Toward using the THEMIS solar telescope in service mode

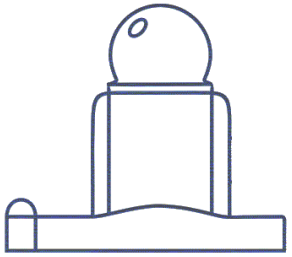
OFRAME Space Weather Days 2026 ; Grenoble, Fr ; Feb. 9th 2026

Étienne Pariat[1,2], Bernard Gelly[1] & Saida Diaz Castillo[1,3]

[1] French-Spanish Laboratory for Astrophysics in Canarias (FSLAC), CNRS, IAC, La Laguna, Tenerife, Spain

[2] Laboratoire de Physique des Plasmas, Sorbonne Université, École polytechnique, Institut Polytechnique de Paris, Université Paris Saclay, Observatoire de Paris-PSL, CNRS, Paris, France

[3] Institut für Sonnenphysik (KIS), Freiburg i.Br., Germany



Outline

- **Introduction: THEMIS early years – 1990's → 2016**

- THEMIS overhaul – 2016 → now
  - THEMIS Adaptive Optics
  - THEMIS magnetic field measurements

- THEMIS near future – now → 2030's
  - IBIS 2.0
  - ANR JET2SB project
  - ESA Space Safety STEREOMAG project

- Long term evolution of THEMIS – 2030's and beyond
  - ESA Space Safety ARMAGMAP project

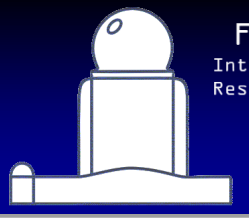
THEMIS Factsheet

Very well-maintained but,
be that as it may,
a pre-AO 20th century instrument !

THEMIS @ OT in June 2025

- **Main French solar telescope**
  - Designed by J. Rayrole, P. Mein & M. Semel
  - Located at Teide Observatory, Tenerife, Spain
  - 1st light in March 1996, & commissioned in 1999
- 1m-class solar telescope, with one the world "slowest" optical design:
  - Aperture: 92 cm ; Effective focal length: 57m
  - Effective focal ratio: f/62
  - 60"x60" to 120"'x120" square field-of-view
- **MulTi Ray spectrograph (MTR2): ideal for high-spectral resolution spectropolarimetry:**
  - Working spectral range: 4000 - 11000 Å
  - **Polarization calibration free**
  - **Ultra-high spectral resolving power**:
    - R ~ 200 000 - 300 000
  - **Simultaneous observations of user-defined set of up to 6 spectral ranges**:
    - ~6-7 Å spec. range width with ~25 mÅ res.

Outline



FSLAC International Research Lab.

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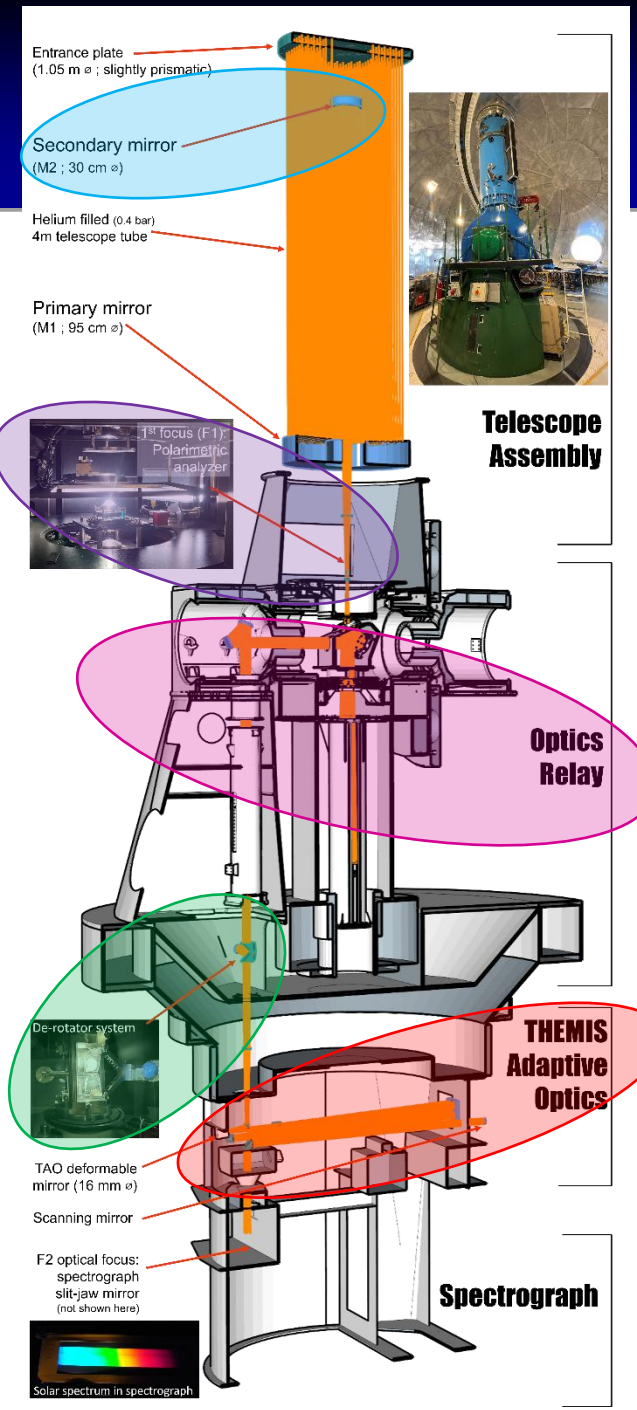
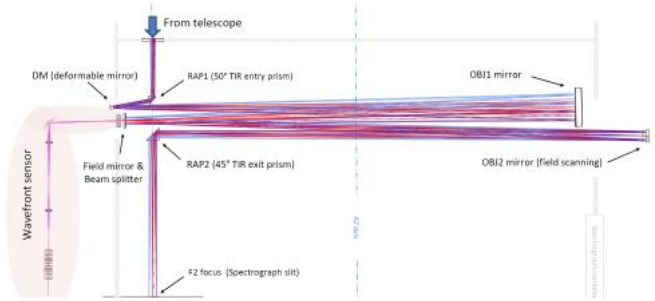
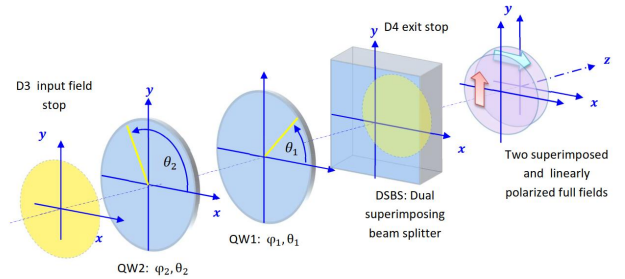
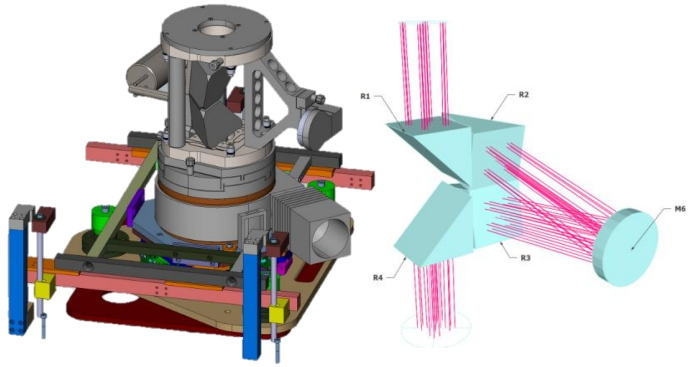
“Total makeover” : 2016 → 2020



- **THEMIS has been widely renewed and redesigned**
  - Thanks to EU funding: ~1M€ from 2 SOLARNET programs
- **M2 mirror re-aluminising** (WHT & THEMIS)
- **Themis Adaptive Optics:** “classical” single-DM adaptive optics based on innovative wavefront sensing and mirror commanding concepts (AIRI@CRAL & THEMIS)
- **Superimposed dual-beam polarimetric analysis** without field limitation (Semel M., Lopez A., Le Men C. & THEMIS)
- **“Polarization- friendly” complete redesign of the whole transfer optics (M3, M4 & M5)** (Le Men, C. & THEMIS)
- **New de-rotator system** (THEMIS)
- + new context, broadband and spectral cameras.

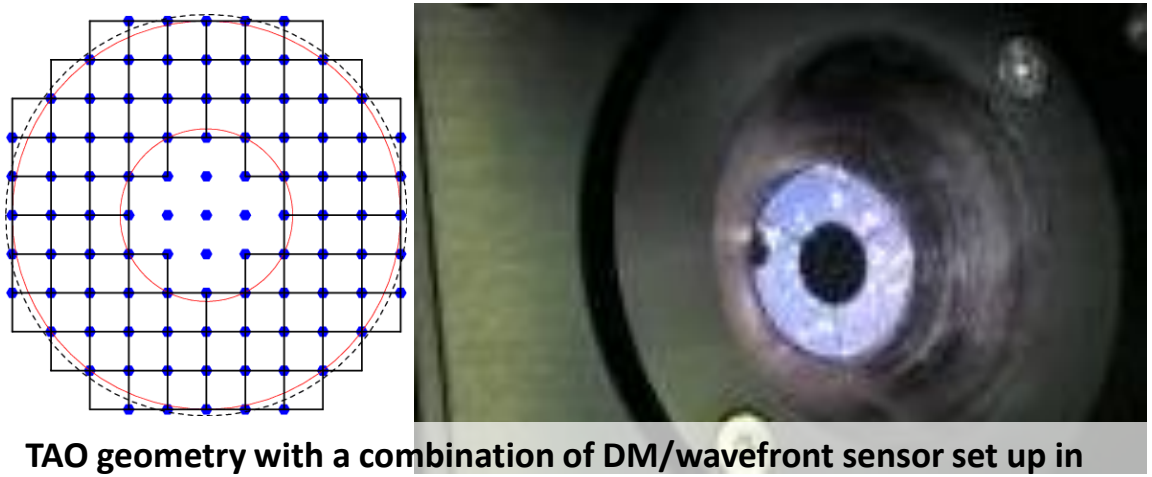






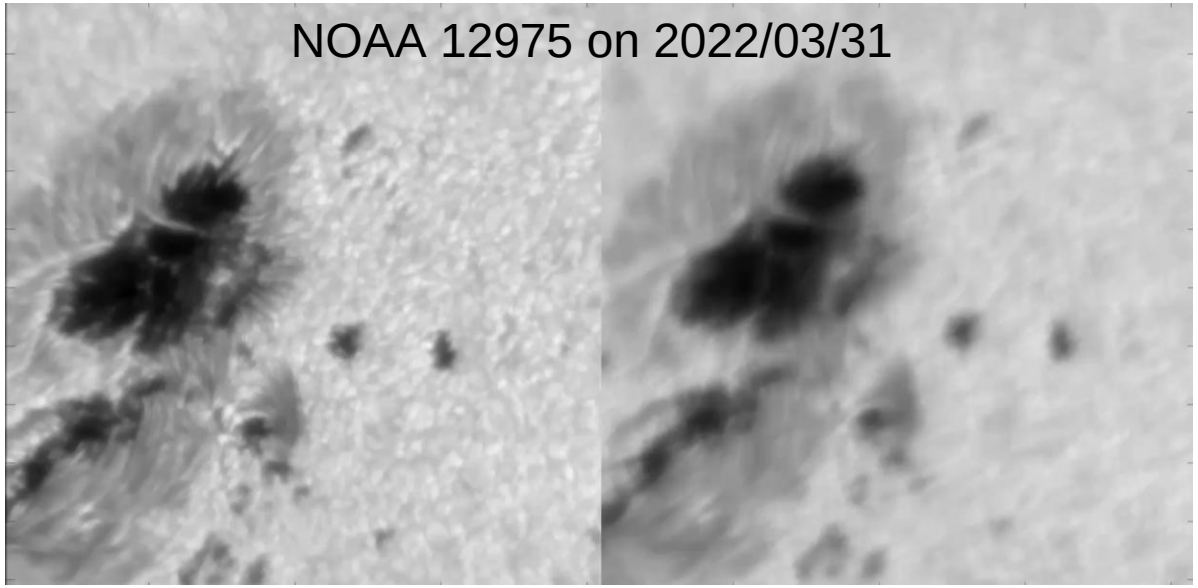
THEMIS Adaptive Optics (TAO)

- Specifications
  - **76 sub-aperture Shack-Hartmann WFS**
    - 380×380 pixel WFS images, Mikrotron EoSens 4CXP detector
  - **THEMIS-optical-path-compatible 16mm DM**
  - **97 actuators** on ALPAO deformable mirror
  - Real time correction (RTC)
    - Computer: CPU i7-4790K (Q2'14) at 4.2 GHz, 4 cores, up to 50 Gflops/core with AVX2 + FMA instructions.

