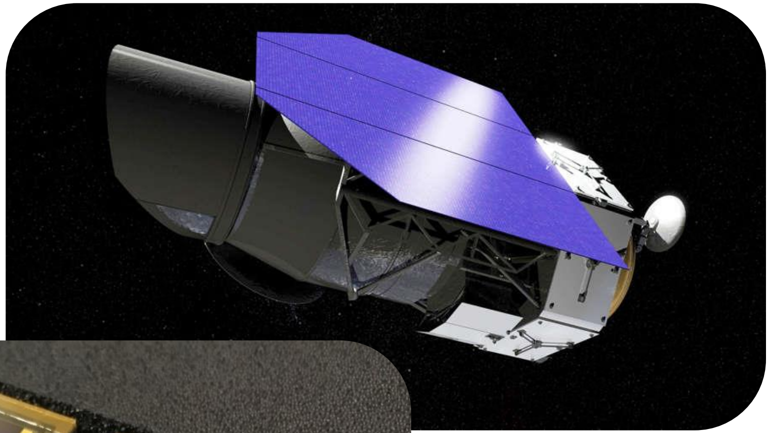
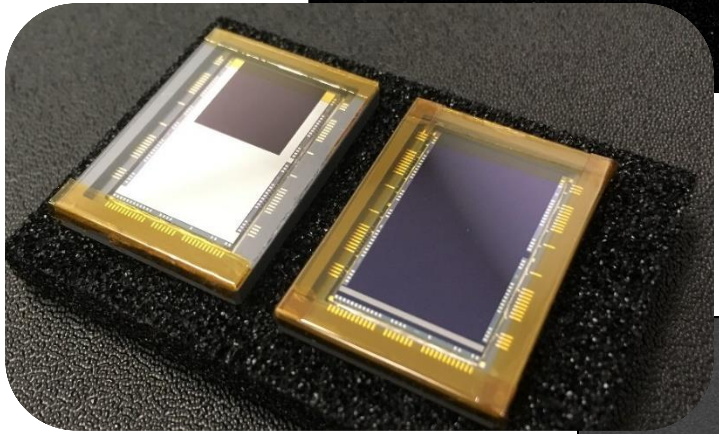
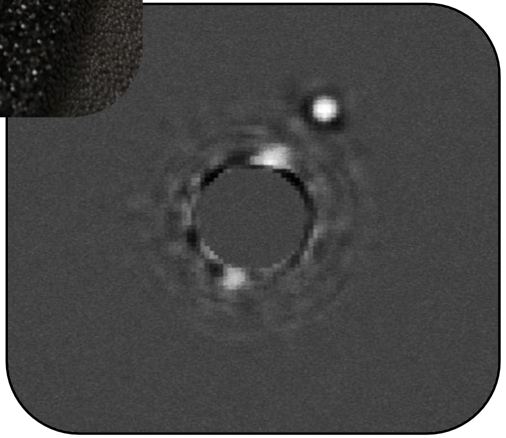
EMCCDs for the Nancy Grace Roman Space Telescope

Detector design, the challenges involved and their ongoing validation

David Hall on behalf of the RST teams at
The Open University and Durham University

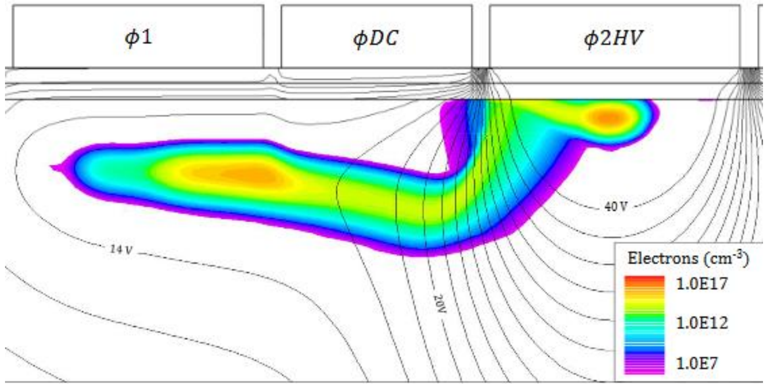


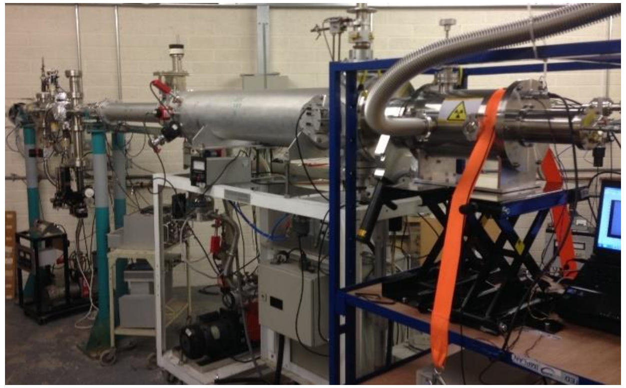




Centre for Electronic Imaging (Open University, UK)

- The Centre for Electronic Imaging (CEI) is a research centre based at the Open University in the UK, sponsored by Teledyne e2v.
- The CEI has worked in collaboration with T-e2v on detector development and characterisation for numerous ESA and NASA missions, including Gaia, Euclid, SMILE, JUICE, RST and many more.
- The CEI worked under contract to JPL on detector characterisation, design and test from 2014-2019, culminating in our development of the bespoke sensor for the Roman Space Telescope, with more recent funding from UKSA to develop a laboratory test camera system.



