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# Developments in the EM-CCD camera for OGRE

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## ABSTRACT

The Off-plane Grating Rocket Experiment (OGRE) is a sub-orbital rocket payload designed to advance the development of several emerging technologies for use on space missions. The payload consists of a high resolution soft X-ray spectrometer based around an optic made from precision cut and ground, single crystal silicon mirrors, a module of off-plane gratings and a camera array based around Electron Multiplying CCD (EM-CCD) technology. This paper gives an overview of OGRE with emphasis on the detector array; specifically this paper will address the reasons that EM-CCDs are the detector of choice and the advantages and disadvantages that this technology offers.

**Keywords:** OGRE, EM-CCD, Soft X-ray, Sounding Rocket, Suborbital Rocket

## 1. INTRODUCTION

Sub-orbital rockets offer an ideal platform for increasing the Technology Readiness Level (TRL)[1] of emerging technologies to reduce the risk of these technologies being used on future large scale missions. The Off-plane Grating Rocket Experiment (OGRE) is a sub-orbital rocket that will be used to prove the space readiness of three separate technologies. The X-ray telescope will be a Wolter type-I optic made using precision-cut and ground single crystal silicon mirrors from Goddard Space Flight Center (GSFC)[2,3] The grating module will consist of densely ruled off-plane gratings made at the University of Iowa, and a camera array based around Electron Multiplying Charge-Coupled Devices (EM-CCDs) designed at the Open University.[4] All three of these technologies have never been tested in space and so are considered high risk for future large scale space missions. EM-CCDs are being used on the Atmospheric-Space Interactions Monitor (ASIM) that is due to be sent to the International Space Station (ISS) in 2015; however, this is a ground facing instrument that will detect optical photons.

With a resolution greater than 2000 and an effective area of 40 $cm^2$ or more over the 0.3 keV to 1.5 keV energy range OGRE will represent a significant step forward in the development of high resolution soft X-ray spectrometers.[5]

To test the performance of OGRE as a high resolution soft X-ray spectrometer, Capella has been chosen as the target. Capella consists of two giant stars with active coronae and it's spectrum is made up of a series of emission lines from highly ionised species. Its' close proximity to Earth (∼13 pc) makes Capella one of the brightest X-ray sources in the sky which suggests that OGRE can expect a count rate of ∼15 counts/second over the ∼300 second observation.[6]

The detailed line spectra that are expected from Capella offer an ideal test-bed to test OGRE's resolution performance, Figure 1.

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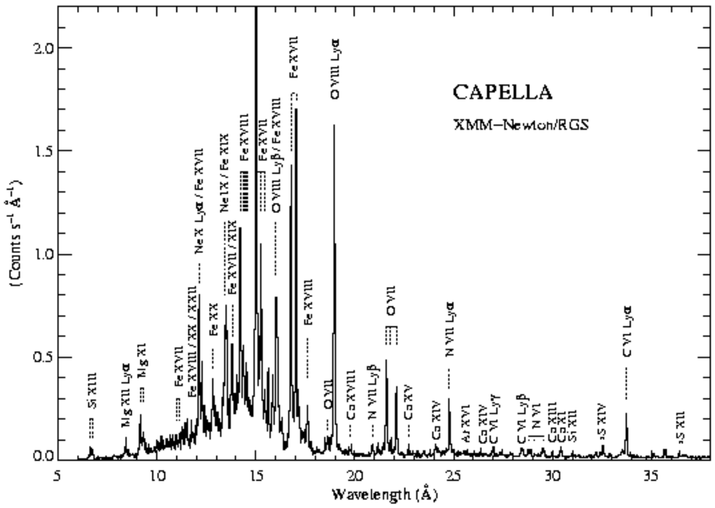


Figure 1. An example of a spectrum from Capella taken using the Reflection Grating Spectrometer (RGS) on XMM-Newton. The spectrum shows a very detailed emission line profile[6]

### 1.1 Precision-cut single crystal silicon mirrors

The focusing optic for OGRE takes advantage of the commercial availability of large bricks of mono-crystalline silicon and the precision polishing techniques that have been developed for the semiconductor industry.

