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THEMIS: the 2006-2012 perspective

and beyond

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Abstract.
Imaging of the solar surface from ground based telescopes has achieved to be diffraction limited almost ten years ago, while diffraction-limited spectropolarimetry is, for obvious reasons of available flux, far from being reachable nowadays. Among the 1-meter class solar telescope currently in operation, THEMIS is the most specifically devoted to high-precision spectropolarimetry with an appealing level of specifications, some of them hardly to be find in any other telescopic installation. We shall discuss in this paper the recent evolution of this telescope toward more polarimetric efficiency and the use of modern detectors, in order to push further its possibilities in and hopefully contribute to open the path of a future large size solar European facility.

Key words. Telescopes – Instrumentation: detectors – Instrumentation: high angular resolution – Sun: photosphere – Sun: chromosphere – Sun: magnetic fields

1. Introduction

THEMIS is a joint operation from France (CNRS) and Italy (CNR) national research agencies. It is a 90 cm solar telescope, currently the third larger in the world, located at Izaña, 2400 m, within the Teide Observatory from the Instituto de Astrofísica de Canarias, on Tenerife (Canary Islands, Spain), and started operating in 1999. Its specific design for high-quality polarimetry includes an alt-az mounting, a helium filled telescope tube, a Stokes polarimeter located at the prime focus, and a multi-mode spectrograph. THEMIS delivers routinely vector polarimetry with an accuracy of 10^{-4} and up to 10^{-6} in some special configurations. The spectrograph design allows the observation of up to 10 wavelengths simultaneously, opening the possibility to perform 3D inversions of the magnetic field structure in the solar atmosphere. Following the last visiting committee of Oct 2003, the management of the telescope decided that to stay fully competitive at the 2010 horizon, the instrument should be modernized in several aspects, namely:

- MTR spectropolarimetry should be done at a better spatial resolution without degrading the SNR. Resolution should improve by a factor of 2 at least. The spectra should be stabilized to raise the SNR. New detectors with a better QE should be fitted at the output.
- All spectropolarimetry should be done with a better temporal resolution to deacrease

the seeing induced cross-talk, but without changing the dual beam scheme, just going 'TBD faster.
- Use the maximum of the spectral coverage of the spectrograph to broaden the nominal accessible domain. In particular, make available a true coverage of the blue (410-450 nm) spectrum
- In general, take advantage of a better photon efficiency to widen the telescope audience to planetary studies (Jupiter, Mercury) and to (some) stellar/cometary studies.

2. New image stabilizer for spectropolarimetry

Besides its polarimetric capabilities and multi-line spectrograph, THEMIS was designed to attain the 0.2” resolution so as to explore the small spatial scales of the solar magnetic field. The benefit to correct for atmospheric turbulence when aiming at high resolution *and* high accuracy spectropolarimetry has been recently addressed in Judge et al. (2004), resulting in the evidence that '*even the lowest order AO correction (just tip and tilt) is essential for accurate spectropolarimetric measurements [...] below 0.3 arcsec*'. This is very exactly the issue we wanted to address. Several solar image stabilizers have been developed in the late 90' (Von der Luehe et al., 1989), (Rimmele et al., 1991), (Ballesteros et al., 1996), most of them to evolve into adaptive optics system as hardware was becoming more affordable for small telescopes. Building an all purpose digital image stabilizer nowadays is not so much of a challenge, except in the case of THEMIS, as we shall see below.

