The Off-Plane Option
for the
Reflection Grating Spectrometer

Webster Cash

University of Colorado
Chandra Spectra Look Like Traditional Ground Spectra.

Can We Afford to Step Back???
In-plane Mount

\[ \sin \alpha + \sin \beta = \frac{n\lambda}{d} \]

Off-plane Mount

\[ \sin \alpha + \sin \beta = \frac{n\lambda}{d \sin \gamma} \]
Radial Groove Gratings
Off-plane Resolution

\[ R = \frac{(\sin \alpha + \sin \beta) \sin \gamma}{B \cos \alpha} \]

At typical values of off-plane angles and 15” telescope resolution
R \sim \text{several hundred} \rightarrow \text{thousand}

Sub-Aperturing improves it further
An Off-plane X-ray Spectrum

Spectrum from Al target shows Al kα (λ=1.49 Å, E=1.4keV) in orders n=2 through n=7. Contamination from O kα (λ=53.6Å, E=0.525keV) is also clearly present in first and second orders. Note that the blaze function is about 30 deg. in azimuthal angle. This spectrum was obtained by the XOGS spectrograph in the beam facility at Marshall Space Flight Center using a 3600 g/mm grating array in the off-plane mount. The signal in the sum of orders 3 through 6 is about 40% of the incident signal. With a CCD these orders can be recombined without loss of signal or resolution.
Off-plane Tradeoffs

PRO
• Higher Throughput
• Higher Resolution
• Better Packing Geometry
• Looser Alignment Tolerances

CON
• Higher Groove Density
Packing Geometry

Central grating must be removed.
Half the light goes through.

Gratings may be packed optimally
Throughput

• Littrow configuration \( \alpha = \beta = \text{blaze angle} \)
  - Better Groove Illumination
  - Maximum efficiency
• Constant Graze Angle
Holographic Gratings

Last year we reviewed approaches to fabricating high density gratings.

At Jobin-Yvon (outside Paris)
Create rulings using interference pattern in resist
Ion-Etch Master to Create Blaze

Radial Geometry – Type 4 Aberrated Beams
Density: Up to 5800 g/mm Triangular (<35 deg blaze)

In UV holographic blazed gratings have very low scatter and good efficiency – same in x-ray?
Raytracing – Arc of Diffraction
Raytrace – 35 & 35.07Å
Raytracing of Wavelength Pairs
\( \lambda \) and \( \lambda + 0.07 \text{Å} \)

10Å

15Å

20Å

25Å

30Å

35Å

40Å

50Å

60Å

70Å

80Å

90Å
Internal Structure of Telescope

Blur Favors Dispersion in Off-plane Direction

Spectral line of HeII 304Å displaying In-plane scatter

Data from a radial grating in the off-plane mount, Wilkinson
Subaperture Effect
Off-plane Grating Module
Locations on Envelope

- Grating Modules
- R450.0mm Inner Mirrors High Energy
- R770.0mm Outer Mirrors Grating Area
- R151.4mm
Can Improve Performance
Can Improve Performance
Raytracing – Arc of Diffraction
Raytrace – 35 & 35.028Å
Raytracing of Wavelength Pairs

$\lambda$ and $\lambda+.028\text{Å}$
Resolution

ASSUMPTIONS:
5500g/mm
15” SXT
2” gratings
2” alignment
Effective Area

ASSUMPTIONS:
- Coverage 40% of outer envelope
- Off-Plane Groove Efficiency 80% of theoretical
- 85% Structure Transmission
- CCD thin Al filter only

Mission Requirement

Energy (keV)

<table>
<thead>
<tr>
<th>Energy (keV)</th>
<th>cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>0.5</td>
<td>500</td>
</tr>
<tr>
<td>1.0</td>
<td>1000</td>
</tr>
<tr>
<td>2.0</td>
<td>2000</td>
</tr>
<tr>
<td>3.0</td>
<td>3000</td>
</tr>
<tr>
<td>5.0</td>
<td>5000</td>
</tr>
</tbody>
</table>

Mission Requirement
Figure of Merit with Spectral Weighting

![Graph showing the figure of merit with spectral weighting for different types of detectors. The graph plots energy (keV) on the x-axis and the area x resolution divided by energy (E(keV)) on the y-axis. The graph includes lines for off-plane with R~3000, off-plane with R~1500, calorimeter, and in-plane.]
Pros & Cons of Off-plane vs. Baseline Design

