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Multi-line Spectropolarimetry at THÉMIS

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Abstract. We describe the multi-line spectropolarimetry mode (MTR) available at the French-Italian solar telescope THEMIS. The major specifications and performances of the instrument are given and, we show or point-out at some of the results obtained during the 2000 observing campaign. Finally, we discuss the major improvements of the instrumentation which are expected to come-up in the near future.

1. Introduction

THEMIS is located at the *Observatorio del Teide, Izaña* in Tenerife (Spain). Light is collected by a 90 cm Ritchey–Chrétien telescope, driven by an altazimuth mount. The polarimeter is located at the telescope's prime focus, before any oblique reflection in the optical path. Hence THEMIS is a "polarization free" telescope. Although it was initially designed for multi-line spectropolarimetry at high spatial resolution, THEMIS is also particularly well-suited for high polarimetric sensitivity measurements.

In the following sections, we shall describe the optical path and the major specifications of the instrument from the telescope down to the detectors. Then, some samples of various results obtained during the 2000 observing campaign will be shown. Finally, we shall outline the perspectives of development expected at THEMIS in the coming years.

2. The telescope and the polarimeter

The light collector is a 90 cm Ritchey–Chrétien telescope put on an altazimuth mount; it is therefore pointing *directly* at the Sun. Pointing and tracking of the Sun are fully performed "by computer", i.e. following calculations based on the JPL solar ephemerides data (Standish et al. 1997). The telescope is enclosed in a tube which is actually filled with Helium. The tube is closed, at one end by a 6.7 cm thick prismatic entrance window (BK7; 1.1 m diameter) and, at the other end by a fused silica exit window (6 mm thick, 8 cm diameter), allowing for a $4' \times 4'$ field of view (FOV) before the polarimeter (Figure 1.).

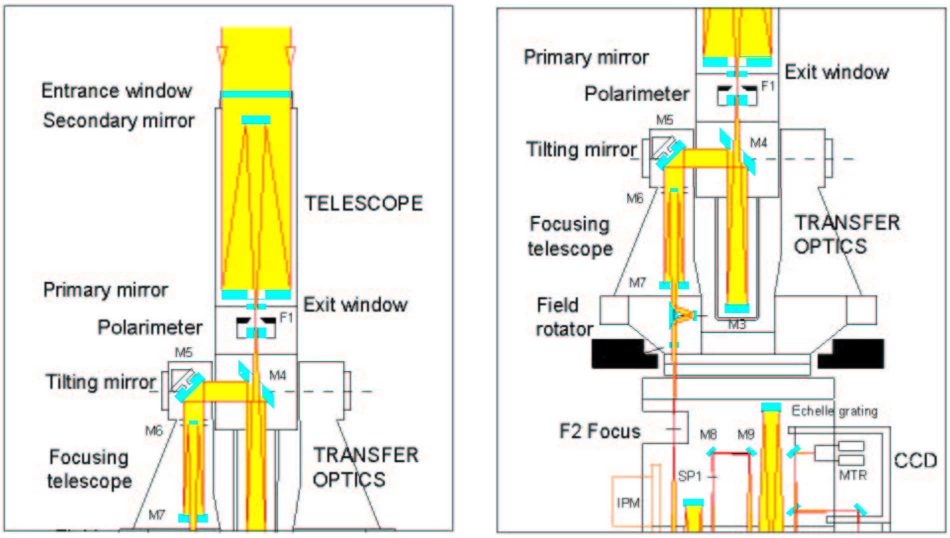

Figure 1. Optical schemes of (left) the telescope and polarimeter, and (right) the F1–F2 transfer optics.

A testing method based on the wave-front reconstruction from defocused images (Roddier & Roddier 1993) has been applied to retrieve the permanent aberrations of the telescope and the transfer optics (§3.). The analysis showed that the reconstructed wave-front is dominated by astigmatisms mainly coming from the entrance window and from mechanical constraints on the primary mirror of the telescope. Measured spatial resolutions are 0.3 to $0.4''$ (@ 0.5 μm) depending on the tube elevation.

The polarimeter consists in two identical achromatic cristalline quarter-wave plates (or QWPs) followed by a calcite beam-splitter (or BS). The QWPs are achromatic over a 400–700 nm spectral range; hence the phase of each of the QWP is $90 \pm 4°$ in that range (see Figure 2.). Each QWP can be independently oriented at 3 different discrete angular positions over a 45° range, 22.5° stepwise. The BS is made of two crossed calcite plates ensuring the same optical path length and, the separation in space of the two orthogonal states of polarization $(I \pm \sigma)$ where $\sigma = Q, U$ or V successively. The time necessary to switch from a set of orientations to another is about 300 ms, in accordance with the numerization time of the detectors.

