A PSF Equalization Technique for the Multi-Order Solar Extreme Ultraviolet Spectrograph (MOSES)

Shane Atwood, Charles Kankelborg
Montana State University

ABSTRACT

The Multi-Order Solar Extreme Ultraviolet Spectrograph (MOSES) is a rocket-borne slitless imaging spectrometer, designed to observe He II (30.4 nm) emission in the solar transition region. This instrument forms three simultaneous images at spectral orders $m=-1, 0, +1$ over an extended field of view (FOV). A multi-layer coating on the grating and thin film filters in front of the detectors defines the instrument passband. Each image contains a unique combination of spectral and spatial information. Our overarching goal in analyzing these data is to estimate a spectral line profile at every point in the FOV.

Each spectral order has different image geometry, and therefore different aberrations. Since the point spread function (PSF) differs between any two images, systematic errors are introduced when we use all three images together to invert for spectral line profiles. To combat this source of systematic error, we have developed a PSF equalization scheme.

Determination of the image PSFs is impractical for several reasons, including changes that may occur due to vibration during both launch and recovery operations. We have therefore developed a strategy using only the solar images obtained during flight to generate digital filters that modify each image so that they have the same effective PSF. Generation of the PSF equalization filters does not require that the PSFs themselves be known. Our approach begins with the assumption that there are only two things that cause the power spectra of our images to differ:
(1) aberrations; and
(2) the FOV average spectral line profile, which is known in principle from an abundance of historical data.

To validate our technique, we generate three synthetic images with three different PSFs. We compare PSF equalizations performed without knowledge of the PSF to corrections performed with that knowledge. Finally, we apply PSF equalization to solar images obtained in the 2006 MOSES flight and demonstrate the removal of artifacts.

1. INTRODUCTION

The MOSES sounding rocket payload reflects three distinct images from a concave diffraction grating onto detectors at the $m=+1,0,-1$ spectral orders. Each image contains unique spectral and spatial information, with each exposure acquiring new and distinct spectral information across the entire field of view.[1] A multi-layer coating on the grating and thin film filters on the detectors limit the number of spectral lines observed. MOSES was launched February 8, 2006 at 18:45:54, observing the He II 30.38 nm emission line.[2] The passband also contains less than 10% Si XI 30.33 nm.

Image and Signal Processing for Remote Sensing XXI, edited by Lorenzo Bruzzone, Proc. of SPIE
Vol. 9643, 96431R · © 2015 SPIE · CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2194357

2. INSTRUMENT CONCEPT

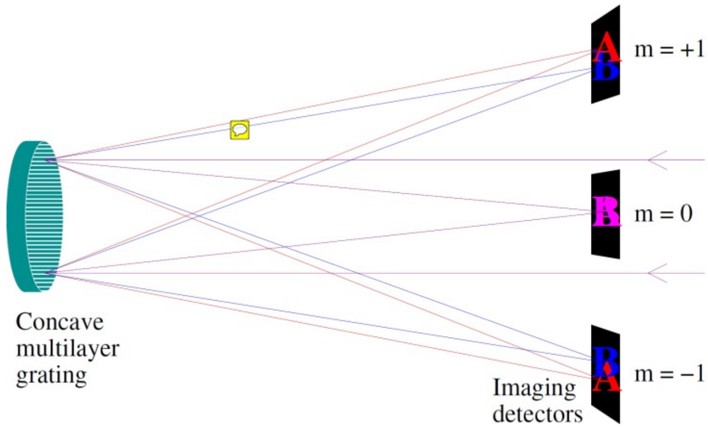

Figure 1: Conceptual sketch of MOSES

Figure 1 displays a simplified conceptual representation of MOSES imaging monochromatic letters "A" and "B," overlapping in the object. In the *m*=+1,−1 orders, the "redder," (longer wavelength) light is dispersed further out from the optical centerline than the "bluer" (shorter wavelength) light by a distance proportional to their difference in wavelength. The central order is a pure imager, with the letters overlapping.

