MOTH II calibration pipeline and data merging with SDO/HMI and SDO/AIA

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Abstract: The development of the numerical pipeline for the automatic calibration of the zero level images obtained from the solar telescope Magneto Optical filters at Two Heights (MOTH) is the aim of my research grant at Università degli Studi di Roma Tor Vergata. The MOTH telescope, located at the Mees Observatory (Maui, USA) and operated by IfA - University of Hawaii and Georgia State University, consists in a dual channel equipment, each mounting magneto-optical filters (MOF) at 589 nm (Na D2-line) and 770 nm (K I-line), respectively. The aim of the MOTH solar full disk observations is the study of the magnetic evolution and dynamics of the solar low atmosphere by mean of the line-of-sight measure of velocity and magnetic field, at two different levels of the solar atmosphere. The MOTH data can be merged with magnetic and velocity field data from *Helioseismic and Magnetic Imager* (HMI) on *Solar Dynamic Observatory* (SDO), for a detailed study of the solar magnetic field, by a three-heights characterization of the solar magnetic evolution, in order to identify signature parameters of solar eruptive events, useful for Space Weather studies, e.g. the flare forecasting.
Within the Solarnet Programme "Mobility for Young Researchers" I had the opportunity to spend 7 weeks at Harvard-Smithsonian CfA, with Solar and Stellar X-ray group (SSXG) team members: I gained a deeper awareness of solar magnetograms analysis techniques, I practiced methods for solar active region analysis and for the identification of Solar eruptive phenomena such as CMEs and flares, also using data from *Atmospheric Imaging Assembly* (AIA) on SDO.
I worked on variations in the polarity inversion line (PIL) in active regions. It has also been evaluated the possibility of matching magnetograms from MOTH and HMI and images from AIA for a preliminary statistics of a flare forecasting model. Moreover, we examined the possibility of incorporating MOTH data, also available in a future SWERTO database in Tor Vergata, into a flux rope model developed in collaboration between Harvard-Smithsonian CfA and MIT Laboratory for Nuclear Science.

MOTH II - Magneto-Optical filters at Two-Heights

Fig. 1: Photo of one optical bench of MOTH.

Instrument specifications:
- Full disk images
- CMOS 3072x3072 pixels
- Aperture: 20 cm
- Pixel scale: 0.75 arcsec/pixel
- Sensitivity: 7 m/s for v; 5 Gauss for B