The decision to build an image stabilizer (hereafter IS) was taken in January 2004, on the basis of an existing local project document, contributed by previous references like Molodij et al. (1996), Aulanier et al. (2003), Cruvellier (2003). The IS was commissioned in 2005 and 2006 and went into service in 2006. The scientific specifications of the device were: **i)** a complete compatibility with all the observing modes (currently 3 observing modes, with or without polarimetric analysis, are possible at THEMIS, each of them with a significantly different pre-slit configuration), **ii)** the stabilizer cannot use a significant fraction of the photons of the current science channels and **iii)** the stabilizer must work on all typical solar objects, e.g. granulation, spots and limb. This broad picture has been translated into functional and technical requirements like:

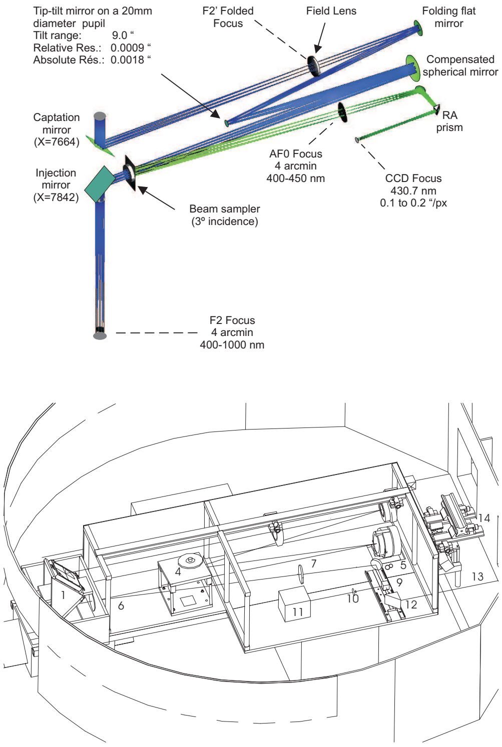

Fig. 1. Top: tip-tilt detour optical layout. Bottom: Corresponding mechanical CAD design

- the IS can work with the mostly unused blue part of the spectrograph bandwidth, below 450 nm
- the correlation algorithm shall be TDB accurate over low contrast scenes (3% rms at worst) at this wavelength
- the closed loop frequency cutoff shall be at least 60 Hz (from Ballesteros, 1996), expecting no mechanical high frequencies from the telescope or the building