3. Transfer optics and the spectrographs

The optical path from primary to secondary focus is displayed in Figure 1. (right). After the polarization analyzer, the two beams go through the oblique holed-mirror M4, and fall on mirror M3 which redirects the light onto the reflecting part of M4. Then the optical path is folded at 90°, along the elevation axis and, it carries-on up to mirror M5 located in one of the pilars of the telescope's mount. There, it is again folded at 90° in order to be sent, along the vertical direction, down to the spectrographs entrance slit(s).

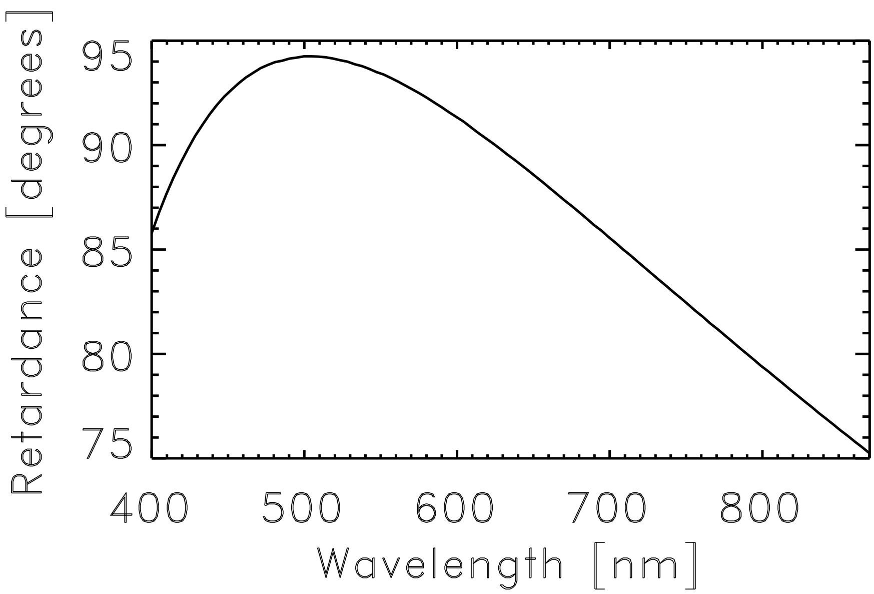

Figure 2. Retardance vs. wavelength of the quarter wave plates used in the polarimeter. Those achromatic QWPs are made of 2 crossed elementary thin cristalline plates of MgF_2 and quartz, with anti-reflection coating (manufactured by *Optique J. Fichou*, France).

From the standpoint of high angular resolution, the transfer optics includes (a) the concave mirror M3 which may be used for a future multi-conjugate adaptive optics system and (b) M5 placed in a pupil image focused by M3, where a tip-tilt mirror could be implemented in order to stabilize image motions due to the atmospheric turbulence.

After M5 the beams go further through re-imaging optics (from $f/17$ to $f/63$) using a small Maksutov–Cassegrain telescope, a derotator (to compensate for the FOV rotation due to the altazimuth mount) and a set of doublet and lenses for the correction of the longitudinal chromatism.

Then, after they have gone through re-imaging and de-rotating optics, the two polarized beams enter an optical device which role is to correct for the *transverse* chromatism due to the BS. This is definitely needed since THEMIS was primarily built for the *multi-line* spectropolarimetry of small-scale magnetic features. Figure 3. displays some details of the optical block at secondary focus (F2). The left part of the figure displays only one “arm” of the optical device, for symmetry reason. It corresponds to the correction optics for one of the polarized beams. First, the transverse chromatism is corrected by one small spectrograph using a small FK5 prism (2°). Then, each beam goes through another set of prisms which role is to re-align each arm’s image as if it was to fall onto a single narrow slit at the spectrographs entrance; this is schematized on the right part of Figure 3. It is important to realize that one narrow slit *per beam* is used at secondary focus.