A set of simultaneous images from each order can be viewed as a tomographic projection of a hyperspectral object with two spatial dimensions *x* and *y* and one spectral dimension λ. We define *x* as the axis along which dispersion occurs. An object $\upsilon(x, y, \lambda)$ forms images at spectral orders m, given by:

$$I_m(x, y) = \int_B \upsilon(x - m\lambda, y, \lambda) d\lambda \quad (1)$$ [2]

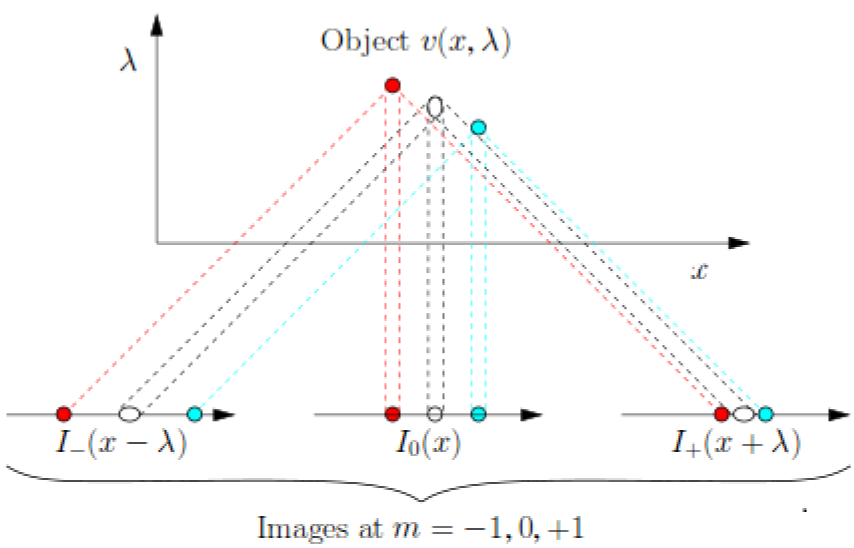

Figure 2: Three compact features, showing the effects of a red shift, blue shift, and a broadening.

3. PSF EQUALIZATION

A unique PSF is associated with each order. The systematic error induced, in particular in the *m*=+1,−1 orders, is noticeable on small scales. The difficulty is not that there are aberrations, but that they vary in each order.

Our PSF equalization scheme is intended to solve this issue.

3a: Motivation

The outboard orders display a systematic tilt in small background features on the quiet sun. In the *m*=−1 order, red shifts move rightward and blue move leftward, and in the *m*=+1 order, red moves left while blue moves right. Therefore, these tilts give false apparent Doppler information as if the entire sun were made of small, weak bipolar jets, with a blue-shifted south jet and red-shifted north jet. The most obvious tell-tale sign is in the difference image shown below. Subtracting the *m*=+1 image from the *m*=−1 image produces a distinct quadrupole, which is the clearest sign of a bipolar jet. This effect has limited MOSES analysis to features whose spectral variations are very large compared to systematic error. The paper by H. Courrier and C. Kankelborg in this volume describes in detail how Doppler shift estimates from MOSES data are influenced by the differing PSFs in our three spectral orders.