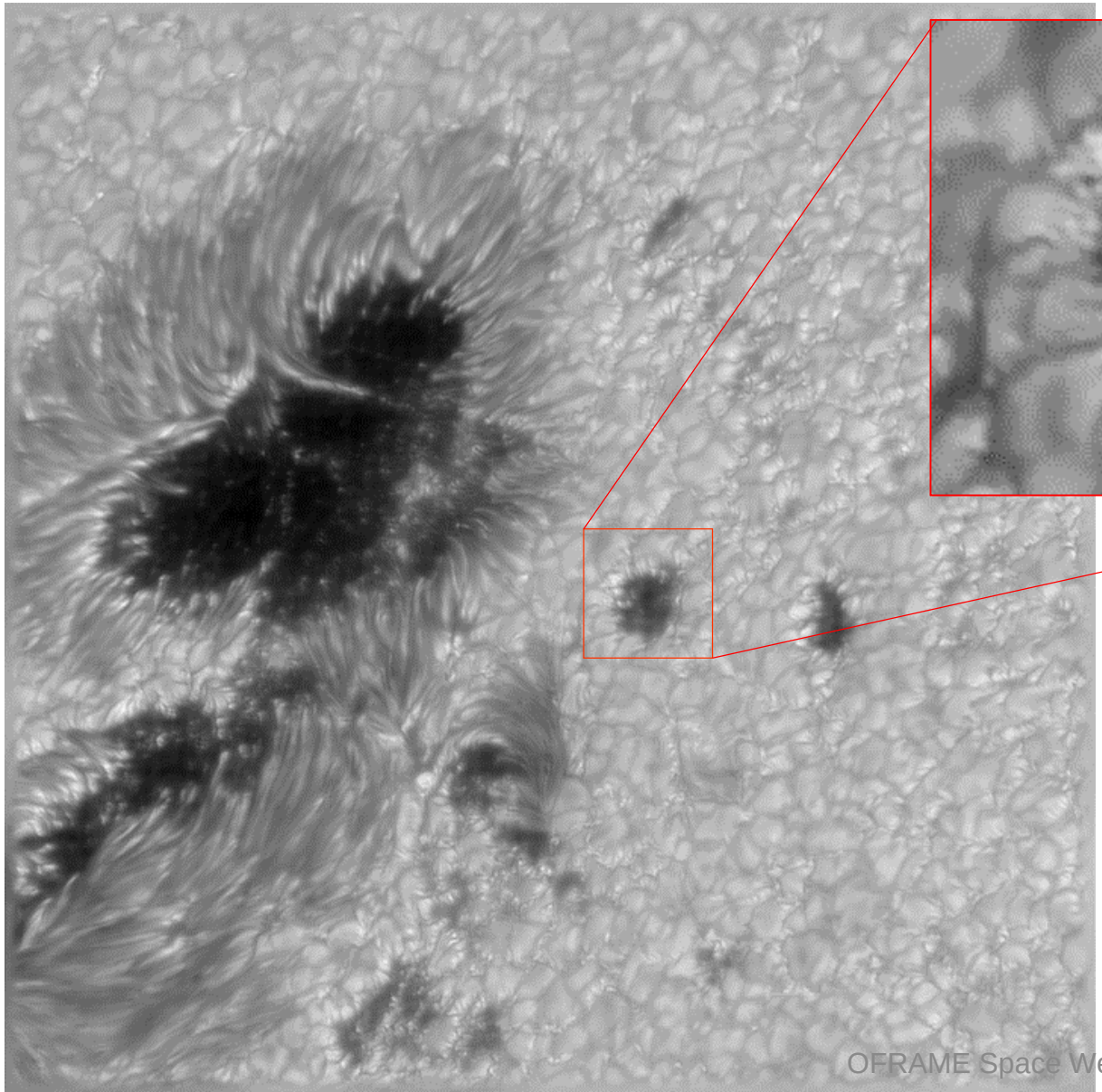


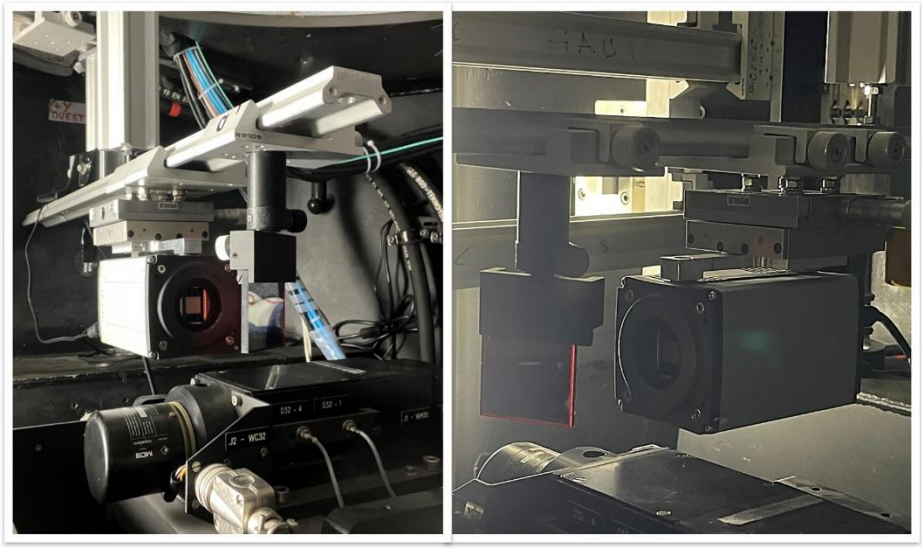
TAO geometry with a combination of DM/wavefront sensor set up in 'Fried configuration' with a spacing number of 10

- Objectives:
  - **✓ Closed AO loop on the Sun**
    - started from scratch mid-2016 → Dec. 2020
  - **✓ RTC software running in CPU @1250 Hz**
  - **Ongoing (→ winter 2025-2026): unsupervised AO system**
    - optimal correction whatever the conditions
    - provide inferred seeing conditions



THEMIS at diffraction limit: NOAA 12975





THEMIS Broadband Imaging (BBI)

- NOAA 12975 on 2022/03/31 observed @ ~630nm with 1nm broadband red filter
- 100 BBI acquisition @ 40 frames/s with a 55”x55” FOV
- Knox-Thompson (speckle) image post processing
- **➔ 0.17’’ resolution (0.035”/pixel) near THEMIS theoretical diffraction limit of 0.15”**
  - **~125 km resolution on the Sun photosphere**

THEMIS Adaptive Optics (TAO): results on granulation

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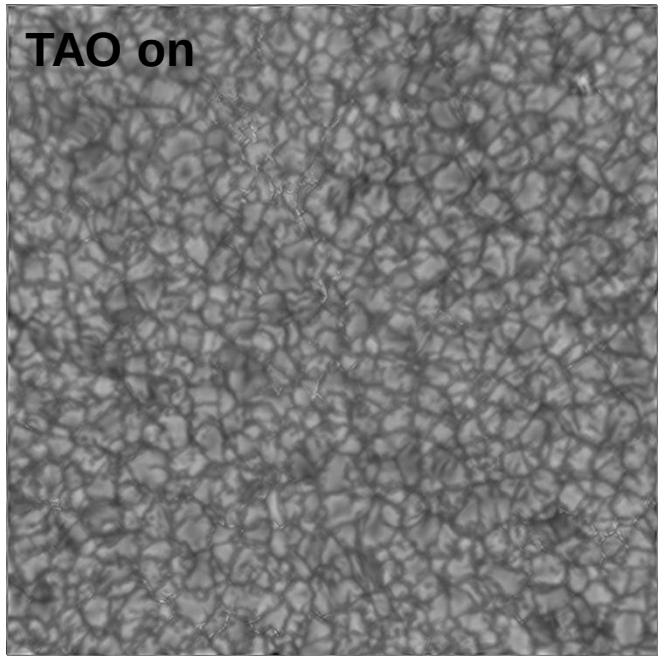
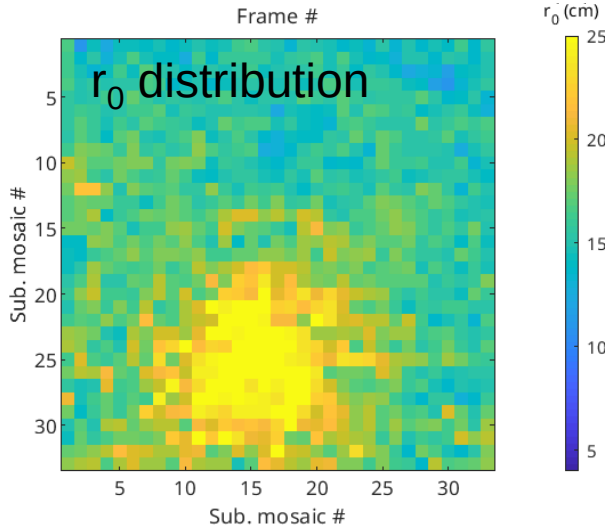
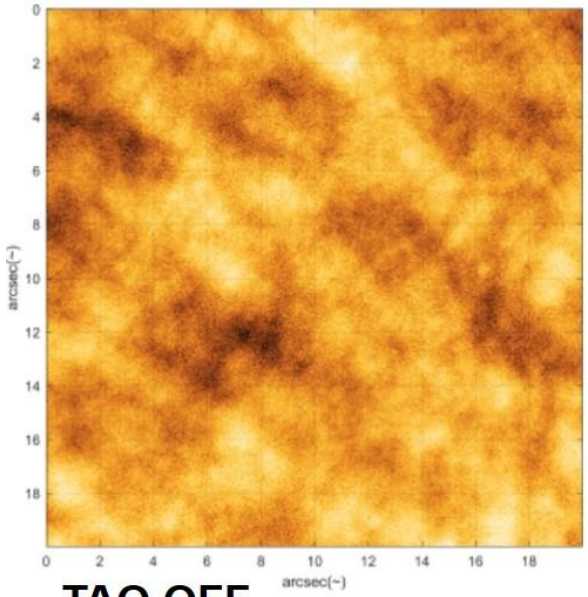
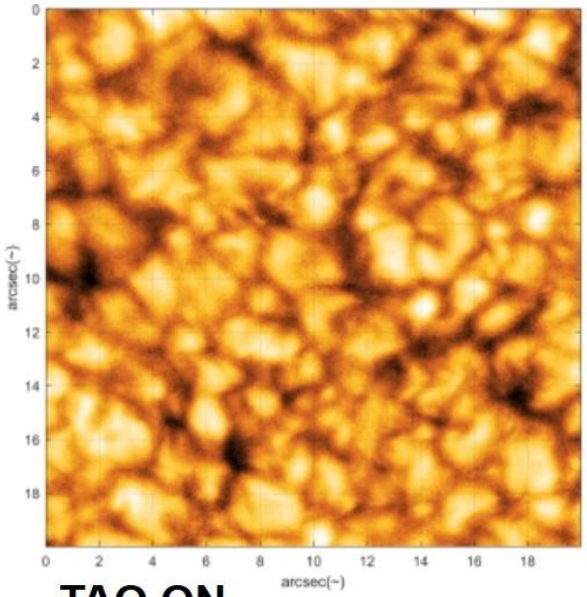


