DELIVERABLE D70.2

AO Prototype for THEMIS and Test Report

WP70 Wavefront Control: Turbulence Characterization and Correction

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Deliverable 70.2 - Development of an AO prototype for THEMIS telescope and test report

Description of work for the WP 70.1.2

70. 1.2 Development of an AO prototype for THEMIS telescope and test report(CNRS lead)

AO systems are installed at most existing solar telescopes to improve their image quality, with excellent results in imaging observing modes, but the combination of polarimetric measurements with adaptive optics is extremely challenging and it is not usually fully addressed. Being THEMIS a solar telescope which provides high polarimetric performance, the implementation of an AO prototype to improve its image quality retaining its unique spectropolarimetric capabilities, would open the possibility to specialize this telescope in high resolution in polarimetry. The possibility of performing very high quality polarimetric measurements using AO is one of the challenges of the future large aperture European Solar Telescope (EST) and the implementation of an AO system at THEMIS will provide an excellent bench to test these observing techniques for EST. This sWP includes the following tasks:

- *Design of the AO system (CNRS-THEMIS, CNRS)*
- *Construction and installation of the AO system (CNRS)*
- *Tests of the AO system (CNRS)*

Participants

Le Men (CNRS), Lopez (CNRS), Gelly (CNRS , Laforgue (CNRS)

Expenses

Personal expenses **as per CNRS timesheets**:

Name	Declared person. day on WP 70.1.2
Arturo Lopez	3
Claude Le Men	121
Bernard Gelly	32.5
Didier Laforgue	0

Missions expenses (CNRS has original documents):

Name	Concept	Date	Place	Expense
Arturo Lopez	THEMIS AO Project review at CNRS	15/09/2014	Paris	Est. €500
Claude Le Men	THEMIS AO Project review at CNRS	15/09/2014	Paris	Est. €500
Bernard Gelly	THEMIS AO Project review at CNRS	15/09/2014	Paris	Est. €700

Summary of Deliverable 70.2 (FRP)

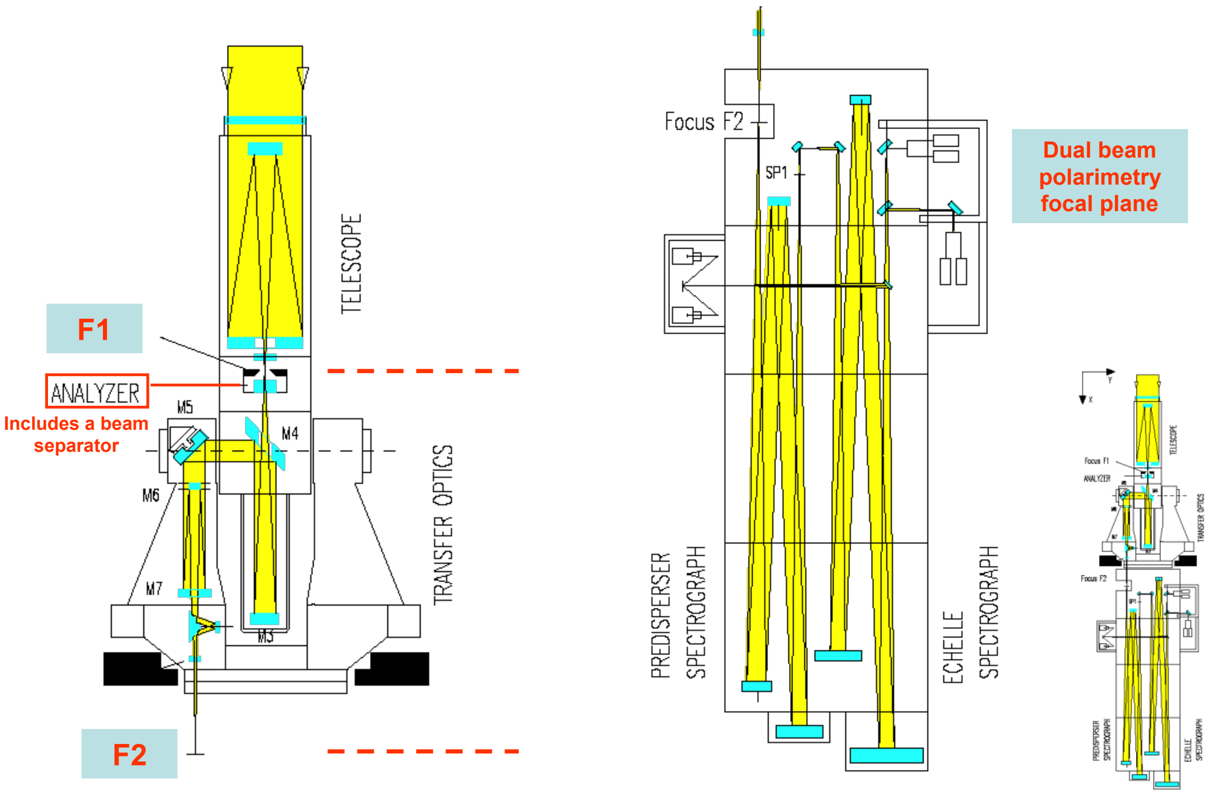
A full conceptual study has been conducted to explore the possibility to implement an adaptive optics system for the THEMIS telescope, taken into account the current technical state of the telescope and the scientific goals deriving from the polarimetric usage of the long slit spectrograph

attached to the telescope. It shall be clear from the beginning that THEMIS has been specifically designed to be a "calibration-free" polarimetric telescope and that we have fight to keep this specification valid, assuming all the consequences.
The result of this conceptual study are 3 technical reports:

- WP7.1.2_TAOP_001_AO_System_Design_Specification_V1.0 doc #1
- WP7.1.2_TAOP_002_Polar_System_Design_Specification_V1.0 doc #2
- WP7.1.2_TAOP_003_Optics_System_Design_Specification_V1.0 doc #3

We shall try to present below a faithful summary of those 3 documents; In the event of misunderstanding this summary or in the case of any discrepancy between this summary and the technical reports, it shall be clear to everyone that these reports are the only valuables references to take into account.

Reminders:



THEMIS has a telescope to collect sunlight that makes an image of the field at the F1 focus. Between F1 and F2 is the transfer optics, which sends the light to the entrance of the spectrograph (in F2). Below F2 and attached to the telescope is the spectrograph. In absence of polarimetry, the spectrograph outputs are several (x,λ) spectra. Polarimetry is done prior to any oblique reflection (Fig. 1), below the F1. The analyzer is made of two crystalline retarders to successively cycle trough the Q, U, V Stokes states ('S' in what follows). We have a slow temporal modulation to go through this cycle. The analyzer has also a beam separator (a calcite Savart plate) which creates a dual beam output that simultaneously delivers the +S and the –S states. This temporal coincidence is mandatory to overcome the atmospheric turbulence and image motion in the demodulation process. However, these 2 beams cannot be as large as the telescope FOV: a preslit masking is required, due to the to limited separation capacities of "reasonable" birefregent separators (16 ʻʻ at THEMIS). The focal plane of the spectrograph changes for dual beam polarimetry, where the (x,λ) spectra are split into

distinctly polarized sub-parts (several configurations are possible). This preslit masking happening very high in the lightpath is totally unsuitable for any active image correction.
Finally, 2-d mapping of the solar surface with (x,λ,S) polarized spectra requires scanning in the y direction to get to the (x, y, λ, S) quantity. For historical reasons, THEMIS M5 mirror (Fig. 1) is our current scanning device. The M5 location is a totally unsuitable place for further image correction devices as it is again too high in the light path.

Some comments on the current system:

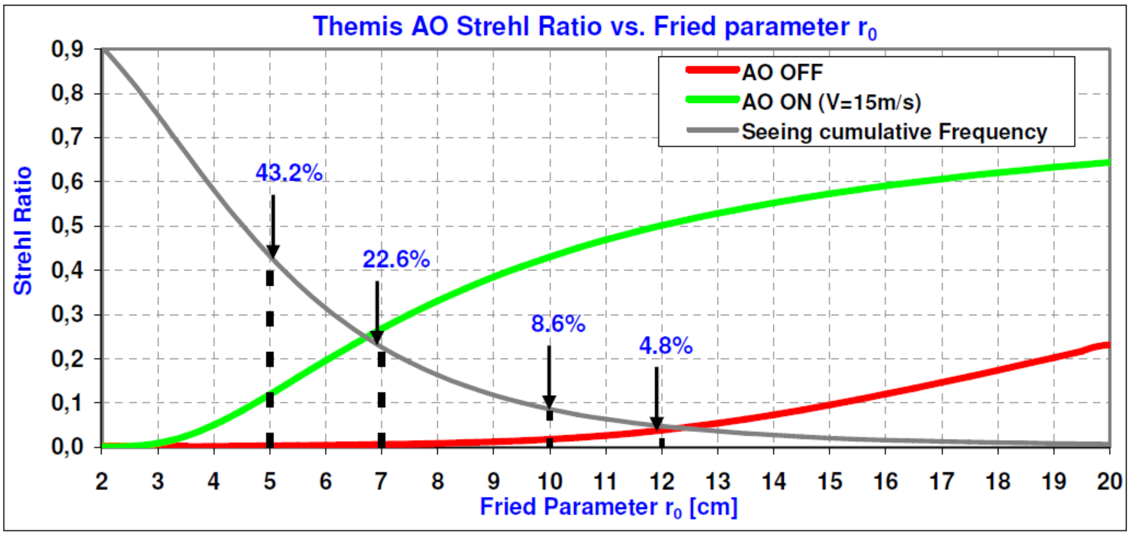
- Polarimetric analysis and beam separation is done at F1 : no contamination of incoming polarization by extra optics happens. No polarimetric calibration is needed we have a better overall duty cycle.
- Analyzed light intensities must be routed downward, in principle "differentially unchanged" until the spectra focal plane.
- In principle 3 measurements would be enough for full polarimetry studies, but practically, 6 measurements are needed in one modulation cycle: I+Q I-Q I+U I-U I+V I-V. This takes already longer than any imaging burst that is used with FP devices.
- Sunlight is largely NOT polarized (a few percent in the best case. Current « hot » science is in the range 10^{-3} to 10^{-5} (relative). High SNR differential photometry requires lots of photons (10^{6} or better). This takes even longer than point 3.
- "Heliographique" in the THEMIS means 2d mapping of the magnetic solar surface using a slit scanning device. This is again a serious constraint on the time its take akes even longer (mapping 2'x2' with a 0.5''x2' slit …)

From all the above, it shall be clear that **this study shall address 4 majors goals together**:

- An AO bench shall be inserted in the main path of the telescope
- This AO shall be robust enough to allow time-consuming polarimetry to take place
- The polarimetric system shall be refurbished in order to work with an open field, but we want to keep the analysis in F1 and the dual beam principle.
- The field scanning shall happen moving the corrected image on the spectrograph slit (hence after the correction stage.

