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The MOTH II Doppler-Magnetographs and Data Calibration Pipeline

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Abstract. The calibration pipeline of the level zero images obtained from the Magneto-Optical filters at Two Heights (MOTH II) instrument is presented. MOTH II consists of two 20 cm aperture instruments, each using a Magneto-Optical Filter (MOF): one at 5896 Å (Na D2-line), the other one at 7700 Å (K I-line). MOTH II instruments thus provide full disk line-of-sight Doppler velocity and magnetic field measurements at two heights in the solar atmosphere. The developed MOTH II pipeline employs a set of standard calibration corrections, a correction for signal leakage, due to the non-ideal behavior of the polarizers, and the geometrical registration between the eight images acquired by four CMOS cameras, relative to two components of the signal in two circular polarization states, in each of the two channels. MOTH II data are used to investigate atmospheric dynamics (e.g., internal gravity waves and magneto-acoustic portals) and Space Weather phenomena. Particularly, flare forecasting algorithms, based on the detection of magnetic active regions (ARs) and associated flare probability estimation, are currently under development. The possible matching of MOTH II data with SDO/HMI and SDO/AIA images into a flux rope model, developed in collaboration between Harvard-Smithsonian CfA and MIT Laboratory for Nuclear Science, is being tested.

Keywords. polarimetric, spectrographs, solar atmosphere, helioseismology, magnetic fields

1. Introduction

The MOTH II (Magneto Optical filters at Two Heights) telescope consists of a dual channel equipment, mounting MOFs (magneto-optical filters) at either 5896 Å (Na D2-line) or 7700 Å (K I-line), respectively. It thus provides full disk line-of-sight Doppler velocity and magnetic field measurements at two heights in the solar atmosphere, 300-400 km and 600-700 km respectively. This allows to characterize the solar atmospheric dynamics, as the dynamics and topology of coronal magnetic loops is controlled by photospheric emergent magnetic field and plasma flow. It also allows to characterize the evolution of solar magnetic activity, in order to identify signature parameters of Space Weather events (e.g. flares).

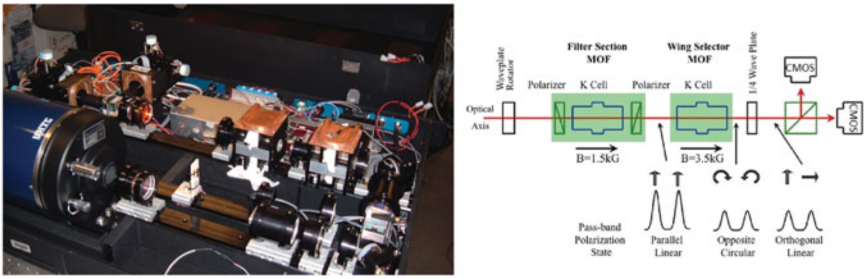

Figure 1. Picture of one channel of the MOTH II instrument (left) and optical scheme of the main section of the instrument (right).

2. The Instrument

The current version of the MOTH II instrument (Figure 1, left) mounts filters in K and Na lines, but two more channels in Ca and He (Murphy *et al.* 2005) are under testing, in order to probe the solar atmosphere at 4 altitudes in total, and to combine with HMI data, which would allow to obtain a 3D reconstruction of the magnetic and velocity fields.

The scheme in the right panel of Figure 1 shows the main elements of the current instrumental setup in one single channel (K or Na), based on Finsterle *et al.* (2004). The scheme shows the two MOF cells, both containing vaporized gas (of K or Na, according to the channel) in a uniform longitudinal magnetic field. The first one is the pre-filter, within two crossed linear polarizers, while the second one is the wing selector. This setup filters the incoming light at the typical wavelength of absorption of the vaporized element contained in the cell; the use of linear polarizers and of half wave retarder along the optical path allow to encode wavelength information into two circular polarization states ($\sigma+$ and $\sigma-$). The light beam is then split into a blue and red component, in order to get the blue and the red wing of the line, acquired by two different CMOS cameras. So in the end a total of 4 frames (R$\sigma+$, R$\sigma-$, B$\sigma+$, B$\sigma-$) are obtained in each channel (Na and K), which means 8 frames during each acquisition.

