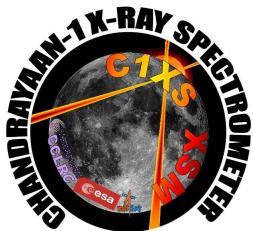


e2v centre for electronic imaging



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



J. Gow, D. R. Smith, S. Narendranath, P. Sreekumar, C. Howe,
B. Kellett, M. Grande, A. D. Holland



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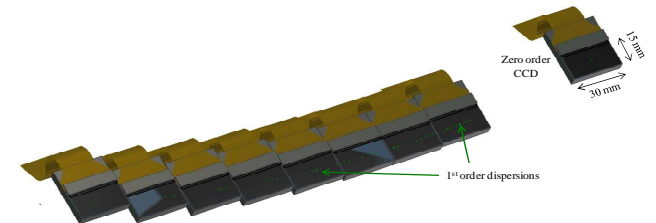
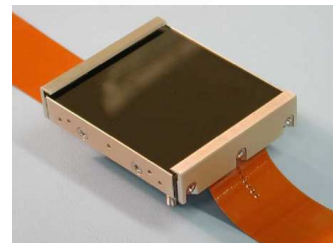
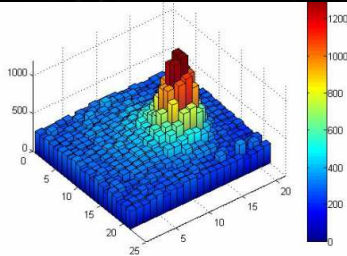
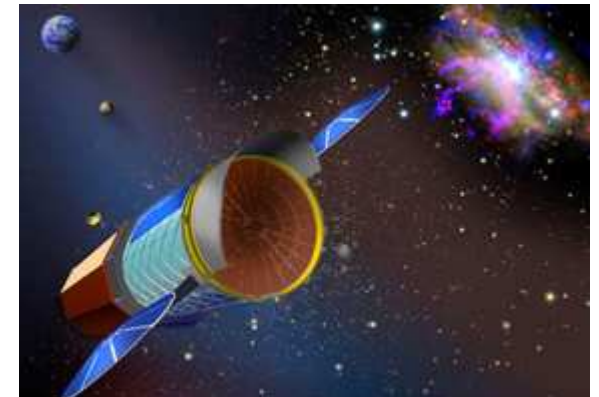
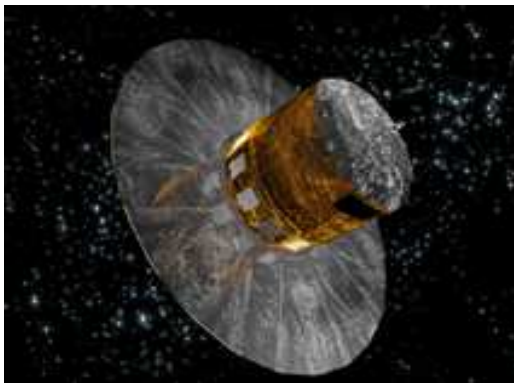
ISTA





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

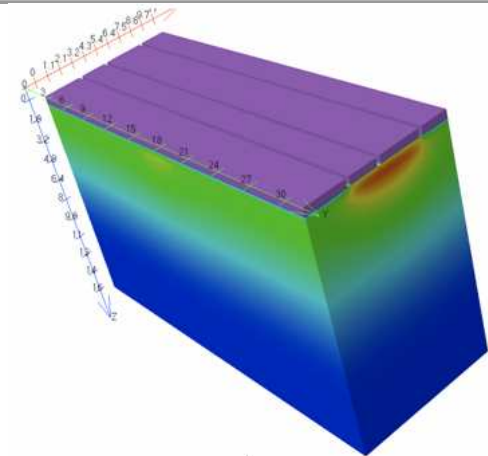


Fundamental Understanding

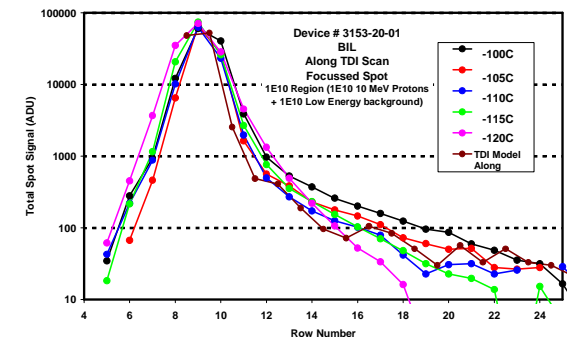


- **Radiation Damage**
 - Developing a physical understanding of the damage mechanisms in silicon
- **Device Modelling**
 - Use of advanced 3D simulation tools and Monte Carlo code to understand device operation
- **Detector Characterisation**
 - Development of test methodologies to both provide feedback 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

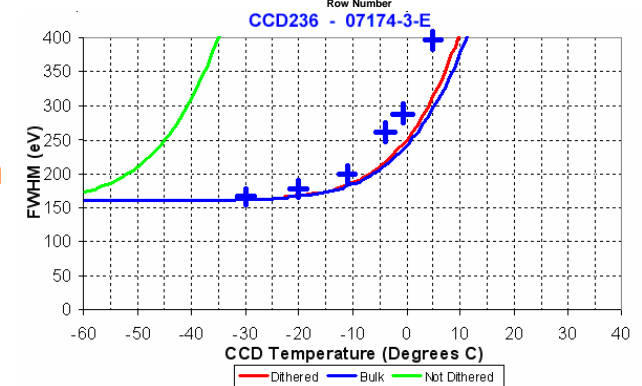
3D simulation



Modelling



Characterisation



Talk Overview

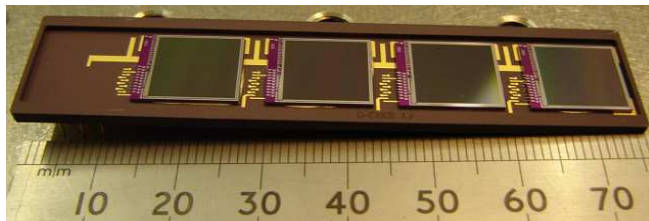


- The swept charge device
- SMART-1 and D-CIXS
- Chandrayaan-1 and C1XS
- The space radiation environment and SPENVIS
- Proton radiation damage assessment
- Effects of a delayed launch date and increased transfer time
- The next generation of swept charge device
- Comparison of the proton fluence received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

The Swept Charge Device



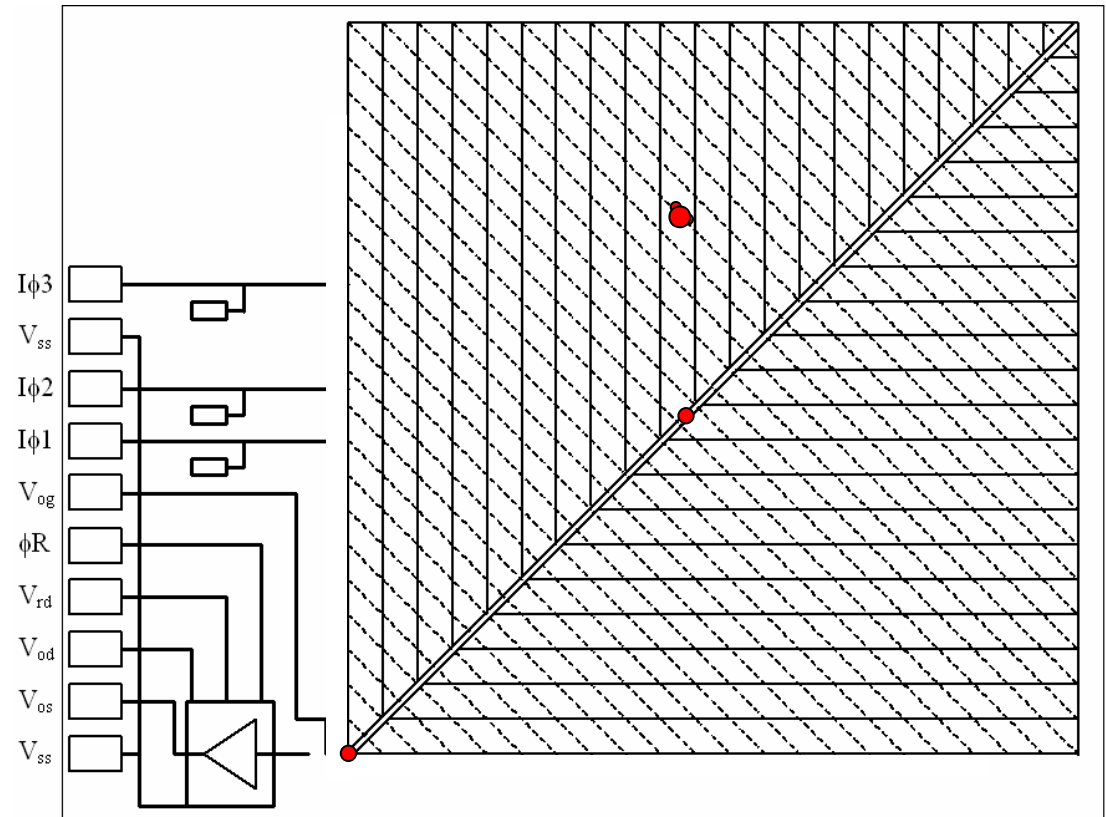
- Developed by **e2v Technologies plc** specifically for X-ray fluorescence analysis
 - **Continuous clocking** used to minimise the surface generated dark current
 - Avoids an Image integration period
 - High rate of periodic charge clocking ($100 \text{ kHz} \cdot \text{sample}^{-1}$)



