Multifoil optics for rocket experiments

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\section*{ABSTRACT}

A novel design of X-ray optical system – wide field telescope for astrophysical rocket experiments is investigated and tested in real space flight experiment. The proposed system is based on 1D and 2D modules with Schmidt Lobster Eye (LE) configuration allowing usage of multi-foil mirrors arranged to Schmidt profile.

\textbf{Keywords:} X-ray optics, X-ray telescopes, Lobster Eye, Ray-tracing, X-ray optical tests

\section{1. INTRODUCTION}

Imaging grazing incidence X-ray space telescopes for astrophysical research typically work at energies between 100 eV and 10 keV, with hard-energy extension up to 80 keV possible mostly based on application of special multilayers. They mostly use the Wolter X-ray optics\textsuperscript{9} providing high angular resolution at a cost of very small field of view of order of 1 degree or less.

The Lobster Eye X-ray lenses\textsuperscript{15,16,17} represent promising alternative for wide field X-ray imaging at a moderate angular resolution of order of 1 arcmin. They are quite innovative so their application in real space experiments is still very limited so that tests in real space environments are extremely important. One possibility to test the novel optical modules in real space flight condition is represented by the sounding rocket experiment.

The REX is the optical instrument used as the payload for the Water Recovery X-ray Rocket (WRX-R) experiment\textsuperscript{18,19,20,21}. The Water Recovery X-ray Rocket (WRX-R) is a research program for the sounding rocket payload which launched from the Kwajalein Atoll in the Marshall Islands on 4 April 2018. WRX-R was the first astrophysics sounding rocket/mission to use a newly developed NASA water recovery system for astronomical payloads which is a cost effective alternative to typical land recoveries which may be related to payload damage.

The WRX-R was prepared by the Pennsylvania State University (PSU), USA\textsuperscript{18,19,20,21}. The primary payload was the soft X-ray spectroscopy of PSU. WRX-R's primary instrument is a grating spectrometer that consists of a mechanical collimator, an X-ray reflection gratings, a grazing incidence mirrors, and a hybrid CMOS detector. The Czech team provided the REX optical instrument as a secondary payload. The unique feature of the REX instrument is that it uses two X-ray Lobster Eye (LE) telescopes for higher energy coverage. It was the first time when the X-ray Lobster Eye (LE) telescopes were used in rocket experiment to observe an astrophysical object. The purpose of the experiment was to verify the manufacturing technologies of the optical systems including multi-foil (MFO) optics with the Timepix detector in the space environment and ballistic trajectory. The REX instrument for rocket experiment consists of two X-ray telescopes with the Timepix pixel detector\textsuperscript{10}. The first telescope uses 2D LE optics (2D-LE-REX) with the focal length of 1065 mm and Timepix detector. The 2D telescope field of view (FOV) is 0.8 x 0.8 deg with spectral range from 3 keV to 60 keV. The second telescope uses 1D LE optics (1D-LE-REX) with the focal length of 250 mm and the Timepix detector as well. The 1D telescope has wide FOV 3.3 x 2.0 degrees and spectral range from 3 keV to 60 keV.
2. THE ROCKET EXPERIMENT

The design of the instrument for the WRX-R experiment (REX) was based on the concept of an optical baffle, which is normally used for NASA Sounding rocket experiments. This is a simple construction of a quill-shaped boulder with the anchor on one of the base of the block, where the baffle is attached to the sounding rocket.

The REX instrument was designed, assembled and tested (environmental and optical tests) in the Czech Republic first. Then, the REX was installed to the rocket and launched from Kwajalein Atoll in the Marshall Islands. The REX optical instrument consists of two parts - vacuum part and hermetic box. The vacuum part contains two X-ray telescopes, one Lobster Eye 1D system with a focal length of 250 mm and the second one Lobster Eye 2D system with a focal length of 1065 mm (Figs 1 and 2). The modules were assembled by Multi-Foil (MFO) technology. The 1D Lobster Eye module is composed of 116 wedges and 56 reflective double-sided gold-plated glass foils (thickness of 145 micrometers). The gold coating allows the material to reflect X-ray photons incoming under small incident angle of up to 0.5 deg. The input aperture is 29 x 19 mm², while the outer dimensions are 60 x 28 x 31 mm. The active area of the module is 19 mm in width and 6 mm in length and the energy range is 3 to 20 keV. The 2D LE X-ray optics of REX is composed of two 1D sub-modules where one-sided gold-plated glass foils are in the vertical respective horizontal arrangement. Each sub-module consists of 55 pieces of thin flat glass foils (thickness of 0.34 mm) which are arranged so that the focal length is around 1.0 meter. The external dimensions of the module are approximately 80 x 80 x 170 mm. The material of the housing of the optical module is an aluminum alloy.

The 1D optical system was located at the front of the device and the Timepix detector\textsuperscript{10} is roughly in the middle of the telescope. The 1D X-ray optic is the analogous optical module as used in VZLUSAT-1 nanosatellite\textsuperscript{11,12}. The 2D X-ray optics is composed of two 1D X-ray optical modules which are rotated by 90 degrees with a common focal length of 1065 mm from the center of the X-ray optics. Modules are located at the front of the device; the detector part is located at the rear part of the vacuum section of the instrument at the end of the composite profile. Parameters of the 1D optical modules of 2D X-ray optics were chosen individually based on real experiments, with respect to the size of the rocket and with respect to the intended Timepix detector. Mathematical simulations were performed for individual X-rays modules for different energies (including the ideal case where the reflectivity is 100 %). The monitored parameters of the X-ray optics are full width at half maximum (FWHM) of the peak and the angular resolution.