The fabrication technique allows the individual silicon mirrors to be cut from a silicon block and then polished to a very high finish without creating internal stress within the silicon. This precision polishing and low internal stress allows large, lightweight mirrors to be developed with high angular resolution. The mirrors are fabricated at GSFC and OGRE will be the first time that mirrors formed this way have been used in a space application. For more details on this process, consult Zhang et al. 2012.[3]

### 1.2 Off-plane gratings

OGRE will use gratings in the off-plane mount to disperse the X-ray photons that have been focused by the silicon mirrors. The off-plane gratings are manufactured at the University of Iowa and are required to fulfill several criteria described below and shown in Figure 2.

- Densely grooved (∼6000 grooves/mm)

OGRE has a baselined focal length of 3.5 m. This is the maximum focal length achievable while maintaining the vehicle stability of a Black Brant IX sounding rocket. The limit in focal length means that the resolution requirement of ∼2000 has to be achieved through the use of densely grooved gratings. The more densely a grating is ruled the higher the dispersion of the X-rays.[5]

- Radially ruled groove profile

The X-ray optic focuses the incident X-rays to a point on the focal plane. The gratings intercept this converging beam, but as the gratings have a physical size along the focal length, the grooves must be fanned to match convergence of the photons.[7]

- Blazed

A grating with sinusoidal grooves will disperse photons equally to either side of zero order. This results in either half of the dispersed photons being lost or the camera array having to be twice as large. If the gratings are blazed, the photons are preferentially dispersed to one side of zero order, increasing throughput without increasing the size of the camera. Blaze has the additional benefit of dispersing photons into higher orders.[7]

• Closely packed

Off-plane gratings are preferred over their on-plane counterparts as off-plane gratings disperse the photons in an arc out of the plane of the direction of the incident photons. In the in-plane case, low energy X-rays are dispersed at a higher angle from the plane of the grating which can lead to occulting of the photons. The Off-plane don't have this affect; therefore, gratings can be stacked much closer together without occulting the dispersed photons with the next grating in the module.

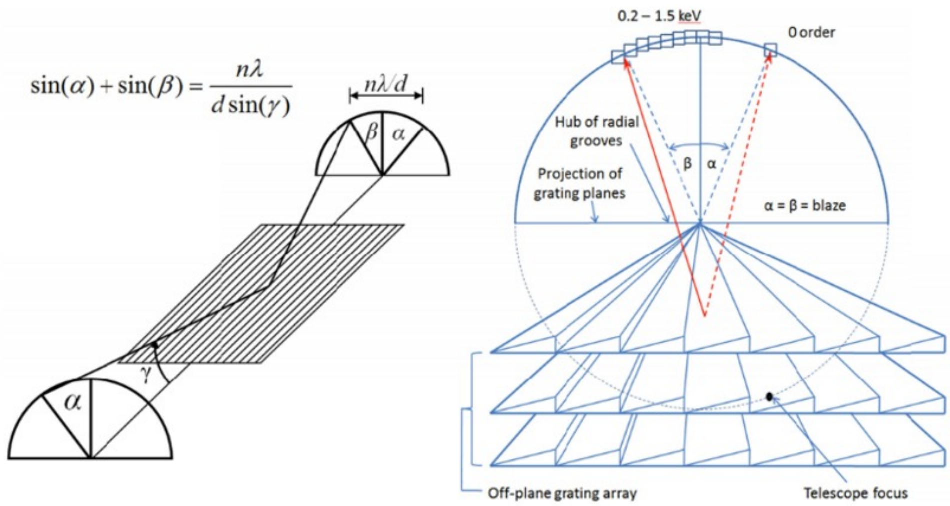


Figure 2. A schematic showing the off-plane grating concept. The dispersion of the X-rays is out of the plane of incidence, the grooves are densely ruled, blaze and radially fanned[7]

For more information on the fabriaction and testing of the gratings consult McEntaffer et al. 2013[8]

### 1.3 Focal plane detector

The devices used on the focal plane will be used to detect the position to which the X-rays are dispersed. This positional information is used to determine the energy of the detected photon allowing the spectrum from Capella to be re-constructed. To achieve this the detector must have a high Quantum Efficiency (QE), especially at the lower energy range of the instrument (0.3 keV), have pixels that are small enough to resolved the features within the arc, cover a large effective area in a cost-effective manner, be able to photon count X-rays and have a native energy resolution better than 0.2 keV.

