Latest technical developments at THEMIS of possible interest for EST

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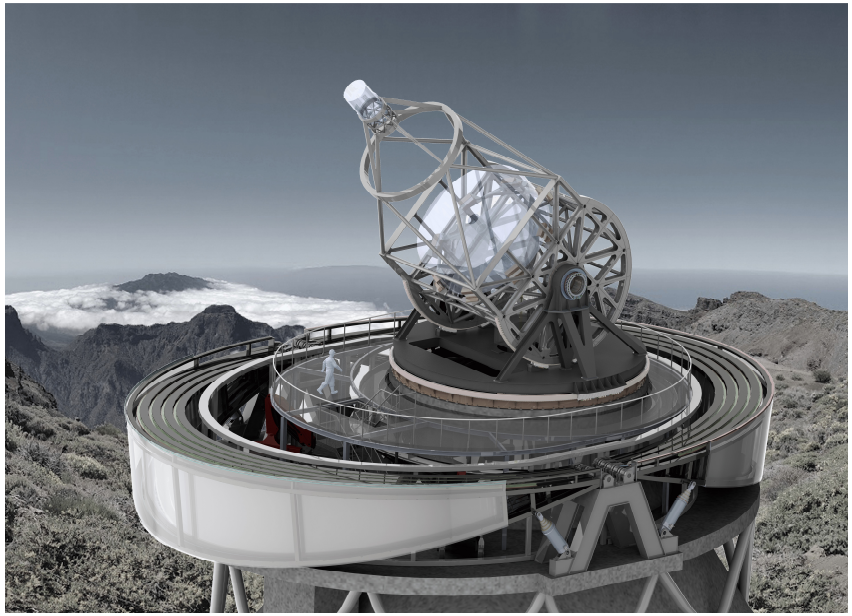
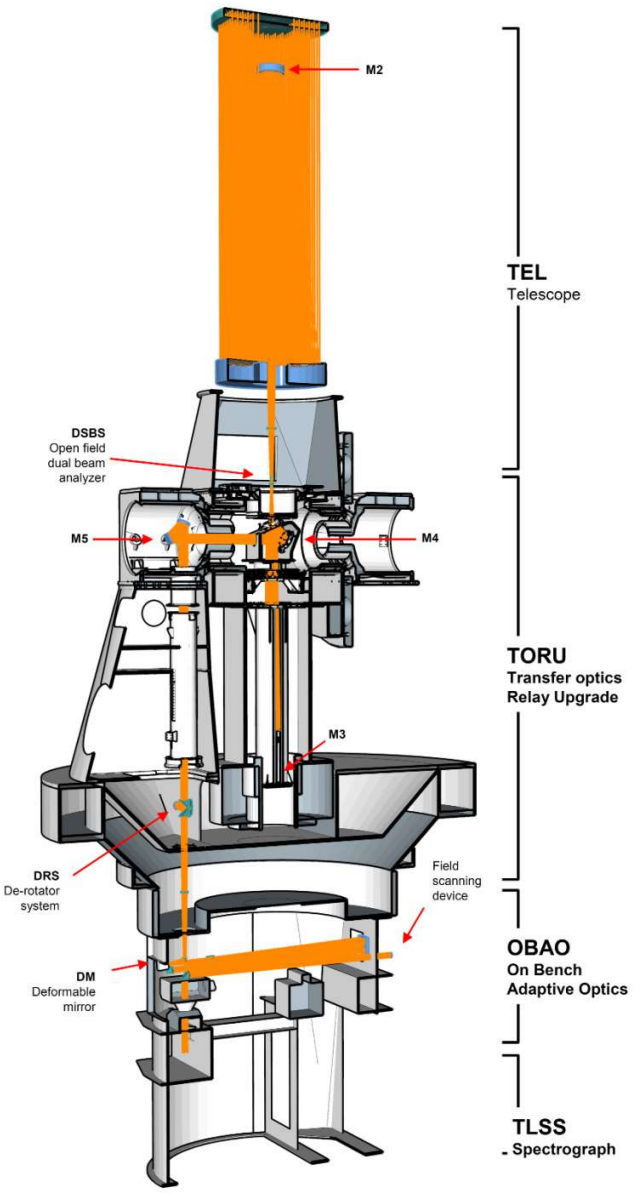


THEMIS overhaul: 2016 → 2020

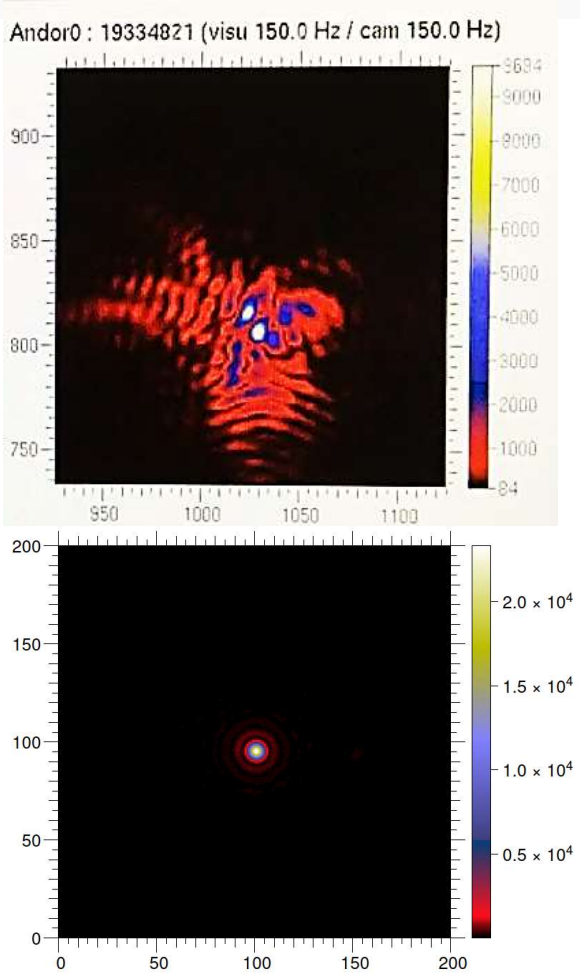


- THEMIS has been widely renewed since 2016 and over 5 years, resulting in a **big success for French teams ,** running on EU money (~1M€ funding came from two SOLARNET EU programs)
- Some of the technical developments we have made are of possible interest for EST
- **Superimposed dual-beam polarimetric analysis without field limitation (1' polarimetric field) (Semel M., Lopez A., Le Men C. & THEMIS)**
- **"Polarization- friendly" complete redesign of the whole transfer optics (Le Men, C. & THEMIS)**
- **TAO "classical" (single-DM) adaptive optics based on innovative wavefront sensing and mirror commanding concepts that can be applied to larger systems (The AIRI team @CRAL & THEMIS)**
- Instrumental and strategic know-how is as good as ever was
- Teams to build and operate do exist
- Bosses to pay some small running costs also can be found

