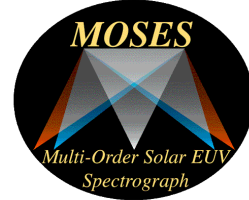


Preventing Systematic Error due to Instrument PSF in *MOSES* Inversions

J. L. Fox, C. C. Kankelborg
Montana State University



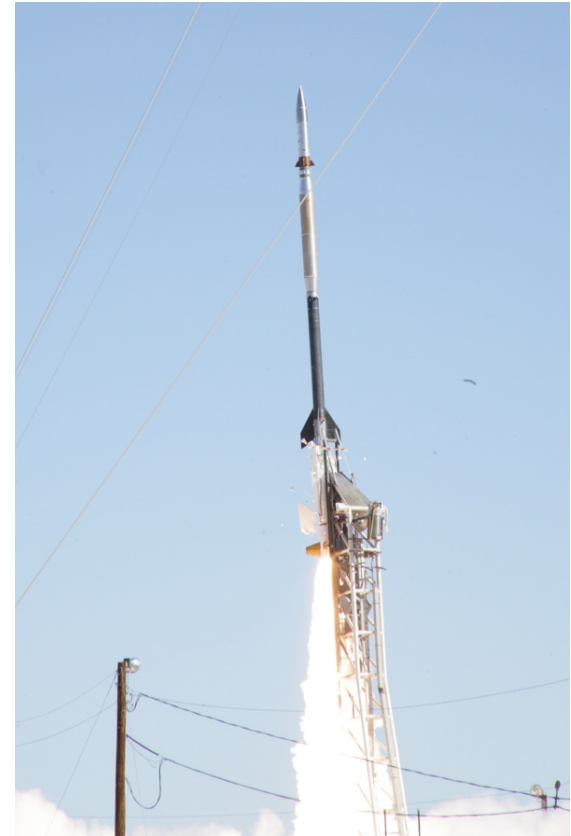
Abstract



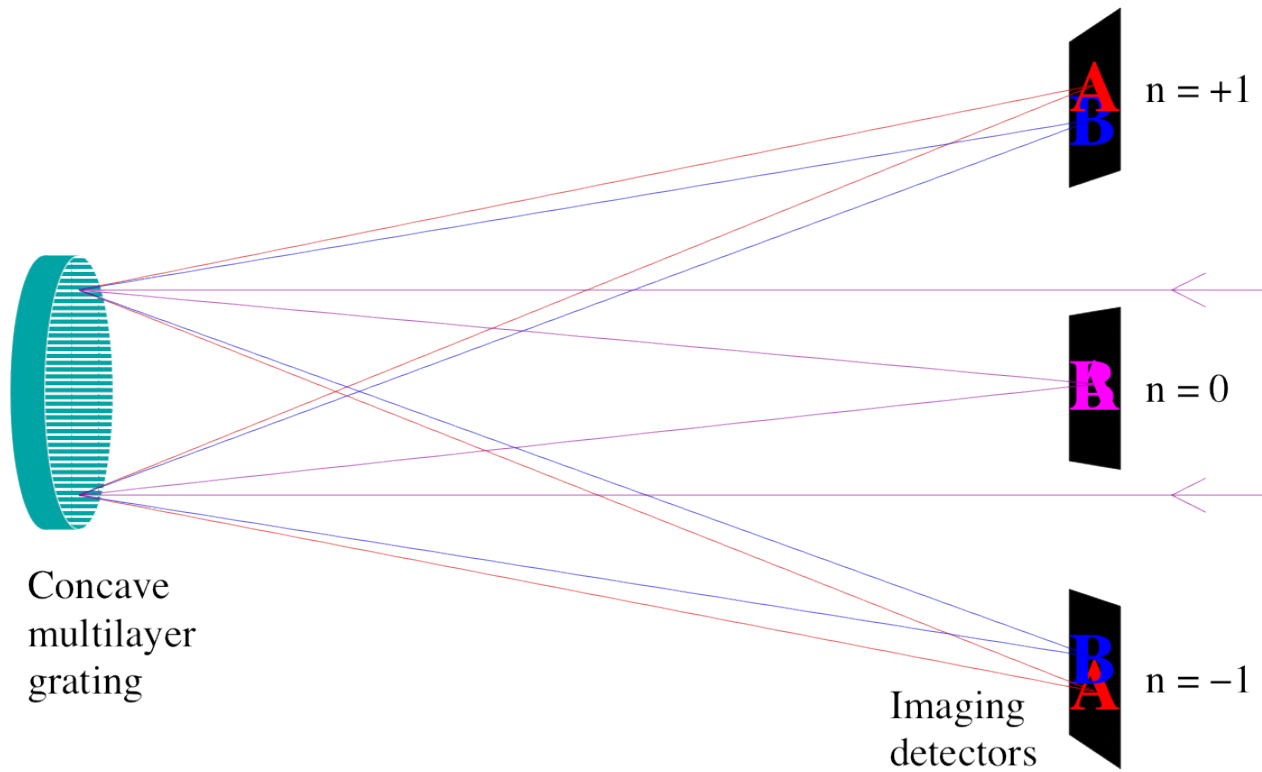
The *MOSES* (Multi-Order Solar EUV Spectrograph) rocket instrument, launched Feb. 8, 2006, uses a novel multi-order slitless technique to perform simultaneous imaging spectroscopy. In $m=\pm 1$ spectral orders, spectral information is entangled with spatial information in the dispersion direction. The $m=0$ spectral order, containing only spatial information, is also used. We must invert or otherwise disentangle spatial and spectral information to perform imaging spectroscopy. Instrumental effects that differ between the spectral orders can mimic or mask spectral features. The point spread functions (PSFs) for different spectral orders are not the same. Differing PSFs can generate spurious doppler shifts during inversion. We describe the effect in detail and propose a remedy.

