Micropore optics; application, modelling and calibration

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See also

Micropore Optics: 
Lobster eye optics – Angel 1979 
Square pore micro-channel plates

- Glass plate full of holes!
  - Thickness 0.9-2.3 mm
  - Transmission ~67%
- Square Pores L~1 mm, d~20μm or ~40μm, wall ~4μm - ~12μm, L/d~50

Cartesian packed pores for Lobster Eye
## MPO Missions/Instruments

<table>
<thead>
<tr>
<th>Mission</th>
<th>Type</th>
<th>Instrument</th>
<th>Lead</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>DXL/STORM</td>
<td>Sounding Rocket</td>
<td>STORM</td>
<td>NASA/GSFC, USA</td>
<td>2 flights, 2012, 2016</td>
</tr>
<tr>
<td>BepiColombo</td>
<td>ESA Cornerstone</td>
<td>MIXS</td>
<td>Leicester University, UK</td>
<td>Launch 2018</td>
</tr>
<tr>
<td>CUPID</td>
<td>Cubesat</td>
<td>CUPID</td>
<td>Boston University, USA</td>
<td>Launch 2019</td>
</tr>
<tr>
<td>SMILE</td>
<td>ESA/CAS S2</td>
<td>SXI</td>
<td>Leicester University, UK</td>
<td>Launch 2021</td>
</tr>
<tr>
<td>SVOM</td>
<td>French/CAS</td>
<td>MXT</td>
<td>CNES</td>
<td>Launch 2021</td>
</tr>
<tr>
<td>Einstein Probe</td>
<td>CAS</td>
<td>WFI</td>
<td>CAS</td>
<td>Probably selected</td>
</tr>
<tr>
<td>Theseus</td>
<td>ESA M5</td>
<td>WFI</td>
<td>Leicester University, UK</td>
<td>Proposed</td>
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<tr>
<td>TAO</td>
<td>NASA MIDEX</td>
<td>WFI</td>
<td>NASA/GSFC, USA</td>
<td>Proposal</td>
</tr>
<tr>
<td>STORM</td>
<td>NASA MIDEX</td>
<td>?</td>
<td>NASA/GSFC, USA</td>
<td>Proposal</td>
</tr>
</tbody>
</table>
Micropore optics development by Photonis, Cosine Research BV, ESA and the University of Leicester, UK

Additional processes offered by Photonis:
Metal coating of pores (Iridium)
Deposition of Aluminium film (filter) on MPO surface
Model point spread function

off-spot angle $\theta = 2d/L$

2°.3 for $L/d = 50$

2-reflection focused spot

0-reflection diffuse patch

3-reflection cross-arms

1-reflection cross-arms

HEW $\sim 1°.5$
## Intrinsic Aberrations

Contributions to central core angular resolution

<table>
<thead>
<tr>
<th>Type</th>
<th>Relation</th>
<th>( F = 300 \text{ mm} )</th>
<th>( d = 27 \mu\text{m} )</th>
<th>( L = 1.35 \text{ mm} )</th>
<th>( F = 1000 \text{ mm} )</th>
<th>( d = 50 \mu\text{m} )</th>
<th>( L = 2.5 \text{ mm} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spherical</td>
<td>( \Delta \theta_s = 4\sqrt{2}(d/L)^3 )</td>
<td>~9&quot;</td>
<td></td>
<td></td>
<td>~9&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Geometric</td>
<td>( \Delta \theta_g = d/F )</td>
<td>~19&quot;</td>
<td></td>
<td></td>
<td>~10&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diffraction</td>
<td>( \Delta \theta_d = 2\lambda/d ) (Energy = 1 keV)</td>
<td>~19&quot;</td>
<td></td>
<td></td>
<td>~10&quot;</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \Delta \theta_i = (\Delta \theta_s^2 + \Delta \theta_g^2 + \Delta \theta_d^2)^{1/2} )</td>
<td>~28&quot;</td>
<td></td>
<td></td>
<td>~17&quot;</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Best possible

**Optimum (for point source detection)** \( L/d \approx 50 \)

**Highest angular resolution occurs for** \( \Delta \theta_g = \Delta \theta_d \)
Intrinsic Slumping Errors

Azimuthal compression and radial expansion of pores around each annulus

Pore radial tilt errors & pore cross-section shear errors

Tilt angle, $\theta_a \sim r^2 / (2R^2)$

Shear angle, $\theta_h \sim r \sin(2\theta)/R$

Tilt error, $\Delta \theta_a \sim (r/R)^2$

Shear error, $\Delta \theta_h \sim 2 \sin(2\theta)(d/L)(r/R)$

<table>
<thead>
<tr>
<th>F (mm)</th>
<th>$\Delta \theta_i$</th>
<th>$\Delta \theta_a$</th>
<th>$\Delta \theta_h$</th>
<th>$\Delta \theta_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>0’.28</td>
<td>0’.17</td>
<td>0’.60</td>
<td>0’.68</td>
</tr>
<tr>
<td>300</td>
<td>0’.48</td>
<td>1’.88</td>
<td>1’.99</td>
<td>2’.78</td>
</tr>
</tbody>
</table>
Manufacturing Errors