AO System Design Specification (1st document)

The first document describes an adaptive optics system suitable for a 1m class telescope like THEMIS, under the (assumed) considerations of atmospheric quality and sky conditions relative to our site. This document does not put the emphasis on polarimetry but rather on the benefit on imaging of an AO correction. It describes the hardware and software components needed to build the system up to the commercial evaluation and preselection of these components. Specifications of the system output are given, again with the assumption that the Tenerife site shall be of the same nature than the La Palma site, where SHABAR and S-DIMM data do exist and were used for this study. An error budget of the system is computed. Finally constraints are derived from all that precedes on the use of the use of the AO system and a preliminary optical scheme suitable for implantation is given. The following table summarizes the top level scientific specification of studied system characteristics:



This figure shows the expected Strehl ratio with and without the designed AO as function of the Fried parameter r_0. Remember that this figure is dependant on the (reasonable) atmospheric model taken as input. Superimposed is the seeing cumulative frequency (both Strehl and seeing are on a 0–1 full scale. It is interesting, to extract the following table from the former figure:

	$r_0 \geqslant 5$ cm	$r_0 \geqslant 7$ cm	$r_0 \geqslant 10$ cm	$r_0 \geqslant 12$ cm
Seeing Probability [%]	43.2%	22.6%	8.6%	4.8%
Strehl Ratio	SR $\geqslant$ 0.12	SR $\geqslant$ 0.27	SR $\geqslant$ 0.43	SR $\geqslant$ 0.50

Table 14-a: AO Corrected Strehl Ratio and Seeing Probability

The **starting operation point** of the AO has been set at $r_{0=}$4.7 cm (which half of the time), which represent the worse seeing that can be corrected, while the **stable operation point** has been set at $r_{0=}$7 cm.

If we combine these numbers with the most demanding observing mode, which is spectropolarimetry mapping of a ~ 1' x 1' region, assuming 200 ms exposure to get to the required SNR plus the time allowed for the polarimetric cycle to complete, we deduce that we need stable AO correction over 10-15 min time to perform this task. We don't have yet the true statistical translation of this criterion (probability of uninterrupted AO correction during a given time at a given average r_0), however we believe this will be closer to the r_0 =10 cm situation, which is 10% of the time. Remember however, that this is the most demanding situation.

Finally, an optical design is presented (Fig. 27-a). This design uses as input a modified F/52.9 input beam (currently F/63) for reasons that represent an overall improvement of the whole transfer optics; (see below).

The important design elements are:

– RAP1 entrance folding prism
– DM: Alpao DM97-15 in a 13.5mm diameter pupil. The mirror incidence is 5º.
– OBJ1: a 150mm diameter concave mirror (R=2200mm) at incidence 0.85º, forming a first image of the F2' focus.
– FM: a 50mm diameter convex mirror (R=-3360mm) at incidence 1.7º, forming an image of the pupil on the scanning mirror, and is also a 4-8% beam sampler.

Figure 27-a: AO Transfer Optics DESIGN

– OBJ2 Scanning Mirror: a 60mm diameter concave mirror (R=2200mm) in a 44mm pupil forming the definitive image on the F2 focus (spectrographs slit) at the unchanged x coordinate but with an F/number slightly lower that the current one (F/60 vs. F/63. This mirror is used to perform the field scanning (±60 arcsec with incidence range of ±0.14º, i.e. ±2.5mrad). The advantages of such a small mirror is that the scanning will be easily more accurate (better than 0.02 arcsec) and faster (<10ms) compared to the 350-500ms of a current M5 step
– RAP2 the output folding prism

Of equal (or greater) importance is the WFS path. This path is in the Y-Z plane of the former Fig. 27-a and is sketched below (Fig. 37-a). This design is studied for specifications and components already defined in this first report, i.e.:
– 68 sub-apertures in pupil (spacing 11.02)
– 28x28 pixels sub-apertures +1 pixel extra separation @ 0.5 arcsec/pixel
– camera Mikrotron EoSens 4CXP-6 @ 320x320 pixels, 7μm pixel, 2.24x2.24mm.

The total track of the beam is 860mm in the Z direction.

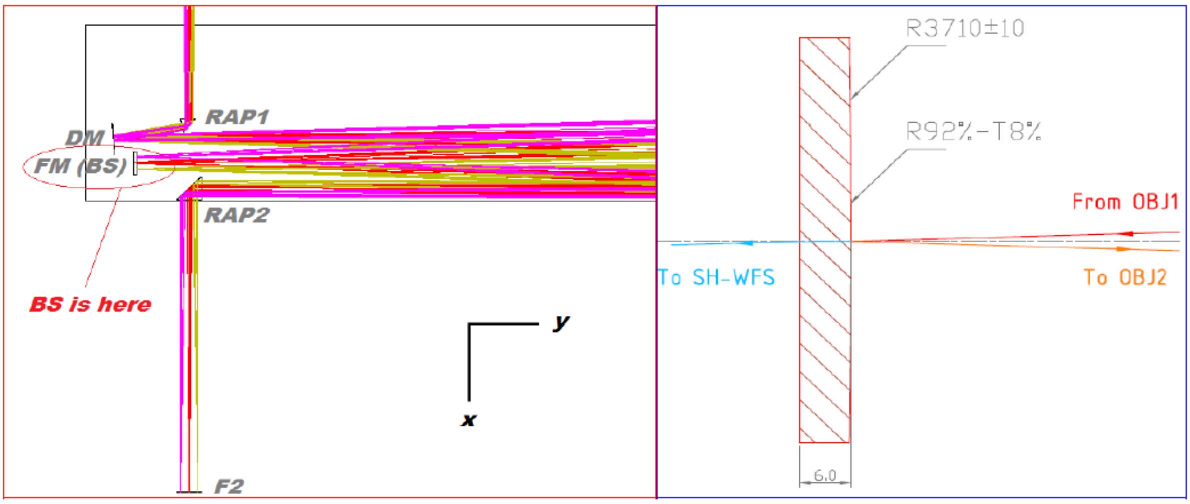


Figure 37-a: Beam Sampler for SH-WFS and both Tip-Tilt sensors

- BS: the Beam Sampler (4 to 8% reflection) is placed just after the DM. Its incidence is 45º to fold the "WFS" beam at 90º on the Z axis (perpendicular to the scheme plane). Special care should be taken on its surface quality as far as it is placed very close to the pupil.
- L1: a pair of commercial doublets to form a diffraction limited image in Fsh1,
- Fsh1: 1st focus of the SH-WFS beam, where SHOULD be placed a 14x14 arcsec2 Field Stop,
- L2: a commercial doublet (F=63mm) to form an image of the pupil of diameter 3.31mm,
- Lenslet: Orthogonal array of round lenses, pitch of 300µm and a focal of 15mm at 500nm, placed in the 3.31mm diameter pupil (spacing 11.02),
- Fsh2: focus of the Shack-Hartmann
- L3: a Colorplan lens (F=90mm) to form an image of the Fsh2 focus on the camera plane (Fsh3).
- Fsh3: camera EoSens 4CXP-6 @ 320x320 pixels, 7µm pixel, 2.24x2.24mm.
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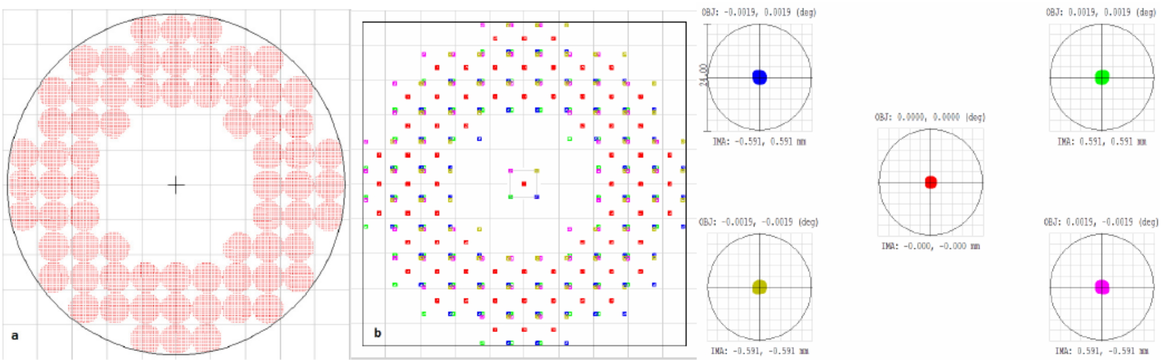
Figure below reminds the 68 sub-apertures arrangement (a), the SH camera image (b) and the spot diagram of the Fsh1 focus for a 14x14arcsec2 field (c).