For each channel we can derive the magnetic field and velocity field maps along the line of sight by inserting the values of the 4 components into equations 2.1 and 2.2, according to Cacciani *et al.* (1990).

$$B_{LOS} = \frac{R^+ - B^+}{R^+ + B^+} - \frac{R^- - B^-}{R^- + B^-} \tag{2.1}$$

$$V_{LOS} = \frac{R^+ - B^+}{R^+ + B^+} + \frac{R^- - B^-}{R^- + B^-} \tag{2.2}$$

The MOTH II data have a pixel scale of 1.46 arcsec/pixel and a cadence of 5 seconds.

The MOTH II instrument is normally located at the Mees Observatory in Hawaii, where in particular the test phase was carried out and the pipeline developed. In November 2016 it was deployed to the South Pole for long observation campaigns, the first campaign was conducted during the Antarctic summer 2016-2017 (November 2016-January 2017), and the second one has started in November 2017.

3. Calibration Pipeline

The MOTH II instrument requires a solid pipeline for the automatic calibration and data reduction. A summary of the pipeline is shown in the flowchart in Figure 2.

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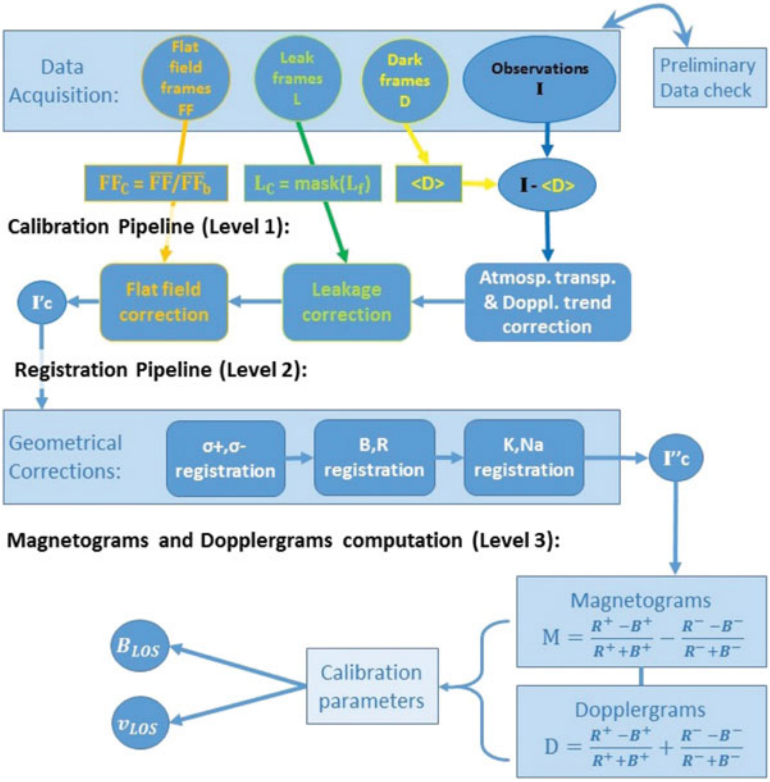

Figure 2. Scheme of the MOTH II calibration pipeline.

Zero Level: acquisition of scientific data and calibration images (flat field, dark and leak), and preliminary data check, performed through a Graphic User Interface to control temperatures, image tracking, dark, flat field, image statistics, etc.
First Level: standard photometric corrections, such as subtraction of the dark current, correction for the flat field and for the variation due to the atmospheric transparency and to the Doppler trend. The main issue of this step of the pipeline is the reconstruction and correction for the unpolarized signal leakage, due to the non-ideal polarizers which constitute MOFs.
Second Level: as the instrument provides 4 images per channel, it is extremely important to geometrically register them pixel-by-pixel in order to compute precise magnetograms and dopplergrams. In particular: there is a translation that has to be removed between images acquired by the same camera ($\sigma+$ and $\sigma-$ components); a translation and a rotation between images acquired by the 2 cameras (blue and red); translation, rotation and scaling between images from the 2 channels (K and Na).
Third Level: computation of the full-disk magnetograms and dopplergrams relative to the two channels of the instrument (K and Na), applying the formulas in equations 2.1 and 2.2 to the calibrated images. A sample of a resulting magnetogram and dopplergram is shown in Figure 3.
MOTH II data, together with data from other instruments (i.e. IBIS, ALTEA, PAMELA) will be made available in the near future in the Space Weather at TOr Vergata (SWERTO) database located on the SWERTO service website (www.spaceweather.roma2.infn.it).