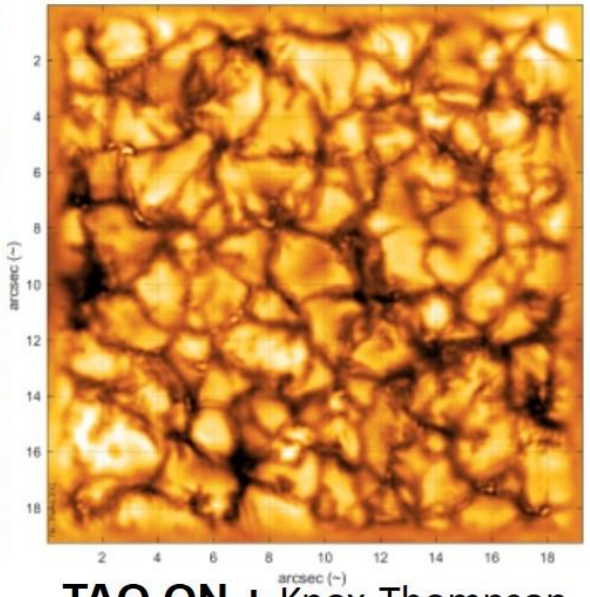




TAO OFF
- seeing "daytime bad" : r_0≈ 3-4 cm
- granulation contrast: 1.6 %



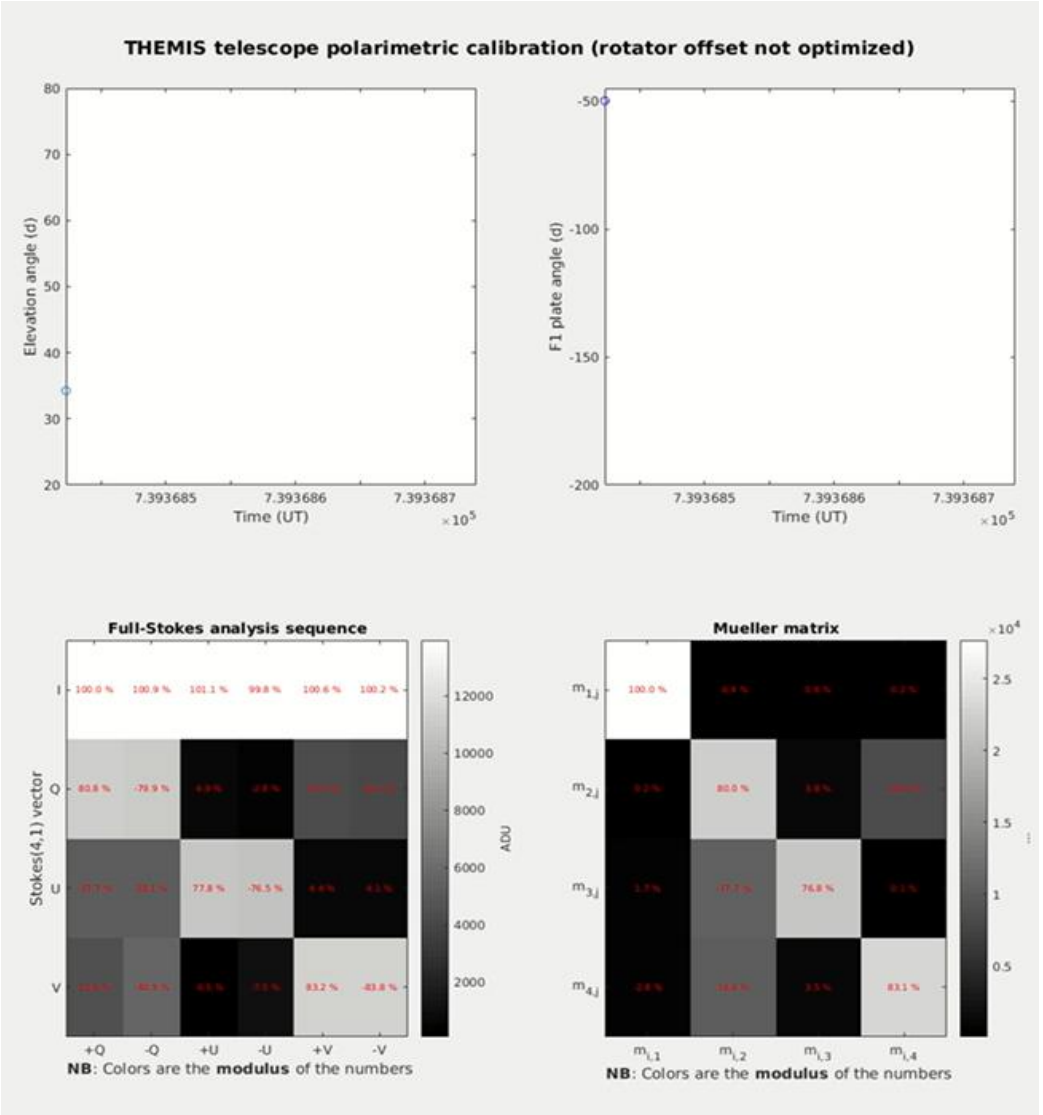
TAO ON
- seeing "daytime bad" : r_0≈ 3-4 cm
- granulation contrast: 4.2 %



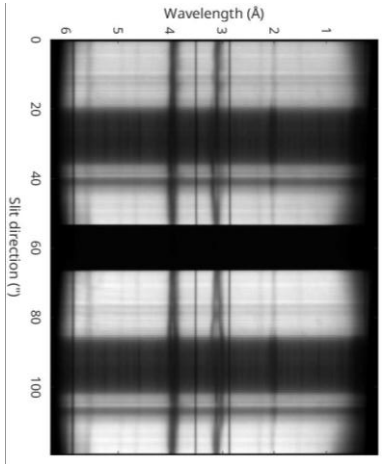
TAO ON + Knox-Thompson reconstruction (100 frames)
- granulation contrast: 9.6 %

- **TAO permits significant quantitative image quality gain:**
  - **in effective seeing**: Fried's coherence length from r_0~7cm (ave. seeing)
    - ~25cm at TAO focus
    - ~17cm on rest of FOV, away from isoplanatic patch
  - **in granulation contrast**: from ~1-2% (bad seeing)
    - to ~10% (with image reconstruction)

THEMIS polarization analysis



- **New "polarization friendly" AO-compatible optical path:**
  - Polarization units + double Savart plates @ F1
    ➔ **dual-beam with beam exchange.**
  - Wollaston prisms in front of spectral cameras:
    ➔ complementary Stokes on camera FOV



- THEMIS Mueller matrix:

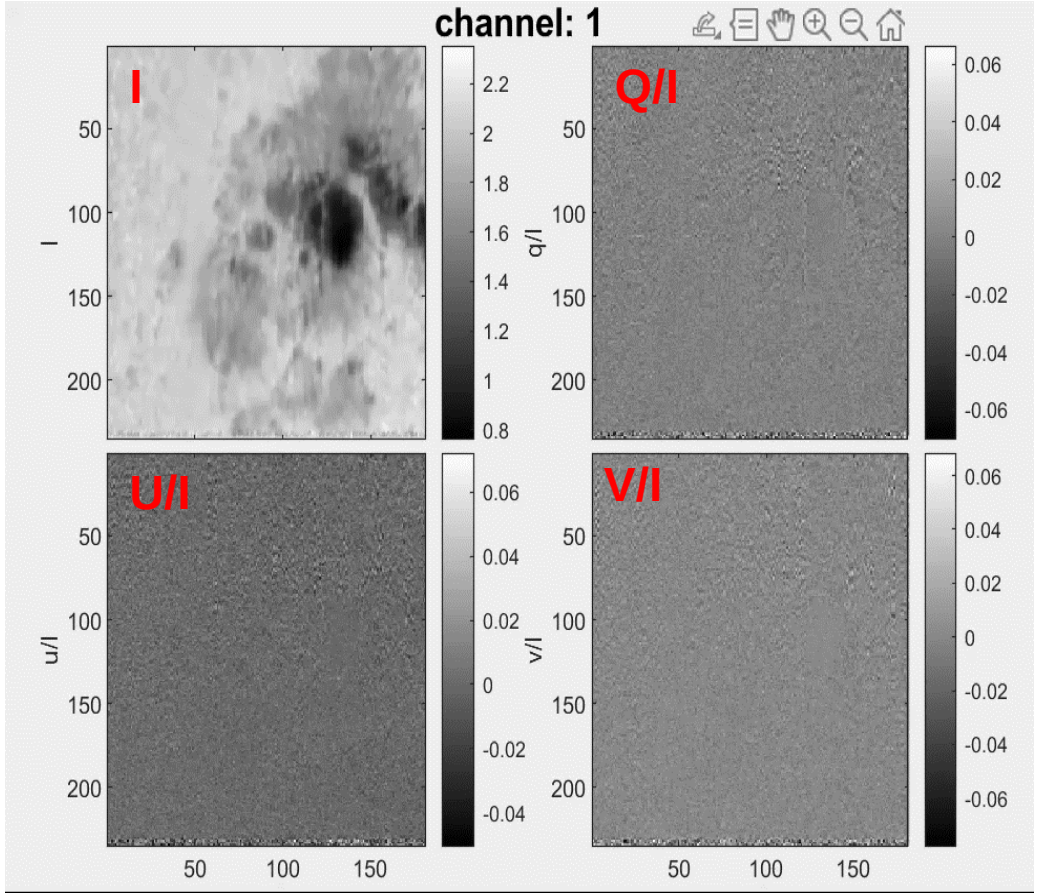
$$M_{THEMIS} = \begin{pmatrix} 1.000 & -0.009 & -0.003 & 0.001 \\ -0.008 & 0.885 & 0.016 & -0.033 \\ 0.014 & -0.436 & 0.872 & 0.033 \\ -0.019 & 0.415 & 0.008 & 0.873 \end{pmatrix}$$

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

- **THEMIS remains a strongly polarization-calibration-free telescope, ideal for excellent spectropolarimetric measurements.**

Stokes parameters maps

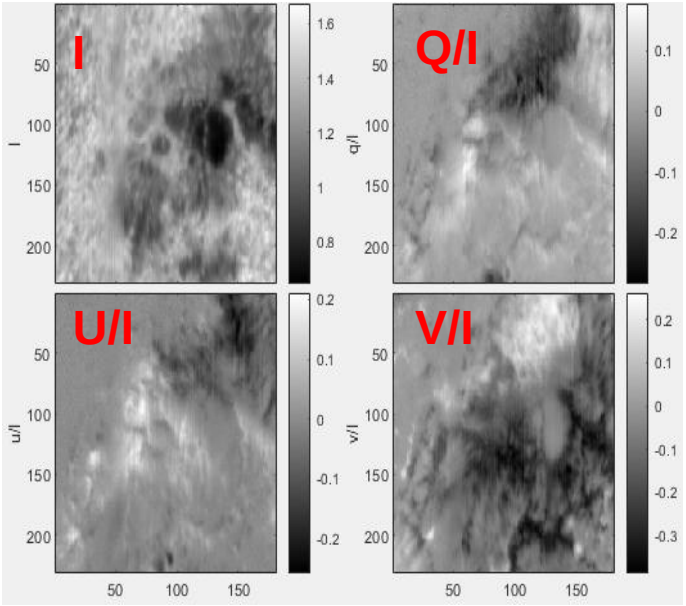
Stokes map datacube
- 256 λ channels after 2x rebinning
- 25mÅ /pixel spectral resolution



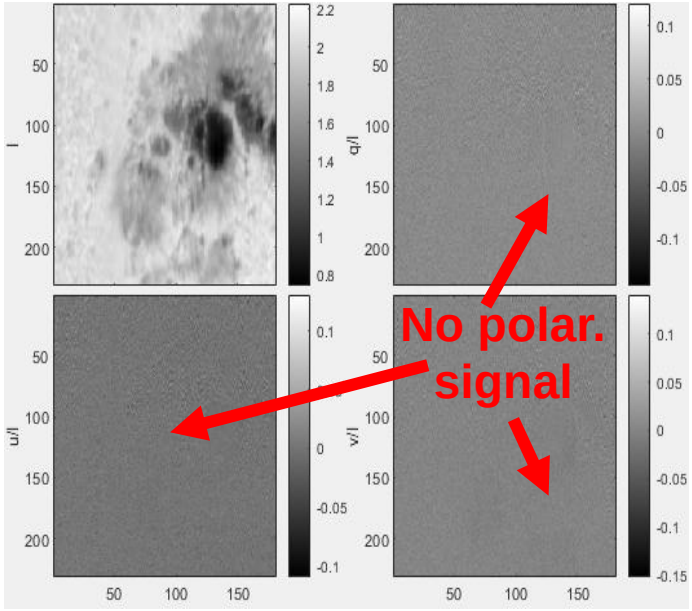
NOAA 14100 ; 29/05/2025 10:30-10:50 UT

- **Complete polarization signal now routinely measured**
  - 4D data array of 4 Stokes parameter (x, y, λ, S).
  - User-friendly software under development.
- **THEMIS goals : B maps with spatial resolution < 0.5”**
  - ~400 km resolution on the Sun (in scanning direction)
  - ~x10 area resolution improvement
    - ~Hinode/SOT; ~x4 better than HMI/SDO

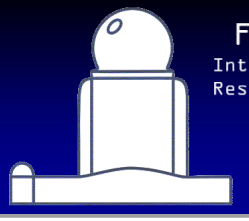
Fe I Line center



Continuum



Outline



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Upcoming : IBIS 2.0 @ THEMIS