Polarimetric system design specification (2nd document)

As we already mentioned, the new THEMIS AO system is designed to feed a long slit spectrograph within a spectropolarimetric telescope. Making compatible the AO system with our spectropolarimetric observing mode is a top level requisite that conditions the scientific future of the telescope.

One feature of the current telescope quite incompatible with any correction device is the field limitation (currently 15"x 2 "), introduced by the preslit at F1 (See "reminders" section). This field limiter works in conjunction with a Savart separator plate to allow the dual beam polarimetry at THEMIS. Dual beam polarimetry means that 2 simultaneous Stokes states (*I+S* and *I-S*), identically affected by atmospheric blurring or any distortion are present at the same time on the spectral plane of the spectrograph, and will be recorded on the same camera. The full Stokes analysis is obtained with a slow (compared to the atmospheric timescales) cycling trough all the polarimetric states. During the demodulation process, some differentiation has to be performed on I+*S* and *I-S* to get to the *S* or *S/I* values. It has been proven that this kind of subtraction is extremely sensitive to ANY changes that may be introduced between the two complementary states, either by setup (like using two cameras / imaging optics), or by recording them separately at intervals larger than the atmospheric turbulence timescale (less than 3 ms). Hence the dual beam setup is one possible answer to have a polarimetry correct at the 10^{-3} relative accuracy or better, however the price to pay in our case is depicted below:

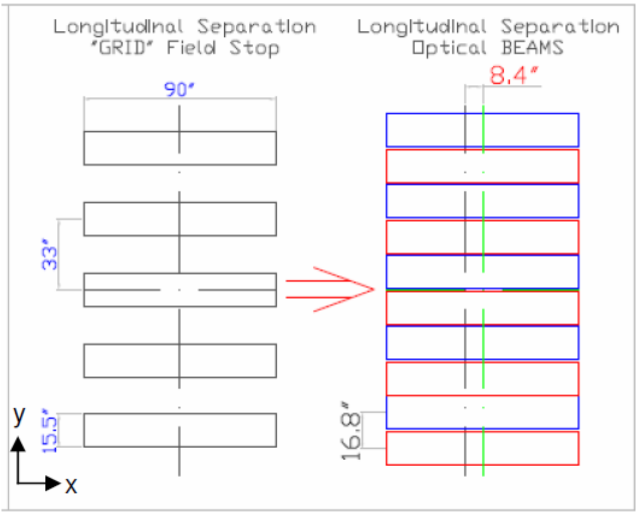
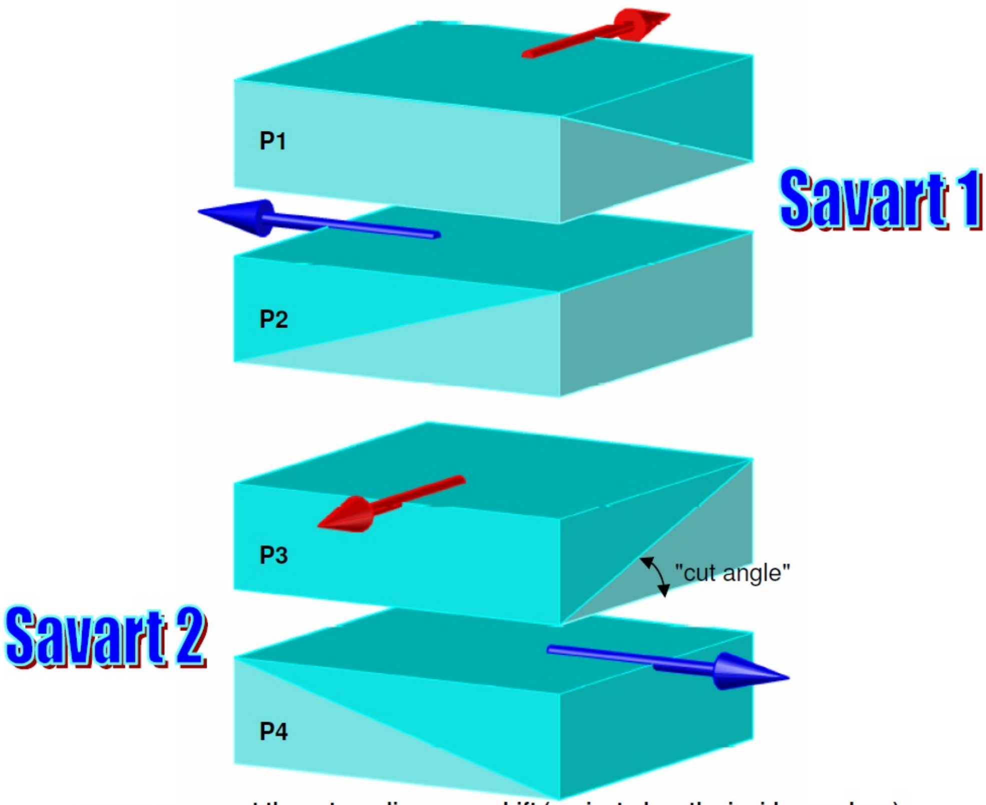


Figure 6: Themis Polarimeter Field Stop "Masks" in F1 and Resulting Optical Beams at 500nm

Fig. 6 shows a typical preslit used at THEMIS (left) and the corresponding focal plane of the spectrograph. The dual beam field (red and blue on the right) is limited to a few 15.5'' x 90'' chunks. To get a complete field requires one more telescope step of 15.5'' in the Y direction.
While this mode is scientifically viable, we stress again that it is completely incompatible with the requirement of an AO wavefront sensor.

Document #2 proposes to override this problem by implementing an open-field polarimeter and explores two solutions, namely:

- same Savart plates as today but with a larger separation involving bigger spaths elements. This is not satisfactory for many reasons explained.
- **a dual superimposed beam-splitter device (DSBS)**. The basic idea is to build a beam-splitter that doesn't separate beams! We want is to create two superimposed beams, each beam being identified by a distinctive polarization state: one linearly polarized along Q and the other along -Q (at 90º). These beams propagate through the transfer optics, and can be separated before the spectrograph slit or the spectral camera, using that linear polarization property (assuming that the transfer optics will preserve the linear polarization states!). A clever way to do that "dual superimposed beam-splitter" is to cumulate two identical Savart beam-splitters the second one being rotated by 180º in order to cancel the separation. Each Savart beam-splitter is composed of two identical plates rotated by 90º one with respect to the other. The principle of such a beam-splitter is shown on Fig. 32 below. This device presents numerous advantages compared to the "single" Savart, among which:
  - No field stop is needed, except for the useful aperture of the beam-splitter with the consequences that it is not necessary to place the polarimeter exactly in the F1 focus.
  - Our slit-jaw and broad band imaging devices can see, at all time, a complete open-field image
  - The polarimeter "field stop" position was maintained by a closed loop system, the so-called "coulisses stabilization", which becomes unnecessary
  - The rotation AND optical axis of the polarimeter are (finally) superimposed. This is a great improvement because it will limit a lot the derotation defects on image position in F2.
  - The thickness of Savart plates is not imposed by the separation value. We can now decrease easily the total glass thickness of the beam-splitter (for example 4 plates of 3mm thickness instead of our 2x12mm one).



arrows represent the extraordinary ray shift (projected on the incidence plane)

Figure 32: Principle of the **Dual Superimposed Beam-splitter**
(**Blue arrow**: Beam 1,Stokes **+Q** ; **Red Arrow**: Beam 2, Stokes **-Q**)

The posterior separation of the DSBS output can happen either before the spectrograph (in F2), or below. Even if it seems a logical option to put a one-fits-all separator in F2, several good reasons point toward having it in the reimaging output of the spectrograph, so that there will be one separator per spectral camera (up to six at the current time). The separation shall be based on a Wollaston calcite element as pictured on the next figure:

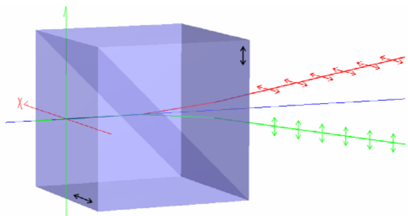


Figure 36-d: Principle of the **Wollaston Prism**

These birefringent prisms shall then be inserted in the reimaging system that matches the output of the spectrograph to the CCD focus as sketched on Fig 36-e:

