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The Off-plane Grating Rocket Experiment (OGRE) system overview

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ABSTRACT

The Off-plane Grating Rocket Experiment (OGRE) is a sub-orbital rocket payload that will make the highest spectral resolution astronomical observation of the soft X-ray Universe to date. Capella, OGRE's science target, has a well-defined line emission spectrum and is frequently used as a calibration source for X-ray observatories such as Chandra. This makes Capella an excellent target to test the technologies on OGRE, many of which have not previously flown. Through the use of state-of-the-art X-ray optics, co-aligned arrays of off-plane reflection gratings, and an X-ray camera based around four Electron Multiplying CCDs, OGRE will act as a proving ground for next generation X-ray spectrometers.

Keywords: OGRE, X-ray, Sub-orbital rocket, Sounding rocket, Capella, Off-plane reflection gratings, EM-CCD, Silicon shell optics, Spectrometer

1. INTRODUCTION

High resolution soft X-ray spectroscopy is a requirement for future X-ray observatories such as the Lynx concept mission.[1] To achieve this requirement, a spectrometer is required that utilizes a high angular resolution large effective area optic X-ray optic, a high resolution and high efficiency grating technology, and a focal plane camera that can be operated at low noise, with good Quantum Efficiency (QE) across the target bandpass (8 to 42 Å, 1500 to 300 eV). A spectrometer such as the one being used on OGRE (due for launch in Q3 2020), would be able to achieve these requirements. Figure 1 shows a CAD model of the system design of OGRE. It includes the position of the optic, gratings, camera, camera electronics, and star-tracker.

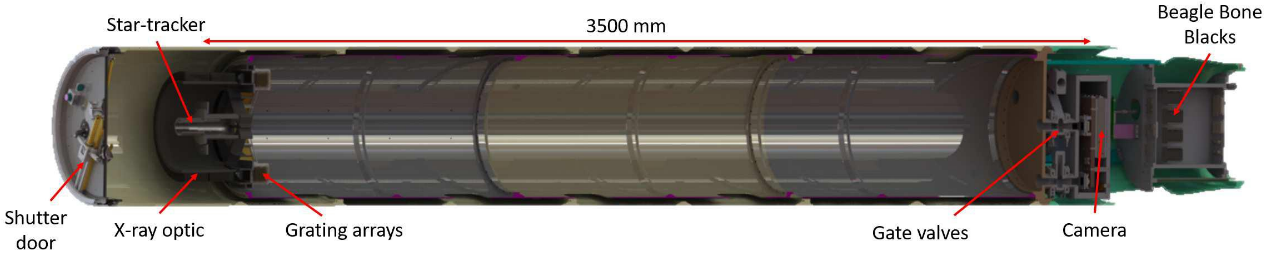

Figure 1. Initial CAD of OGRE showing the X-ray optic, star-tracker, grating module, and camera.

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Like the reflection grating spectrometer on XMM-Newton,[2] OGRE will use reflection gratings to disperse incident X-rays into an arc on the focal plane, although OGRE's grating configuration will be off-plane compared to the in-plane gratings on XMM-Newton. The three main elements that make up OGRE (optic, grating, and detector) will be discussed in detail in the following sections.

2. OPTICAL ASSEMBLY

Lightweight silicon X-ray mirrors are being developed at Goddard Space Flight Center (GSFC). This group is developing an X-ray optic technology that is able to produce Chandra like angular resolution (0.5 arcsecond), but at a fraction of the weight. Chandra has the highest angluar resolution X-ray optic ever produced. The GSFC optic design is based around the machining and alignment of thin silicon segments that are aligned around a central meta-shell.[3–5] Figure 2 shows the most recent CAD model for the optic. Grating modules are also shown attached to the optic spider structure.