MOSES Mission

- NASA Sounding rocket:
launched Feb. 8, 2006
- Performs Multi-Order
Slitless Imaging
Spectroscopy at 30.4 nm



A 3-Order Slitless Spectrograph



Result: $I(x + D\lambda)$, $I(x)$, $(x - D\lambda)$.

Point Spread Functions

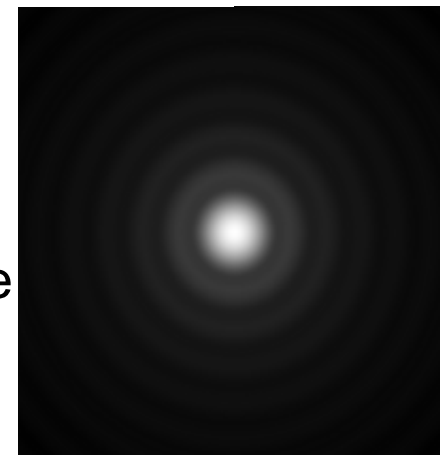
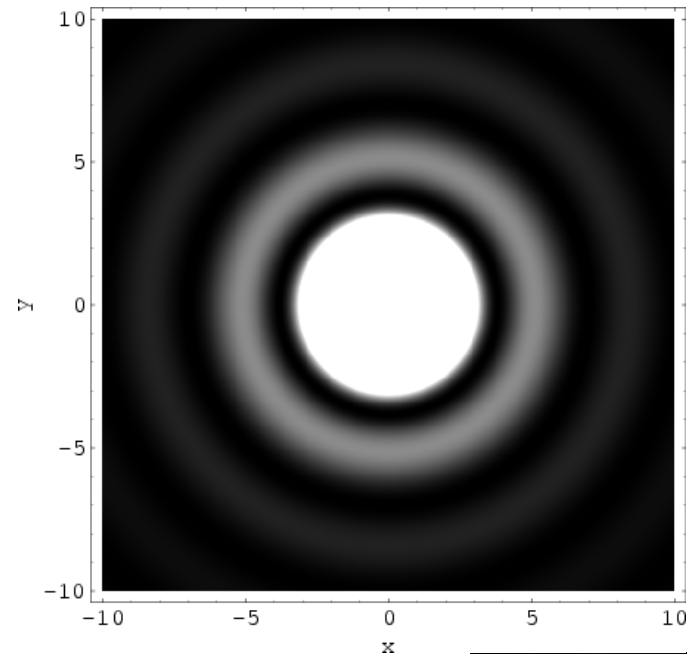
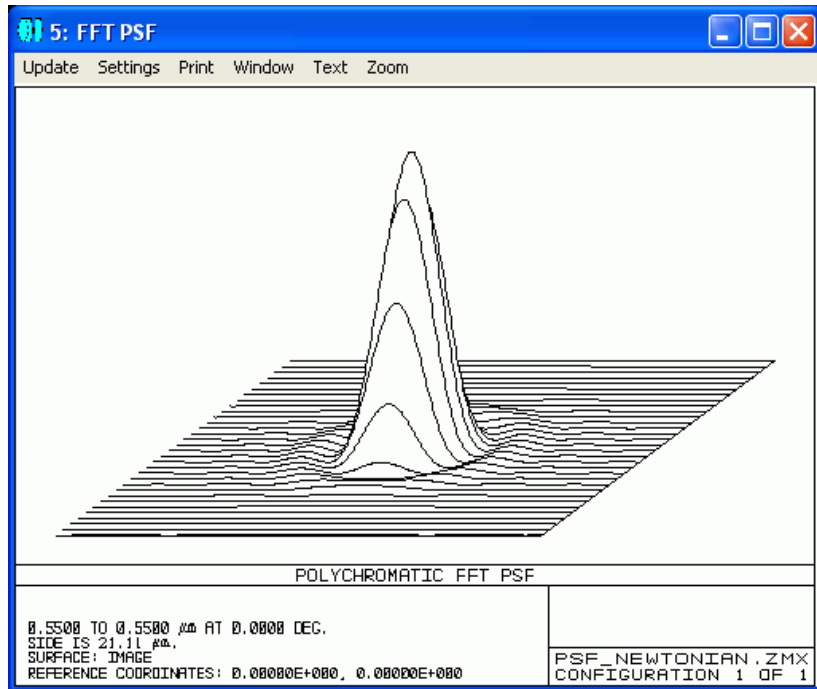
- Represent the response of an optical system to a point source or perfectly collimated plane wave.
- Assuming shift invariance and no image plane distortion it can be represented mathematically as a convolution kernel. That is:

$$I(x, y) = \int PSF(x-u, y-u) O(u, v) dudv$$

$$I = PSF \cdot O$$

- The Modulation Transfer Function (MTF) is the Fourier transform of the PSF.

Famous PSF's Include...



The Airy Disk: Images from Zemax (above), www.iue.tuwien.ac.at/phd/minixhofer/node59.html (above right), support.svi.nl/wiki/ImageFormation (right)

Famous PSF's Include...

COMPARISON of HUBBLE SPACE TELESCOPE FAINT OBJECT CAMERA IMAGES

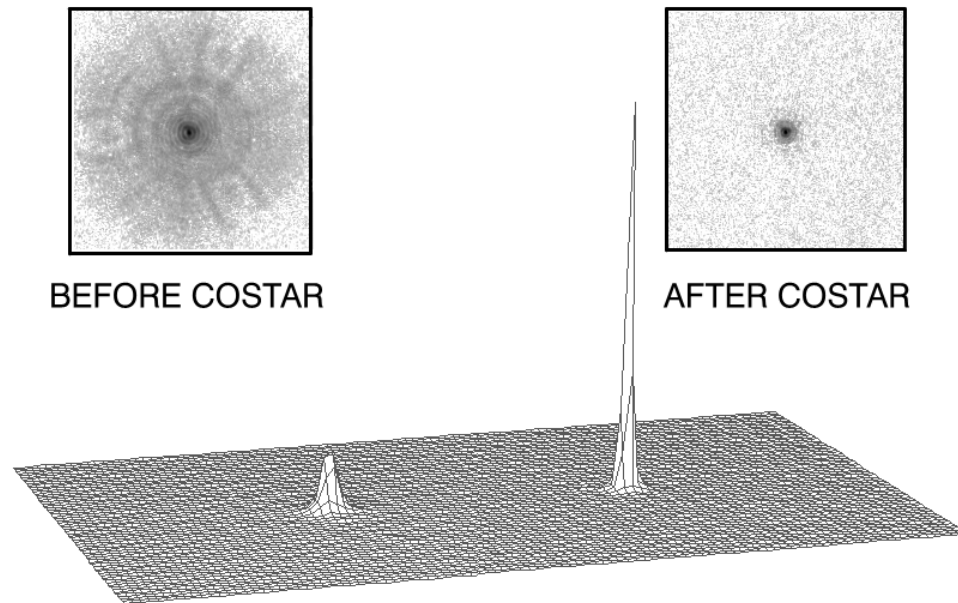
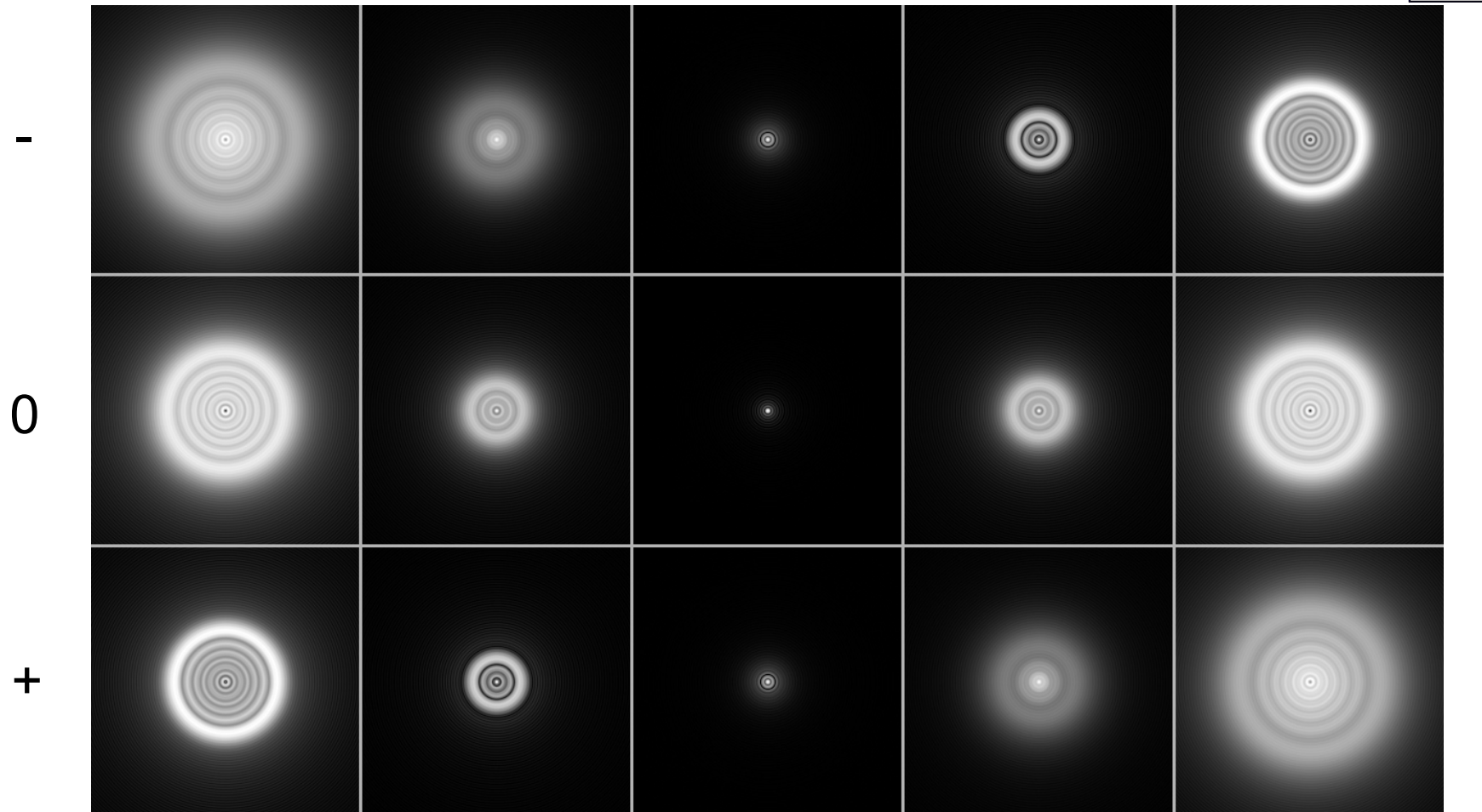