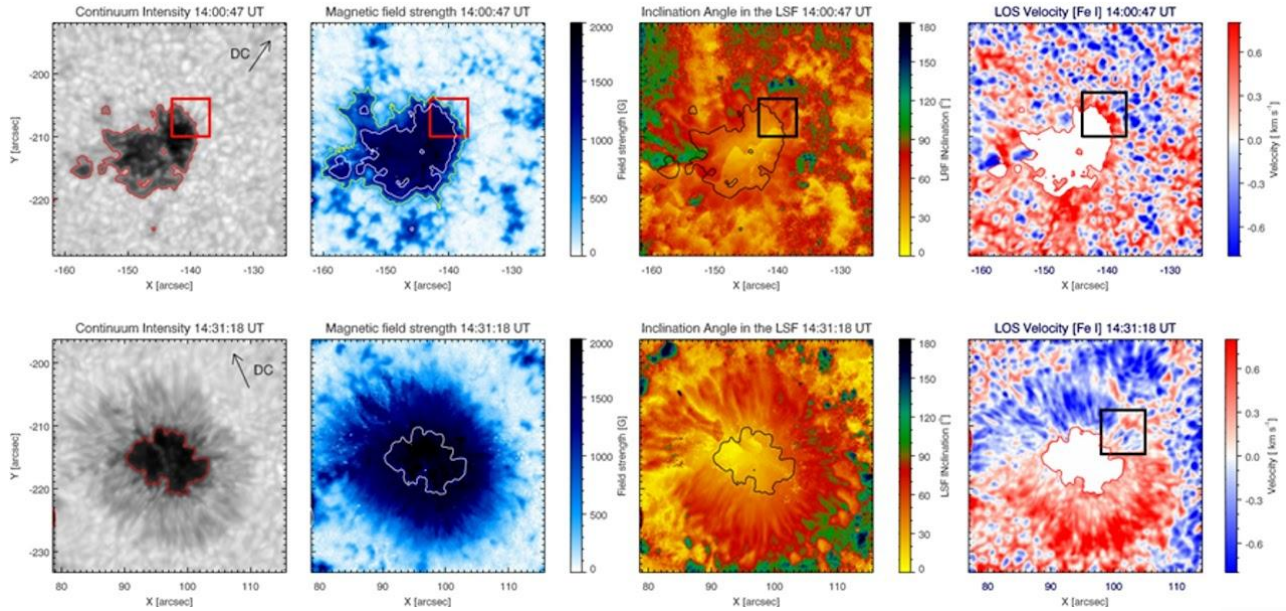
IBIS : Interferometric BIdimensional Spectrometer

https://www.ibis20.inaf.it

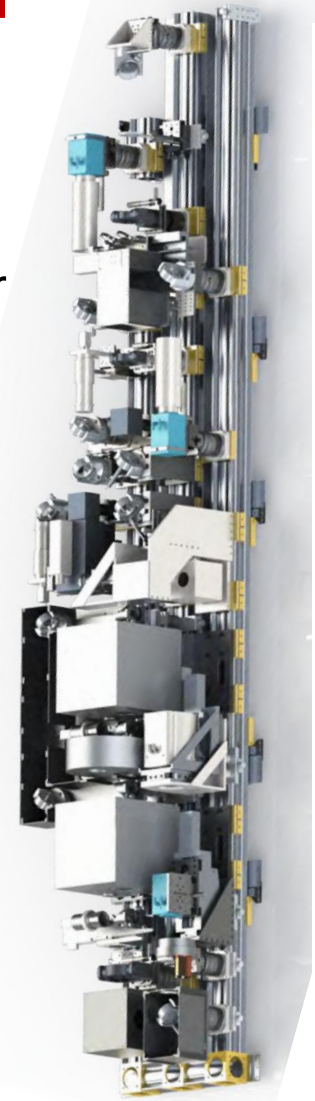
- spectro-imager (x, y, λ) : dual Fabry-Perot & interference filters
- 200 000 spectral resolution
- short exposure times / polarimetric mode

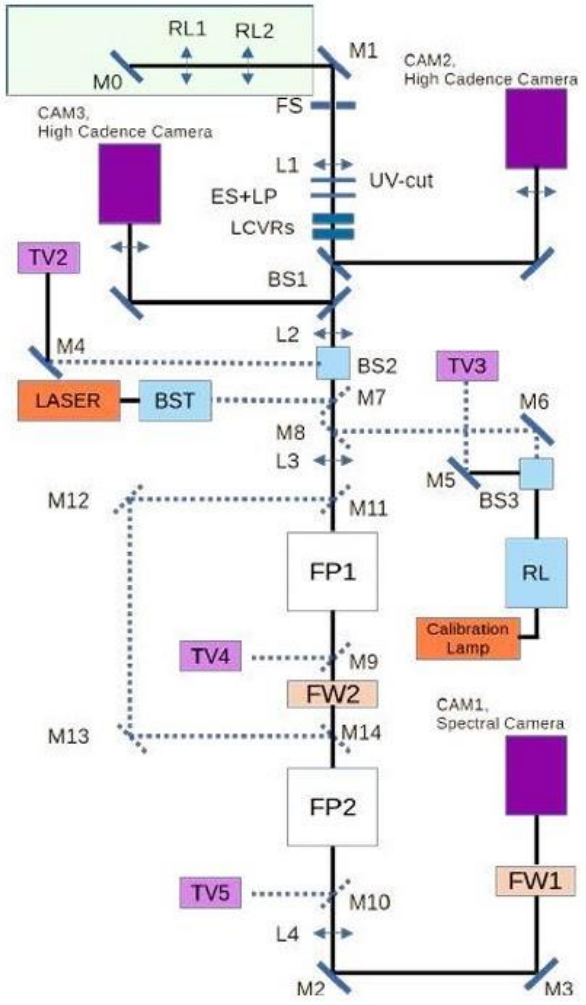
Between 2003 & 2019 IBIS was running at the Dunn solar tower

- ~100 papers based on IBIS over 15 years



Intensity, magnetic field strength, field inclination angle & l-o-s velocities on 2012 May 28 (14:00-14:30 UT): before (top) and after (bottom) penumbra formation. **(Murabito et al. 16)**





Ermolli et al. 2024

Upcoming : IBIS 2.0 @ THEMIS

IBIS upgrade, IBIS 2.0 has been looking for a suitable host telescope since 2019.

IBIS 2.0 as guest instrument at THEMIS

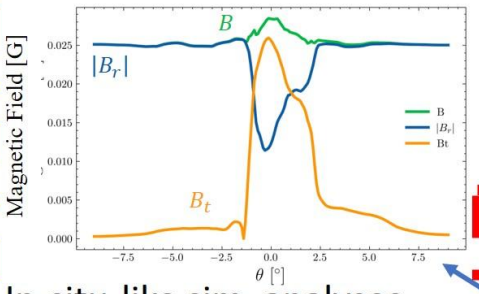
- **IBIS2.0 is an outstanding synergic complement of THEMIS long slit spectrograph**
  - TAO performance attractive for IBIS
  - THEMIS has no equivalent instrumental mode
  - Foster and renew French-Italian scientific collaboration in high-resolution solar physics, beneficial at large for EU solar physics (e.g. EST)

Installation schedule

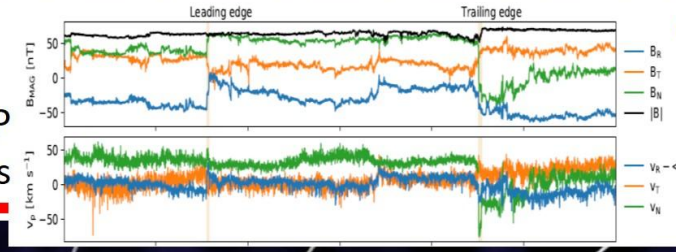
- ➔ Memorandum of Understanding signed between INAF and CNRS in winter 2024-2025
- Nov. 25: preparatory installation of optical bench
- Spring 2026 : IBIS 2.0 installation & commissioning.

Nov. 2025

THEMIS in ANR JET2SB Project

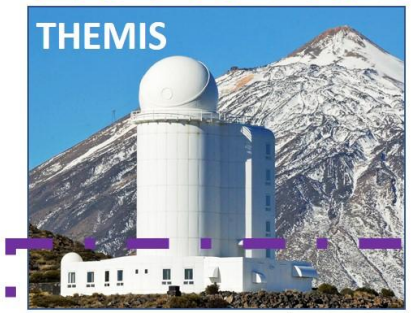


In-situ-like sim. analyses

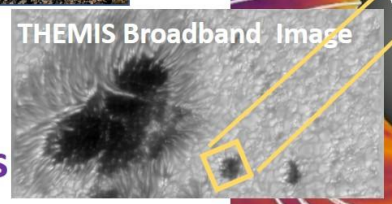


In-situ PSP measurements

WP 3: In-situ analyses



WP 1: solar atmosphere observations



- **Do/to which extend, solar jet-like events induce Switchbacks?**
- **How do they contributes to the acceleration of the solar wind?**

ANR-25-CE31-7416
PRC project
10/2025 → 03/2029
~710 k€

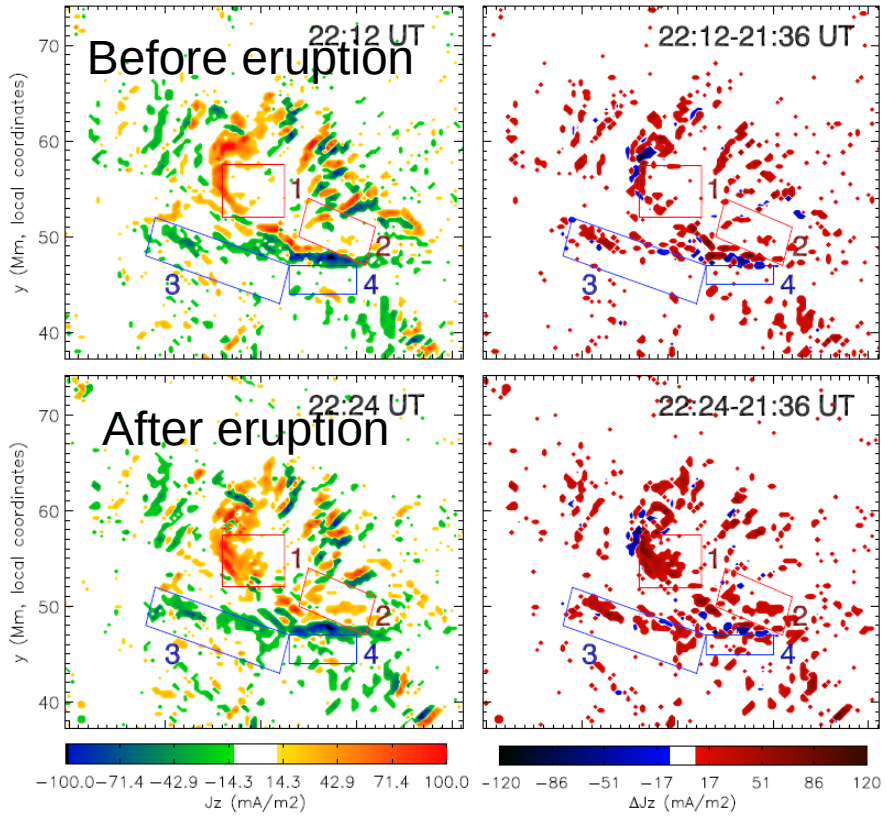
LPC2E
C. Froment
T. Dudok de Wit
+ 1 post-doc

LPP Laboratoire de Physique des Plasmas
S. Masson,
G. Aulanier
J. Touresse,
L. D'Herbomez,
J. Romero Castañeda

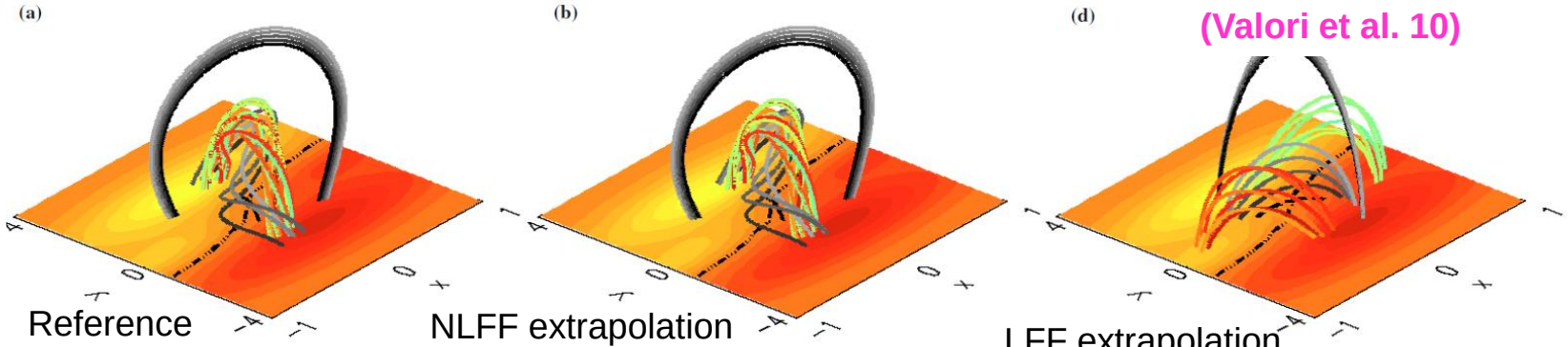
FSLAC International Research Lab.
E. Pariat,
B. Gelly,
Saida Diaz Castillo

Electric currents : key role and their estimation

Janvier et al. 16



(Valori et al. 10)



Reference TD config.