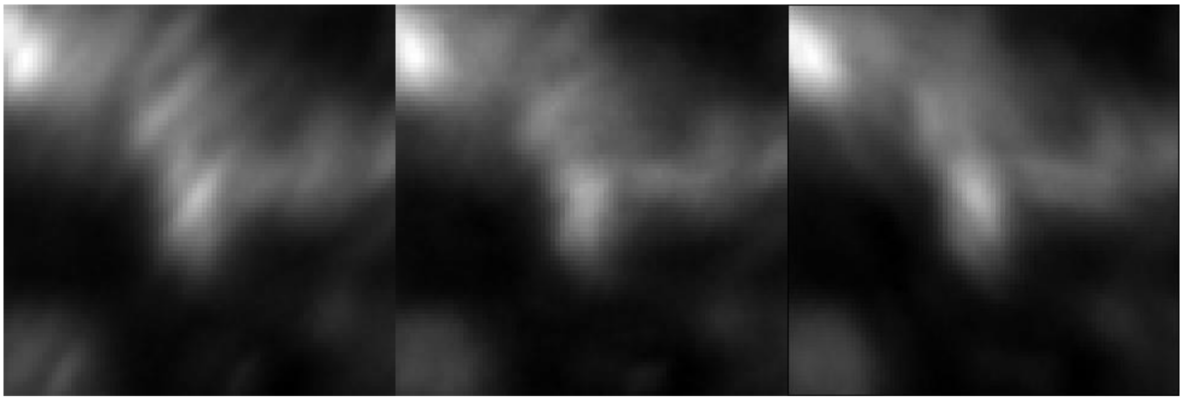

Figure 3: The images in the *m*=−1,0,+1 orders. Note the systematic tilt especially visible in the outboard orders.

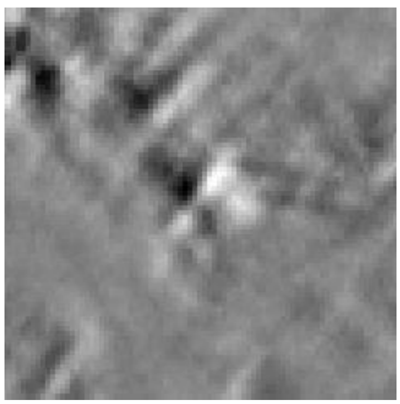

Figure 4: A difference image of the *m*=−1 image minus the *m*=+1 image. The quadrupole (circled) is characteristic of a bipolar jet in MOSES difference images. This one is purely an artifact of instrument PSF.

3b: PSF Equalization

In each order, the observed image can be understood as a convolution of the "true" image with each order's unique PSF. In Fourier space,

$$\tilde{I}'_m = \tilde{\kappa}_m \tilde{I}_m \tag{2}$$

where the tilde represents the 2-D Fourier transform with respect to x and y, the I' represents the observed image at each order m, the unprimed I the image in the absence of instrument PSF, and κ_m the PSF. In this paper, we use integral representation for compactness. In practice, our Fourier transforms and convolutions are carried out discretely on digital data.[3]

Instruments on sounding rockets are subject to vibrations during launch and subsequently operate in microgravity. Ground-based measurements of the PSFs are therefore suspect. Rather than attempt to ascertain each PSF, we calculate a PSF-compensated image inferred only from flight data. For each order m, we define

$$\tilde{I}''_m = \tilde{\kappa}' \tilde{I}_m \tag{3}$$

We call κ' the intermediate kernel. Each image I''_m can now be directly compared to the others, as they now share a common PSF. For the intermediate kernel we choose the Fourier-space geometric mean of all the kernels:

$$\tilde{\kappa}' = \left[\prod_n \tilde{\kappa}_n\right]^{\left(\frac{1}{N}\right)}, \tag{4}$$

where N=3 is the number of orders, each with a unique, however unknown, PSF.

We now assume the power spectra of the "true" images I_m are the same except for a smearing due to the average line profile P:

$$\frac{\left|\tilde{I}_m\right|}{\left|\tilde{I}_n\right|} = \frac{\left|\tilde{P}_m\right|}{\left|\tilde{P}_n\right|} \tag{5}$$

This assumption is predicated on the idea that all images are taken of the same solar surface. The average line profiles cause a smearing only in the x direction.

Now we generate a PSF equalization filter C_m for each order from only observed quantities:

$$\tilde{I}''_m = \tilde{C}_m \tilde{I}'_m, \qquad \tilde{C}_m = \frac{\tilde{P}_m}{\left|\tilde{I}'_m\right|}\left[\prod_n \frac{\left|\tilde{I}'_n\right|}{\tilde{P}_n}\right]^{\left(\frac{1}{N}\right)} \tag{6}$$

Under the assumption that the power spectra vary only due to the known mean line profiles (5), the result of the filter (6) is the same as the results of equations 2 and 3, as can be verified by direct substitution.

4. NUMERICAL VERIFICATION

To numerically verify the procedure, we apply the three different PSFs shown in figure 5 to three copies of an $m = -1$ exposure from the MOSES 2006 flight (Figure 6). To complete our simulated observations, we scale the images to a specified mean photon count rate, and add independent Poisson noise to each of these three images after the convolution.

