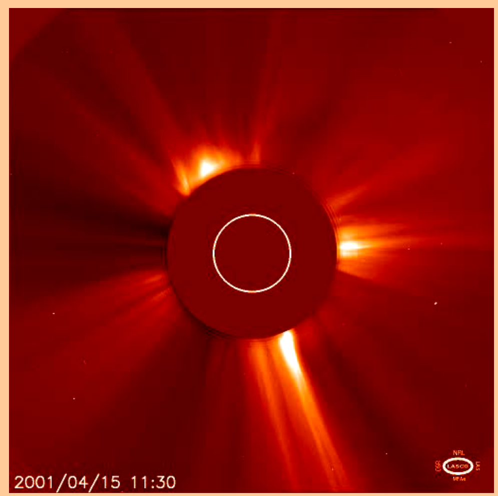


Solar flares



Protons | **Ions**

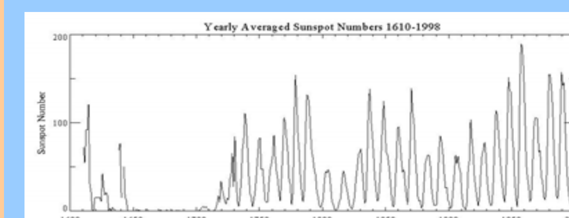
keV- 500 MeV | few 1-10 MeV/n

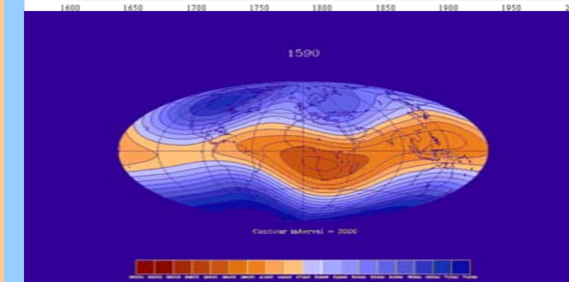


Cosmic rays

Ions

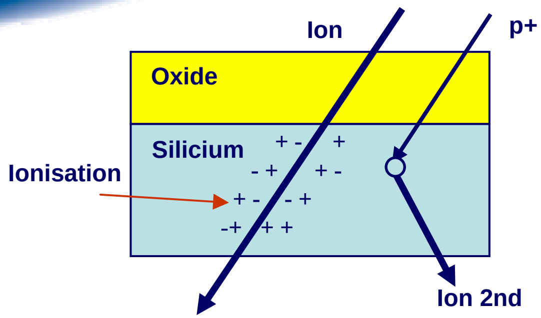
max ~ MeV/n

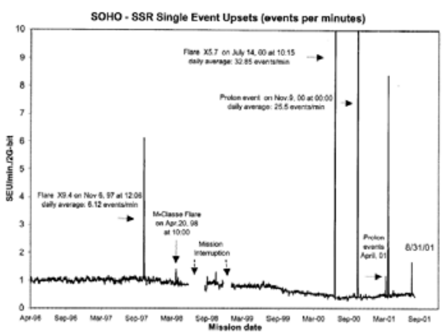


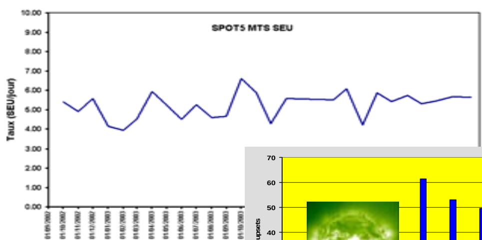


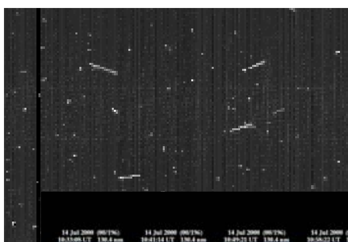
Main types of radiation effects

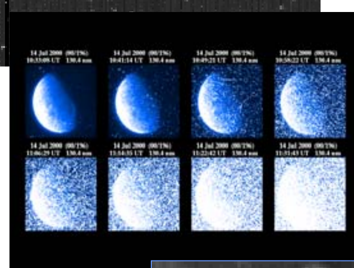
Single event effects

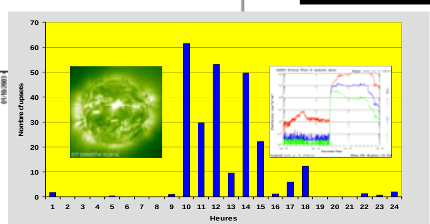


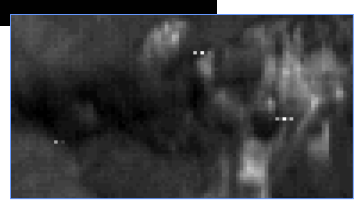




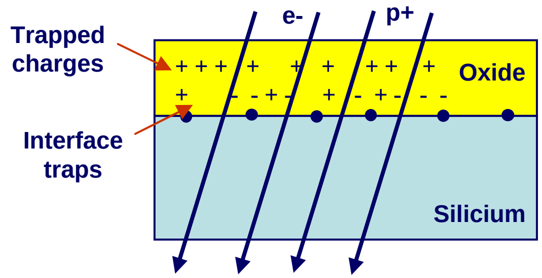


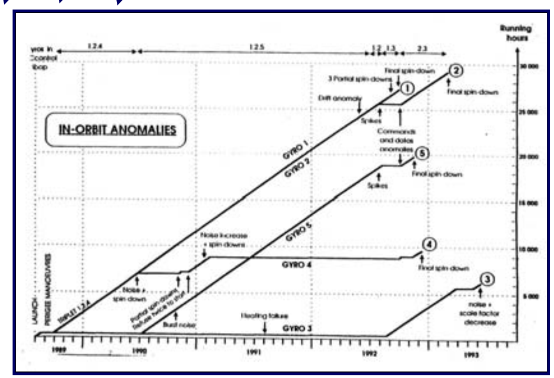


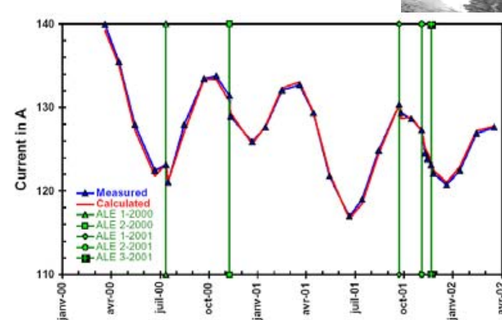




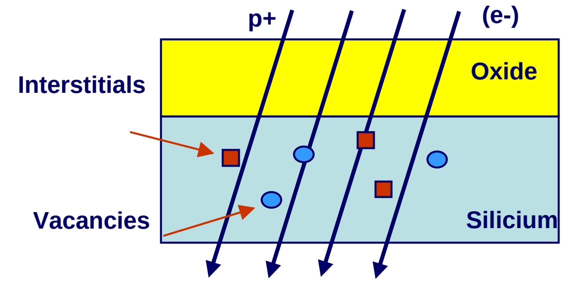
Ionising dose

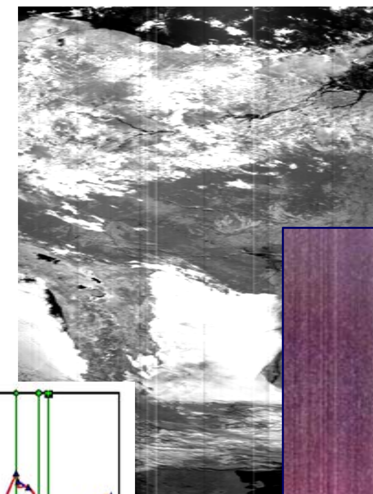


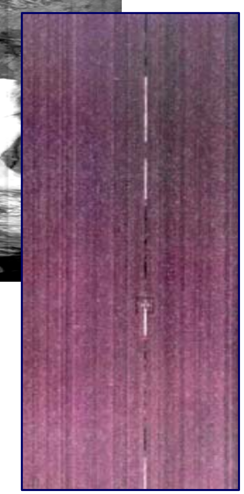




Atomic displacement







Known (to the author) system effects

Electrical Architecture (Generic) **- Equipment loss** **- Self switch-off, disjunction, reset, reboot, redundancy swapping**	**Dose, Latch-up (SEL)** **SET**
On-board energy **- Solar panel degradation**	**Dose, Displacements**
Attitude and orbit control system **-Possible attitude loss** **-Star tracker out of loop** **-Inertia wheels disturbances** **-Switch off ion thruster**	**SEU** **Proton transients (SAA, flares)** **SET** **SET**
On board management **-Disturbances of on board computer, resets, mode refusal, safe-hold mode** **-Mass memory**	**SEU**
Imaging systems **-« UFOs »** **-Hot pixels, RTS** **-Dark current, non linearity,… etc**	**Proton transients** **Displacements** **Displacements, dose**
Time references **- Frequency jumps**	**Dose on SAA passes or flares**

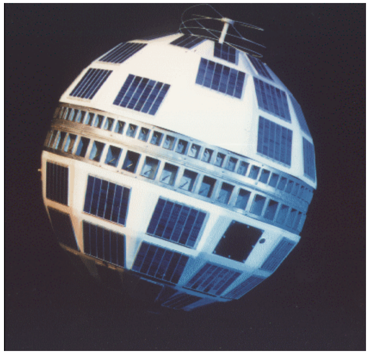
Cumulated effects

- Few records, evidenced in degraded mission cases, harsh planetary environments, or ultra-sensitive systems

- Artificial radiation belts
- HIPPARCOS
- The GALILEO probe at JUPITER
- Ultra sensitive systems

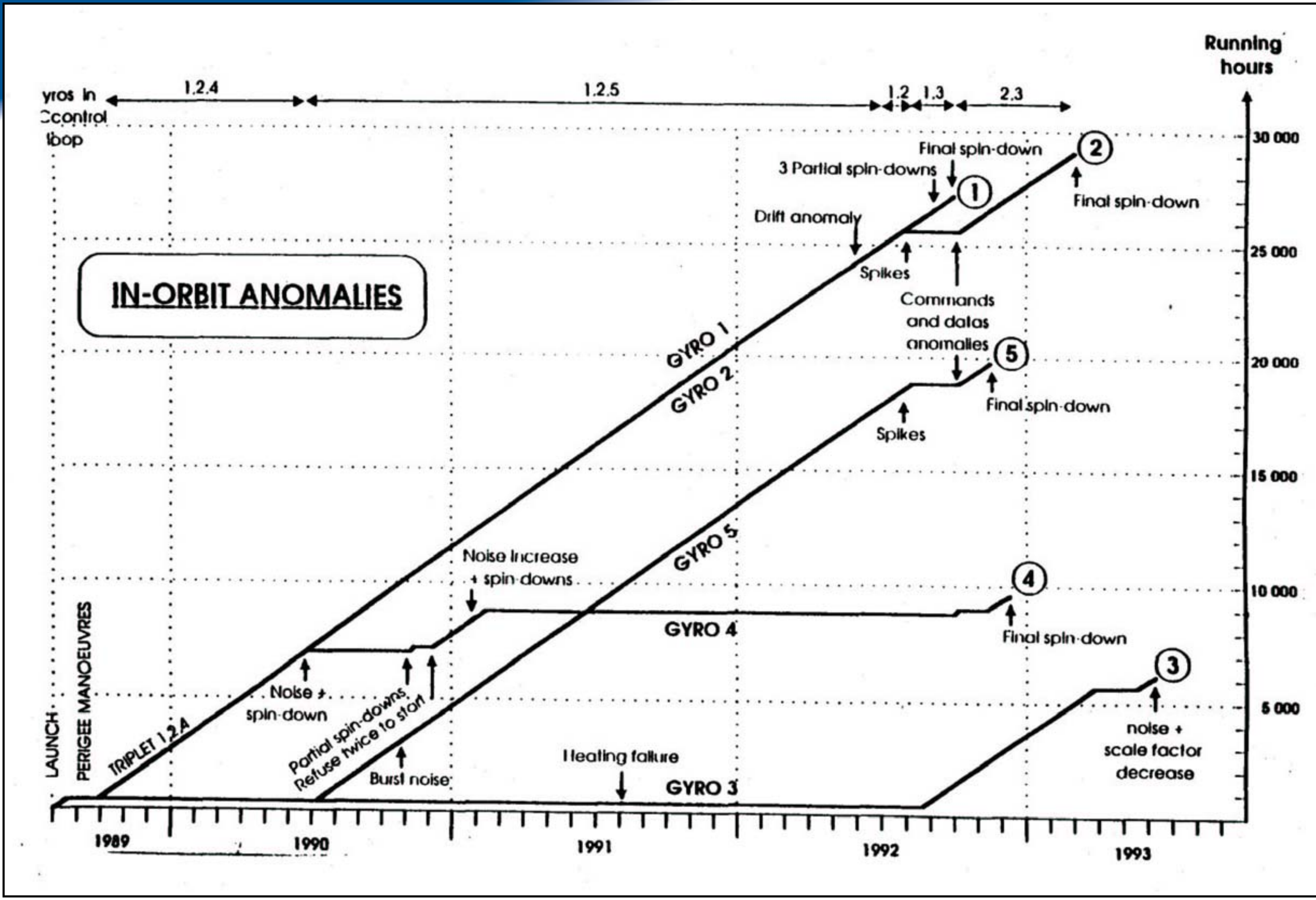
Artificial radiation belts

- 9 July 1962 : Starfish nuclear experiment
- 10 July 1962 : launch of TELSTAR-1
- 21 Feb 1963 : TELSTAR loss (diode)
- 7 satellites lost in 7 months