NLFF extrapolation (use of **j** distribution)

LFF extrapolation (no use of **j**)

- **Electric currents are fundamental for the understanding of solar eruptions, both**
  - for structure and level of eruption-available energy of active magnetic systems, e.g. AR, filaments, …
  - for the eruption process itself, as magnetic reconnection develops where intense current sheets build-up

- Estimations and study of vertical electric current density (j_z) is becoming a standard by-product of vector magnetic field measurements **(e.g. Janvier et al. 16; Barczynski et al. 20, Artemyev et al. 21)**

Electric current estimation and the 180° ambiguity

- Estimation of the vertical electric field component suffers from a major limitation due to the fundamental 180° ambiguity on measurement of the transverse (to the line-of-sight) **B** component
  - Oppositely directed transverse fields (by 180°) produce the very same Zeeman signal

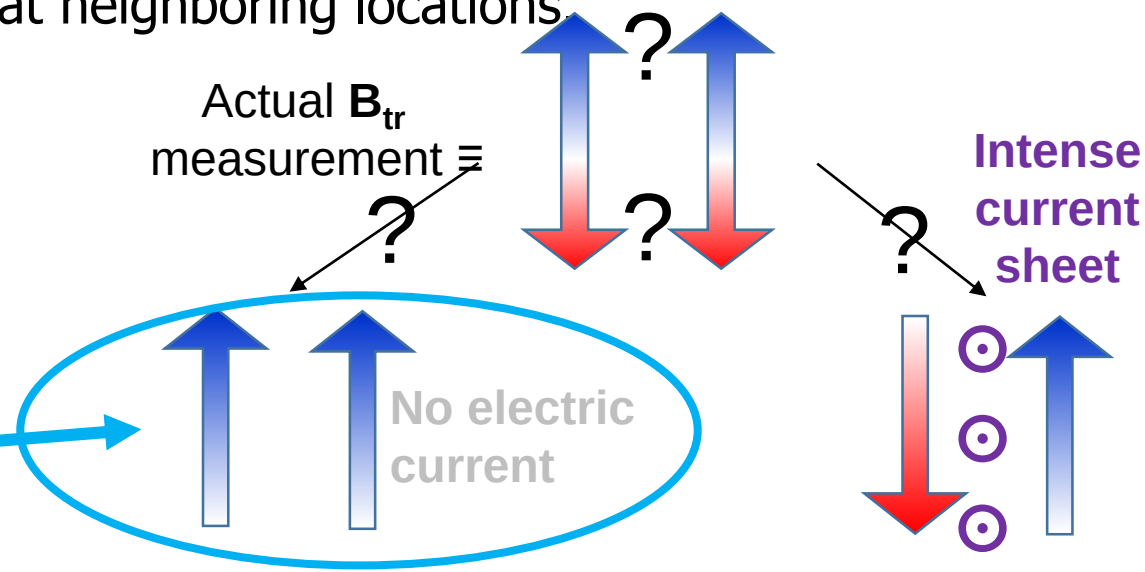
$$\mathbf{B}_{\rm obs} = B_{\rm los}\mathbf{e}_{los} + \zeta\, B_{\rm tr}\mathbf{e}_{tr} \quad \text{with ambiguity} \quad \zeta = \pm 1$$

- **Estimation of j_z strongly dependent on 180° fundamental ambiguity**

$$j_z = \zeta \left(\frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y} \right)$$

- Removal of the 180° ambiguity is usually done thanks to empirical method (model dependent):
  - cf. reviews of **Metcalf et al. 06, Leka et al. 09**
  - Less-energetic/ "well-behaved" ambiguity solution usually preferred ; possibly in contradiction to pre-eruptive state

- Particularly critical for identifying intense current sheets, inducing magnetic reconnection, which requires estimating the relative orientation of $\mathbf{B}_{tr}$ at neighboring locations



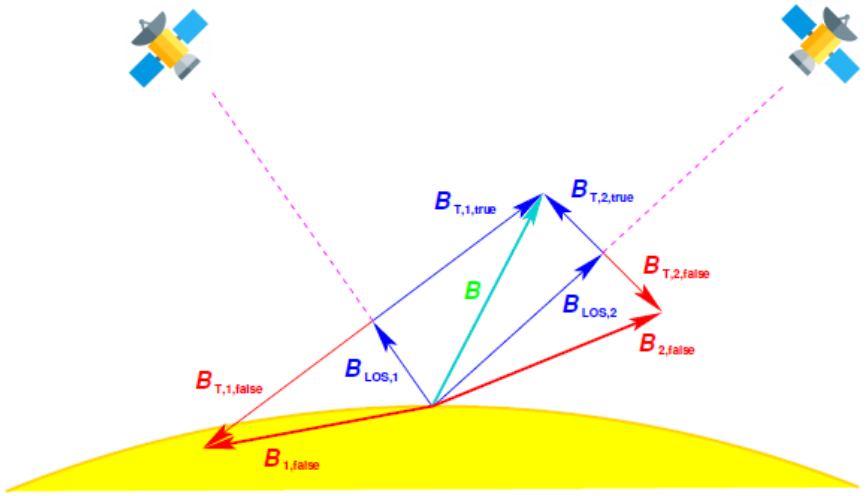
Stereoscopic Disambiguation Method (SDM)

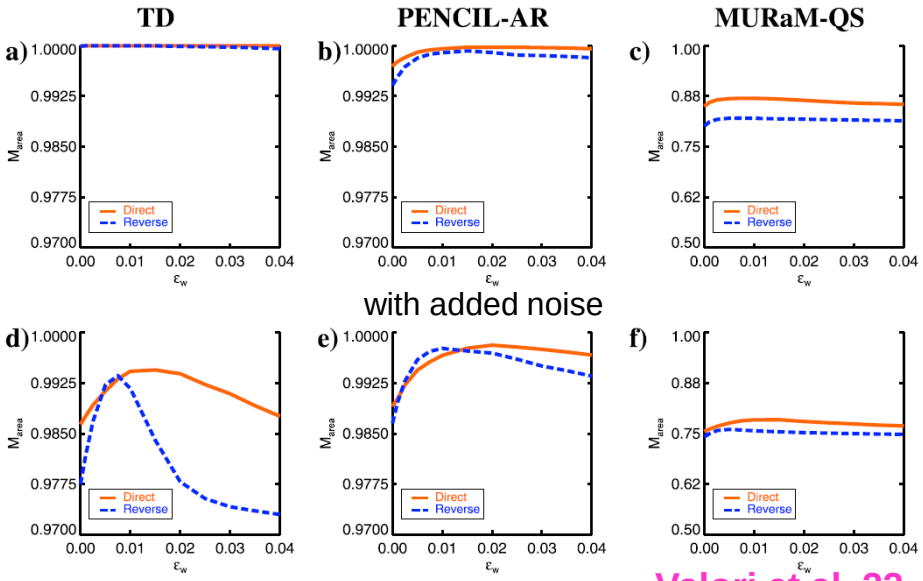
- For the first time, Solar Orbiter's PHI instrument (Solanki et al. 20) is providing **B** measurements away from the Sun-Earth line.
- **Observations of the same solar region from both PHI and Earth's orbit (e.g. SDO/HMI) can enable the unique observational removal of the 180° ambiguity.**
  - Line of sight measurement of one of the spacecraft shall enables the unambiguous choice on the direction of the transverse field of the second spacecraft.
  - Application to real data may be hardous: instruments do not look at the same plasma column along line-of-sight.
- **Stereoscopic Disambiguation Method (Valori et al. 22)**

$$\mathbf{B}_{\rm obs} = B_{\rm los}\mathbf{e}_{los} + \zeta\, B_{\rm tr}\mathbf{e}_{tr} \qquad \zeta = \frac{B^{\rm B}_{\rm los} - B^{\rm A}_{\rm los}\cos\gamma}{B^{\rm A}_{\rm w}\sin\gamma}$$

  - Proof-of-concept and rigorous test on diverse synthetic dataset (analytical field, MHD sim. of AR; radiative transfer in quiet sun)
  - High accuracy of the method