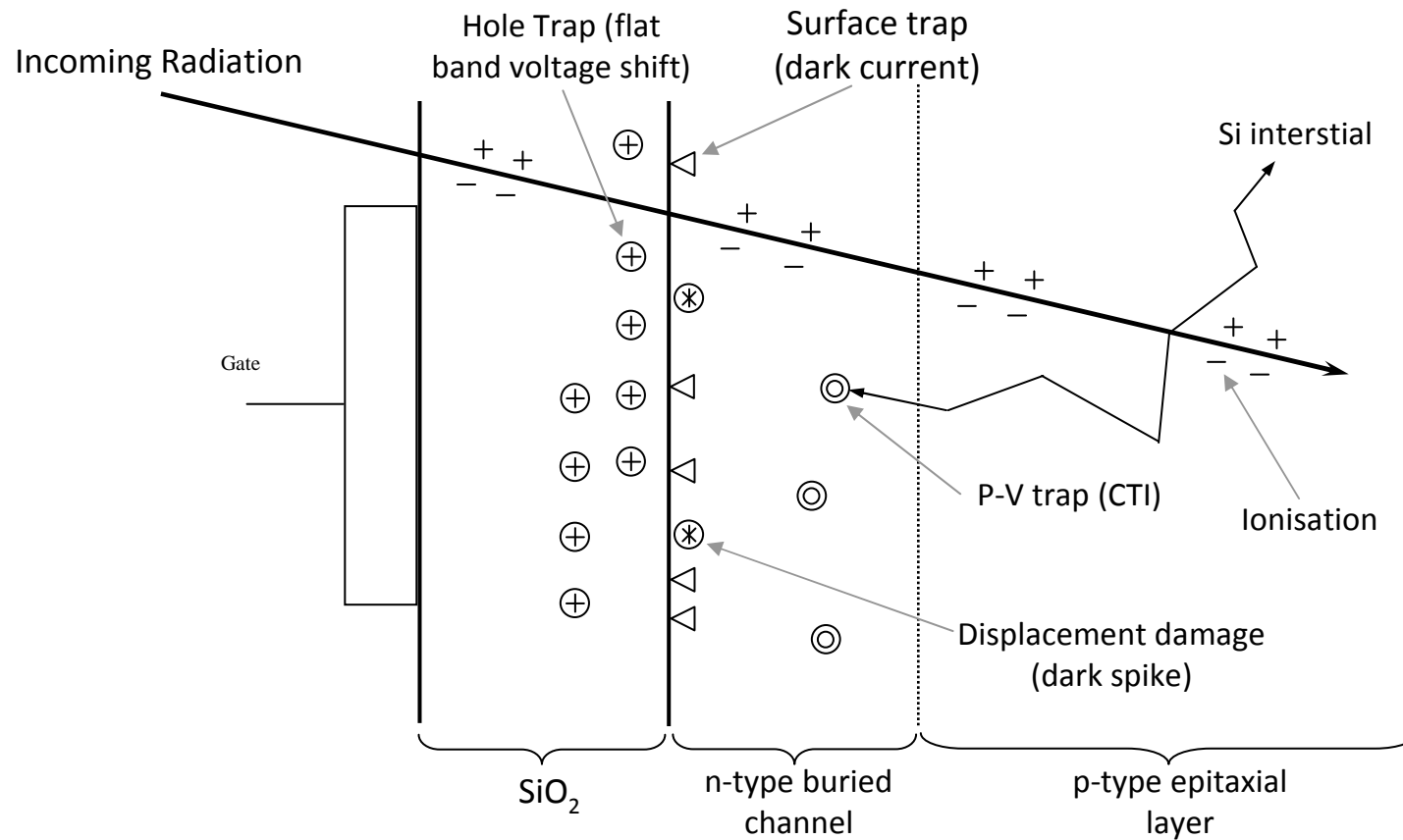
CCD54 Module

Linear output of 575 'pixels'

↑
Measured X-ray charge



Radiation damage effects



SMART-1 and D-CIXS

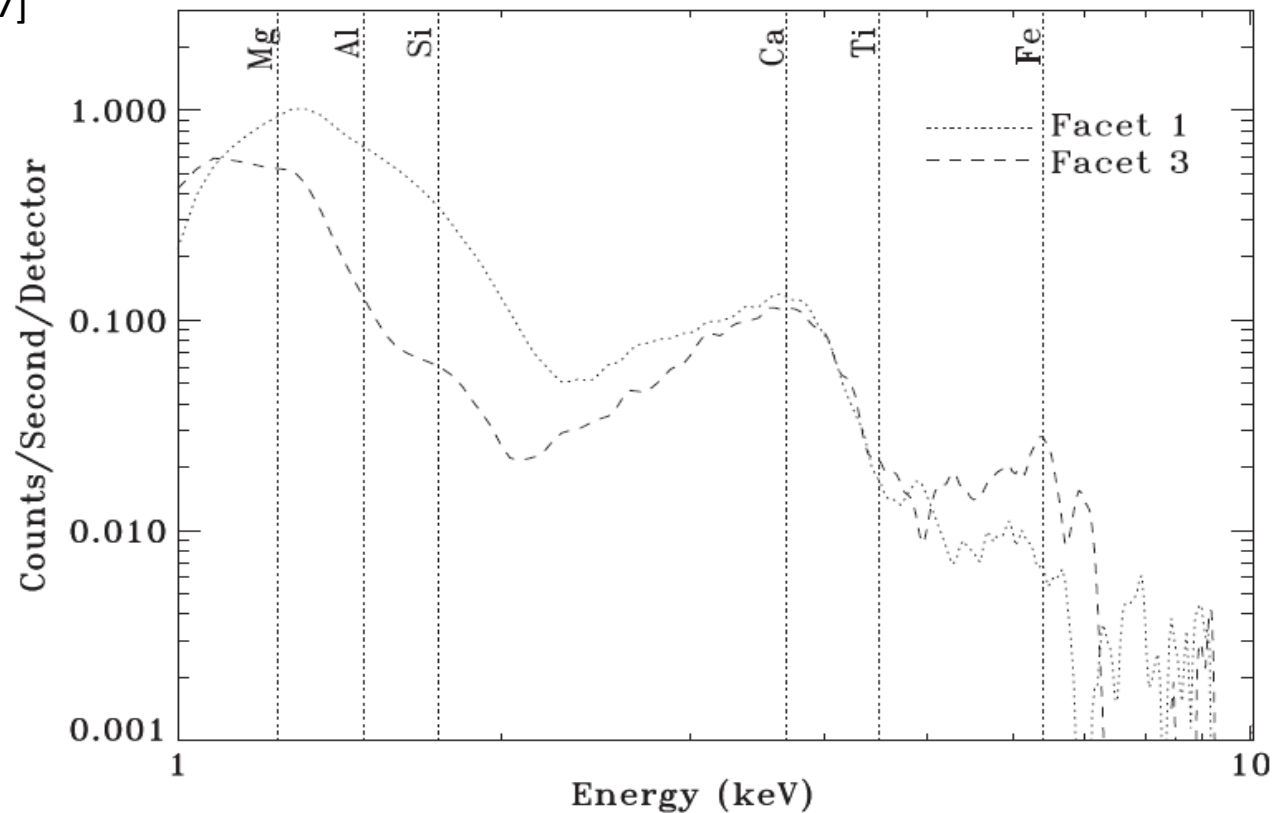
- **Small Missions for Advanced Research in Technology (SMART-1)**
 - European Space Agency technology demonstrator mission for an Ion propulsions engine
 - Spent 15 months and 332 Earth orbits to get into Lunar orbit
 - 4 months in lunar orbit before intentional crash into the surface in September 2006
 - 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