Explosion	Location	Date	Yield	Altitude km	Nation
Argus I	South Atlantic	8-27-58	1 kt	~200	USA
Argus II	South Atlantic	8-30-58	1 kt	~250	USA
Argus III	South Atlantic	9-6-58	1 kt	~500	USA
Argus III	South Atlantic	9-6-58	1 kt	~500	USA
Starfish	Johnson Island (Pacific)	7-9-62	1 Mt	~400	USA
?	Siberia	10-22-62	? 100s of kilotons	?	USSR
?	Siberia	10-28-62	submegaton	?	USSR
?	Siberia	11-1-62	megaton	?	USSR

HIPPARCOS



GYROSCOPES

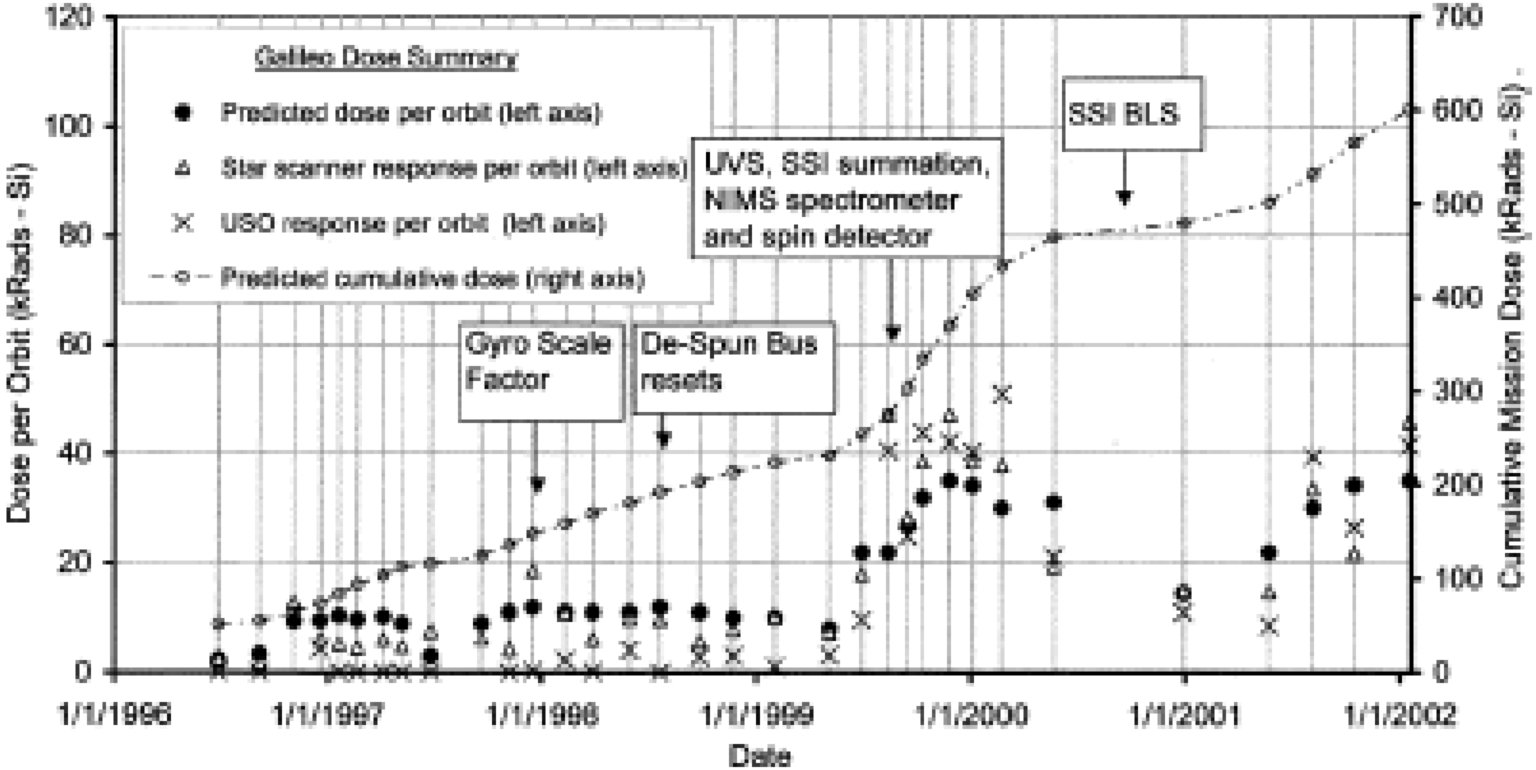
Both nominal and redundant units failed successively

Attributed to TID degradation of bipolar PROMs and optocouplers

Nominal mission lifetime exceeded in more aggressive orbit.

GALILEO probe at JUPITER

■ Timeline of effects



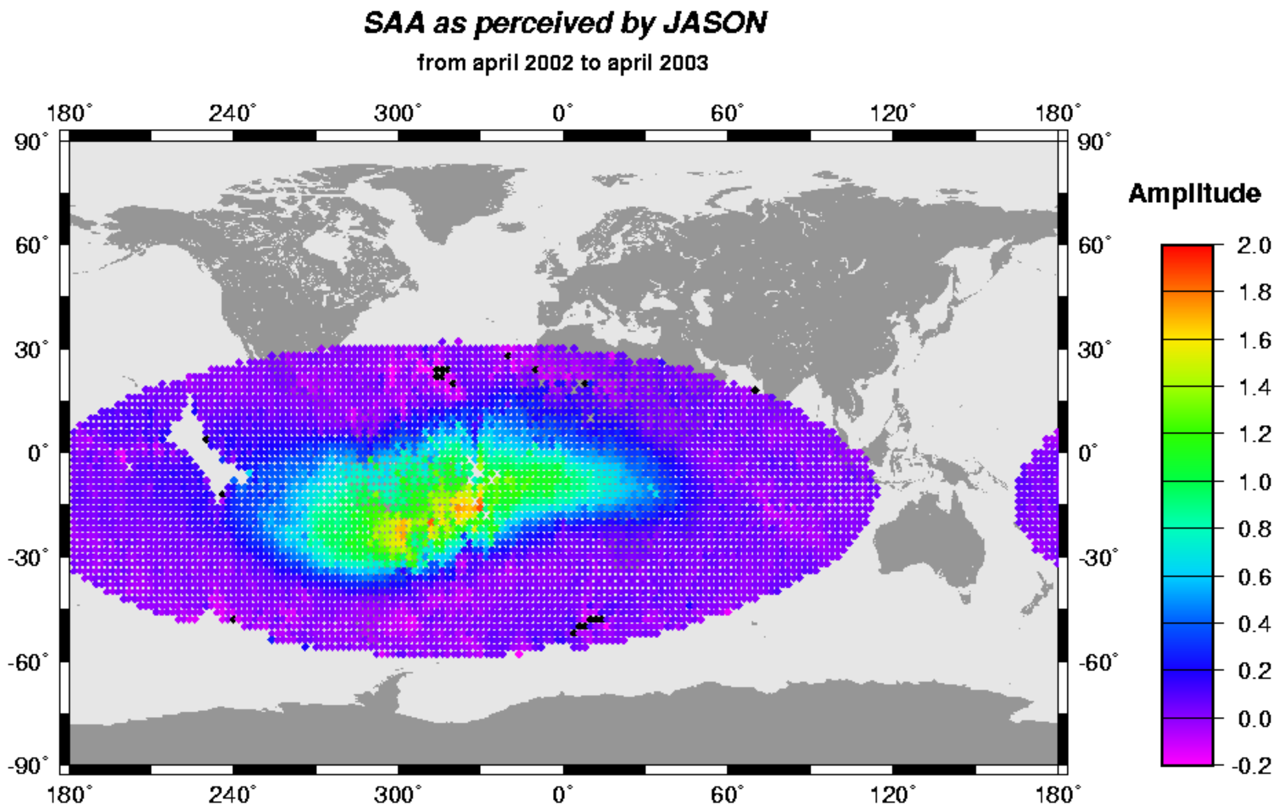
GALILEO probe at JUPITER

- After Amathea encounter, data collection stopped
- Deepest orbit in the radiation belts
- Spacecraft switched to safe mode (proton SET in command and data system)
- Recorder could not be played back
- Problem due to OP133 LED in tape position encoder
- JPL used a current annealing strategy
- Recorder was restarted and data retrieved

This is a perfect example of the application of excellent radiation effects knowledge in a practical mission case