Rouillard et al. 20

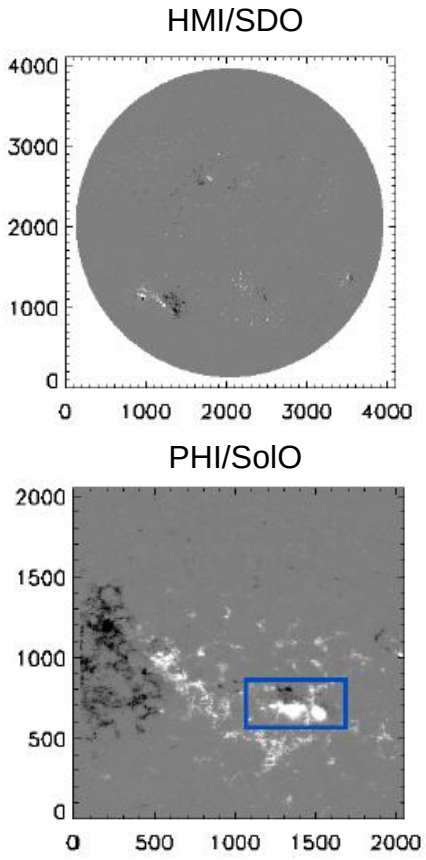


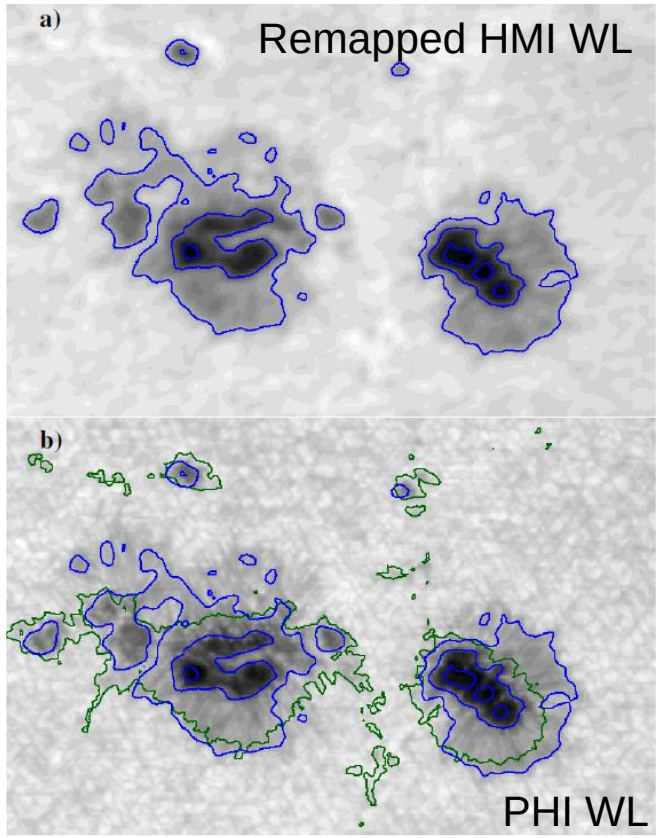


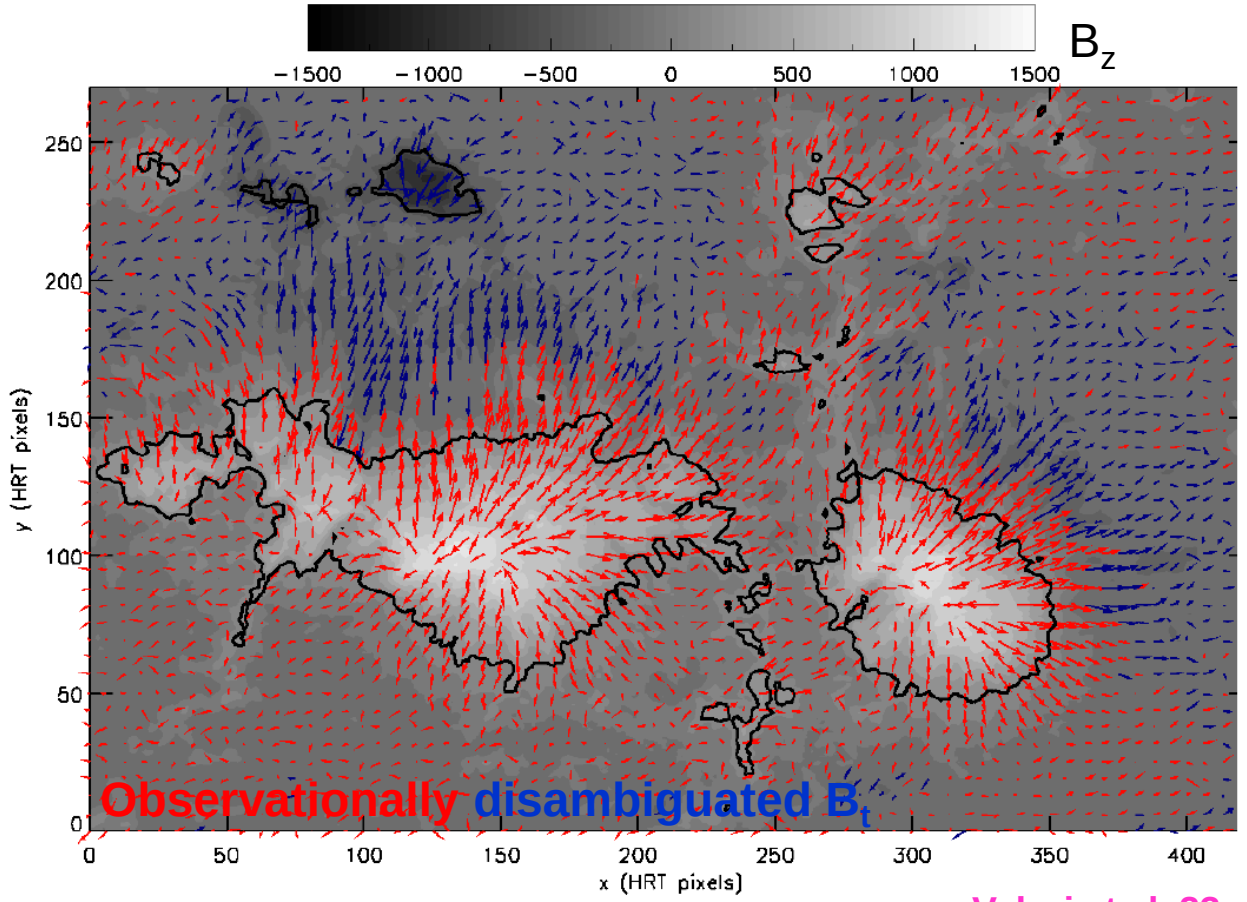
Valori et al. 22

First observationally disambiguated vector B map

- Application of the SDM method to observed data from HMI/SDO and PHI/SolO
  - March 17th 2022, ~3h45 UT ; separation angle of 27°
- **Successful observational disambiguation of the 180° ambiguity (Valori et al. 23)**





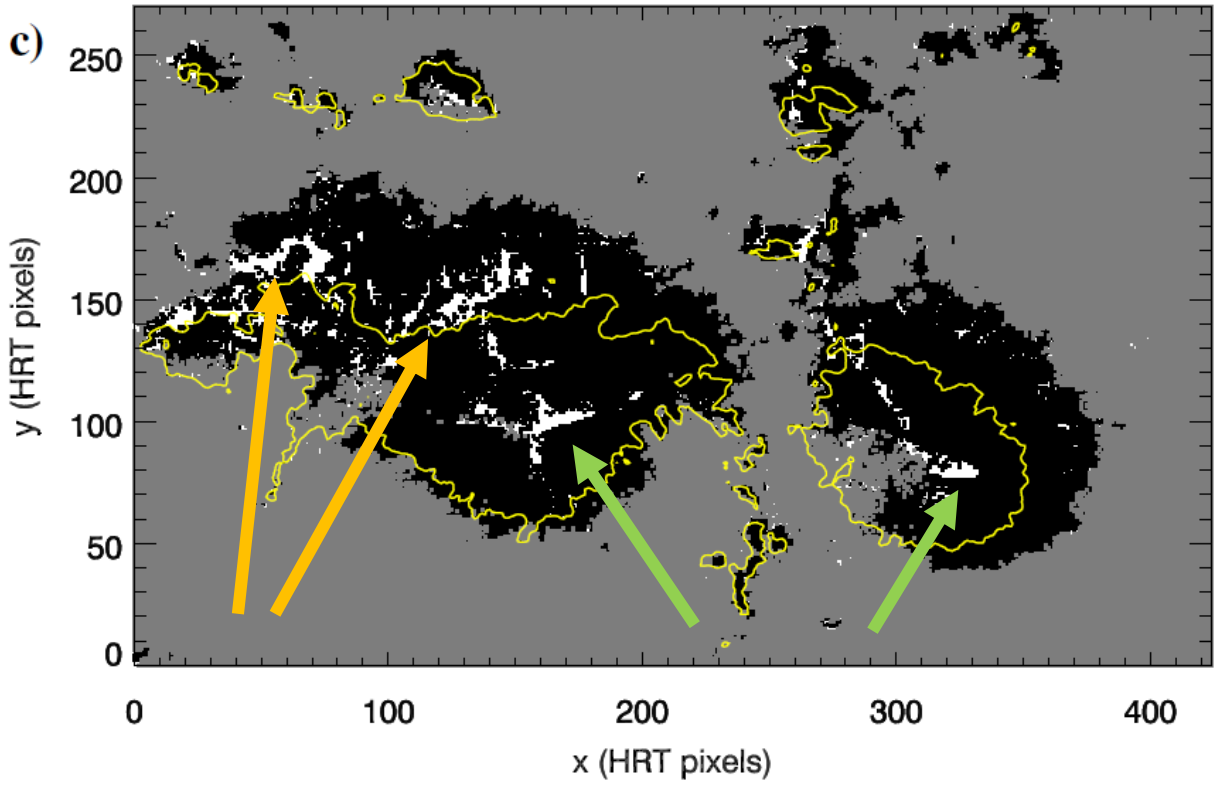


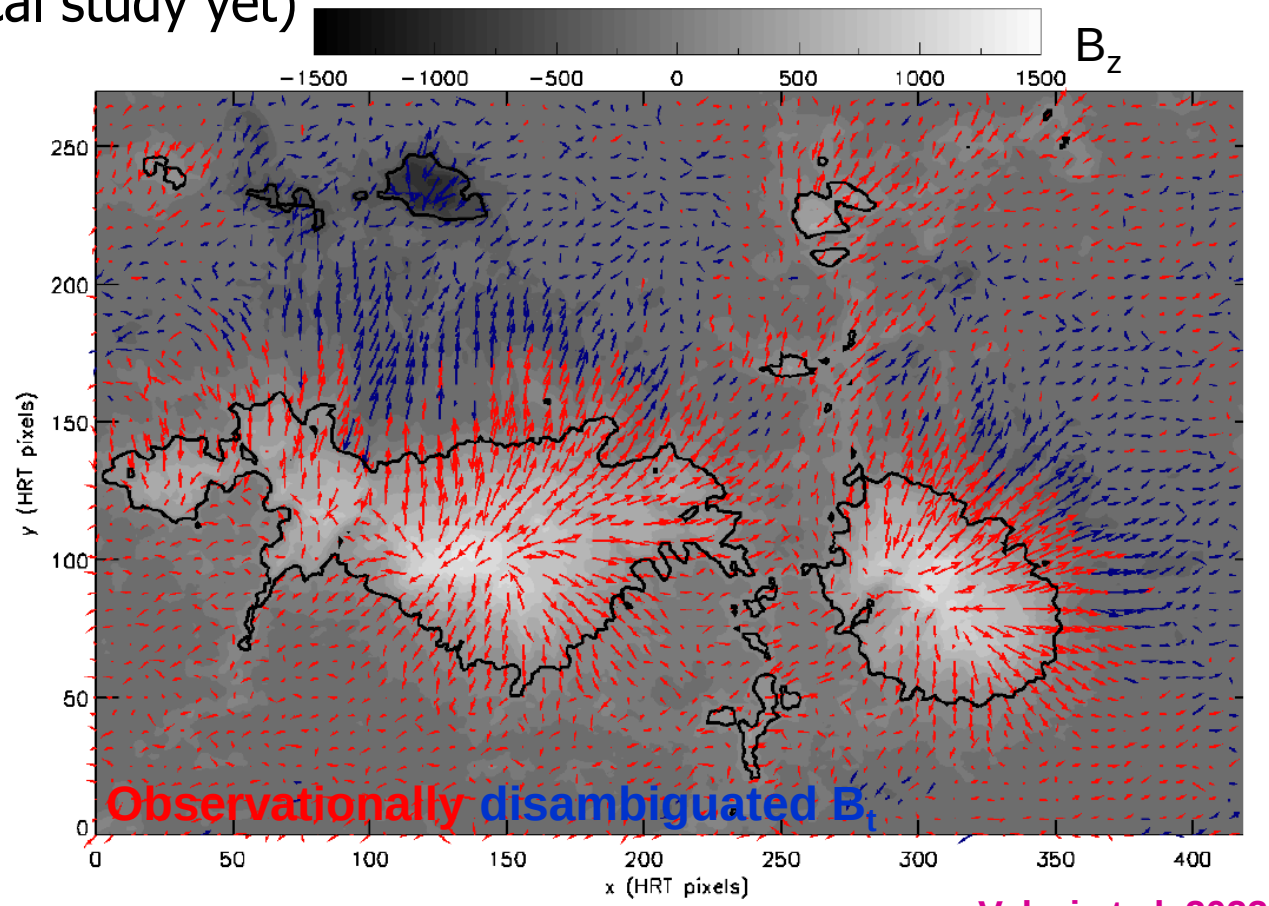
Valori et al. 23

Differences with standard 180 disambiguation method

- Basic comparison of the SDM method with classical method for disambiguation (Metcalf et al. 06)
- **Two main types of locations of disagreements** : **inversion lines** & **centers of umbras**
- Standard disambiguation method works "overall" well but likely fails in key regions of interest for eruptiveness of active region (though no statistical study yet)

