e2v centre for electronic imaging

Predicting the effects of radiation damage on the Chandrayaan-1 X-ray spectrometer (C1XS) instrument

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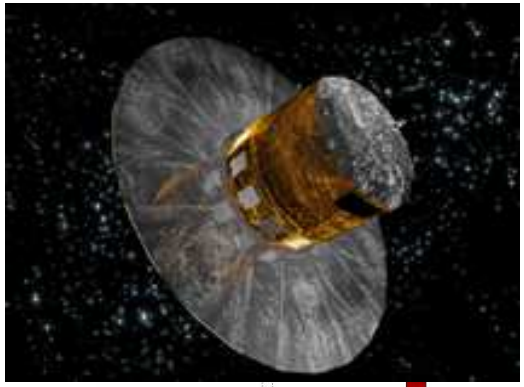
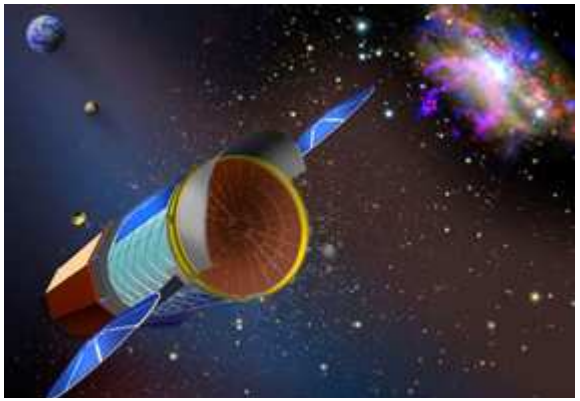
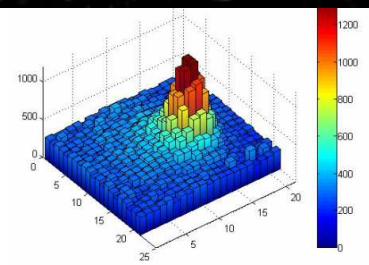
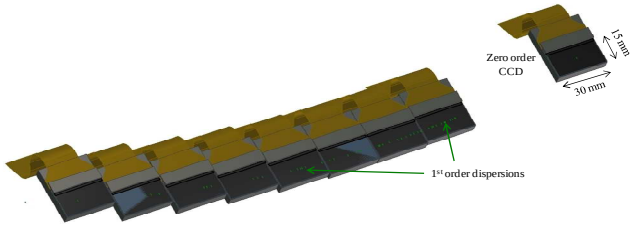
Key Space Projects

- Gaia – *providing a high resolution 3D map of 1 billion stars in the Milky Way*
  - Contributing to the radiation damage knowledge through device modelling
- Euclid – *to map Dark Energy through micro-lensing of galaxies*
  - Leading the CCD radiation damage evaluation & evaluating p-channel technology
- International X-ray Observatory (IXO) – *next gen. high energy observatory*
  Leading the study of the CCD camera for the grating readout





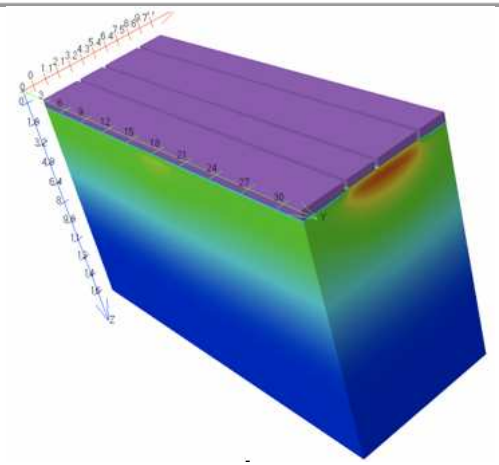




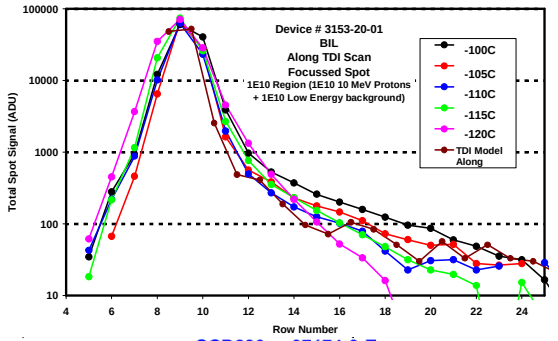
Fundamental Understanding

- **Radiation Damage**
  - Developing a physical understanding of the damage mechanisms in silicon
- **Device Modelling**
  - Use of advanced 3D simulation tools and Monte Carlo code to understand device operation
- **Detector Characterisation**
  - Development of test methodologies to both provide feedback on new detectors and test techniques
- **X-Ray and Optical Testing**
  - Using a combination of X-ray and optical techniques to enable an understanding of device operation

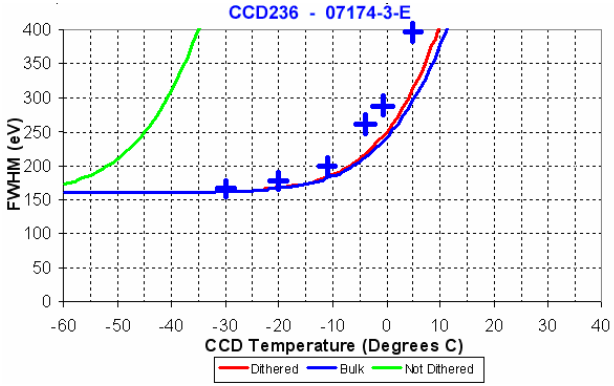
3D simulation



Modelling



Characterisation

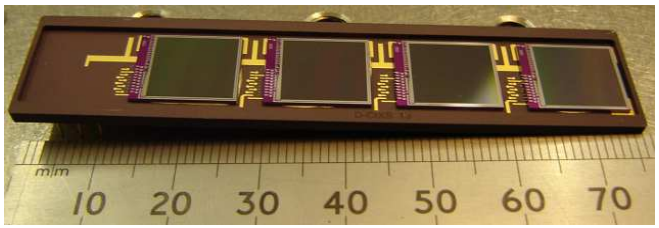


Talk Overview

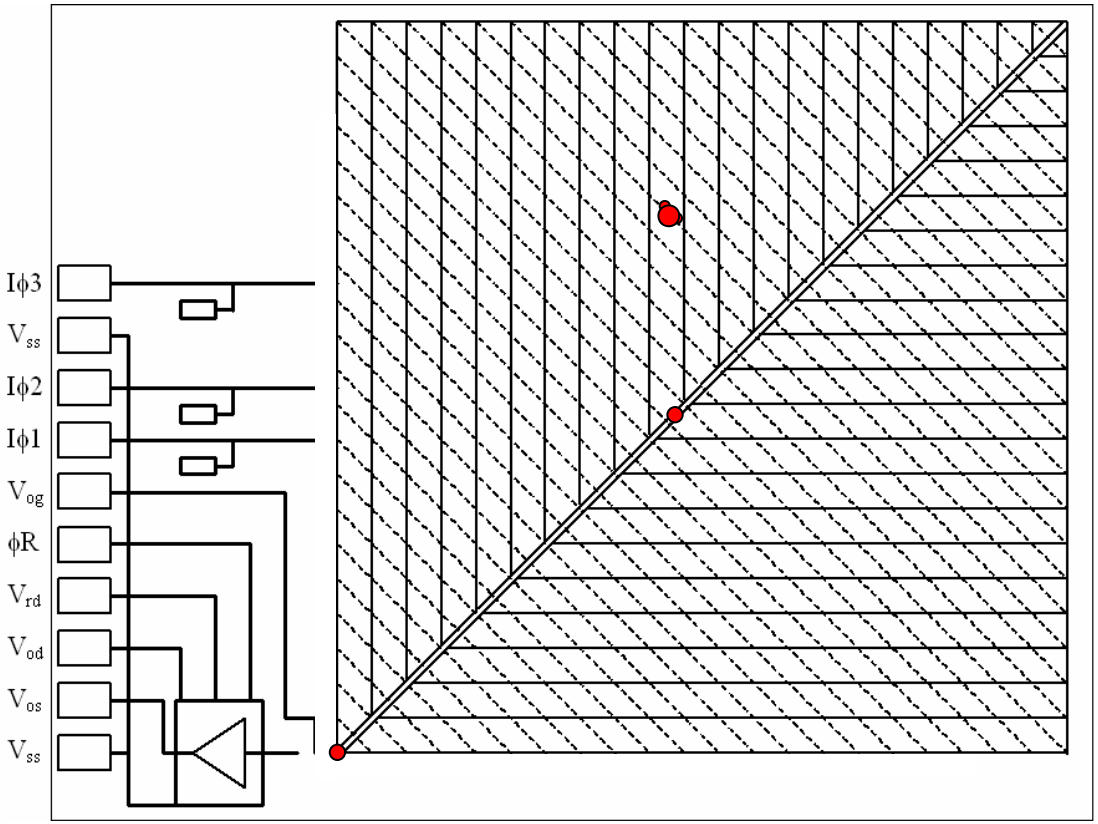
- The swept charge device
- SMART-1 and D-CIXS
- Chandrayaan-1 and C1XS
- The space radiation environment and SPENVIS
- Proton radiation damage assessment
- Effects of a delayed launch date and increased transfer time
- The next generation of swept charge device
- Comparison of the proton fluence received and the SPENVIS prediction

The Swept Charge Device

- Developed by **e2v Technologies plc** specifically for X-ray fluoresce analysis
  - **Continuous clocking** used to minimise the surface generated dark current
  - Avoids an Image integration period
  - High rate of periodic charge clocking (100 kHz.sample^{-1})



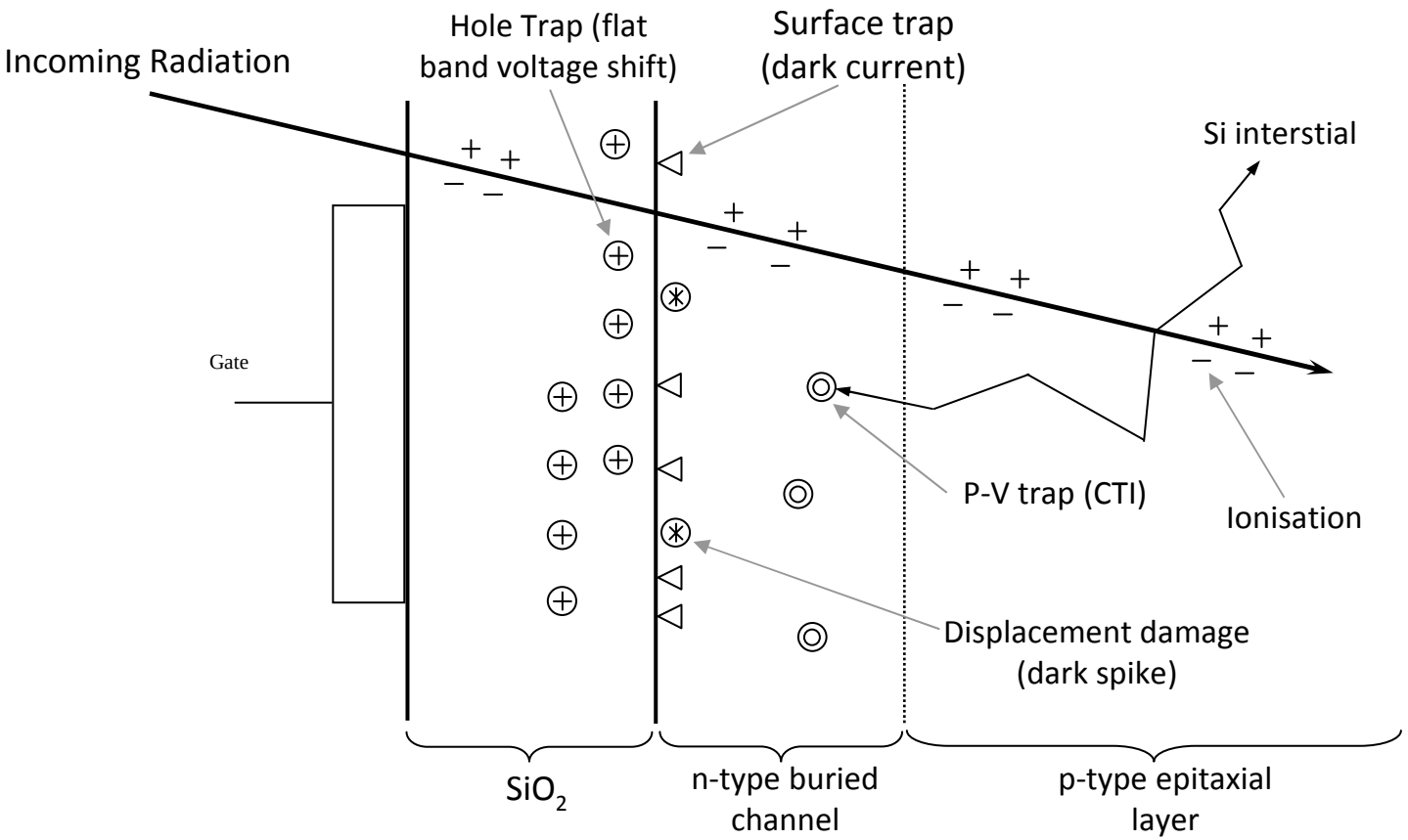
CCD54 Module



Linear output of 575 ‘pixels’

Measured X-ray charge

Radiation damage effects



[Janesick 2001]