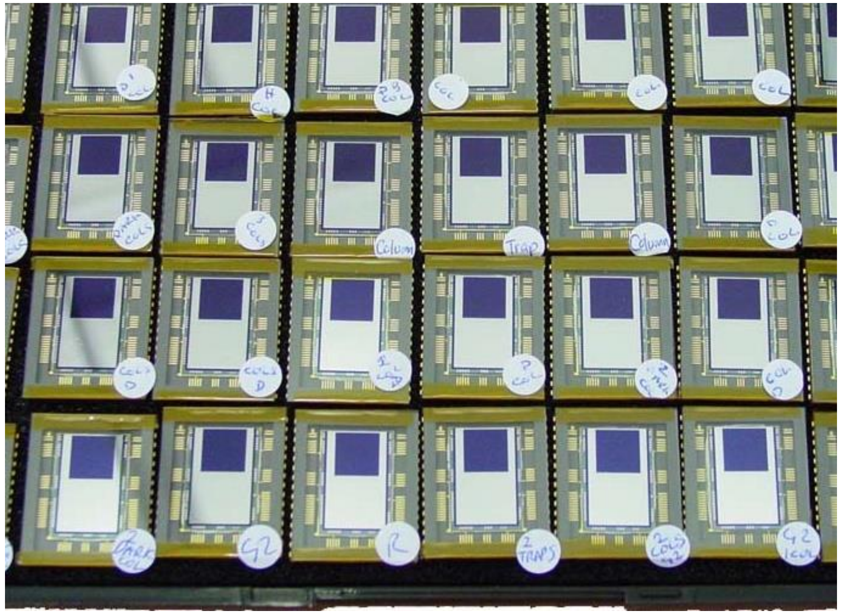


Proton Irradiation of EMCCDs

David R. Smith, Richard Ingley, and Andrew D. Holland

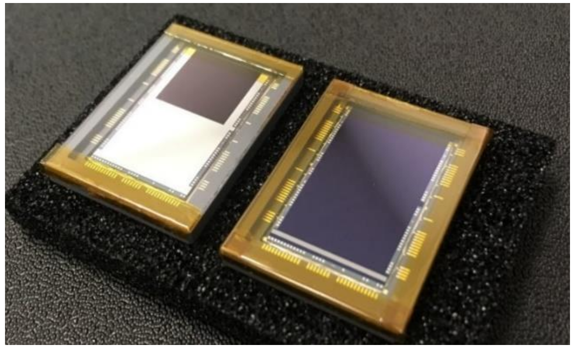
Abstract—**This paper describes the irradiation of 95 electron multiplication charge coupled devices (EMCCDs) at the Paul Scherrer Institut (PSI) in Switzerland, to investigate the effects of proton irradiation on the operational characteristics of CCDs featuring electron multiplication technology for space use. This work was carried out in support of the CCD development for the radial velocity spectrometer (RVS) instrument of the European Space Agency's cornerstone Gaia mission. Previous proton irradiations of EMCCDs, have shown the technology to be radiation hard to $\sim 10\times$ the required six-year Gaia lifetime proton fluence, with no device failures or unexpected operational changes. The purpose of the study described in this paper was to further investigate the statistical probability of device failure as a result of radiation damage, the large number of devices and high proton fluence used, making the study equivalent to testing ~ 50 complete RVS CCD focal planes to the expected end of life proton dose. An outline of the earlier EMCCD proton irradiations is given, followed by a detailed description of the proton irradiation and characterization of the 95 devices used in this latest study.**

Index Terms—**Charge coupled devices (CCD), electron multiplication charge coupled devices (EMCCDs), Gaia, proton irradiation, radiation damage, radial velocity spectrometer (RVS).**



Detector development towards RST

- A customised variant of the T-e2v CCD201 EMCCD, the CCD311, has been selected for the CGI using new design enhancements, developed and recommended by the OU in previous phases of work with T-e2v and JPL, that reduces the susceptibility of the instrument to radiation induced traps and the effects of instrument background.
- Further information can be found on the publication repository of the CEI Research Fellow who worked on the studies: http://oro.open.ac.uk/view/person/nb7695.html
- While EMCCDs share many design attributes with traditional CCD detectors, their mode of operation, susceptibility to radiation, and parameters for optimisation differ dramatically. The performance will be strongly impacted by subtle changes in operational parameters that will either inflate or reduce the required observation time for science targets by orders of magnitude.
- We have proposed a 4-year work plan towards full characterisation, radiation testing and optimisation of the flight model devices, input to the performance modelling and validation, while providing support towards in-orbit monitoring of radiation damage and software development for the data correction.



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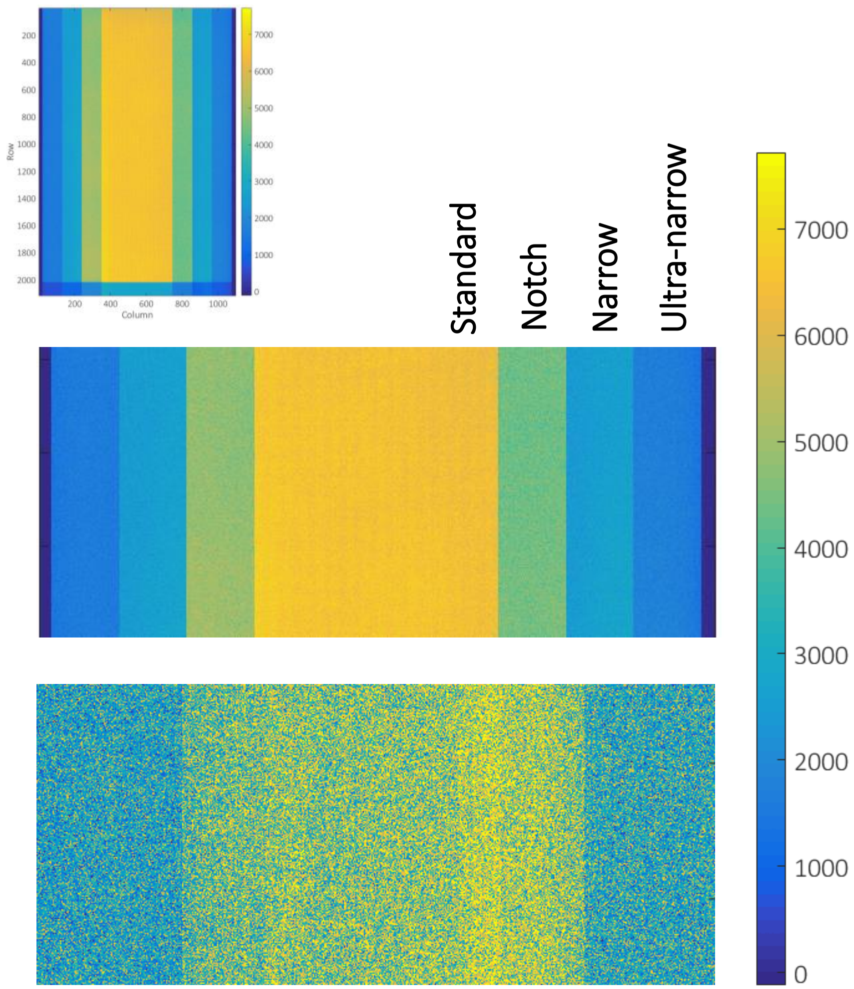
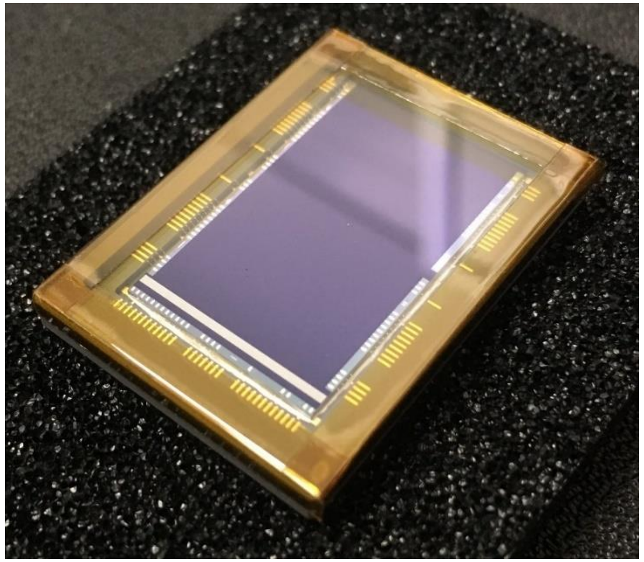
A new custom sensor





