Off-Plane Grating Array for Constellation-X

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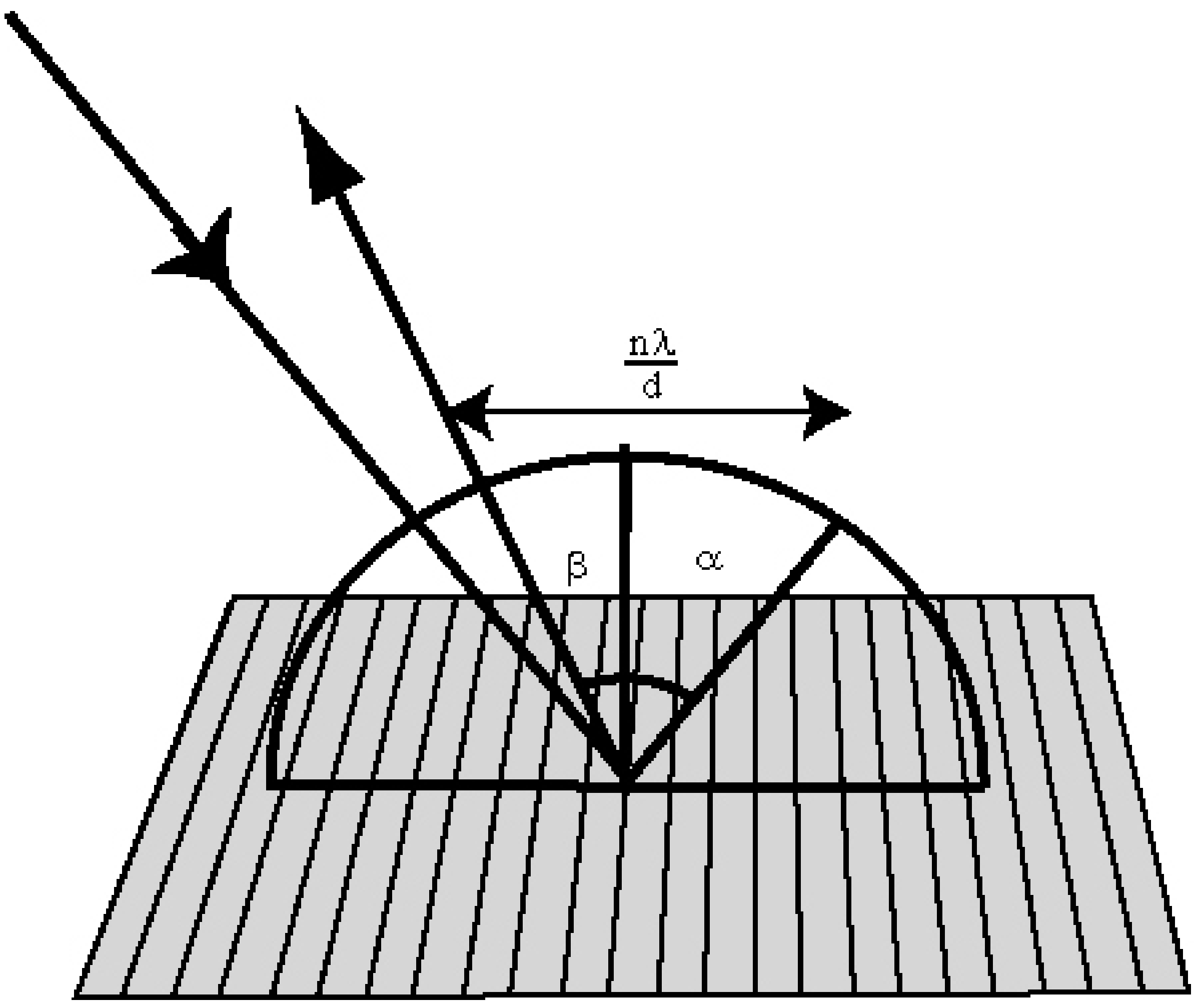
Reflection Grating Array

Currently An In-Plane Design
Resolution of 400

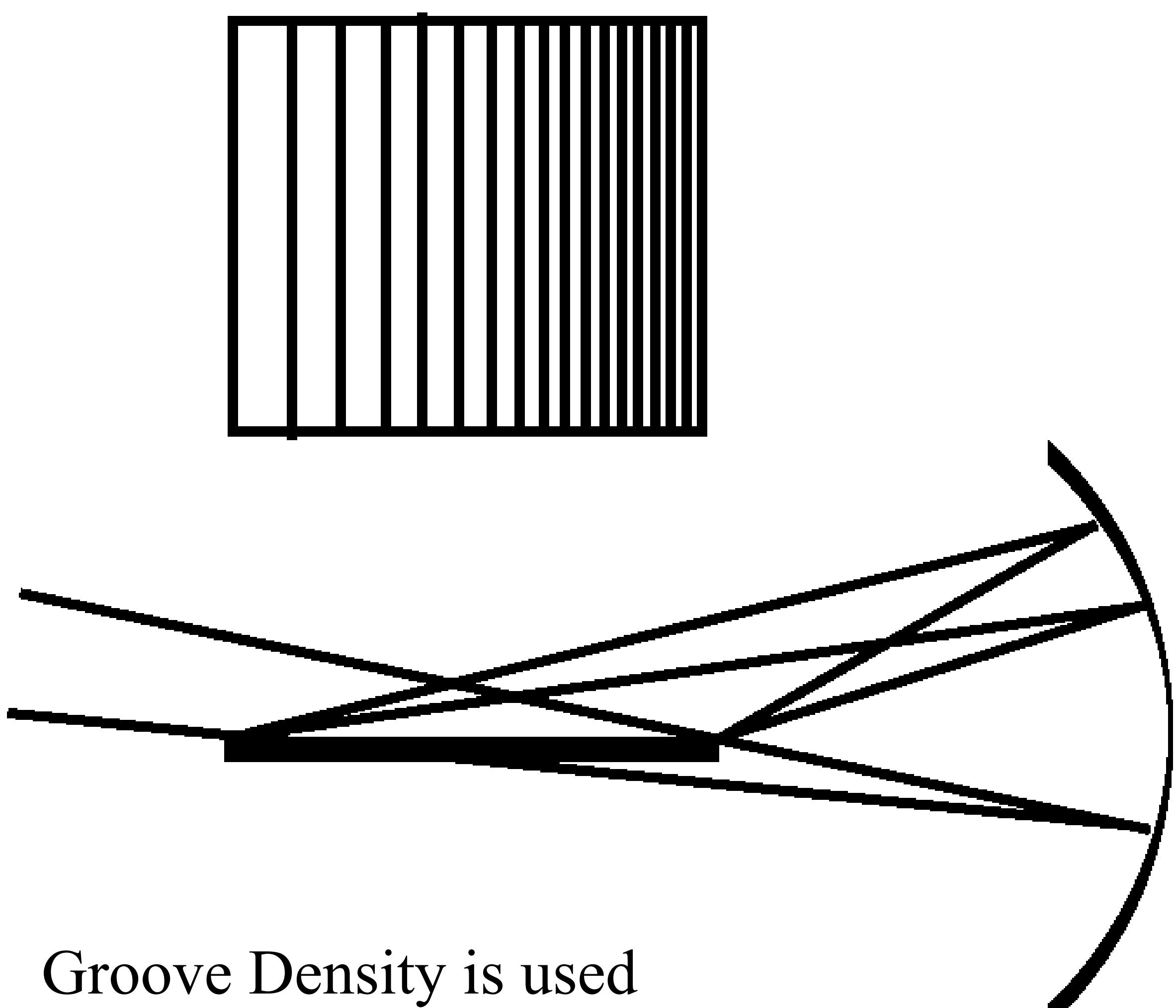
Results from Chandra and XMM
Underscore Importance of