OGRE uses several diffracted orders to achieve the effective area and resolution across the energy range; therefore, the detector must be able to differentiate between two photons of different energy and order that have been dispersed to the same point on the focal plane, hence the requirement of a native energy resolution better than 0.2 keV.

In the baseline design for OGRE the focal plane detector array consists of EM-CCDs, specifically the e2v CCD207-40.[9] The CCD207-40 is a 1600 pixel x 1600 pixel full frame EM-CCD with 16 $\mu$m x 16 $\mu$m pixels. The camera array will be mounted to a large thermal mass that will be LN2 cooled before launch, allowing the detectors to be operated at -80 °C during the flight.

To avoid contamination on the detector during launch, they will be sealed and under vacuum. When at altitude, a gate valve will open exposing the EM-CCDs to space allowing observations to occur. At the end of the observation time the gate valve will close again to protect the camera from being contaminated during re-entry allowing post-flight calibration.

# 2. EM-CCD

EM-CCDs are based on conventional CCDs with a multiplication register incorporated into the design after the serial register but before the readout node, Figure 3. The multiplication register is able to increase the number of electrons in the charge packet through impact ionisation. By having one of the electrodes in the multiplication register held at a high potential (∼50 V), electrons are accelerated through the potential and can impact with other electrons in the silicon lattice causing them to become ionised. The probability of impact ionisation occurring is small (∼0.015), but the number of elements in the multiplication register is high (>500), allowing large gains to be possible.[4]

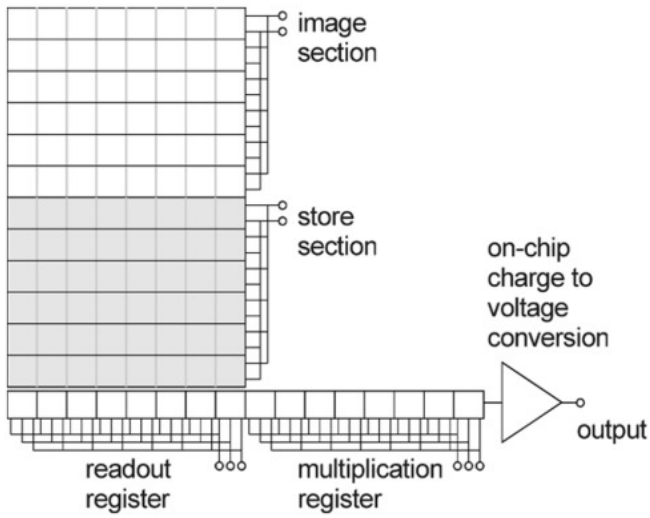


Figure 3. Schematic of an EM-CCD showing the multiplication register added after the serial register and before the output node[10]

## 2.1 High speed

Through the use of multiplication gain it is possible to suppress the readout noise from the detectors. Readout noise increases with increasing frame-rate; however, multiplication gain can be used to suppress this readout noise allowing the detector array to be operated at the 1 frame-per-second baseline readout speed with sub-electron equivalent noise.

High readout rate relaxes the tolerances on the stray light rejection needed for OGRE. EM-CCDs are highly efficient at detecting optical photons; therefore, optical background can swamp the target X-ray signals. To avoid this, aluminium optical blocking filters are either mounted in front of the camera array or directly deposited onto the detectors. The faster the readout speed, the thinner these filters can be which improves the QE of the detectors, compared to using thicker filters, which leads to the maximisation of OGRE's effective area.

High readout speed also allows pointing towards bright X-ray sources while avoiding pile-up. This is not necessary for OGRE, but showing that the camera array can readout quickly with no increase in noise floor makes EM-CCDs a more desirable detector for future space missions.