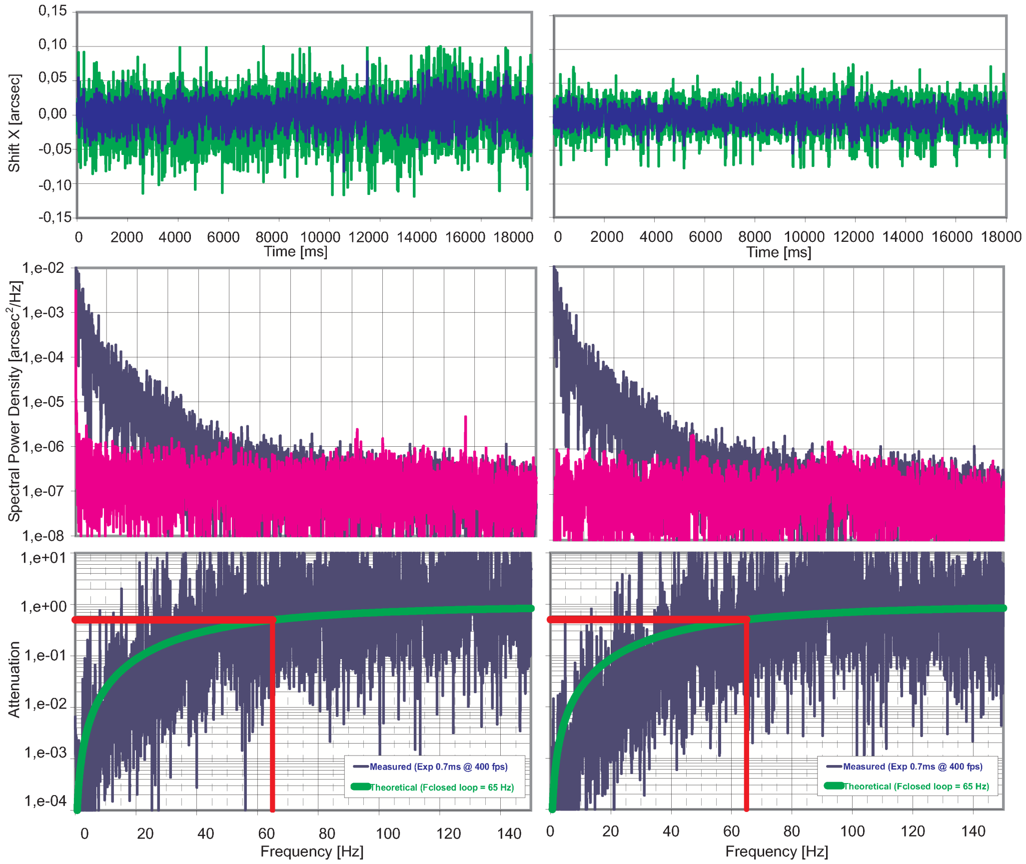

Fig. 2. Results of the qualification run over a sunspot in April 2006. Left column are results from measurements during BAD seeing conditions and right column during GOOD seeing conditions. Top to bottom are: (a)the temporal behavior of the image motion residuals over 18 secs, the light gray is at nominal rate and the dark gray is smoothed to a 10 ms equivalent, (b)the power spectra of image motions with (light gray) and without (dark gray) stabilization, and their ratio (e.g. the transfer function), with an overplot of the crossover frequency estimation

– the stabilization must interact with the general command-control to allow the possibility to scan the solar surface while stabilizing at the same time

And to these requirement we can add two comments: using the blue part of the spectrum actually enhances somewhat the granulation contrast, but also, a large provision must be made for important variations (1 to 100) in the available flux that may occur due to the instrumental settings when changing the observing setup.

The final optical layout of the tip-tilt is shown on Fig. 2 top. The original F2 focus is sent to a re-imaging doublet to obtain a 20mm pupil on the agile mirror. A flat folding mirror is required to keep inside the available volume. The piezo platform works in the pupil plane and its axes can match exactly the axes of the camera and of the slit in F2 by using a small rotation stage. A spherical mirror and an injection mirror send the F2 focus to its original destination. On the way out, the beam crosses a semi-transparent plate that picks up 12% of the

Table 1. Stabilizer device qualification results on various solar scenes

	Limb	Spot		Granulation	
Date	March 06	April 06			
Image size (px)	256x32 or 32x256	200x200			
Exp. time (ms)	0.5	0.5			
Fps	543 (1.84 ms)	400 (2.50 ms)			
Analysis cutoff freq. (Hz)	270	200			
Seeing during measurements	bad	bad	good	bad	good
rms residual image motion (”)	0.074	0.031	0.020	0.052	0.036
ν_c (-3dB) cross. freq. (Hz)	50	65	65	65	65

beam intensity for wavelengths below 450 nm. This light goes through a 45 mirror to a 50/50 beam splitter which is simultaneously feeding the motion detection camera and the alternate feed for our slit-jaw camera.

This design was first checked with an optical software package, then the actual layout went through a static qualification once implemented in the telescope. The conclusions are that the tip-tilt additional optics preserve the optical quality of the telescope at F2 ($0.22''$ at worst) over a field of $140''$ at least, and whitout noticeable chromatic shift.

After testing a classical fast CCD camera, we decided to use an 8 bits CMOS camera with a resolution of 0.15”/px, allowing the readout of a 72x72 pixels area at 2000 fps. Image motions are detected using the ’Sum-Absolute Difference’ (SAD) function (Vassiliadis et al., 1998). The SAD of 2 identical images is zero at the origin and positive elsewhere. When applied to astronomical (solar) images randomly displaced by atmospheric turbulence, it is minimum at the (x, y) location of the displacement value. The estimation of the image motion is then translated in finding the minimum of a SAD function. The SSE2 assembly instructions included in the latest Intel processor allow to compute the SAD function over 128 bits words, or rather blocks of 16 x 8 bits pixels, hence speeding up very significantly the result. For a real-time application, it is a nice alternative to FFT based correlation functions reputedly slower if not used with a specific hardware. Our code (SAD2006) computes the SAD function in 16 pixels chunks over 2304 (48x48) pixels inside a 5184 (72x72) pixel (reference image, and estimates its minimum in 0.3 msec on a 2.0 GHz PIV processor. Given the typical parabolic shape of the SAD function, a simple barycenter computation add sub-pixel precision to the result. We estimate the accuracy of this algorithm in real life to perform nicely to $1/5^{th}$ of a pixel taking noise and seeing into account.