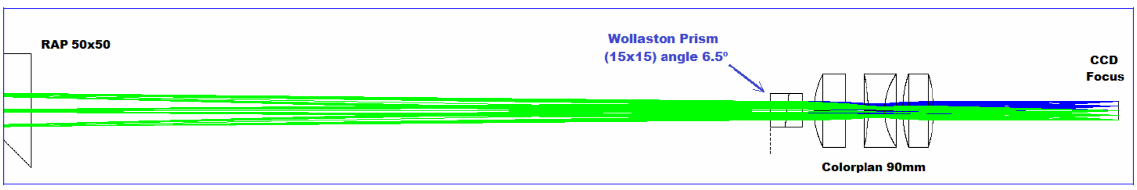
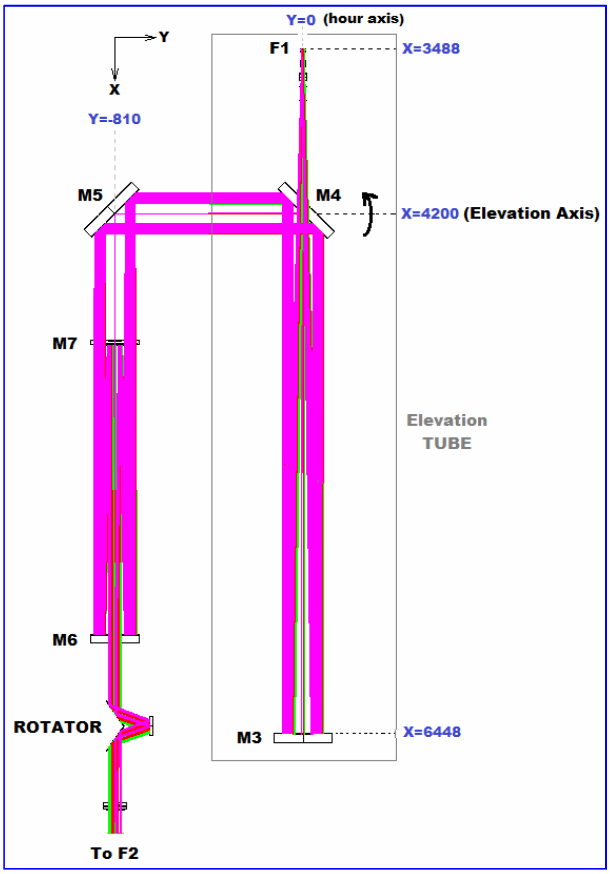


Figure 36-e: WOLLASTON in the Re-imaging System of the MTR spectrographs Cameras
(2 arcmin Field, Camera iXon EMCCD DU 887 512x512 pixels 16µm)

Current specifications of these elements are based on our present field size and CCD cameras sensor formats. Any (future) change of camera would require a change of these Wollaston elements.

Once addressed the **serious** problem of having an open field dual beam polarimeter, we have studied the quality of the propagation of the two orthogonal polarization states generated by this new analyzer, from the F1 level down to the spectra focal planes. These beams are themselves purely linearly polarized at 45º and - 45º of the longitudinal y-axis of the F1 "pre-slit". We want to compute the effect of the transfer optics on this linear polarization. To do this, the Mueller matrix of the transfer optics, or rather the parts that affect the polarimetric state of the input, e.g. M4, M5 and Rotator (see Fig. 9 below) , is calculated, depending on all optical surfaces and all angles.



<u>**Transfer Optics Components**</u>:
(represented for elevation=90º)

Moving with Elevation:
(elevation rotates around y-axis)
- **M3**: Collimation mirror, incidence=0º (diameter 250mm)
- **M4**: Elevation mirror, **incidence=45º** (diameter 300mm)

Fixed with Elevation:
- **M5**: Scanning mirror, **incidence=45º** (diameter 290mm)
- **M6**: Cassegrain telescope 1^{st} mirror incidence=0º (diameter 210mm)
- **M7**: Cassegrain telescope 2^{nd} mirror incidence=0º (diameter 210mm)

Rotator, composed of 3 mirrors:
- **R1**: Rotator mirror 1, **incidence=55º** (rectangular 150x80mm)
- **R2**: Rotator mirror 2, **incidence=20º** (diameter 80mm)
- **R3**: Rotator mirror 3, **incidence=55º** (rectangular 150x80mm)

(F1 and Rotator rotate around x-axis)

Figure 9: Optical Design of the Themis transfer Optics
(Cotes "X" in the Themis referential are given in mm, Scale about 1:28: 1mm for 28mm)

Then a given date of observation is used to generate a realistic combination of daily varying angles, and these are input to the Mueller matrix. Results are intensity variations, coming from Stokes vectors changes along the day because of cross talk (Figure 29 **top**). The result of the present situation is not good when looking at the changes along one day in the 2 intensities of the analyzer beams. We see intensity changes up to 5% created by mutual cross-talk between I and Q, U and V. However, for the current dual beam system (beam are separated just after the analysis, and nothing else happens) this problem is mostly addressed by carefully flat-fielding of the data, and an intelligent a-posteriori treatment of the beam balancing using the polarization of the continuum as a zero reference. An arguable issue for this (typical) day is near to 0 hour angle, where rapid intensity variations can possibly happen within a longer polarimetric observation and that would result in insufficient flat-fielding and non-recoverable polarimetric errors. Still for most of the day the polarimetry would be ok thanks to a correct data analysis.

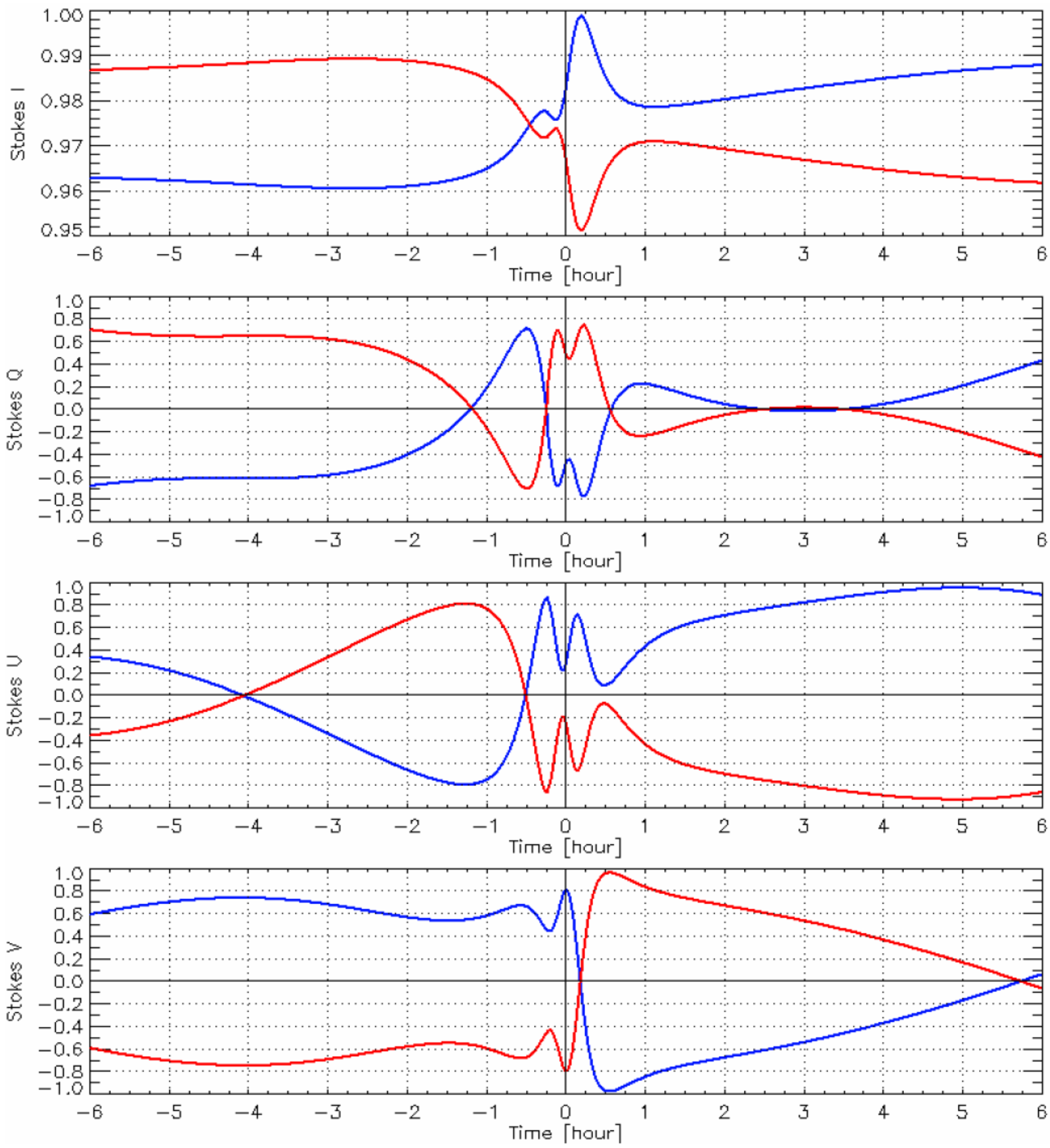


Figure 29: **Beams 1 & 2 Stokes vectors @ 500nm** for a **Solar North** slit vs. Time
(**blue**: Beam 1; **red**: Beam 2; **Input 1 [1, 0, +1, 0]** ; **Input 2 [1, 0, -1, 0]**)

But this situation is not sustainable if we want to use the new DSBS device defined in the former section. The problem is not the DSBS itself but from the Wollaston element used to separate the beams next to camera imaging stage. This element will not only separate the beams but also linearly reanalyze them, and the intensity balance shall of course not change after the separation. This means that any departure from the pure linear polarisation generated at the DSBS due do the transfer optics is traduced in intensity changes non recoverable after the Wollaston. Figure 29 shows on the 3 lower panels the departure from the "pure U, pure –U" situation **for our current transfer optics**. As expected, the ±U input states are drastically changed. Beams 1 & 2 Stokes U sign can even be exchanged between -4 and -0.5 hours before solar noon (beam 1 +U becomes -U !). Other polarizations are present (Q and V is largely not zero) du to cross talk and should not be.
So looking at this figure, it is clear that some critical parts of the transfer optics must be changed to improve the situation.