Themis Adaptive Optics TAO initial specifications and objectives

- Specifications
  - 90 cm diameter solar telescope;
  - **76 sub-aperture Shack-Hartmann wavefront sensor** (10×10);
  - 380×380 pixel WFS images, Mikrotron EoSens 4CXP detector;
  - **97 actuator Alpao DM** (11×11);
  - RTC computer: CPU i7-4790K (Q2'14) at 4.2 GHz, 4 cores, up to 50 Gflops/core **with AVX2 + FMA instructions.**

- Objectives
  - **close the AO loop on the Sun** (started from scratch mid-2016, job done December 2020);
  - **unsupervised AO system** (optimal correction whatever the conditions)
  - flexible RTC software to implement and experiment new algorithms (Julia lang)
  - **RTC software running in CPU (no GPU) @1250 Hz**



Thiebaut, E., Tallon, M. et al, SPIE proceedings 2022

TAO linearized model of wavefront sensor data and DM commands in the THEMIS system

WFS data — Actual wavefront — Actuator commands — … some noise

$$\boldsymbol{d}_t = \boldsymbol{S}.(\boldsymbol{w}_t + \boldsymbol{M}.\boldsymbol{a}_t) + \boldsymbol{z}_t$$

Sensor linear response — Mirror influence matrix

$\boldsymbol{G} = \boldsymbol{S}.\boldsymbol{M}$ is the **interaction matrix**

$\boldsymbol{y}_t = \boldsymbol{d}_t - \boldsymbol{G}.\boldsymbol{a}_t$ are ≈ open loop data

$\mu_t > 0$ and $\boldsymbol{W} \approx Cov(w_t)$ are loop parameters to enforce **spatial regularization**

$\rho_t > 0$ is a loop parameter to impose **temporal continuity**

- Wavefront is represented in the basis of influence functions of the DM
- No predictions in TAO v.2 (but will appear in TAO v.3)

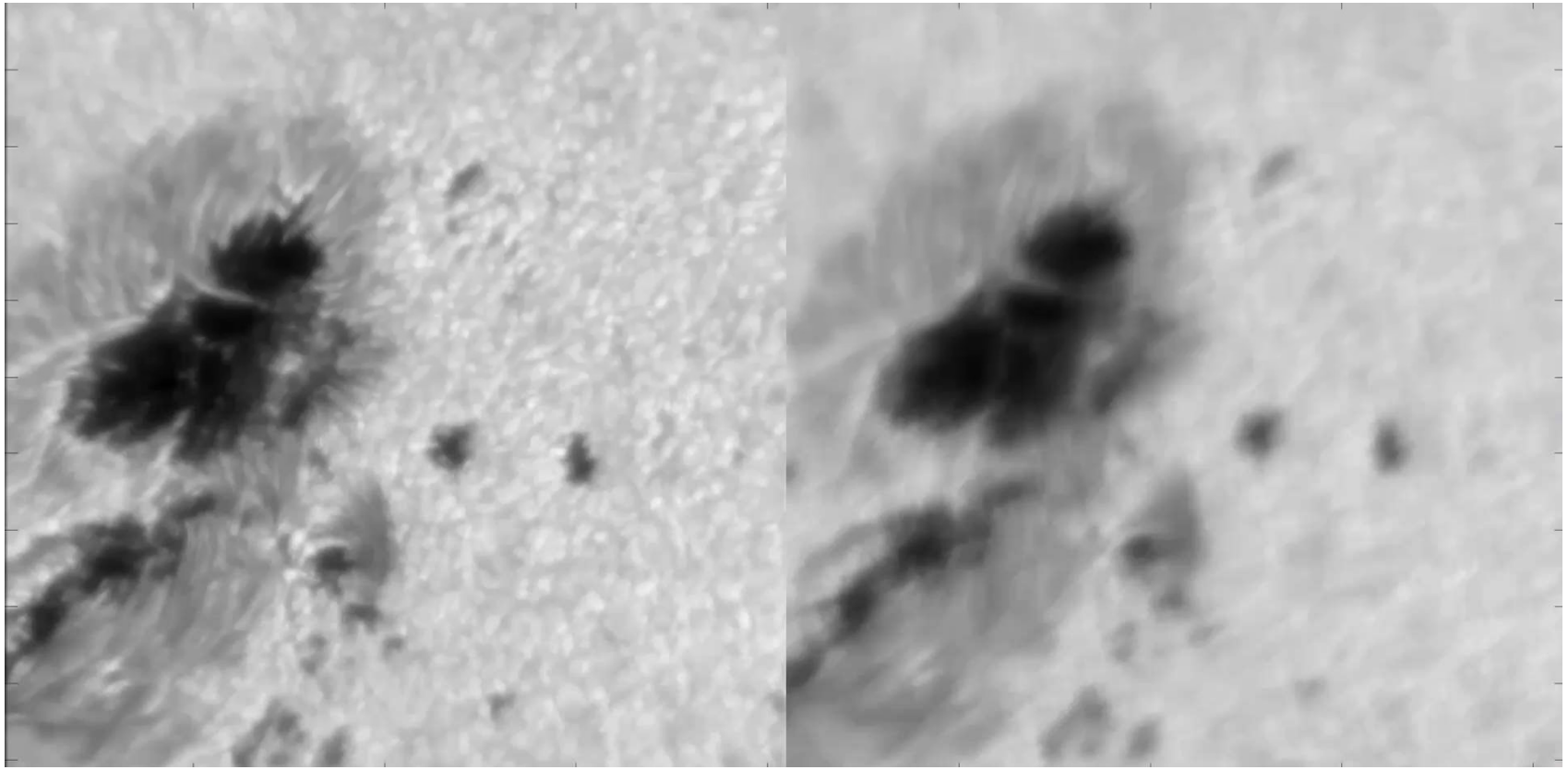
$$\boldsymbol{a}_{t+\delta t} = argmin\{ \|\boldsymbol{y}_t + \boldsymbol{G}.\boldsymbol{a}\|^2_{Cov(\boldsymbol{z}_t)^{-1}} + \mu_t \left|\left|\boldsymbol{a}\right|\right|^2_{\boldsymbol{W}} + \rho_t \left|\left|\boldsymbol{a} - \boldsymbol{a}_t\right|\right|^2 \}$$