## 2.2 Low equivalent readout noise

Through the use of multiplication gain, the equivalent readout noise from the device is reduced. This reduction allows event recombination to occur off-chip without a large increase in readout noise. When events are recombined, the noise associate with the signal is increased by a factor relating to the number of pixels combined and the readout noise. If the readout noise has been suppressed to sub-electron levels, this increase in noise is small.

Multiplication gain also increases the amount of signal in a charge packet. If the X-ray events is split between many pixels, the multiplication of small amounts of charge will allow all of the charge cloud to be identified, making complete charge collection easier.

## 2.3 QE

Thin filters, as discussed in Section 2.2, maximise the QE of the camera array. Figure 4 shows the dependence of QE on filter thickness across the OGRE bandpass. It can be seen that the low energy QE is highly dependent on the thickness of Al.

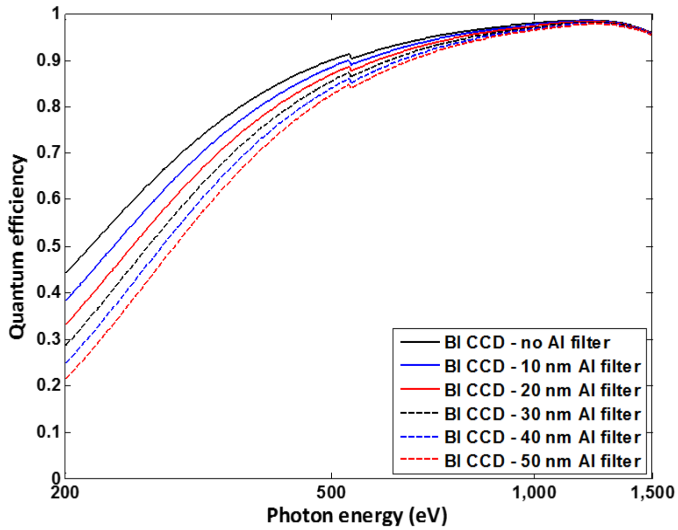


Figure 4. The QE of the detectors at the low energy end of OGRE's bandpass depends on the thickness of Al that is used for the optical blocking filter

To achieve the OGRE baseline effective area performance across the bandpass, the QE at lower energies has to be optimised through the use of thin filters. The high performance of the EM-CCDs relaxes the stray-light tolerance of the detector array allowing thinner filters can be used. The desire for thin filters exists, the challenge is in the manufacture of such filters. A thick filter will have greatest impact on QE at 0.2 keV hence, the effective area at low energies is detector QE driven. Thin filters are essential to achieving a greater than 40 $cm^2$ effective area at the low energy range of OGRE.

## 2.4 Optical blocking filters

Optical blocking filters can either be directly deposited onto the EM-CCD or mounted in front of the camera array. Both methods have advantages and disadvantages, hence, a study will be needed to decide what approach to take. Ultimately, the decision may come down to which technology is most readily available and cost-effective.

Filters deposited directly onto the surface of the detector were used on the Reflection Grating Spectrometer on XMM-Newton. The CCDs used for the RGS were coated in three different thickness of Al (45 nm, 68 nm and 75 nm) with a 26 nm insulation layer between the silicon and Al made of $MgF_2$[11,12] Directly deposited filters have the advantage of being able to be layered very thinly over the detectors. Directly deposited filters also do not require a support mesh and are as robust as the detector itself. However, the deposition in non-trivial and would necessitate the involvement of an outside vendor to perform the deposition. The CCDs themselves are a non-disposable part and so any damage caused by the processing would greatly add to the cost of the focal plane. The deposition onto the CCDs can also prove to be non-uniform. Al depositions are prone to "pin-holes" - micron size holes in the filter than allows optical photons through. So long as these defects are not in the arc of diffraction, the pin-holes affects can be removed. This is more common with thicker layers of Al.[13] Another issue can be that the Al clumps together causing a non-uniform layer on the CCDs and so a QE that varies with position on the detector.

