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# Evaluating UV detector enhancement technologies for the next generation of space telescopes: the path to CASTOR

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## ABSTRACT

As space agencies consider the next generation of large space telescopes, it is becoming clear that high performance Ultraviolet (UV) imaging will be a key requirement. High-performing CMOS image sensors that are optimised for UV detection performance will therefore be essential for these missions to be able to fulfil their science requirements. The CASTOR mission, a 1 m UV space telescope project, will be utilising the large format CIS303 and CIS120 detectors from Teledyne e2v for three large focal planes covering the $UV$, $u'$ and $g'$ bands, respectively. Typically, silicon sensors have a very low quantum efficiency (QE) in the UV band between 150-300 nm, and the 2d-doping technology from NASA/JPL will therefore be utilised to improve the quantum efficiency. The Open University will perform electro-optical testing and space qualification of the CIS303 and CIS120 detectors, including a comparison of different UV coating and enhancement technologies. This paper covers the specification of radiation testing of the CIS303 and CIS120 detectors at the Open University, and characterisation of the QE-enhancing surface treatments.

**Keywords:** CASTOR, detectors, CMOS Imaging Sensors, UV, radiation damage

## 1. INTRODUCTION

Imaging in the ultraviolet (UV) band is critical for various astrophysical investigations, including the study of stellar formation, the characterisation of exoplanet atmospheres, and the distribution of dark matter. However, as UV light is very effectively blocked by Earth's atmosphere, space-borne UV telescopes are essential, especially if faint objects are targeted. With the Hubble Space Telescope being the only space telescope that employs dedicated UV instrumentation as a payload, a number of new UV space telescopes and missions have been proposed.[1–3]

One such mission is CASTOR,[4] a 1-meter UV space telescope project led by the Canadian Space Agency (CSA). CASTOR aims to provide high-resolution imaging and spectroscopy in the UV and blue-optical wavelengths, between 150-550 nm. CASTOR features three large focal planes, each tailored to different spectral bands: $UV$ (150-300 nm), $u'$ (300-400 nm), and $g'$ (400-550 nm). Imaging will be performed in all three bands simultaneously, while low-resolution (R=300-420) grism-mode spectroscopy will be done in $UV$ and $u'$. It will further have a digital micro-mirror device-based configurable UV multi-object spectrograph (UVMOS) in a parallel field, providing access to the $UV$ band with R $\sim$ 1500.

The field of view will be $0.44\times0.50$ deg$^2$ with a resolution of 0.15" and will therefore deliver very high spatial resolution imaging over a field over 50 times larger than the Hubble Space Telescope field. CASTOR will use a mixture of planned survey time, guest observer programs, and have a Target-of-Opportunity (ToO) mode, which will be able to repoint the telescope within a short period (~2 hours).

Within its first 5 years of operation, CASTOR will image ~5% of the sky to reach a depth of $m_{\mathrm{AB}} \sim 27$ in the three bands (about 1.3 mag deeper than the Nancy Grace Roman Telescope u-band) and provide the

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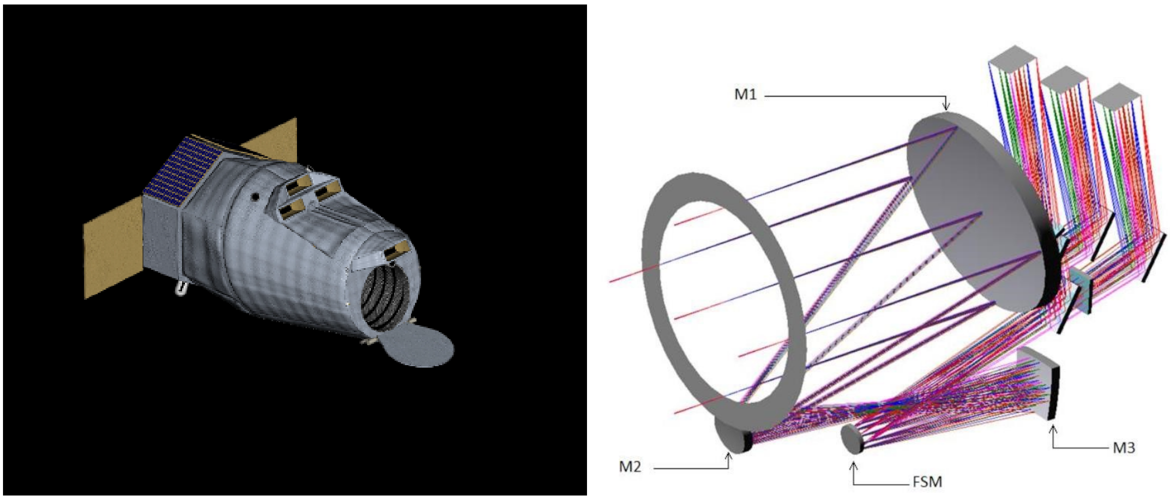