→ Requires to solve an inverse problem (*argmin*…) at each step (all terms may change with time)

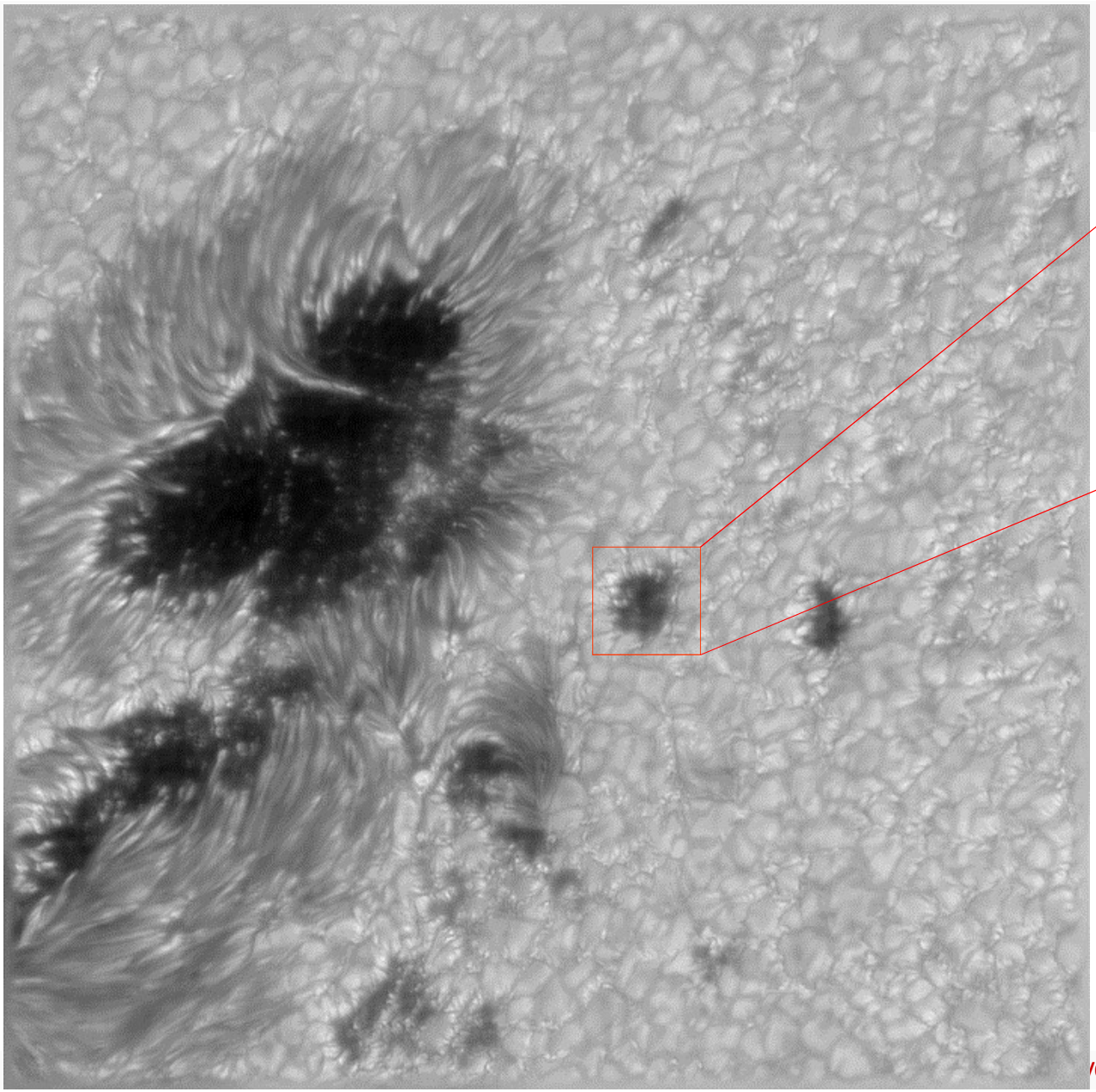
Thiebaut, E., Tallon, M. et al, SPIE proceedings 2022

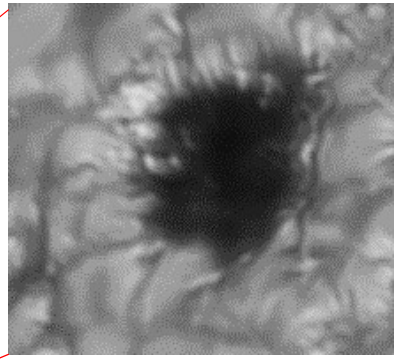
TAO going live on NOAA 12975

- Successive recordings in equivalent seeing conditions
- 55’’ square field, 20 fps (0.3 ms), 2k x 2k (0.03’’ /px)



TAO + TSI : NOAA 12975





- 31/03/ 2022
- with post processing THEMIS Knox-Thompson (TSI)
- 55X55” FOV
- **0.17 ’’ res (0.035 “ pixel) near diffraction limit**
- 630 / 1 nm red filter