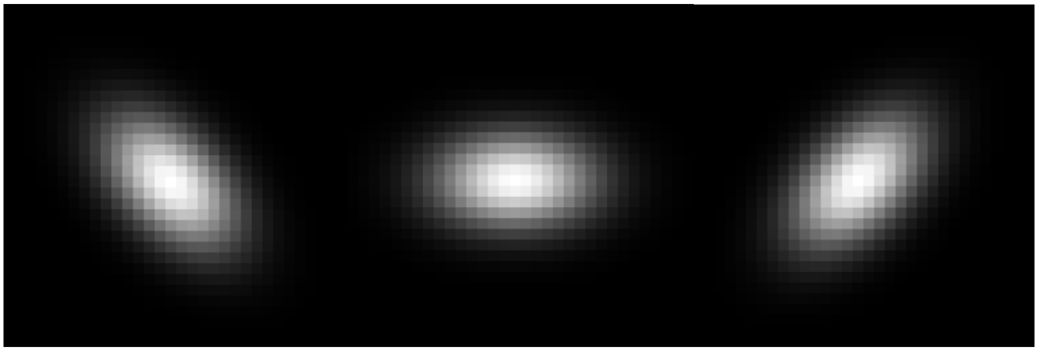

Figure 5: The PSFs used for convolution

We then pass these simulated data to our PSF equalization code, which has no *a priori* knowledge of the PSFs. For comparison, we employ a "cheated" technique in which we explicitly generate the intermediate kernel from the known PSFs, and convolve this with the original image from figure 6. The use of symmetric PSFs and three copies of the same image guarantees the assumptions of our technique are satisfied exactly. What we are testing is the effect of noise on the algorithm.

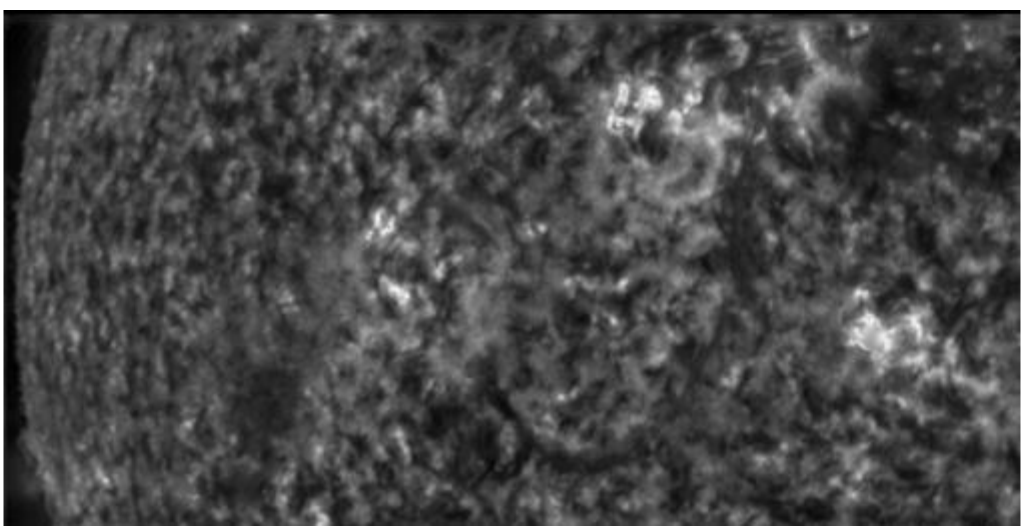

Figure 6: A MOSES flight exposure from the 2006 launch, scaled as the square root for contrast.

We next generate a reduced chi-squared statistic for each order as a measure of fidelity, comparing the results of the PSF equalization routine to the "cheated" I'' A plot is shown below. The technique produces generally good results for photon counts below 100,000. At high photon counts, the chi squared values transition to a power law.