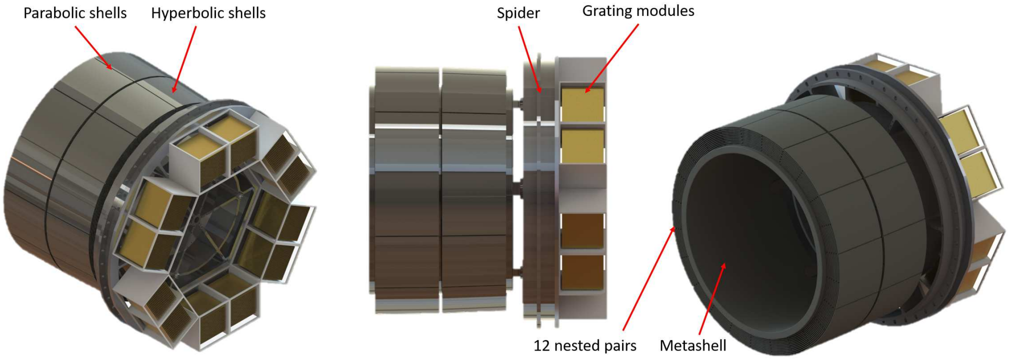

Figure 2. CAD of the X-ray optic, mounted onto the structural shell with spider structure. The 12 grating modules are shown mounted onto this spider structure.

For OGRE, an X-ray optic with shorter focal length than would be required on an orbital mission is being developed so that it can fit into a sub-orbital rocket envelope. The focal length on OGRE is 3.5 m compared to at least 10 m on missions such as the Lynx concept study.[1] This mirror will be based on the full meta-shell design, and have 12 segments in the circumferential direction ranging from a diameter of 330 mm to 388 mm. This optic will produce a high quality focus on the focal plane, 3 - 5 arcseconds HPD, and will be the basis for the high resolution that the OGRE spectrometer requires. A more detailed optical design discussion can be found in Donovan et al.[6]

Once the optic has been manufactured, it has to be mounted onto the rocket in a way that allows its precision alignment to the focal plane while still being strong enough to survive launch vibrations. Finite element analysis has shown that an optical bench design, similar to the one used on WRXR,[7] will sufficiently damp launch vibrations to not cause damage to the optic. The optical bench on WRXR was cantilevered from the focal plane bulkhead, which provided a 2 m length of cylindrical aluminum to damp any vibrations. The method of precision alignment in-situ is still be investigated.

Off-plane reflection gratings for soft X-ray applications are designed, manufactured, and tested at Penn State University. Many papers have been written on the fabrication and testing of these gratings,[8–13] and so in this paper we will focus on the design of the OGRE grating, the modules in which the gratings will be housed, and how these modules will be incorporated into the rocket.[6]

OGRE's X-ray optic will be treated as 6 independent 60° azimuth optics. This allows the gratings to sub-aperture the optics PSF, increasing the spectrometer resolution from what would be achieved if the optic was being treated as a whole system. The gratings will be mounted onto the spider structure of the X-ray optic, Figure 2. By operating the gratings at a yaw to the incident X-rays, it is possible to make the gratings on adjacent 60° azimuthal sections of the optic diffract X-rays to the same CCD; therefore, only 3 detectors are required on the focal plane, Figures 3[6] and 5. This is possible through the alignment of the adjacent grating modules in opposing yaw configurations. Operating in Littrow configuration also allows the diffraction efficiency of the gratings to be optimized at the detector location.[14] The arcs of diffraction from opposing segments will diffract in opposite directions across the detector and they will overlap. The separation of the overlapping spectral lines will be possible using the inherent energy resolution of the detector. The gratings on OGRE are planned to be 75 mm (dispersion) x 100 mm (cross-dispersion), have an average groove period of 160 mm (they are radially grooved to match the convergence of the optic), and have a blaze angle of ∼30°.

The central EM-CCD is able to sample the X-ray optic focus as the gratings do not completely cover the optic area. The optic is made from conical segments whereas the gratings are rectangular. The packing of the grating modules requires edges on the optic to be left uncovered, Figure 4.

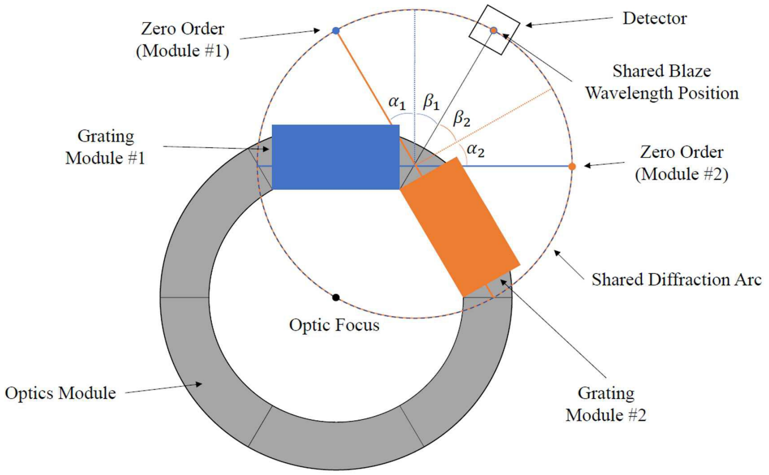

Figure 3. Schematic showing the how two 60° azimuthal spans of optic can disperse their spectra onto a single detector by having the grating arrays in opposite yaw configurations.[6]