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

- 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

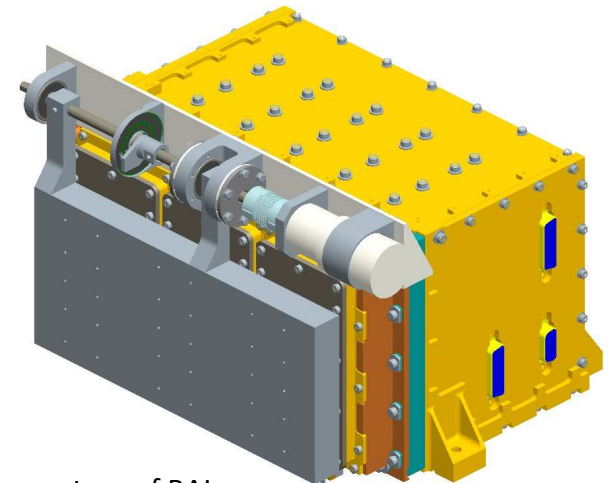
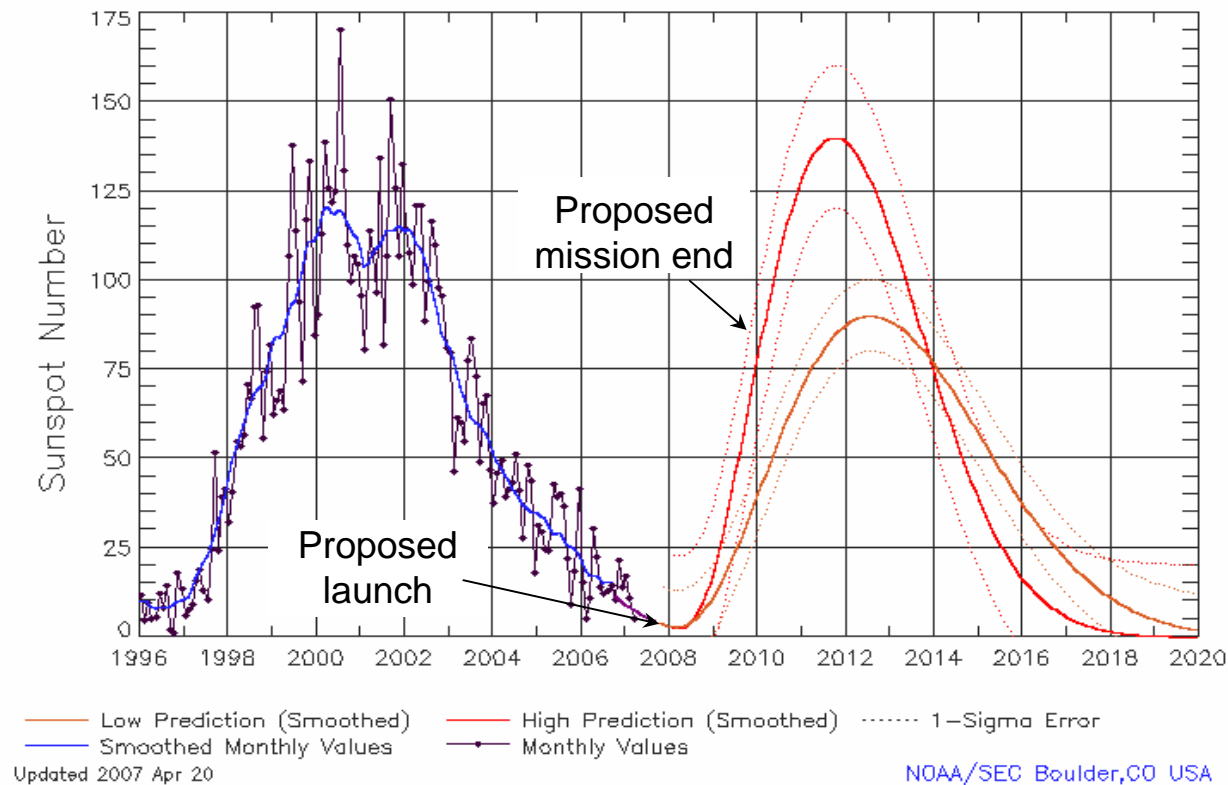


Image courtesy of RAL




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



 **SPENVIS Project: EUCLID** 
Model packages 
Planet: Earth

- Coordinate generators**
- Spacecraft trajectories
- or
- Geographical coordinate grids
- Radiation sources and effects**
- Spacecraft charging**
- Atmosphere and ionosphere**
- Magnetic field**
- Meteoroids and debris**
- Miscellaneous**
- Geant4 Tools**
- ECSS Space Environment Standard**

Orbit generator



- Input details into the orbital generator

SPENVIS Project: EUCLID
Orbit generator
Mission definition -Earth-

Output
Help

▲ UP

Trajectory generation: use orbit generator ▾

Number of mission segments: 3 ▾

Mission end: total mission duration ▾

Mission duration: 6.54 days ▾

Account for solar radiation pressure: no ▾

Account for atmospheric drag: no ▾




Reset Next >>

Tool developed by

© ESA ☆☆☆

Orbit generator



 **SPENVIS Project: EUCLID** 
Orbit generator 
Parameters for segment 1

Segment title:
Twice around the Earth

Orbit type: general

Orbit start: calendar date

29 Feb 2008 16 : 34 : 16

Representative number of orbits : 1.99

Altitude specification: semi-major axis and eccentricity

Semi-major axis [km]: 18148.14

Eccentricity: 0.64

Inclination [deg]: 17.85

R. asc. of asc. node [deg w.r.t gamma50] : 353.10

Argument of perigee [deg]: 179.00

True anomaly [deg]: 12.53

<< Back Next >>

Orbit generator



SPENVIS Project: EUCLID
Orbit generator
Mission summary

Output
Help

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Number of mission segments: 3

Segment 1: Twice around the Earth
Orbit type: general Orbit start: 29/2/2008 16:34:16 Nr. of orbits: 1.99
Segment 2: Two more then to the moon
Orbit type: general Orbit start: 1/3/2008 6:1:15 Nr. of orbits: 1.98
Segment 3: To the moon
Orbit type: general Orbit start: 3/3/2008 11:43:29 Nr. of orbits: 0.38

<< Back Run

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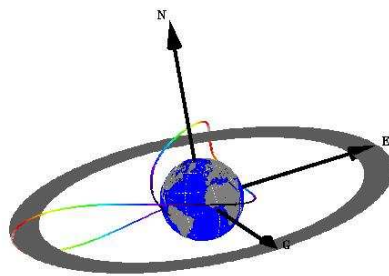
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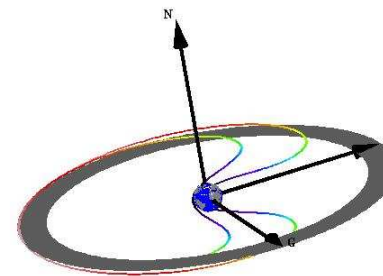
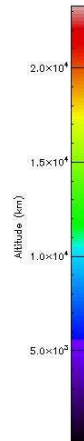


Orbit generator

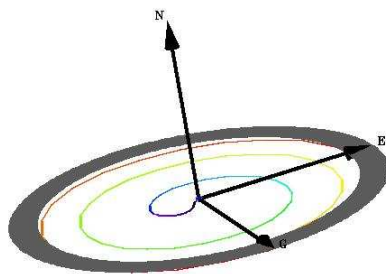
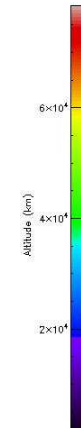
- ~ 7 days transfer from the Earth to the Moon
- 730 days at in Lunar orbit



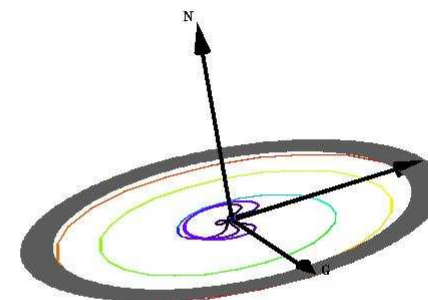
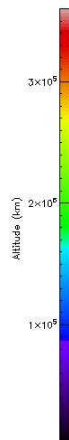
Segment 1



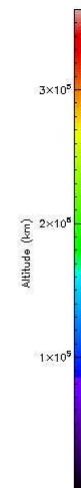
Segment 2



Segment 3



Earth-Moon transfer





Radiation sources and effects

SPENVIS Project: EUCLID
Model packages
Planet: Earth

UP Output
Help

- Coordinate generators
- Radiation sources and effects**
 - Radiation sources**
 - Trapped proton and electron fluxes
Trapped proton flux anisotropy
 - Solar proton fluences
 - Solar cell radiation damage**
Damage equivalent fluences for solar cells (EQFLUX)
NIEL based damage equivalent fluences for solar cells (MC-SCREAM)
 - Radiation doses**
Ionizing and non-ionizing dose models for simple geometries
 - Single event effects**
 - Ion energy and LET spectra
Single event upset rates
- Spacecraft charging
- Atmosphere and ionosphere
- Magnetic field
- Meteoroids and debris
- Miscellaneous
- Geant4 Tools
- ECSS Space Environment Standard



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- Trapped radiation models

SPENVIS Project: EUCLID
Radiation sources and effects
Trapped radiation: Model parameters

UP Output Help

Trapped radiation models

Proton model: AP-8	Electron model: AE-8
Model version: solar maximum	Model version: solar maximum
Model developed by: 	Model developed by: 

Reset Run

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Radiation sources and effects

SPENVIS Project: EUCLID
Model packages
Planet: Earth

UP Output
Help

- Coordinate generators
- Radiation sources and effects**
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 - ECSS Space Environment Standard



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Radiation sources and effects



- Solar proton models

SPENVIS Project: EUCLID
Radiation sources and effects
Solar proton models: Parameters

UP

Output
Help

Solar proton model: JPL
Confidence level [%]: 95
Geomagnetic shielding: ignore

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Model developed by
JPL

© ESA

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Radiation sources and effects