The other option is to use a filter mounted on a support mesh which can be placed in front of the camera array. Filters of this type are being used on ASTRO-H where Al is deposited on a polyimide layer that is supported by a silicon mesh[14,15] The filter is separate from the detector array; therefore, there is little chance in damaging the camera with this option. It is also possible to achieve an even deposition with companies that specialise in such technology, Figure 5. Mesh supported filters do have some disadvantages. The supporting mesh will block incident X-rays which will reduce throughput, causing a drop in effective area of OGRE, especially at the lower energy end of the bandpass. However, the ASTRO-H filter have a 96% transparency showing that technology is advancing to a point where mesh blocking is minimised. The filter will need an interface on the rocket which should be trivial, but will have to be incorporated into the design. The mesh will be brittle as it is required to be very thin, increasing the likelihood of damage either during integration, vibration testing or launch; therefore, this filter type would have to be very carefully investigated before it is selected. Finally, mesh filters tend to be thicker than their deposited counterparts as the Al is deposited onto a polyimide layer which will reduce the QE of the detector, especially at the lower energy end of the bandpass and could cause OGRE to miss is' $\sim$40 $cm^2$ effective area target.

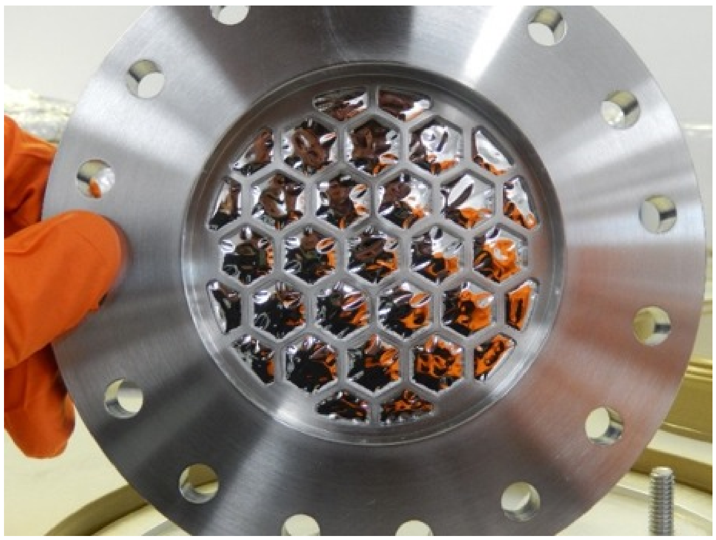

Figure 5. Photo of an Al filter mounted on a BN100KF flange with an Al mesh support

### 2.5 Modified Fano factor

Multiplication gain is a stochastic process; therefore, an additional component of shot noise is added to the signal causing a degradation in the native resolution of the detector. This resolution degradation caused when using an EM-CCD to detect X-rays has been described by the Modified Fano Factor and has to be taken into account when designing OGRE. If the native resolution of the detector is degraded to be worse than 0.2 keV then the EM-CCD is not appropriate for use on OGRE. Based on using an EM-CCD with high gain allowing the readout noise to be suppressed to 1 electron (as a worse case scenario), the theoretical native resolution of the detector is $\sim$0.185 keV and so the Modified Fano Factor should not cause issues for OGRE[16,].[17]

## 3. CONCLUSION

OGRE is a test-bed for technologies with a low TRL so that they can be de-risked for future X-ray missions. The technologies being used have limited or no space environment heritage making them high risk items.

The precision-cut and ground single-crystal silicon mirrors and University of Iowa manufactured off-plane gratings are new technologies that will be space tested using OGRE, whereas EM-CCDs have been used in terrestrial applications for many years and CCDs have a large amount of space heritage. This suggest that EM-CCDs are lower risk than the other elements of OGRE; however, they have never been used in space for X-ray photon counting applications.

EM-CCDs have been chosen for use on OGRE as they are able to be operated with a high frame rate, without a large increase in readout noise. This allows the OGRE focal plane array to have thinner optical blocking filters as stray-light tolerance is increased. Thinner filters increase detector QE which increases the effective area of the instrument, especially at the lower end of OGRE's bandpass making it easier to achieve the >40 $cm^2$ effective target. EM-CCDs also bring low energy signals out of the noise and allow event recombination of split events without a large increase in noise.