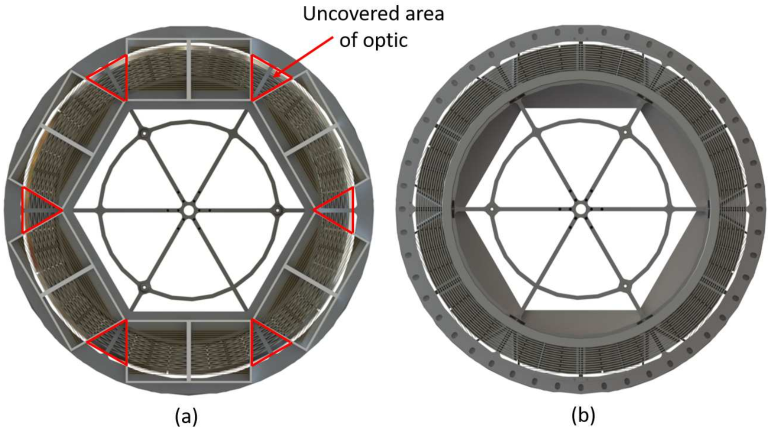

Figure 4. CAD of the X-ray optic and grating from the back (a) and from the front (b). The area shown in red has no grating coverage over the optic and it is repeated every 60°

Producing high fidelity gratings is only the first challenge of producing the grating modules of the OGRE spectrometer. Arrays of these gratings need to be co-aligned to each other to high tolerances (on the order of a few arcseconds). Arcminute alignment tolerances have been achieved for WRXR,[15] but this alignment method will have to be dramatically improved for OGRE. Several mechanisms for this alignment are under consideration.

Some factors that need to be considered when thinking about the alignment process are the material that the grating module is made from, how long the gratings will take to align, and how the populated grating modules will be mounted and aligned onto the X-ray optic. On WRXR the gratings were co-aligned into a stainless steel module as matching the thermal properties of the gratings to the module was not considered to be important (due to the loose alignment tolerances). On OGRE it is likely that Invar-36 will be used as this material has a coefficient of thermal expansion that is closely matched to the silicon wafers that the gratings will be imprinted onto. The use of Invar-36 will mean that the gratings will not become deformed in the grating module due to heating effect.

The speed at which the gratings can be aligned is determined by the cure time of the epoxy that we use. Hysol 9309 is a low expansion during cure epoxy that has been shown to be strong enough to hold gratings during a sub-orbital rocket launch. Hysol has a working time of 20 minutes, will be 70% cured after 12 hours, and achieves a full cure after 3 to 5 days at room temperature. Based on these numbers, the schedule assumes that only one grating can be aligned per day. OGRE will contain ∼220 gratings; therefore, Grating alignment will take at least 220 days.

The mounting of the gratings onto the X-ray optic has to be achieved in a method that allows high precision mounting and in-situ adjustments of the modules positions. To maintain the high resolution of the instrument, co-alignment of the grating to the optic is paramount. The most likely way the gratings will be attached to the optic is by using the optics spider structure as a support. It is likely that the gratings will be aligned to the optic before the optic is installed onto the rocket and then the optic-grating system will be aligned to the focal plane. The in-situ adjustment capability will have to take this into account.

3. FOCAL PLANE CAMERA

The focal plane camera on OGRE is based around 4 e2v CCD207-40s, an EM-CCD with active area of 26.11 mm (columns) x 25.73 mm (rows) and 16 μm pixels. The final design of the camera in terms of interfacing to the rocket is still under consideration, as are the parameters for the readout; therefore, this section will focus on the requirements of the camera, which aspects have been finalized, and what trade-offs will have to be decided upon in the final design. Figure 5 shows the current design for the focal plane camera. Three spectral EM-CCDs and the central optic focus EM-CCD are all mounted onto a shared cold bench that is cooled using LN2 reservoirs.