Higher Spectral Resolution

Classic In-Plane Mount



Varied-Line Space Gratings



Groove Density is used
to offset coma when
grating is in converging beam

Reflection Gratings on Con-X

Baseline RGS is like XMM

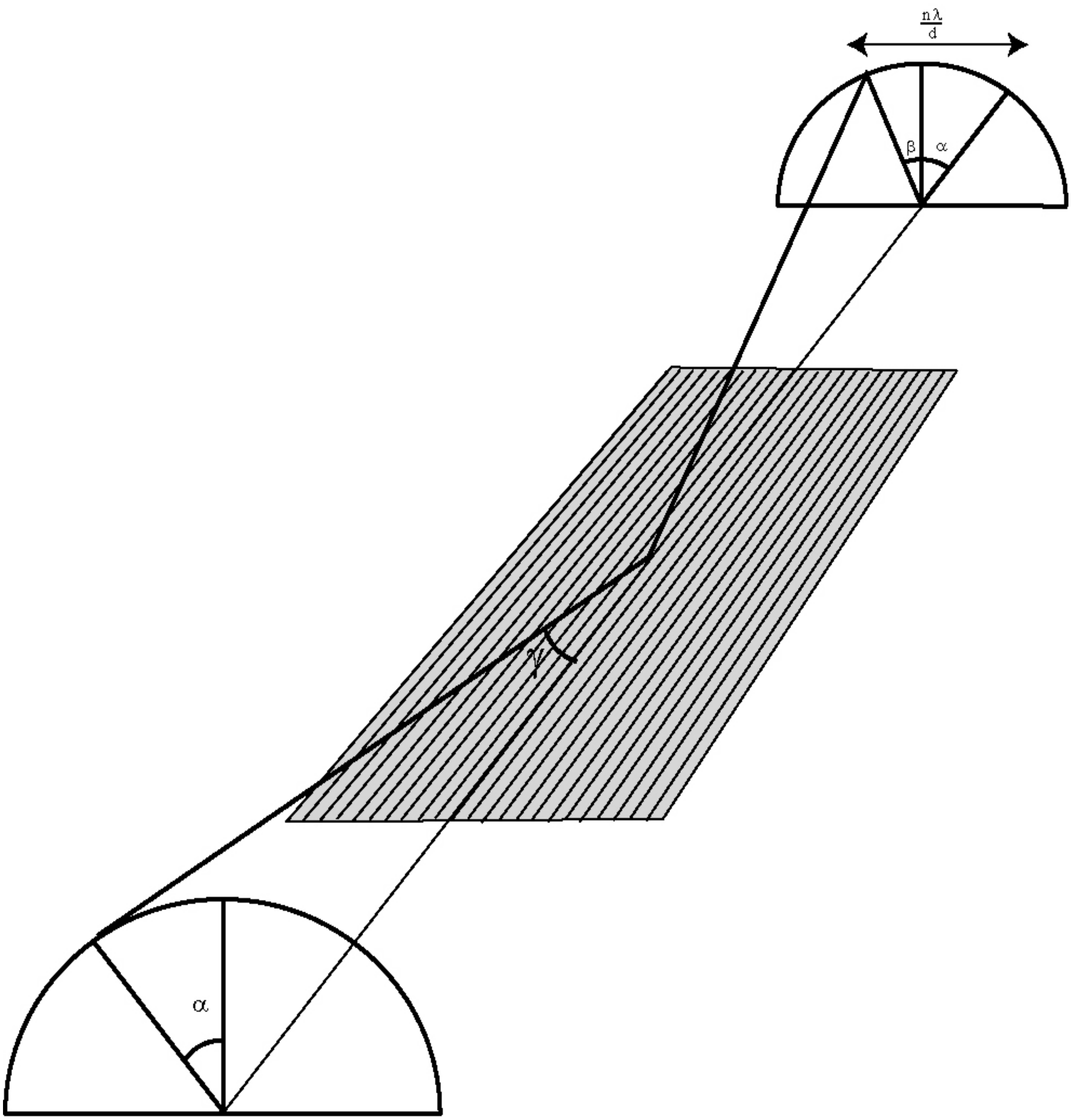
But there is an attractive alternative

Dates to 1979 work I did that showed
reflection gratings could be put in a
converging beam.

Natural geometry for grazing
incidence
is the “off-plane” or “conical
diffraction”
mount.