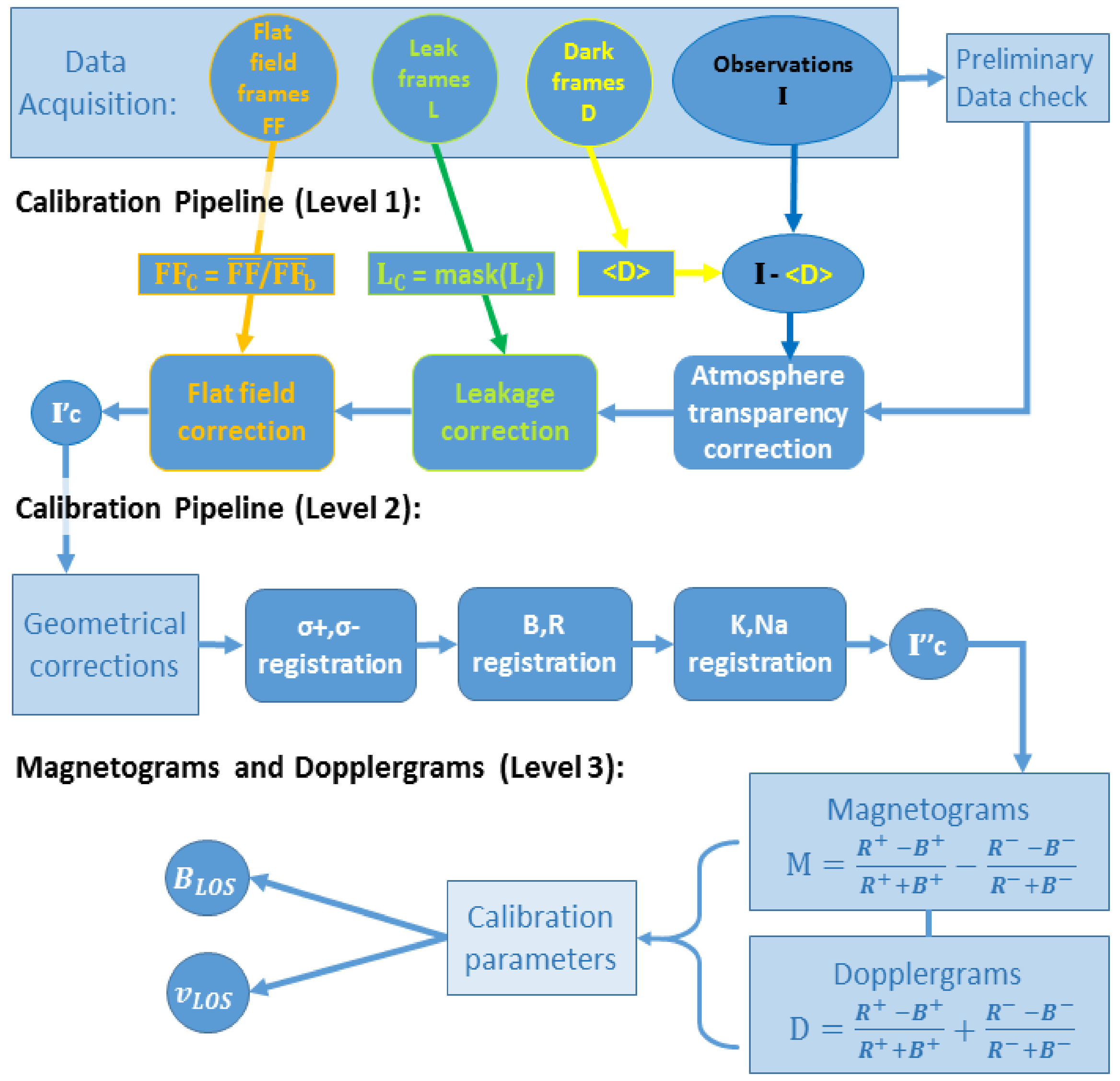
line	λ (nm)	Formation height (km)
K I	770	300-400
Na D2	589	600-700
Ca I	*422*	*1000*
He I	*1083*	*1900*
Fe I (**HMI**)	617	100

Table 1: Spectral absorption lines observed by MOTH and HMI/SDO, and corresponding heights of formation.

Observations carried on by the solar telescope MOTH have the main purpose of studying the dynamics and magnetic evolution of the solar photosphere, this allows to characterize in particular solar active regions, by the line-of-sight measure of velocity and magnetic field, at two different levels of the solar atmosphere (between 300 and 700 km).

The MOTH instrument consists in a **dual channel** equipment, each mounting **magneto-optical filters** (MOF) at 589 nm (Na D2-line) and 770 nm (K I-line), respectively. The main elements are a series of polarization analyzers, a MOF, constituted by a cell containing vapors of K (or Na) immersed in a longitudinal magnetic field within two crossed linear polarizers, and a wing selector. This setup separates the light beam in a blue wing and red wing of the K (or Na) line and encodes wavelength information into two circular polarization states (σ+ and σ-). The final datacube includes four components R(σ+), R(σ-), B(σ+), B(σ-), for which it has been developed a calibration and data reduction pipeline (summarized in the flow chart on the right), with the final purpose of computing **magnetograms and dopplergrams at two heights of the solar atmosphere**. This allows to evaluate the magnetic gradient along the Line-Of-Sight:

$$\nabla B_{LOS} \propto \frac{B_{Na}^{LOS}}{B_{K}^{LOS}}$$



The instrument is usually operated at the Mees Observatory (Maui, USA), but currently (December 2016-February 2017) it is located in **Antarctica**, where two UTOV team members are carrying on an observation campaign.
MOTH data will soon be available in a **database managed by Tor Vergata: SWERTO** (Space-Weather at the University of Rome Tor Vergata). The instrument is suitable for a ground based network of MOTH telescopes around the world. Upgrading the instrument for on-satellite flights is also under evaluation.