To test the quality of the stabilizer on several solar scenes and actually measure the transfer function of the system, we setup a second identical CMOS camera, making sure that the temporal sampling of the stabilized image exceed the speed of the actuation, so as to avoid temporal frequency aliasing in the result. Images were acquired in consecutive bursts of 8000 frames stabilized and non-stabilized. Motion detection over raw images and relative to a time origin are computed using the same SAD algorithm than for the IS, then a Fourier analysis is performed.

Table 1 summarizes both the setup conditions and the main results of the tests. Middle and bottom plots on Fig. 2 are showing example spectra and transfer functions in the above mentioned conditions. The crossover frequency at -3dB establishes at about 65 Hz, which is the current system status. We do not see on these plots any evidence for high-frequencies that would indicate some mechanical vibrations inside the instrument or building. This is quite important in the perpectice of a possible evolution of this system toward a full adaptive optics design.

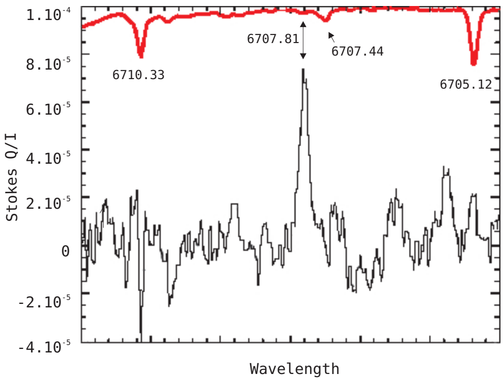

Fig. 3. Linear Q/I polarization of the Li 670.78 nm over the quiet Sun. Top thick line is the reference intensity. The unprecedented quality of this result is also largely coming from the stabilization of the spectra.(Data courtesy López Ariste and Themis).

3. New cameras for the MTR mode

MTR is the multiline spectropolarimetric mode of THEMIS that has been designed to observe up to 10 spectral lines simultaneously (Rayrole et al., 1998). The combination of that many possible lines with the option to have one camera per Stokes component resulted in THEMIS needing a maximum pool of 20 cameras to run. For a refurbishing of this ageing system, it has been decided that only 6 wavelengths at once will be available for the future. This lower number still allows a nice set of chromospheric/photospheric and magnetic/non-magnetic lines to be observed (and still no other telescope allows it). Similarly, it has been approved that the main interest of having one camera per Stokes component is the access to a wider field. However, a faster camera can do the job as well in the same time, even with a higher polarimetric accuracy. Hence the new pool of camera will have only 6 units. The selected camera is a commercial off-the-shelf product from Andor Technologies using an E2V L3 vision chip, whose main features are summarized in the Tab. 2. We expect the on-chip amplification feature to be very useful in smoothing the spectrograph output efficiency over several decades from 400 to 650 nm. Also, the improved quantum efficiency allows to observe lines like HeI 1083 nm, which was impossible before.