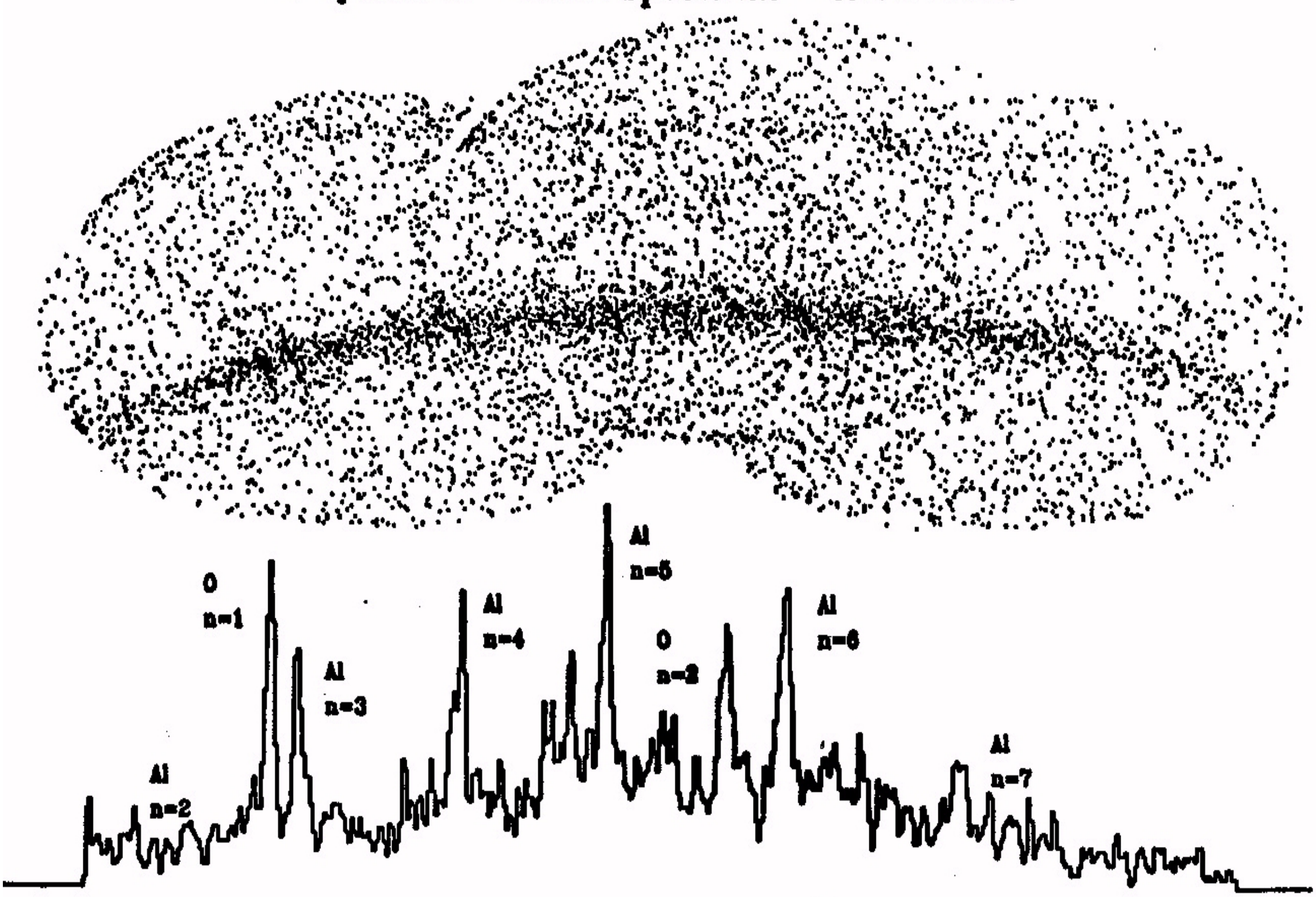
Cash, W., “X-ray Optics 2: A Technique for High Resolution Spectroscopy,” *Appl. Opt* , 30, 1749-1759, 1991.

The Off-plane Mount



An Off-plane X-ray Spectrum

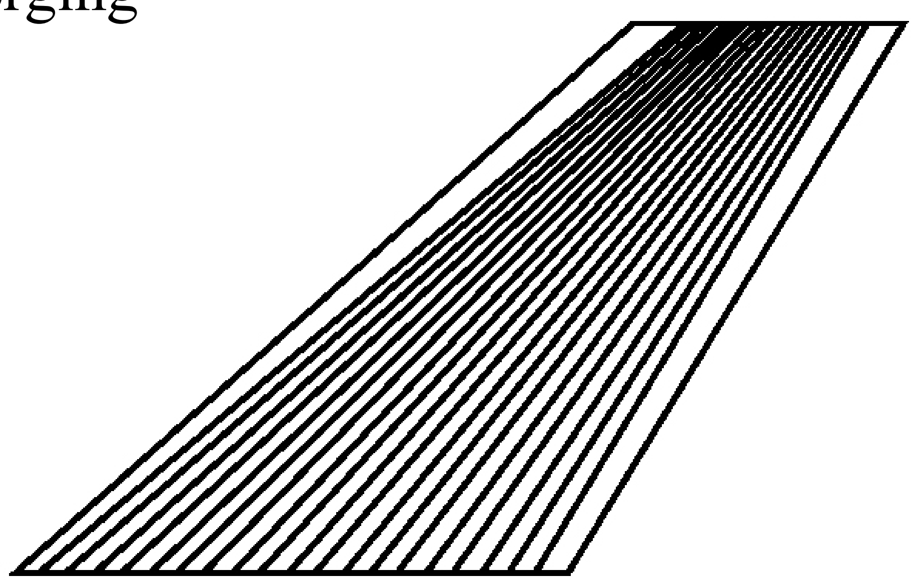
Al Spectrum – XOGS Spectrum – MSFC Beam

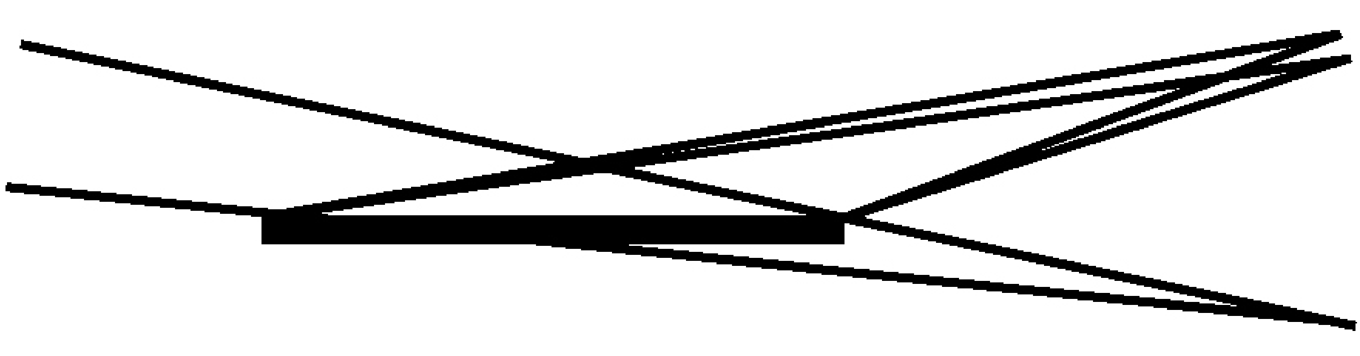


Spectrum from Al target shows Al kα (λ=8.3A, E=1.4keV) in orders n=2 though n=7. Contamination from O kα (λ=23.6A, E=0.525keV) is also clearly present in first and second orders. Note that the blaze function is about 20 deg. in azimuthal angle. This spectrum was obtained by the XOGS spectrograph in the 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.