SPENVIS Project: EUCLID
Model packages
Planet: Earth

Output
Help

UP

<u>Coordinate generators</u>
Radiation sources and effects
Radiation sources
<u>Trapped proton and electron fluxes</u>
<u>Trapped proton flux anisotropy</u>
<u>Solar proton fluences</u>
Solar cell radiation damage
<u>Damage equivalent fluences for solar cells</u>
<u>NIEL based damage equivalent fluences for solar cells (MC-SCREAM)</u>
Radiation doses
<u>Ionizing and non-ionizing dose models for simple geometries</u>
Single event effects
<u>Ion energy and LET spectra</u>
Single event upset rates
Spacecraft charging
Atmosphere and ionosphere
Magnetic field
Meteoroids and debris
Miscellaneous
Geant4 Tools
ECSS Space Environment Standard

Radiation sources and effects

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

Al shielding thickness

Shielding depths: table of values

Shield depths [mm]

1
2
5
10
15
20
25
30

Dose model: non-ionizing energy loss

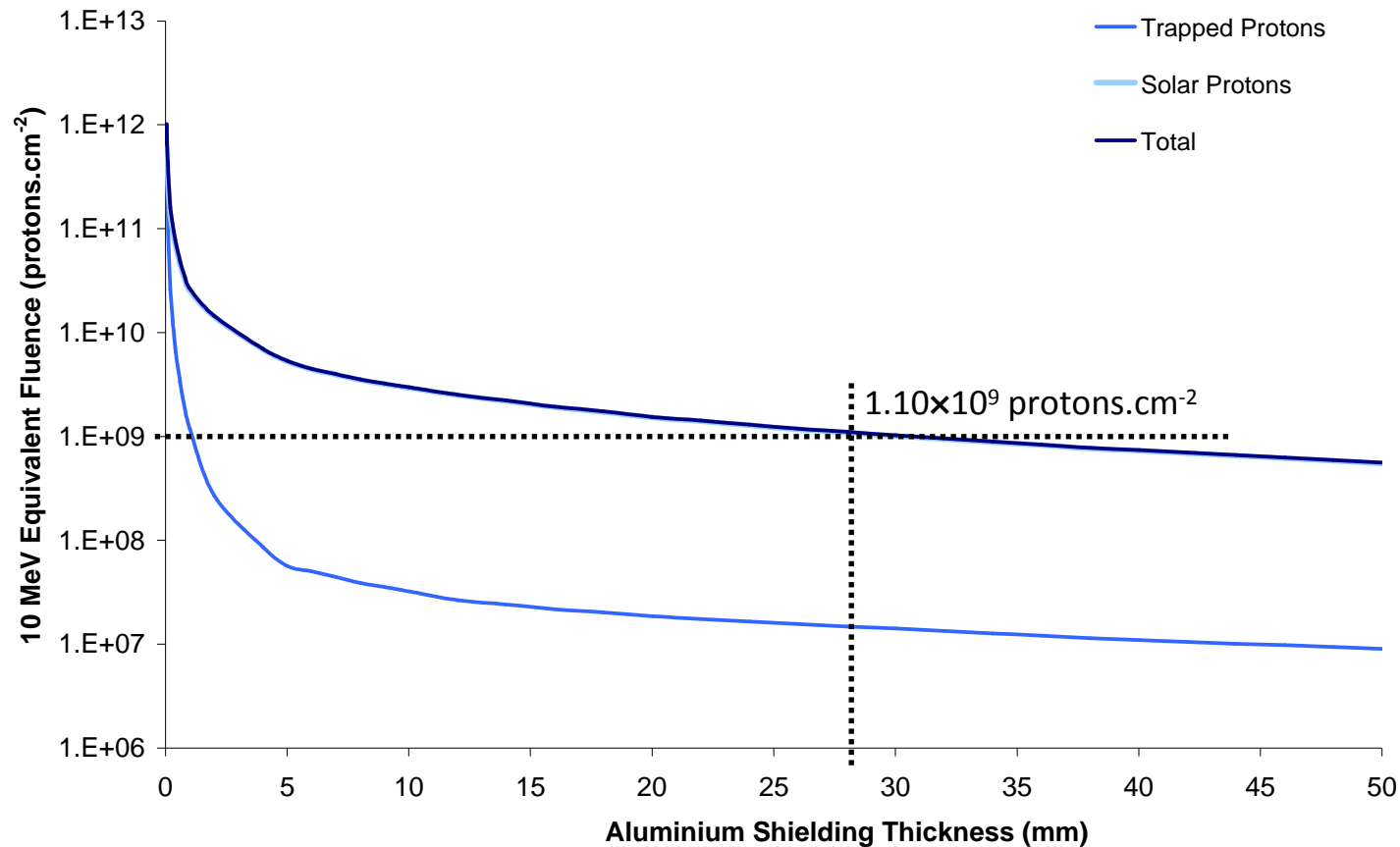
Damage factor [g(Si) MeV⁻¹]: 1.0E-11

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Tool developed by



Space Radiation Environment

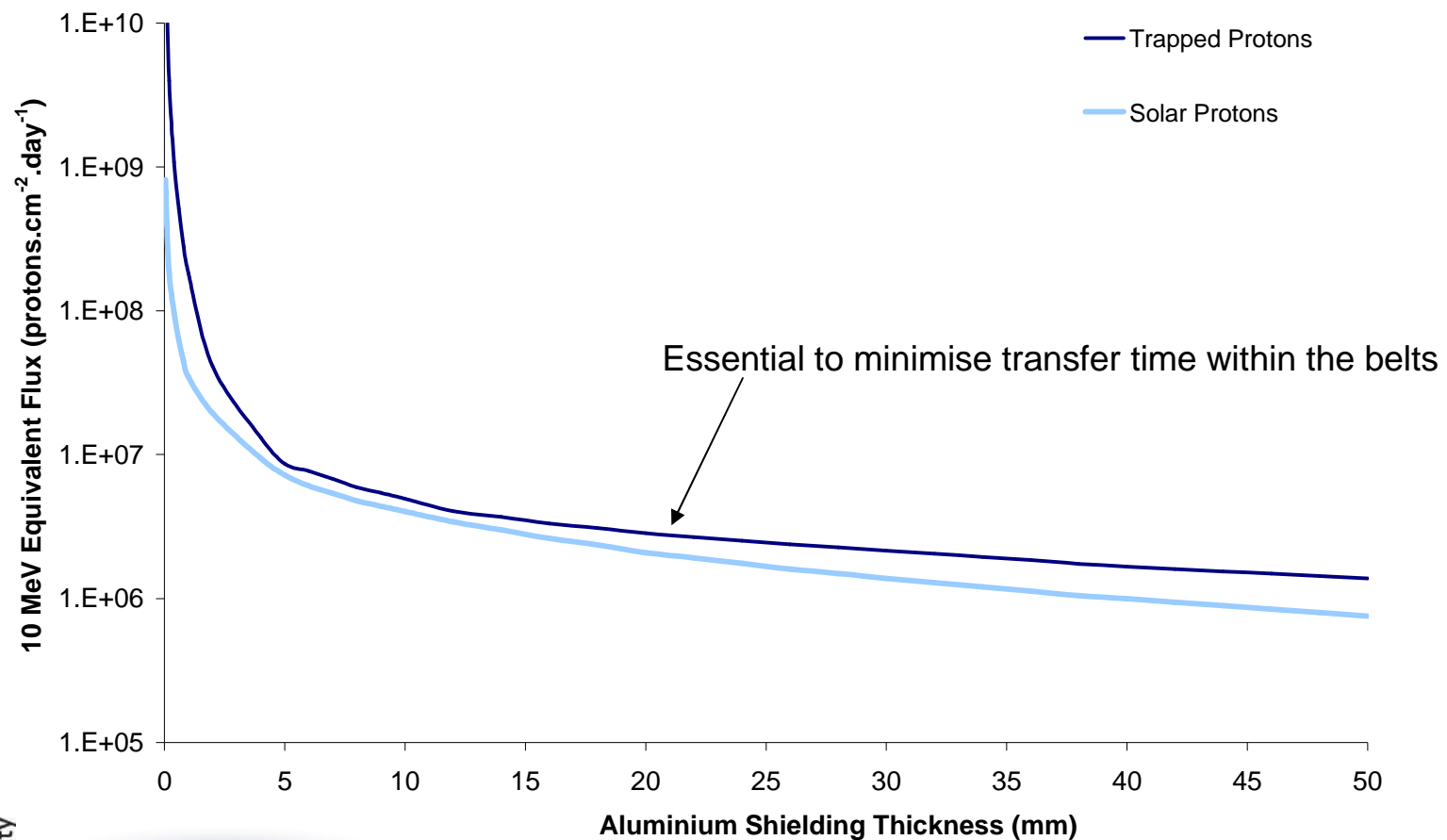


- Recommended using at least 3 mm of Al and 6 mm of Ta shielding
- The moon will shield the front 2π during the lunar stage of the mission
- End of life (EOL) 10 MeV equivalent proton fluence of **5.5×10^8 protons.cm⁻²**