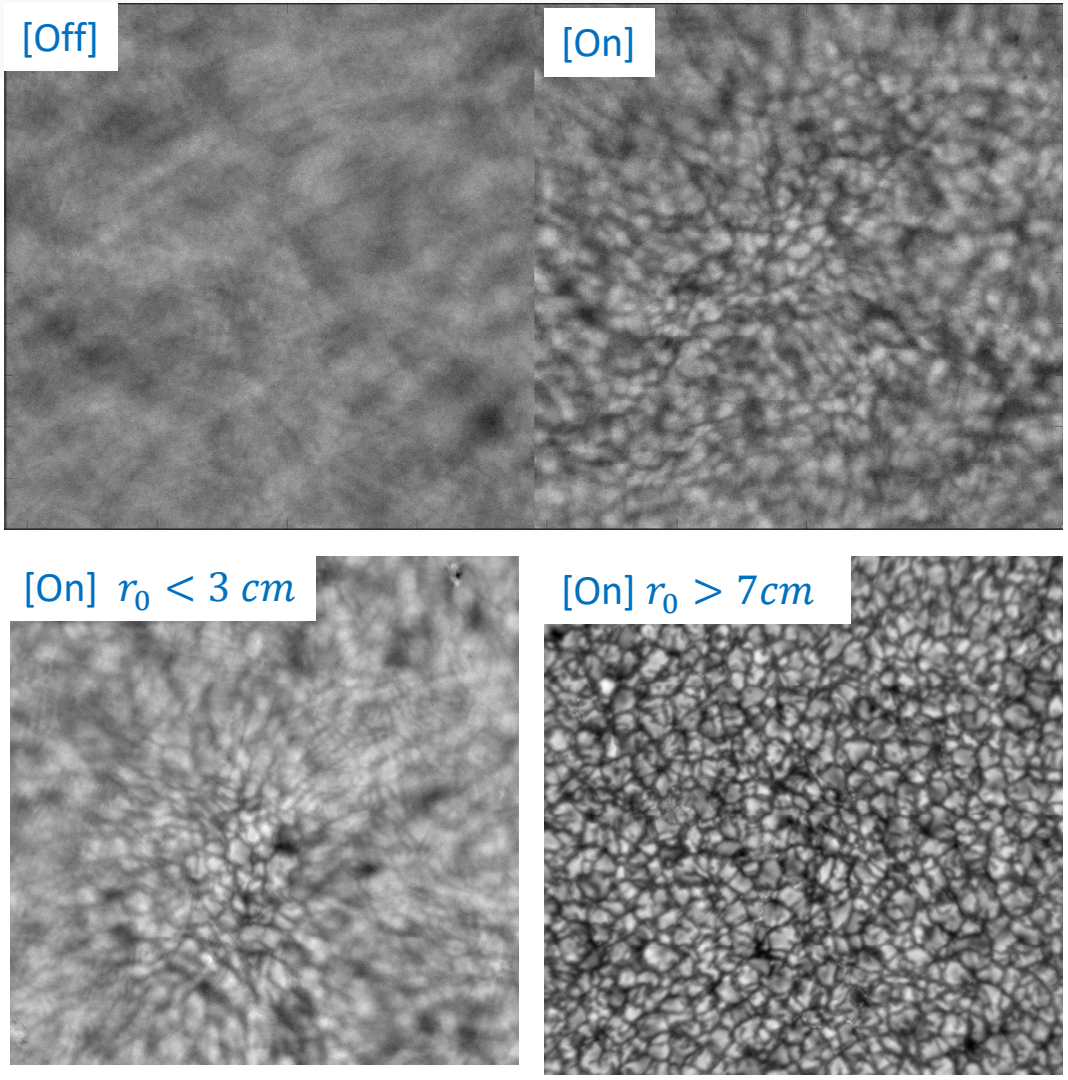
TAO v2.5 on granulation

- Isoplanatic patch can be severely reduced by high altitude turbulence
- Ground layer conjugated AO show limitations coming from high altitude seeing not dectected by

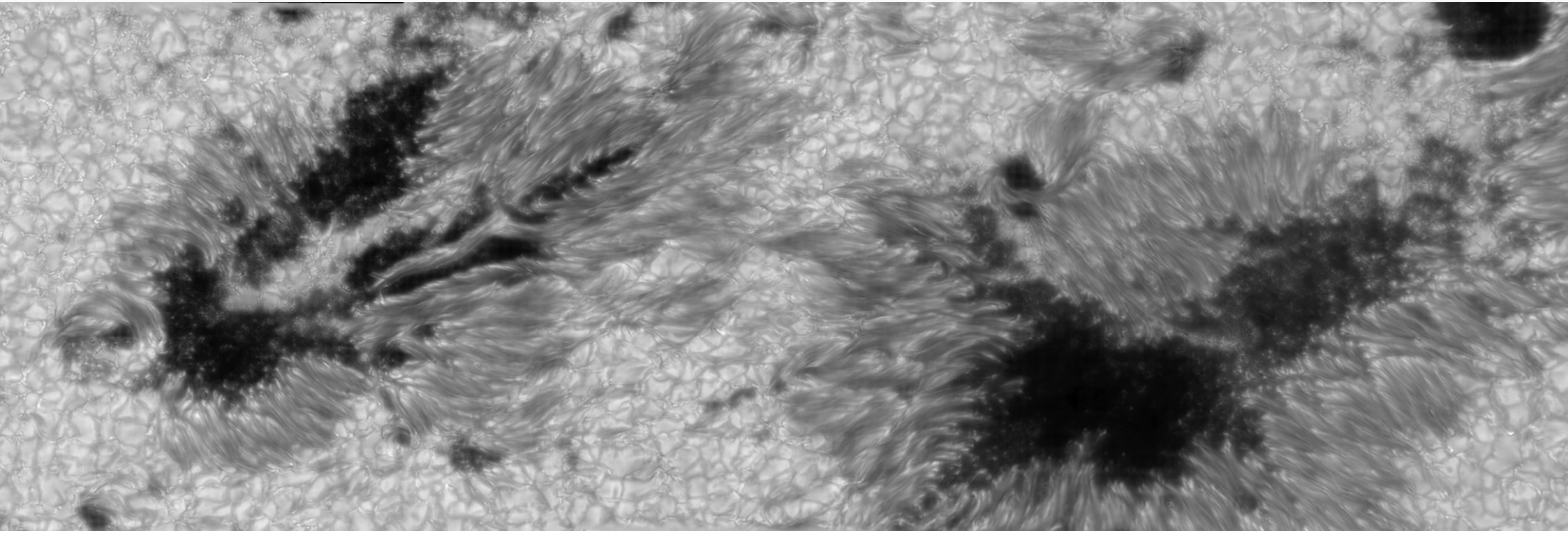
Given:

$\alpha = r_0 \,/\, D$

the same kind of result on a 4m telescope would require $r_0 = 28\ cm$



TAO + TSI NOAA 13354 wide field

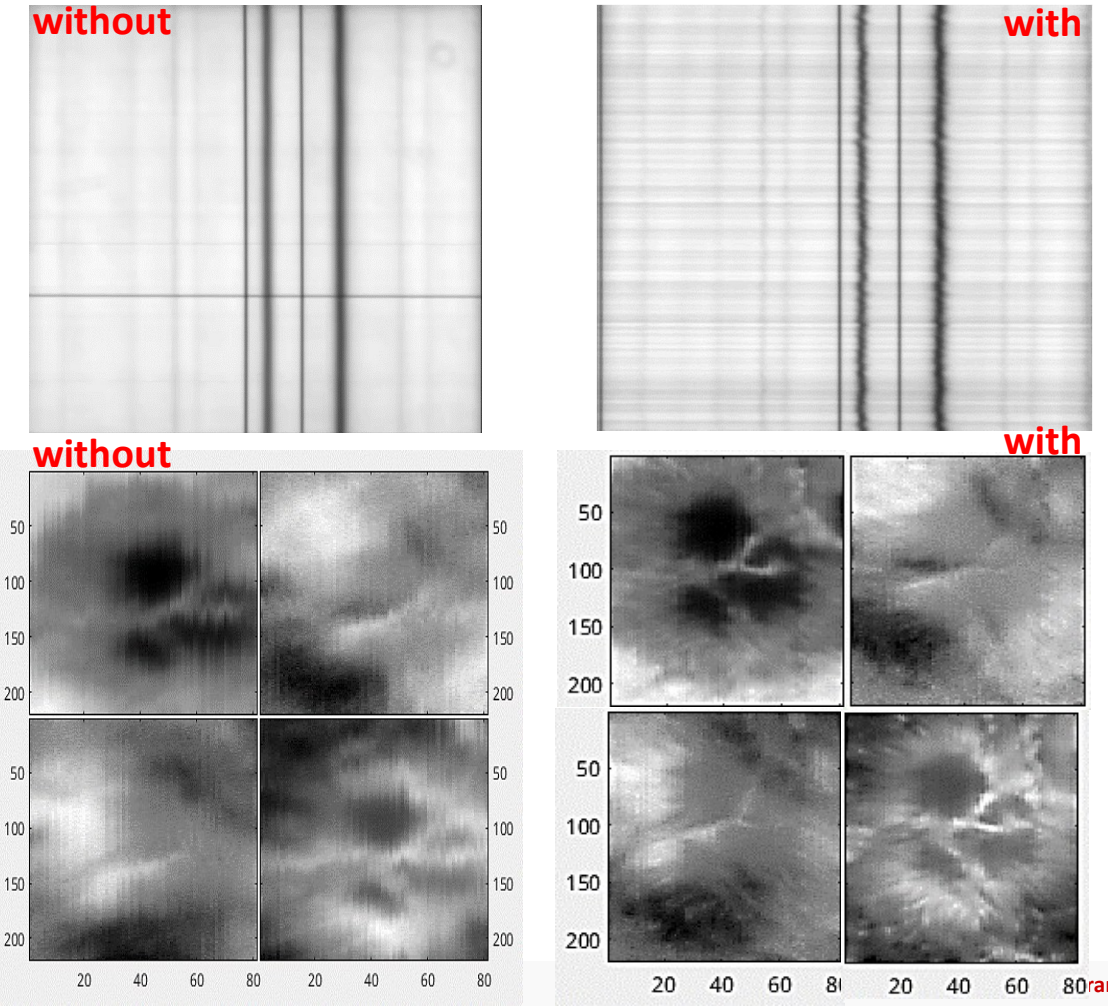


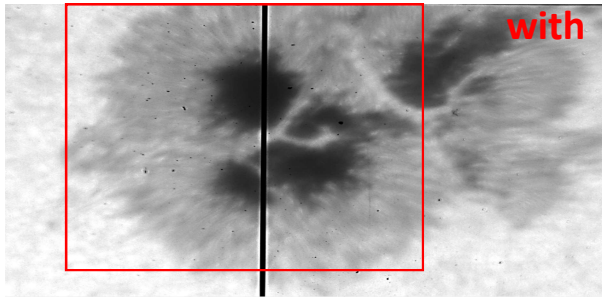
- NOAA 13354 from 2023/06/28
- 180x50 '' field
- **0.17 '' res (0.035 '' pixel) near diffraction limit**
- 630 / 1 nm red filter

- Solar telescope **with robust and innovative AO**
- Record bursts **and restore from residual seeing**
- Stitch
- => Routine operation with pipeline !

TAO for spectropolarimetry

110” spatial field (0.06’’/px), ~5.5 A spectral field , 3mA /px



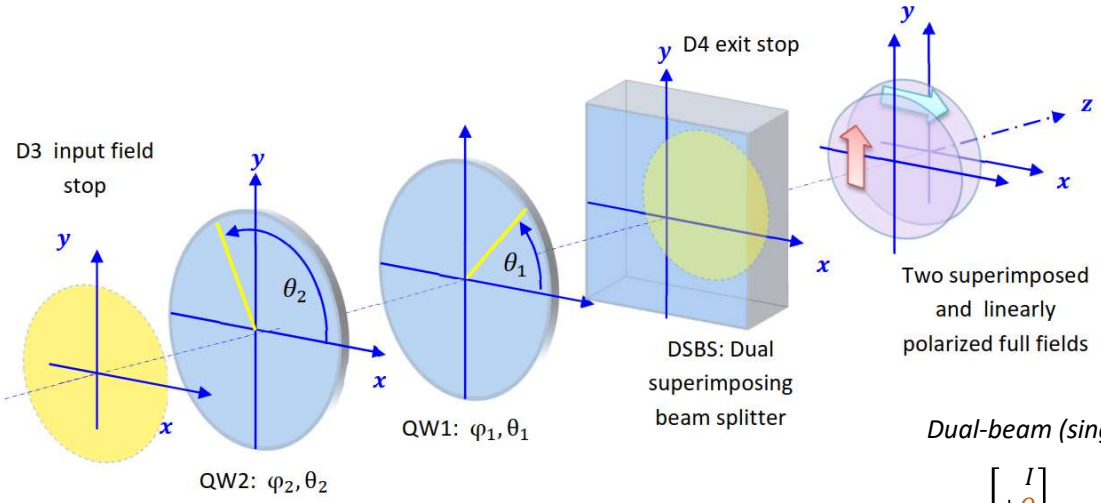


- **Stokes maps** are the last necessary step before running a magnetic field inversion software

Our goals are B maps spatial resolution better than 0.5” arcsec (3 times better than before, and comparable to HINODE results)

THEMIS new polarimetric analysis scheme

Full-Stokes analyzer (An4) **located at the F1 prime focus**, is designed to deliver **dual-beam polarimetry with beam exchange**.