Radial Groove Gratings

Compensate
For Coma in
a converging
beam





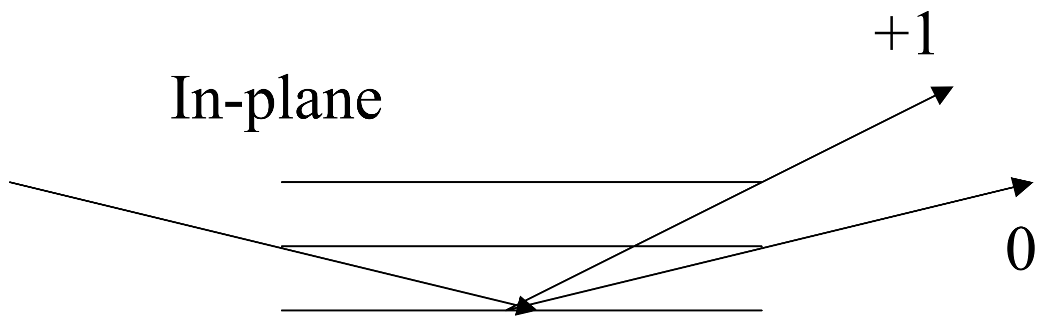
Advantages

- Higher Throughput
- Higher Resolution
- Better Packing Geometry

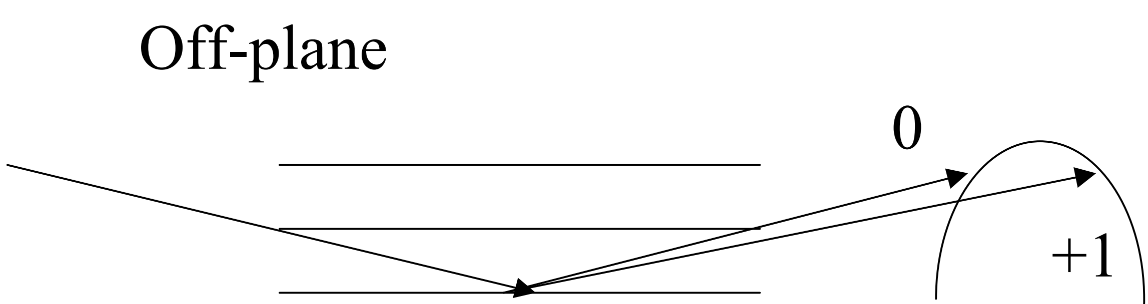
Disadvantages

- Higher Groove Density

Packing Geometry



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



Gratings may be packed optimally

Throughput

- Better Groove Illumination
- Fewer available orders
- Constant Graze Angle

Typically a factor of two

Better Groove Illumination

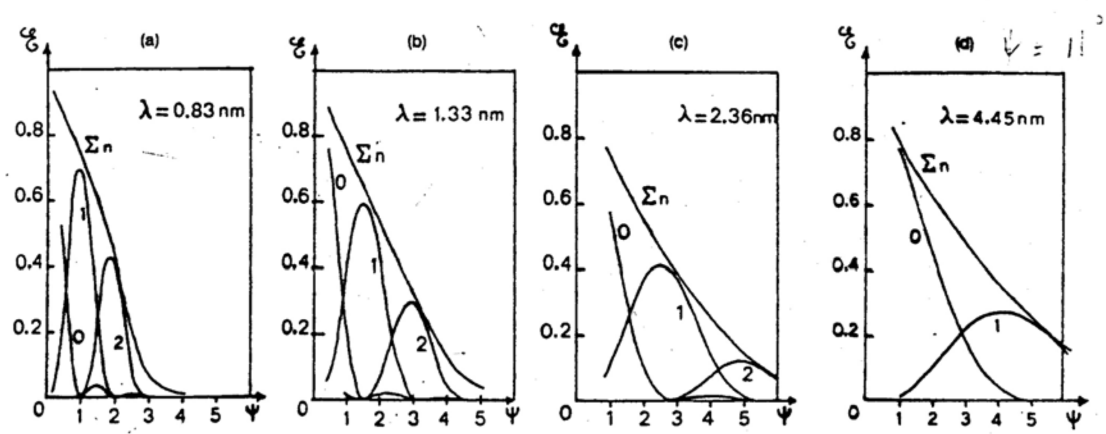


Fig. 1. **Theoretical absolute efficiencies for a 3600-grooves/mm, 5° blaze angle, 90° apex angle gold grating as a function of the grazing angle ψ, for an extreme off-plane mounting and four different wavelengths. The incident wave vector lies in a plane parallel to the grooves and perpendicular to the grating surface. Curves for zero, first, and second orders are given, as well as the total energy reflected by the grating Σn.**