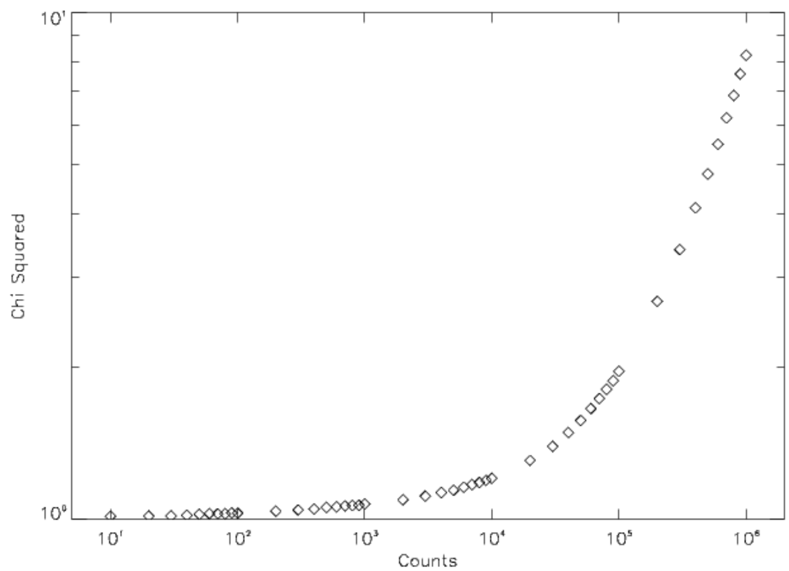

Figure 7: A plot of reduced chi-squared as a function of image mean photon count.

Beyond this point, our signal-to-noise ratio (figure 8) no longer improves with increased photon count. Evidently, we are limited to an SNR of 400. We suspect this results from roundoff error propagating through the filter generation and convolution operations. In practice this does not matter, because the full well of our MOSES detectors (and the conversion of each EUV photon to multiple electrons) limit us to count rates significantly lower than 100,000.

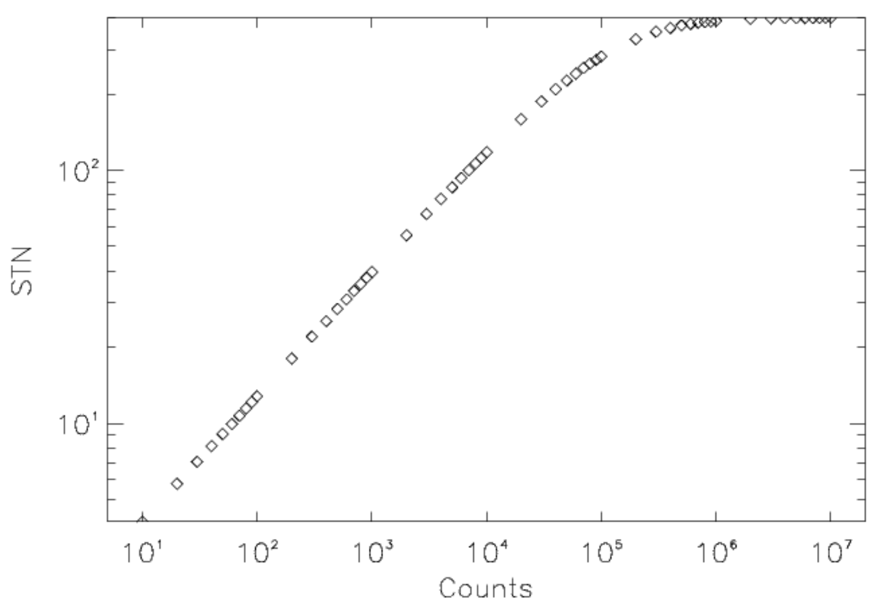

Figure 8: Signal-to-noise as a function of photon count.

5. APPLICATION TO MOSES 1 DATA

PSF equalization filters (equation 6) have been calculated using the best exposures from the 2006 flight. These filters will be applied to the rest of the data set.

Applying the correction filters to the small solar feature in Figure 3 yields the image in the right half of figure 9. The systematic error attributed to PSF variation has been visibly suppressed.