- Already costed into the ESA programme are 6 devices (2 representative EM devices and 4 characterisation devices) that are to be delivered to the OU by November 2021.
- However, no funding is currently available to enable the important work at the OU using these detectors to be implemented.

Durham University's contribution to the RST

- Prof Richard Massey (University of Durham) was Co-I of the laboratory camera test system at Caltech/JPL that is being used to test other instruments on Roman. He has visited JPL to discuss parallels between CGI and the Hubble Space Telescope, and provided software to the University of Alabama that is currently being used to simulate CGI data.
- Radiation damage has limited the science return of many previous astronomy missions. Since the Hubble Space Telescope's mirror was fixed, Charge Transfer Inefficiency has become its wide-field camera's most serious instrumental defect.
- Without postprocessing to correct its data, Hubble would have been unable to measure the brightness, position or shape of astronomical objects with sufficient precision for its most important scientific achievements.
- Solving these challenges has required close interaction between instrument and science teams.
- Roman CGI's science observations will be degraded by radiation damage in a significantly different way to optical and infrared imaging from previous missions.

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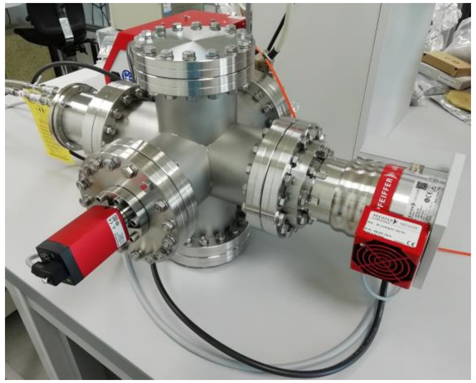
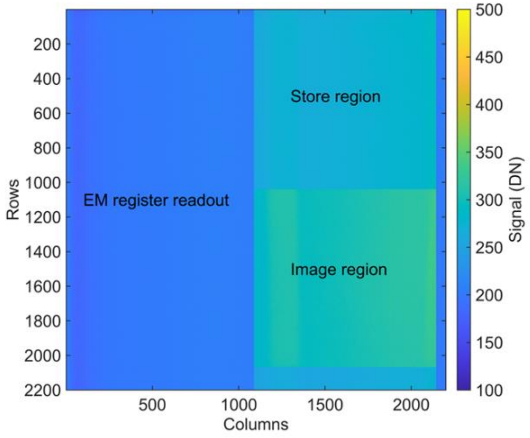
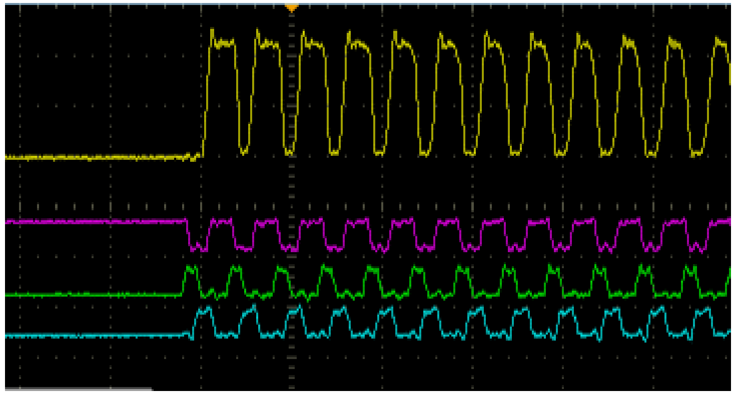
Latest funded developments (Dec 2020 - Mar 2021)