SMART-1 and D-CIXS

Image courtesy of ESA

- **S**mall **M**issions for **A**dvanced **R**esearch in **T**echnology (SMART-1)
  - European Space Agency technology demonstrator mission for an Ion propulsions engine
  - Spent 15 months and 332 Earth orbits to get into Lunar orbit
  - 4 months in lunar orbit before intentional crash into the surface in September 2006
  - Also included some scientific instruments including the **Demonstration of a Compact Imaging X-ray Spectrometer** (**D-CIXS**)

- **D-CIXS**, built at the Rutherford Appleton Laboratory (RAL)
  - Consisted of 6 modules, each containing 4 **Swept Charge Device** (SCD) devices
  - On arrival at the Moon it detected Calcium, Iron and other elements in the Mare Crisium lunar region and further north.
  - Suffered significant damage to the SCD devices whilst in the Earth radiation belts

Image courtesy of RAL

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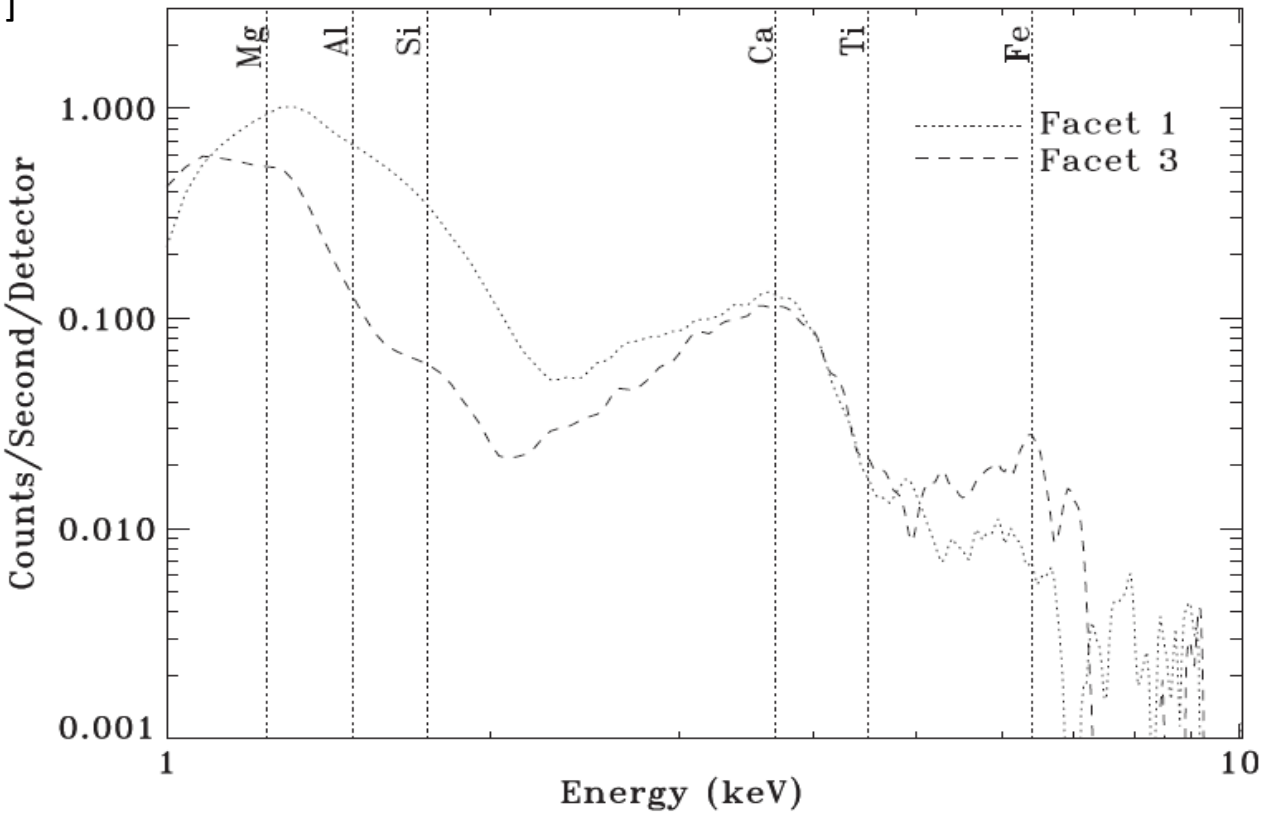
SMART-1 and D-CIXS

- XRF Spectra recorded by the D-CIXS instrument. Facet 3 was over the centre of Mare Crisium. Facet 1 was observing the highlands to the north east of Crisium [Grande *et al.* 2007]



Chandrayaan-1 and C1XS

Image courtesy of ISRO

- Chandrayaan-1 (Moonshot One)
  - **Indian Space Research Organisation** (ISRO)
  - Launched using an Indian Polar Satellite Launch Vehicle (PSLV-XL)
  - A 2 year mission in a 100 km polar orbit
  - Create a **3D atlas of the Moon**
  - Conduct **chemical and mineralogical mapping** of the entire lunar surface for distribution of elements
    - Magnesium, Silicon, Aluminium, Calcium
    - Radon, Uranium, Thorium

- Chandrayaan-1 X-ray Spectrometer (**C1XS**)
  - Developed at RAL, and provided by ESA
  - Consisting of 6 modules, each containing 4 **SCD** devices
  - **Energy Range: 1 – 10 keV**
  - **Energy Resolution: 180 eV @ 1.45 keV**

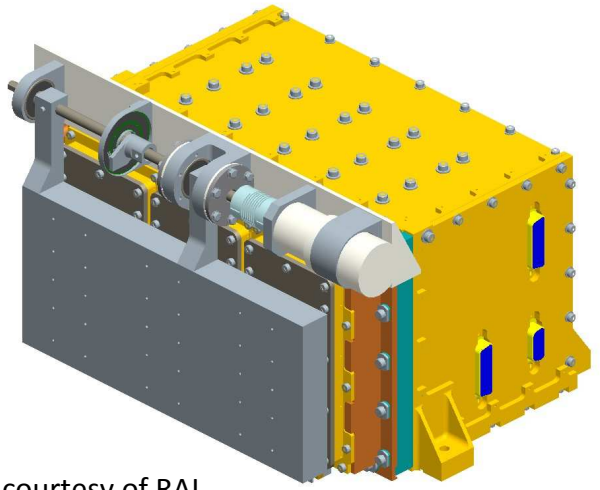


Image courtesy of RAL

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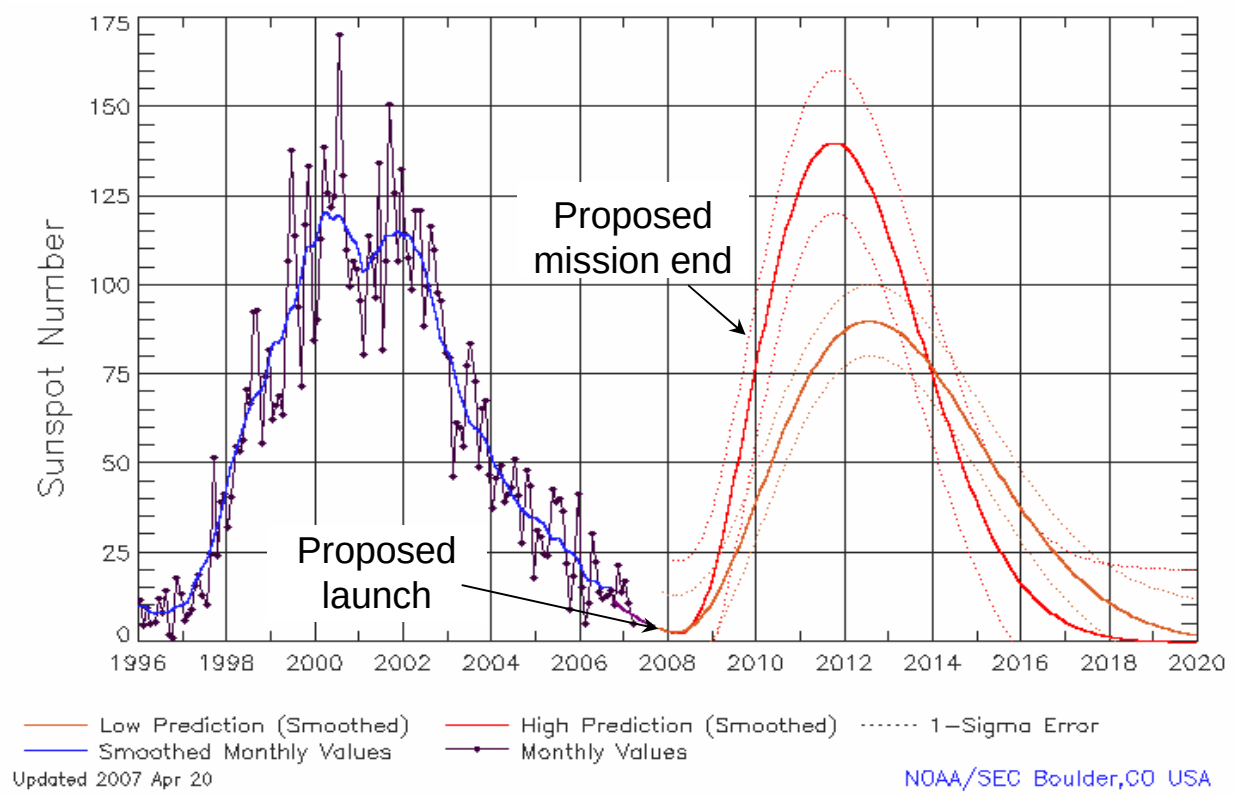
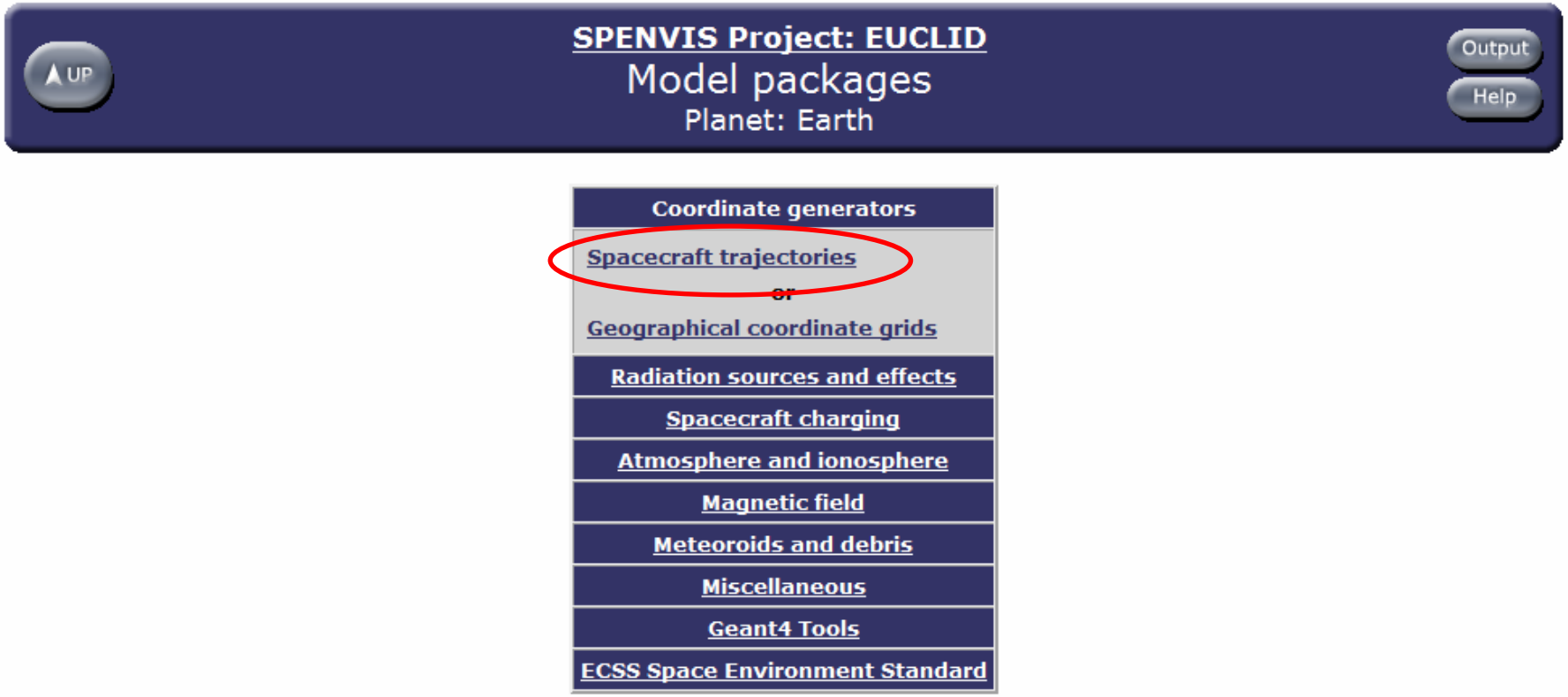
SPENVIS analysis

- Orbital parameters for spacecraft transfer provided by ISRO
- Orbital conditions for lunar orbit based on NASA data sheet
- Using appropriate dates