Ultra-sensitive systems

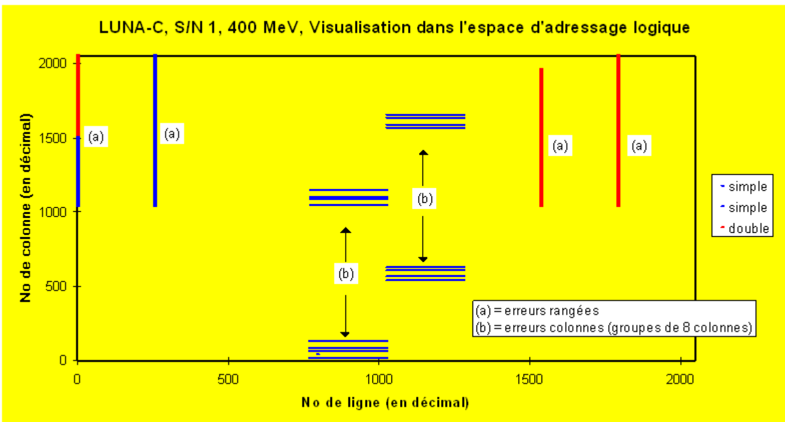
- DORIS / JASON-1 frequency shifts

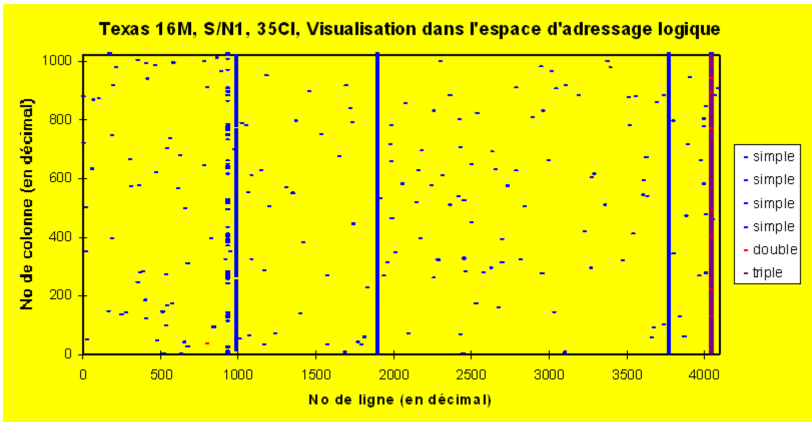


Single event effects

- Numerous records, major contributor to radiation induced spacecraft anomalies

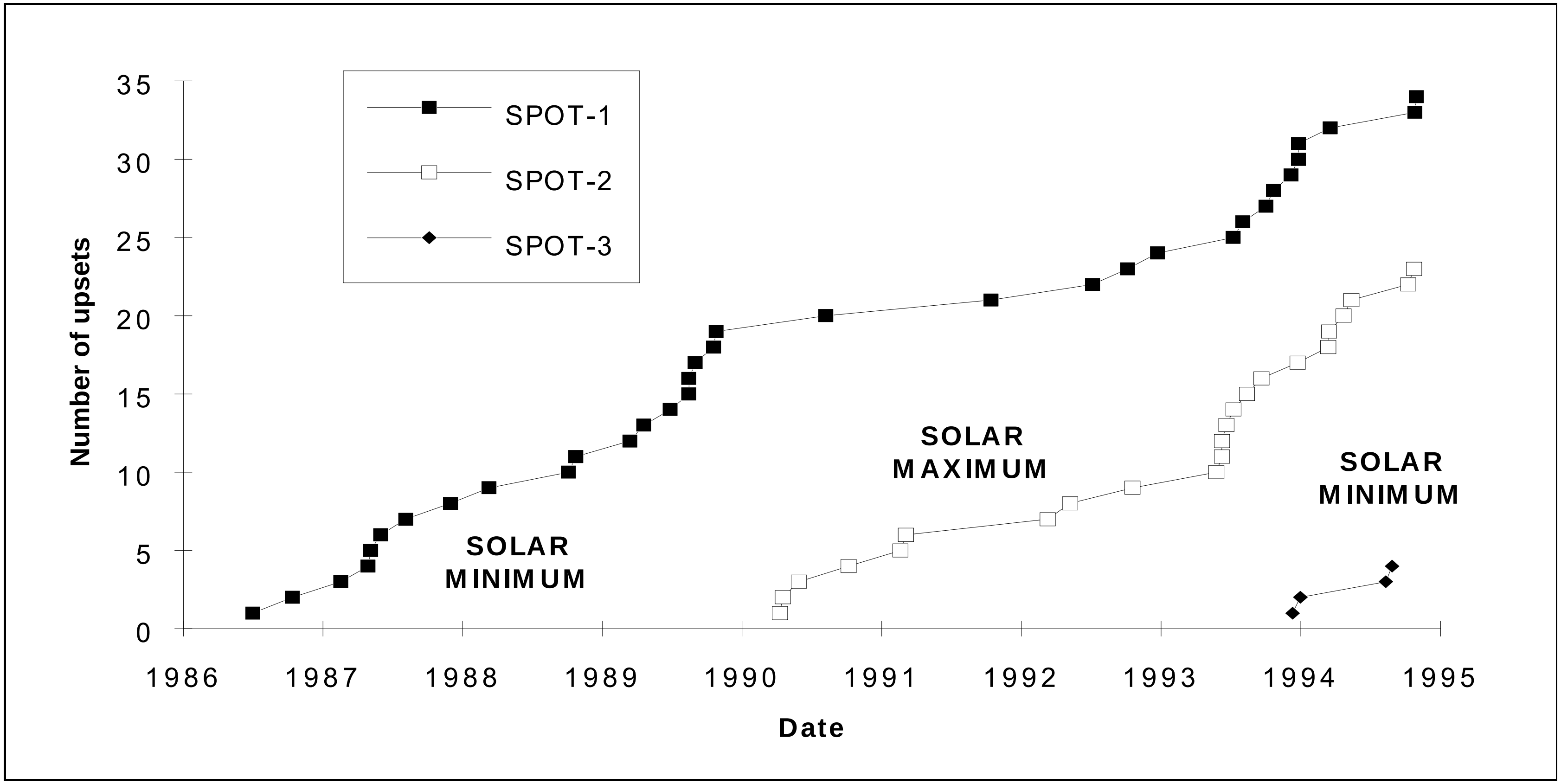
- Galactic cosmic rays
- Solar particles (protons, ions)
- Trapped protons





Cosmic ions

SPOT-1, 2, 3 OBC upsets (SSO orbit)



Cosmic ions

SOHO at L1 events (except SSR)

TABLE I
ESR EVENTS

Date	Unit	Event
04/12-1996	ESR	Attitude Control Unit – PSU reset
19/11-1997	ESR	Attitude Control Unit – self switch-off
03/03-1998	ESR	Centrale Data Mana. Unit – switched
28/11-1999	ESR	Attitude Control Unit – PSU reset
07/01-2000	ESR	Attitude Anomaly Detector – spurious
28/11-2000	ESR	Attitude Control Unit – PSU reset
14/01-2001	ESR	Attitude Control Unit – PSU reset

TABLE II
BDR EVENTS

Date	Unit	Event
12/01-1997	BDR1.2	Switch-off triggered by protection
01/04-1997	BDR1.1	Switch-off triggered by protection
16/05-1998	BDR2.1	Switch-off triggered by protection

TABLE III
VIRGO EVENTS

Date	Unit	Event
09/09-1996	VIRGO	Crashed – self switch-off event
07/05-1997	VIRGO	Latch-up - self switch-off event
20/05-1997	VIRGO	Latch-up – self switch-off event
26/05-1998	VIRGO	Power fail – self switch-off event
12/07-1999	VIRGO	Latch-up in DAS – (1st SEL)
11/02-2000	VIRGO	Latch-up in DAS – (2nd SEL)
30/03-2001	VIRGO	Latch-up in DAS – (3rd SEL)

TABLE IV
LASCO EVENTS

Date	Unit	Event
19/03-1996	LASCO	Voltage anomaly – requiring reboot
10/06-1996	LASCO	Voltage anomaly – requiring reboot
19/12-1996	LASCO	Voltage anomaly – requiring reboot
26/04-1998	LASCO	Hung-up – requiring reboot
28/03-2000	LASCO	PROM off – requiring reboot

Power supply events : SETs on PM 139 or UC1707J

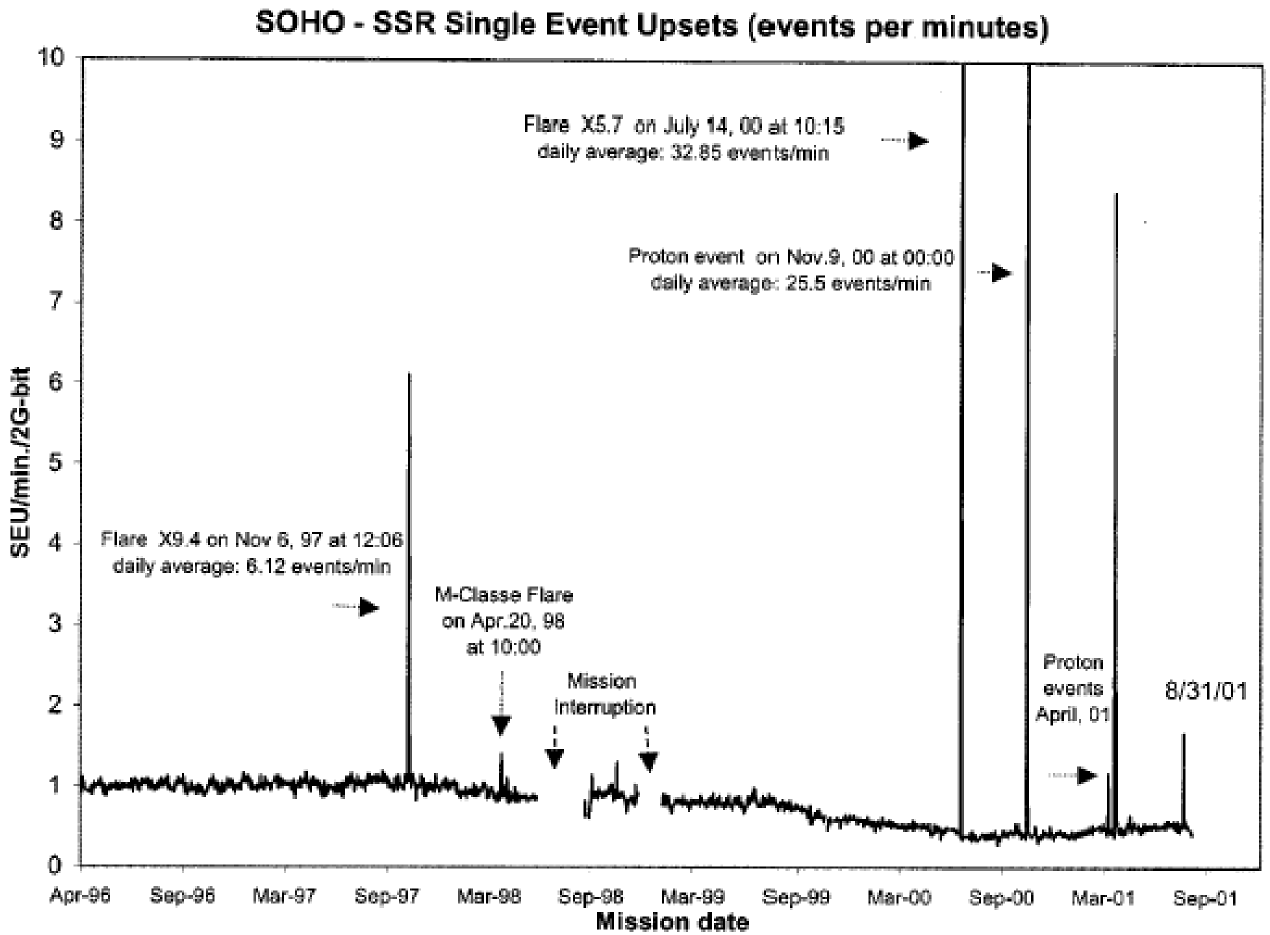
Solar particles

MAP at L2 processor reset

- MAP (NASA spacecraft) orbiting at L2
- 5 November 2001, switch to safehold condition
- Due to processor reset
- 3-7 November 2001 : large solar event
- Solar ion SET on PM139 from reset circuitry
- Consolidated by CREDO / MPTB (QinetiQ UK) measurement of flare ions