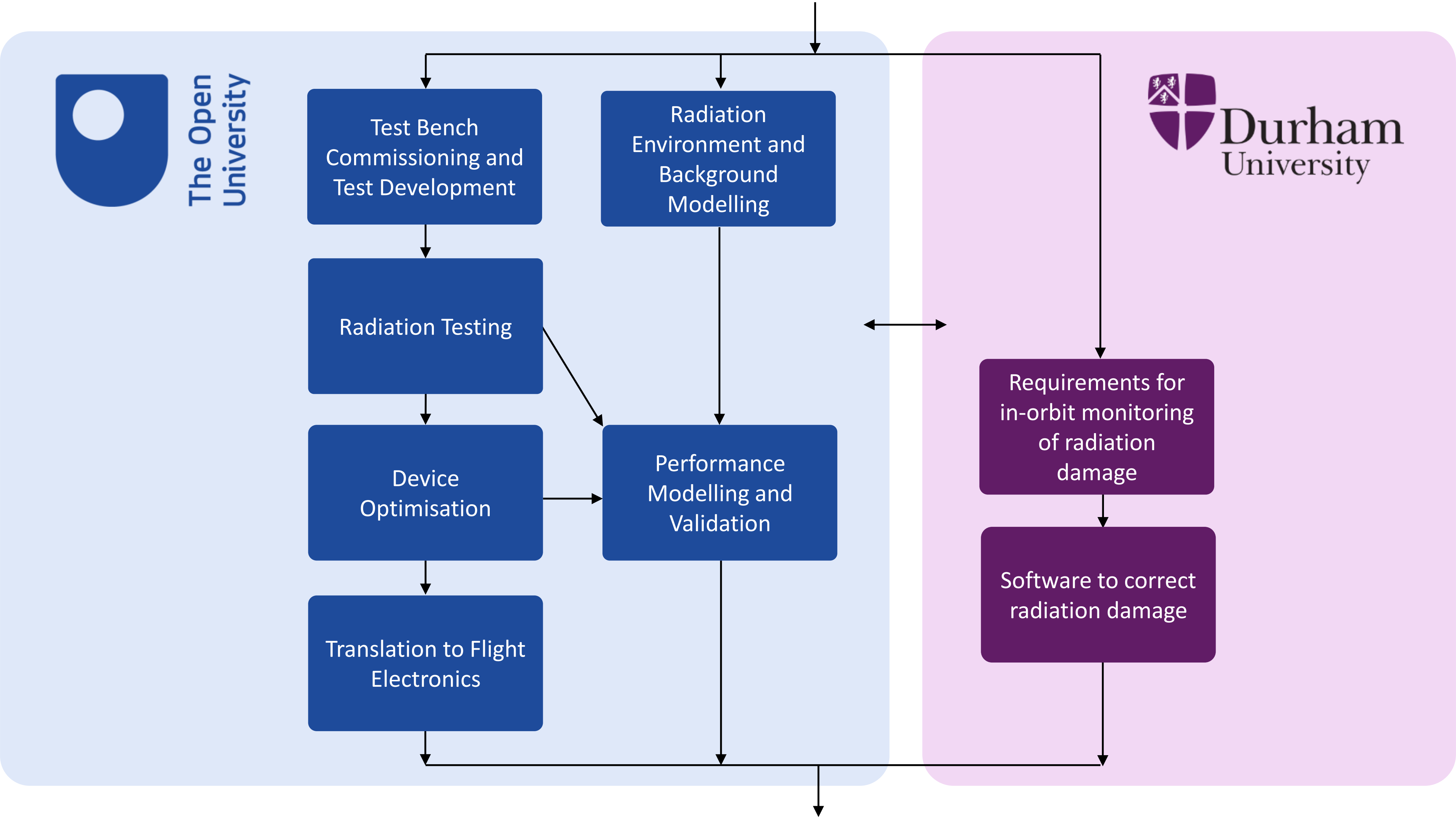
- Funding received from UKSA for December 2020 to March 2021 under their NSIP International programme.
- Covered several programmes involving EMCCDs, including the development of a new laboratory test camera system.
- The new camera system is up and running, able to offer us the flexibility of our characterisation and optimisation systems while also running in the flight-like mode.





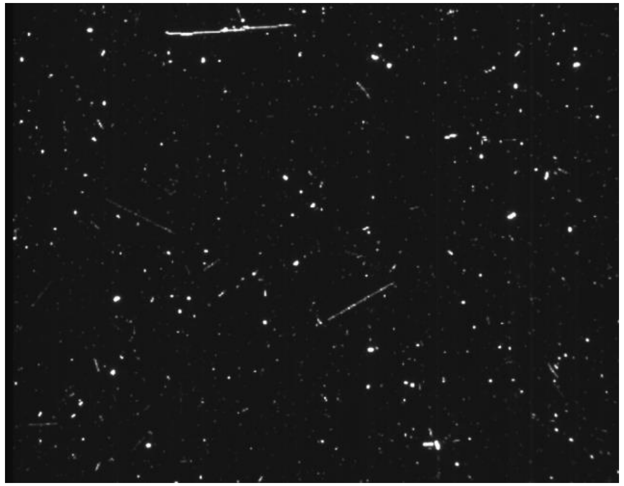


The next steps for UK support of RST hardware



OU: Test Bench Commissioning and Test Development

- In optical photon counting mode, subtle changes to the projected scene change detector performance dramatically.
- Accurate projection of representative CGI scenes is therefore deemed critical to accurately measure performance and perform optimisation, pre- and post-irradiation.
- NASA JPL have developed an optical scene projection system using a high-resolution OLED display that can reproduce accurate CGI science scenes.
- As part of this work, the Open University will upgrade and further develop their optical scene projection system to replicate secondary particle distributions and stimulate Fe55 X-rays for calibration and performance measurements.
- The commissioning of this test bench system and optical scene projection system will be followed by a series of validation tests where Demonstration Model (DM) EMCCDs (or equivalent) are tested according to specifications outlined by JPL/ESA. These results will then be incorporated into validation documents and the test plans for the radiation and optimisation campaigns.



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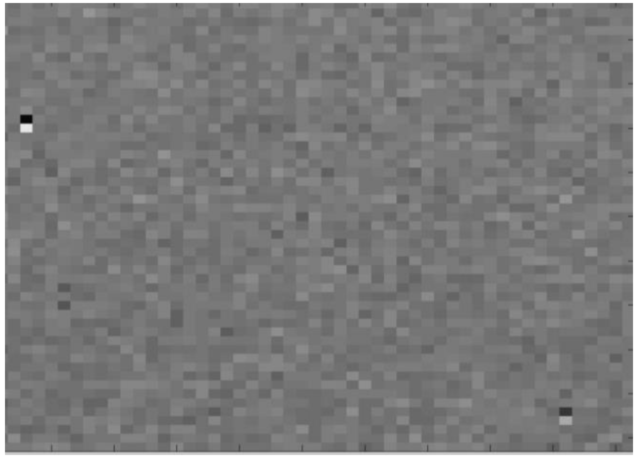
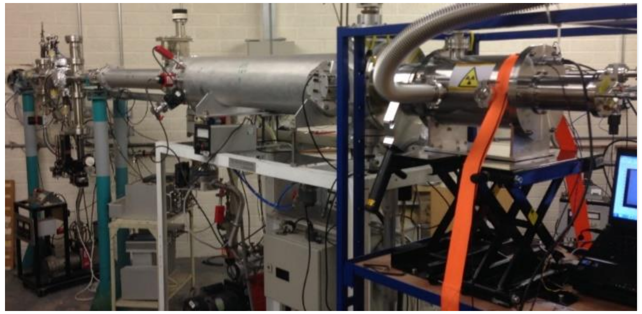
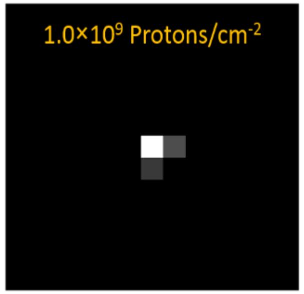
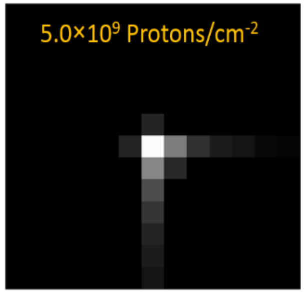
OU: Detector radiation testing