1) Multifibre structure

Regular array of packed multi-fibres
25x25 for 40 μm pores
35x35 for 20 μm pores
Shear distortion at corners - removes flux from the cross-arms

Shear error amplitude modeled as a Gaussian

$$\theta_h = A \exp(-r_f^2 / 2\sigma_f^2) ; \sigma_f \sim 4d ; A \sim 4 \text{ degrees}$$

$R_f$ is radial distance of pore from corner of multibre
Manufacturing Errors

1) Multifibre structure

- focused spot
  - diamond shaped
- &
- cross arm
  - displacement/waviness
- cause:
- multifibre tilt errors
  - between rows and/or columns

- cross-arm Modulation (loss of flux)
  - Cause:
  - Large shear angle errors at multifibre intersections

Data at 1.49 keV. Single plate illuminated at an angle
Manufacturing Errors

1) Multifibre structure

- Horizontal: Central core + Broader wings
  - Multibre modulations

- Vertical: Central core + Broader wings
  - Multibre modulations

In addition to shear and tilt errors there will be pore wall figure errors:
Modelled as two populations of pores; Inner 25:25 & Outer 5 pore band (50:50 split)
Outer band has rms figure error ~4 times Inner population.
Manufacturing Errors

2) Large scale bias angle variation

Type 1) Introduced when plates are cut from a block. Not serious as long as multiple plates in a frame are mounted with same relative bias angle.

Type 2) Variation across a plate due to slumping (or mounting) process. Potentially more serious.
Contributions to FWHM for SVOM breadboard plate

<table>
<thead>
<tr>
<th>Contribution</th>
<th>FWHM (arc mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td>geometric pore size ( d = 20 \mu m )</td>
<td>0.07</td>
</tr>
<tr>
<td>spherical aberration pore ( L/d = 50 )</td>
<td>0.15</td>
</tr>
<tr>
<td>slumping - intrinsic radial tilt errors</td>
<td>0.17</td>
</tr>
<tr>
<td>slumping - intrinsic shear errors</td>
<td>0.60</td>
</tr>
<tr>
<td>surface roughness 11 Å rms, ( \omega_b = 10 \text{ mm}^{-1} )</td>
<td>2.46</td>
</tr>
<tr>
<td>figure errors at centre of multifibres</td>
<td>2.48</td>
</tr>
<tr>
<td>shear errors at centre of multifibres</td>
<td>-</td>
</tr>
<tr>
<td>multifibre tilt errors along primary axes</td>
<td>3.54</td>
</tr>
<tr>
<td>figure errors at edge of multifibres</td>
<td>9.92</td>
</tr>
<tr>
<td>shear errors at edge of multifibres</td>
<td>-</td>
</tr>
<tr>
<td>global shear errors</td>
<td>-</td>
</tr>
<tr>
<td>global tilt errors</td>
<td>-</td>
</tr>
</tbody>
</table>

Combine* to give observed FWHM ~ 6’.5

*Not rms sum

Compare with intrinsic + slumping errors which predict ultimate angular resolution in range 1 – 3 arcminutes depending on focal length.
SVOM Breadboard Model

X-ray Testing

Al support frame – array of 21 MPOs 40x40mm²
spherical surface R=2000mm – F=1000mm
Machining accuracy ±10μm
2x 20μm MPOs, 2x 40μm MPOs, 1x 20μm Ir coated
MPOs, 2x40μm Ir coated MPOs

Mass of frame plus 21
MPOs ~1 kg

Leicester TTF – source at 27 m
MPE Panter – source at 128 m
Data versus Simulation

X-ray image and simulation at 1.49 keV
## Efficiency Measurements

<table>
<thead>
<tr>
<th>MPO</th>
<th>X-ray R (mm)</th>
<th>Thickness (mm)</th>
<th>Double reflection efficiency</th>
<th>Best FWHM (arcmin)</th>
</tr>
</thead>
<tbody>
<tr>
<td>YC001-A6</td>
<td>1874</td>
<td>1.05</td>
<td>0.87</td>
<td>6.46</td>
</tr>
<tr>
<td>YC001-D1</td>
<td>1970</td>
<td>1.20</td>
<td>0.90</td>
<td>6.39</td>
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<tr>
<td>YC001-D5</td>
<td>1906</td>
<td>1.20</td>
<td>0.92</td>
<td>7.52</td>
</tr>
<tr>
<td>YC001-C3</td>
<td>1906</td>
<td>1.70</td>
<td>0.97</td>
<td>7.55</td>
</tr>
<tr>
<td>YC001-C4</td>
<td>1906</td>
<td>1.70</td>
<td>0.95</td>
<td>7.15</td>
</tr>
</tbody>
</table>

Single reflection efficiency in range 0.93 – 0.98
MPO Calibration

Measurement

Understanding

Manufacturing → Modelling

Thankyou