- **Pro:**
  - Greater Resolution from Sub-aperturing
  - Greater Collecting Area – higher groove efficiency
  - Less Sensitivity to Grating Alignment
  - Less Sensitivity to Grating Flatness
  - Lower scatter in Dispersion Direction
  - Fewer Gratings Required
  - Thicker Substrates Acceptable
  - Smaller Structure Required

- **Con:**
  - Higher groove density required
Difficulties of High Resolution ($\lambda/\Delta\lambda>1200$)

- flatter gratings
- tighter alignment
- tighter focus
- telescope depth of focus adjustment
- zero order monitor essential to aspect solution
- more difficult calibration
- greater astigmatism
  - higher background
  - more source overlap
Depth of Field Problem

Solutions for Study:
Smaller Gratings
Curved Gratings
Adjust Telescope Segments

Hope that it is merely a matter of mounting existing shells at different radii
Resolution Degradation

E/δE

Grating Resolution (arcsec)
Off-plane Grating Module

Holder

Gratings Qty. 20

Grating size:
10cm x 10cm x 0.2cm
Graze angle: 2.7°

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# Off-plane Grating Resolution Options

<table>
<thead>
<tr>
<th>$\frac{\lambda}{\delta \lambda} \sim 1000$</th>
<th>$\frac{\lambda}{\delta \lambda} \sim 5000$</th>
</tr>
</thead>
<tbody>
<tr>
<td>- SXA (Al/SiC) substrates</td>
<td>- Glass/Si substrates?</td>
</tr>
<tr>
<td>- Easy tolerances</td>
<td>- More difficult tolerances</td>
</tr>
<tr>
<td>- Simple mount</td>
<td>- More difficult mount</td>
</tr>
<tr>
<td>- No thermal gradient</td>
<td>- Probable thermal gradient issues</td>
</tr>
<tr>
<td>- Mass OK</td>
<td>- Mass constraint more difficult to meet</td>
</tr>
</tbody>
</table>
## Off-plane Grating Estimated Tolerances

<table>
<thead>
<tr>
<th>Error type</th>
<th>Zero-order Allowable Tolerances</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Equation</td>
</tr>
<tr>
<td><strong>Surface error</strong></td>
<td>$\delta = \frac{s}{20}$</td>
</tr>
<tr>
<td>$\delta_x$</td>
<td>$\delta_x = \frac{s}{20 \cos \theta}$</td>
</tr>
<tr>
<td>$\delta_y$</td>
<td>$\delta_y = \frac{w}{10}$</td>
</tr>
<tr>
<td>$\delta_z$</td>
<td>$\delta_z = \frac{s}{20 \sin \theta}$</td>
</tr>
<tr>
<td>$\theta_x$</td>
<td>$\sin \phi = \frac{w}{5h}$</td>
</tr>
<tr>
<td>$\theta_y$</td>
<td>$\phi = \frac{\omega}{20}$</td>
</tr>
<tr>
<td>$\theta_z$</td>
<td>$\phi = \frac{\omega}{10 \sin \theta}$</td>
</tr>
</tbody>
</table>
# Off-plane Grating Module

## Estimated Mass

<table>
<thead>
<tr>
<th>Materials</th>
<th>Gratings (Kg)</th>
<th>Holder (Kg)</th>
<th>Lightweight</th>
<th>One Module (Kg)</th>
<th>Qty Modules</th>
<th>Total mass (Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SXA/SXA</td>
<td>1.16</td>
<td>1.20</td>
<td>none</td>
<td>2.36</td>
<td>32</td>
<td>75.65</td>
</tr>
<tr>
<td>SXA/SXA</td>
<td>1.16</td>
<td>1.20</td>
<td>25%</td>
<td>2.17</td>
<td>32</td>
<td>69.53</td>
</tr>
<tr>
<td>SXA/6061</td>
<td>1.16</td>
<td>1.11</td>
<td>none</td>
<td>2.27</td>
<td>32</td>
<td>72.73</td>
</tr>
<tr>
<td>FS/Invar/Ti</td>
<td>0.88</td>
<td>1.568</td>
<td>70%</td>
<td>2.45</td>
<td>32</td>
<td>78.36</td>
</tr>
<tr>
<td>FS/Titanium</td>
<td>0.88</td>
<td>1.488</td>
<td>30%</td>
<td>2.37</td>
<td>32</td>
<td>75.82</td>
</tr>
<tr>
<td>FS/GrEp/Invar</td>
<td>0.88</td>
<td>1.687</td>
<td>none</td>
<td>2.57</td>
<td>32</td>
<td>82.17</td>
</tr>
</tbody>
</table>
Wavefront Error: Resolution 1000