![Fig. 1 The Lobster Eye 1D optics - there is only one reflection, hence the energy range is wide, from the optical light up to 30 keV.](https://example.com/fig1.png)
Fig. 2 The Lobster Eye 2D optics - composed of two 1D sub-modules, there are two reflections, hence the energy range is from the optical to 10 keV.

<table>
<thead>
<tr>
<th></th>
<th>1D optics</th>
<th>2D optics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length of 1D module (mm)</td>
<td>56</td>
<td>150</td>
</tr>
<tr>
<td>Width of 1D module (mm)</td>
<td>29</td>
<td>60</td>
</tr>
<tr>
<td>Height of 1D module (mm)</td>
<td>31</td>
<td>75</td>
</tr>
<tr>
<td>Aperture (mm)</td>
<td>19x25</td>
<td>54x54</td>
</tr>
<tr>
<td>Number of foils</td>
<td>56</td>
<td>46</td>
</tr>
<tr>
<td>Foil thickness (mm)</td>
<td>0.145</td>
<td>0.3</td>
</tr>
<tr>
<td>Foil distance (mm)</td>
<td>0.30</td>
<td>0.75</td>
</tr>
<tr>
<td>Effective aperture (mm)</td>
<td>14x7,1</td>
<td>21,2x21,2</td>
</tr>
<tr>
<td>@100% reflectivity</td>
<td>239mm²</td>
<td>448mm²</td>
</tr>
<tr>
<td>Foil reflection surface</td>
<td>Au</td>
<td>Au</td>
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<tr>
<td>Foil surface roughness (nm)</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Field of view (°)</td>
<td>3.5°x4.5°</td>
<td>0.65°x0.81°</td>
</tr>
<tr>
<td>Focal length (mm)</td>
<td>250</td>
<td>1425</td>
</tr>
</tbody>
</table>

Tab. 1 Parameters of LE optical modules for the REX rocket experiment.

Fig. 3 The LE telescopes integration into the rocket platform.
Before the rocket flight, both LE REX telescopes were tested in ground based X-ray test facilities. The 1D LE REX optical X-ray module was tested in vacuum tunnel at the University of Colorado. The 1D module was tested at 4.5 keV (Ti-Kalpha) with the Timepix detector. Distance from the front of the optical module was 280 mm and distance between source and detector was 50 m. The best focus image was obtained with 1000 s exposure time. The measured FWHM was 1.6 mm and the gain was 185. Further X-ray tests were performed at the PSU and at the PANTER facilities.

The test arrangement at the Penn State University is shown in the Fig. 4. Where source - Fe-55 (5.9 keV) and Detector - Timepix (256 x 256 px, 55 µm), no cooling and Source-to-detector distance is 47 m.

![Fig. 4 The PenState (PSU) test experiment arrangement.](https://www.spiedigitallibrary.org/conference-proceedings-of-spie)

Fig. 5 The PSU X-ray beamline.

- ~47 meter long X-ray beam line
- Diameter at the detector end ~ 1 meter
- ~ 1e-6 T vacuum at the detector end
The 2D optical modules were tested at 3.0 keV (Ag-Lalpha), 4.5 keV (Ti-Kalpha) and 8 keV (Cu-Kalpha) in the Panter X-ray test facility\textsuperscript{22}. The 2D LE X-ray optic REX is composed of two 1D sub-modules. The first sub-module of 2D optics was more distant from detector and foils were in the vertical arrangement. The sub-module B was closer to detector and foils were in the horizontal arrangement. The distance between the first optical module and the detector was 1150 mm, the distance between the source and the beginning of the first optical module was 123 m. For the best focus images and the measured FWHM at different energies see dedicated paper\textsuperscript{22}. Experimental setup in the vacuum chamber.
(and time pressure) did not allow us to make an image without the optics and therefore it was not possible to evaluate the gain G.

4. CONCLUSIONS

The X-ray REX optical instrument for the rocket experiment was developed, assembled and tested. The REX instrument was launched in space onboard the sounding rocket to verify its fitness in the rocket application and potential for future space applications. The REX instrument consists of two optical systems - 1D and 2D X-ray optics with the Timepix pixel detector. Both optical modules were assembled by multi-foil technology.

These X-ray systems were tested in the vacuum chambers at three test facilities. The best focus image for the 2D X-ray LE optics (2D-LE-REX) was found with the FWHM in the vertical direction 2.1 mm and in the horizontal direction 1.8 mm. The best focus image for the 1D X-ray LE optics (1D-LE-REX) was found with FWHM of 1.6 mm.

These optical systems (2D/1D LE optics with Timepix detector) were installed in the Water Recovery X-ray Rocket and launched in April 2018. The preliminary results show that the REX optical instrument worked well and data will be processed and published in the following months.

5. ACKNOWLEDGEMENTS

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