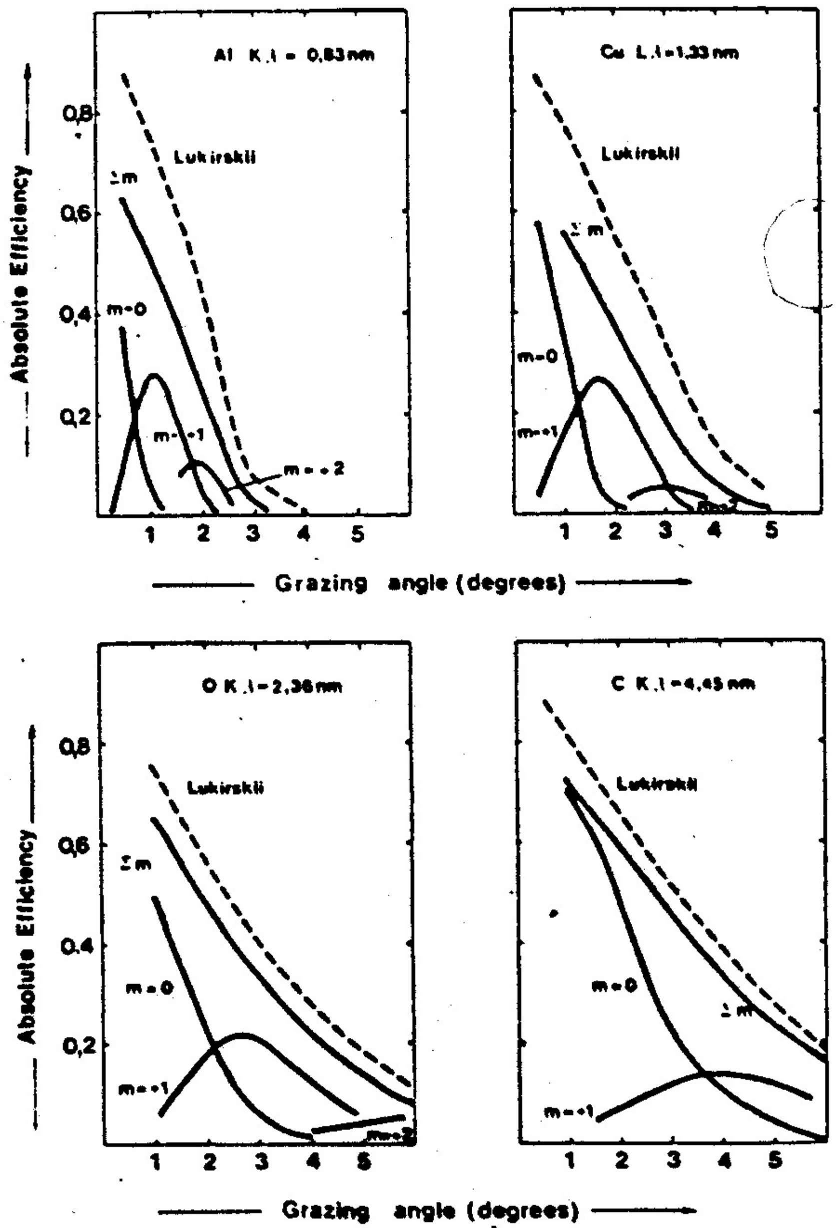
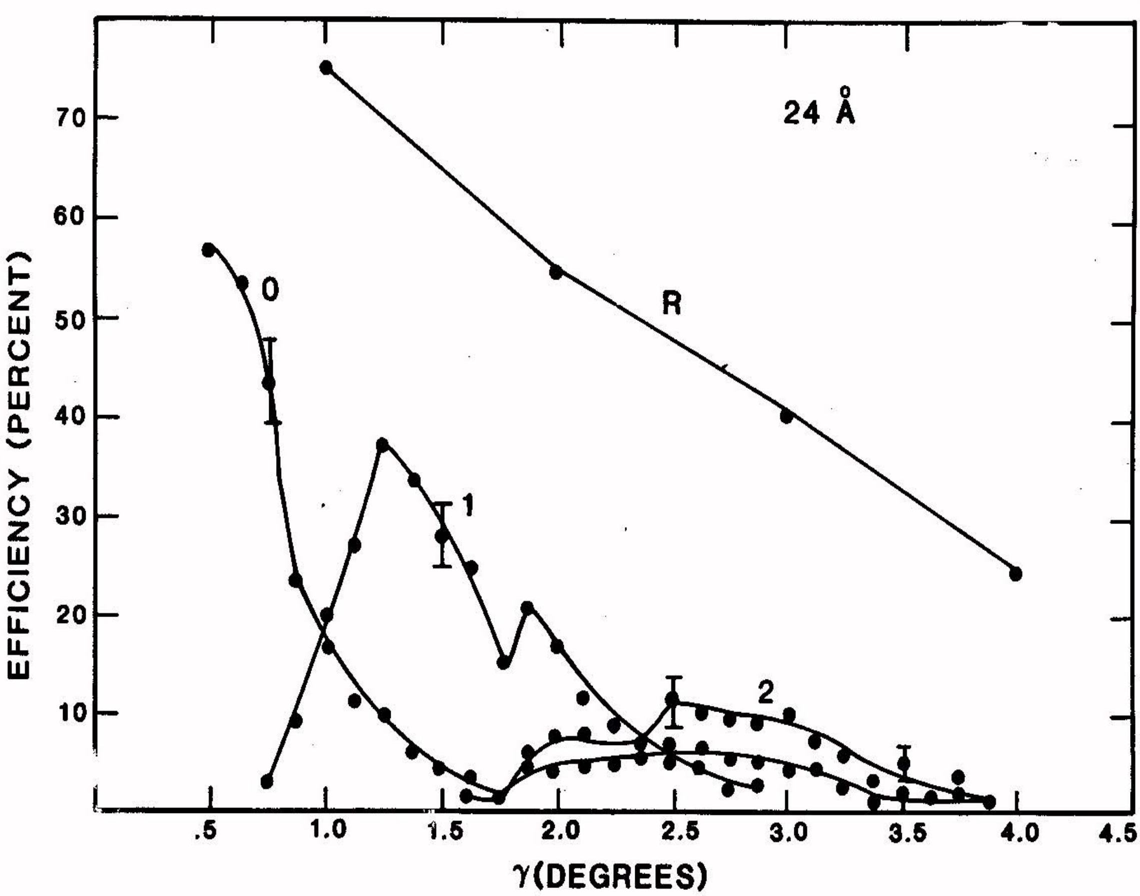


Fig. 1. The absolute diffraction efficiencies for various wavelengths of a gold coated grating ruled with 3600 grooves/mm. Σm represents the total energy reflected by the grating. The dotted lines give the reflection coefficients of gold as described by Lukirskii. The $m = +1$ maxima for Al, Cu, O, and C are, respectively, 0.28, 0.27, 0.22, and 0.14.



24 Å
R
0
1
2
70
60
50
40
30
20
10
EFFICIENCY (PERCENT)
.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
γ(DEGREES)

Resolution

$$R = \frac{(\sin\beta - \sin\alpha)\sin\gamma}{B\cos\beta}$$

B is blur in radians

In-plane:

Graze Angle $\theta = \frac{\alpha + \beta}{2}$

So: $R = \frac{2\theta}{B}\left(1 - \frac{\alpha}{\beta}\right) \approx 1.3\frac{\theta}{B}$