Image Sharpness Before and After COSTAR

The Hubble Space Telescope: image from
www.cv.nrao.edu/~pmurphy/images/astro/

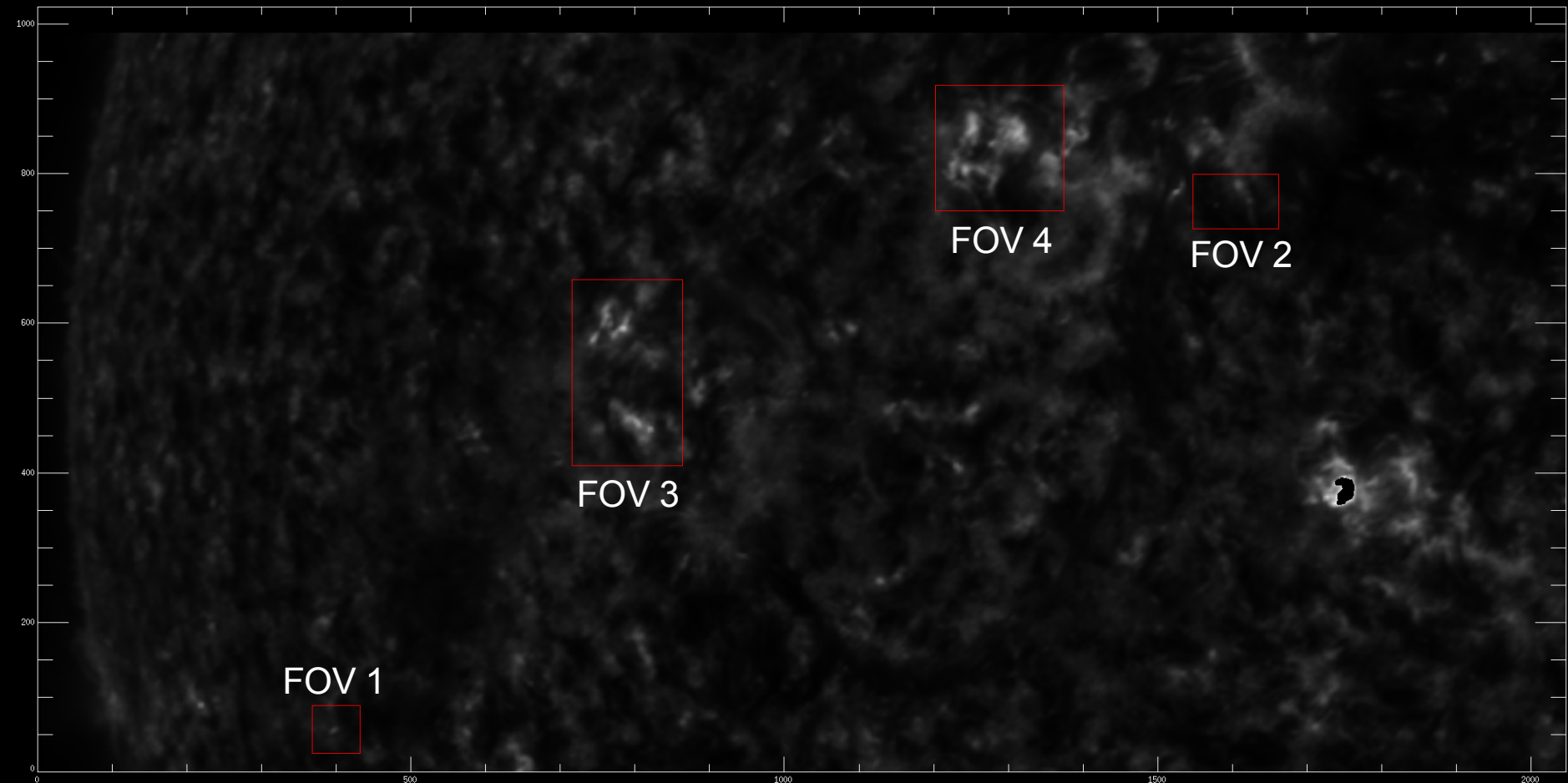
Famous PSF's Include...



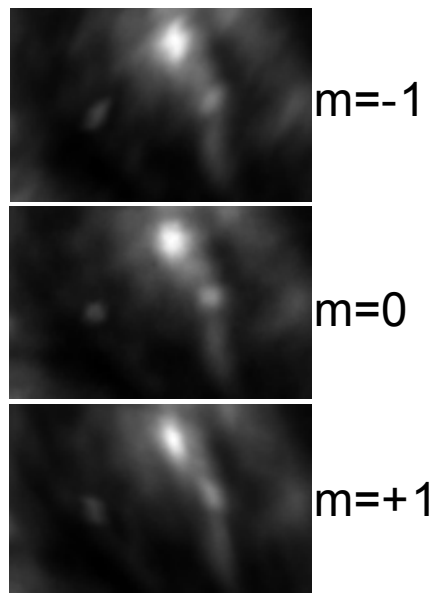
inside Spherical Aberration: image from Wikipedia outside