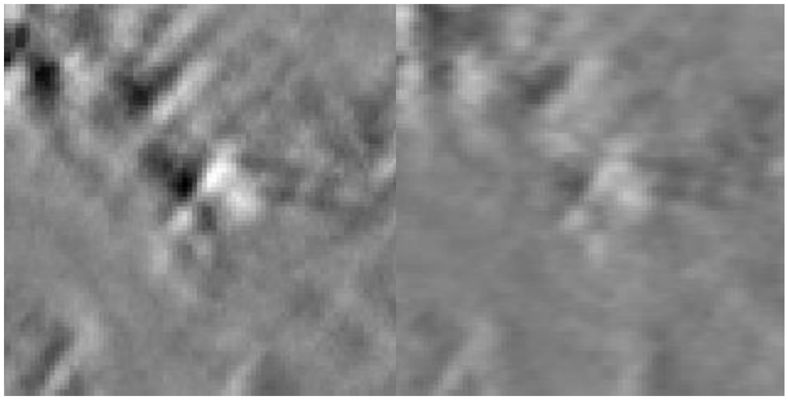

Figure 9: The before and after of the quadrupole from figure 4. The images have the same scaling.

It is important that our correction technique corrects only artifacts, while leaving true solar features intact. To assess this, we examine a blue-shifted jet with difference images from the m=+1,−1 orders, before and after processing. Figure 10 shows the difference between the m=-1 and m=+1 images of a blue shifted jet, before and after PSF equalization. Of course, we cannot know in principle which aspects of these difference images are solar in origin and which are artifacts. However, we notice that after PSF equalization, the difference image is simplified in morphology, but retains the evident blue shift. This is not merely a matter of removing detail by smoothing. Since our equalization filters yield images that conform to a single power spectrum that is the geometric mean of the original power spectra, the filtering operation is a delicate compromise that involves small amounts of both blurring and deblurring.

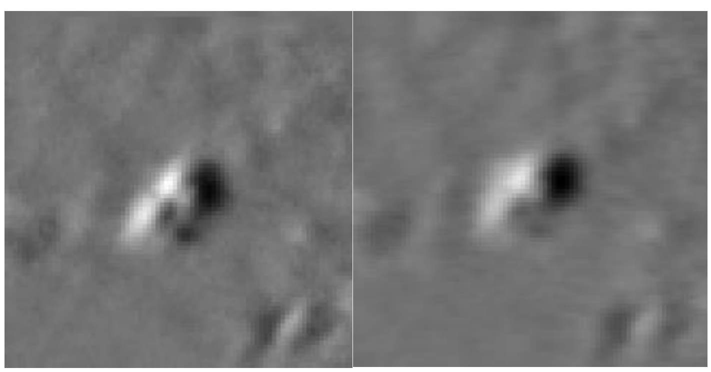

Figure 10: At left is the m=−1 minus m=+1 difference image prior to processing. At right is the same image post-processing. The Doppler signature of this blue-shifted jet remains after correction.

6. CONTINUING WORK AND CONCLUSIONS

We have tested our PSF equalization technique numerically on noised synthetic data, and compared the results to an explicit equalization, without noise, that benefits from knowledge of the PSFs. Chi-squared is of order unity for realistic photon counts, and so we conclude that noise has little effect on the fidelity of our PSF equalization scheme.

Next, we applied the method to actual MOSES data. Artifacts that stand out in inter-order image differences are visibly suppressed, while true solar features of size scales larger than the artifacts appear to retain their essential Doppler and spectral characteristics. Our PSF equalization filter adjusts only the image power spectra and not the phases. This implicitly assumes symmetric PSFs. While estimates of MOSES' PSFs indicate some asymmetry[4], the visual results of PSF equalization of MOSES data look promising.

We still need to verify that spatially varying line profiles (the very thing we wish to observe) are not incompatible with the PSF equalization technique. In future studies, we propose to generate more sophisticated synthetic datasets with spatially varying line profiles and mildly asymmetric PSFs like those inferred for MOSES. Other possible concerns include the presence of contaminant lines in the data. Hyperspectral data appropriate to such numerical verifications are available from a number of sources, including the NASA IRIS mission.[5]

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