The document #2 studies a number of alternatives based on not only the optical components but also coatings that are to be applied to the surfaces. The reader can refer to the full study for all the details. To summarize a long and very detailed development, the currently preferred solution requires:

- to replace each of the elevation axis M4 and M5 45° incidence mirrors by 2 mirrors at 22.5 ° incidence coated with phase enhanced silver coatings (4 mirrors instead of 2).
- to replace the current derotator by a new concept derotator made of 4 glued RAP prisms at 100° in a 5 reflections design. This element by far the worst one in its current implementation, and the one that impact more the polarimetric budget.
- for a general simplification of all the former changes, and although it does not affect the polarimetric budget, the M2 shall be lightly reshaped (or changed) to modify the f/63 telescope beam to a f/62.9 and move up the F2 focus.

The Mueller model of the new design **is shown on Fig. 60**. As expected this configuration gives excellent results on maintaining the Stokes parameters ±Q (in this example case, but the same would happen for ±U. Absolute Q parameter is kept greater than 0.98 all the day long (compared to the ±0.7 of the current transfer optics). The intensity variation is always better than 0.982. This behaviour makes this new optical configuration the best choice to implement our new open field polarimeter in a dual beam configuration.

To conclude this section, Fig. 58 presents a sketch of the optical modifications required to change the transfer optics to the new configuration. One shall note the disappearance of the "small telescope". The overall global throughput of the new design is always 2 times better than the current one, except in the blue (400 - 450 nm) where it is even much better.

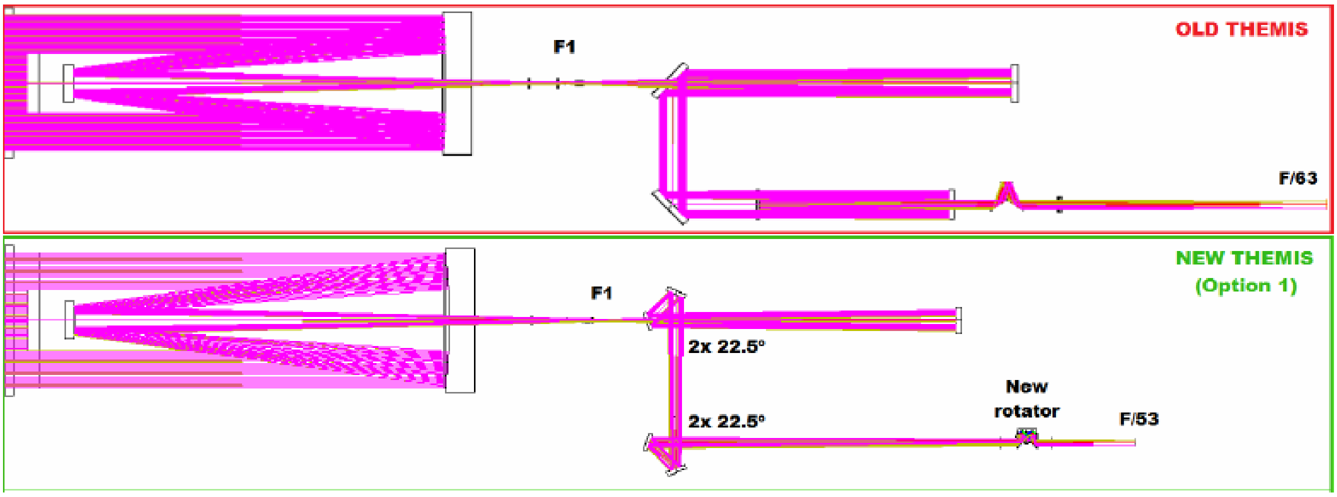


Figure 58: Optical Design of configurations 1 (vs. Current configuration)

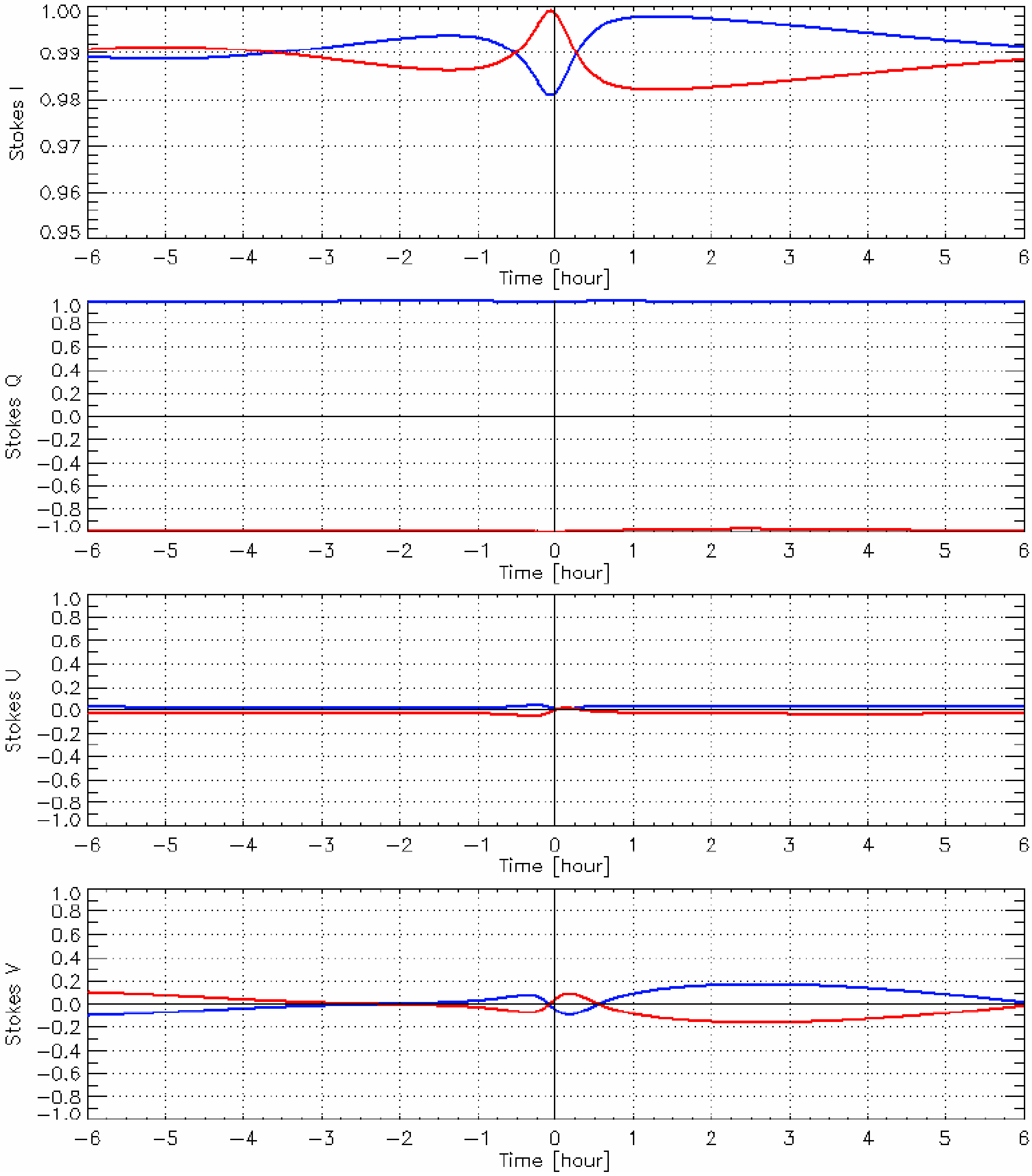


Figure 60-1: **CONFIG 1 Beams 1 & 2 Stokes vectors @ 500nm** for a **Solar North** slit vs. Time
(**blue**: Beam 1; **red**: Beam 2; **Input 1 [1, +1, 0, 0]** ; **Input 2 [1, -1, 0, 0]**)

Optics system design specification (3rd document)

This document details the changes required to implement the new optical path of THEMIS that has been specified in the former 2 documents. This opto-mechanical preliminary study is done from the telescope entrance and moving downward

From the entrance to F1

The report indicates the specification of the new M2, manufacturing tolerances. It outlines the installation procedure, and the qualification of the new F1 focus, using a dedicated curvature sensor. The goal of the qualification method will be to:

- Set the F1 focus at the theoretical position of 3773 ± 0.19 mm.
- Qualify the residual off-axis coma at two symmetric radial coordinates (+/- 110 arcsec) to verify and eventually adjust the M2 angle (if the coma values are not opposite).
- Qualify definitively the resulting image quality of the REAL WORLD design, measuring static aberrations for example the Zernike function factors from Z4 (defocus) to Z11 (sphericity) for being the typical real static aberrations that can present real optics (due to polishing and/or mechanical holders).