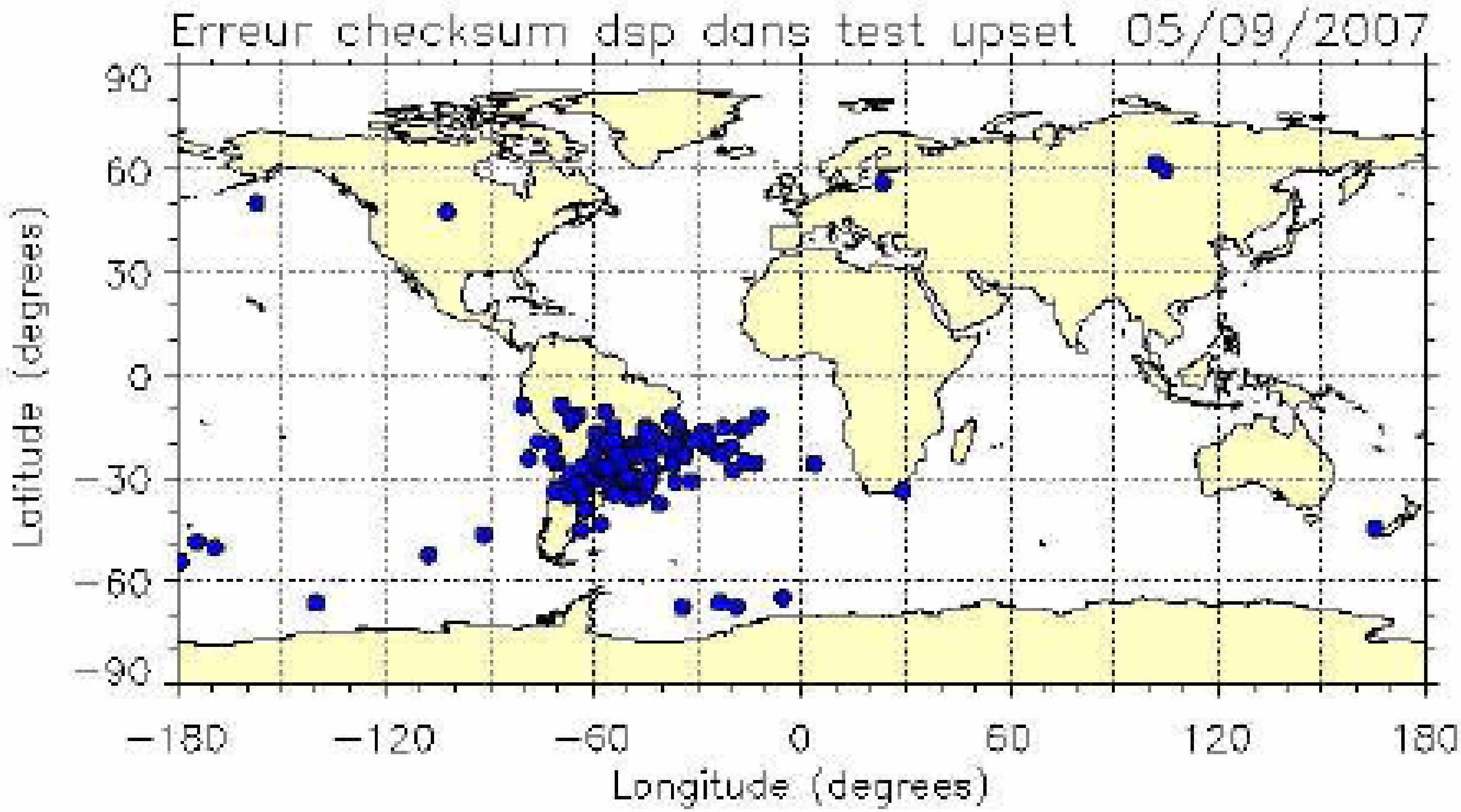
Solar particles

SOHO at L1 SSR upsets



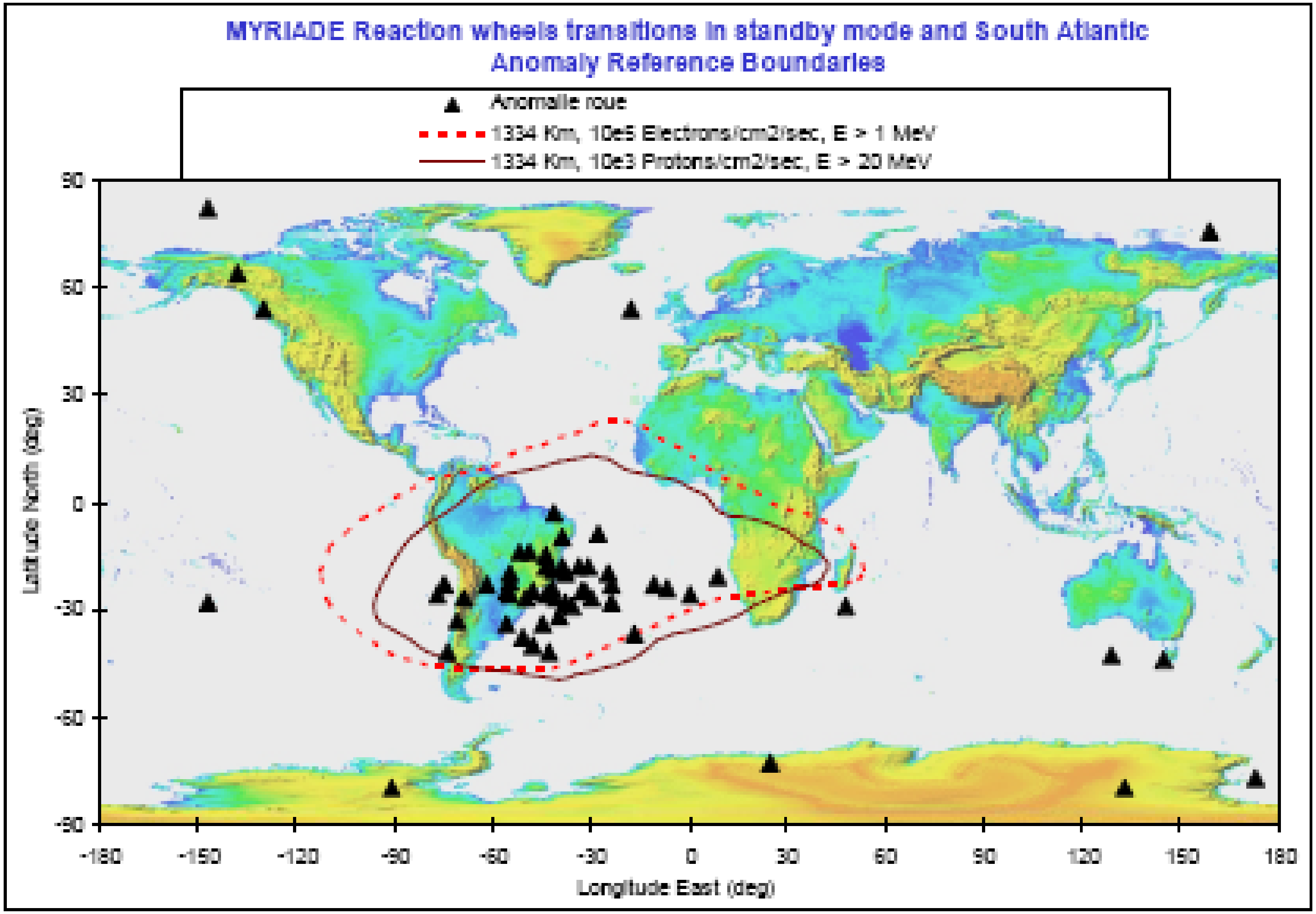
Trapped protons

DEMETER BANT DSP upsets



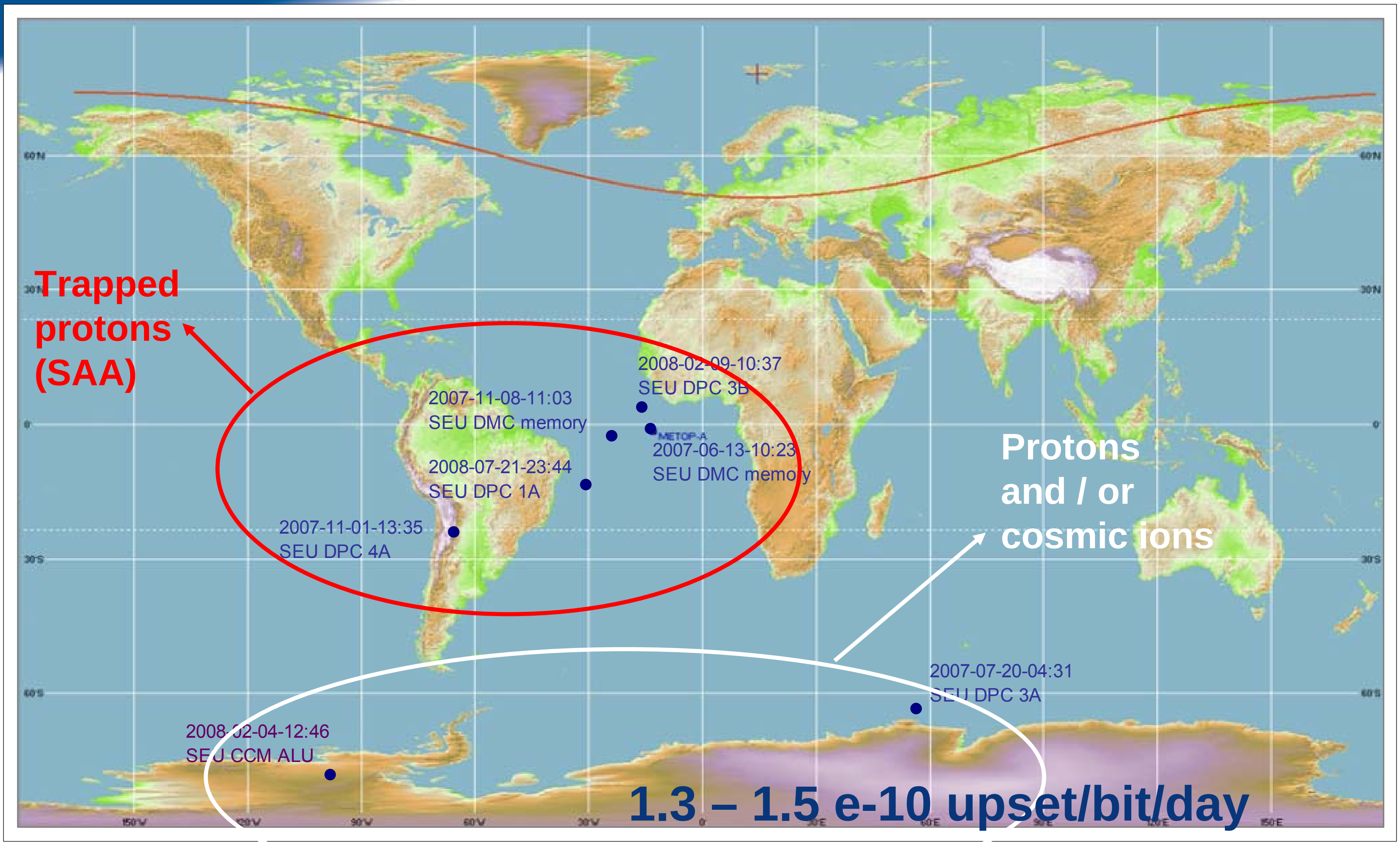
Trapped protons

MYRIADE reaction wheels resets



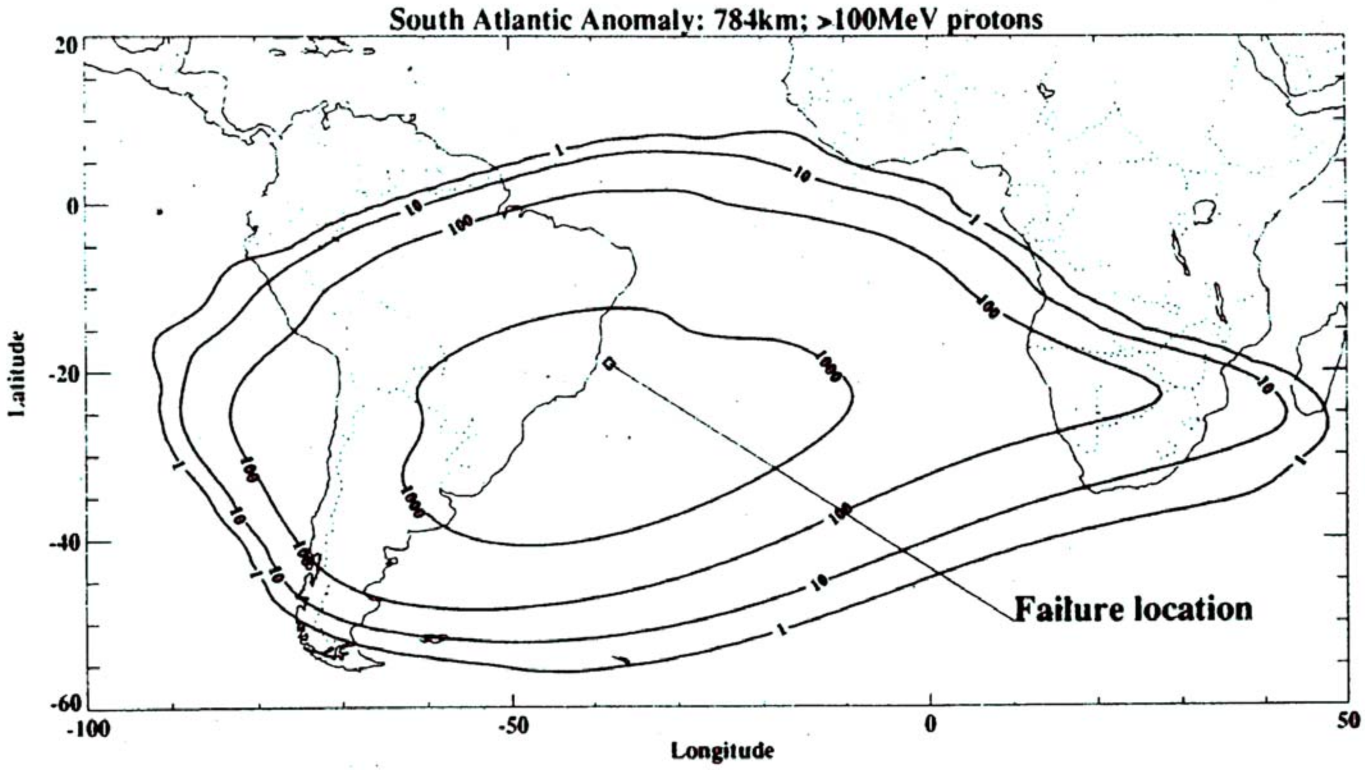
Trapped protons

IASI/METOP : SEUs on rad-hard memories



Trapped protons

PRARE / ERS-1 instrument loss (SSO)