Table 2. Main specifications of the new MTR camera

Foundry	Thinned back-illuminated
QE	> 90% (500 nm)
Format	512x512 px (16 m square)
Well-Depth	200 000 ē
Frequency	10 MHz, 35 msec readout
Amplification	1 to 1000
Converter	14 bits
Cooling	-80°C
Dark current	< 0.005 ē /px/s)

A nice example of the additional quality brought by only one camera is visible on Fig. 3 which shows the Li 6708 line over the quiet Sun. The understanding of Lithium surface abundance of solar type stars remains a difficult topic with huge implications from the history of the star angular momentum and mixing to the existence of internal gravity waves, to the diagnosis of extrasolar planets on solar type stars (Charbonnel et al., 2006). While this light element is barely distinguishable in intensity and a very difficult target (Brault & Mueller, 1975), its linear polarized spectra is well above our noise level which in this case was only a few 10^{-6}. Indeed THEMIS is now much better than its original specification of 10^{-3} relative accuracy.

The complete acquisition system for MTR2 is sketched on Fig. 3. Each camera is connected to a proximity computer, to ensure a full acquisition speed in parallel to that point. The rest of the architecture is based on 3 main buses: data (1/10 Gb concentrator), command (1 Gb), and for convenience the video bus for real time control is implemented in hardware rather than software. The system shall be operational in early 2007.

4. New cameras for the MSDP mode

Unlike the MTR, the MSDP mode is not affected by a convolution of the image with a narrow slit. The slicing of the field of view

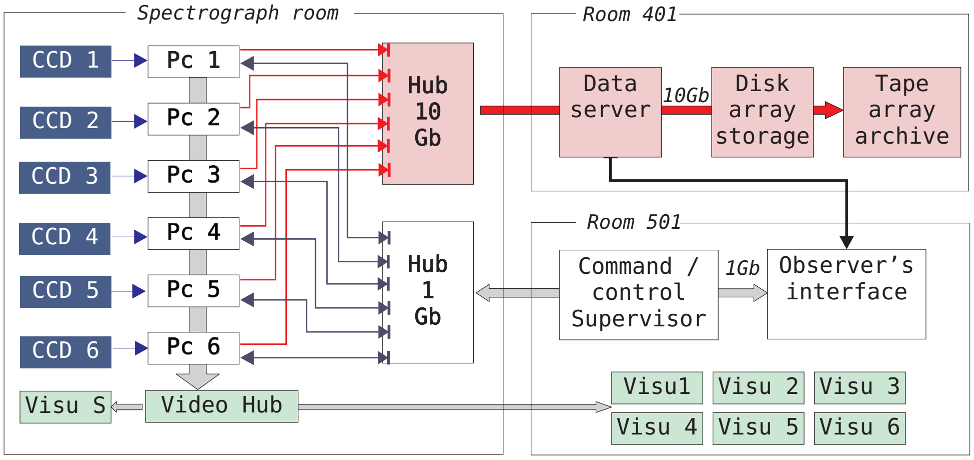

Fig. 4. Sketch of the full acquisition system for the MTR2. The physical distances to bridge when connecting the 3 rooms are about 50 meters and there is a large cable winding drum to cross due to the alt-azimuth mount.