Illustrating the PSF Problem

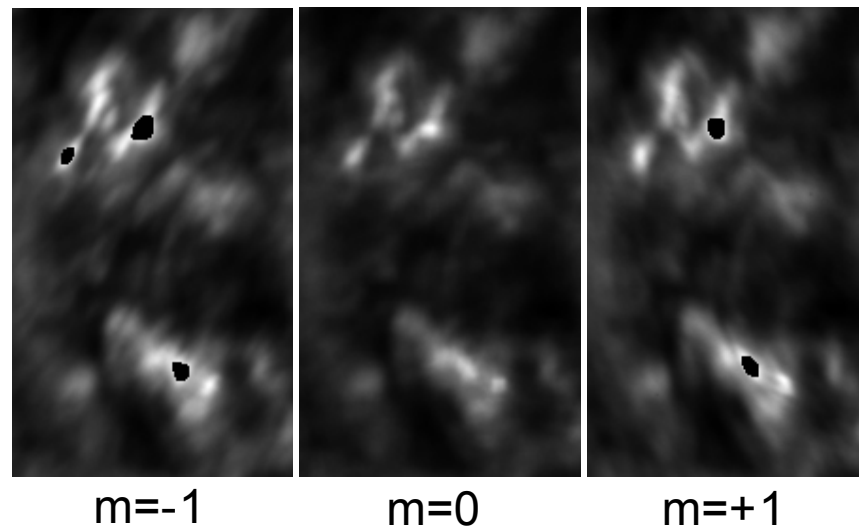
A sample $m=0$ order image. The fields of view indicated in red follow.



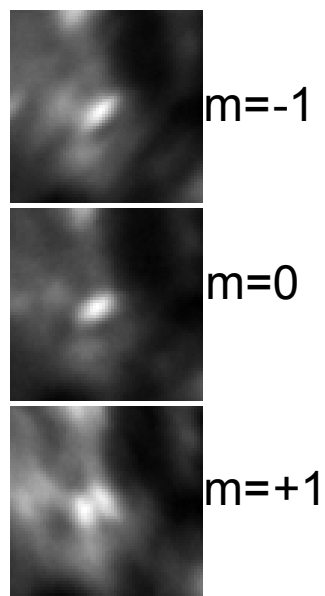
FOV 2



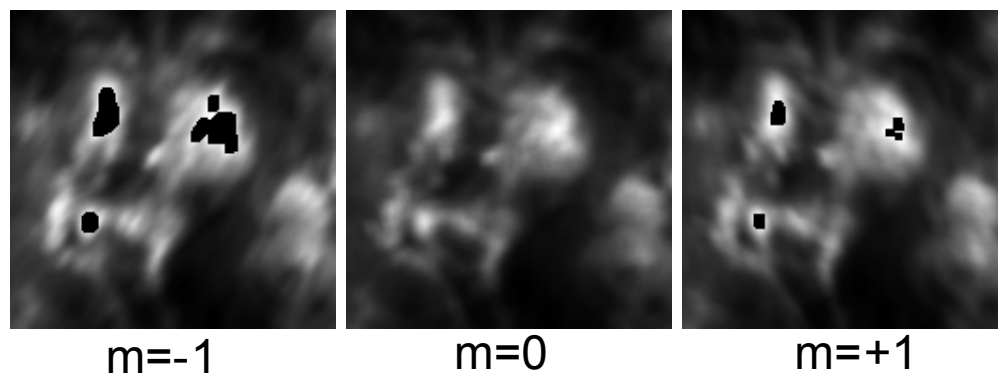
FOV3



FOV 1



FOV 4



The apparent difference between PSF's visible in the previous examples can lead to spurious doppler shifts.

- Consider a point source with a “rest” wavelength profile.
- Anisotropic PSF's (e.g. ellipses with different tilt angles) cause this point source to take on the appearance of a bidirectional jet.
- The image at right is derived from data. Are there jets or not?