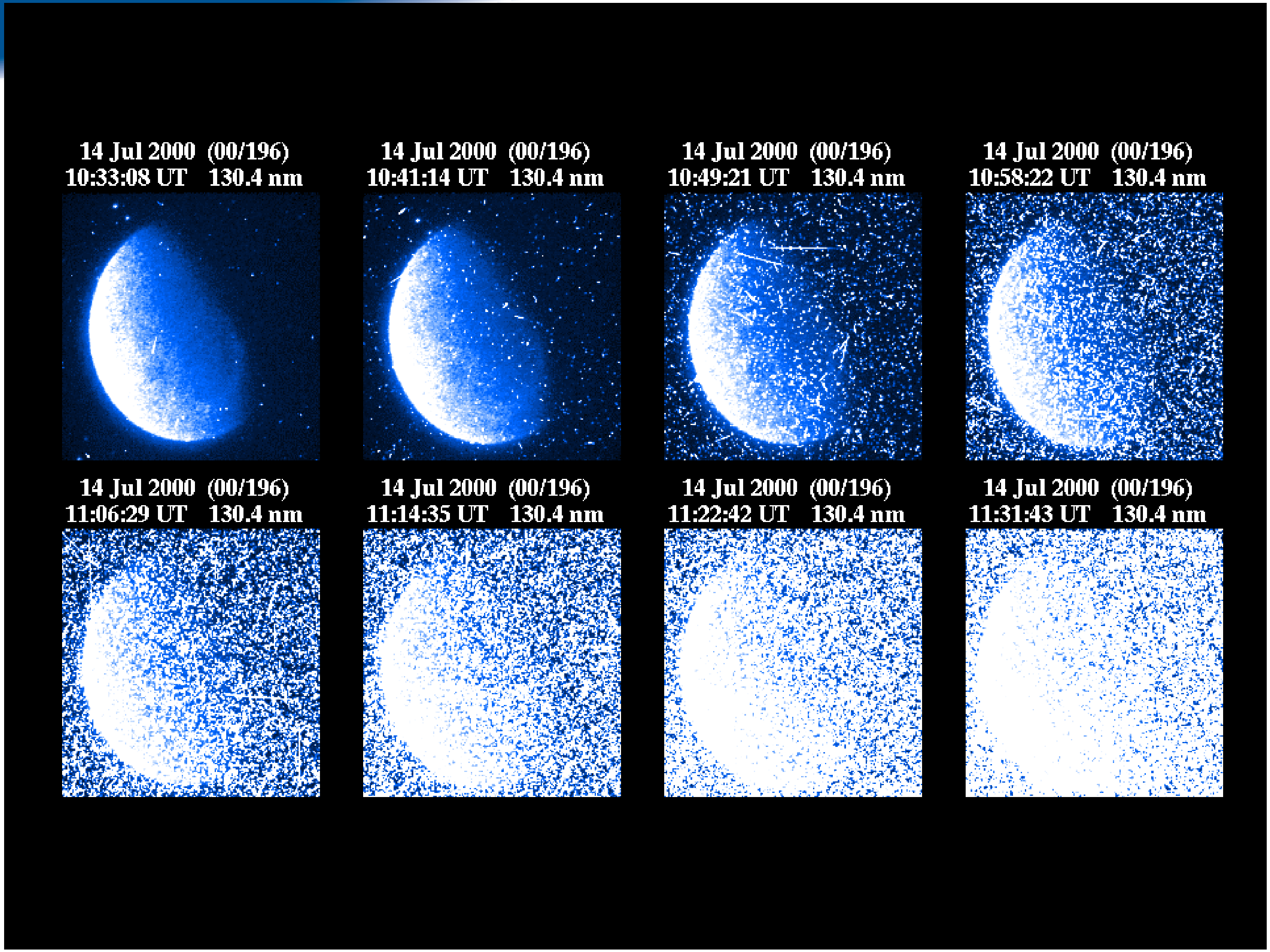
- Latch-up on 64-kbit CMOS SRAM, after 5 days
  9 W, 16 to 32s, instrument lost

The particular case of sensors

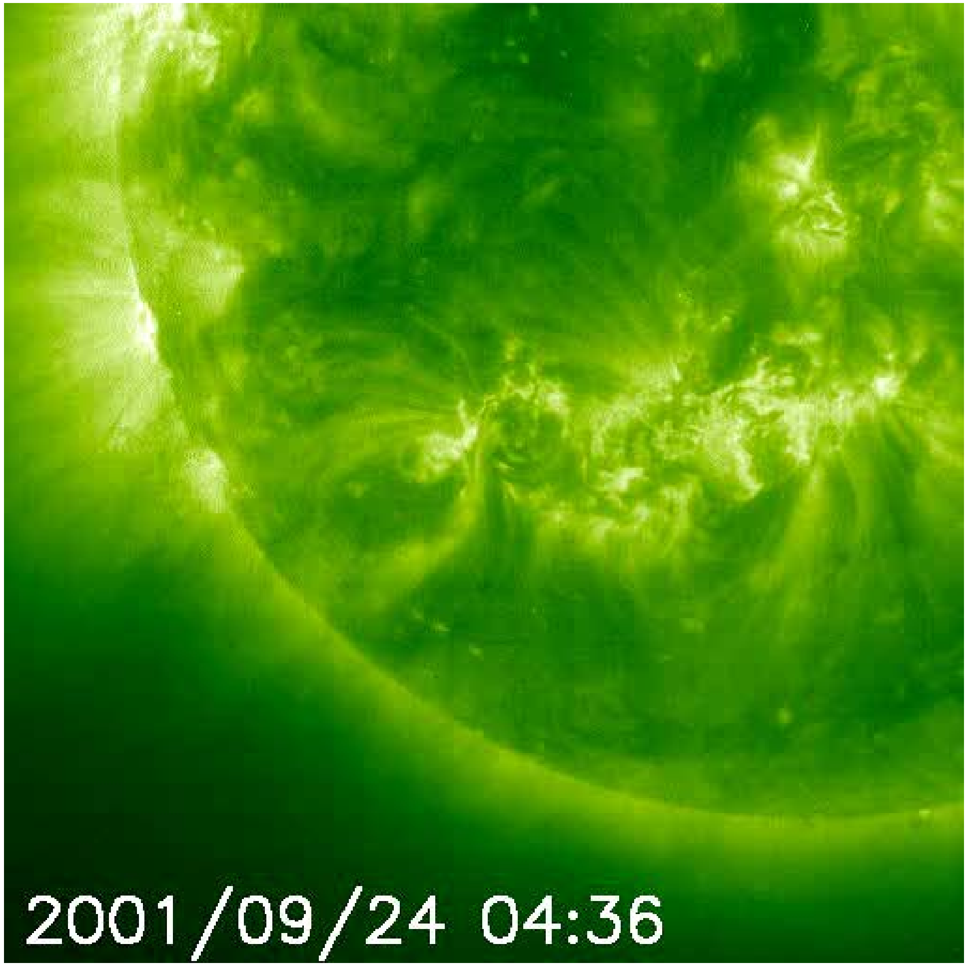
- External sensors are particularly exposed to radiation
  - By nature (charge collection devices), they are sensitive to radiation effects
  - Charge collection after a proton (or ion) impact
  - One or many pixels may be affected
  - On matrix detectors, tracks can appear

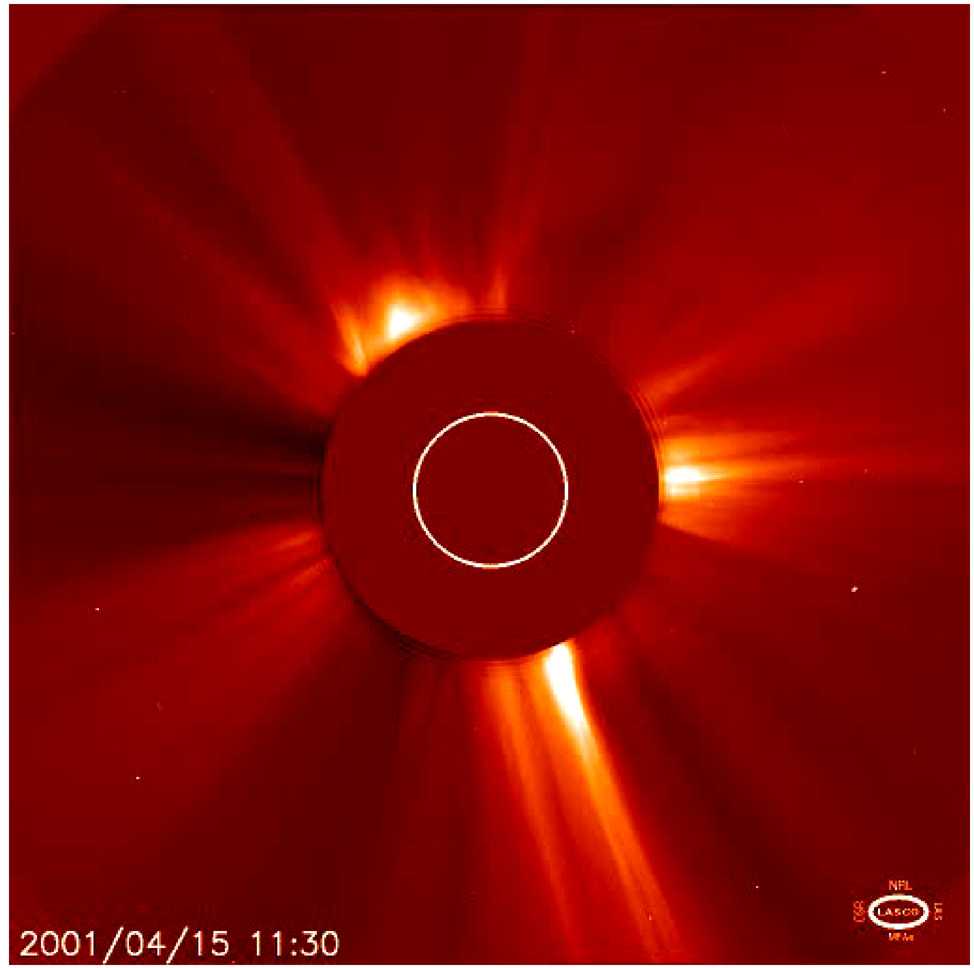
- Transient signals
- Permanent or semi-permanent damage