Space Radiation Environment



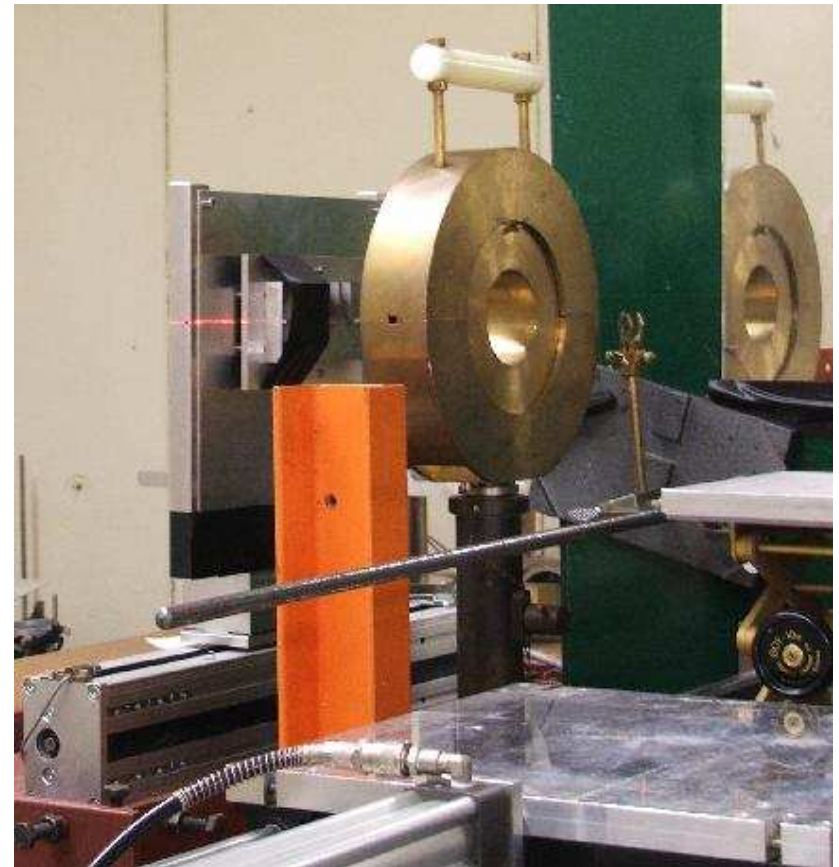
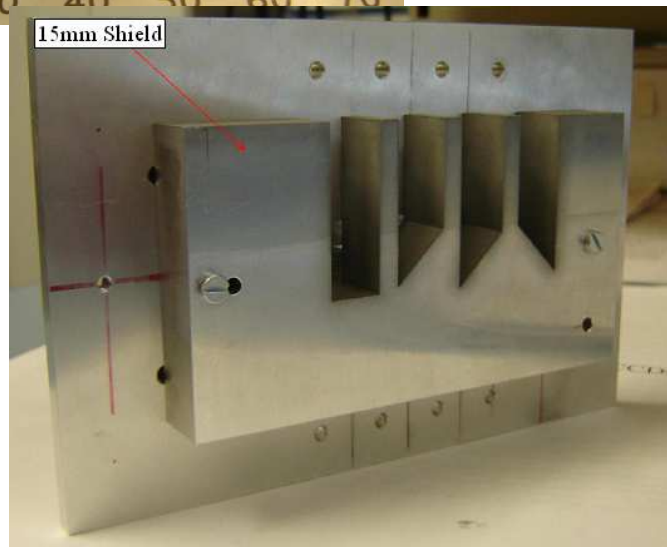
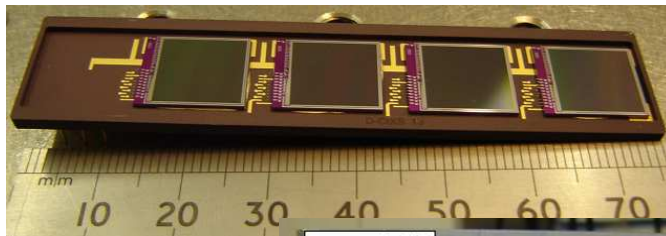
- Average proton flux calculated using **AP-8 trapped** and **JPL-91 solar proton** models, as a function of shielding thickness



Proton Irradiation and CCD Analysis



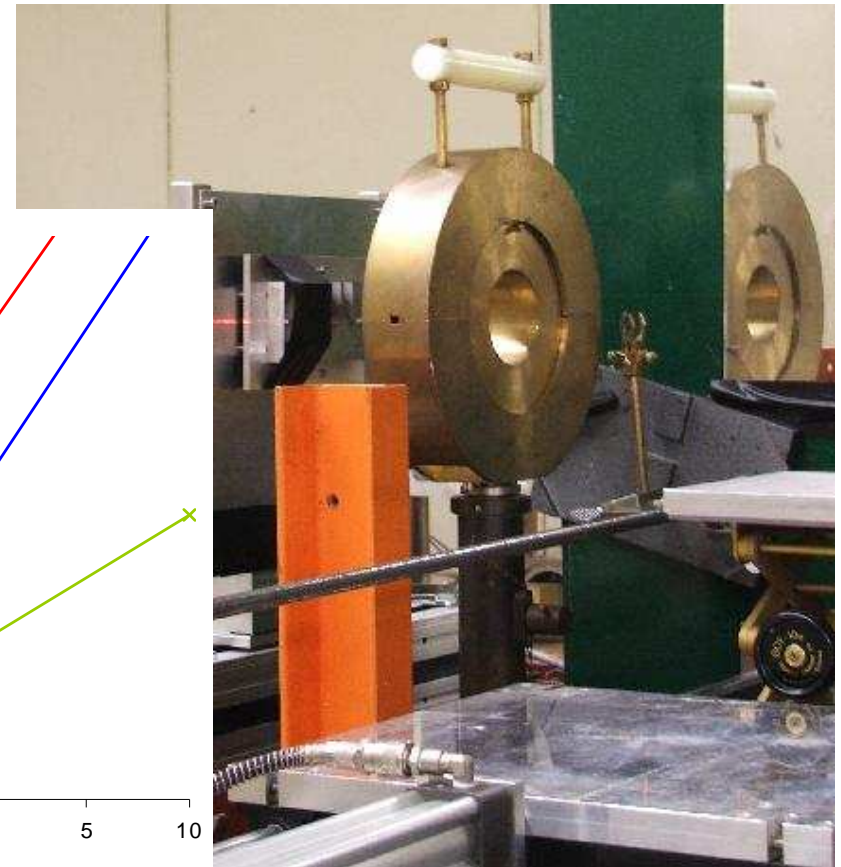
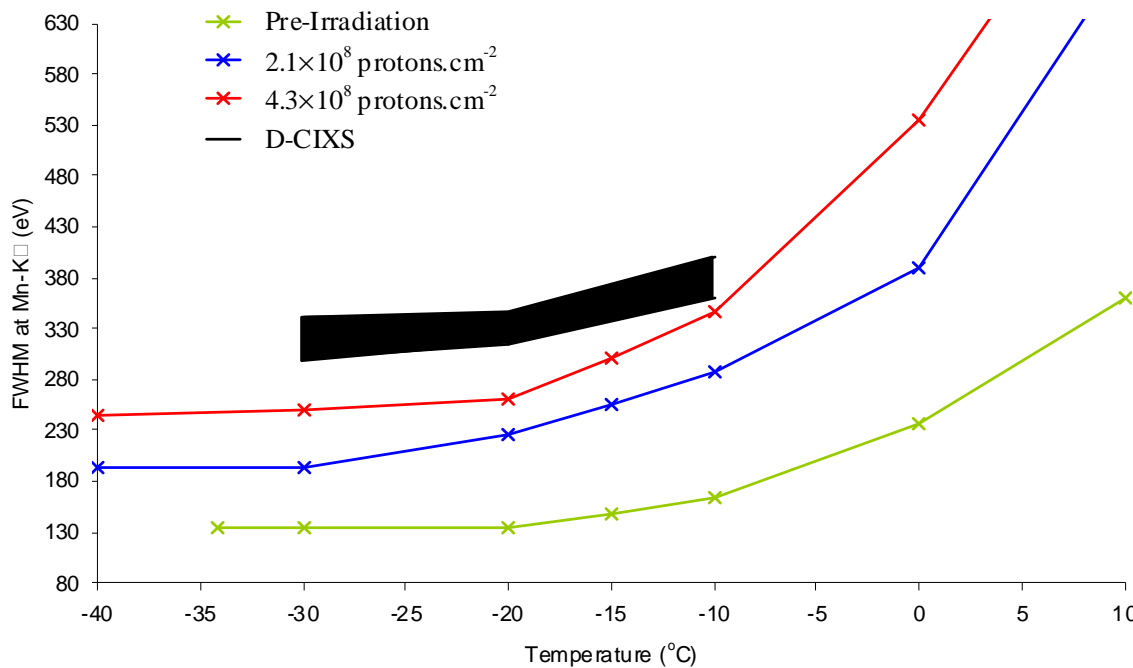
- Irradiation performed at the Kernfysisch Versneller Instituut in Groningen