- CGI will spend 5 years within the L2 radiation environment where it will be subjected to displacement damage effects from high energy protons that cannot be stopped through instrument shielding.
- Mitigation against radiation-induced charge trapping sites was a significant driver for the Roman Telescope EMCCD technology development programme, following which the “notch” pixel architecture was selected for incorporation into the flight model.
- Even with the mitigation offered by the notch design, the effects of radiation damage will severely compromise the ability of the instrument to image planets and debris disk at the lowest flux levels.
- In this work, we will complete a detailed radiation damage assessment at both cryogenic (168-188 K TBC) and room temperature, measure CGI performance pre-and post-irradiation and provide a recommendation for optimal instrument performance based on storage temperature.
- These results will feed directly into JPL performance validation models, and also into the wider modelling activities.









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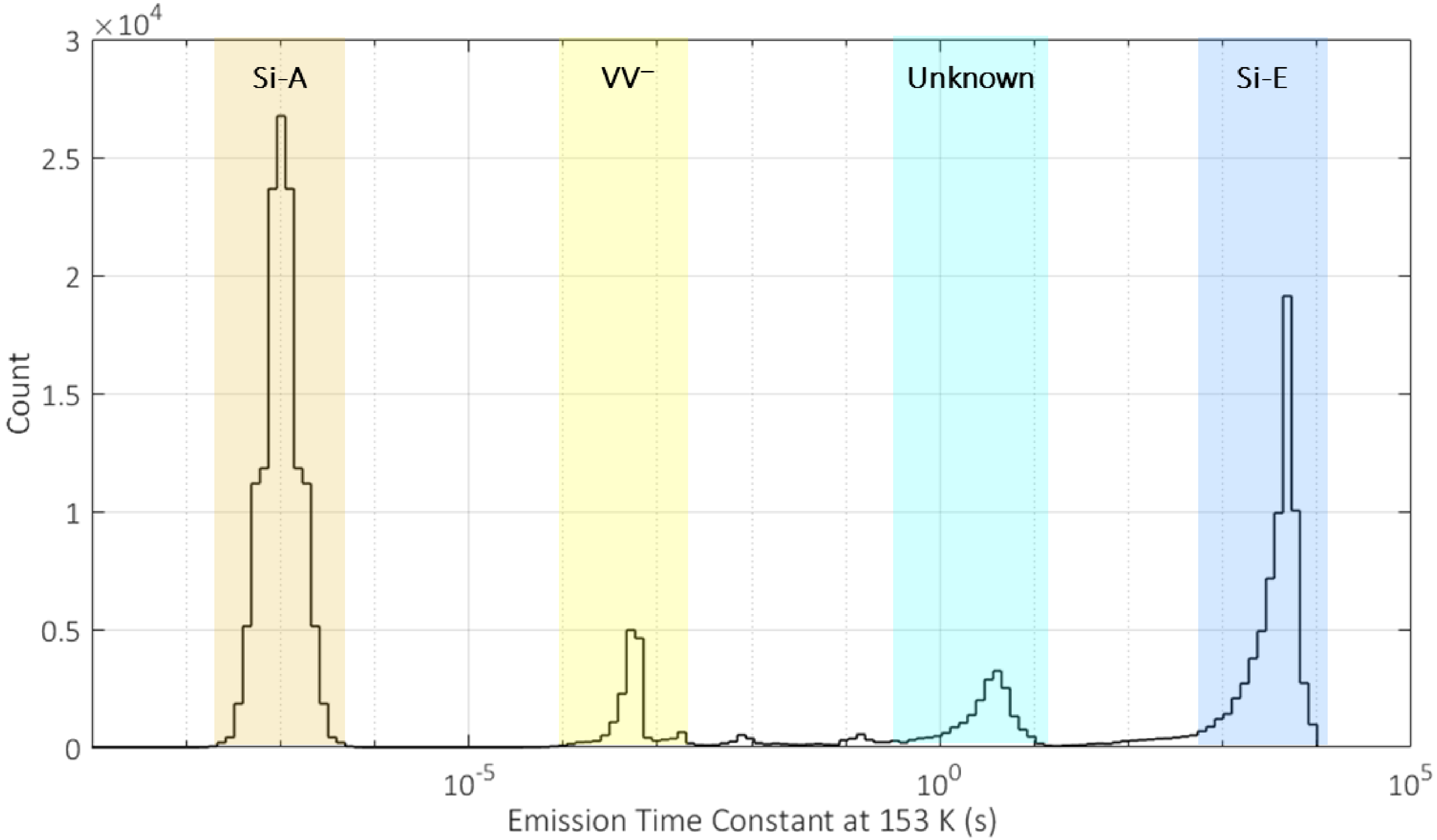
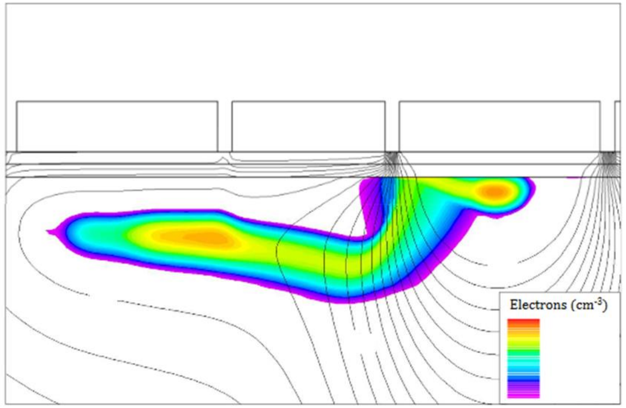
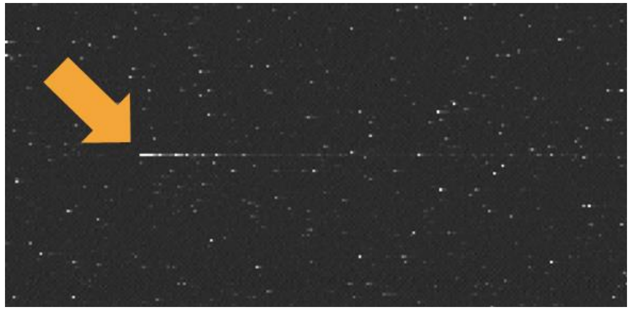
Radiation damage analysis