Blurring of VIS camera on NASA / POLAR



Solar protons “filmed” by SOHO





Galileo at Jupiter

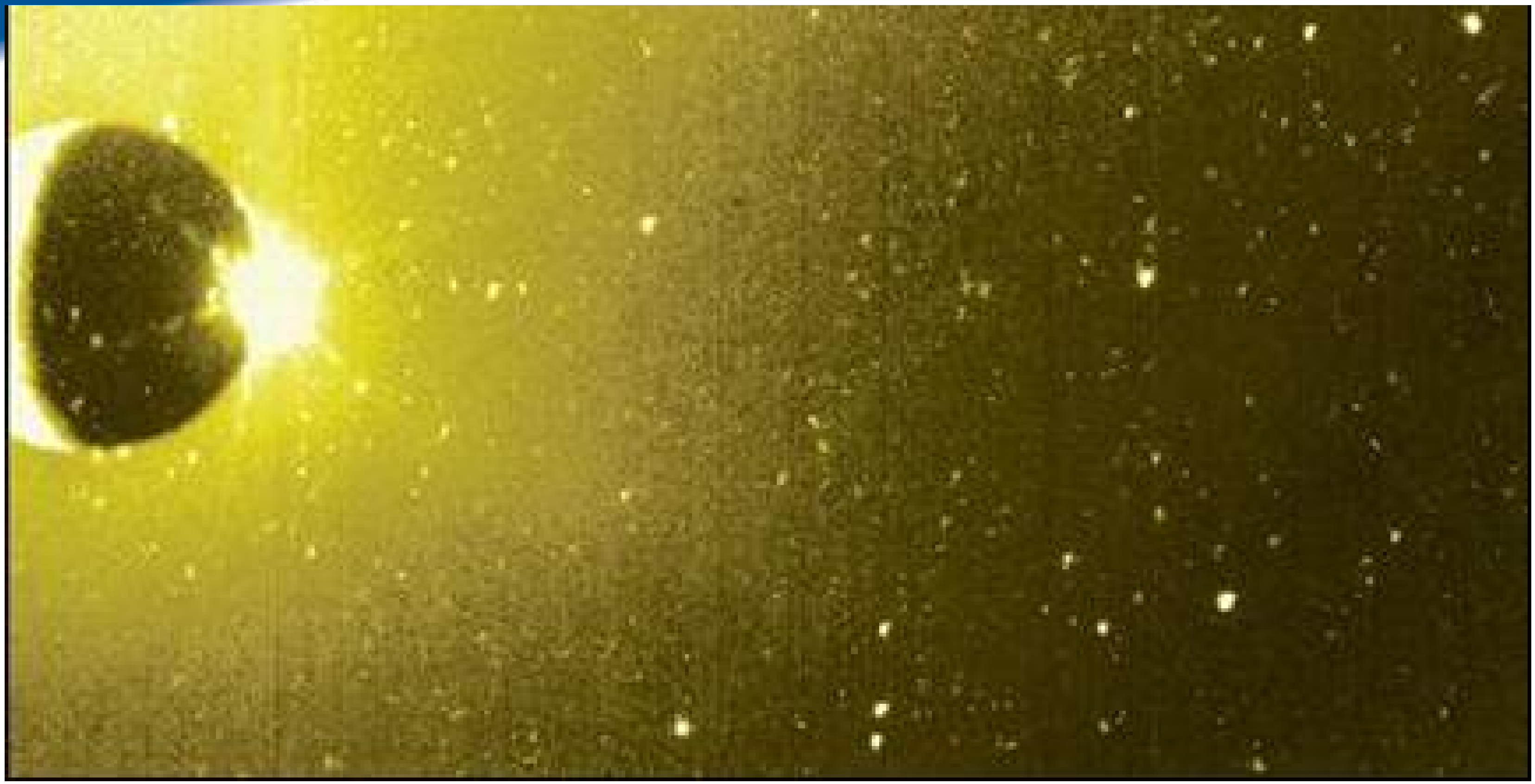
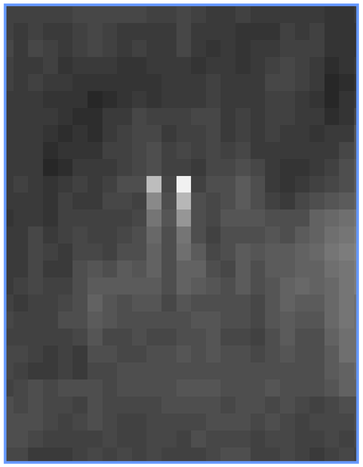
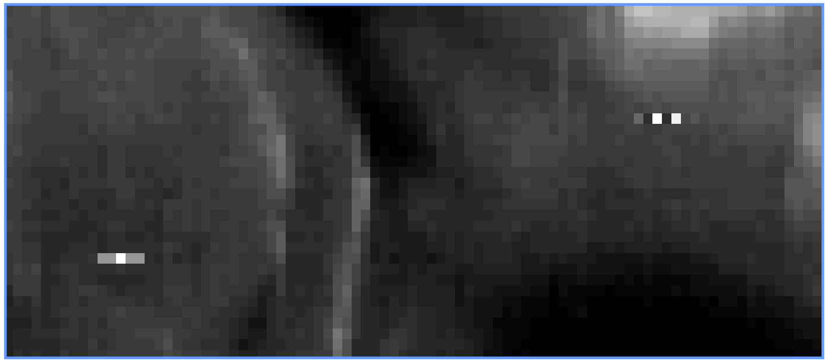
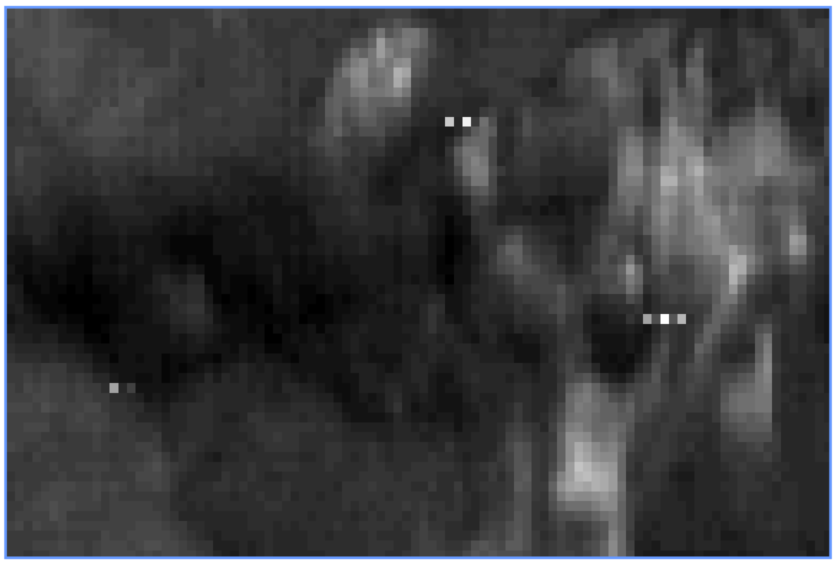


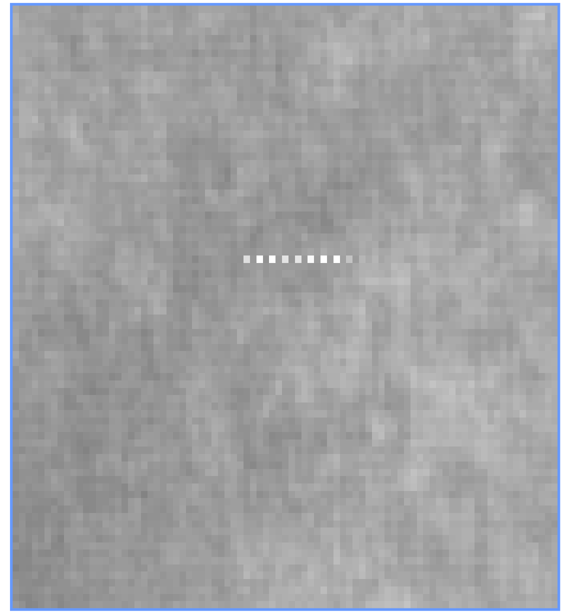
Image of a Sodium volcanic plume on the moon Io contaminated by speckles due to Jupiter radiation belts, JPL image

SPOT "UFOs"