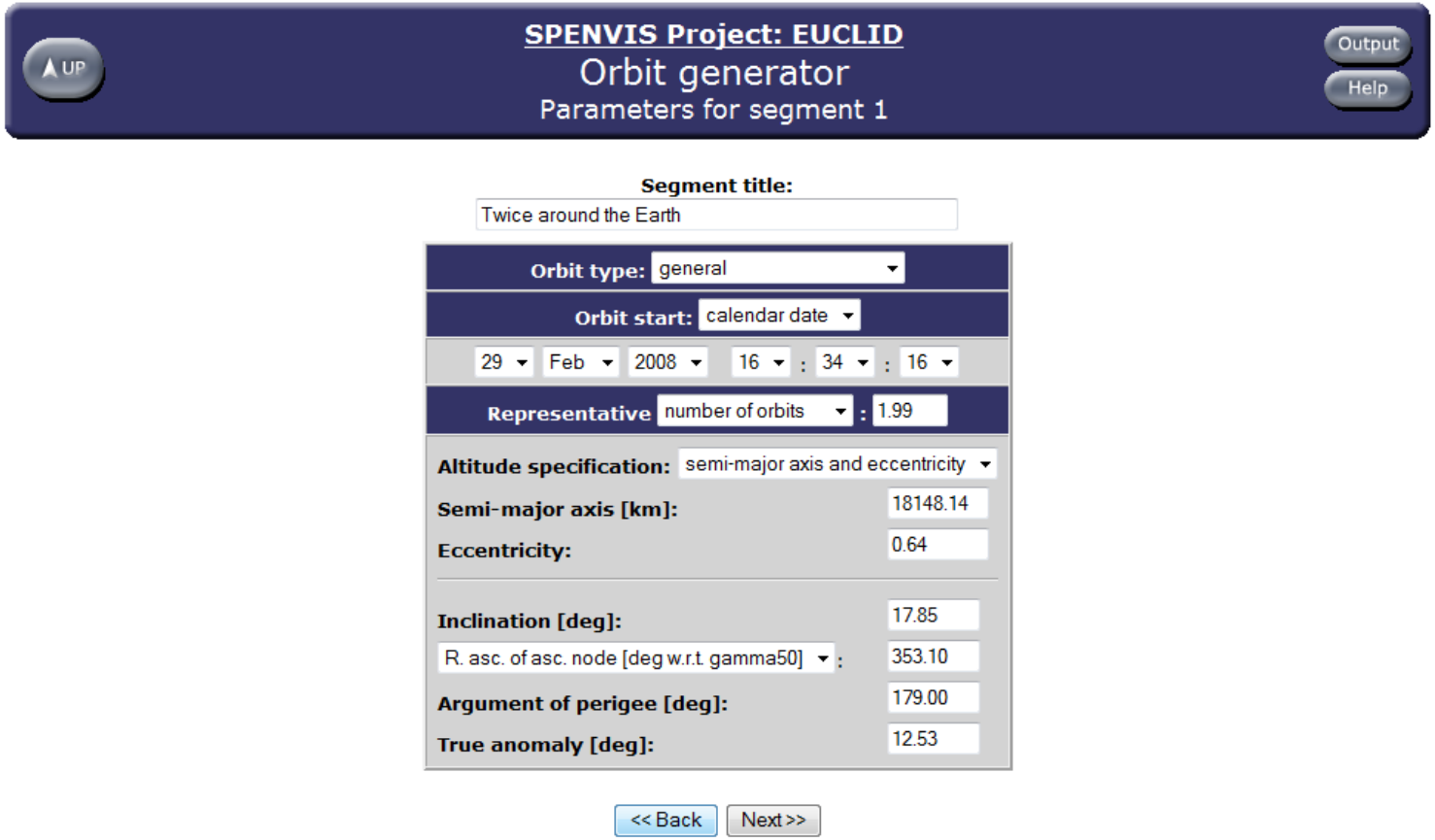
Orbit generator



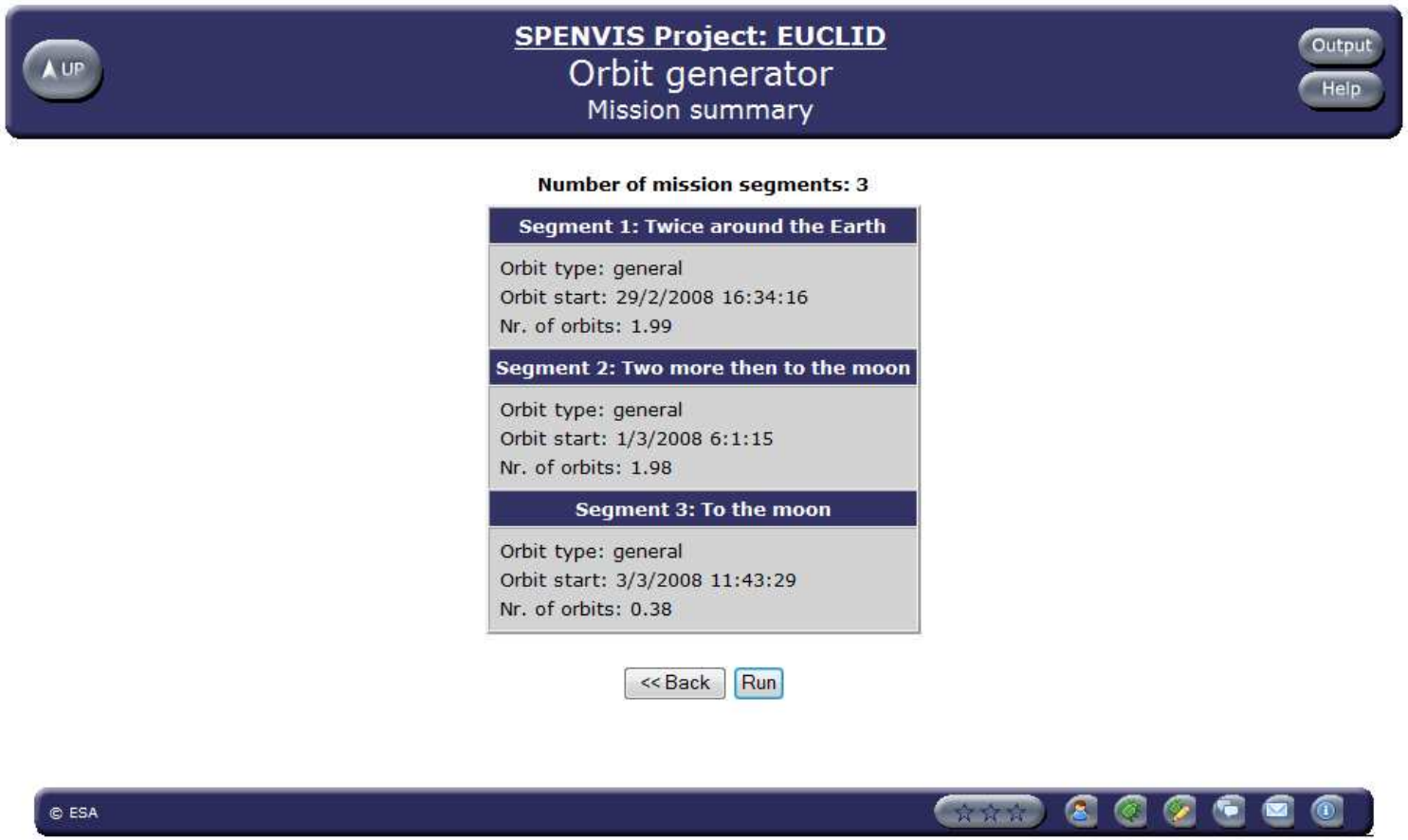
Orbit generator

- Input details into the orbital generator

Orbit generator

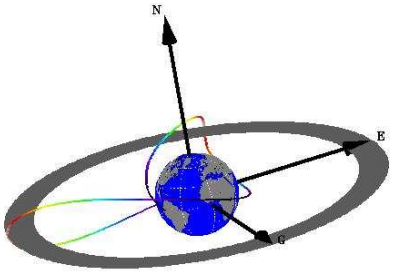


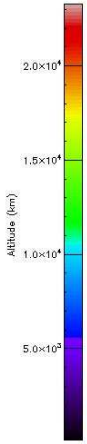
Orbit generator



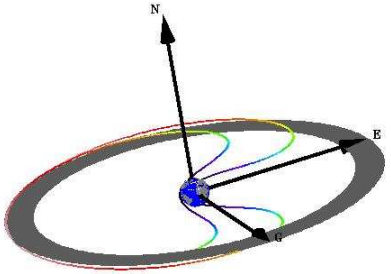
Orbit generator

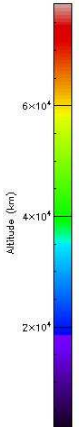
- ~ 7 days transfer from the Earth to the Moon
- 730 days at in Lunar orbit





Segment 1





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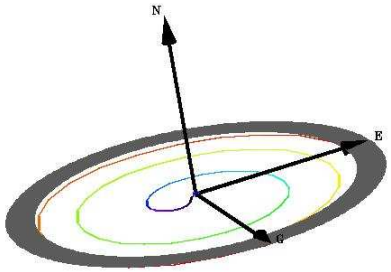

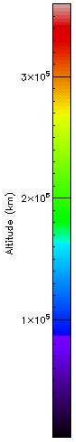

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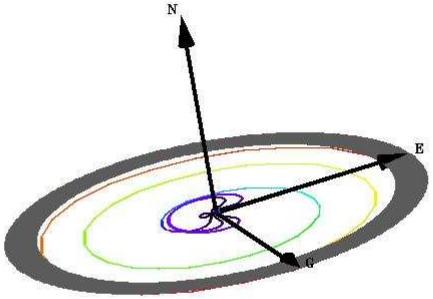
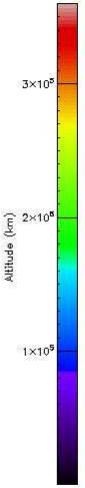
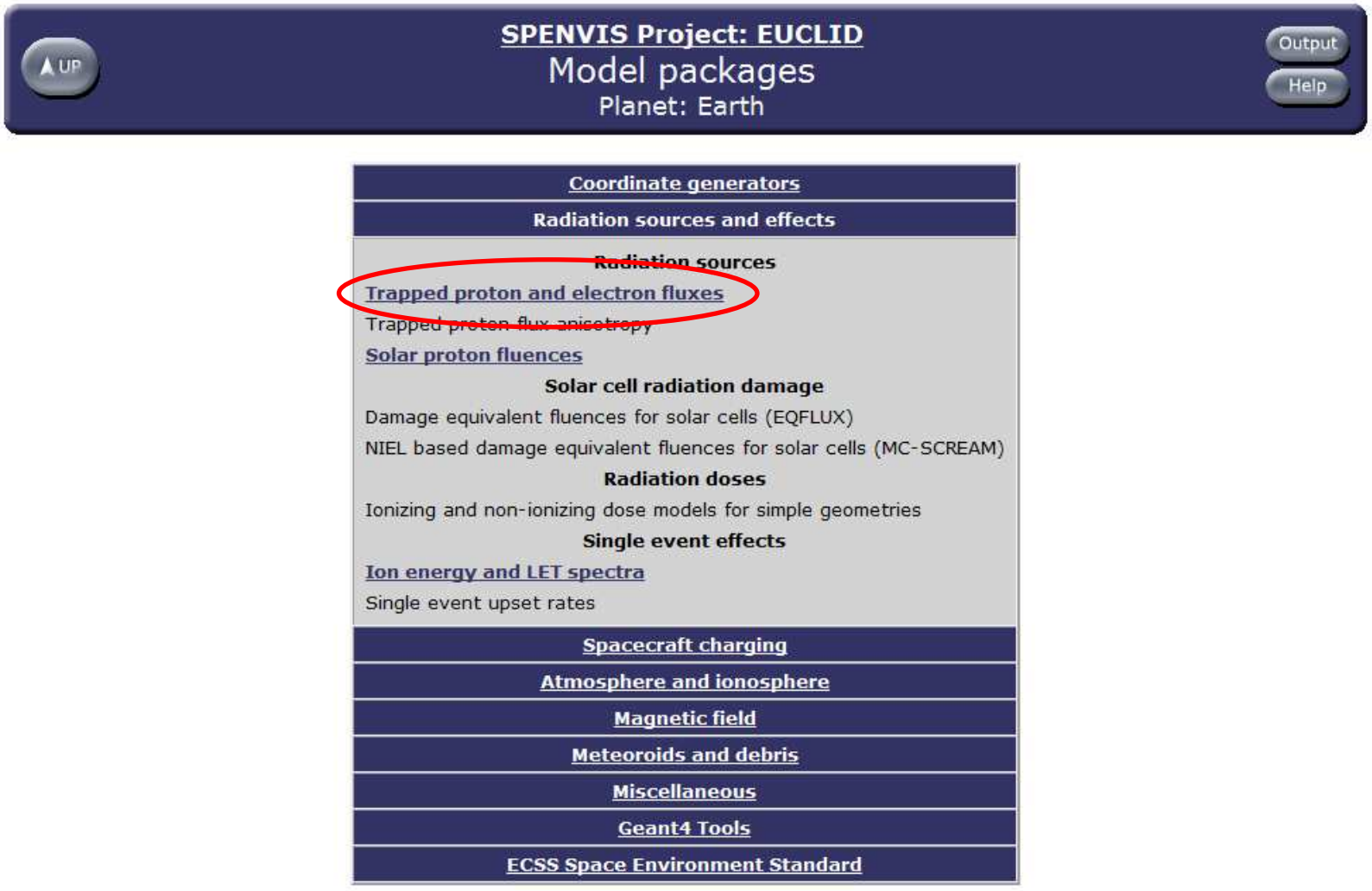