Figure 1. An artists rendition of the CASTOR spacecraft (right) and the proposed optical design for CASTOR (left)

widest, deepest, and highest resolution legacy survey available in the UV and blue optical.[5] It will therefore provide transformative science within a wide array of science topics, including Cosmological surveys focusing on the mass power spectrum, the distribution of dark matter, and tests of gravity on cosmological scales; unique high-sensitivity UV access to a vast array of astrophysical transients ranging from tidally disrupted stars to gravitational wave events; the evolution of cosmic star formation, on sub-galactic scales, including the connection between the growth of stellar mass to the assembly of dark matter halos; echo mapping of AGNs to probe the geometry, kinematics and physical conditions of photo-ionized gas in active galaxies; the discovery of new Galactic satellites and streams, and the outermost structure of our Milky Way galaxy; the UV/blue-optical properties of stars of all sorts, ranging from young and hot stars, degenerate objects and even chromospheric activity in M dwarfs; the star formation and chemical enrichment histories of nearby galaxies and clusters; characterization of exoplanet atmospheres from time series transit photometry and spectroscopy, and phase curve analyses; the identification of the smallest and/or most remote objects in the outer solar system, as well as the surface chemistry of small bodies from their UV to IR spectral energy distributions.

This paper outlines the detector technology to be used for CASTOR, the UV enhancement methods that can be used to achieve the necessary quantum efficiency in the UV region, and the radiation testing that will be done as part of the space qualification of the detectors.

## 2. DETECTOR TECHNOLOGY

The main detector technology selected for CASTOR is the newly developed CIS300 series of detectors from Teledyne e2v.[6] These detectors are developed with a modular design, which means they can be manufactured in a range of formats. To cover the $0.44\times0.50\ \mathrm{deg}^2$ field at the required resolution, each of the three focal planes will utilise four large format CIS303-66 detectors, which feature 9k × 8.6k pixels at a 10µm pixel pitch.

The CIS303 has a number of operating modes including Rolling and Global Shutter, High Dynamic Range (HDR), and a staircase mode, where multiple non-destructive reads are performed during integration. The device is capable of operating at 8 frames per second (fps) with 12-bit resolution in both rolling and global shutter modes and can read out selected rows and columns in a region of interest. It has multiple gain settings, with both a $\times1$ and $\times10$ pixel gain, and 5 pre-amplifier gains ($\times1$, $\times3$, $\times7$, $\times15$, and $\times31$), which can be combined in any way. Using the highest pixel gain setting, the full well capacity is $>15\mathrm{k\,e^-}$ with a noise of $<2\,\mathrm{e^-}$ in rolling shutter and $>5\,\mathrm{e^-}$ in global shutter mode. Using the lowest pixel gain setting, the full well capacity increases to $>140\mathrm{k\,e^-}$ with a noise of $<30\,\mathrm{e^-}$ in rolling shutter mode.

The detectors will be delivered in a 3-sides buttable package, minimising the dead space between adjacent image regions to 2 mm. The package will be made from silicon carbide ensuring the detector can operate in a

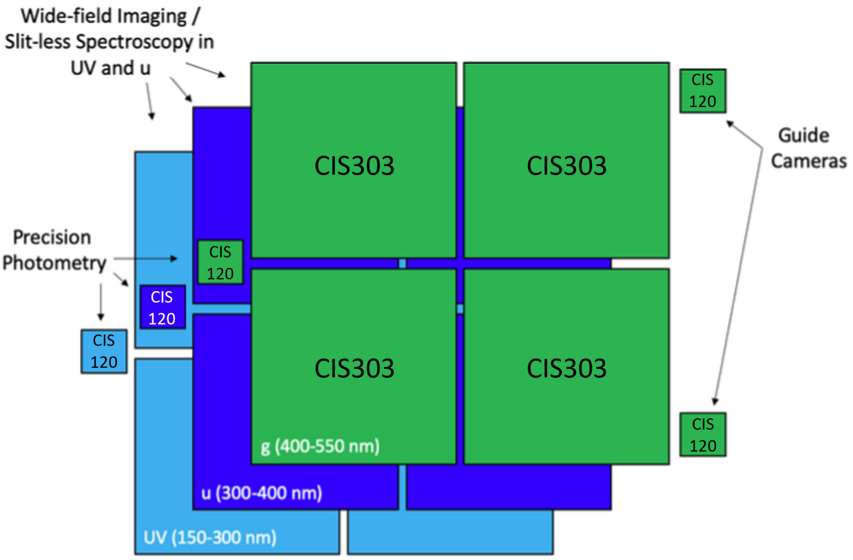

Figure 2. Device layout of the CASTOR focal plane arrays. Each of three bands will have four CIS303-66 detectors for wide-field imaging (and slit-less spectroscopy for $UV$ and $u'$ only), and one CIS120 for precision photometry. The $g'$ band focal plane will have two extra CIS120 devices for guiding.

large temperature range while maintaining an image area flatness within 25µm.