Input

$$S = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix}$$

modulation (QW)

$$S_Q = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} \quad S_V = \begin{bmatrix} I \\ V \\ Q \\ U \end{bmatrix} \quad S_U = \begin{bmatrix} I \\ U \\ V \\ Q \end{bmatrix}$$

We use a double Savart plate that generates the dual beam feature and **also superimpose both beams so that they behave as one**, differing only by their linear polarization state.

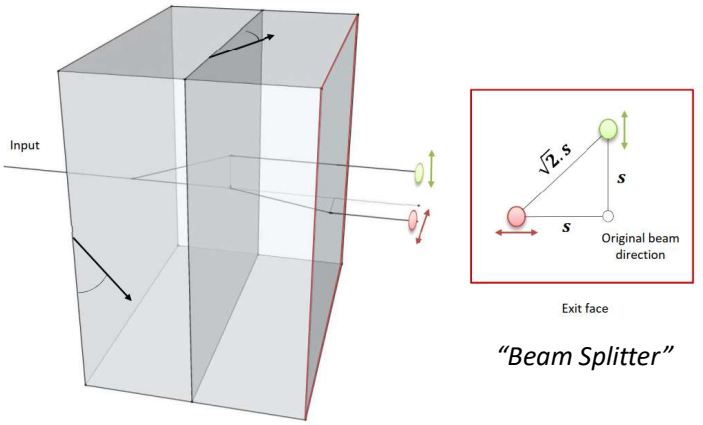
Dual-beam (single Savart plate)

$$S_{+Q} = \begin{bmatrix} I \\ +Q \\ 0 \\ 0 \end{bmatrix} \quad S_{-Q} = \begin{bmatrix} I \\ -Q \\ 0 \\ 0 \end{bmatrix}$$

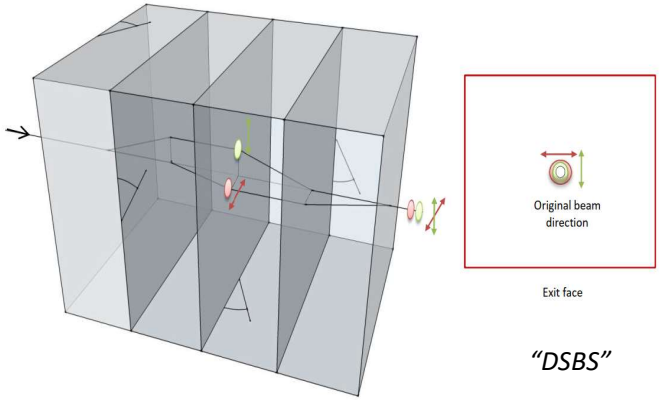
$$S_{+V} = \begin{bmatrix} I \\ +V \\ 0 \\ 0 \end{bmatrix} \quad S_{-V} = \begin{bmatrix} I \\ -V \\ 0 \\ 0 \end{bmatrix}$$

$$S_{+U} = \begin{bmatrix} I \\ +U \\ 0 \\ 0 \end{bmatrix} \quad S_{-U} = \begin{bmatrix} I \\ -U \\ 0 \\ 0 \end{bmatrix}$$

Beam exchange



"Beam Splitter"

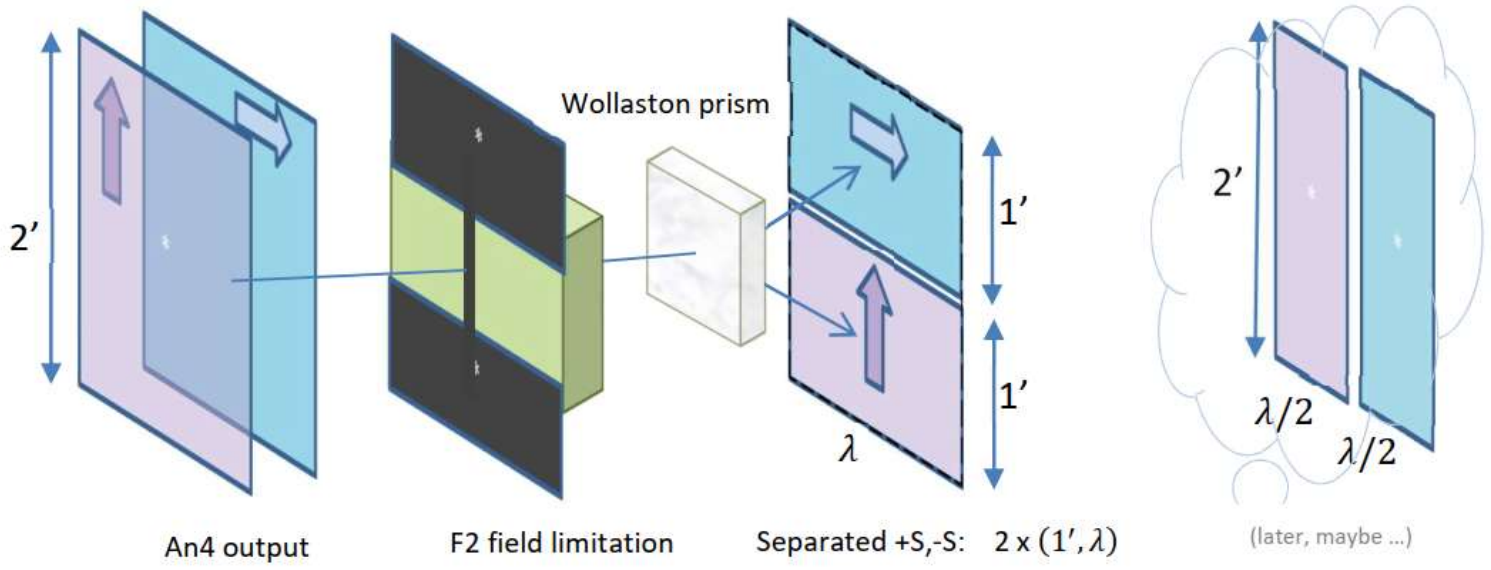


"DSBS"

THEMIS new polarimetric analysis scheme

- Thanks to THEMIS "**polarization friendly**" new optical path (**geometry of the elevation axis, field rotator, coatings)** , this output can travel through the telescope and reach the spectrograph cameras "minimally perturbed"

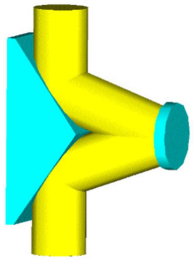
- **Just in front of the spectral cameras**, a Wollaston prism splitter (one per camera**) separates the superimposed beam** into complementary Stokes components to form the spectral focal plane.

