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

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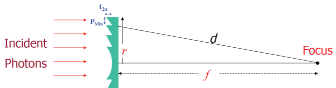
ABSTRACT:

The Virtual Telescope for X-ray Observations (VTXO) 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 VTXO 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 forced transfer to a Geostationary Transfer Orbit(GTO). Over the summer the tasks that were looked 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 useable for the mission.

PFL FOCAL LENGTH:

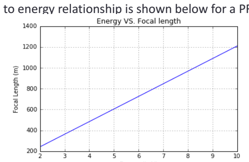
The Focal Length can be calculated from the following equation:



$$f = \frac{p_{Min} d}{2\lambda} = 4.033\left[\frac{p_{Min}}{1\,\mu m}\right]\left[\frac{d}{1\,cm}\right]\left[\frac{E_\gamma}{1\,keV}\right] m$$

Where p_{min} is the PFL minimum pitch (pitch at the outer most radius), d is the PFL diameter, and λ is wavelength to be imaged.

The focal length to energy relationship is shown below for a PFL with p_{min}=10 um and d=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. (Skinner, 2001)

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

$$\boldsymbol{\theta}_E = 0.2\left(\frac{\Delta E}{E}\right)\left(\frac{d}{F}\right)m''$$

Where ΔE is energy variance, E is energy, d is diameter of the lens, and F is focal length. ΔE = 0.15 keV.

This is the equation used for diffractive angular resolution:

$$\Theta = 1.22 * \left(\frac{\lambda}{d}\right)\left(\frac{180}{\pi}\right)3600 * 1000\, m''$$

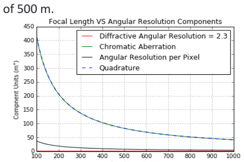
Where λ is wavelength and d is diameter.

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

$$\Theta_p = \frac{\Delta X}{F}$$

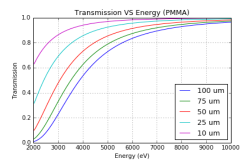
Where ΔX is pixel size and F is focal length. ΔX=18μm based on Teledyne H2RG-18.

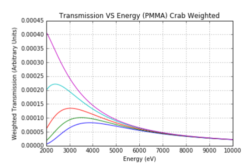
This shows chromatic aberration is the dominating term and is less that 100 m″ at a focal length of 500 m.

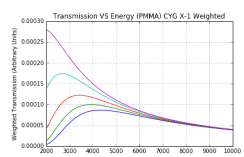


ATTENUATION:

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 PFLs. This study was done in order to see the affect 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 μm 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.







Calculations were done assuming a 40% efficiency

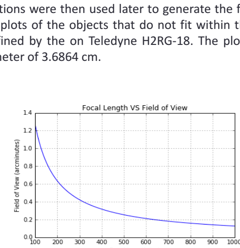
FIELD OF VIEW:

The field of view for the telescope is calculated to see which objects fit within the field of view of the telescope. The field of view equation can be seen below:

$$FOV = \left(\frac{D_D}{F}\right)\left(\frac{180}{pi}\right)60'$$

Where D_D 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 defined by the on Teledyne H2RG-18. The plot shown below uses a detector diameter of 3.6864 cm.



POINT SOURCES:

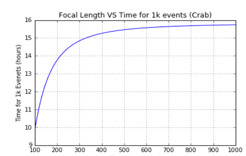
Sources:	Time (hours):	Γ:	Energy Flux (erg/s/cm²):
Sco X-1(1)	0.2	-2.1	2.2E-7
Cyg X-1 Soft(2)	1.2	-1.5	3.0E-8
Cyg X-1 Hard(2)	3.4	-2.1	1.0E-8
Cyg X-3 Soft(3)	1.7	-2.1	7.5E-9
Cyg X-3 Hard(3)	4.6	-2.1	1.9E-8
GX 5-1(4)	1.4	-4.7	4.9E-8

Diameter of the PFL is 3cm, **Γ** is the spectral index

Sources: (1) (Bradshaw, Titarchuk, & Kuznetsov, (The Astrophysical Journal, 2007)), (2) (Shaposhnikov & Titarchuk) , (3) (Szostek, Zdziarki, & McCollough, (Mon. Not. R. Astron. Soc., 2008)) , (4) (Tan, et al., (The Astrophysical Journal, 1992)) ,(5) (Strickman, Johnson, & Kurfess, (The Astrophysical Journal, 1979))

THE CRAB:

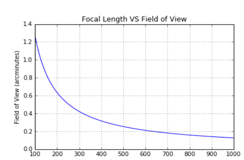
The Crab Nebula is approximately 4′ by 6′ which does not fit within the field of view of the telescope for the considered focal lengths, because of this the plot shown below was generated to show the relationship between the field of view and the time it takes to get 1,000 photons. To generate the plot, it must be considered that the pulsar is about 10% of the total crab flux while the nebula generates the other 90%. Thus the nebula will be background for the pulsar.



Γ = 2.1, Energy Flux = 2.2E-8 $Erg/s/cm^2$ (5)

SOLAR FLARE:

Using the results presented in Dennis et al. (Solar Physics, 279 (2012)), the X-ray spectrum generated by solar flares contains several emission lines, included a strong line at 6.699 keV (Fe XXV). The size of magnetic loops associated with solar flares is modeled to be ~0.2 m′ in size, and would fit in the FOV of VTXO for a PFL designed designed to image at 6.7 keV, for focal lengths less than 700 m. Assuming a photon flux from the Fe XXV line in a flare of 20,000 photons/(cm^2 s), one second of observation would yield > 50,000 photons assuming a 3 cm diameter PFL with 40% efficiency.



Sources: (6) (Dennis, Skinner, Li, & Shih, 2012)

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″, with a total of 75 m″ due to chromatic aberration.