At 2 degree graze and 15” resolution
R=600

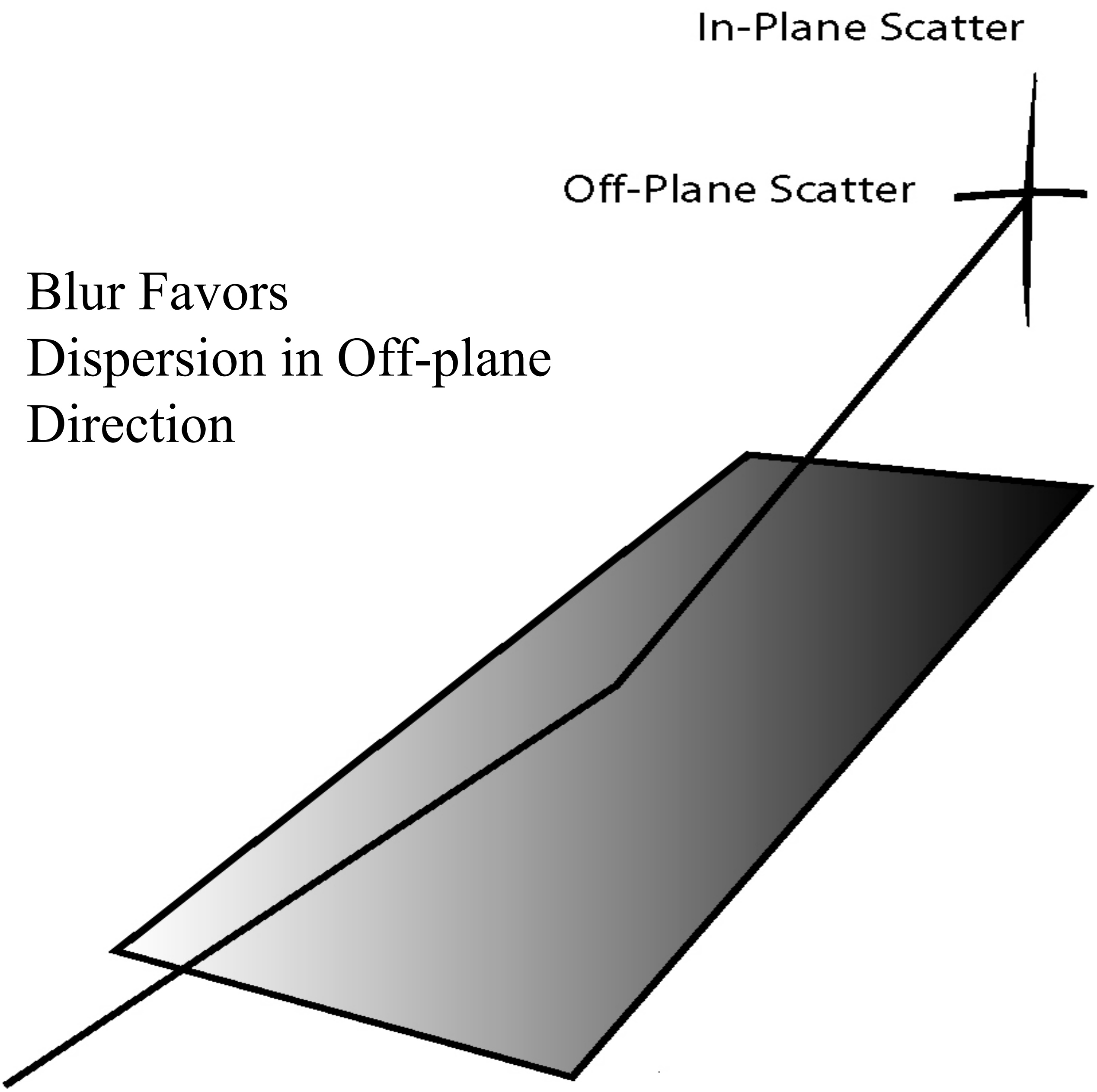
Resolution (cont)

Off-plane

$$R = \frac{2\tan\beta \sin\gamma}{B} \approx \frac{4\theta}{B}$$

At 2 degrees and 15” resolution
R=1800

Internal Structure of Telescope



Blur Favors
Dispersion in Off-plane
Direction

ALL X-ray Telescopes Have This Internal Structure

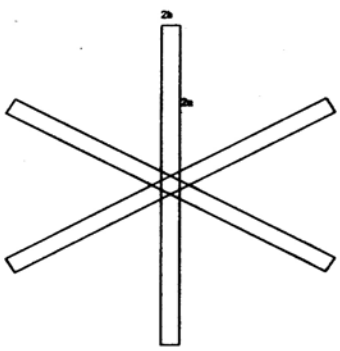


Fig. 4. Schematic showing how a rectangular response to a small section of an annulus leads to a small core plus extended wings.

inant, portion of the signal. In practice[4] we usually see $r^{-1.5}$ distributions which indicate that the linear form from a stopped down annulus is typically of a $1/\sqrt{x}$ form rather than rectangular.

The wide scattering wings lead to confusion as to what the true resolution is of a telescope. It has been pointed out that in solar and x-ray astronomy the signal-to-noise is good enough that it is often possible to resolve features separated by a FWHM even when the core contains a small fraction of the signal.[8] In celestial x-ray astronomy, where the signals are much weaker, it is rarely so simple.

To evaluate a broad image distribution an arbitrary encircled energy level must be used, the level depending on the application. Good arguments can be made for the 50% level for fairly bright sources and 90% for weak sources. We carry through analysis using these two levels.

As the annulus opening is stopped down the characteristic $r^{-1.5}$ distribution disappears, and the resolution depends more on the mirror surface tolerances. Thus we expect to find the physical extent (in one dimension) of the 50 and 90% points to be much closer in the stopped-down case than in the open case.

In our simple case of the $1/r$ distribution coming from a rotating rectangle, it is clear that the 50% point is at a radius of $0.5a$ and the 90% point is at $0.9a$. However, in the limit as the annulus is stopped down, the width remains at $2b$. The effective gain in resolution will be 0.5θ for the 50% flux level and 0.9θ for the 90% level.

B. Comparison to Data

In Fig. 5 we present a profile of the focal image created by the full annulus. The full width at half-maximum (FWHM) is 0.240 mm, which at a focal length of 2284 mm represents a resolution of 21″. In Fig. 6 we have taken the part of the × which came from the wide stopped-down aperture and plotted its profile in the narrow direction. We find the FWHM has

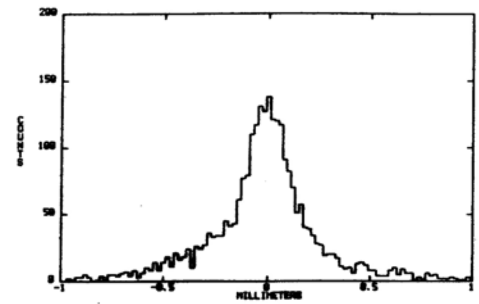


Fig. 5. Profile of the best focus of 13-Å radiation taken with the full annulus.

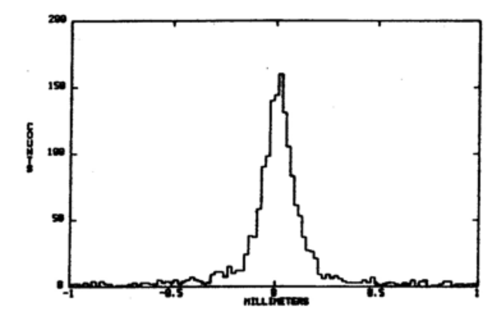


Fig. 6. Profile of the best focus of 13-Å radiation taken with a 38° section of the annulus.