Proton Irradiation and CCD Analysis



- Irradiation performed at the Kernfysisch Versneller Instituut in Groningen



Proton Irradiation and CCD Analysis

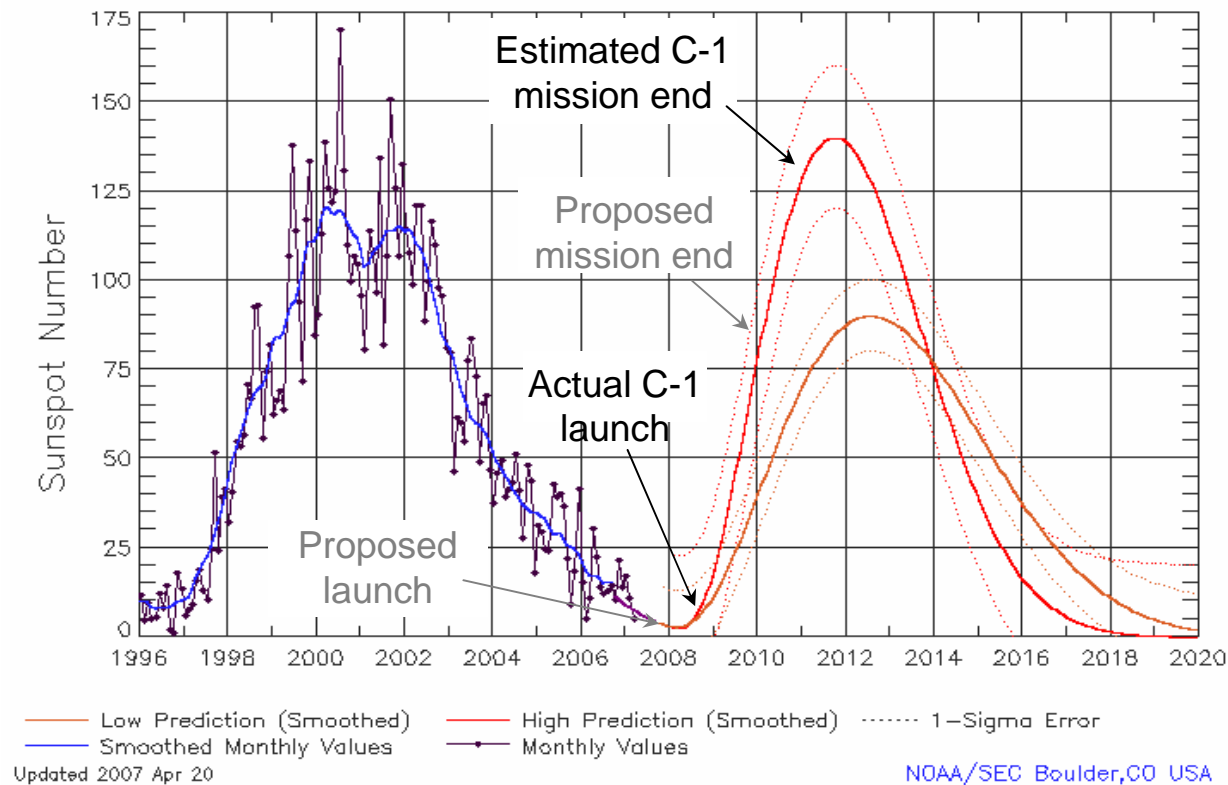


- **Recommended**
 - Operational temperature of $-20.0\text{ }^{\circ}\text{C}$
 - Operating potentials and timings
 - Increasing the gain provided by the camera system
- Location of C1XS onboard Chandrayaan-1 was changed and the C1XS design modified to provide improved thermal isolation between the 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

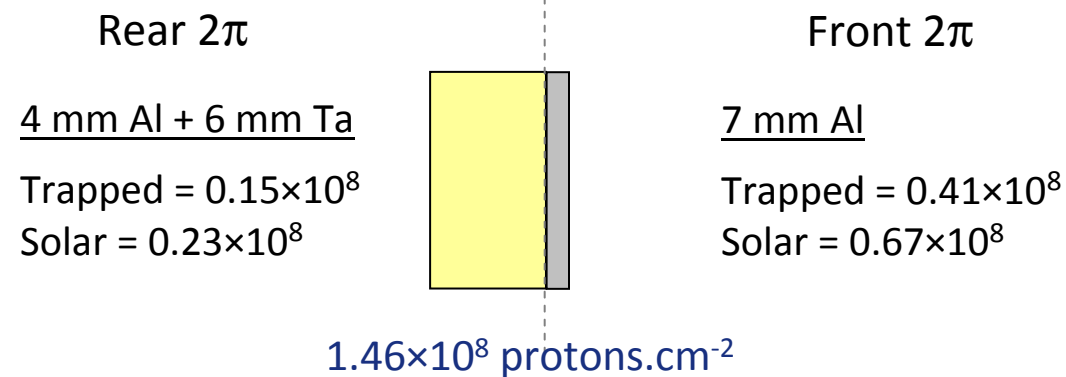




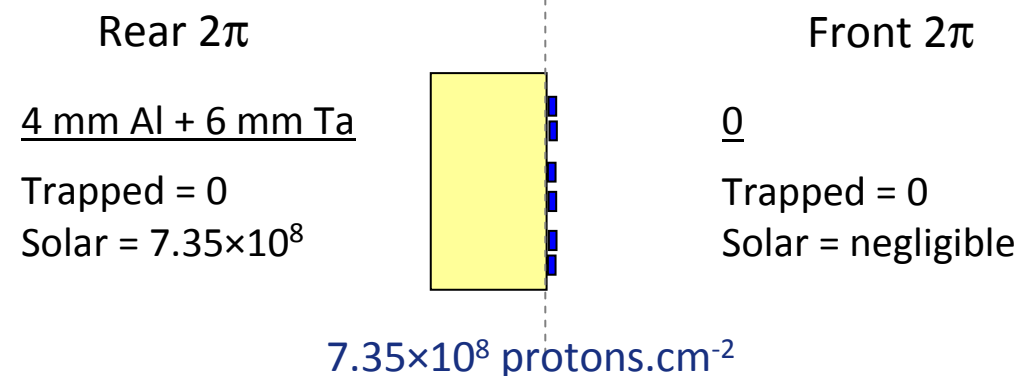
Space Radiation Environment

- End of life 10 MeV equivalent proton fluence = $8.81 \times 10^8 \text{ protons.cm}^{-2}$

Transfer



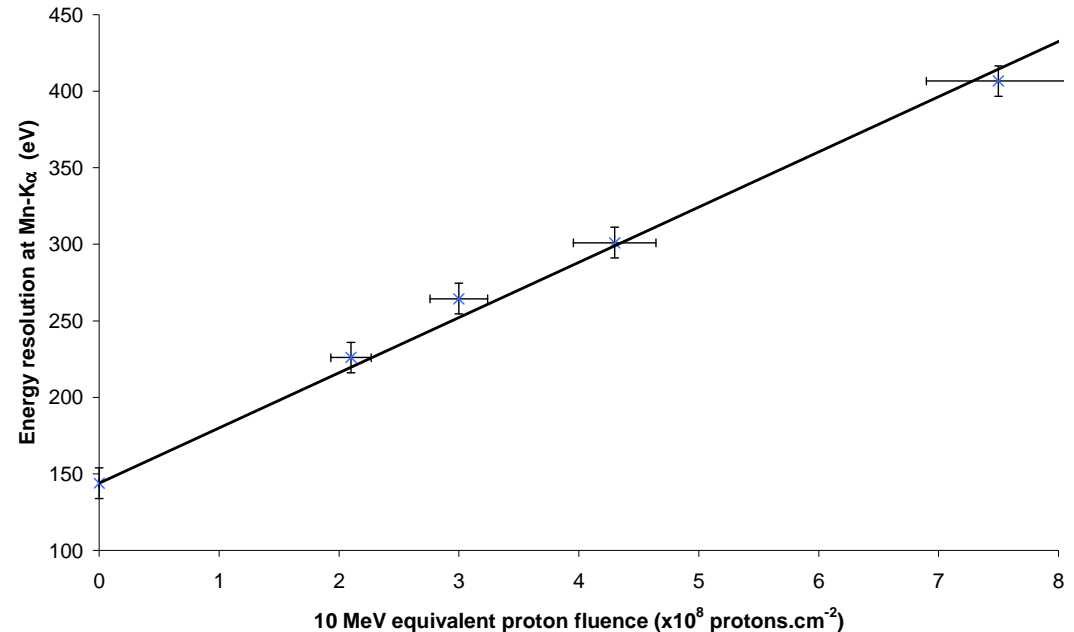
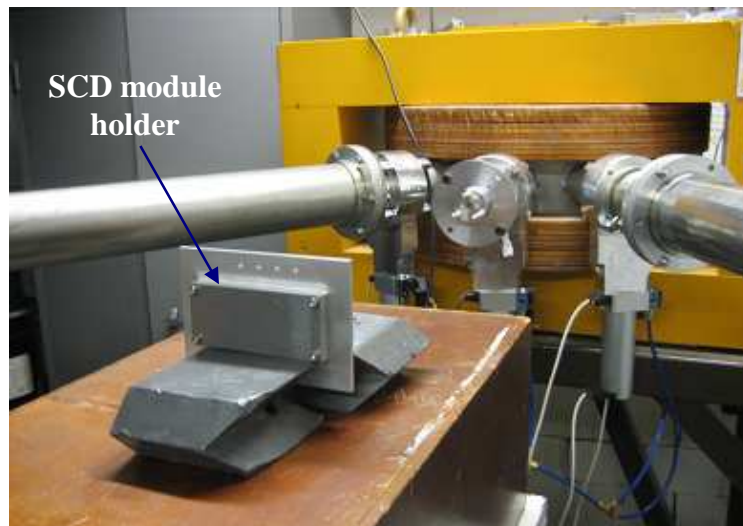
Lunar