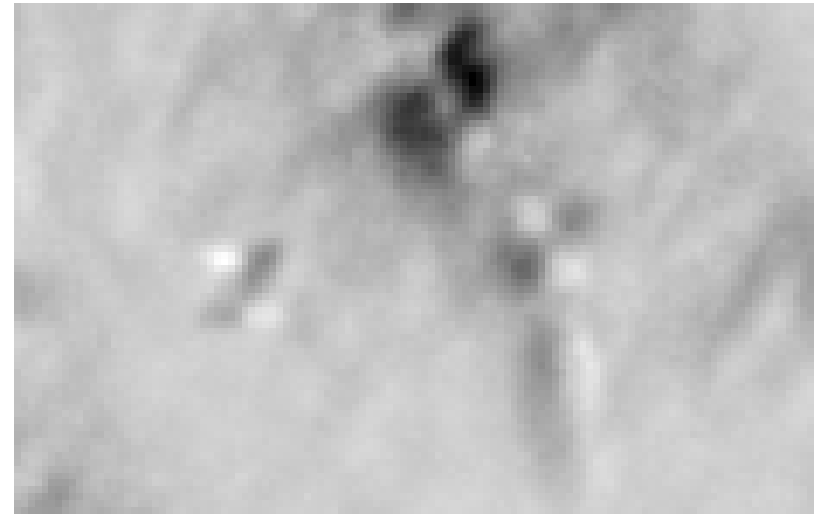
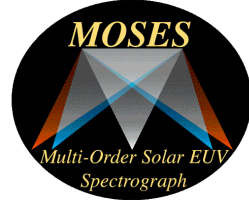


figure 1: Difference image $I_{+1}-I_{-1}$ for FOV 2



What are the instrument PSF's?



- The PSF's have not been measured in EUV.
- They can't be measured directly without access to an arcsec resolution collimated EUV point source.
- Can we estimate them from the data, without knowing what the object really looks like?

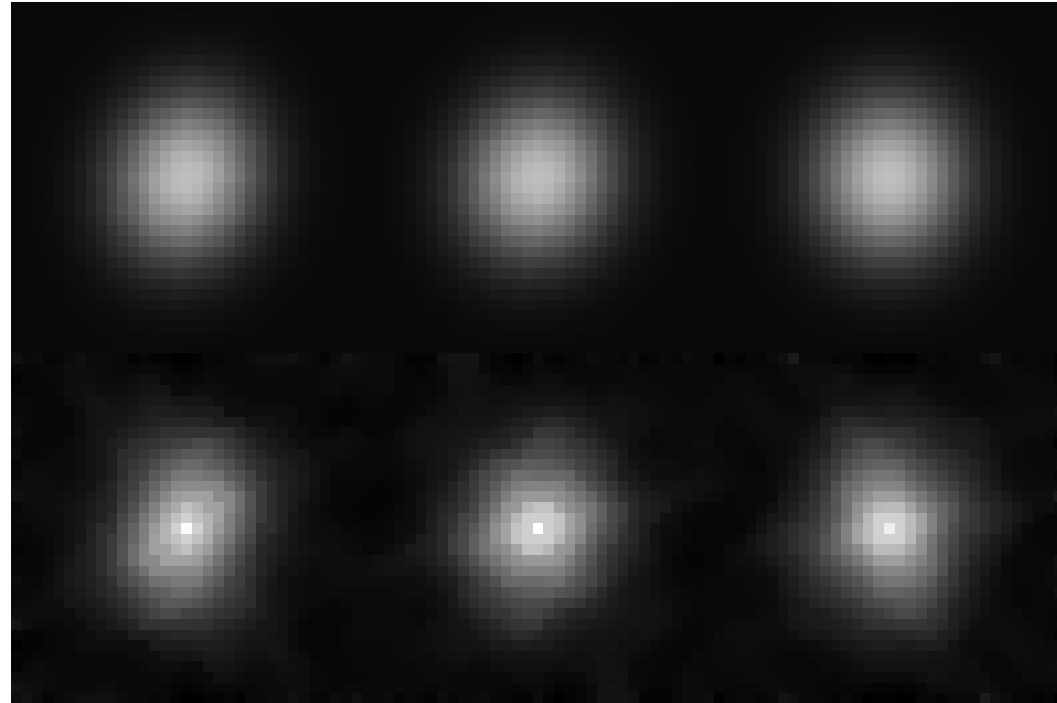
Autocorrelation Method

- Autocorrelate 32x32 pixel subarrays, apodized with a \cos^2 function.
- Take the minimum of the stack of autocorrelations at each pixel.
- Propose: This minimum is the autocorrelation of the PSF.
- Use a variant of the Wiener-Khinchin theorem to compute the PSF from its autocorrelation.