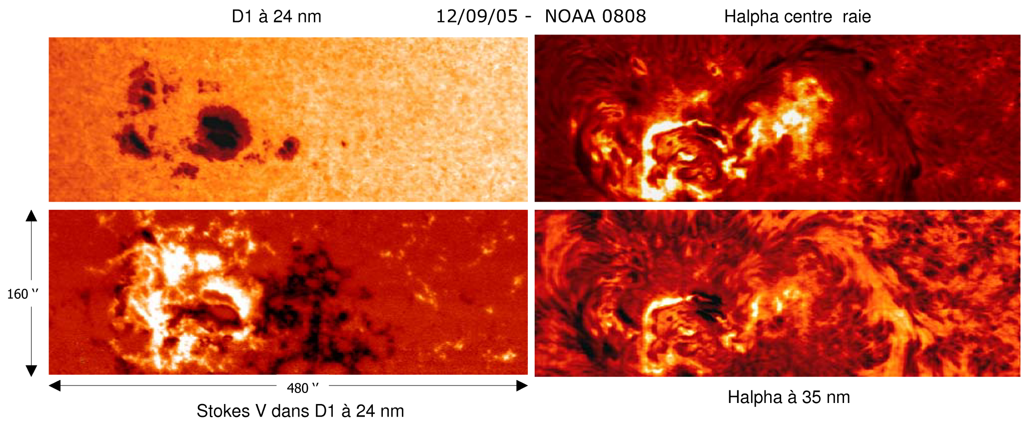

Fig. 5. Left: Top NaD1 map of NOAA 0808 at 24nm from line center. Bottom: Stokes V of the above map. Right: Same map in the chromosphere at H_α line center (top) and H_α at 35 nm from line center. All maps are simultaneous. (Picture courtesy B. Schmieder & P. Mein)

given by the (mandatory) grid shaped pre-slit is handled by the data analysis software which rebuilds the entire field in the 2 simultaneous wavelengths (Mein, 2002). Improving the duty cycle speed and spatial resolution have been the main issues of our renewing of the MSDP. In principle the MSDP can maintain the spatial resolution of the telescope at F2 (0.22″), but the minimum exposure times are typically of 300 ms, consequently the pixel size needed should be rather 0.2″ than less. It does not require very big CCD full-well capacities because images can be averaged off-line to give the required SNR (even more so with a tip-tilt), but, for reasons of beam aperture at the output, the pixel size must be 10 μm at least. The acquisition should handle 2 to 3 i/s, compatible with the exposure times, and with the maximum acceptable duration of a complete scan over a field of 5' (typically 3mn). Further trade-off between the size of the field and the duration of the scan is an observer's decision.

Following this analysis, the THEMIS team made a selection over available commercial products at the fall of 2004. The preferred chip was a 1500x1000 Kodak KAF 1603ME (microlensed version), with square 9 μm pixels, QE ranging from 45 to 77% across our spectrograph bandwidth, and a readout speed of 10 MHz allowing for 8 i/s at most. The project was completed in summer 2005.

Fig 5 shows the results of the study of NOAA 0808 from Sep 12th, 2005 18:12UT using this new system. THEMIS MSDP allows the simultaneous observation of 2 lines (in this case H_α and NaD1). Given to the spectral slicing made by the prism boxes, several wavelengths are available along the line profile at once. Full-Stokes polarimetry is possible and vector magnetic maps have been computed for the first time in 2006 (Mein et al., 2006), soon to be checked against the same MTR maps. For its moderate accuracy in polarimetry and its speed faster than any other instrument, the MSDP may become a challenging instrument to tunable filters for the mapping of large magnetic regions.

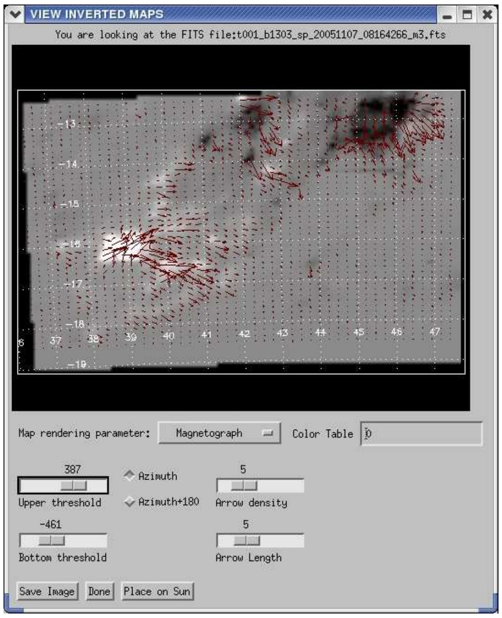

Fig. 6. Example of the analysis tool of the INVTOOLS package. The image shows the scanned solar region in terms of longitudinal flux with arrows representing the field vector overplotted. The data arises from the inversion code included in the package. Note the visualization options and the 'fundamental ambiguity switch'

