Virtual Telescope for X-Ray Observation: Phase Fresnel Lens Design and Mission Concept

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ABSTRACT:
The Virtual Telescope for X-ray Observations (VXO) is an X-ray imaging mission which makes the use of precision formation flying of two cubesats that form a virtual X-ray telescope. One cubesat has an X-ray camera while the other cubesat has a Phase Fresnel Lens (PFL). The PFL is a lens that makes use of diffractive optics to focus X-rays at a focal length determined by certain PFL design parameters and X-ray energies. The goal is to have a sub-arc second angular resolution for astronomical observations. In principle, PFL’s image near the diffraction limit and this allows for better angular resolution in X-ray band. After preliminary studies to find an optimal energy for a 3 cm PFL, the VXO performance as a function of focal length was determined. Assuming 40% PFL efficiency, the time to acquire 1,000 X-rays from various astronomical sources was determined. Many sources had the time to be approximately 1 hour which is less than the expected time (2 hr) to hold the focused transfer to a Geostationary Transfer Orbit (GTO). Over the summer the tasks that were loaded into were the design of the PFL as well as the mission concepts. From the design of the PFL the deliverables were a material selection for the PFL as well as the design components for the fabrication of the PFL; a search of scientific literature obtained the flux of various sources in order to deliver a list of sources useful for the mission.

PFL FOCAL LENGTH:
The focal length can be calculated from the following equation:

\[ f = \frac{\lambda}{\Delta E} \left( \frac{\sin \Theta}{\sin \Theta_{\text{min}}} \right) \]

Where \( f \) is the PFL minimum pitch (pitch at the outer most radius), \( \lambda \) is the PFL diameter, and \( \Delta E \) is wavelength to be imaged.

The focal length to energy relationship is shown below for a PFL with \( \lambda = 120 \) um and \( \Delta E = 3 \) cm.

ANGULAR RESOLUTION:
There are three components that go into the angular resolution of a PFL: Chromatic aberration, diffractive angular resolution, and angular resolution due to the finite pixel size. These components are then combined in quadrature to show the dominating term. (Skriner, 2002)

Chromatic aberration can be described by the equation and figure shown below:

\[ \delta \theta = 0.2 \frac{\Delta E}{f^2} \]

Where \( \delta \theta \) is energy variance, \( f \) is energy and \( f \) is focal length. \( \Delta E = 0.15 \) keV.

This is the equation used for diffractive angular resolution:

\[ \theta = 1.22 \left( \frac{\lambda}{f} \right) \left( \frac{D}{f} \right) \left( \frac{1000}{\text{mm}} \right) \]

Where \( \lambda \) is wavelength and \( D \) is diameter.

Angular Resolution per Pixel can be calculated with the equation below:

\[ \theta_{\text{pixel}} = \frac{\Delta \theta}{\text{d}} \]

Where \( \Delta \theta \) is pixel size and \( f \) is focal length. \( \Delta \theta = 0.03 \) based on Telescope H2025-18.

This shows chromatic aberration is the dominating term and is less that 100 m\(^{-2}\) at a focal length of 500 m.

ATTENUATION:
Two materials were considered for substrate materials which were silicon and PMMA. Silicon was chosen because PFL’s have been fabricated out of this material, and work is being done on PMMA for PFL’s. This study was done in order to see the effect that a substrate would have on the incoming X-rays regarding attenuation. The transmission plot was generated for various thickness of the materials. Silicon was found to attenuate the X-rays much more than PMMA. The transmission plot was then weighted to the Crab Nebula and Cygnus X-1 to see which energy band transmitted best. From these plots it can be seen that the 4 to 5 keV band has good transmission. The same plots for Si had peaks at the higher energy bands while being much smaller at the lower energies. For 10 \( \mu \)m of silicon, 50% transmission occurs at approximately 4.6 keV. From these plots an energy of 4.5 keV was selected and PMMA was selected as a substrate material.

FIELD OF VIEW:
The field of view for the telescope is calculated to see which objects fit within the field of view of the PFL. The field of view can be seen by below:

\[ \text{FOV} = \frac{\lambda}{f} \left( \frac{1000}{\text{mm}} \right) \]

Where \( \lambda \) is the detector diameter, and \( f \) is the focal length.

These calculations were then used later to generate the focal length to time for 1,000 events plots of the objects that do not fit within the field of view of the telescope designed by the on Telescope H2025-18. The plot shown below uses a detector diameter of 3.6864 cm.

CONCLUSION:
In conclusion, the design of a PFL is dependent upon the science that is wanting to be done. A PFL is a low mass lens capable of imaging near the diffraction limit. Although a PFL does have chromatic aberration there are methods of counter acting it and keep it to a minimum. With all the background information gathered and trade offs that were observed given the following selections of a 500 m focal length, PFL diameter of 3 cm, and energy of 4.5 keV leads to the diffractive angular resolution being approximately 2.31 m\(^{-2}\), with a total of 75 m\(^{-2}\) due to chromatic aberration.