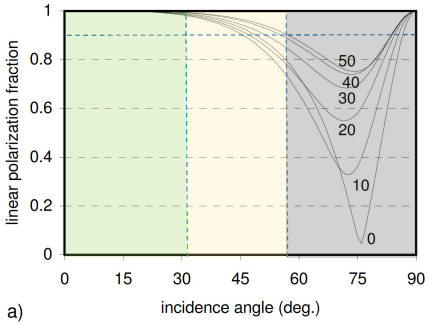


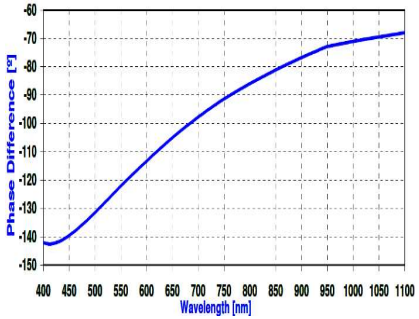
- 2 possible configs, the "easy one" is only used for now

Example of a "polarization friendly" field rotator

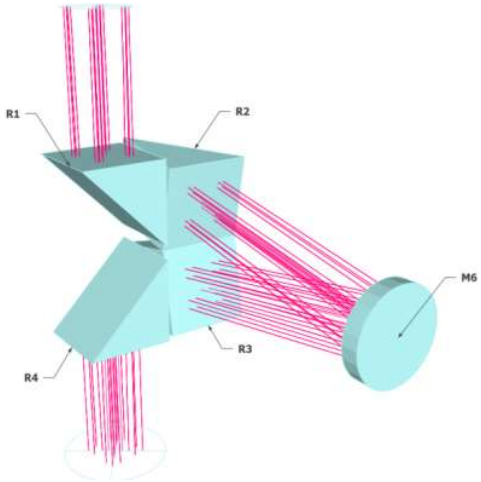
- **BAD (really bad …)**
- Made of 3 mirrors with incidence = **55º** / 20° / **55°**
- chromatic retardance is enormous (60°)

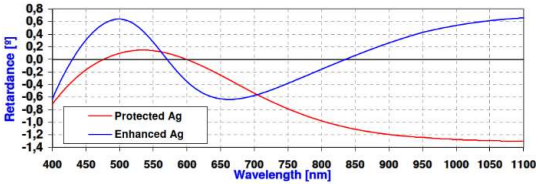






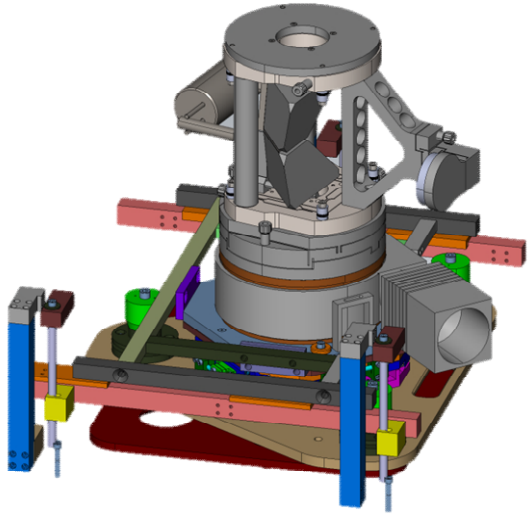
- **MUCH BETTER !!**
- Rotator, composed of 2 prisms and one mirror incidence=45º /45°/ 10° / 45° /45°
- **Retardance cancellation** of the crossed prisms@100° (zero retardance for 90° only)
- **Coating required** on prisms hypothenuse



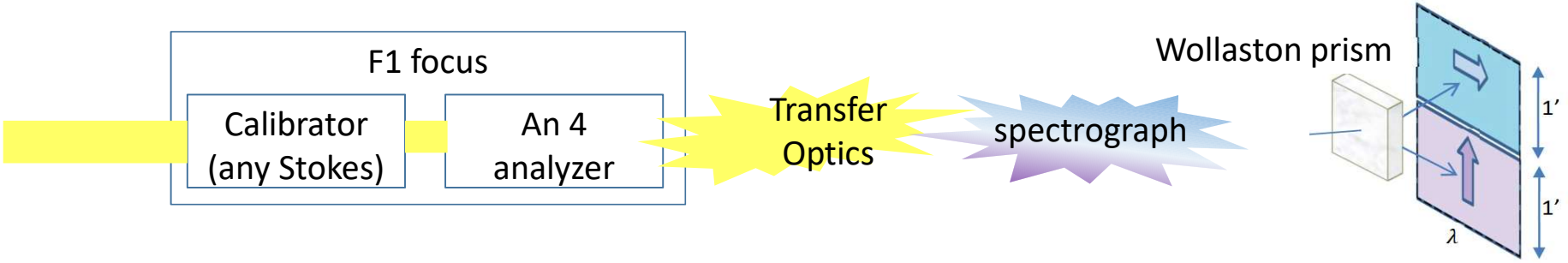


$$\mathrm{M}_{Rot}(Ag)=\begin{bmatrix} 0.943 & 0.057 & 0 & 0 \\ 0.057 & 0.943 & 0 & 0 \\ 0 & 0 & 0.007 & -0.941 \\ 0 & 0 & 0.941 & 0.007 \end{bmatrix}$$

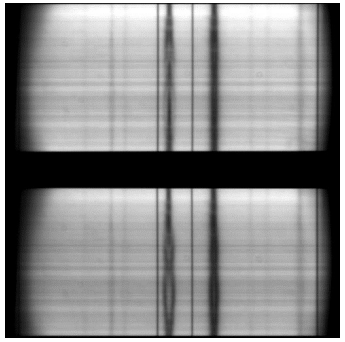
$$\mathrm{M}_{ROT}=\begin{bmatrix} 0.9991 & 0.0009 & 0 & 0 \\ 0.0009 & 0.9859 & -0.0205 & 0.1605 \\ 0 & 0.0179 & 0.9989 & 0.0189 \\ 0 & -0.1607 & -0.0157 & 0.9859 \end{bmatrix}$$



