Imaging Spectroscopy with *MOSES* Sounding Rocket Data

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TESS Meeting
Indianapolis, IN
April 27, 2015

Abstract

The Multi-Order Solar EUV Spectrograph (MOSES) forms $\lambda 304\,\AA$ EUV images at three spectral orders from an objective multilayer grating. The images encode spatial and spectral data over a 20 x 10 arc minute field of view. Numerous examples of compact transient brightenings are present in data obtained during a 2006 flight. We employ an inversion algorithm which incorporates the instrument point spread functions and noise model and present spectra derived thereby which show strong doppler shifts associated with these brightenings. Spatial structure (0.5" pixels) and temporal evolution (10 s cadence) of these events will be presented.

MOSES Instrument Schematic

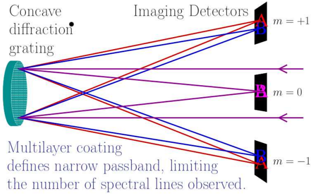


Image at spectral order m is formed by projection through the Object, $I_{\odot}(x, y, \lambda)$:

$$d_m(x, y) = \mathcal{P} I_{\odot} \equiv \int_{\lambda_1}^{\lambda_2} I_{\odot}(x + m\lambda, y, \lambda)\, d\lambda \qquad (1)$$

m $\neq$ 0 images are overlappograms, m=0 image is integrated intensity. Invert images to deconvolve spatial and spectral information.

SMART Inversion of *MOSES* Data

Recover $I_G(x, y, \lambda) \approx I_\odot$ by iterative inversion:

1. $d'_m = \mathcal{P} I_G$ (eq. 1)
2. $I_G \leftarrow I_G(x + m\lambda, y, \lambda) \prod_m \left[\frac{d_m(x+m\lambda,y)}{d'_m(x+m\lambda,y)}\right]^{\gamma_m}$
3. Apply smoothing to I_G.
4. Iterate, adjusting γ_m so $\chi^2_{R,m} \rightarrow 1$.

Problem: $\chi^2_{R,m}$ (and therefore γ_m) are global. Local overfitting is allowed, can and does occur, and drives $\chi^2_{R,m} \rightarrow 1$ prior to acceptable fitting of other regions.

Solution: Make the correction step 2.spatially dependent on the local residual and noise level. Do not allow overfitting to occur.

Multiresolution Methods 1

- MR transforms, including wavelet transforms, decompose images into coefficients $W_j(x, y)$ localized in both position (x, y) and size scale j.
- $W_j(x, y)$ is considered to arise from the noise if $W_j(x, y) < 3\sigma_j$, where σ_j is the standard deviation at scale j of the MR transform of the noise.
- The noise level σ_j is made independent of the signal, and thus of position (x, y), by applying an appropriate variance stabilizing formula, e.g., Anscombe transformation for Poisson noise.

Multiresolution Methods 2

- Let $R_m(x,y) = d_m(x,y) - d'_m(x,y)$, and $W_j^R(x,y)$ its MR transform. The statistically significant residual $\bar{R}_m(x,y)$ is generated by thresholding $W_j^R(x,y) < 3\sigma_j = 0$, then applying inverse transform.

- Noting that $d_m(x,y) = d'_m(x,y) + R_m(x,y)$ the regularized correction step 2. in *MOSES* inversion now becomes

$$I_G \leftarrow I_G(x + m\lambda, y, \lambda) C_m(x + m\lambda, y),$$

where

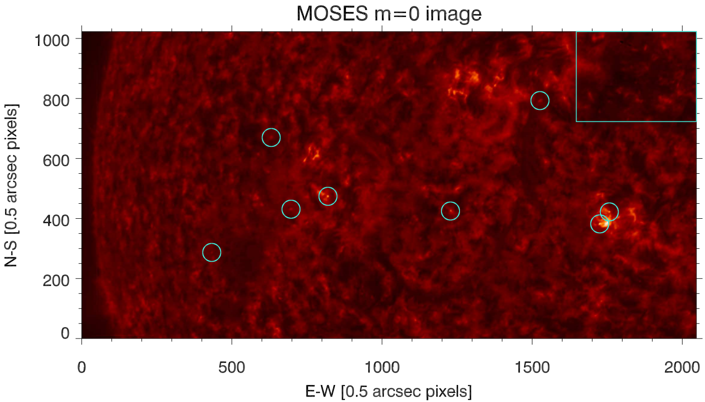
$$C_m(x + m\lambda, y) \equiv \prod_m \left[\frac{(d'_m + \bar{R}_m)(x+m\lambda,y)}{d'_m(x+m\lambda,y)} \right]^{1/3}$$

- Here we have chosen to fix $\gamma_m = 1/3$. Note $C_m \rightarrow 1$ as $R_m(x,y)$ becomes *locally* insignificant compared to the noise, i.e., overfitting is not permitted at any scale.