Gray: no comparison -- Black: agreement -- White : disagreement

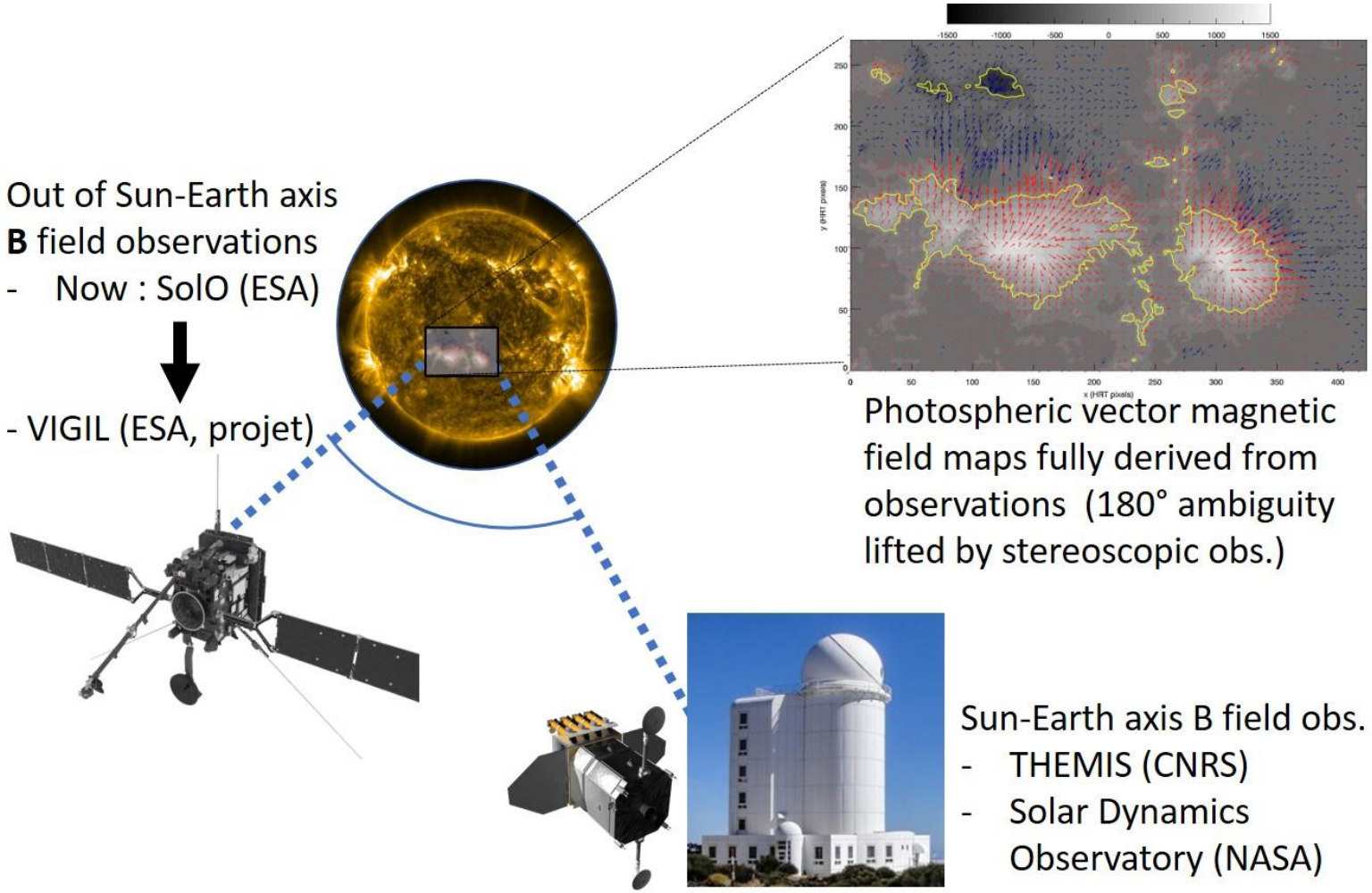




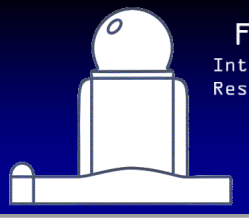
Valori et al. 2023

ESA Safe Safety STEREOMAG project

- **VIGIL/PMI will provide first systematic magnetograms from outside the Sun-Earth line**
  - **combined Earth's orbit, will enable regular stereoscopic magnetic observations.**
- THEMIS STEREOMAG project for ESA Safe safety program ⇒ prepare for the stereoscopic magnetic observations enabled by VIGIL/PMI
  - SDM methods still must be thoroughly and robustly tested.
    - Effect of resolution
    - Better magnetic inversion
  - Tests needs high-quality high-resolution observations
  - THEMIS capable of producing vector magnetic field maps of solar active centers. + in-house expertise on SDM



Outline

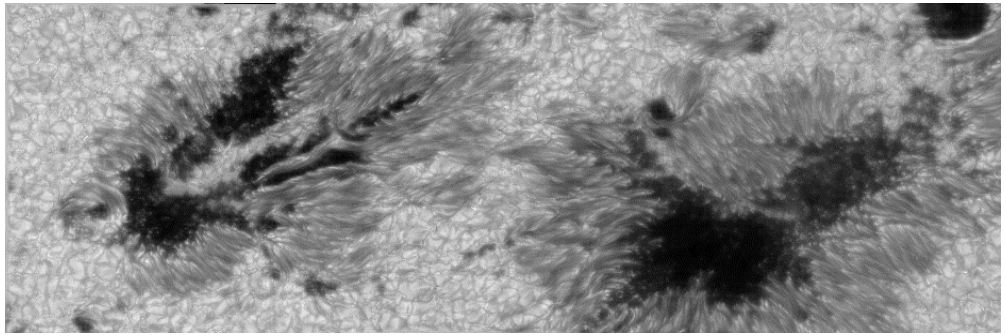


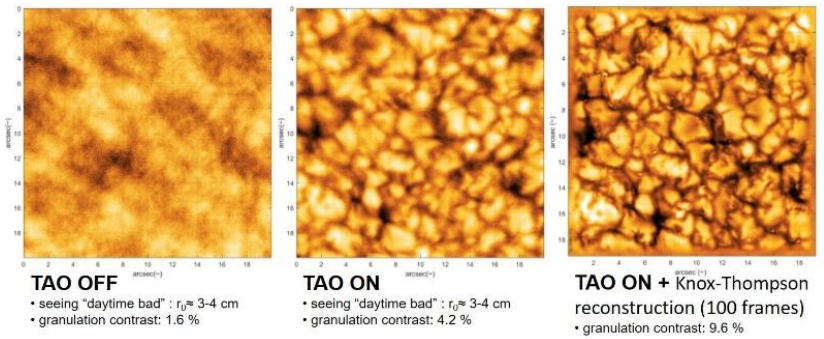
FSLAC International Research Lab.

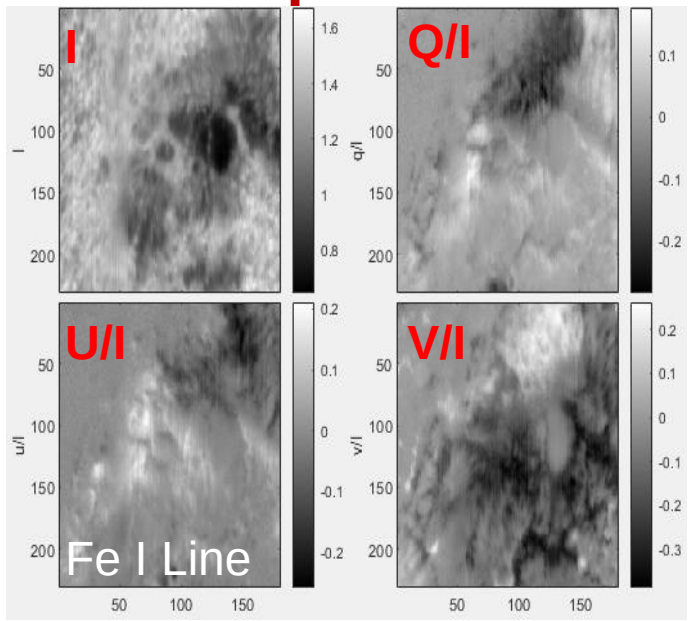
- Introduction: THEMIS early years – 1990's → 2016
- THEMIS overhaul – 2016 → now
  - THEMIS Adaptive Optics
  - THEMIS magnetic field measurements
- THEMIS near future – now → 2030's
  - IBIS 2.0
  - ANR JET2SB project
  - ESA Space Safety STEREOMAG project
- **Long term evolution of THEMIS – 2030's and beyond**
  - ESA Space Safety ARMAGMAP project

THEMIS in the next few years

- **THEMIS is presently a competitive telescope with unprecedented capacities**
  - THEMIS is a real challenger in the 1m-1.5m class of solar telescopes.
  - Installation of the IBIS 2.0 will trigger a larger European-wide interest.
  - Growth of staff (PhD, Postdoc) thanks to key projects: JET2SB, STEREOMAG







- **Since its commissioning, THEMIS has been running in obs. campaign mode**
  - Duty cycle: 6-7 months of observation campaigns (April-November) ; 4-5 months of maintenance & instrumental developments. (November-April)
  - Observation proposal submission & selection on scientific merit by THEMIS Time Allocation Committee
  - Variability of scientific objectives and targets (granulation, quiet sun, coronal holes, filament, AR, …) from one campaign to another
  - Telescope set-up can strongly changes from campaign to campaign : advantage of THEMIS high versatility

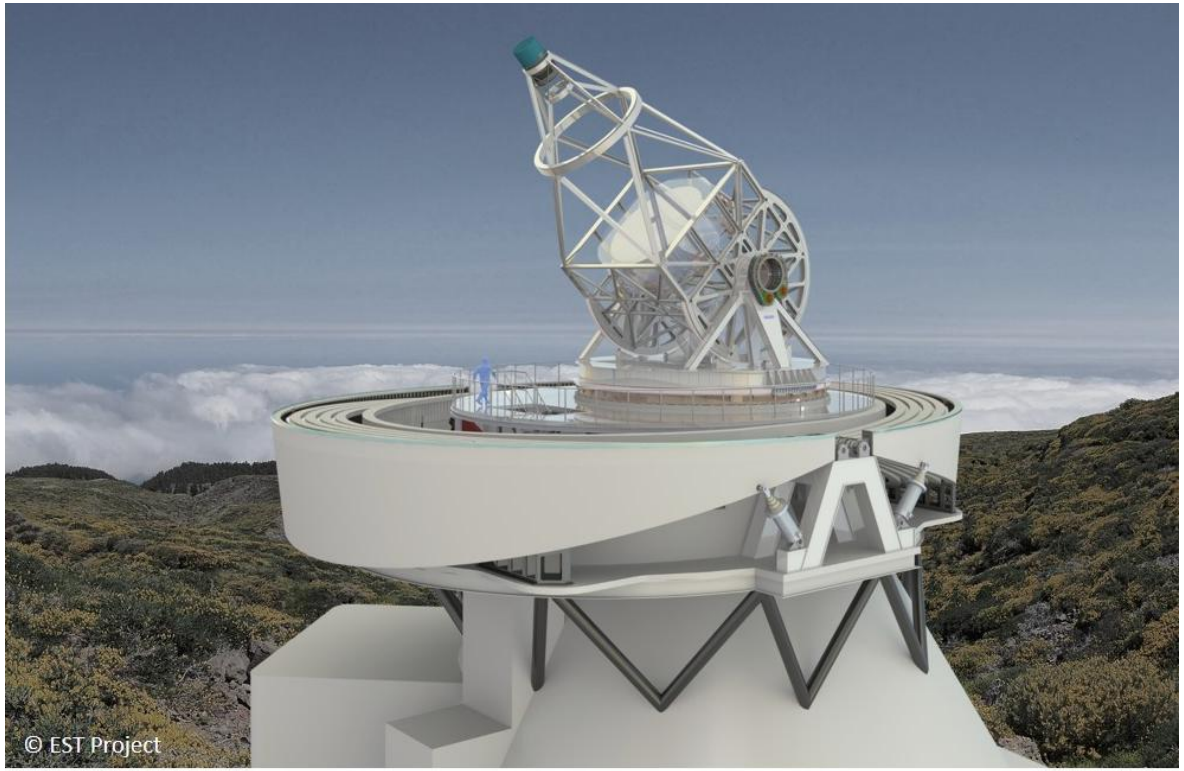
European Solar Telescope

THEMIS **IS NOT** the future of research-oriented ground-based solar physics because

the European Solar Telescope

IS THIS FUTURE !

Cf. talk on the European Solar Telescope tomorrow

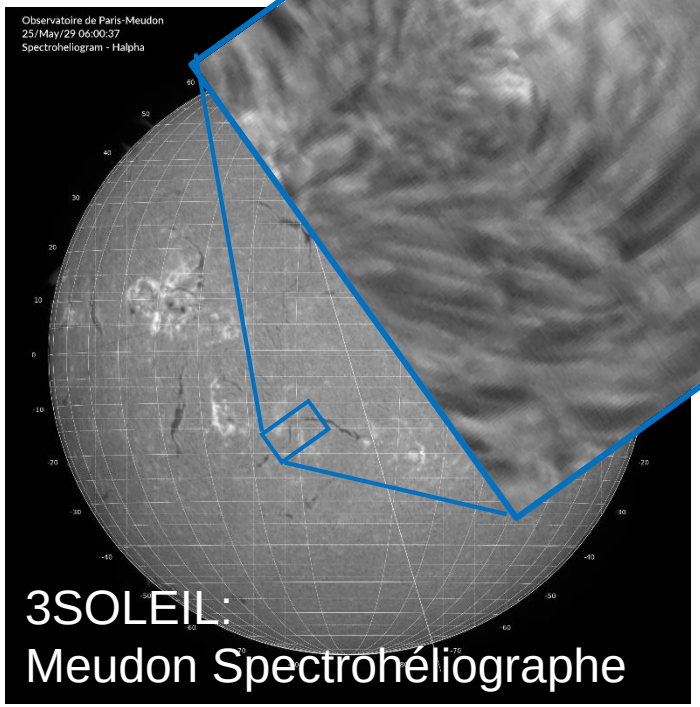


Where will THEMIS be in 10 years ?