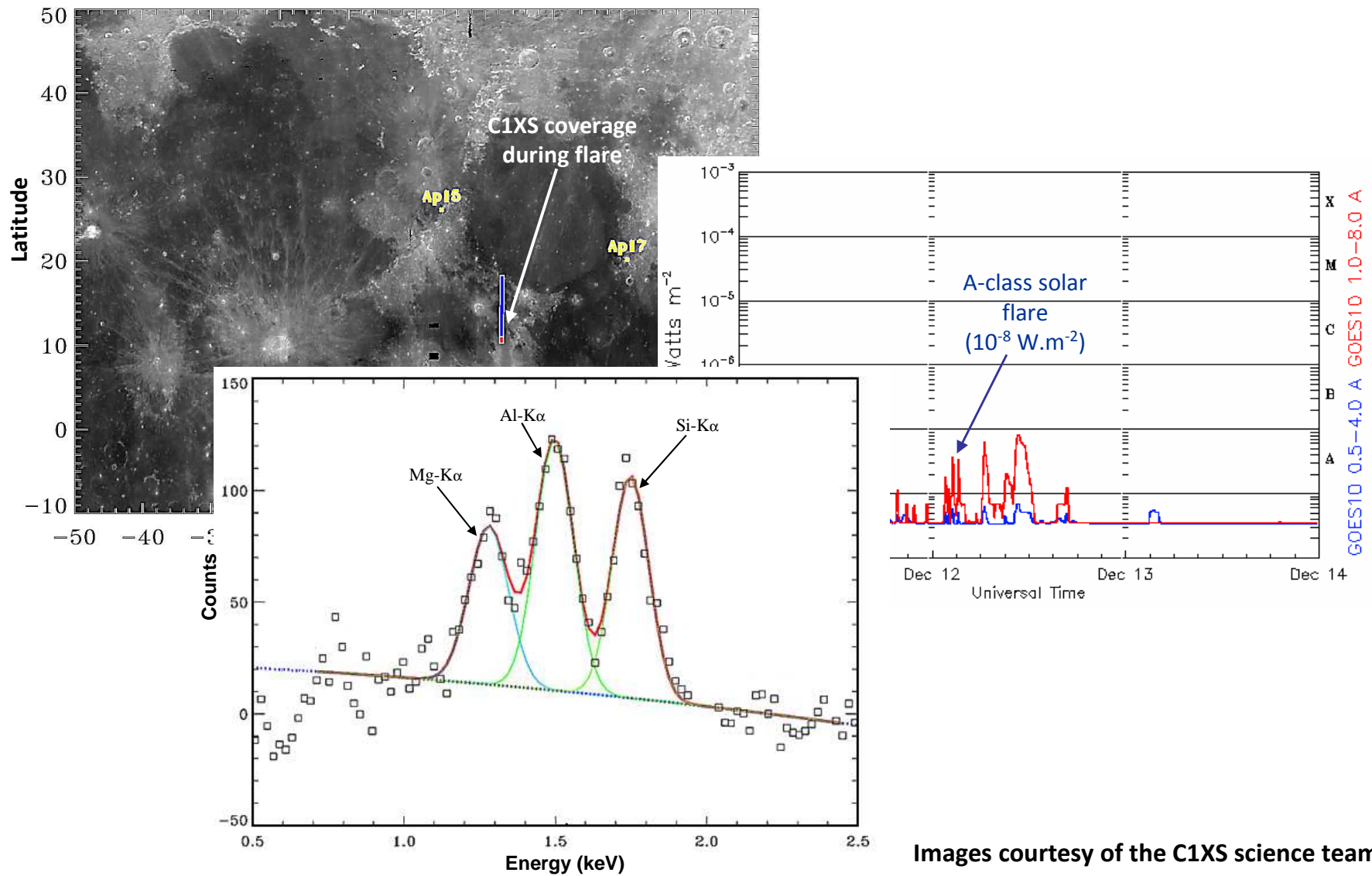
Proton Irradiation and CCD Analysis



- 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



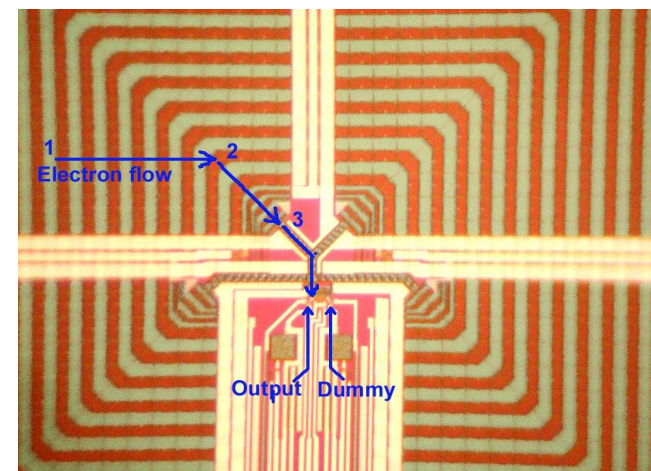
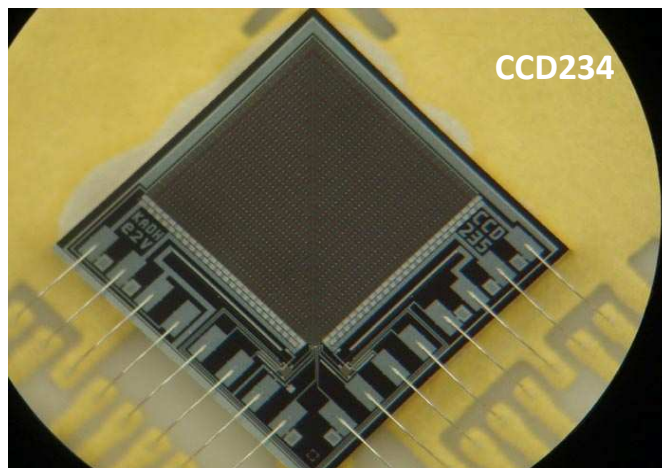
C1XS – Initial results



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)