Transfer Optics Design (from F1 to F2')

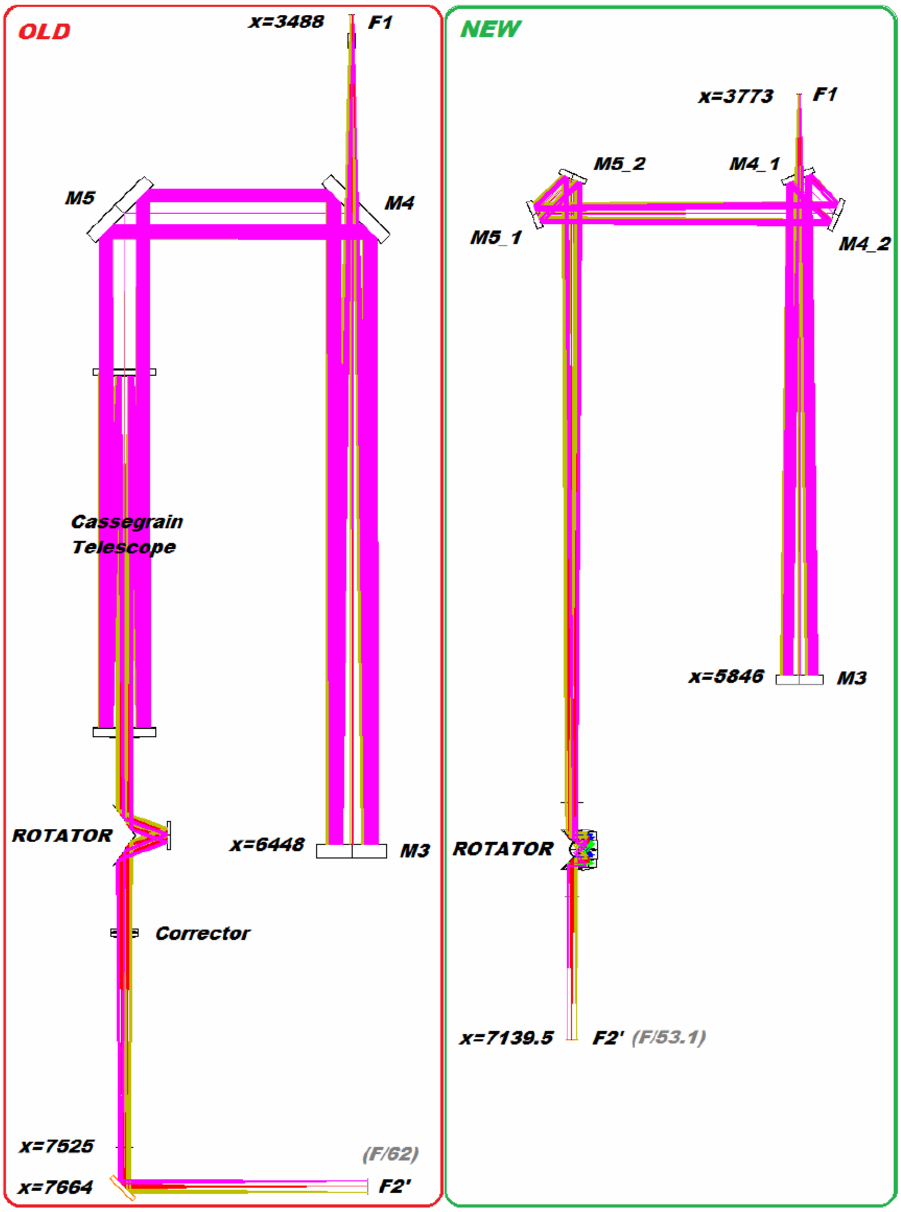


Figure 11-a: Current Optical Design (left) vs. New proposed Optical Design (right)

The major differences between old and new design comes mostly from 2 modifications:

– changing the M2 reduces moderately the focal length of the telescope and allows to use a new smaller M3 about 600 mm above its current position.
– changing the M3 allows to form directly the F2' focus at a position that makes easier the AO bench so that we can get rid of the small Cassegrain telescope and lens corrector; This F2' is formed at a smaller scale (F/53.1) and closer to the rotator to make the new rotator optics smaller and more tolerant. A positive consequence of this direct imaging is that the beam footprints over the design are considerably smaller. These smaller footprints result in many other advantages.

All the new components are studied separately for their optical design, coatings and alignment tolerances. A special emphasis is given to the **rotator** study. This new rotator uses bonded right angle prisms (total reflection prisms) with two different coatings, an antireflection coating on their in/out faces and the hypotenuse face shall receive a specific MgF2 + TiO2 coating to minimize and make wavelength independent the phase difference of the S and P rays. Manufacturing tolerances are indicated.

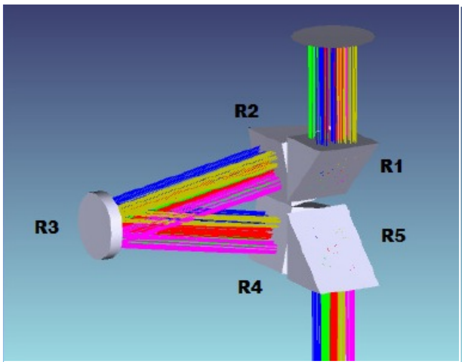


Figure 14-a: New ROTATOR Design

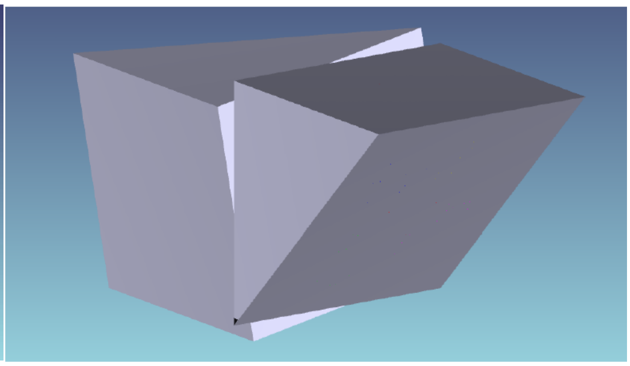


Figure 15-c: Rotator's RAP bonding (RAP 1 & 2 example)

The model F2' focus is then estimated in spot-diagram (excellent), longitudinal chromatism (4 times better than the current one), MTF, FEE. One striking point is the gain in transmission which is impressive as can be seen on the next Fig. 21-a

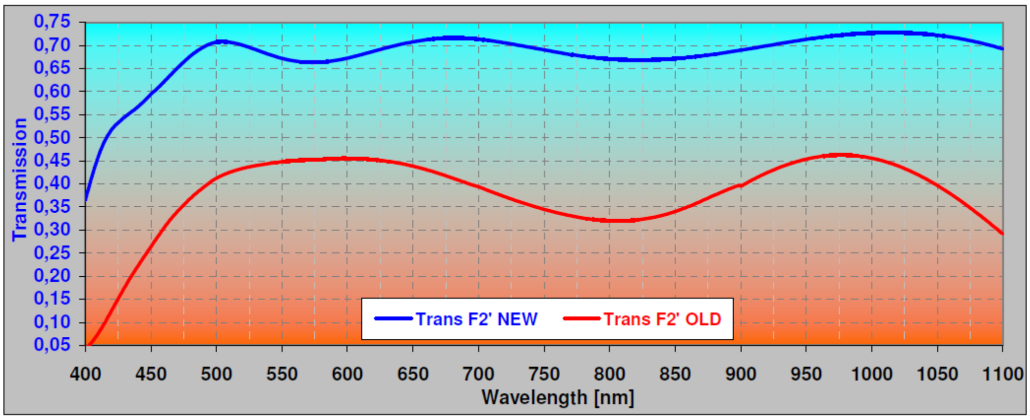


Figure 21-a: Transmission at F2' Focus of the New Design vs. Current Design
(blue: New Design Transmission; red: Current Design Transmission)

This section also addresses also the question **of tolerance and qualification** of:

- The F2' longitudinal position. This specification relies on the M3 figure and on the M3 mount and adjustments;
- The elevation axis alignment: this is a very important point that conditions almost everything behind. Remember that our current 45° M4 and M5 mirrors doing this function are replaced by 4 22.5° mirrors (named M4_1, M4_2, M5_1, M5_2) . The new elevation axis will go from M4_2 to M5_1. The critical part is the M4_2 mount being

inside the elevation and subject to flexion. Preliminary estimates shows that stability under load of the mount shall be ≤ 0.00033°

- The rotator alignment: this is also a critical issue that may have the same devastating effects than the elevation axis if not done properly. The incoming and exit beams MUST be aligned with the rotator rotation axis at better than 0.0015º (about 5arcsec). This is a very demanding number. Sources of misalignment can be separated into two categories: errors of alignment of the motorized rotating stage (with respect to the beam) and errors of alignment of the rotator optics themselves (with respect to the beam). Each of these error sources is discussed and alignment specification is proposed.

This is clearly the part of the study whose implementation would require more time and money. Next, **qualification procedures and tools required** for the practical actions are described for F2' position measurement, elevation axis alignment and rotator alignment.

AO Transfer Optics Design (from F2' to F2)

An optical description and a sketch of this AO optical path have been given previously, and we will not repeat it. Fig. 27-b shows the mechanical integration of Fig. 27-a inside the spectrograph cylinder. The optical parts are concentrated on the sides. The scan mirror must stay somehow outside but this will not be a problem

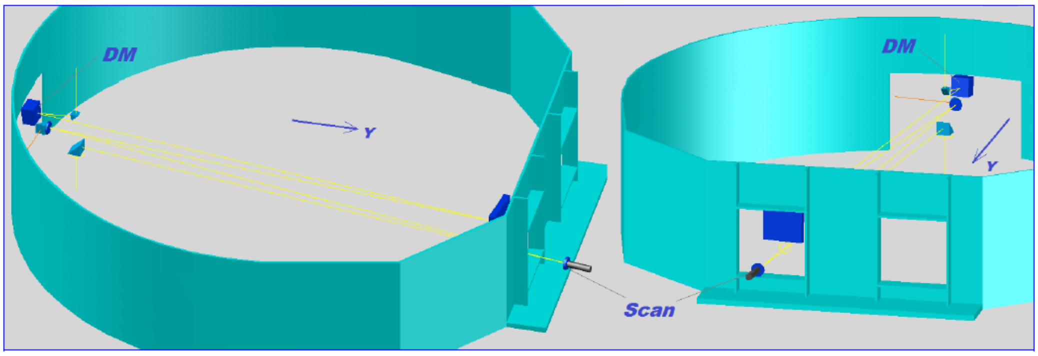


Figure 27-b: Mechanical INTEGRATION **of the AO Transfer Optics Design**

Tolerance and qualification of the AO optics have been studied: in the AO Transfer Optics between F2' and F2, three goals have to be achieved:

- The pupil longitudinal position on the DM. This is achieved through tuning the field lens and the DM positions
- The beam alignment between RAP2 (exit of the AO) and the spectrograph predispersor grating. This is done tuning preferably the OBJ2 mirror (also in the pupil)
- The F2 longitudinal position (x=8532mm) is qualified with the same experiment than the F2' focus is qualified

Finally, it is mandatory to qualify the DM flattening on a separate optical bench.