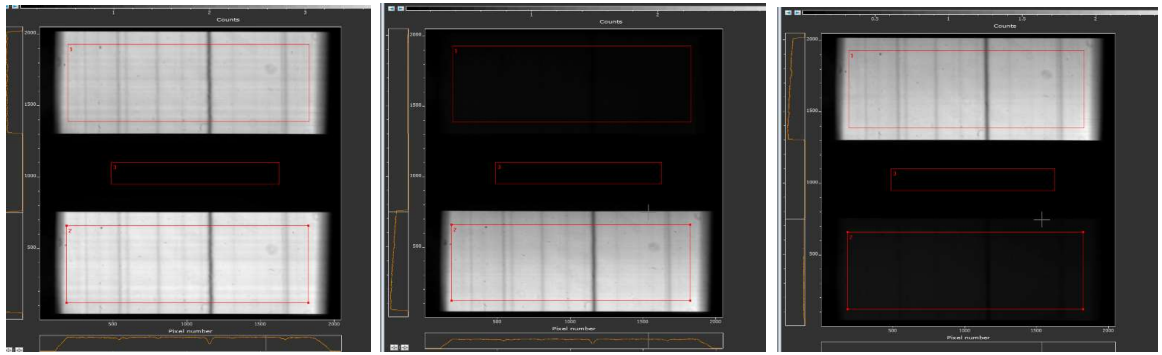
THEMIS polarimetric calibration



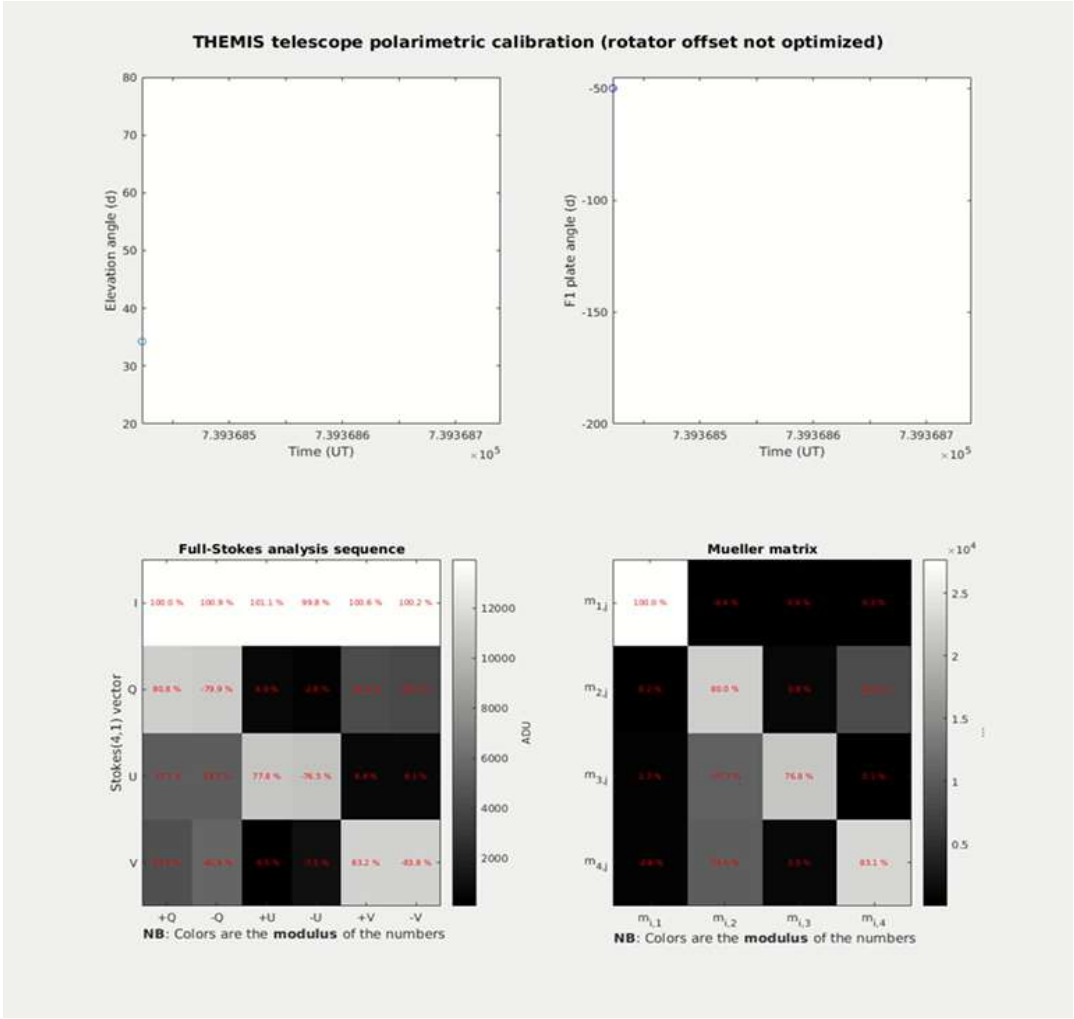
Analysis of natural solar spectrum



Analysis of calibrated solar spectrum



THEMIS Mueller matrix@~600nm



- $M_{THEMIS} = \begin{pmatrix} 1.000 & -0.009 & -0.003 & 0.001 \\ -0.008 & 0.885 & 0.016 & -0.033 \\ 0.014 & -0.436 & 0.872 & 0.033 \\ -0.019 & 0.415 & 0.008 & 0.873 \end{pmatrix}$

- Averaged over one full day
- Includes changing elevation axis and field derotation
- Quite constant along one day

Takeaway

- THEMIS is now a competitive XXIst century telescope, and the installation of the IBIS 2.0 spectroimager (end of 2025) will trigger an even larger europeanwide interest. THEMIS is a real challenger in the 1m to 1.5m class of solar telescopes and an a French and European asset.

- Several French teams have demonstrated their ability to successfully design, build, and operate on the sky new solar instrumentation using innovative concepts

- Several other French teams are leaders in the theoretical and numerical exploration of the solar magnetic field generation, surfacing, shaping of the corona configuration and driving the space weather events.

- We are clearly qualified in all the aspects of this business, and we are many (not “4 FTEs “ !!!)

… and nevertheless

THEMIS **IS NOT** the future of our community

because

the European Solar Telescope **IS THIS FUTURE**

Business continuity (… when shit happens…)