5. THEMIS data and analysis software

THEMIS instruments are producing large volume of not-user-friendly raw data. A typical good observing day can yield 200 - 500 Gb, the unit base item being either a MTR spectrum (which most of the time is only a part of a scan and has little value as is), or an MSDP raw frame which is also a complex product, that need to be properly handled by a dedicated software and reconstructed for wavelength and field. It is out of the scope of this paper to discuss the details of these processes. However at management level, some tidying of the analysis tools was necessary in order to speed up the obsrvation/data analysis/publication cycle of the THEMIS observers. This has been done at THEMIS for the MTR processing and at BASS 2000 (the French solar national database for non-spatial instruments) for the MSDP processing. Since 2005, THEMIS is making available at the telescope and also as off-line software two data analysis packages: SQUV and INVTOOLS.

- SQUV is a package of IDL developed functions to handle the raw MTR data. It accepts data from any configuration of the MTR sub-modes (3 are possible), and apply the typical reduction steps, flat and dark corrections, line curvature de-slanting, demodulation of the Stokes parameters, and construction of the Stokes maps from the initial scan data. The operations are controlled using a widget-based interface, and once the critical choices have been checked by the scientist, the program can be left running without further attention. This 'automatic' batch mode is saving a lot of time.
- INVTOOLS is a mixed fortran/IDL package that plugs into the output of the SQUV program. It contains a set of tools intended

to help the user analyze the results he has just observed. They are mostly organized around an inversion code able to retrieve the magnetic field vector from the doublet of Fe photospheric lines at 630 nm. The first tool handles the data files created by the SQUV package and allows the user to create maps of the scanned region in the wavelength of choice and for all Stokes parameters.The resulting maps can be saved, or projected against the solar disk with an overlying of solar coordinates, to give a few examples of its capabilities. The second tool is an inversion code for the Fe doublet at 630 nm. These two lines are well known for their high sensitivity to the photospheric magnetic fields.It is based on a Principal Component Analysis (PCA) algorithm. PCA techniques have been probed for their robustness and speed. A typical THEMIS photospheric scan is inverted in 5 to 10 minutes. With such performance the code can be safely been put to work by any user during the observation and the vector field is inferred in almost real time. This capability is unique to THEMIS to this day. More tools are also provided to check and visualize the inversion results.

In conclusion, to measure and map the vector field has been many times put forward as one of our top goals. THEMIS becomes thus the first solar telescope ever to provide the vector magnetic field in real time thanks to this code.

6. Planned changes for the near future

To complement the above set of new features, we are currently studying the speeding up of the polarimetric analysis duty cycle so as to match the improved speed of the detectors and decrease the seeing induced cross-talk. TTL driven achromatic LCD retarders combinations are now being considered as replacements for our mechanically driven quartz/MgF2 units. The CAD drawing phase for the mechanical parts is ready and a test bench for the qualification of Meadowlark retarder plates is being designed for 2007. Such a device would be available by mid-2008.

Recently, on the grounds of a preliminary study of wavefront measurement made during the summer 2006, the Themis Board authorized the qualification of a deformable mirror as a first step toward the evolution of the stabilizer device toward an AO system by the same home team; This qualification will start in early 2007 with an OKO mirror using 48 actuators. Our broad picture is to propose a correction for the first 20 Zernike polynomials using the same ingredients that we put in the stabilizer, and reusing the same optical bench. The device may be in operation by the end of 2008, early 2009.

7. 2012 and beyond, OPTICON, and the broader European perspective

So far, high quality spectropolarimetry at THEMIS has been greatly improved by the stabilization of the images. The full exploitation has only started, helped by the availability of suitable reduction codes, and boosted also by the arrival of modern cameras for both the MTR and MSDP observing modes. In this framework, plans are crafted to extend the lifetime of this installation so as to continue its scientific exploitation. 2012 is for us a minimum threshold to reach, even at the expense of changing the current operational model for another more economical one. However, the complexity of the various THEMIS subsystems for the instrumental setups, the handling of the observation, the cold water production, the periodic changes of the helium content of tube, etc, will possibly prevent forever its successful use by non-trained personnel only.