σ_x^2	21.5	22.9	22.7
σ_y^2	28.7	27.1	26.9
tilt, θ	-16.6°	-21.1°	-0.3°

Elliptical Gaussians with
the same moments as
results below

A.C. method results;
median filtered



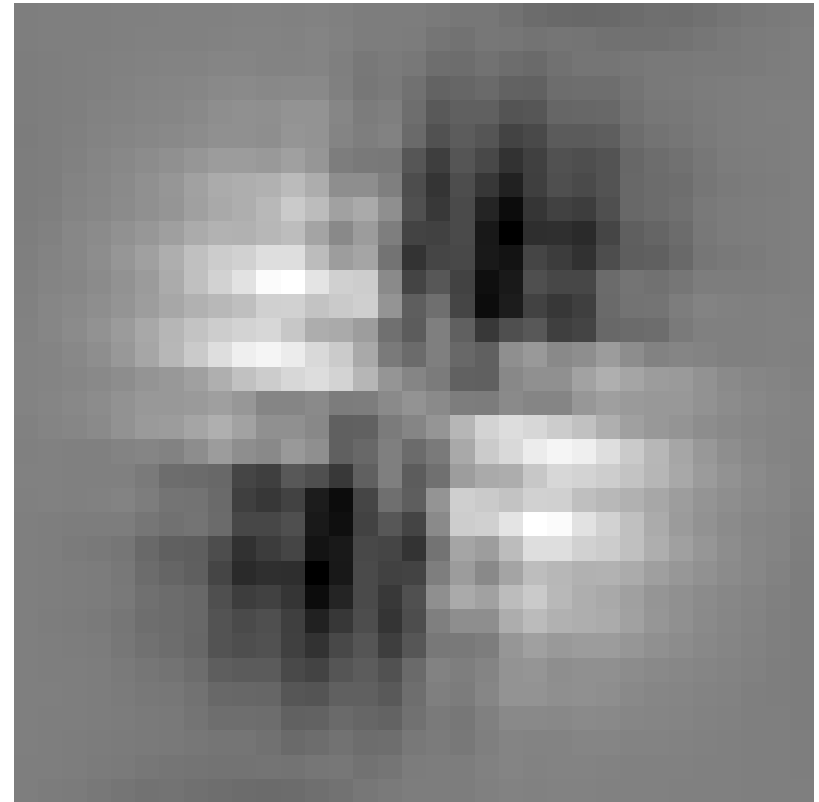
$m=-1$

$m=0$

$m=+1$

figure 2

- The image to the right shows the difference between +1 and -1 gaussian functions from fig 2.
- Compare this pattern to the small quadrupolar features in fig 1.
- These functions would give a fictitious bidirectional doppler shift of $\sim 22 \text{ km/s } 1\sigma$ away from the origin.



What can we do about it?

- Remap all data to have an identical compromise PSF, p_C .
- $\mathcal{P}_C = \text{FFT}(p_C) = \min(\mathcal{P}_+, \mathcal{P}_0, \mathcal{P}_-)$
- $\mathcal{I}'_x = (\mathcal{P}_C / \mathcal{P}_x) \mathcal{I}_x$
- Possible variations on this theme:
 - Include the expected He II linewidth $\mathcal{A}(k_x)$ in the compromise for the outboard orders
 - Try for a less maximally fat compromise, $\mathcal{P}_C = \min(\alpha \mathcal{P}_x, 1)$, $\alpha \sim 2$

What can we do about it?

- Build them into the forward model?
- Remove them from the data before doing inversions using Extended Nijboer-Zernike theory or Fourier methods?
- In either case we subject ourself to risk of numerical instabilities and greatly amplified noise.
- Standard methods exist to address this (Wiener filtering etc...) but basically we've added another (worse, potentially) inversion problem on top of our original one.



Conclusions, Future Work



- The PSF's of *MOSES* orders are different and the effect on inversions is probably non-negligible.
- We must have a good idea what the PSF's are to fix the problem.
- We may be able to estimate the PSF's from the data.



Conclusions, Future Work



- It may be possible to model the telescope response to derive the PSF's. Accurate knowledge of the optical parameters of the telescope would be necessary (get Tom Rust/Seth Chart to do a seminar).
- Is there a collimated EUV point source in the house?