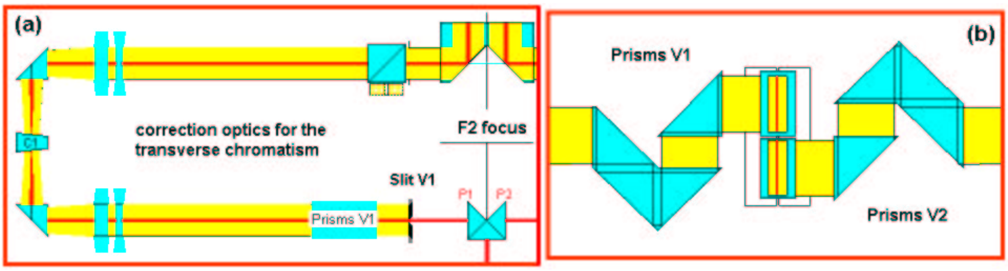

Figure 3. The F2 optics block is meant for (a) the correction of the transverse chromatism due to the beam-splitter and (b) ensuring co-spatiality of the images at the spectrographs entrance. Only one "arm" of the optical block have been displayed in (a), for symmetry reason.

The F2 optical set can be modified such as to transform the default MTR mode as a "2 state of polarization, 1 detector" mode. This is made quite easily by translating one of the re-alignement prisms, V_1 (or V_2, see Figure 3.), respectively to the other set of prisms. The later version of the MTR mode has been widely used during the 2000 observing campaign. Although at the price of a $^1/_2$ reduction of the largest available FOV along the slit ($\sim 120''$ with the default mode) it allowed, indeed, for high polarimetric sensitivity measurements i.e. typically at the 10^{-4} level (e.g. Trujillo Bueno et al. 2001).

The spectrographs consist in a predisperser with 3 interchangeable gratings (1200, 150 or 79 grooves mm^{-1}), followed by an echelle grating (79 grooves mm^{-1}). All the observing programmes for the MTR mode have been using, so far, the 150 grooves mm^{-1} predisperser, with a typical resolving power about 3.5×10^5. Dispersion values may vary with the selected spectral lines set – for which selection a mask has to be put at the predisperser's focus (SP1; cf. Figure 1.). However, we provide in Table 1. rather typical figures computed for a single spectral domain configuration.

Up to know, the MTR mode allows for the *simultaneous* observation of 6 spectral domains (depending on the configuration i.e. the number of detectors needed for collecting the 2 orthogonal states of polarization coming from the BS). Roughly speaking, one can pick "any" spectral domain – each of them 5 to 6 Å wide – through a ~ 260 nm range in the visible. One has also to bear in mind that the overall throughput of THEMIS is optimum between 450 nm (e.g. the 455.4 nm line of Ba II has been succesfully observed) and the IR triplet of Ca II, among the spectral lines of most interest in the near IR.

4. Detectors, acquisition system and data policy

The MTR detectors use the Thomson TH–7863 chip; it has 384×288 pixels, 12 bits coded. Each pixel is 23×23 μm^2 and the full-well is about 10^6 charges. The numerization time for each CCD camera is 250 ms.

Each CCD is linked by optical fiber to one buffer. Up to 20 *parallel* links, read at a 3.1 Mb s^{-1} rate, are available. The digital conversion is made sequentially, at a maximum rate of 1 frame per second per CCD. The aquisition

Table 1. Dispersion and spectral pixel values (for a $\gamma = {}^1/_4$ magnification factor) vs. wavelength for the MTR mode using the 150 grooves mm^{-1} predisperser + echelle grating combination.

λ [Å]	Å/mm	spectral pixel [mÅ]
4554	5.05	13.2
5890	5.66	14.7
6301	6.25	16.3
8542	9.80	25.5

is performed by a VME device based on a 68030 processor architecture and controlled by a real-time C program under VxWorks (made by *Observatoire de Paris*, DASOP). The disk server as a capacity of 78 Gb (RAID disks) and data writing on disk is performed at 7 Mb s^{-1}.

All THEMIS/MTR data are archived at the French database BASS 2000 in *Observatoire Midi-Pyrénées*, Tarbes (http://bass2000.bagn.obs-mip.fr). The data policy is such that data become public after the one year of exclusivity allocated to the observers.

5. Performances of the MTR

The MTR spectropolarimetric mode is quite versatile. It provides so far to users 2 different options which can be equally chosen depending on the scientific programmes.