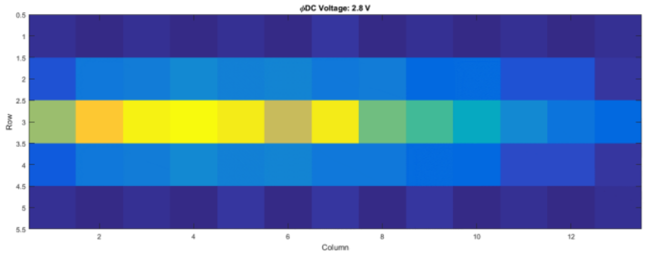


OU: Detector optimisation

- One of the biggest detector-related challenges for CGI is management of the inter-dependant parameters such as CTE and CIC and dark current that must be considered together in order to achieve optimum instrument performance.
- Radiation Induced charge-loss is highly dependent on the clock timings chosen to operate the instrument. Even small modifications to the clock timings can improve charge transfer performance dramatically depending upon the interplay of radiation induced traps with the illumination scene and clocking scheme.
- The Open University has popularised the “trap-pumping” technique as a means to identify and characterise radiation induced defects within EMCCDs. The properties of these traps can be measured and then used to optimise the sensor against radiation-induced damage to a much higher precision than that seen on previous space missions.
- The science targets for CGI will illuminate the sensor with flux levels ranging over three orders of magnitude. The integration times are expected to vary from 1 s up to 100 s, but the optimal integration time for a science target will depend upon the interplay of CTE, dark current, the instrument background and CIC.

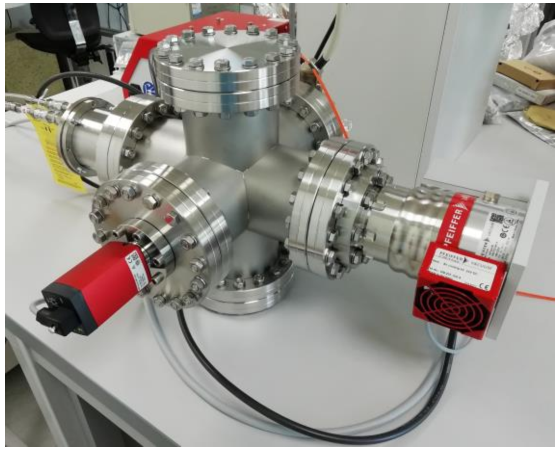


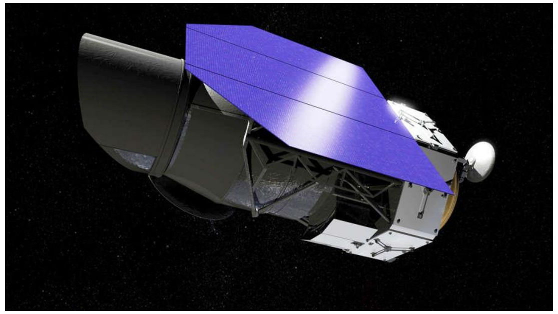




OU: Translation to Flight Electronics

- The measurement and optimisation processes implemented on the OU's flexible high-speed camera system would not be possible on the flight electronics system, but there will be subtle differences in the operation and output of the flight electronics when compared to the laboratory test system.
- While the laboratory system will allow highly detailed analysis of the generation of CIC and radiation-induced defects in the device, small changes in the clock waveforms between the two systems, down to the level of the precise shape of the rising and falling clock edges, may still have a major impact on the performance achieved in orbit.
- Therefore, the optimisation results will need to be translated to the flight electronics to ensure that optimal in-flight performance is achieved.





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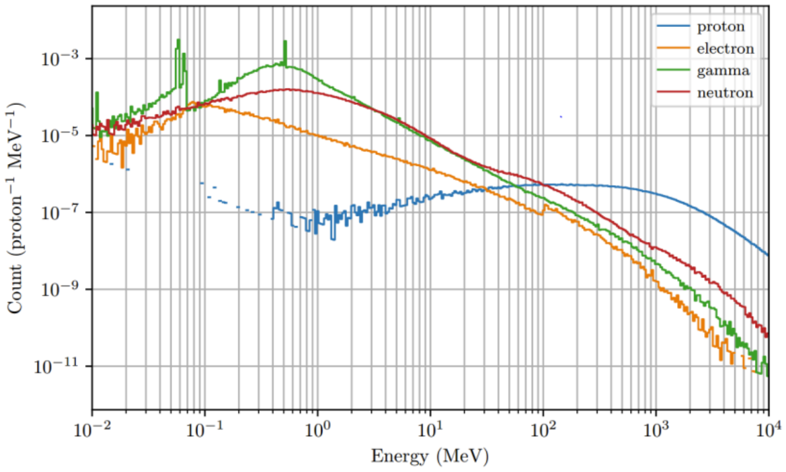
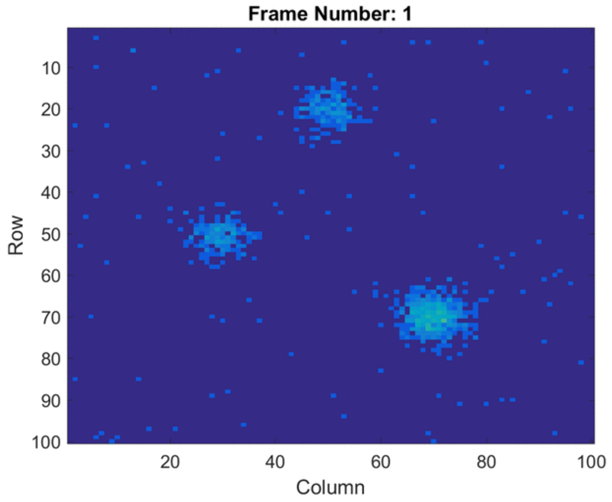
OU: Radiation Environment and Background