Constellation X Off-plane Grating Mount rms Wavefront Error Budget (15 arcsec max)
All errors are presented as rms wavefront error

Total allowable error
21 µm

Spare
8.054 (rss)

Fabrication 2.87 µm (rss)
Mount 10 µm (WAG)
Test (λ/50) .013 µm
Stability 6.23 µm (rss)
Alignment 10 µm (estimate)
1g Sag .09 µm (calc)
Temp (bulk) ±2.5°C 2.02 µm (rss)

Substrate Figure (3λ)
1.9 µm (requirement)
Replication Epoxy cure strain 1.0 µm (calc)
Replicate Separation Strain 1.9 µm (WAG/3λ)
Creep 0.5 µm (WAG)
Thermal gradient (0.5°C)
6 µm (calc)
Water absorption (assume 0.3%)
1.6 µm (calc)
Jitter (on orbit)
.0003 µm (WAG/calc)
Mount 2 µm (WAG)
Replication epoxy bimetallic effect 0.0005 µm (calc)
Reflective coating bimetallic effect 0.3 µm (calc)

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Wavefront Error: Resolution 5000

Constellation X Off-plane Grating Mount rms Wavefront Error Budget (2 arcsec max)
All errors are presented as rms wavefront error

Total allowable error 2.77 mm

Spare 0.754 µm (rss)

Fabrication 1.16 µm (rss)
Mount 1.5 µm (WAG)
Test (λ/50) 0.013 mm
Stability 0.62 µm (rss)
Alignment 1.75 µm (estimate)
1g Sag 0.11 µm (calc)
Temp (bulk) ±2.5°C 0.21 µm (rss)

Substrate Figure (1.5λ) 0.95 µm (requirement)
Replication Epoxy cure strain 0.23 µm (calc)
Replicate Separation Strain 0.6 µm (WAG/1λ)
Creep 0.1 µm (WAG)
Thermal gradient (0.1°C) 0.5 µm (WAG/calc)
Water absorption (assume 0.3%) 0.35 µm (calc)
Jitter (on orbit) 0.003 µm (WAG/calc)
Mount 0.2 µm (WAG)
Replication epoxy bimetallic effect 0.008 µm (calc)
Reflective coating bimetallic effect 0.07 µm (calc)

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## Off-plane Grating Prototype: steps and schedule

<table>
<thead>
<tr>
<th>Phase</th>
<th>Task</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Preliminary feasibility study of type 4 aberration corrected grating distribution to approximate radial distribution</td>
</tr>
<tr>
<td></td>
<td>(Jun ‘02 to ~Oct ‘02)</td>
</tr>
<tr>
<td>2</td>
<td>Preliminary study of blaze process using existing masks (30° profile goal).</td>
</tr>
<tr>
<td></td>
<td>(work done in parallel with step 1)</td>
</tr>
<tr>
<td>3</td>
<td>Contingent upon step 1&amp;2 positive result.</td>
</tr>
<tr>
<td></td>
<td>Deliverable: 58x58x10mm parallel groove sample with 30° blaze angle.</td>
</tr>
<tr>
<td></td>
<td>(Oct ‘02 to ~Feb ‘03)</td>
</tr>
<tr>
<td>4</td>
<td>Contingent upon positive test of sample.</td>
</tr>
<tr>
<td></td>
<td>Deliverable: 58x58x10mm radial groove distribution with blazed profile.</td>
</tr>
<tr>
<td></td>
<td>(Mar ‘03 to ~Jun ‘03)</td>
</tr>
<tr>
<td>5</td>
<td>Ray-tracing to optimize recording configuration</td>
</tr>
<tr>
<td></td>
<td>Deliverable: 120mm square radial distribution with blazed profile and flight groove density.</td>
</tr>
<tr>
<td></td>
<td>TBD</td>
</tr>
</tbody>
</table>
In Conclusion, Off-plane Can:

- Match RGS to Calorimeter Scientifically
  - R~1500
  - greatly eased tolerances
- or Significantly Enhance Con-X Science
  - R~3000
  - tolerances at currently expected levels

Study funded by the Con-X project. First results in January.