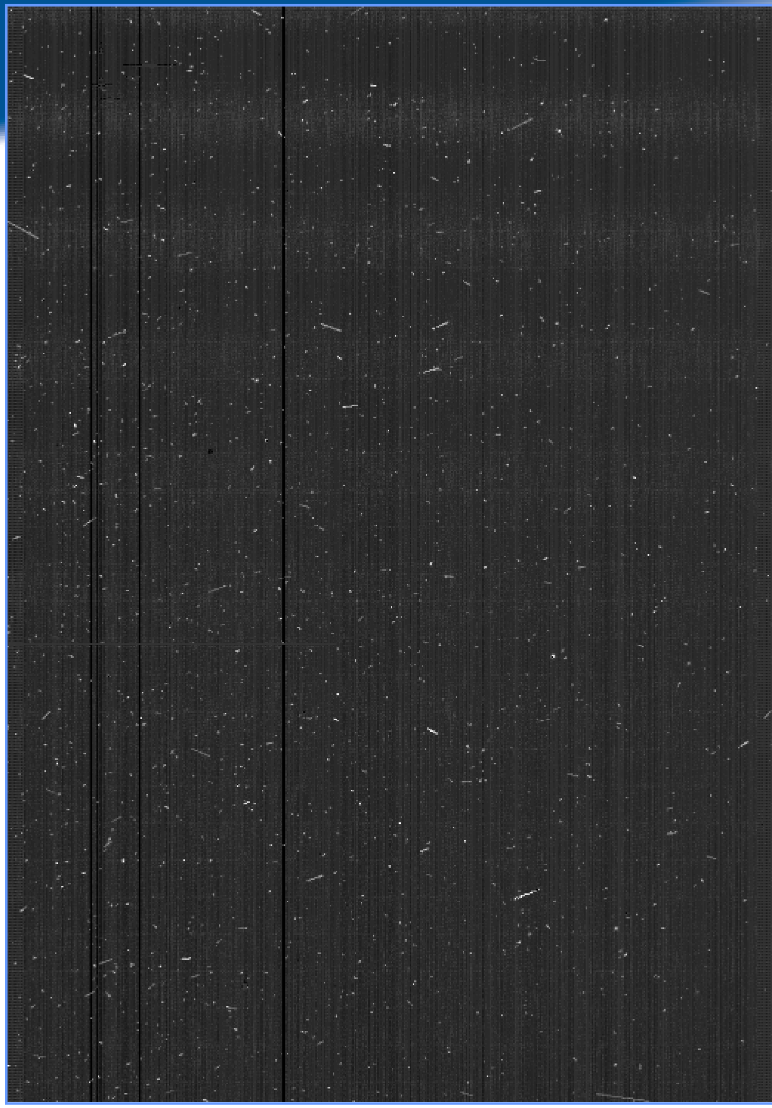






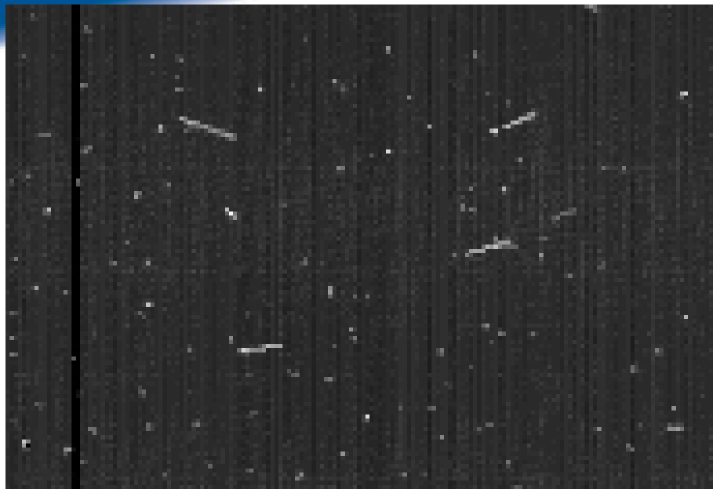


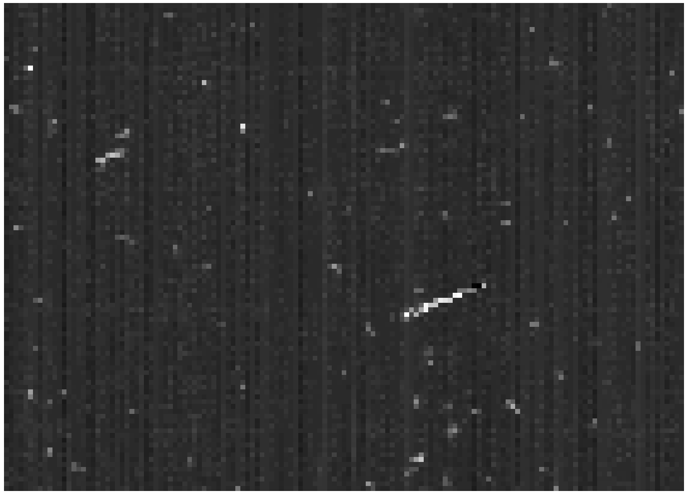
Jason-1 star tracker transients



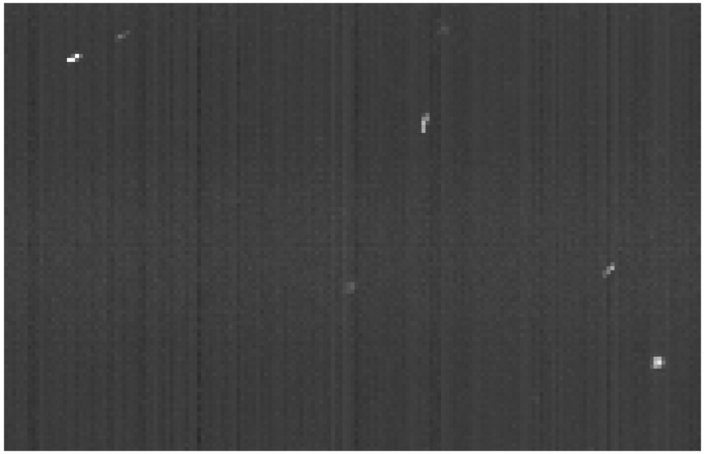
Proton tracks in SAA passes

Jason-1 star tracker transients





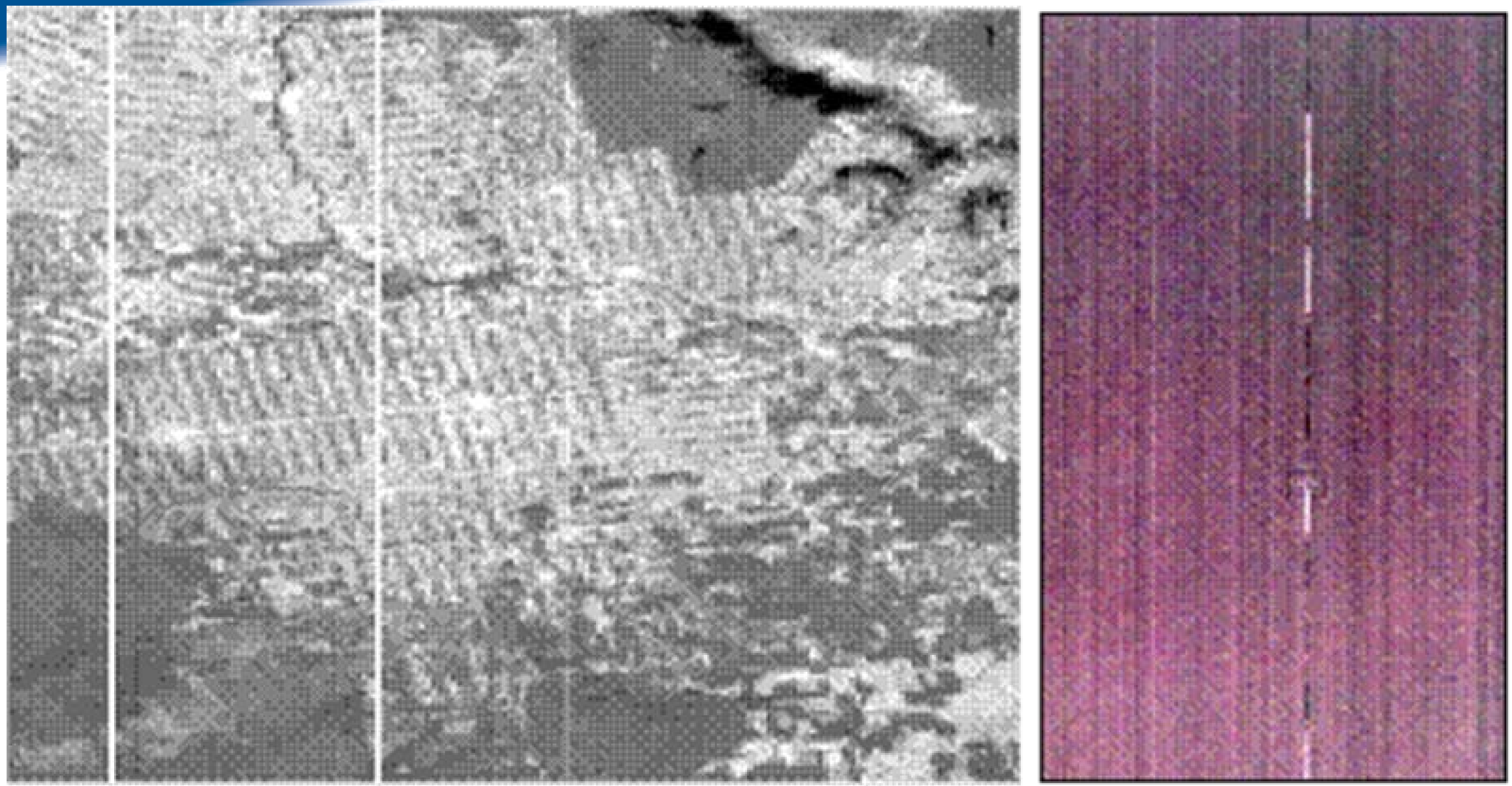
SAA passes



Clear star field

Same star tracker on JPL GENESIS probe was blinded 4 times during April 2002 SPE.

Permanent or semi-permanent damage



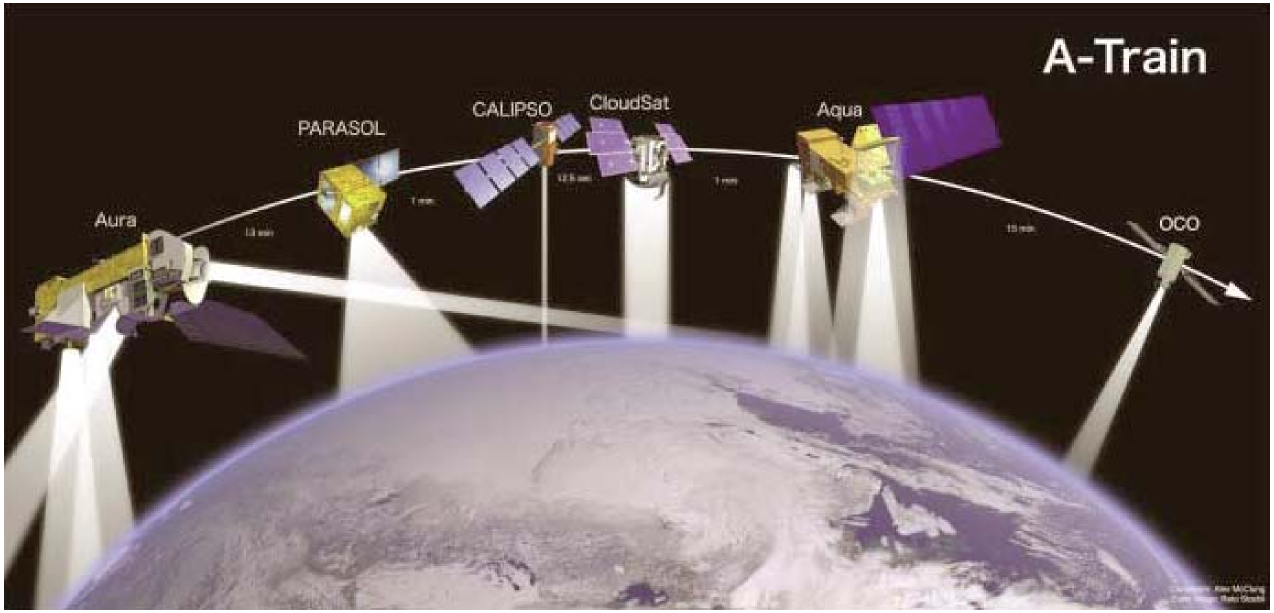
Hot pixels (left) and RTS (right) on SPOT-5 MIR detectors

Space weather action cases

NASA Lidar on CALIPSO

-An SEU on one of the Lidar components can lead to a constantly powered X-band emitter with a risk of burn-out if this lasts too long

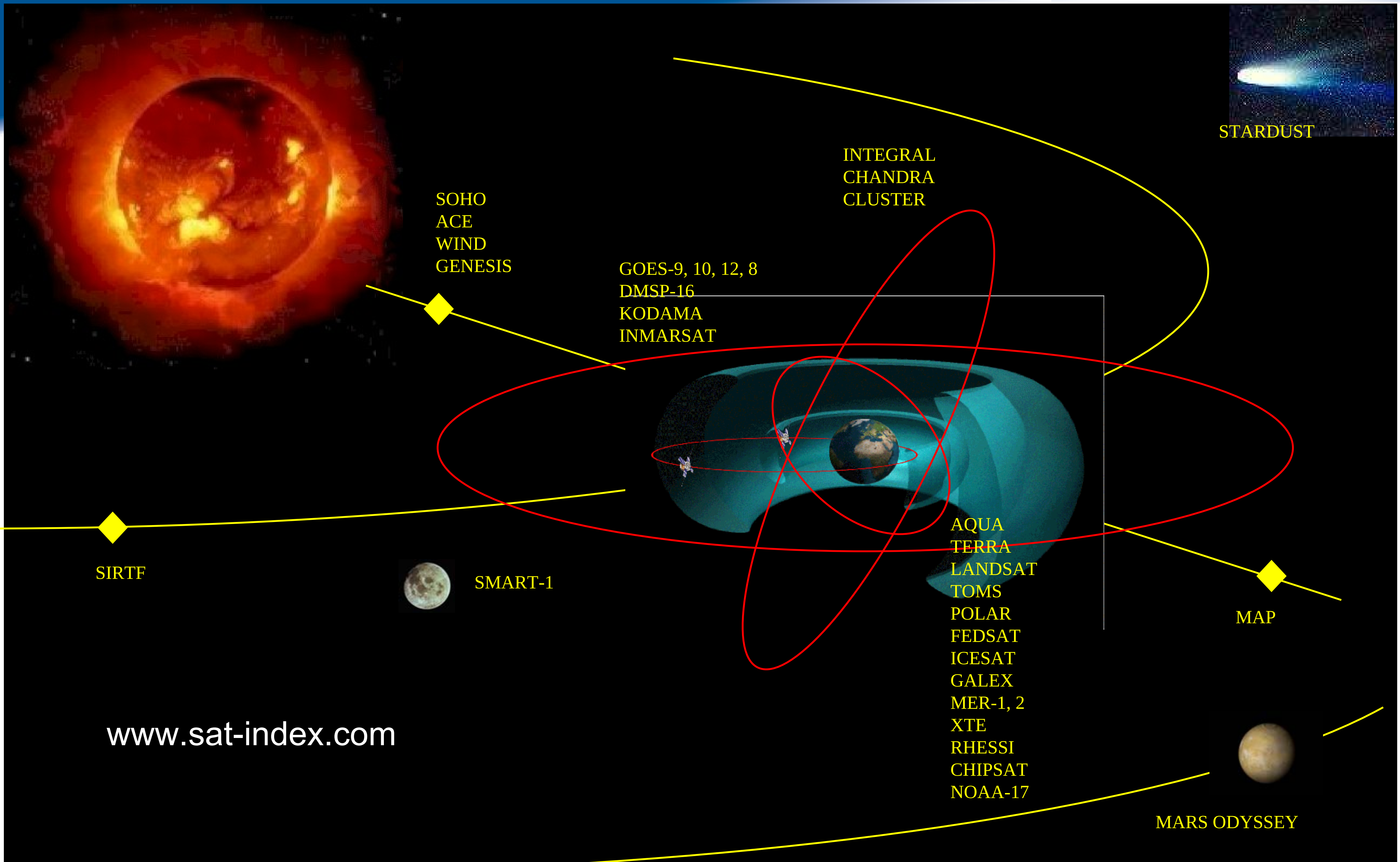
-We switch-off this payload on NASA SW solar flare warning



Space Weather operation on CALIPSO

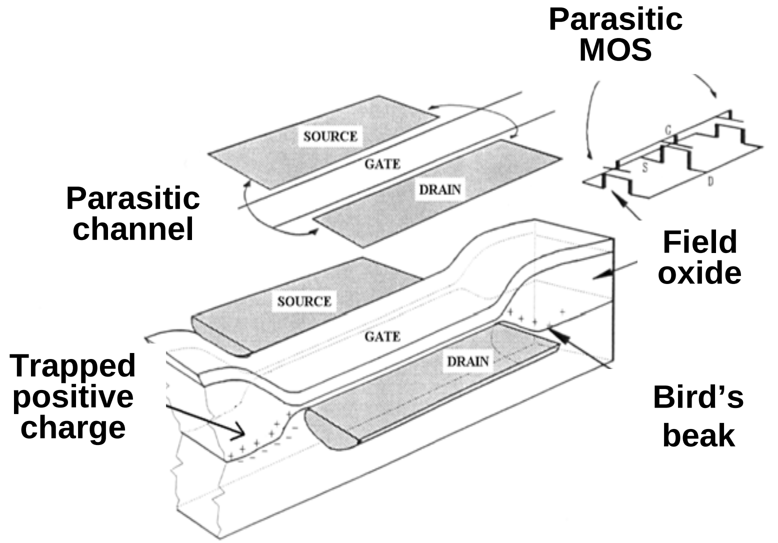
- **12.07.06**: We received notification of a space weather 100 MeV warning at 7:11 PM on Wednesday, 12.06.06. Because of this warning we have turned off the CALIPSO payload controller, and we expect that we won't resume operations before Monday, 12.11.06.
- **12.11.06**: The space weather forecast is improving and plans to resume CALIPSO operations are being finalized. Plans to resume operations follow:
  - December 12, 2006: Reactivate Payload Controller provided conditions remain less than 100 MeV
  - December 13, 2006: Apply power to laser system, Configure PL in Standby provided conditions are less than < 10 MeV. Resume data acquisition at earliest opportunity (late 12/13/2006 or early 12/14/2006).
- **12.12.06**: CALIPSO reactivation began today when the CALIPSO Payload Controller was successfully turned on at 12:14 UTC. A 10 MeV space weather alert remains in effect until 16:00 UTC today. The 10 MeV alert must be clear before further activation of the CALIPSO payload can be performed. We anticipate favorable conditions and plan to continue CALIPSO reactivation on December 13, 2006.
- **12.13.06**: Space weather conditions deteriorated overnight. The NOAA Space Environment Center issued 100 MeV and 10 MeV warnings and alerts at 03:00 UTC December 13, 2006. In response to these conditions, the payload controller was turned OFF at approximately 12:15 UTC 8:06 UTC December 13, 2006 as a precautionary measure. Space weather warnings at both the 10 MeV and 100 MeV levels remain in effect until 23:59 UTC December 13, 2006. It is possible that these warnings will be extended later today.
- **12.14.06**: Space weather conditions continue to be unfavorable for CALIPSO operation. Space weather 100 MeV and 10 MeV warnings remain in effect through at 01:00 UTC December 15, 2006 and we anticipate that these warnings will be extended later today. The solar activity forecast predicts at least a 75% chance of additional proton events through December 16, 2006 with NOAA sunspot Region 930 responsible for the elevated activity. Tentative plans are being developed to begin CALIPSO reactivation on Monday, December 18, 2006 and return to science operations with X-band data transmission on December 19, 2006. Correction (see change made below): The CALIPSO payload controller was powered OFF at 8:06 UTC on December 13, 2006 and not at approximately 12:15 UTC as initially reported.•
- **12.20.06**: CALIPSO resumed nominal data acquisition December 19, 2006 at 13:56 UTC. Payload performance is nominal based on a review of telemetry received last night and early this morning. CALIPSO will remain in nominal data acquisition until a planned drag make up orbit maneuver tentatively planned January 16, 2007.
- **01.12.07**: The CALIPSO payload will be out of service between 08:45 UTC on January 15, 2007 until 13:28 UTC on January 17, 2007. The down time is necessary so the CALIPSO satellite can perform a drag make up orbit maneuver to maintain its position in the A-train constellation and to perform a periodic check of the redundant CALIPSO laser system. The next scheduled outage will occur in support of an overall A-Train inclination manoeuver sequence with the first of three CALIPSO maneuvers tentatively scheduled on March 8, 2007.