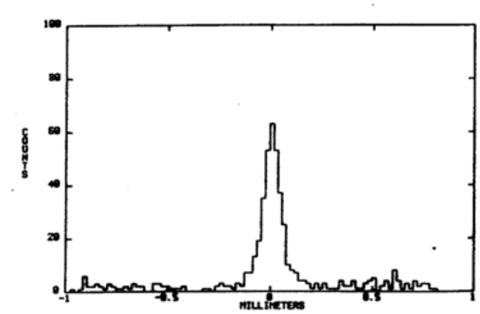


Fig. 7. Profile of the best focus of 13-Å radiation taken with a 9.6° section of the annulus.

fallen to 0.140 mm, which is 12″. In Fig. 7 we show the profile from the narrow leg of the ×. It has a FWHM of ~0.100 mm or 9″. Thus, we immediately see an improvement of over a factor of 2 from stopping down the aperture.

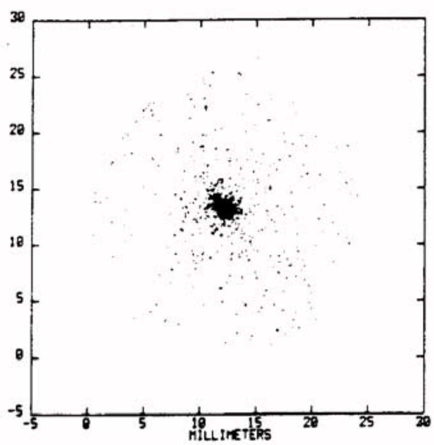


Fig. 1. Image of 13-Å radiation observed with the full aperture of the paraboloid/hyperboloid telescope.

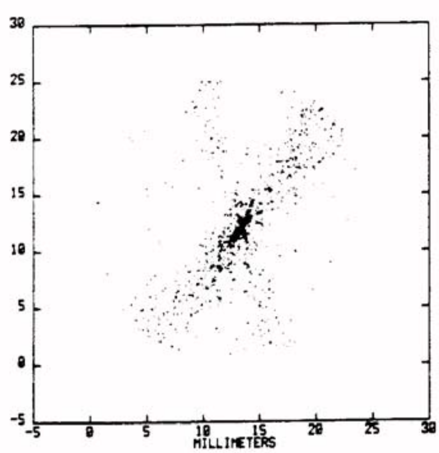


Fig. 2. Image of 13-Å radiation observed with substantial portions of the aperture masked off.

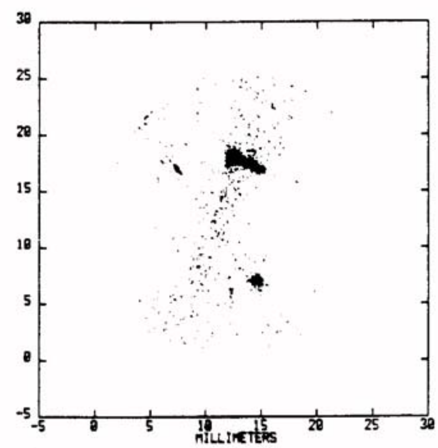


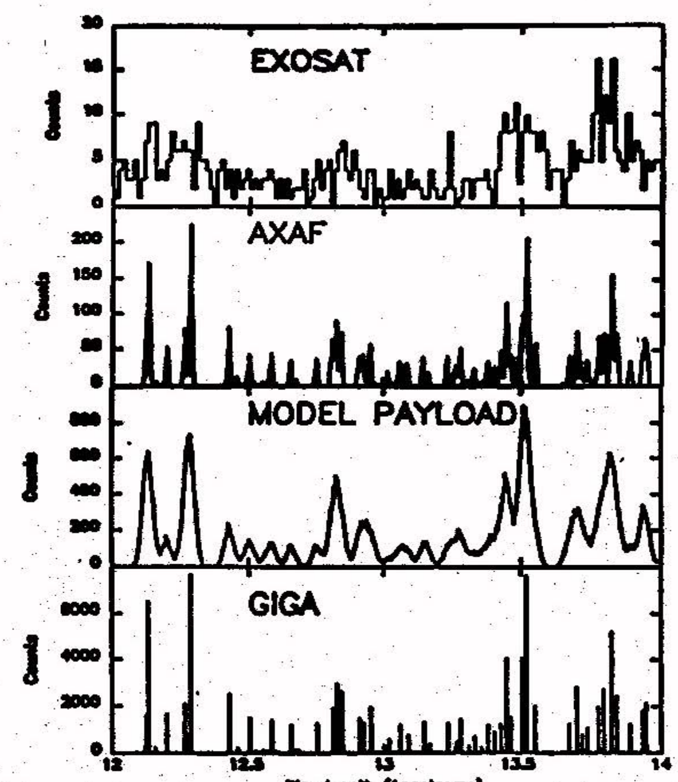
Fig. 3. Exposure as in Fig. 2, except with the detector moved 45 mm out of focus.

This Concept Proposed for XMM in 1989

GIGA

THE GRAZING INCIDENCE GRATING ARRAY FOR XMM

A PROPOSAL TO ESA AND NASA JANUARY 31, 1989



Focal Plane

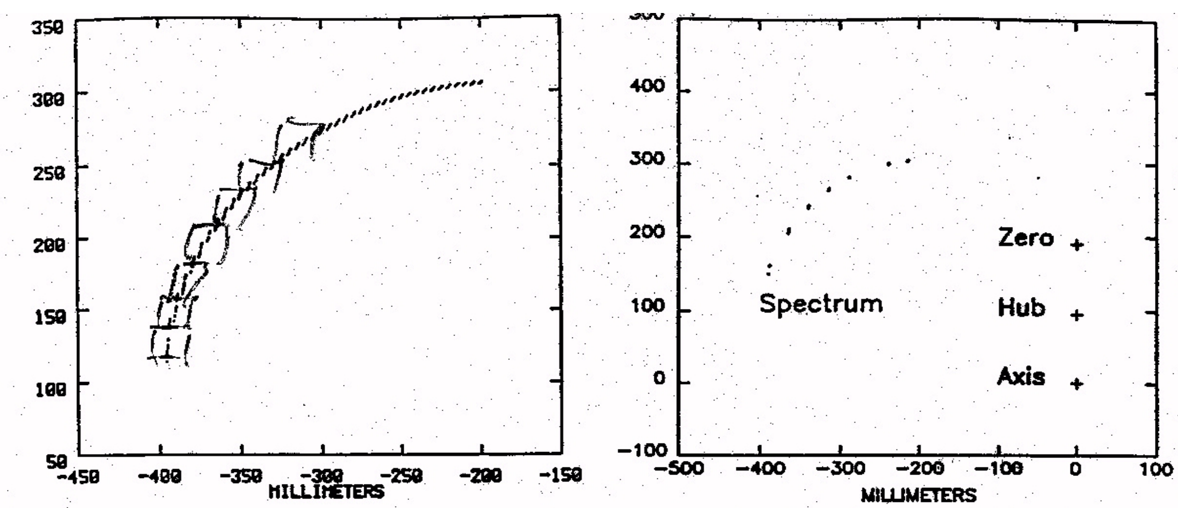


Figure 18: In the left diagram we present raytracing of first order light with wavelengths equal to integer numbers of angstroms from 40Å at the top right to 79Å at the bottom left.
At right we lay out the focal plane. We show the position of the telescope optic axis, the position of the grating hubs, the zero order light, and the arc of diffraction.