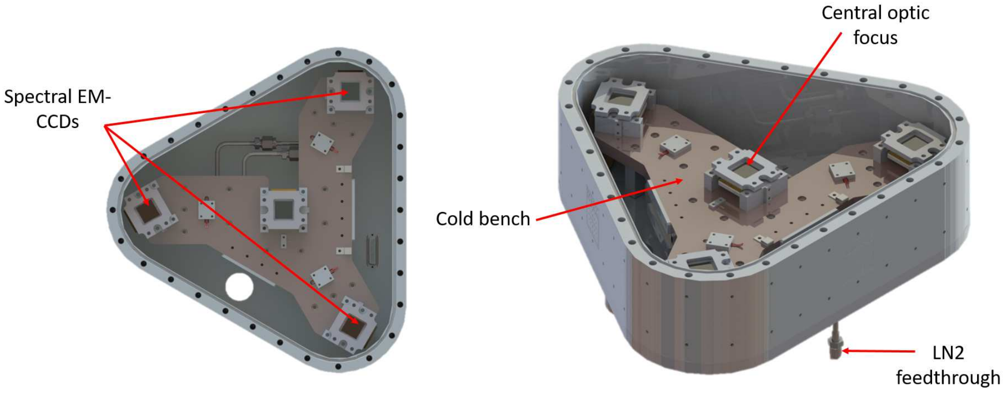

Figure 5. CAD of the OGRE camera. The three spectral EM-CCDs are shown, together with the central detector that is used to image the telescope focus

The CCD207-40 is a full-frame device and due to the overlapping spectra on the focal plane from different 60° azimuths of the spectrometer, 2D information is required. Any photons that hit the detectors during readout will most likely have to be ignored as the precise location that they interacted with the silicon will not be known (full frames are being stored on board the rocket and so photon events that occur during readout can be analyzed at a later date). Minimizing the readout time of the detector with respect to the integration time will be important to maximize the scientific return.

Digital Signal Processing (DSP) with occur onboard OGRE before any data is telemetered. The DSP will identify X-ray events that fall in the expected energy range from Capella, sum charge in adjacent pixels to collect any split charge, calculate the centroid of the X-ray event and telemeter that centroids X, Y, and charge cloud size to the ground. This will minimize the bit-rate required and simplify telemetry. Full frames will also be stored on the rocket to be analyzed after is has been recovered. The DSP is performed using four dedicated Beagle Bone Blacks on the camera motherboard.[16]

EM-CCDs have been chosen as the detector for OGRE as they offer a high speed readout while maintaining a low readout noise through the use of multiplication gain. The multiplication gain will cause a degradation of the detectors spectral resolution, but the overlapping energies are sufficiently different in energy that his degradation will not be problematic.[17–19]

Approximately 500 X-ray photons are expected during the 300 seconds flight. The ability of an EM-CCD to bring low energy X-ray events out of the noise will ensure that we are able to identify every photon that is incident onto the detector.

4. SYSTEM LEVEL CONSIDERATIONS

There are many system level considerations on OGRE that are specific to short duration sub-orbital rockets and a few of them will be considered in this section.

4.1 Cooling

To minimize the dark current in the silicon detectors, cooling will have to be provided. On past missions, such as the Water Recovery X-ray Rocket (WRXR), liquid nitrogen was used to cool the detector before flight.[7] This was achieved using a PID controller and solenoid to gradually reduce the temperature of the detector to the desired level. On OGRE, the detectors will not need to get as cold (target temperature is -100°C) allowing a cold reservoir of LN2 to be used. This reservoir will be cooled with liquid nitrogen and in turn will cool a cold bench via conduction. The temperature of this cold bench will be controlled using heaters. This will allow a greater level of control of the cooling than was possible with WRXR.