The degradation in spectral resolution caused by using multiplication gain has been shown to not affect the native resolution of the EM-CCDs enough to make it impossible to separate photons of different energy at the same point on the focal plane.

A successful sub-orbital rocket flight using these technologies would show that they are capable of being used on longer term missions.

### 3.1 Acknowledgments

In the Acknowledgments section, appearing just before the References, the authors may credit others for their guidance or help. Also, funding sources may be stated. The Acknowledgments section does not have a section number.

## REFERENCES

[1] Definition of Technology Readiness Levels, NASA, `http://esto.nasa.gov/files/trl_definitions.pdf`

[2] Zhang, W.W. et al., Lightweight and high angular resolution x-ray optics for astronomical missions, *Proc. SPIE,*, **Vol. 8147**, (2011)

[3] Zhang W.W. et al., "Next Generation X-ray Optics: High-resolution, Light-weight, and Low-cost," *NASA RFI Submission, 28 October 2011*, `http://pcos.gsfc.nasa.gov/studies/rfi/Zhang-William-RFI.pdf&gt`, (2012)

[4] Jerram P. et al., "The LLLCCD: Low light imagining without the need for an intensifier", *Proc. SPIE,* **Vol. 4306**, (2001).

[5] DeRoo C., et al., "Pushing the boundaries of X-ray Grating Spectroscopy in a suborbital rocket", *Proc. SPIE,*, **Vol. 8861**, (2013).

[6] Audard M., et al., "The XMM-Newton view of stellar coronae: High-resoltuion X-ray spectroscopy of Capella", *Astronomy and Astrophysics*, **Vol. 365**, (2001).

[7] McEntaffer R.L, et al., "Developments of the Off-Plane X-ray Grating Spectrometer for IXO", *Proc. SPIE,*, **Vol. 7732**, (2010).

[8] McEntaffer R.L, et al., "First results from a next-generation off-plane X-ray diffraction grating", *Experimental Astronomy,* **Vol. 36, Issue 1-2**, (2013).

[9] e2v CCD20-40 datasheet, "CCD207-40 back-illuminated 2-phase IMO series Electron Multiplying CCD Sensor", *e2v Technologies Ltd.,* **Draft B, ISM**, (2009).

[10] Robbins M. S. et al., "The Noise Performance of Electron-Multiplying Charge-Coupled Devices", *IEEE Trans. Elect. Dev.,* **Vol. 5**, (2003).

[11] Brinkman A., "The Reflection Grating Spectrometer on board XMM", *Proc. SPIE*, **The First XMM workshop: Science with XMM, ESTEC, Noordwijk, The Netherlands**, (1998).

[12] den Herder J. W. et al., "The Reflection Grating Spectrometer on board XMM-Newton", *Astronomy & Astrophysics,* **Vol. 365**, L7–L17 (2001).

[13] Ryu K.K., et al., "Development of CCDs for REXIS on OSIRIS-REx", *PROC. SPIE*, **Poster Presentation 9144-199**, (2014).

[14] NASA, "Materials & Coatings: Blocking Filters with enhanced throughput for X-ray microcalorimetry", *NASA Tech Briefs*, (2012)

[15] de Vries C.p., et al., " Filters and calibration sources for the Soft X-ray Spectrometer (SXS) instrument on ASTRO-H", *Proc. SPIE,* **Vol. 7732**, (2010).

[16] Tutt J. H. et al., "The Noise Performance of Electron-Multiplying Charge-Coupled Devices at X-ray energies", *IEEE Trans. Elect. Dev.,* **Vol. 59, Issue 1**, (2011).

[17] Tutt J. H. et al., "The Noise Performance of Electron-Multiplying Charge-Coupled Devices at Soft X-ray energy values", *IEEE Trans. Elect. Dev.,* **Vol. 59, Issue 8**, (2012).