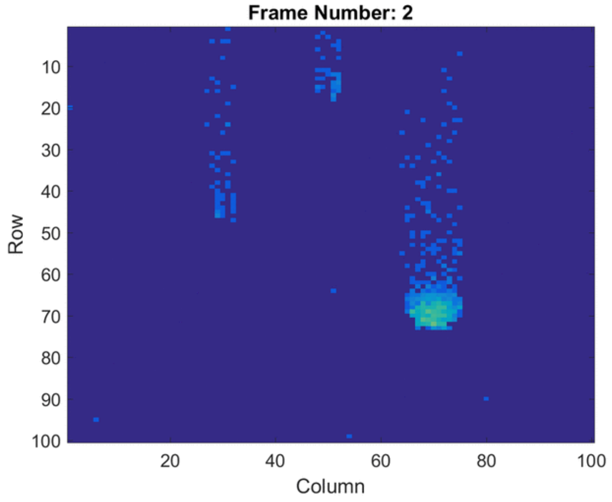
- The CGI detectors will be subjected to a complex background of primary and secondary radiation generated by the interaction of the radiation environment with components of the instrument optics and it's shielding.
- Since CGI will operate in the single optical photon counting regime, all aspects of instrument background require attention since the presence of even a few high energy particles per frame can reduce the useable image area of the device by up to 20 %.
- The Open University has expertise in the use of GEANT4 as a means to simulate the background of an instrument while incorporating the design of the instrument, as demonstrated through work on the ATHENA WFI and SMILE SXI.
- Outputs of this software include the spatial and energy distribution of secondary radiation, including particle type.
- These models can be used to constrain the expected secondary particle background that will be experienced by CGI, and then used as an input to the detailed radiation damage campaigns.



OU: Performance Modelling and Validation

- Charge transfer modelling has been a valued contribution to previous flagship missions including Hubble, Gaia and the soon to be used Euclid mission.
- The CGI will also benefit from the existence of a performance model that accurately replicates physical processes occurring within the EMCCD.
- Through incorporation of the properties of radiation induced traps, the set of optimised operating parameters and the simulated instrument background the model will be able to accurately predict the performance of CGI throughout the mission duration, and so contribute to correction strategies aimed at maximising the science yield of the instruments.
- Through collaboration with Teleydne-e2v, the Open University has access to many of the key design characteristics of EMCCDs and so can accurately replicate the pixel designs in TCAD programs such as SILVACO.
- These models can then provide precise information concerning charge storage and transfer characteristics, enabling highly accurate CTE modelling in the presence of radiation induced traps.





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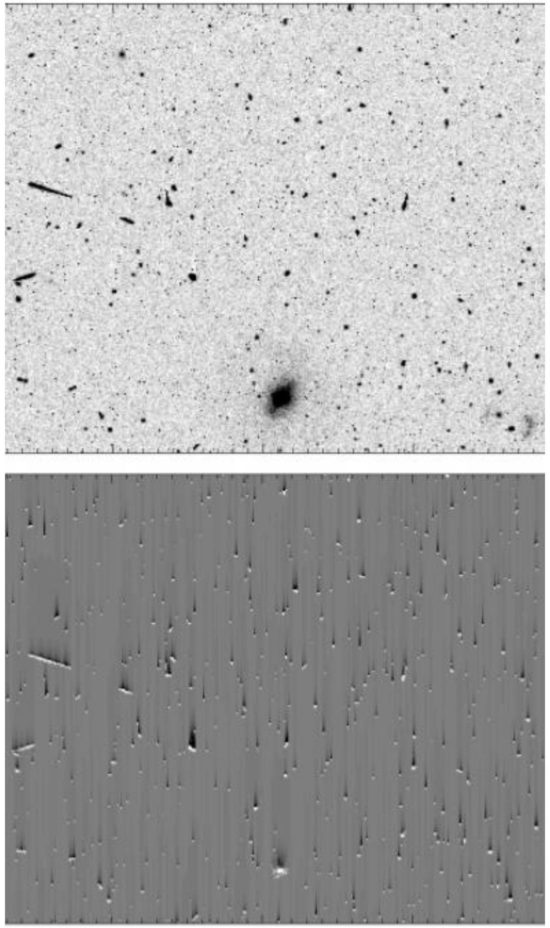
Durham: In-orbit monitoring of radiation damage

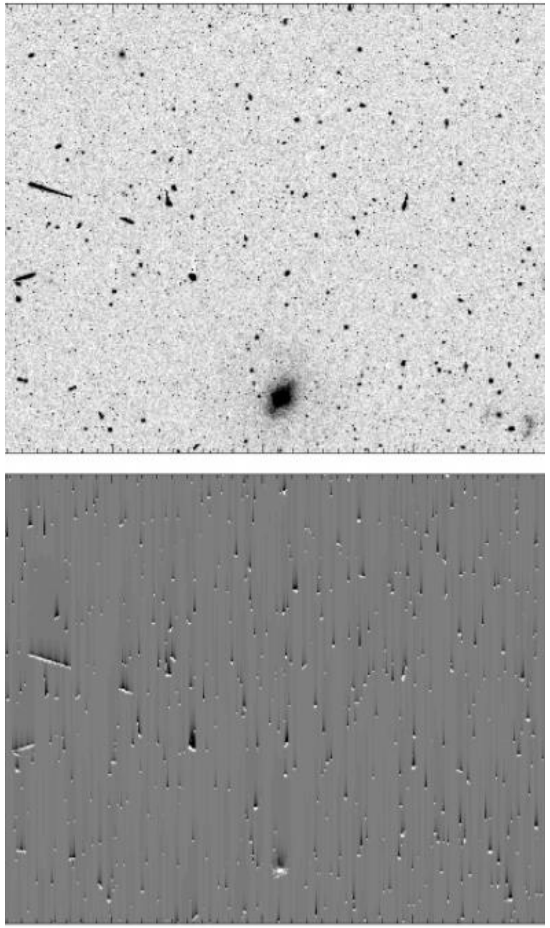
- The general behaviour of an irradiated CCD can be predicted from pre-launch tests. In-orbit, however, the specific amount and spatial pattern of sustained damage is stochastic.
- The nature of the damage is also sensitive to the precise energy spectrum of incident radiation, which remains poorly understood at Lagrange point L2.
- Durham University aim to develop an efficient sequence of calibration observations to monitor the amount and type of radiation damage throughout the Roman mission.
- These must be achievable using only the hardware capabilities in-orbit, and deliver the model parameters useable by a fast algorithm for data post-processing.
- Interaction with the science goals and science team will also support the goal of this proposal for more direct UK involvement in Roman science exploitation.
- This work is urgent. The sequence of calibration observations must be defined before launch, then be carried out immediately after launch, as soon as Roman is in the space environment.