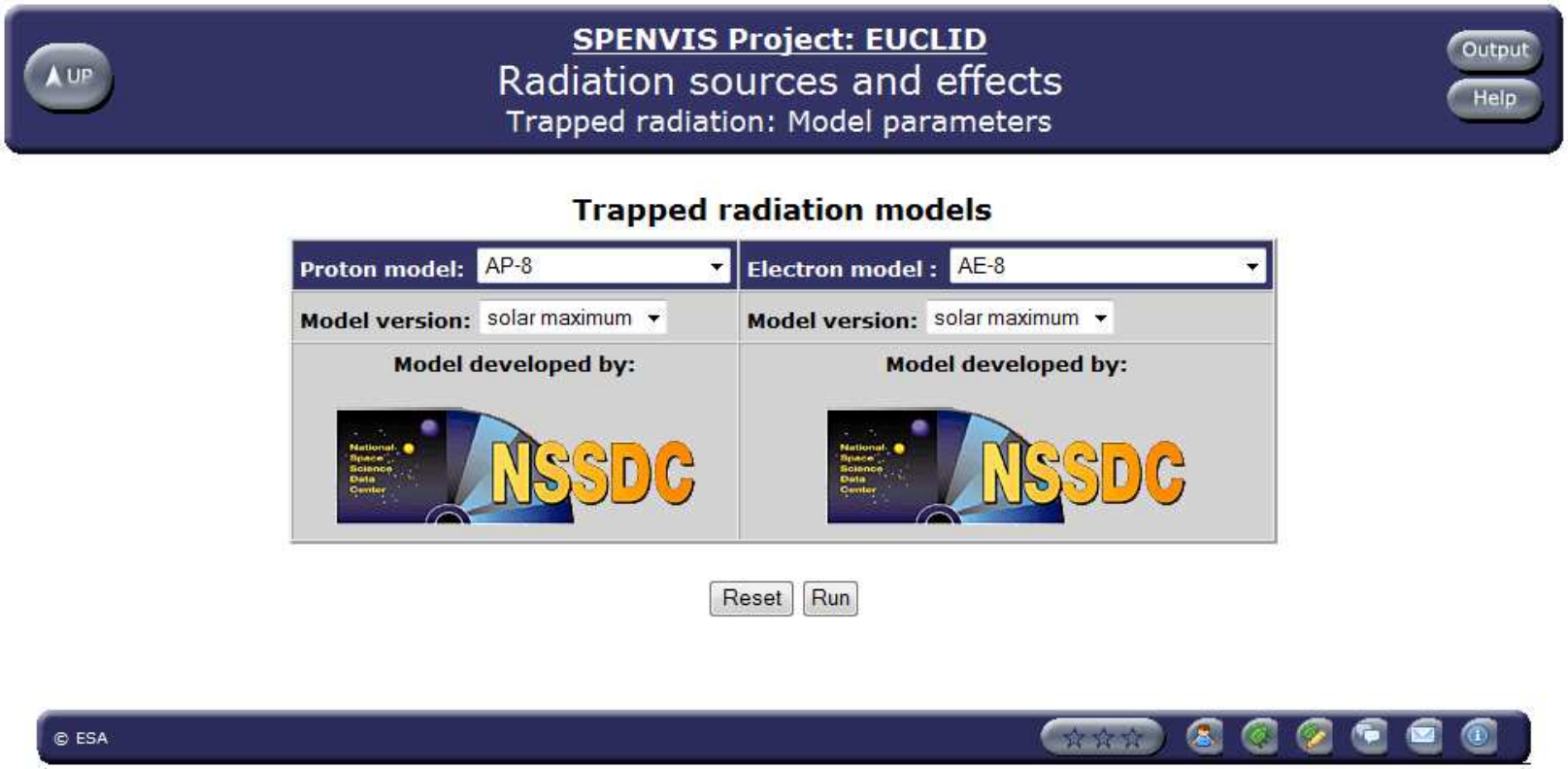


Earth-Moon transfer

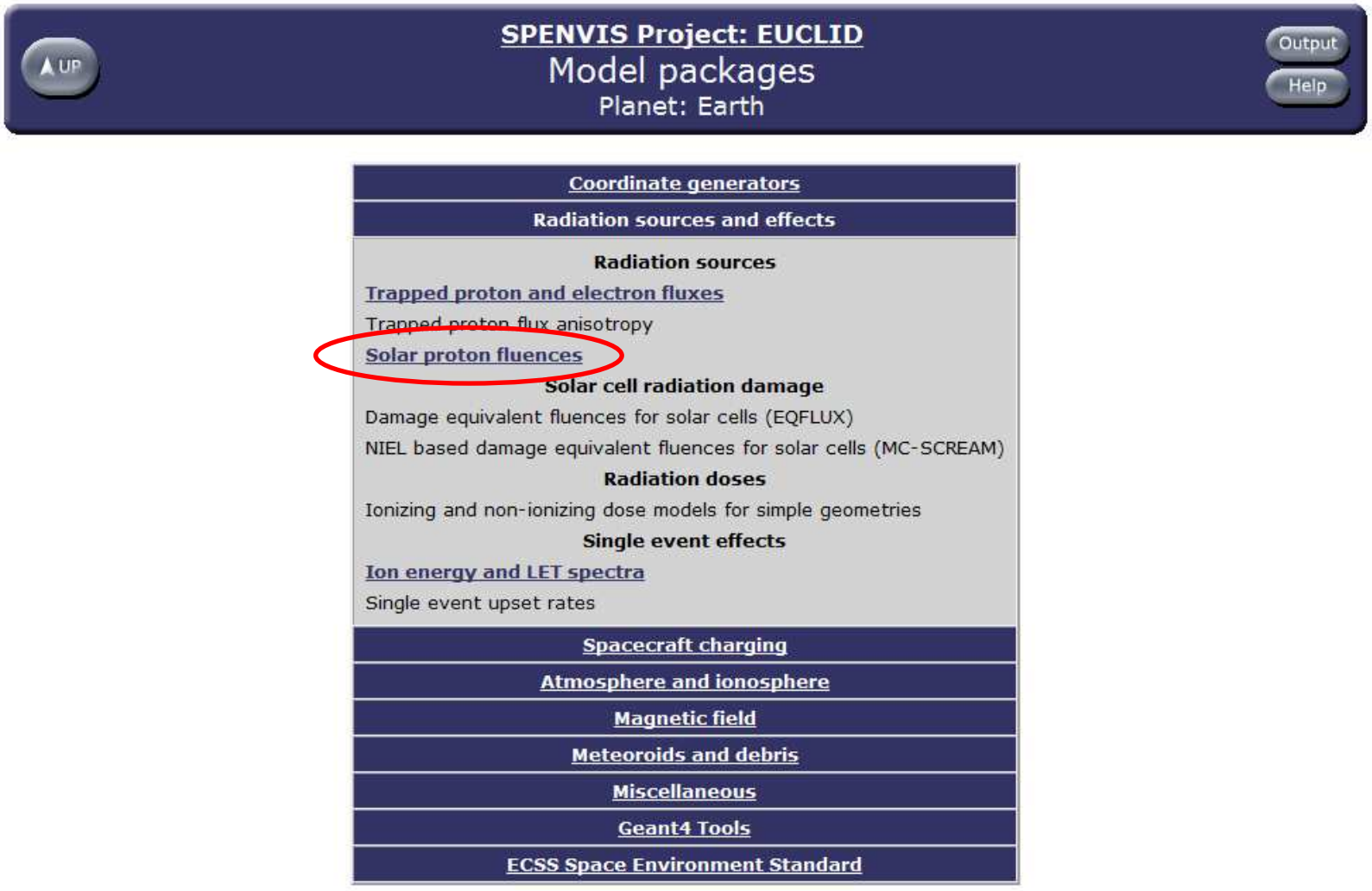
Radiation sources and effects



- Trapped radiation models

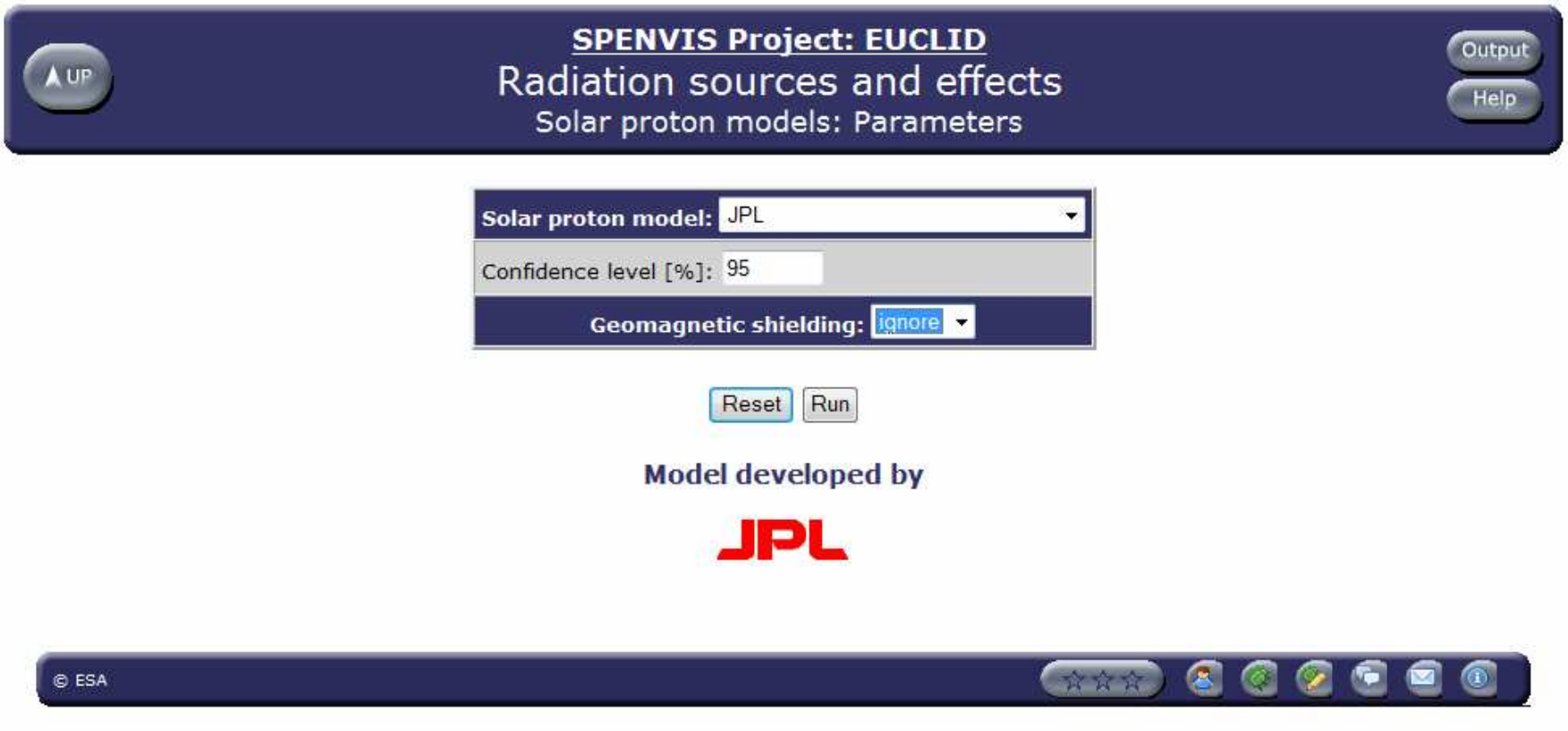


Radiation sources and effects

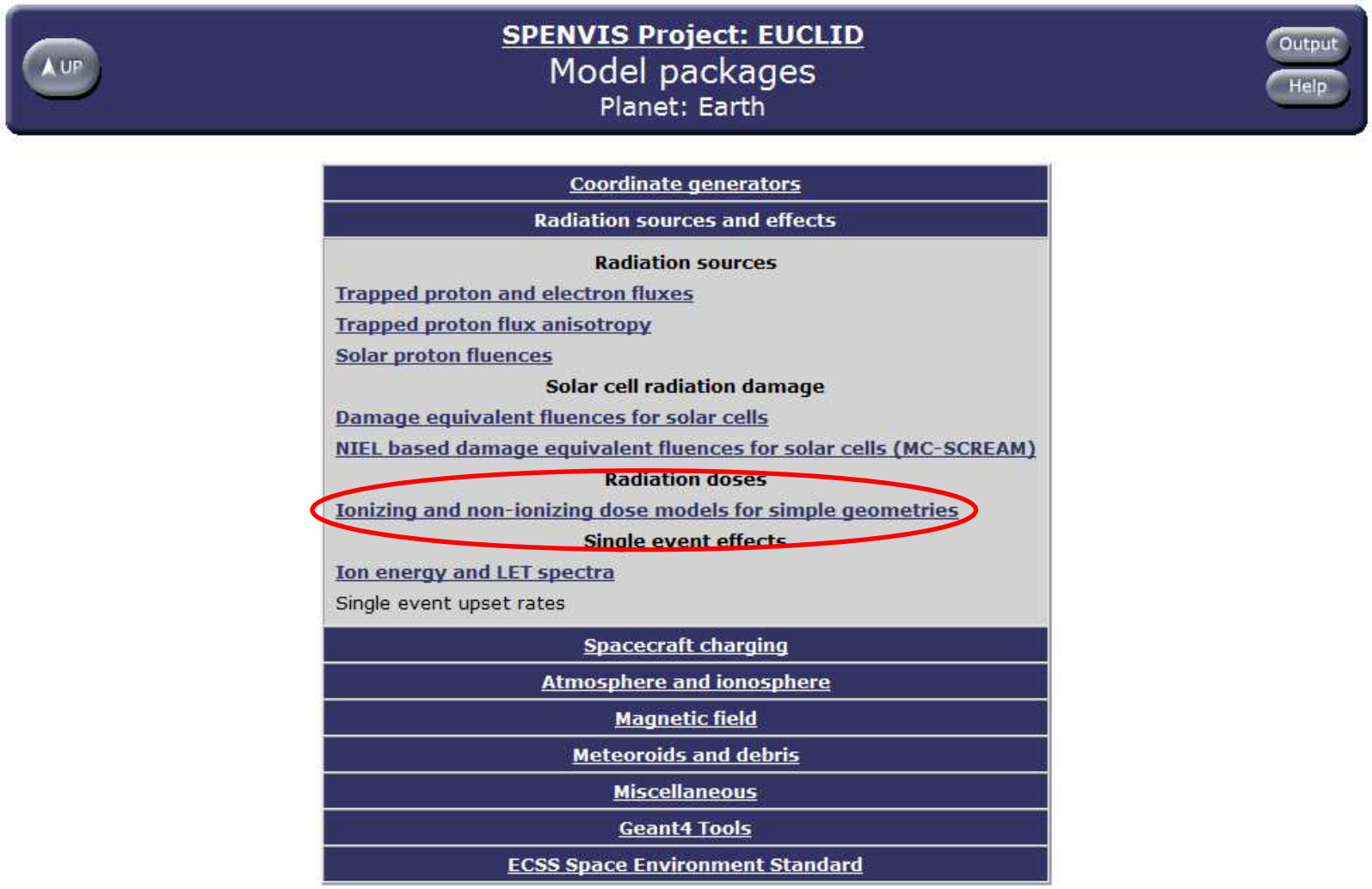


Radiation sources and effects

- Solar proton models

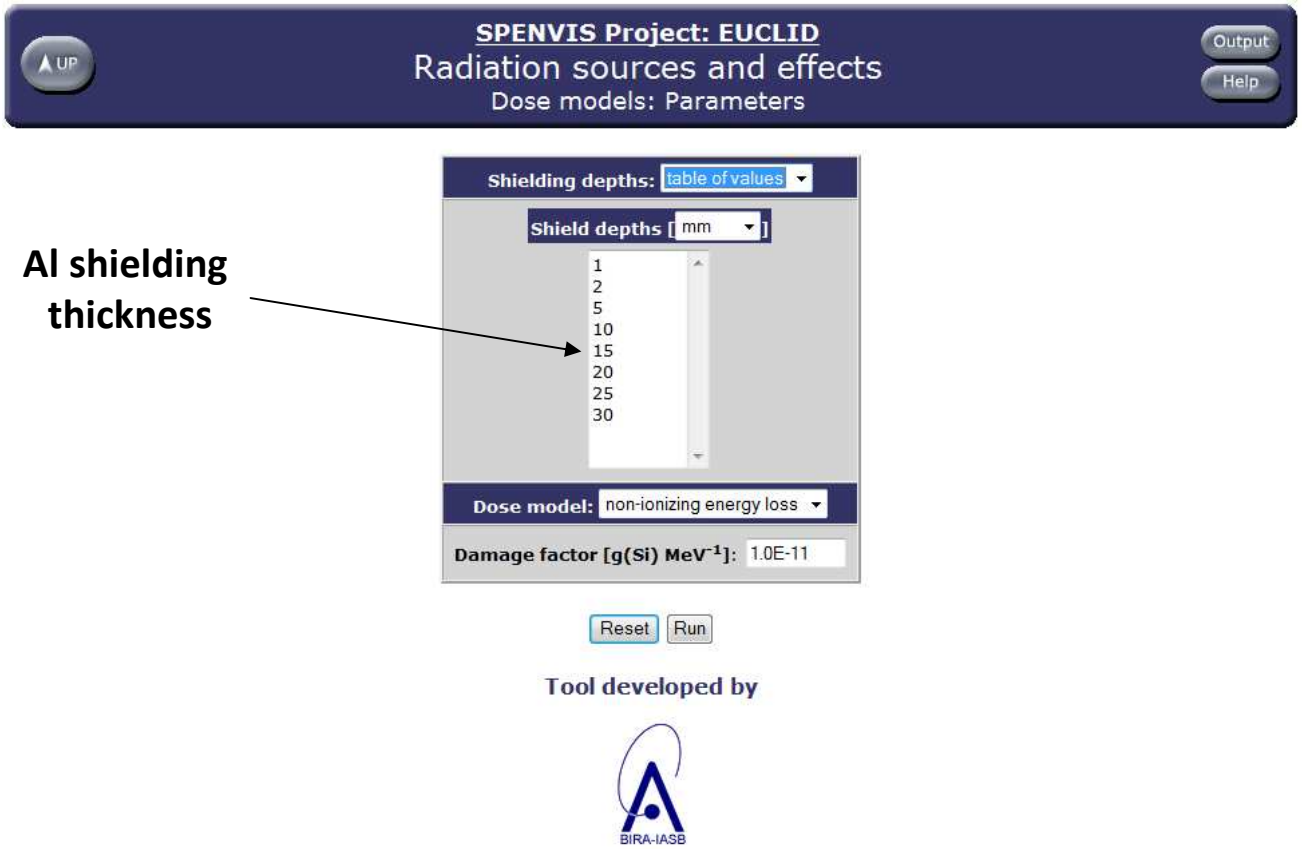


Radiation sources and effects



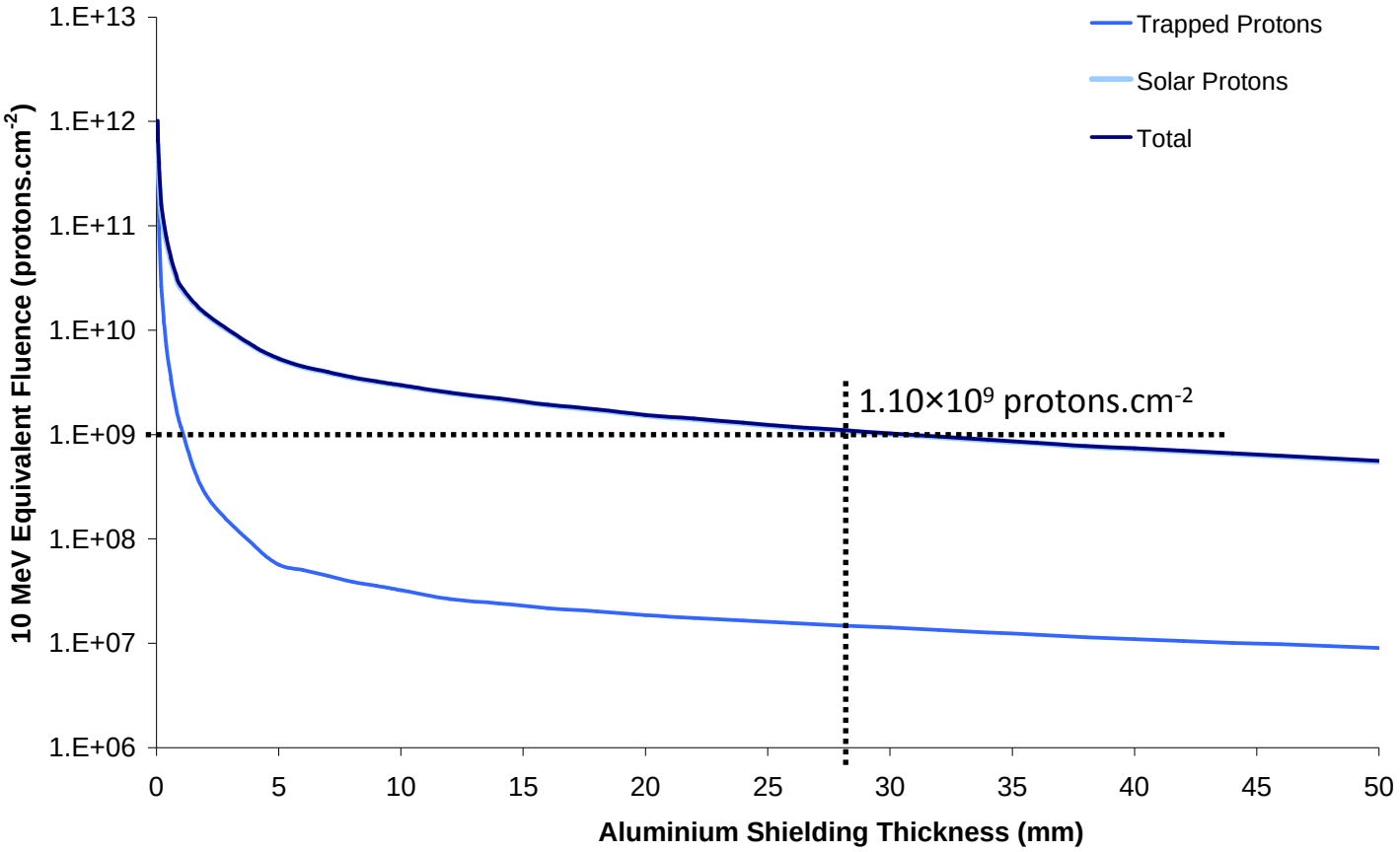
Radiation sources and effects