Shack-Hartmann Wavefront Sensor Design

Fig 38-a shows again the Shack-Hartmann branch of the AO optical path. (Remember this branch is in the y-z "horizontal "plane). This branch is feeding 3 sensors:

- SH-WFS at 500 nm, 20nm bandwidth (see photonic budget in TAOp-001), the main AO sensor
- Solar Tip-Tilt Sensor at 430 nm, 10 nm bandwidth (current sampling). This sensor will relay the SH-WFS when the seeing r0 is below r_0= 4.7 cm. **It will drive the same AO-DM in tip-tilt mode only**
- Mercury Tip-Tilt Sensor on the whole 400 to 800 nm spectra (current sampling), for Mercury observations.

Entrance to this branch is through the beam sampler (FM-BS) bonded to a folding RAP prism bonded itself to an (LC) field lens. This lens will form a 6mm pupil on a 2 axis scanning mirror (Scan WFS). This scanning device will allow the WFS to see a slightly (+/- 10 arcsec) different object than the given field centre. Of course the anisoplanatic angle limits strongly the efficiency of an off-centre correction, but still the flexibility of this feature will be very welcome during practical observations.

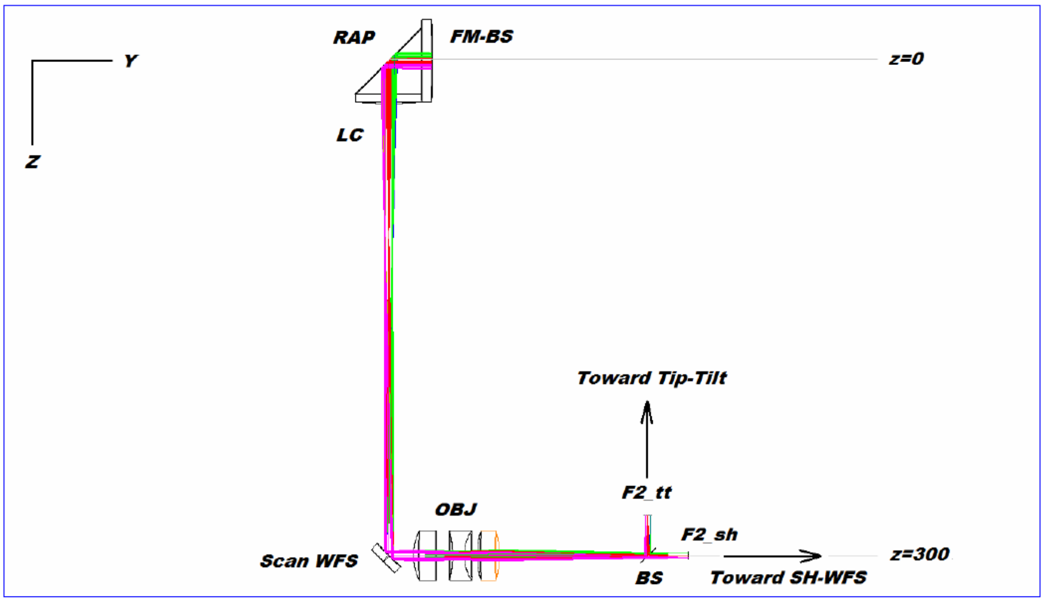


Figure 38-b: **SH-WFS SCANNING** device in the SH beam common path
(32x32 $arcsec^2$ Field represented)

Using the OBJ lens just behind the scanning mirror, we form a focus with a high optical quality. This focus is the REFERENCE focus for the posterior systems (Shack-Hartmann, Solar Tip-Tilt and Mercury Tip-Tilt). This focus aperture is F/20.4 with a scale of 88.9µm/arcsec. You can see in figure 38-b that we divide the beam in two paths just before this focus. This division is done by a retractable mirror (BS):

- Mirror OUT: Focus F2_sh, the beam follows on the Y axis toward the SH-WFS
- Mirror IN: Focus F2_tt, the beam is folded toward -Z for BOTH Tip-Tilt Devices.

Notice that all the photons are sent OR to the SH-WFS OR to the Tip-Tilt devices. The F2_sh focus is equipped with (motorized) calibration pinholes and targets. Finally the design of the terminal SH-WFS is shown on Fig. 39-a

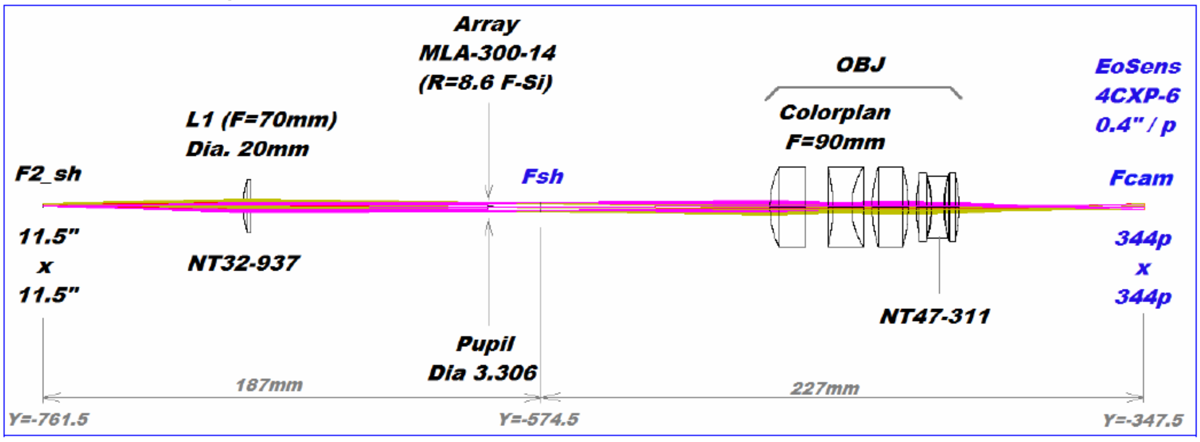


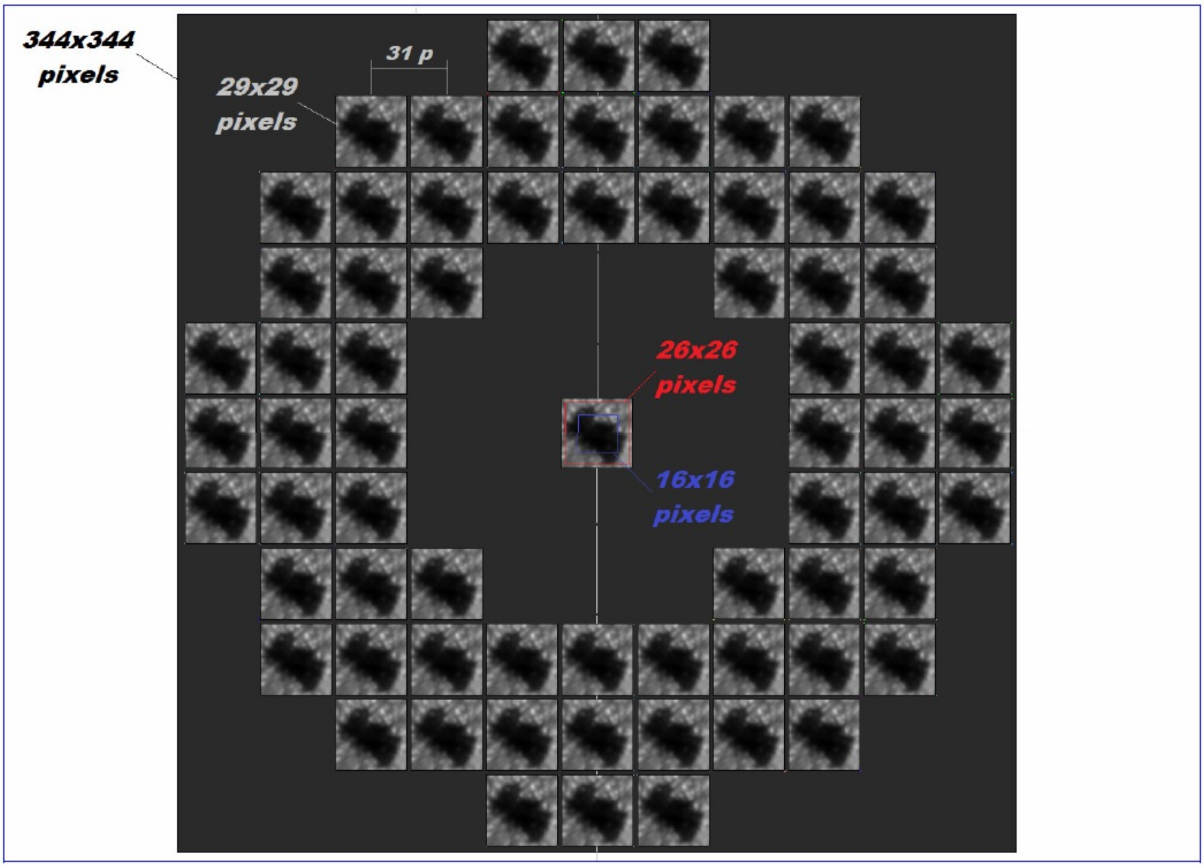
Figure 39-a: **Shack-Hartmann WaveFront Sensor Design** (plan YZ)