The Canary Islands are providing a very appropriate test bench for lots of European collaboration in solar astronomy. European countries are currently operating there 4 world-class major solar facilities, soon to be 5: the 1m NSST operated by Sweden (RSAS), the 60 cm DOT operated by the University of Utrecht, the 60 cm VTT operated by the Kiepenheuer Institute für Sonnenphysics from Freiburg and the 90 cm THEMIS operated by CNRS/CNR. First light of the 1.5 m GREGOR from KIS

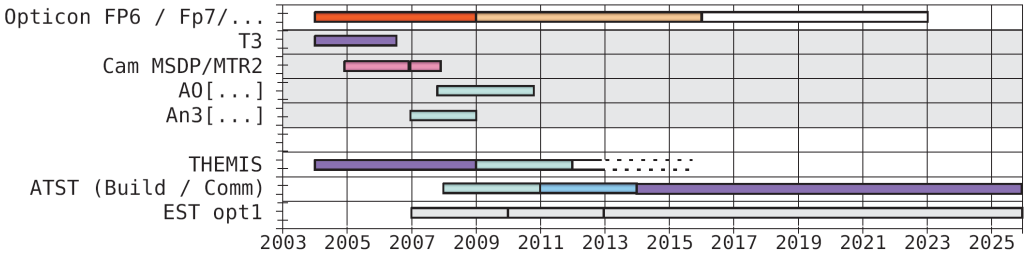

Fig. 7. THEMIS current and planned technical developments are indicated over a gray shaded area. The building of the An3 analyzer has been approved as of Dec. 06 and the in-house qualification of a deformable mirror for the adaptive optics will start in 2007. Themis operations at the current funding level will possibly not extend after 2009, however the scientific yield of today's technical improvement are expected to deliver results until about 2012, the minimum delay allowing to reasonably exploit an updated THEMIS.

is planned for 2008. All these solar telescopes participate to the OPTICON I3 European program, and among them THEMIS has been particularly active in the 'Access Program' providing 'access units' (e.g. days of observations) to not-by-the-law users (Opticon access office, 2004-2006). This action shall continue into the FP7 program.

While these meter class telescopes are currently handled at national or university levels, the underlying scientific community, if properly federated, has obviously the expertise and size to conduct and successfully achieve much larger projects than just the upgrading its present facilities. A couple of recent meetings are just stating this, like the "Mondragone resolution" (see ESF exploratory workshop, 2006) *(i)An organization shall be established at the European level with the task to define and to co-ordinate the effort necessary to ensure access of European solar astronomers to, and promote creation of, worldwide leading ground based observing facilities. (ii) The Undersigned shall seek national and European funding for a viable and active partnership in the design, construction and operation of the ATST*[1]

This meeting was followed by a brainstorming session of telescope operators in Freiburg leading to the creation of a consortium structure (EAST)[2] whose mission is defined like: *[...] ensuring access of European solar astronomers to world-class observing facilities. In order to achieve this goal, EAST shall : (i) develop, construct and operate a next-generation large aperture European Solar Telescope (EST) in the Canaries (ii) coordinate the operation and scientific use of optical solar facilities in Europe, (iii) co-ordinate and facilitate efforts of its members to participate in other solar facilities such as the Advanced Technology Solar Telescope* It is out of the scope of this paper to discuss the pro and cons of the many paths that extend in front us. However, Fig. 7 indicates an agenda for THEMIS technical improvements, and his exploitation time-line; The 2012 horizon for THEMIS is possibly not very different of the lifetimes of the already existing other Canarian solar telescopes. If we do not believe that only one ATST will fullfil the needs of both the US and EU community after 2015, we better start immediately planning for the EST.

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[1] Advanced Technology Solar Telescope: see Keil et al. (2003)

[2] European Association for Solar Telescopes

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