Multiresolution SMART Algorithm

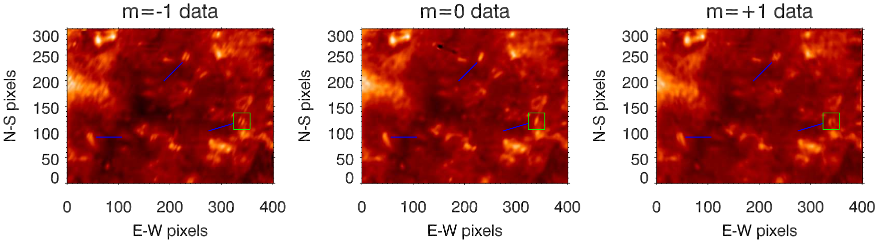
1. $d'_m = \mathcal{P} I_G$ (eq. 1)
2. Convolve with PSF(x, y): $d'_m \leftarrow d'_m * PSF(x, y)$
3. Get significant residual $\bar{R}_m(x, y)$
4. Calculate $C_m(x, y)$
5. Convolve with PSF$(-x, -y)$:
   $C_m(x, y) \leftarrow C_m(x, y) * PSF(-x, -y)$
6. Correct: $I_G \leftarrow I_G(x + m\lambda, y, \lambda) C_m(x + m\lambda, y)$
7. Iterate until $\bar{R}_m(x, y) = 0$

Context Image



$d_0(x, y)$. The integral (1) primarily contains the HeII 303.8Å and SiXI 303.3Å lines. Many explosive events (some circled) are observed. Let's zoom in on the upper right rectangular inset.

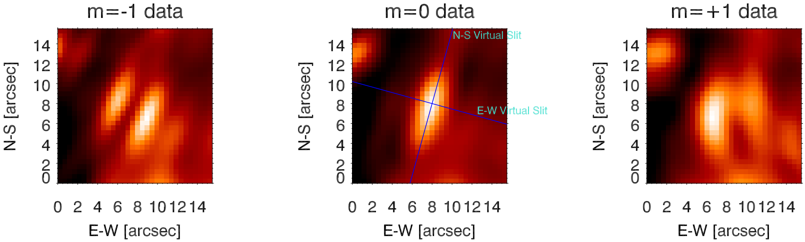
Context Image Inset



Inset from context image. The three panels show the inset as viewed in *MOSES* three spectral orders.

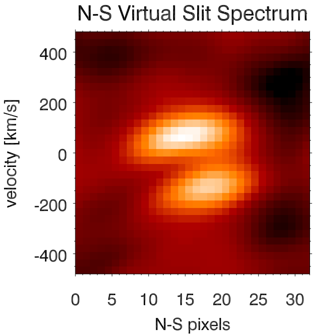
Numerous explosive events are seen in this small field of view snapshot. We take a closer look at the event boxed in green.

Explosive Event 1



A close up look at *MOSES* three perspectives on the spatial spectral cube $I_{\odot}$ of a HeII 303.8Å explosive event. Each order m represents a projection of $I_{\odot}$ from a different angle. $I_{\odot}(x, y, \lambda)$ is approximately recovered by inversion of these three projections. For display purposes we'll show spectra along the "virtual slits" shown above.

N-S Virtual Slit

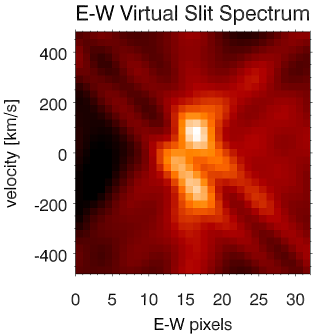


Recovered cube $I_G(x, y, \lambda)$ along the N-S virtual slit from the previous figure is shown at left.

Spatial pixels are 0.5", velocity pixels are 30 km/s.

This event shows 150 km/s upflows and 90 km/s downflows along the same line of sight. Greater emission is seen in the downflows.

E-W Virtual Slit

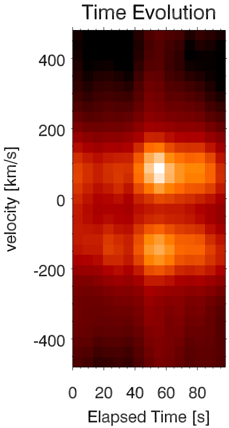


Recovered cube $I_G(x, y, \lambda)$ along the E-W virtual slit from the previous figure is shown at left.

Artifacts from reconstruction with only three projections are seen as a cross hatched, "plaid" pattern.

We are investigating multiscale methods and radioastronomical CLEAN algorithms for "plaid" reduction.

Time Evolution of Explosive Event



Recovered cube $I_G(x, y, \lambda)$, at the point where the virtual slits cross, as a function of time.

Changes in brightness are observed, but the flow velocities are roughly constant in over the 90 second observation time.

Summary and Conclusions

- We've applied *MOSES* SMART inversion algorithm to recovery of $I_G(x, y, \lambda)$, i.e., cotemporal spectra over a wide field of view.
- Numerous explosive events are observed over our field of view. With MOSES, it is possible to obtain spectra for all of these events in a single snapshot.
- We've shown a single example above in greater detail, where flow speeds well in excess of the sound speed are observed.
- Artifacts are to be expected in few projection tomography. We've gained much understanding of the nature of these artifacts, and future effort will be put to understand and mitigate these systematic errors.

The *MOSES* sounding rocket is supported by NASA grant NNX14AK71G.

References

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2. J.L. Starck, F. Murtagh, and A. Bijaoui, "Image Processing and Data Analysis: The Multiscale Approach", Cambridge University Press, Cambridge (GB), 1998.
3. Fox, J. L. (2011) PhD Thesis, Montana State University.