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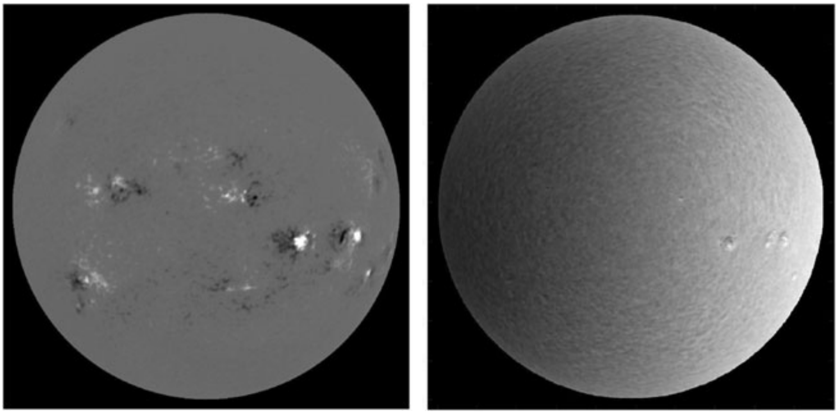

Figure 3. Sample of a final Magnetogram (left) and Dopplergram (right) in K channel.

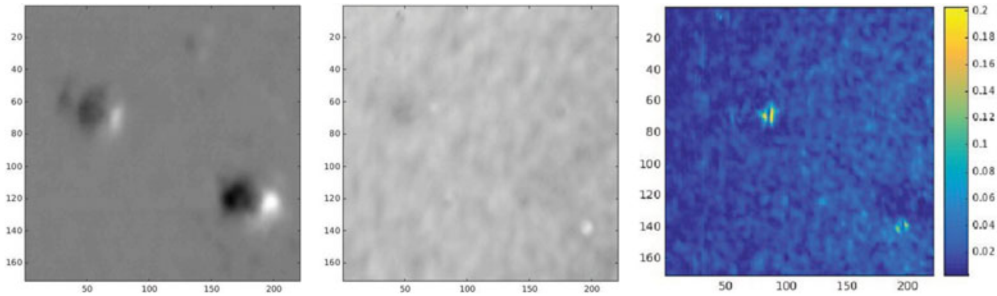

Figure 4. Magnetogram (left), Dopplergram (center) and power spectra displayed in color scale at 7 mHz (right) of the 175x225 pixels area, containing both the flaring AR 12628 (top-left) and the flare-quiet AR 12627 (bottom-right), on 21st January 2017.

4. Preliminary Data Analysis

A preliminary data analysis has been carried out on the recent dataset of magnetograms and dopplergrams acquired during the South Pole campaign. In particular several C-class flares were registered on the 21st January 2017, mostly from AR 12628. It is interesting to analyze the magnetic and doppler signal measured in the area containing both the flaring AR 12628 and the flare-quiet AR 12627. A power spectra analysis of the doppler signal in that area, in every pixel, has been carried out in a 6 hours interval, computing the power spectra of the signal with a moving window over intervals of 42 minutes with an overlap of 10 minutes. Flaring AR 12628 shows high power signal compared to the flare-quiet AR 12627. The max power of the spectra occurs at a frequency of 7 mHz (Figure 4). This enhancement may be attributed to power in an acoustic halo observed in the penumbral regions. Further studies will be carried out in the near future to investigate this result.

Other applications of MOTH II data are currently under development, such as flare forecasting algorithms, based on the detection of magnetic ARs and associated flare probability estimation, and possible matching of MOTH II data with SDO/HMI and SDO/AIA images into models for magnetic loops in ARs.

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