Conclusions: During this experience with the Solarnet "Mobility for Young Researchers" Programme, the basis for a collaboration between Università di Roma Tor Vergata and Harvard-Smithsonian Center for Astrophysics have been settled. It involves the matching of magnetograms from MOTH and HMI for a tri-dimensional study of solar magnetic fields in active regions. This will make possible a statistical analysis for a preliminary flare-forecasting model. Also AIA observations can be used to correlate the information about the solar emissions with magnetic field observations.
However, a proper analysis of matched MOTH and HMI magnetograms requires a large amount of simultaneous data analysis, which will become possible in the near future, at the end of the ongoing MOTH measurement campaign in South Pole.

Data merging: MOTH, HMI and AIA

The use of multi-height magnetograms from MOTH, in combination with AIA/SDO and HMI/SDO, will provide a great opportunity for the detailed study of the magnetic field variations with height, and magnetic active regions characterization.
During my visit at Harvard-Smithsonian CfA, I had the opportunity to collaborate with the *Solar and Stellar X-ray group* (SSXG), which is principally involved with instrumentation on many spacecraft including AIA and HMI.

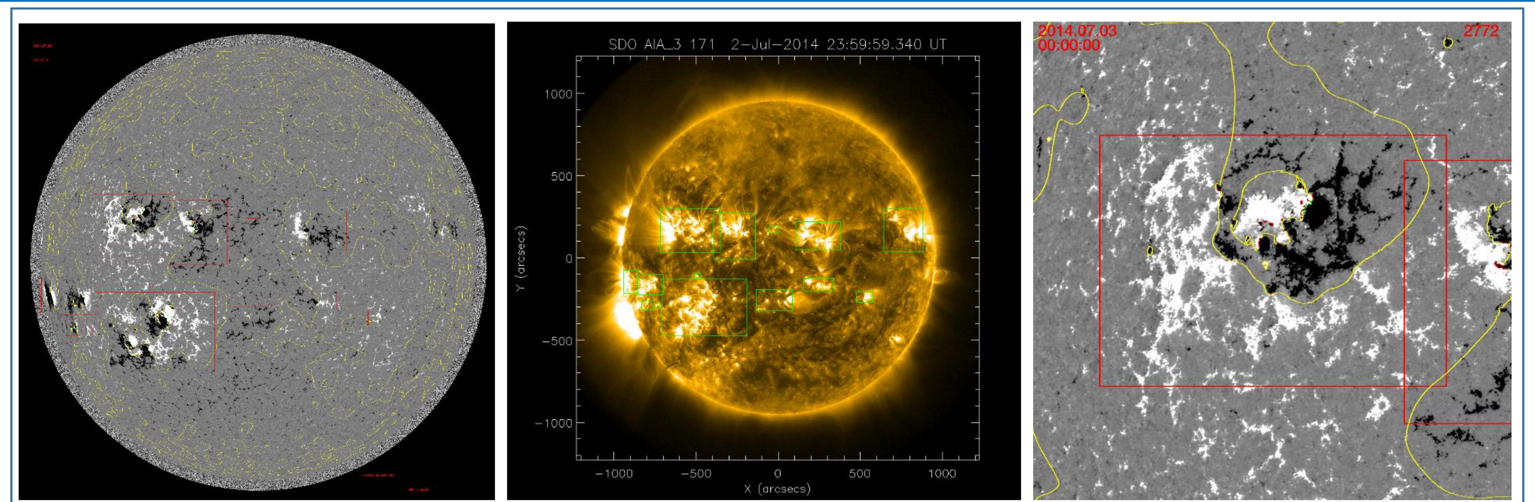


Fig. 2 On the left panel: full disk HMI magnetogram with the ARs identified in the red boxes and the PIL in yellow, computed with the PIL module. In the central panel: full disk AIA observation in the wavelength of 171 Å, with the ARs identified in the green boxes. On the right: Zoom of the AR 2772 analyzed with the PIL module (Polarity Inversion Line - yellow; computed transversal magnetic field – green; vector magnetic field – red).

In particular I learnt computational methods for the analysis of solar magnetograms, and I established a collaboration with the **SDO Feature Finding Team** (FFT), which is an international consortium of solar and computer scientists producing an **automated feature recognition system for SDO**.
During this collaboration, the variations in the **polarity inversion line (PIL)** in active regions have been studied taking advantage of the FFT polarity inversion line detection module[(a)]. An example of a PIL computation is shown in Fig. 2, where the module is applied to an active region (NOAA number 2772) observed with HMI on 3rd July 2014.
In PIL code, the AR is identified in HMI magnetograms directly from the NOAA classification. The same code can be applied to MOTH magnetograms, with the asset of incorporating the **AR detection** within the computation. A preliminary attempt of AR detection in a MOTH magnetogram is shown in Fig. 3.