The Fsh focus is re-imaged here at F/4 on the our camera detector. An image of the WFS camera (obtained with our current AO software in simulation mode) is show on Fig. 39-c with the following key parameters:

- camera: Mikrotron EoSens 4CXP-6, pixel 7µm, 10bits, 3000fps for ROI 320x320 pixel

- ROI: 344x344 pixels (2600 fps without exposure time, 1500fps with 0.3ms exposure).
- 68 SUB-IMAGES of 29x29 pixels (11.5x11.5arcsec2)
- scale: 0.4 arcsec/pixel
- sub-images pitch: 31 pixels (2 pixels of separation between images)

The correlation function is computed by the "Sum of Absolute Difference" (SAD) method, and then squared (SAD2). The sub-pixel position is then interpolated using a 2D quadratic interpolation algorithm (2QI). Extensive details about the software and SH-WFS study can be found in TAOp-001 (Document #1).



Additional optical designs

Additional optical designs studied in Document #3 are

- the implantation of a **camera dedicated to both field control and high-quality broad band imaging** in parallel with the use of the spectrograph . Assuming an open field analyzer and a redesigned scanning, we have the possibility to provide high quality G band imaging **and** (scanning) spectropolarimetry at the same time, which is a very nice feature.
- The **spectrograph field lens must be changed** to tune the spectrographs to the new pupil specifications (Exit Pupil at F2: diameter 42.6 mm at 2586 mm above the F2 (vs. 92.6 mm at 5950mm)).
- Instruments beams splitters are studied into detail from a system point of view. It is explained in document #2 that the separation of the analyzed beam is better perform at camera level (instead of F2 level). Once a camera is selected and a field is chosen, the Wollaston prism IS DEDICATED to that configuration. NO changes can be done on the field or the camera WITHOUT changing the Wollaston angular separation. It is essential, to decide of the instrumental configurations before designing the beam-splitters. In a minimum assumption approach, a selection of separators elements has been done. This selection will be subject to further revision when the new instrumental configurations / wavelengths channel will be decided.

Budget /schedule

CONCEPT	Sub-concept	Optics	Mechanics	Electronics	Total cost
Telescope up to F1	Optical Path	102.000 €	0 €	0 €	**102.000 €**
	Polarimeters	20.000 €	0 €	0 €	**20.000 €**
	Qualification	2.000 €	11.000 €	10.000 €	**23.000 €**
Transfer Optics (from F1 to F2')	Optical Path	98.700 €	110.000 €	0 €	**208.700 €**
	Qualification	4.700 €	5.000 €	1.000 €	**10.700 €**
Transfer Optics (from F2' to F2)	Optical Path	54.500 €	30.000 €	60.000 €	**144.500 €**
	Scanning Syst.	0 €	0 €	12.000 €	**12.000 €**
	F2' Target Stage	3.000 €	4.000 €	3.000 €	**10.000 €**
	DM Qualification	5.000 €	15.000 €	0 €	**20.000 €**
Shack-Hartmann & Tip-Tilt Sensors	WFS Scanning	400 €	1.000 €	8.700 €	**10.100 €**
	$F2_{SH}$ Target Stage	1.500 €	1.500 €	3.000 €	**6.000 €**
	SH-WFS	3.310 €	8.000 €	18.500 €	**29.810 €**
	Tip-Tilt "Sol & Star"	1.600 €	6.000 €	3.500 €	**11.100 €**
Additional Functions	G-band Imaging	14.500 €	3.000 €	19.000 €	**36.500 €**
	Spectro. Field Lens	7.000 €	0 €	0 €	**7.000 €**
	Beams Splitters (13)	52.000 €	9.000 €	0 €	**61.000 €**
		370.210 €	**203.500 €**	**138.700 €**	**712.410 €**

Table 16-a: Project Solarnet WP7.1.2 Proposed **BUDGET**
(**hottest costs in red**)

Table 16-a shows he total budget that rises up to 715 k€ for the equipment. This budget falls into about 52% for optics, 29% for mechanics and 19 % for electronics (& informatics).
The mechanical costs of the Transfer Optics (110k€) and of the AO Transfer Optics (30k€) are estimated. These real costs would be determined by both mechanical engineers working on these tasks (mechanical studies starting in September 2014). The Adaptive Optics implementation in itself, including SH-WFS and both Tip-Tilts represents a total cost of about 250k€ over the 715k€ (35%). This confirms that inserting the AO in Themis was not the major problem, nor task, nor cost, but rather OPENING the Field of our F1 polarimeter while maintaining a DUAL-BEAM configuration in F1 (which has been a prerequisite). Opening this F1 polarimeter field allows us to implement the AO, a downstream scanning system and a more simple & accurate polarimetric measurement, but at the COST of modifying the optical design from F1 to F2.

A first proposition of schedule and manpower was given in the report TAOp-001, at the end of the first study in October 2013. We remind that this study was limited at the Adaptive Optics part of the complete study. After both studies (TAOp-002 on Polarimetry & TAOp-003 on Optical Design), it becomes evident that the job to do is much more important than the one described in TAOp-001, particularly in opto-mechanics. As far as the project timing is and up-down one (project limited to 4 years), the schedule in itself is unmodified (in terms of timing), but the manpower has to be revised, i.e. increased in terms of manpower (the Themis “team” being very small). **The proposed schedule and manpower are shown in table 16-b.**

Solarnet WP7.1.2	2013	2014	2015	who	T	tx	etp
TAOP	1st project's year	2nd project's year		who	T	tx	etp
Tasks	5 6 7 8 9 10 11 12	1 2 3 4 5 6 7 8 9 10 11 12	1 2 3 4		[m]	%	[m]
TAOp_001 (AO Syst. Design)				clm	5	50	2,5
TAOp_002 (Polar Syst. Design)				clm	3	90	2,7
TAOp_003 (Optic Syst. Design)				clm	5	90	4,5
Project Review				bg			
Decision				bg			
Optics study (components)				clm	8	70	5,6
Mechanical Study (**System**)				clm	8	20	1,6
Mechanical Study 1 (**Plans**)				rg	8	95	7,6
Mechanical Study 2 (**Plans**)				sc1	8	95	7,6

Solarnet WP7.1.2	2015...	2016	2017	who	T	tx	etp
TAOP	3rd project's year	4th project's year		who	T	tx	etp
Tasks	5 6 7 8 9 10 11 12	1 2 3 4 5 6 7 8 9 10 11 12	1 2 3 4		[m]	%	[m]
Purchases DEAD LINE	!						
Supply follow-up (AO, Opt, ...)				clm	7	15	1,1
Supply follow-up 1 (mechanics)				rg	8	30	2,4
Supply follow-up 2 (mechanics)				sc1	8	30	2,4
Scanning Computer &Software				dl	4	95	3,8
AO Software realization				clm	8	80	6,4
Integration (Optics, Mechanics)				clm	3	95	2,9
Integration (Optics)				sc2	3	95	2,9
Integration (Mechanics)				rg	3	95	2,9
Integration (Mechanics)				sc1	3	95	2,9
1st project report (@36 months)				bg			
Telescope Qualification (Optics)				clm	3	95	2,9
Telescope Qualification (Optics)				sc2	3	95	2,9
AOP qualification				clm	3	95	2,9
Scientific Qualification				bg			
2nd project report (@48 months)				bg			

bg: Project Manager (B. Gelly)
clm: System Engineer (C. Le Men)
rg: Mechanical Engineer (R. Gonzalez)
sc_1: Mechanical Engineer (subcontracted)
sc_2: Optical Technician (subcontracted)
dl: Software Engineer (D. Laforgue)

Manpower etp [m]	
clm	32,9
rg	12,9
sc1	12,9
sc2	5,7
dl	3,8

Table 16-b: Project Solarnet WP7.1.2 Proposed **SCHEDULE** & **MANPOWER**
(**Red arrow**: 18 months of clm's imputation)

It shall be stressed that there is very significant difference in manpower from the original proposal. This comes from the selection of the alternative #3 in the proposal, as the only one resulting in a physical integration.

Manpower identified by System Design Studies TAOp-001 (AO) TAOp-002 (Polarimetry) & TAOp-003 (Optics) (including studies manpower)		**Manpower asked in 2012**
System & Optical Engineer (Themis UPS853 - clm)	32.9 months	33.0 months
Mechanical Engineer (Themis SL - rg)	12.9 months	17.0 months
Software Engineer (Themis UPS853 -dl)	3.8 months	5.0 months
Mechanical Engineer (sub-contracted)	12.9 months	0.0 month
Optical Technician (sub-contracted)	5.7 months	0.0 month
Total	**68.2 months**	**55.0 months**

Table 16-d: Technical Manpower Proposal for this study

The divergence between the manpower proposal in 2014 and the one proposed in 2012 (+13.2 months) is essentially due to the obligatory modification of the transfer optics between F1 and F2'. This modification is imposed by the specifications (open-field dual-beam polarimeter in F1) and generates a higher quantity of work, principally in optics and mechanics.