- Use the NIEL dose model to provide a 10 MeV equivalent proton fluence



Al shielding thickness

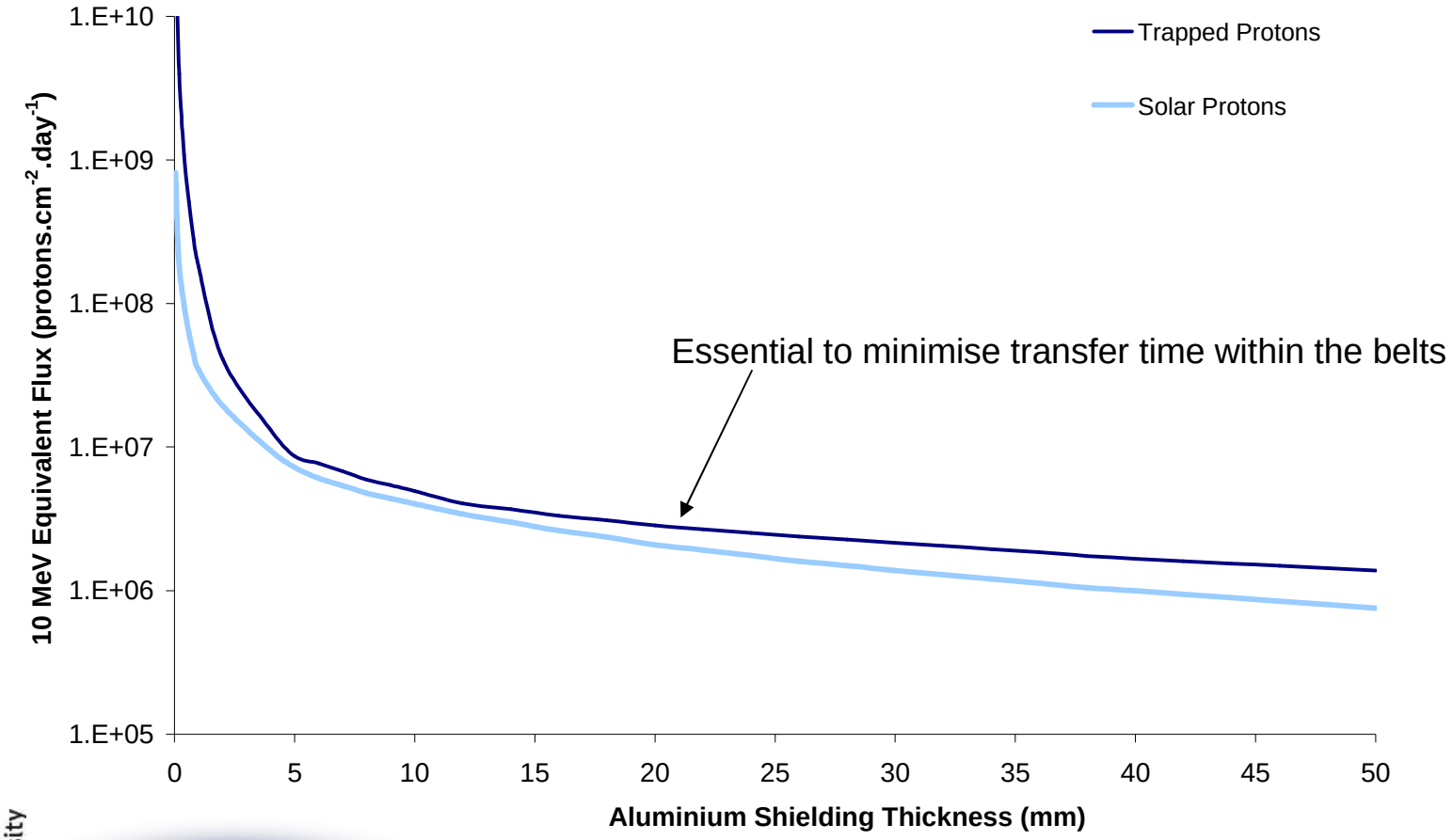
Space Radiation Environment



- Recommended using at least 3 mm of Al and 6 mm of Ta shielding
- The moon will shield the front 2π during the lunar stage of the mission
- End of life (EOL) 10 MeV equivalent proton fluence of **5.5×10^8 protons.cm^{-2}**

Space Radiation Environment

- Average proton flux calculated using **AP-8 trapped** and **JPL-91 solar proton** models, as a function of shielding thickness