CCD236, showing the combination of the four imaging areas

Detector Calibration



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

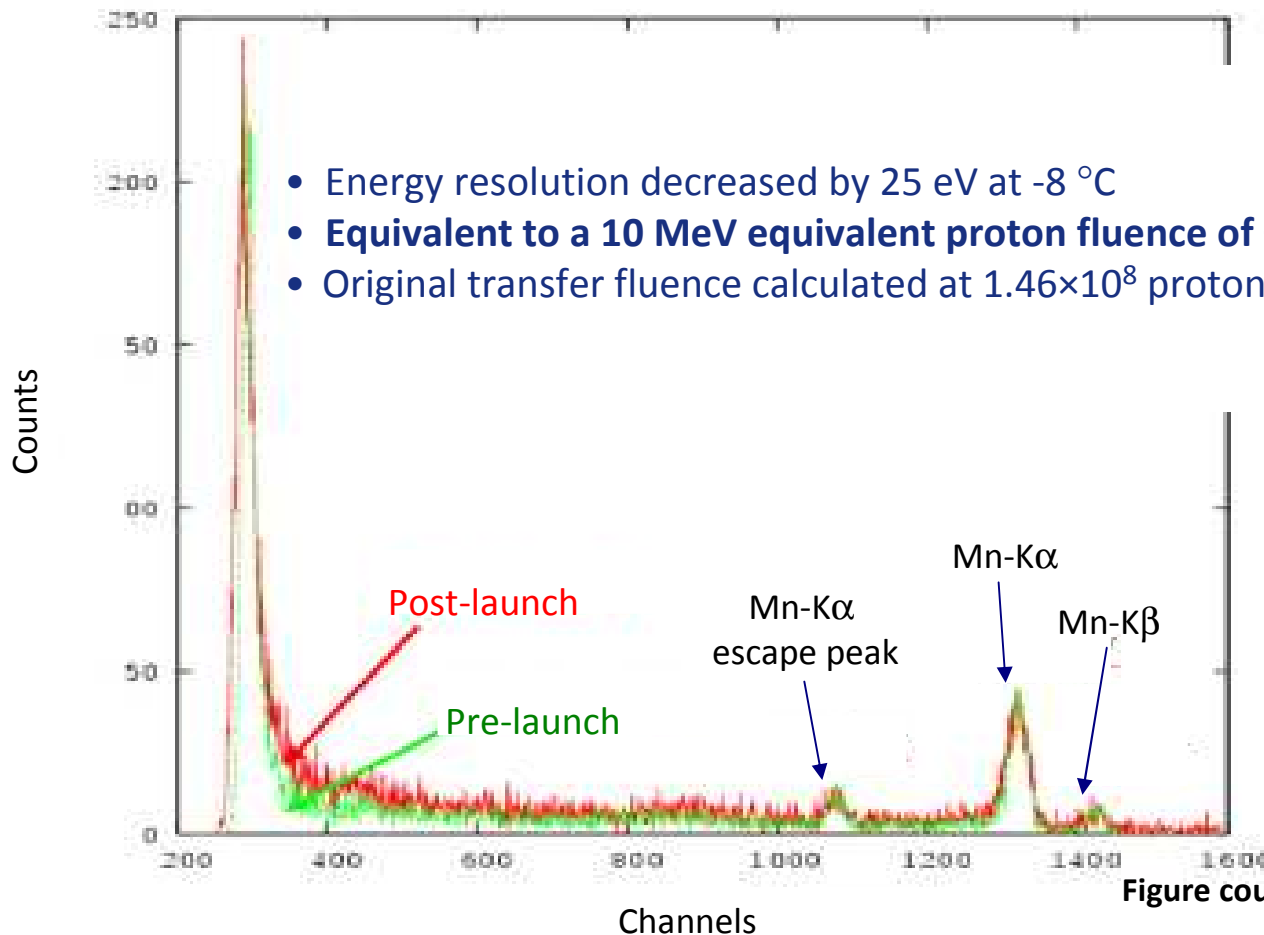
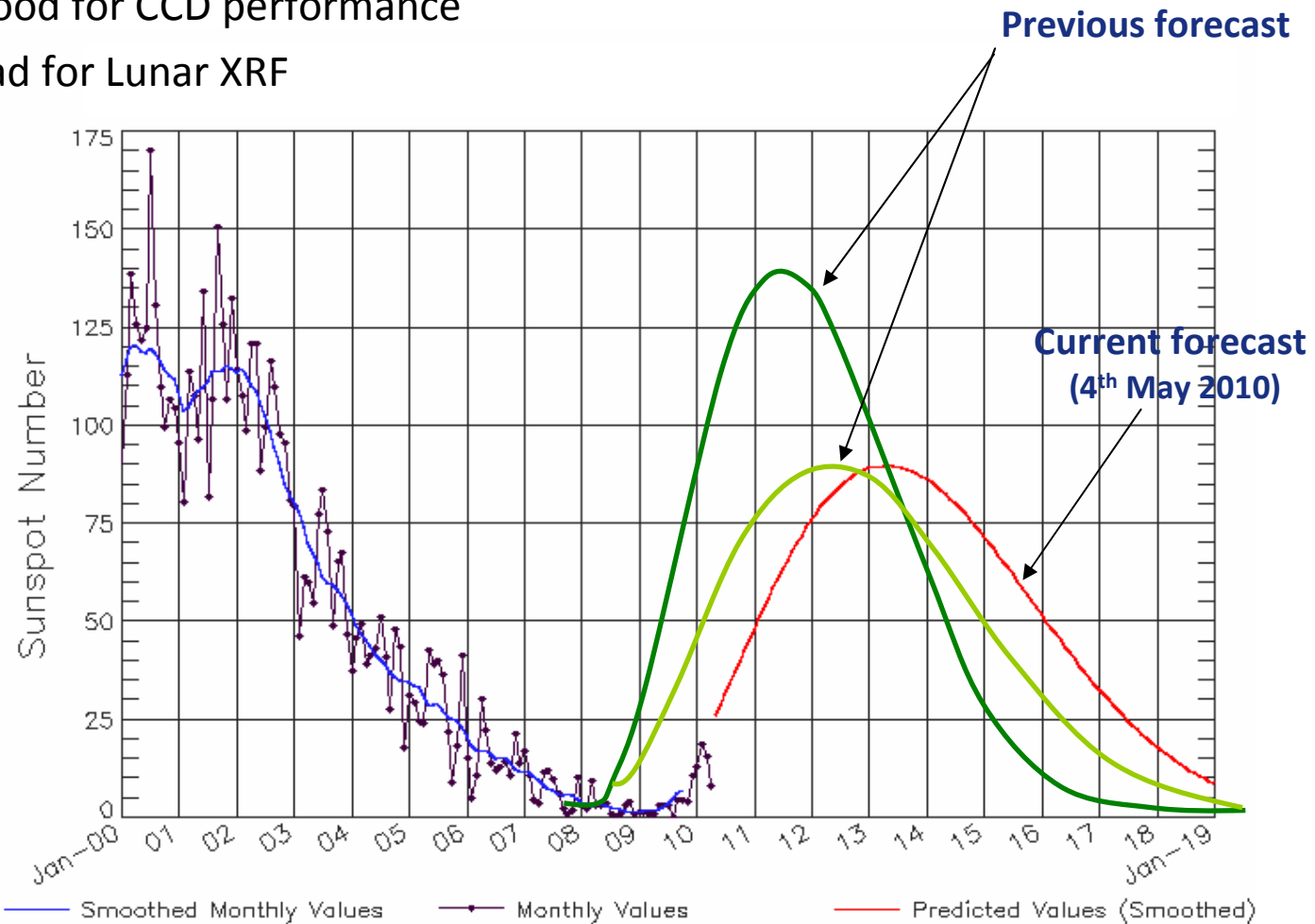


Figure courtesy of ISRO

Solar cycle 23 and 24



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



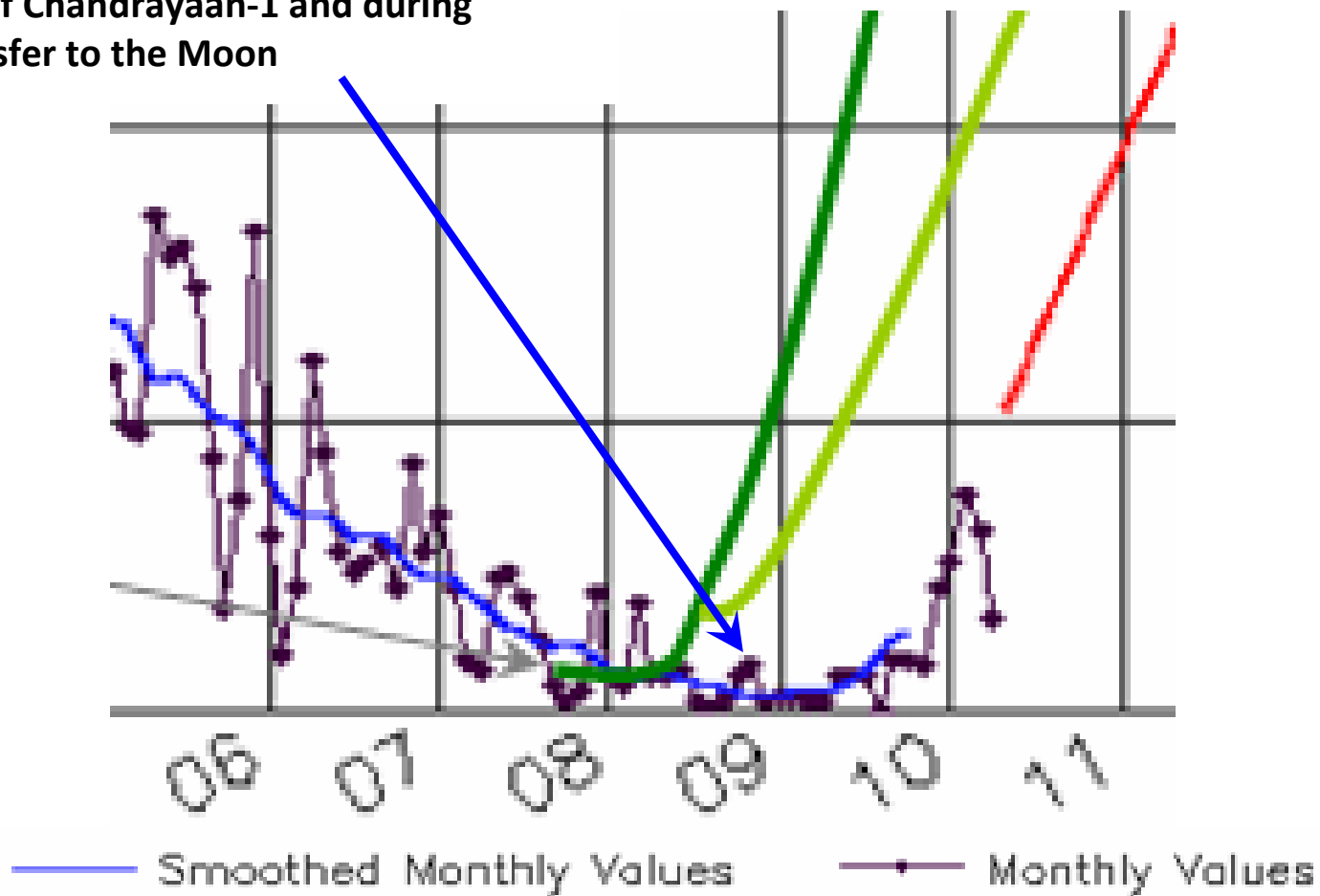
Updated 2010 May 4

NOAA/SWPC Boulder, CO USA

Solar cycle 24



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



Comparison of proton fluence



Under solar minimum conditions,
using SPENVIS

0.56×10^8 protons.cm⁻²

Based on estimated proton fluence based
on decreased performance

0.52×10^8 protons.cm⁻²



- 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