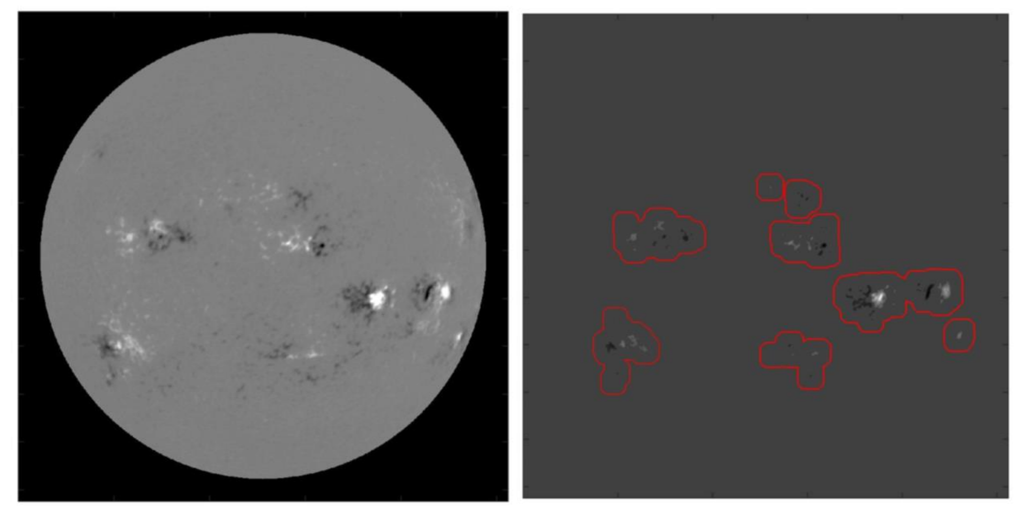


Fig. 3 Left: Sample of a MOTH magnetogram; Right: computed ARs contours.

Thanks to this partnership, the possibility to incorporate MOTH data into the **Virtual Solar Observatory (VSO) database** is under evaluation.
Another collaboration has been established at CfA, with the purpose of using MOTH data in the modeling of the active region magnetic loops[(b)]. In particular this research line is focused on the MHD modeling of steady states in solar coronal loops, where the input parameters of the model are provided from the magnetic observations. In this study the coronal loops are modeled using **a non-linear force free field (NLFFF) modeling** that uses the AR magnetic field, reported by MOTH and HMI magnetograms. The magnetogram provides the boundary conditions for the magnetic field extrapolation in the corona. Using the NLFFF modeling, magnetic field lines are fitted to the observed coronal loops. Fig. 4 shows the fitted magnetic field lines together with the AIA image, and it is possible to see that the model provides a good match to the AIA data.

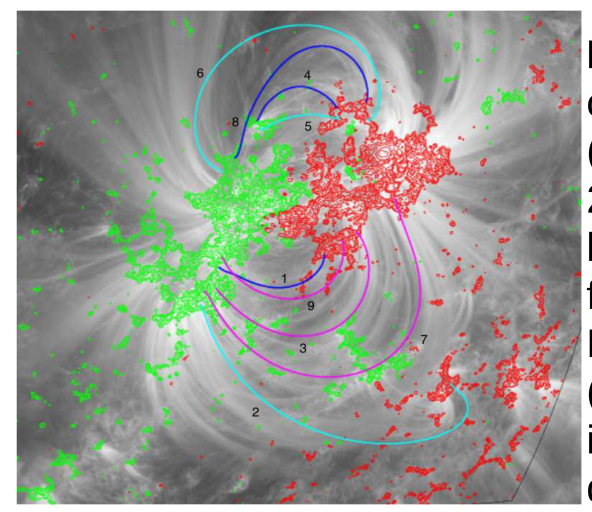


Fig. 4 SDO observation of an active region (11564) on 7th September 2012. The gray background image is from AIA 171 Å channel. Red (positive) and green (negative) contours indicate magnetic flux distribution based on the HMI magnetogram. The magnetic field lines were traced through the NLFFF model.

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