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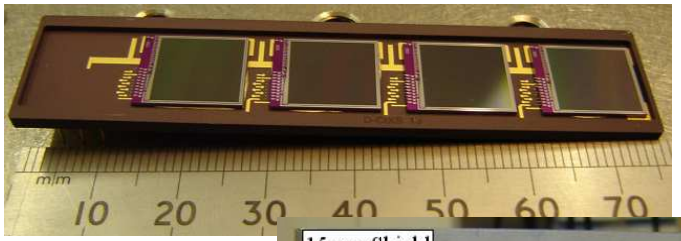
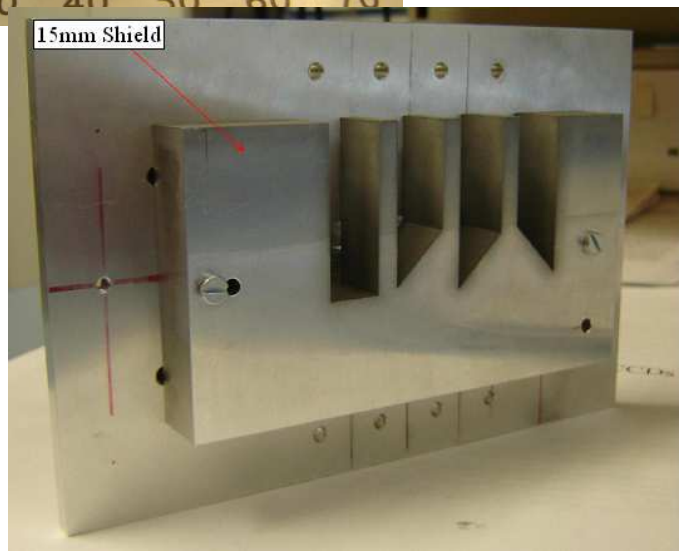
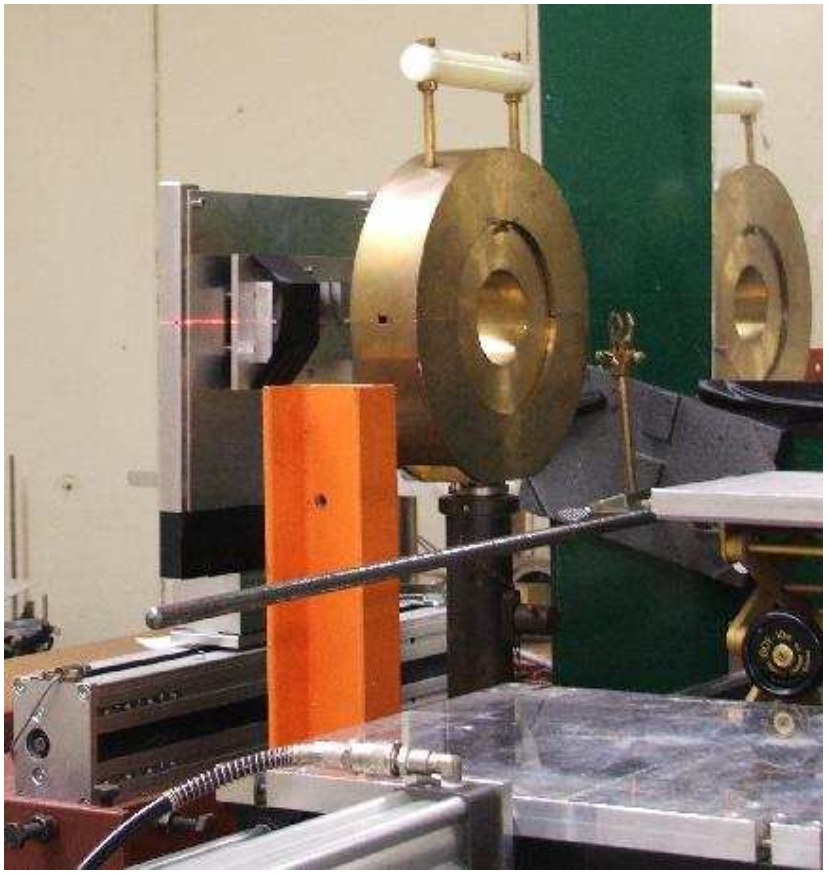
Proton Irradiation and CCD Analysis

- Irradiation performed at the Kernfysisch Versneller Instituut in Groningen







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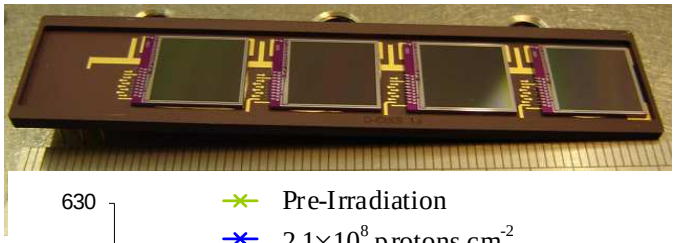
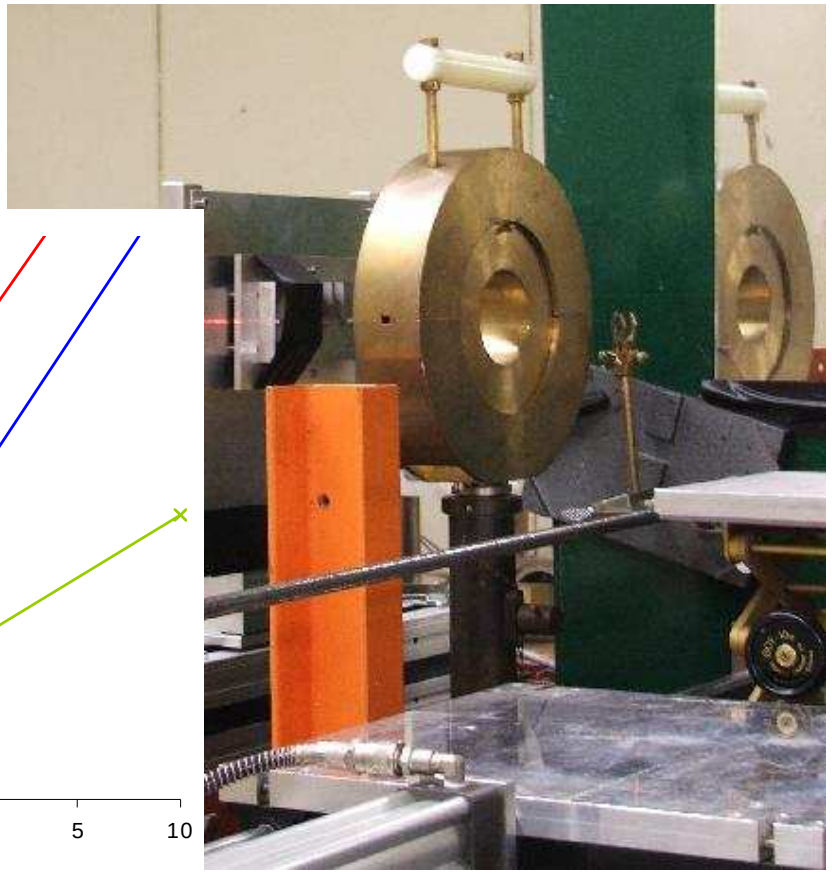
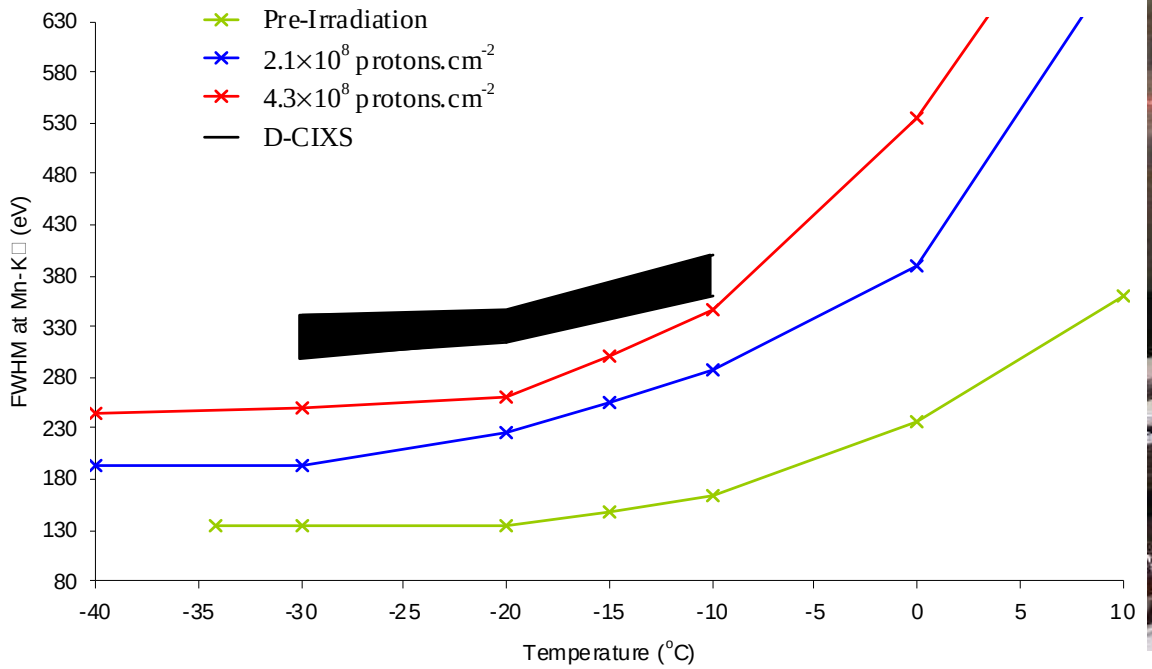




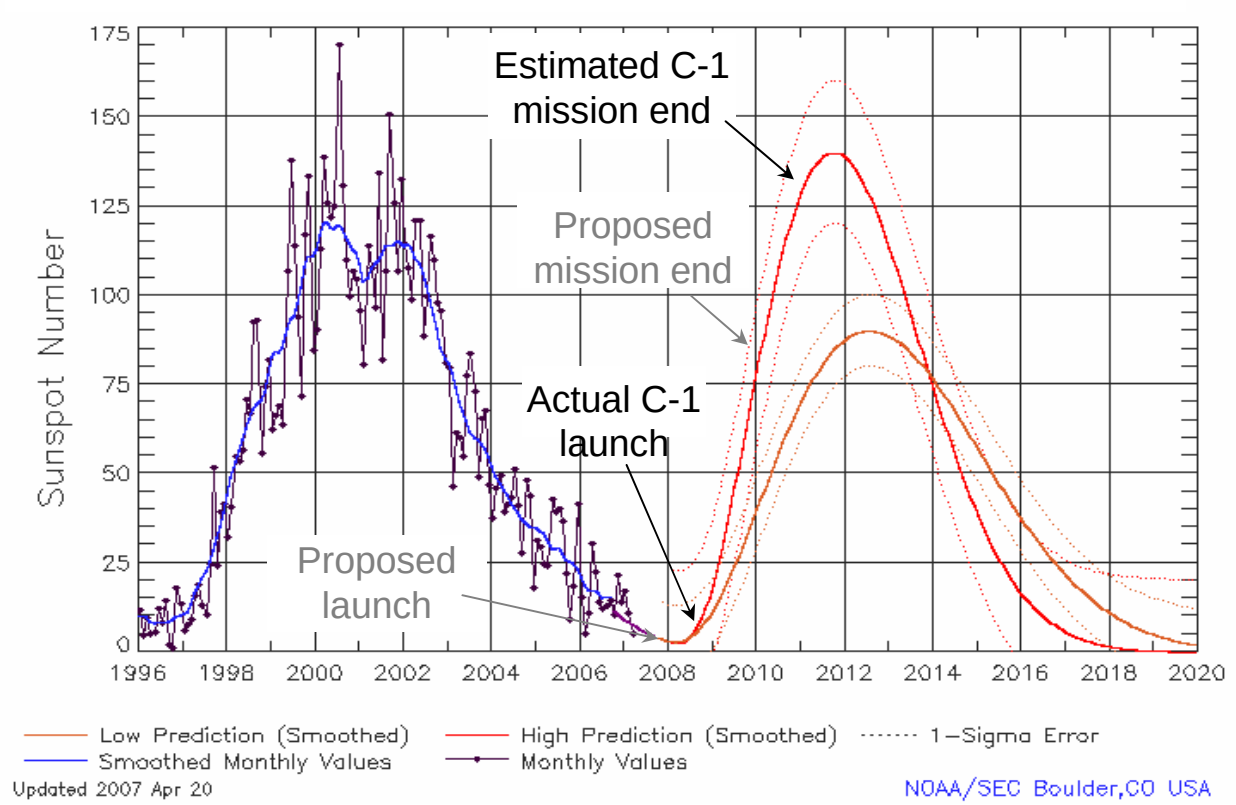


Proton Irradiation and CCD Analysis

- **Recommended**
  - Operational temperature of -20.0 °C
  - Operating potentials and timings
  - Increasing the gain provided by the camera system
- Location of C1XS onboard Chandrayaan-1 was changed and the C1XS design modified to provide improved thermal isolation between the C1XS drive electronics and the CCD54s
- **Shielding increased** to a 4 mm thick Al electronics box and 6 mm of Ta behind the CCD54 modules, with the window, shielding the detectors during the transfer orbit, reduced to 7 mm of Al due to the short amount of time spent within the belts.
- Code was developed in MATLAB to analyse the CCD54 read-out, with analyse using isolated or combined events as recommended to RAL. Isolated and a combination of three events was adopted for use on C1XS.
- Identified increased charge transfer inefficiency within the central transport channels as the main source of decreased energy resolution

SPENVIS analysis

- Launch delayed to 22nd October 2008
- Transfer time increased from 7 to 16.8 days
- Steps repeated to calculate the



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Space Radiation Environment

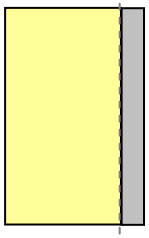
- End of life 10 MeV equivalent proton fluence = **8.81×10^{8} protons.cm^{-2}**