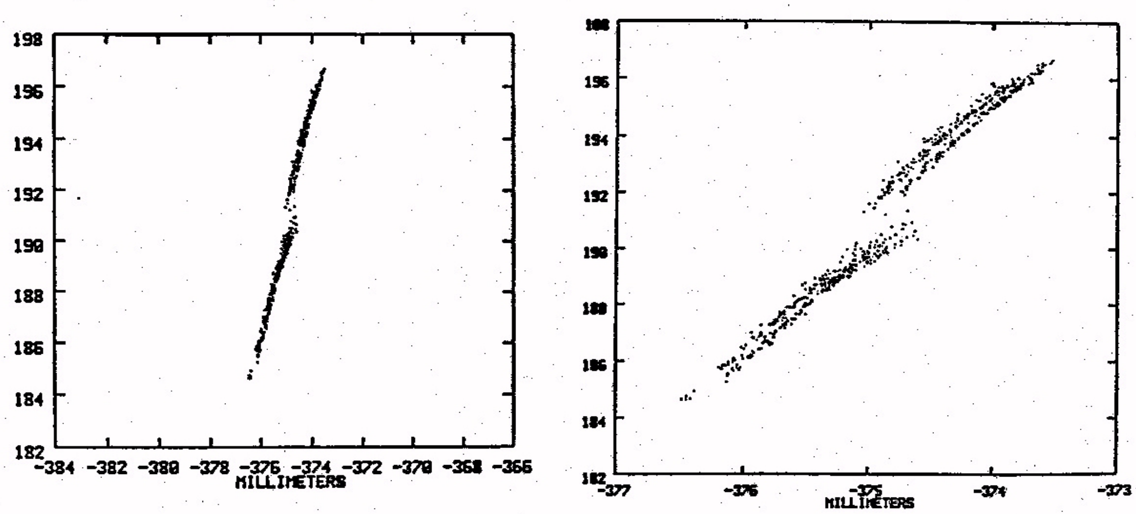


Figure 19: Raytracing of two wavelengths (75 and 75.05Å) of light separated by one part in 1500 shows cleanly split lines and thereby indicates resolution of about 3000. On the left the images are plotted in focal plane coordinates. On the right the x-axis has been expanded to better demonstrate the high resolution. The two images are from the two boxes of gratings.

For Con-X

Can use the extra capability for:

- Higher resolution
- Higher Collecting Area
- Lighter Gratings
- Even poorer telescopes

Or Some Combination as desired

If the Off-plane mount and its desirable properties are to be available to Con-X it needs better proof.

Main worry is the fabrication of the gratings. High groove density and blaze in a radial configuration.

A program that provides for the fabrication and testing of a single grating would suffice to put the worries to rest.

Off-Plane Development Program

Six Month Evaluation - 2001
Build Test Radial Master - 2002
Evaluate in Lab – 2002
Build Flight Master – 2003
Begin Replication Program - 2004
Launch - 2008?

For Test Phase We Need:

A Blazed Radial Grating
Circa 6000 g/mm – 8m to hub
Large Enough to Test - 1cmx5cm ?

Status of Grating Vendors

Contacted all Major Potential Vendors

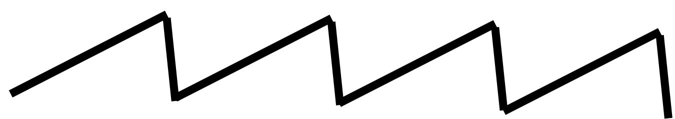
Two Outstanding:

Hyperfine Inc, Boulder
Jobin-Yvon, Paris

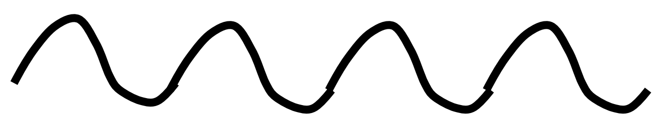
Each has capability in holographics and in mechanical ruling. But, Hyperfine favors mechanical and JY favors holographic

Groove Profiles

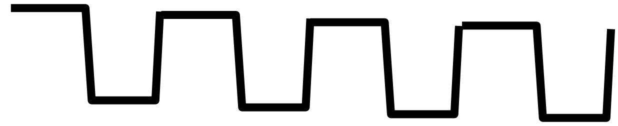
Triangular



Sinusoidal



Laminar



Holographics

At Jobin-Yvon

Rule Using Interference Pattern in Resist

Ion-Etch Master to Create Blaze

Radial Geometry No Problem

Density: Up to 8000 g/mm Laminar
Up to 5800 g/mm Triangular (<35 deg blaze)

Very Low Scatter, Good Efficiency

Mechanical

Hyperfine

Modify Ruling Engine to Make Radials

Made Several Radials 10 years ago

Up to 7200 g/mm, any blaze angle or laminar

More scatter and ghosts

Two Technical Paths are available for Radial Grating Manufacture

Somewhat different capabilities

Apples to Apples Comparison

Set Effective Blaze Angle to be the Same

$\gamma = 2.7$ degrees

Leads to same spectral response

Then see what is needed to match throughput and resolution of 400

To Match In-plane Design

Three times fewer gratings

3000g/mm, 17 degree blaze (easy)

Greatly reduced assembly, alignment and stability requirements

The off-plane remains a very attractive alternative, even baseline requirements

Can Improve Performance

Increase Resolution to 800 by going
to 6000 g/mm

Factor of two in resolution can be achieved
by using β=63deg

Another factor of two can come from further
sub-aperturing.

Resolution of 2000 to 4000 appears feasible in the off-plane mount

Summary

Have reviewed state of off plane grating technology and potential.

Still appears very attractive.
Potentially provides higher resolution and/or reduced difficulty.

Next step is build and demonstrate a holographic test master.