Each of the three focal planes will further be utilising a CIS120 device from Teledyne e2v, as a precision photometer placed next to the CIS303 devices. The g-band focal plane will also be using two CIS120s as wavefront sensors / for star tracking to do precision pointing of the telescope. The CIS120 also has a 10µm pixel pitch but is a 2k × 2k pixel device and is therefore somewhat smaller than the CIS303-66. The pixel architecture is similar, but the CIS120 uses a slightly older technology, so it does not have dual pixel gain settings or staircase mode.

With the four CIS303-66 devices on each focal plane and the CIS120 devices, the total pixel count for CASTOR will be almost one billion.

## 3. UV ENHANCEMENT TECHNOLOGIES

To image objects at the dimmest magnitudes of the science requirements, the detectors will need to have a very high quantum efficiency (QE). Silicon has a very short absorption depth at UV wavelengths, resulting in the most photons being absorbed in the first few nanometres of material. On an untreated silicon surface a significant proportion of the light absorbed in the silicon at UV wavelengths are not collected and detected, because they recombine at the surface. To improve charge collection, the back surface must be passivated.

One passivation technique is Teledyne e2v's own UV-enhanced passivation technique, which uses low-energy boron implantation. This implant is activated by a UV laser to create a 40 ± 10nm p+ layer. This is a non-photosensitive 'dead layer' where photo-generated charge cannot be collected as image signal, severely reducing the effective QE. To improve this performance, it is vital that this dead layer is minimised and so a further etching process is performed to make this layer thinner improving the UV performance.[7]

CASTOR has baselined the 2D-doping technology developed by NASA/JPL[8] to effectively reduce the dead layer to near zero thickness. This technology uses low-temperature molecular beam epitaxy (MBE) to passivate back-illuminated silicon detectors. During MBE growth, an atomically thin, highly concentrated delta layer of dopants is embedded within nanometers of the photon-incident surface. The MBE process allows for nanoscale control of dopant density and position within the deposited layer to enable near 100% internal QE and long-term stability.

The other technology is black Silicon (bSi) delivered by Aalto University and a spin-off company Elfys. Here a low-temperature (-120°C) reactive-ion plasma etch is used to produce a nano-structured surface of closely spaced spikes with average height 500 nm and width 100 nm. This surface then receives a conformal coating of 20 nm $Al_2O_3$, deposited by atomic layer deposition, with negative surface charge to provide a suitable electric field in the sensor to passivate the surface and form a charge-collecting p-n junction, which can enhance the performance.[9] There is no dead layer as the surface is passivated by the external field from the coating. The technology has been tested down to 200 nm showing impressive performance[10] and has been applied to CMOS image sensors with good results.[11]

These three technologies will be characterised and compared directly across a number of parameters, principally UV QE performance down to at least 150 nm. The influence these UV enhancement technologies have on other important detector parameters, such as noise, dark current, etc. will also be tested, along with an assessment of manufacturing processes, operational functionality and handling issues.

For this purpose, each of the three technologies will be applied to four CCD120s and will be delivered by Teledyne e2v to be tested at the Open University using international UV beamline facilities.

## 4. RADIATION DAMAGE ASSESSMENT

As with any telescope in space, CASTOR will be subject to high-energy radiation from the Sun and the galactic background. CASTOR will be partially protected by the magnetosphere in the dawn-dusk low-Earth Sun-Synchronous Orbit (SSO), which is baselined but will still have to pass through the South-Atlantic anomaly.

From orbital radiation environment analysis paired with FastRad and Geant4 simulations, precise estimations of the total dose the detectors will receive during the mission lifetime can be predicted. This will help inform the end-of-life fluence levels to be used in the radiation damage testing and determine the amount of shielding needed. The exact shielding design can be refined by simulations using Geant4, which can help achieve an optimal trade-off between mass and performance.[12, 13]

To assess how the performance of the detectors are affected by the radiative environment, a rigorous radiation damage assessment will be performed. This will include both Total Ionizing Dose (TID), which primarily creates charge traps at the Si-SiO interface thus increasing the dark current; Total Non-Ionizing Dose (TNID) which primarily displaces atoms in the silicon lattice, creating lattice defects that can increase image lag; and Single Event Effects (SEE), where a local over-density of ionized charges is induced, which produce latch ups and soft-effects and can potentially be destructive to device operation.

## 5. SUMMARY

The CASTOR mission will provide high-resolution imaging and spectroscopy over a very large field in the UV and optical wavelength bands. With the combination of legacy surveys and Guest Observer programs, CASTOR will be able to address a wide range of science topics, while at the same time having the flexibility to address the needs of diverse research communities.

To be able to deliver these science goals the detector performance is of high importance, and a program to test and characterise the chosen detectors has therefore been started at the Open University in collaboration with Teledyne e2v. This will include testing of different UV enhancement technologies to ensure the necessary throughput in the *UV* band, and radiation damage testing to assess how the detector performance is affected by the high levels of radiation in the space environment, and how the detectors and spacecraft can be best shielded.

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