Transfer

Rear 2π

4 mm Al + 6 mm Ta

Trapped = 0.15×10^{8}
Solar = 0.23×10^{8}



Front 2π

7 mm Al

Trapped = 0.41×10^{8}
Solar = 0.67×10^{8}

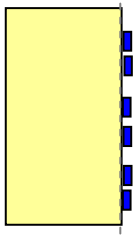
1.46×10^{8} protons.cm^{-2}

Lunar

Rear 2π

4 mm Al + 6 mm Ta

Trapped = 0
Solar = 7.35×10^{8}



Front 2π

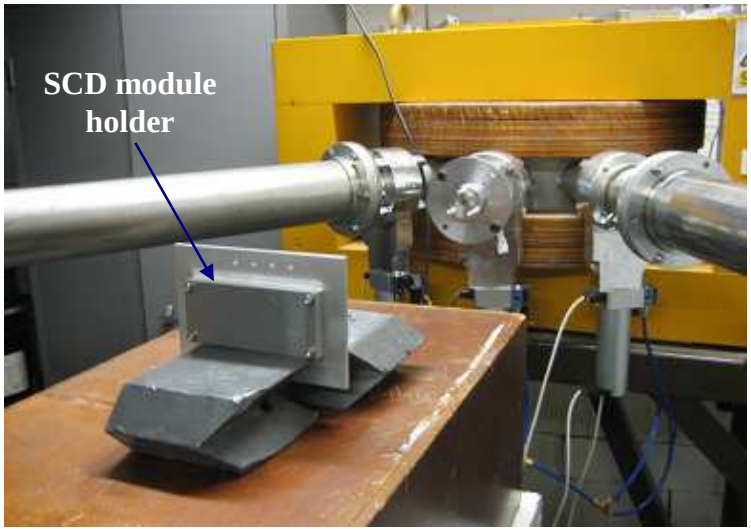
0

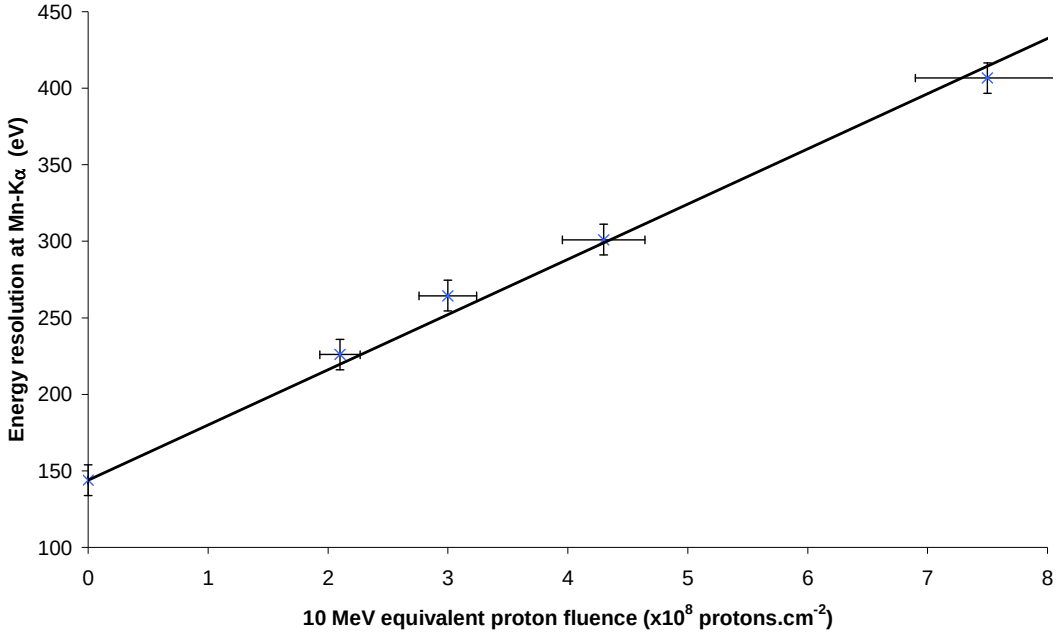
Trapped = 0
Solar = negligible

7.35×10^{8} protons.cm^{-2}

Proton Irradiation and CCD Analysis

- Investigation into the dark current
- Energy resolution as a function of energy and temperature
- Improvement into instrument and device performance
- Modifications to future device design to improve charge transfer efficiency
- Creation of a model to simulate in flight performance based on temperature and received proton fluence





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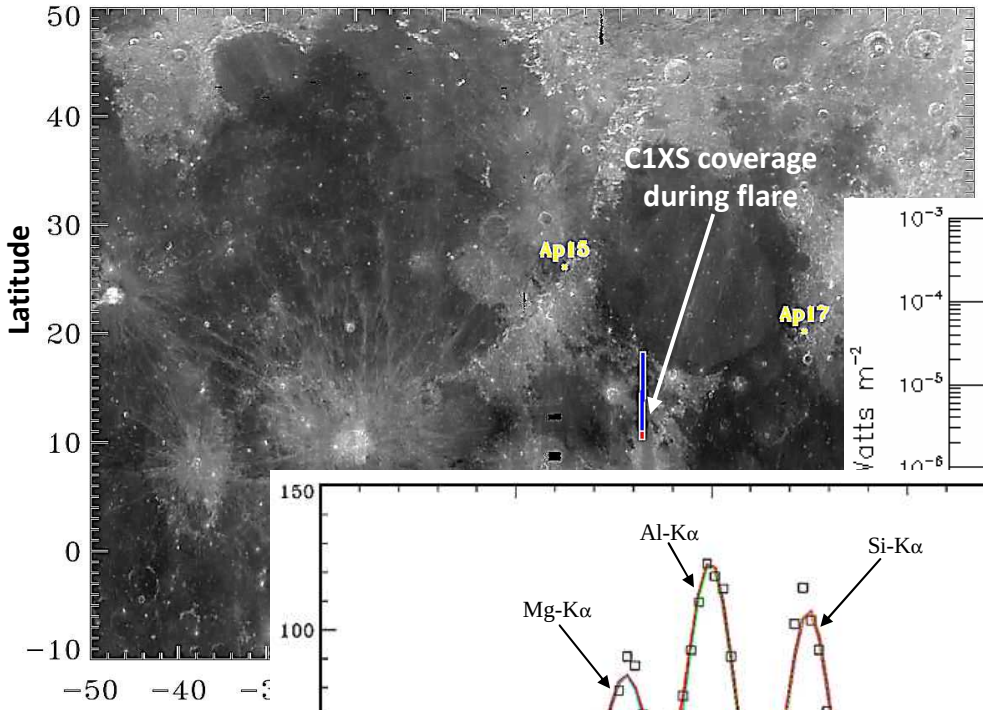
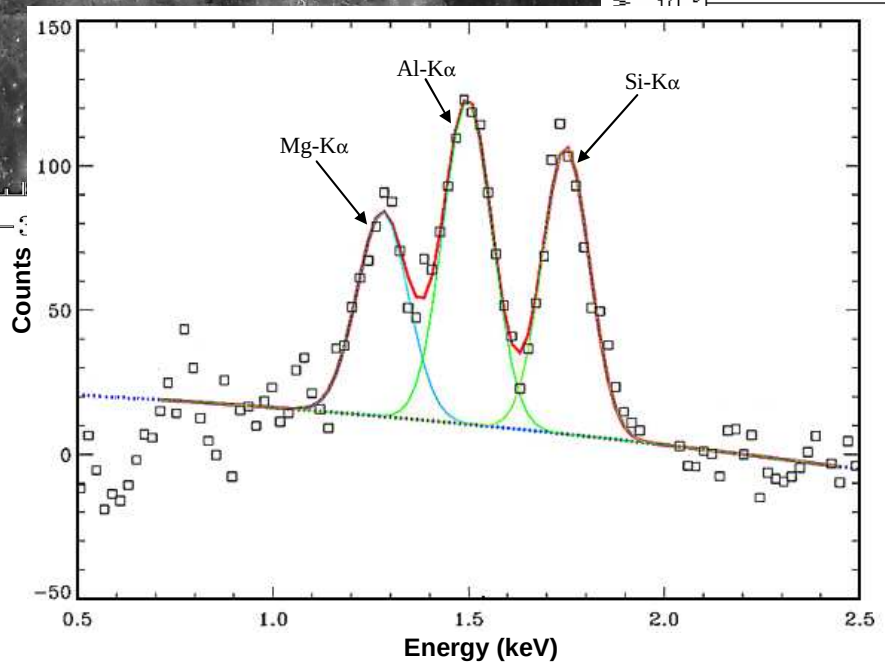
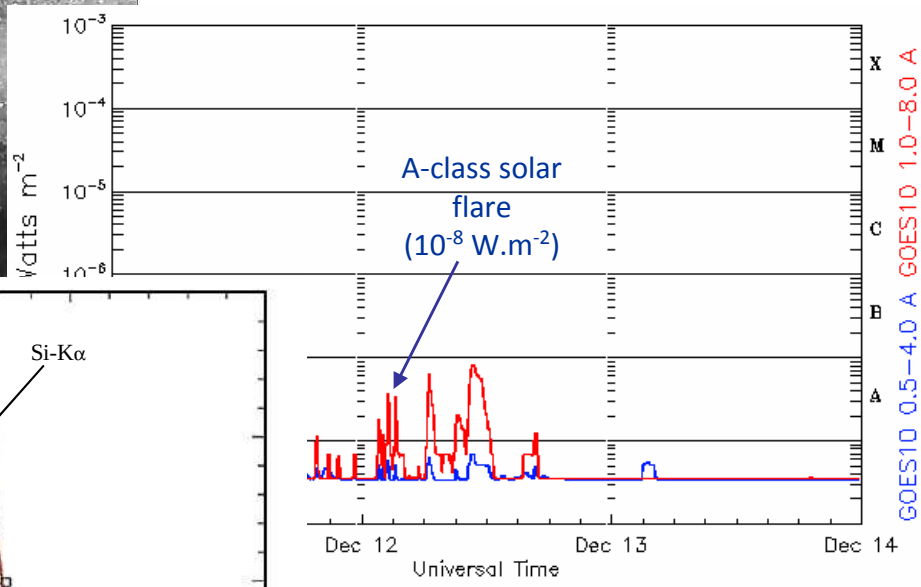
C1XS – Initial results



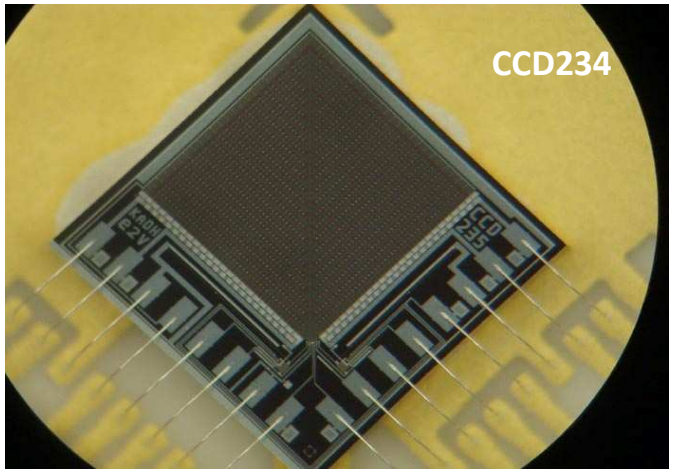




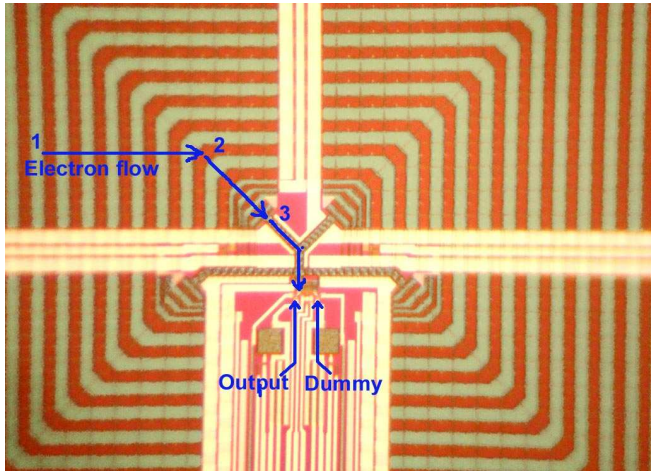
Images courtesy of the C1XS science team

The next generation SCD

- Only one central transport channel (reduced volume compared to the CCD54)
- Increased sample size (100 µm, increased from 25 µm)
- Two-phase clocking operation
- Inclusion of a dummy output to enable suppression of clock-induced pickup from the video signal
- Three variants
  - CCD234 a 110 mm^2 device (comparable size to the CCD54)
  - CCD235 a 5.2 mm^2 device
  - CCD236 a 420 mm^2 device (effectively a set of CCD54's in a four leaf clover design)



e2v



CCD236, showing the combination of the four imaging areas

The Open University

Detector Calibration

- Fe-55 X-ray calibration source used on the 21st of November 2008 to measure instrument performance