A strong demand concerns the study of the weak linear resonance polarization of spectral lines as observed at small μ's, i.e. very close to the solar limb (Stenflo & Keller 1996, 1997). Observations of this kind have yet been succesfully performed with THEMIS. They have been reported by Paletou & Molodij (2001), Arnaud et al. (2001) and Trujillo Bueno et al. (2001). A typical example would be the observation of the Sr I @ 460.7 nm made on May 29, 2000 (Trujillo Bueno et al. 2001). We used an integration time of 7 s per frame (giving, at the limb, a number of counts $\lesssim {}^1/_2$ the saturation limit) and, we recorded a serie of 200 images equivalent to 50 frames per analysis position together with the following temporal sequence: (Q, U, $-Q$, V). The collection of those frames at the limb took 25 mn and the complete sequence, including dark-current and flat-field images, was recorded in roughly 1 hour. Note that a 600 ms exposure time would be sufficient for repeating the same observation in, say the b_1 line of Mg I. Further in the red part of the spectrum, 4 s would be needed for a similar observation in the IR triplet of Ca II.

Other scientific programmes concern e.g. the full-Stokes magnetometry of active regions, the detection and study of magnetic flux emergence, measurements of the intra-network magnetic field, or the study of moving magnetic features at high spatial resolution. In Figure 4., we display maps made from an observation of November 25, 2000 (PI: N. Meunier, OMP Tarbes, France). On the left, we show a spectro-image of active region NOAA 9236 reconstructed

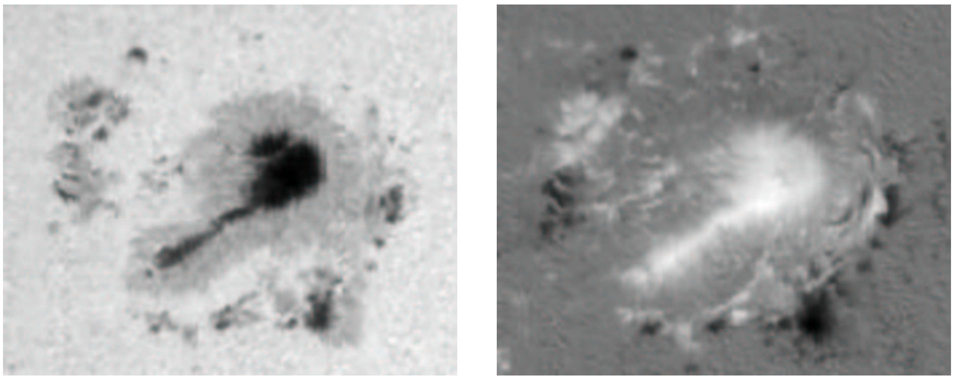

Figure 4. Observations of November 25, 2000: (left) a spectro-image taken from the neighbouring continuum of Ni I @ 676.8 nm and, (right) a quicklook map of the longitudinal magnetic field of active region NOAA 9236 (courtesy Nadège Meunier, OMP Tarbes, France).

from the continuum near the Ni I @ 676.8 nm spectral line. On the right, we display the longitudinal magnetic field map of the active region. The total FOV is $136'' \times 110''$. The main technical parameters of this observations were: 170 scan steps of $0.8''$ with a $0.5'' \times 110''$ slit, 4 frames per step and a 500 ms exposure time per frame. The full observing sequence including calibrations took 35 mn for 4 spectral domains, in that case, resulting in the simultaneous observation of 6 different "useful" spectral lines (for which a total of 8+1 detectors were running simultaneously).

Results from observations taken earlier this year, as well as in 1999 can also be found in López Ariste et al. (2000, 2001)

6. Conclusions & Perspectives

THEMIS is experiencing full scientific operations for more than 6 months per year, since 1999. The observing time is opened to the international community and proposals can be submitted either at the French–Italian time allocation committee, or at the Spanish CAT. Further informations can be found on the web @ http://www.themis.iac.es.

A new polarimeter will be implemented in 2001. The commissioning is scheduled for February–March 2001. Although the 2 QWPs plus a beam-splitter at prime focus concept will remain, this polarimeter will allow for the so-called beam-exchange in all Stokes parameters (Donati et al. 1990, Semel 1993). More generally it will be possible to assign each of the QWPs independently to "any" orientation over the 360° range by use of encoded wheels; a resolution better than 0.02° will be achieved. Together with this new architecture, we shall offer 3 nominal sets of QWPs: (1) 400–700 nm achromatic which are available since 1998, (2) 600–900 nm achromatic QWPs whose retardance vs. wavelength is similar in shape to the 400–700 nm one, and (3) 470–565 nm achromatic QWPs for an increased polarimetric precision in this spectral range.

A preliminary report on the performances of the new polarimeter will be released to the community at the end of the commissionning phase, sometime during next spring (2001).

Acknowledgments. THÉMIS is operated on the Island of Tenerife by CNRS–CNR in the Spanish *Observatorio del Teide* of the *Instituto de Astrofísica de Canarias*.

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