4.2 Evacuating the payload

The cold detectors require high-vacuum pressure levels to prevent material depositing onto the silicon, which reduces detector QE. Sounding rocket launch preparation currently requires a period before launch in which all systems, including vacuum pumps, are switched off. This requires a vacuum pump system that can be switched remotely. On WRXR, an ion pump was implemented on a small chamber that isolated the detector from the main payload using a gate valve. Unfortunately, the gate valve had a small leak when closed and the ion pump struggled to pump the volume. This had led to the desire to move away from an ion pump and to have an onboard turbo pump. This could be remotely switched on and off and would allow a good vacuum to be maintained without the need for high voltage. However, it is unclear how launch will affect the pump. It is not required during flight, but if it were to fail destructively it could have an impact on the spectrometer. If the pump was large enough to be able to evacuate the telescope section and the detector chamber, gate valves may not be needed which would remove a failure mode from the rocket. However, on WRXR there was evidence that the rocket skins leaked under the stresses of launch, Figure 6. Such a leak on OGRE would contaminate the detectors and impact the scientific yield. Due to problems pre-launch with the WRXR ion pump, the gate valve was held open during launch.[7]

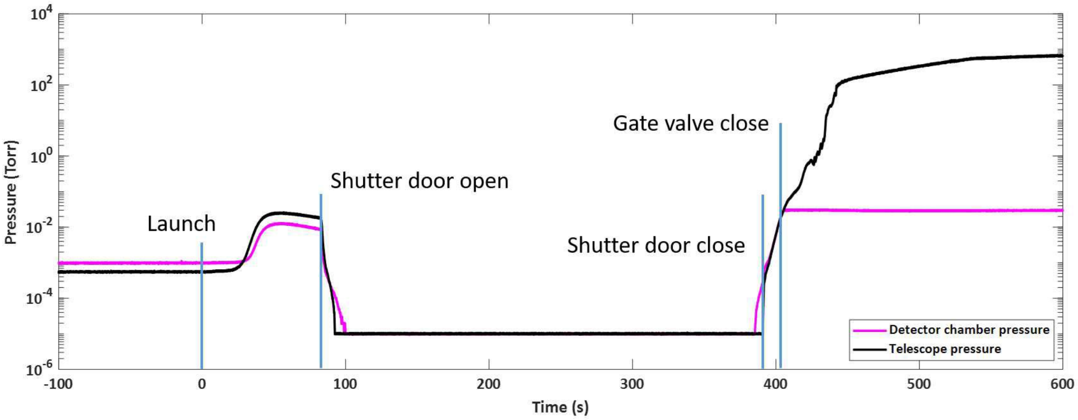

Figure 6. Pressure in the detector chamber and telescope section on the recent launch of WRXR. Just after launch, the pressure was seen to rise in the both the detector chamber and telescope section. This rise in pressure could lead to contamination on the OGRE detectors. During the WRXR launch the gate valve was held open.

4.3 Pointing

To make sure the telescope is pointing in the correct direction, an ST5000 star-tracker will be included in the rocket design. The star-tracker is aligned to the telescope pre-flight and is used to keep the telescope on target during the flight. This is achieved by pre-loading the star-tracker with the target star-field. Once the star-field is correctly identified, the attitude control system is used to keep the telescope centered on the target. If the star-tracker refresh rate is not able to adequately sample our pointing a metrology system may be required to retrieve the pointing knowledge of the telescope.

Optical photons will be focused by the optic with the same angular resolution as the X-ray photons. By taking advantage of the high optical flux that is expected from Capella, it may be possible to use the optic focus detector to measure the position of the optic relative to the focal plane over time. This will give additional information about the pointing of the rocket during flight which may allow a more accurate reconstruction of the position of X-ray events with respect to optic position.

If required, the metrology system will be designed to monitor the position of the X-ray optic with respect to the detector bulkhead. It will use an aspect camera and a series of corner cubes to record the changes in the position of the optic over time.

5. SUMMARY

OGRE is a sub-orbital rocket project that is being designed to provide the highest spectral resolution soft X-ray astronomical observation to date. To make this sub-orbital rocket a reality, three key elements (the optic, gratings, and X-ray camera) have been through many design cycles and manufacturing is ready to begin. To implement these techonolgies onto a sub-orbital rocket, several system level challenges now need to be addressed. These include the mounting of the optic and grating in a way to achieve the high alignment tolerances required, the cooling of the detectors in a way that will minimize contamination, and understanding the pointing knowledge that we require and how that knowledge can be achieved. To meet the scheduled launch date of Q3 2020, steps are being taken to address these issues ready for the start of payload build-up in mid-2019.

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