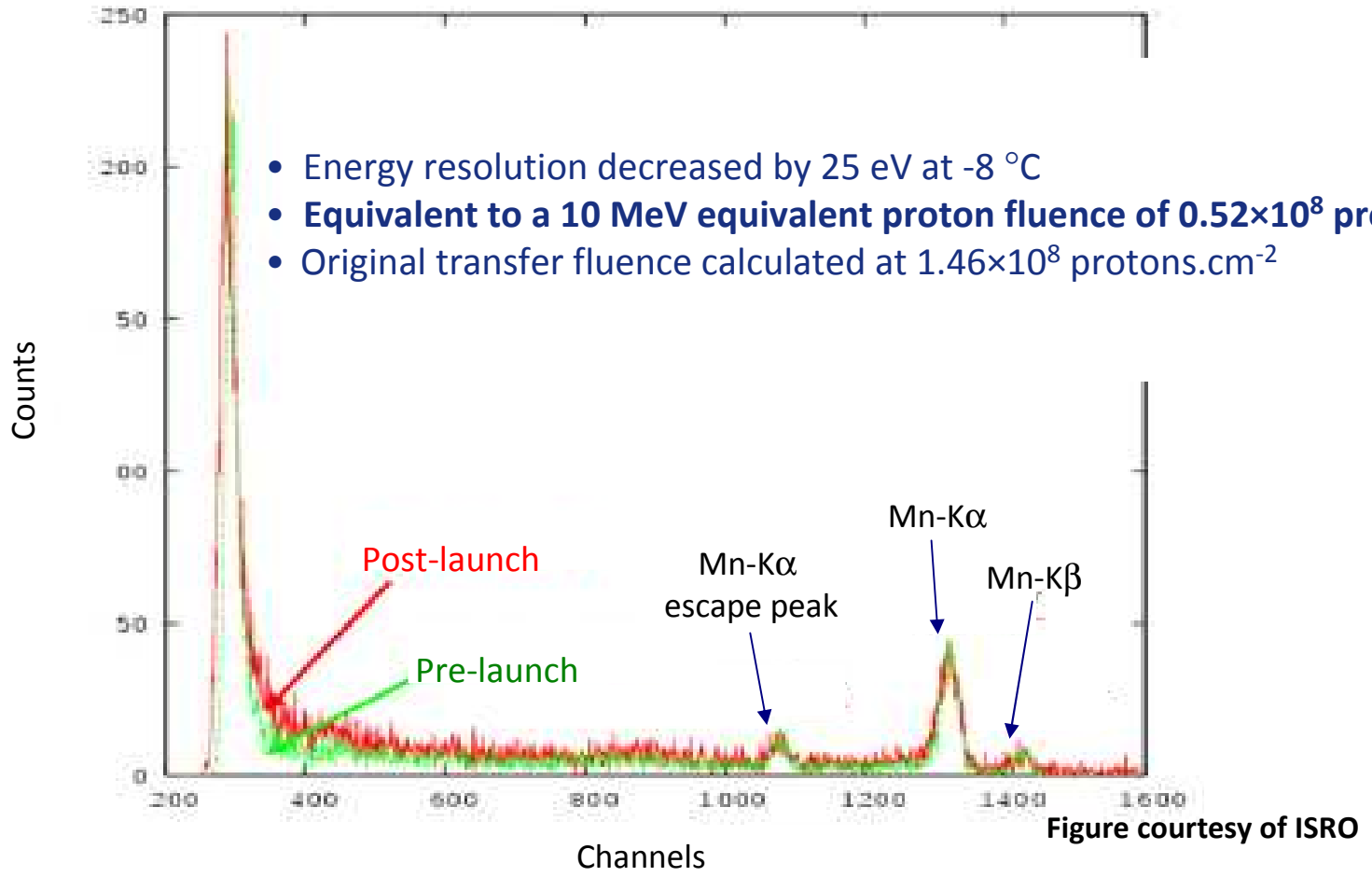
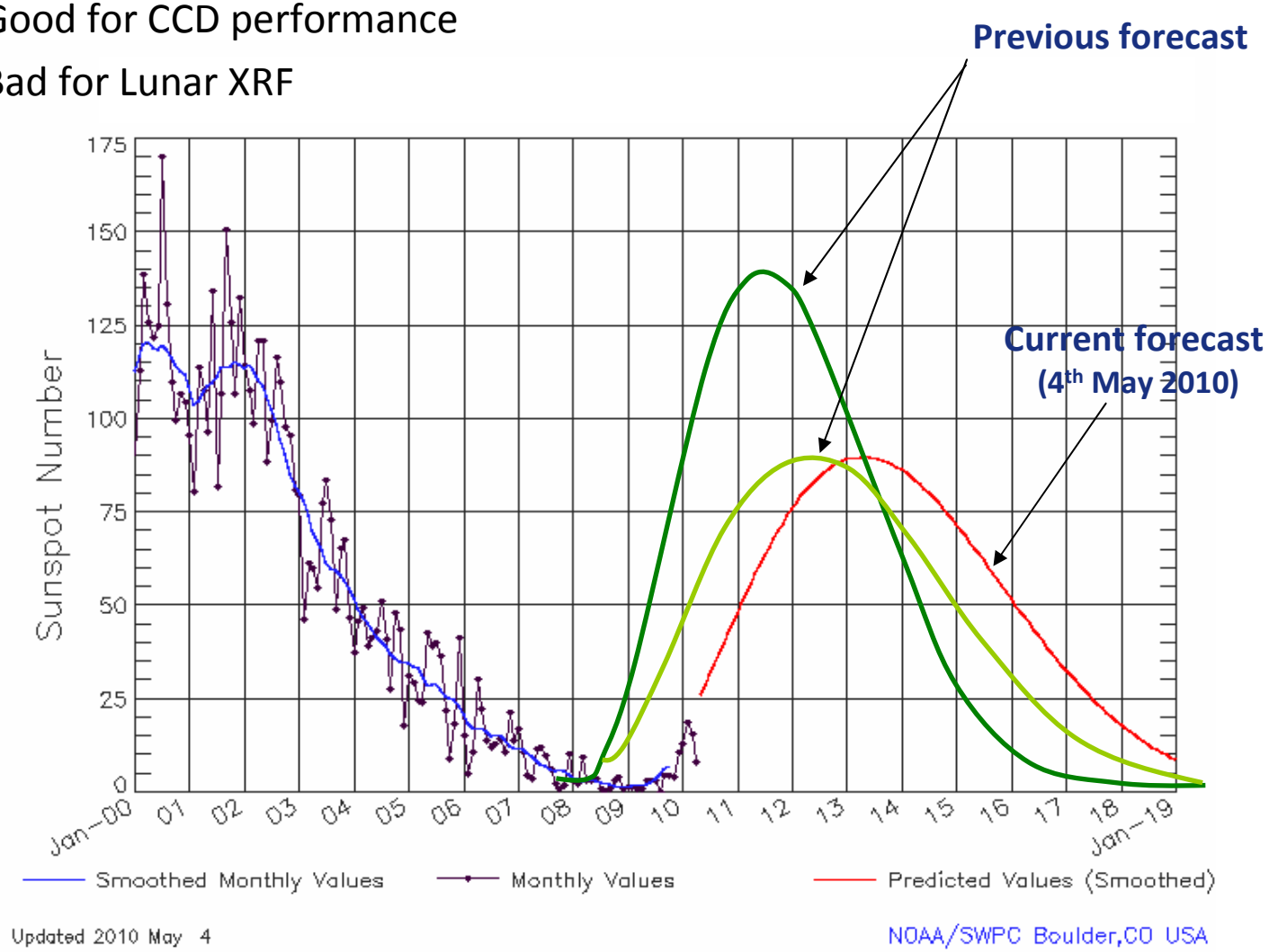


Figure courtesy of ISRO

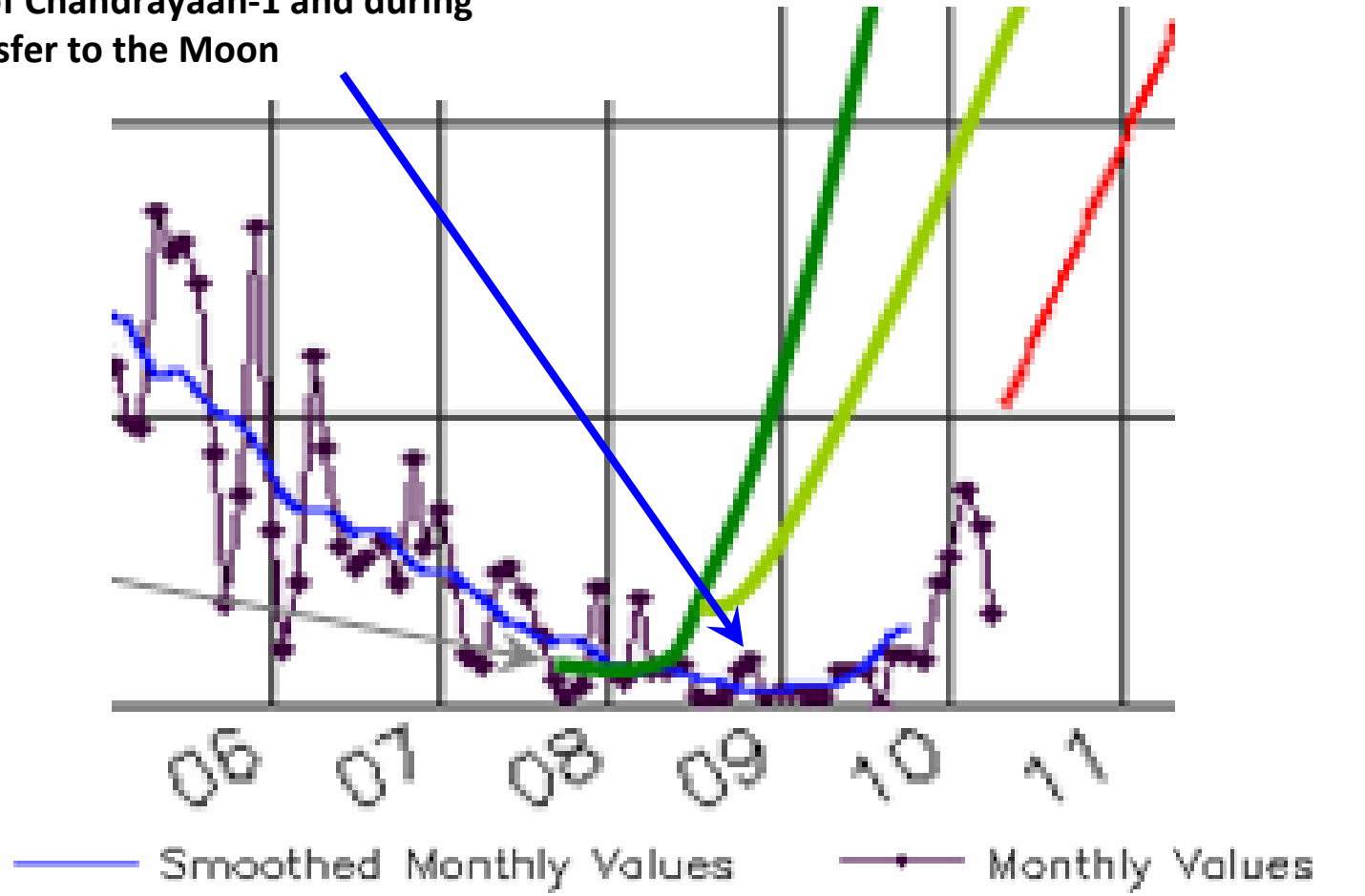
Solar cycle 23 and 24

- Conditions at the start of cycle 24 were very quite
  - Good for CCD performance
  - Bad for Lunar XRF

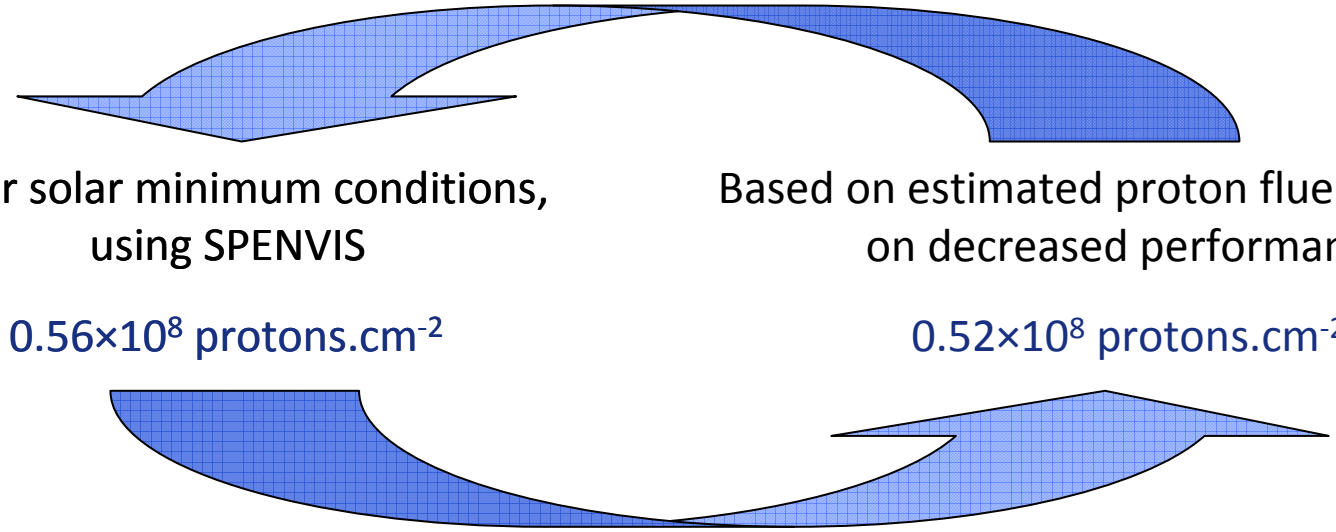


Solar cycle 24

Very little solar activity around the launch of Chandrayaan-1 and during the transfer to the Moon



Comparison of proton fluence



- Further analysis over a period of months is being performed and will be discussed at SPIE in San Diego later this month
- Comparisons to onboard dosimetry are also underway, with the aim to publish later this year

Summary

- SPENVIS used to provide an end of life 10 MeV equivalent proton fluence, to which a number of devices were irradiated
- Analysis performed to recommend mission operating conditions and changes to future device structure
- C1XS demonstrated excellent performance while in orbit around the Moon (there is a flight spare)
- Next generation devices demonstrated twice the radiation hardness when compared to the original
- SPENVIS and model data in close agreement