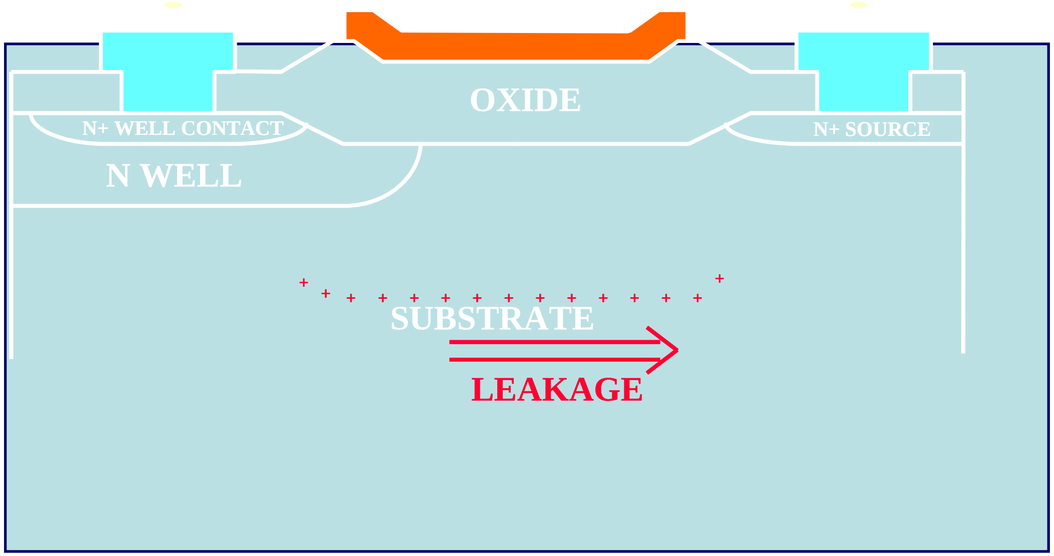
Effects of a major SW event (oct-nov 03)



Technological trends - dose

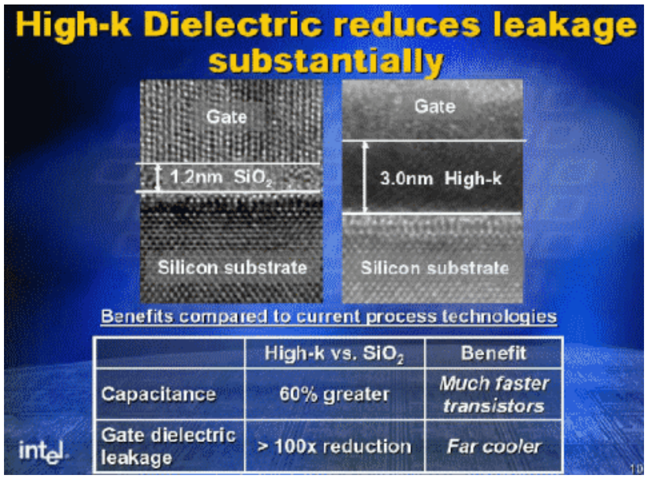
- In general, advanced technologies tend to have quite good TID figures
- Downscaling implies thinner gate oxides
  - favourable to better TID performance (less oxide traps)
  - lower gate leakage with dose
  - drawback : higher influence of interface states → rebound effects
- But reduction in spacing brings other mechanisms such as parasitic channel (source – drain leakage)

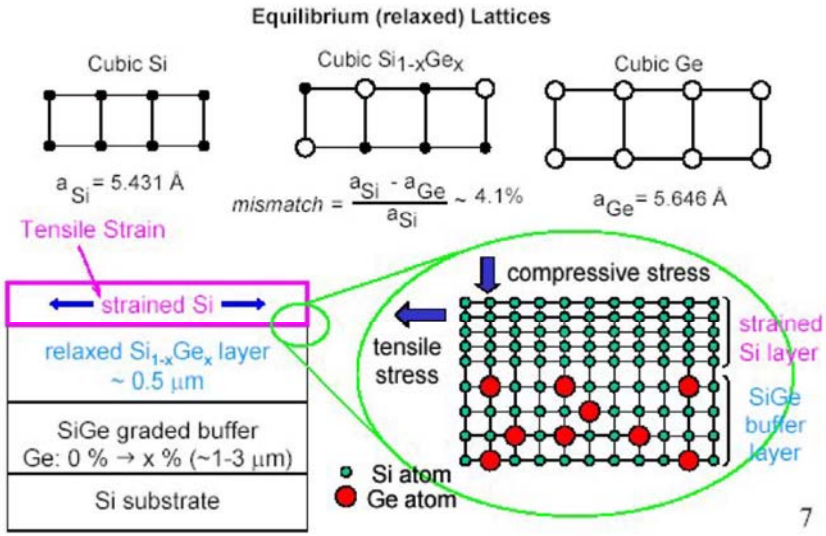




Technological trends - dose

- It has been observed that the use of nitride passivation has a strong negative impact on TID performance
  - mechanism still to be elucidated, probably related to H+ migration
- The (few) available results on high-k dieletric and strained silicon technologies do not show to date a negative impact of these features on TID performance





Technological trends - SEE

- Both VDD reduction and geometry downscaling lead to lower charges stored on the nodes Qnode=VDD x Cnode
- New generations have lower SEE threshold critical charges → higher SEU sensitivity
  - 1980's : heavy ions
  - 1990's : protons
  - 2000's : atmospheric and thermal neutrons

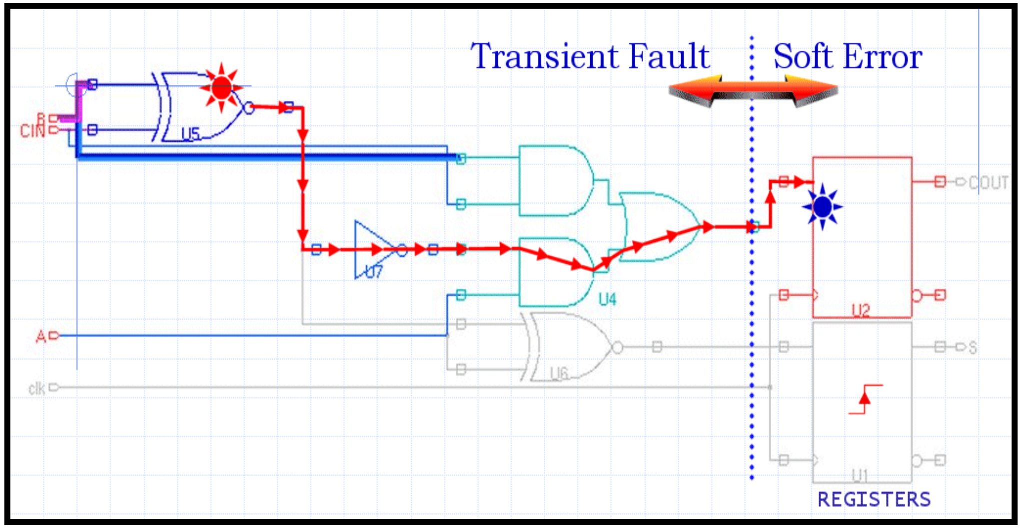
Conditions	FIT/Mb Neutrons	FIT/Mb alpha Am241	TOTAL
Sea level	1300	2200	3500
Alt.1500 m	3000	2200	5500

CMOS 0.13um, Los Alamos NSC

1000 FIT = 1 error per 114 years, for 128 Mbytes=> 1 error per 14 days at ground level

Technological trends - SEE

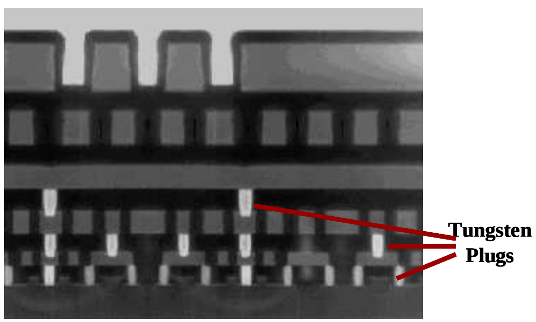
- More sensitive but harder to shoot at (smaller) targets
  - device SEU sensitivity more or less the same
  - i.e. for a sensitive memory, the surface of the die
- Transient pulses become larger than gate transition times and can propagate to outputs
- With frequency increase, probability of capture in latches increases



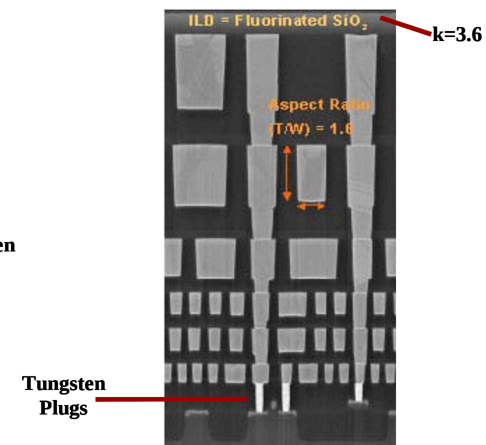
SER in combinatorial logic becomes comparable to SER in latches

Technological trends - SEE

- Good news :
  - crosstalk, substrate noise,… and atmospheric neutrons problems
  - brings interest of large manufacturers for SEU/SET mitigation
  - technology / internal coding or fault tolerant techniques
- Bad news (for rad-hard products)
  - use of tungsten interconnections
  - p+ / W interaction leads to high LET recoils
  - latent p+ SEU rate recently evidenced on some rad-hard devices
  - does not concern classical / commercial devices (already sensitive)



Intel 0.25µm Process (Al)
5 Layers - Tungsten Vias
Source: *Intel Technical Journal* 3Q98



Intel 0.13µm Process (Cu)
Source: *Intel Technical Journal* 2Q02

Dedicated instruments and experiments

- **Space environment monitors**
- **Technology experiments**

Space environment monitors

- Space environment monitors are of great help as witnesses of conditions during the anomaly
- Generic data from environment observatories (e.g. GOES, POES)
- Monitoring on the host satellite
  - "Black box" for future investigations
  - Particularly useful in GEO where conditions may vary with longitude

Technology experiments

- Technology experiments, e.g :
- SEE monitoring (SEU, SET, SEL, SEB,…) can give useful information
  - on the raw SEE rate on devices before system filtering
  - and thus give an idea of the raw level of perturbation
- Dosimetry and/or dose drift measurements can give information
  - on the actual dose level received and state of components
  - on remaining lifetime
  - provide anticipation on possible recovery techniques

Conclusions

- Radiation-induced spacecraft anomalies have been observed since the very beginning of the space era
- Radiation effects anomalies have their origin at the component level but the observed anomaly is a system response
- Radiation effects knowledge is a tremendous added value for engineering anomaly way-outs (e.g. JPL / Galileo)