Top panel: the HST ACS/WFC image after CTI correction. Bottom panel: difference image. 2009 RAS, MNRAS 401, 371–384

Durham: Software to correct radiation damage

- Software development for the CTI correction in RST requires a new approach to the perturbative correction used by previous optical and infrared satellite imaging, because of the low numbers of photoelectrons per source.
- If the photoelectrons encounter one or more charge traps during readout, they could be moved almost anywhere in the EMCCD.
- It is therefore impossible to correct such imaging by analysing a single exposure in isolation.
- Fortunately, Roman will acquire multiple exposures of each exoplanet target – which we will analyse simultaneously.
- We propose to first develop a new class of charge traps in the arCTIc software package (https://github.com/jkeger/arcticpy) that are able to represent the stochastic nature of both trapping and release.
- This will then lead on to the development of a forward-modelling algorithm to correct science data via a Markov Chain Monte Carlo search over possible sky image, exploiting our autofit Probabilistic Programming Language (https://github.com/rhayes777/PyAutoFit).



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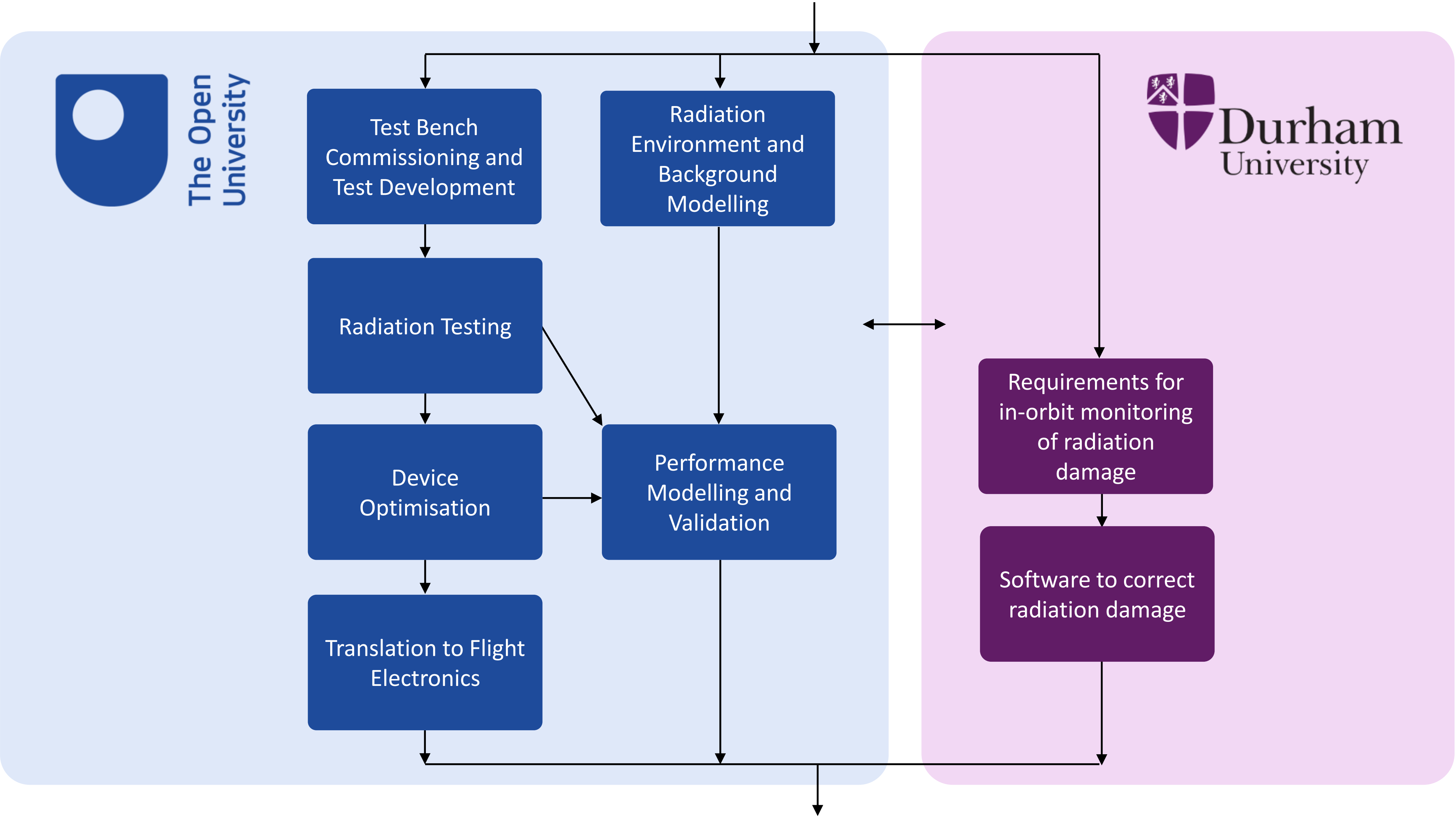
Summary


The Open University
Test Bench Commissioning and Test Development
Radiation Environment and Background Modelling
Radiation Testing
Device Optimisation
Performance Modelling and Validation
Translation to Flight Electronics
Durham University
Requirements for in-orbit monitoring of radiation damage
Software to correct radiation damage