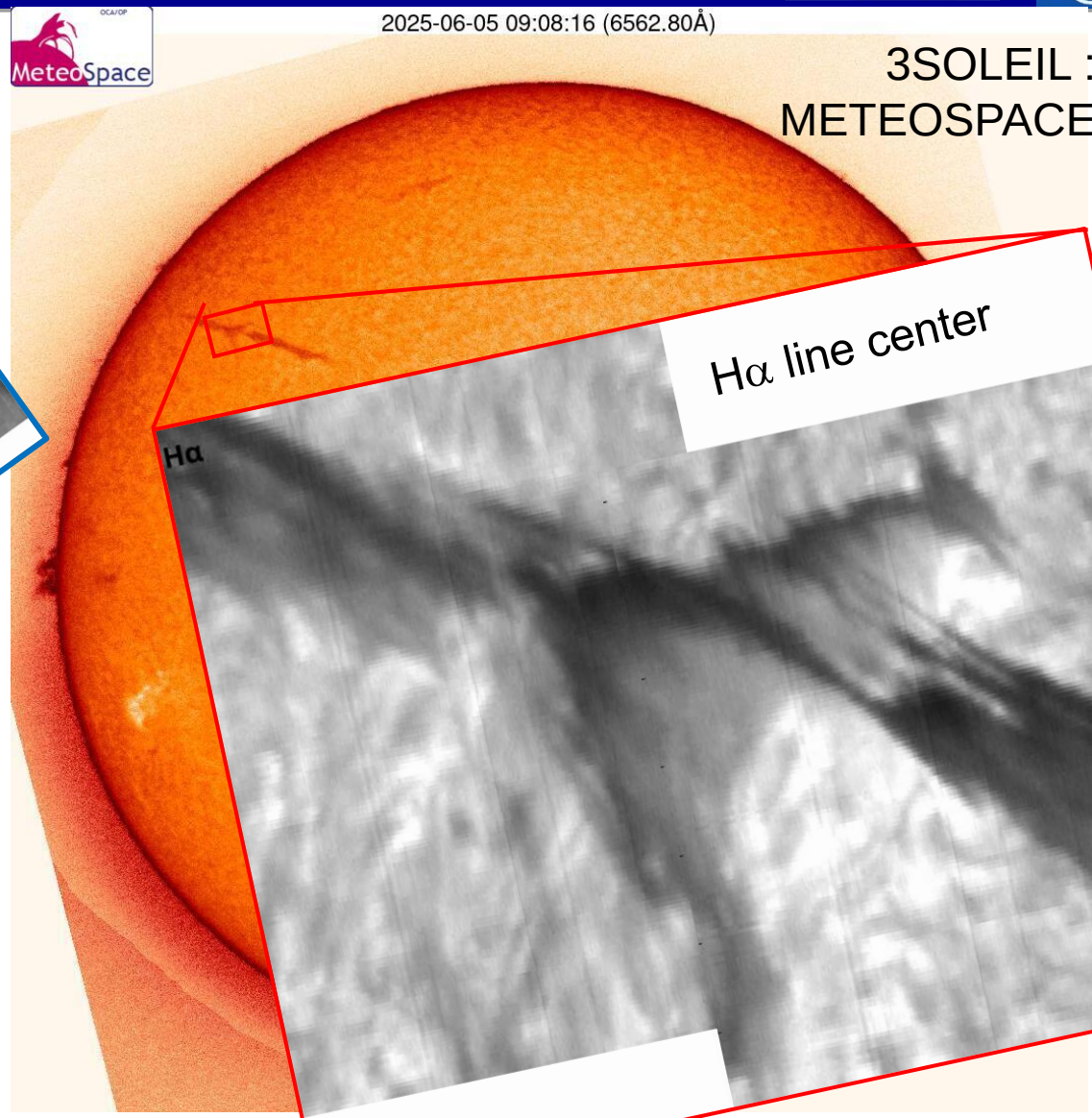
- THEMIS will eventually be outdated by >4m-class telescope such as DKIST (USA), the European Solar Telescope (in project), the Chinese Giant Solar Telescope.
  - **THEMIS relevance as an observation-campaign oriented telescope will faint**
- **THEMIS will remain an existing French facility**
  - 50 yrs of THEMIS exploitation costs (~200 k€/yr) ≈ Costs of ending exploitation (site restauration >10 M€)
  - Track record that cession of infrastructure is illusory
  - No real project for transformation of an highly-solar-observation-oriented building
- **The exploitation of THEMIS in service mode, oriented toward space-weather, appears as the most relevant use for THEMIS beyond the 10 years horizon.**
  - THEMIS can provide unique type of datasets of interest for SW applications (see hereafter)
  - Research for SW is a strength of the French heliophysics community:
    - THEMIS evolution fitting with ATST perspectives
  - THEMIS is presently an INSU observation station (ANO-3)
    - Mutualization/merging of several solar-related SNOs of INSU with orientation toward SW
    - THEMIS SW-oriented-observation would fit within this evolution

THEMIS synergies with 3SOLEIL

- THEMIS observations can be highly complementary to several dataproducts of 3SOLEIL

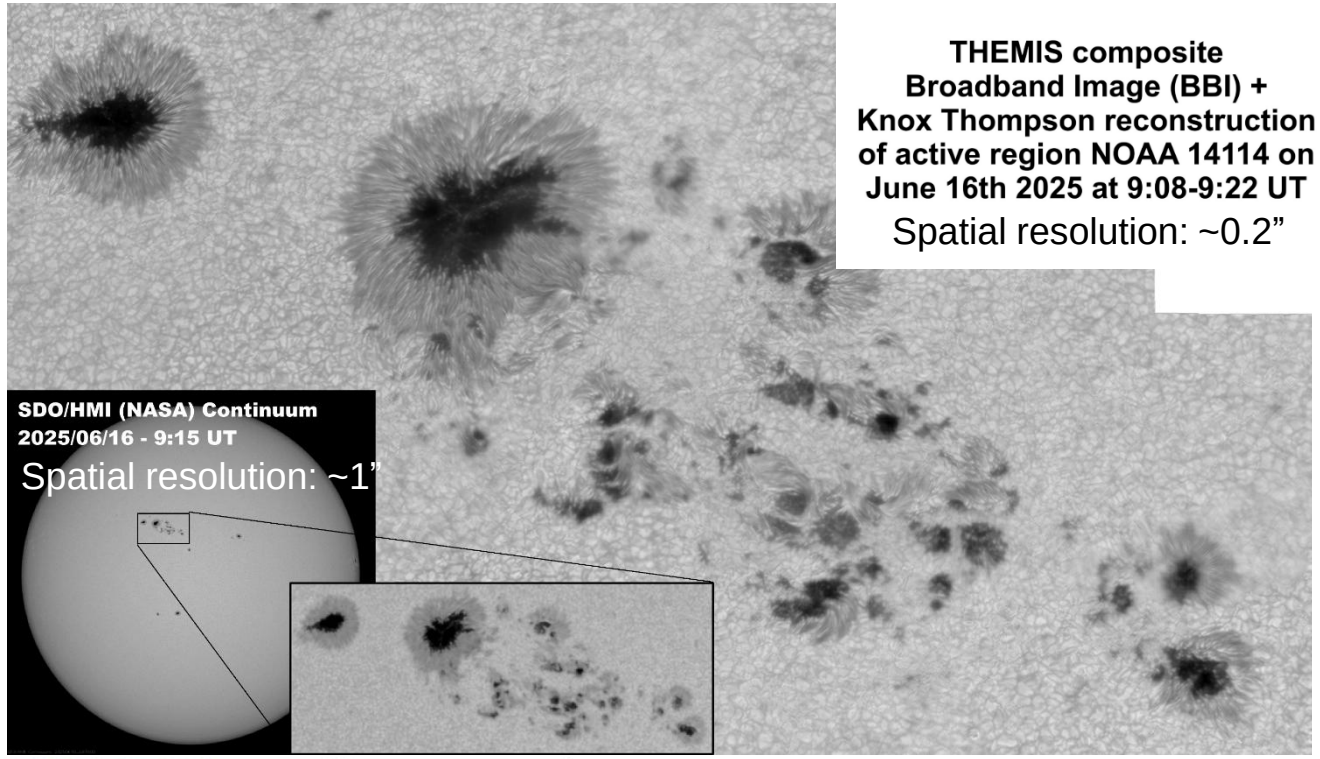


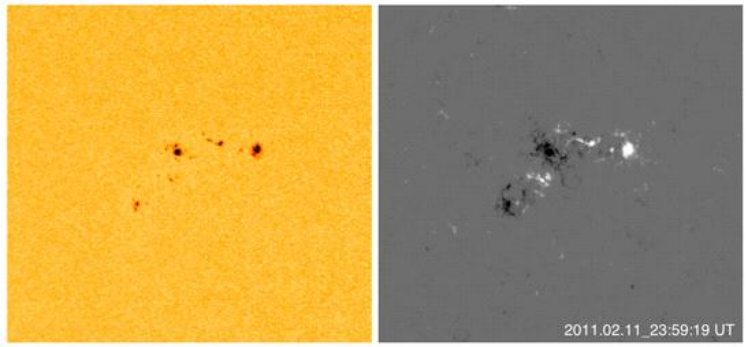
3SOLEIL:
Meudon Spectrohéliographe



3SOLEIL :
METEOSPACE

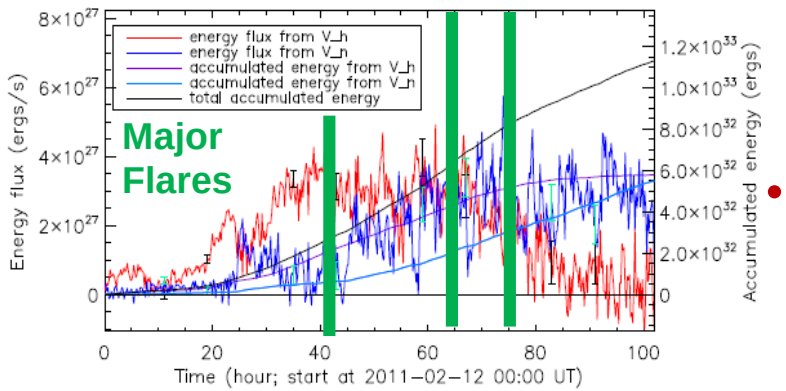
Ground base observation of ARs





White light (SDO/HMI) B_{los} magnetogram

Liu & Schuk 12

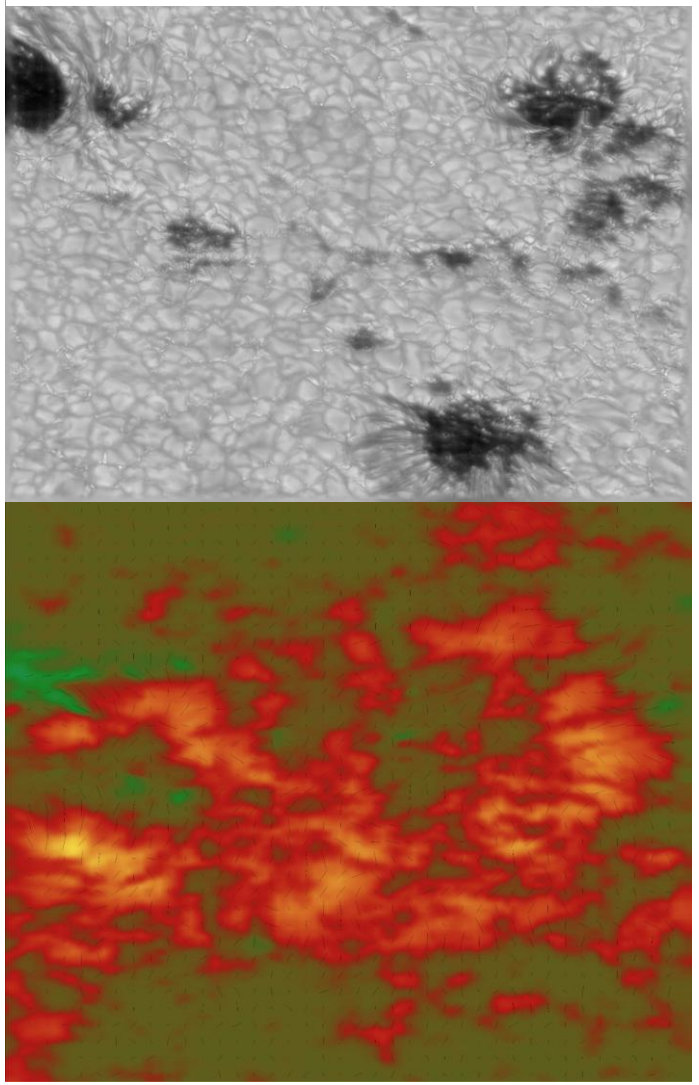


- Space instruments have a fantastic operative availability
  - no night, no weather/seeing issues
- A very large fraction of data >95% is basically irrelevant for space weather, in particular for eruption prediction.
- **Ground-based instruments can reach unrivaled resolution, in particular in region prone to solar eruptions**
- Several properties of solar activity sources, in particular their magnetic energy content, do not evolve on a second-to-hour time scale.
- **High-quality observations at 6hr-1day cadence can be sufficient: e.g. vector magnetograms for high-fidelity coronal B reconstruction**

ESA Safe Safety ARMagMap_THEMIS project

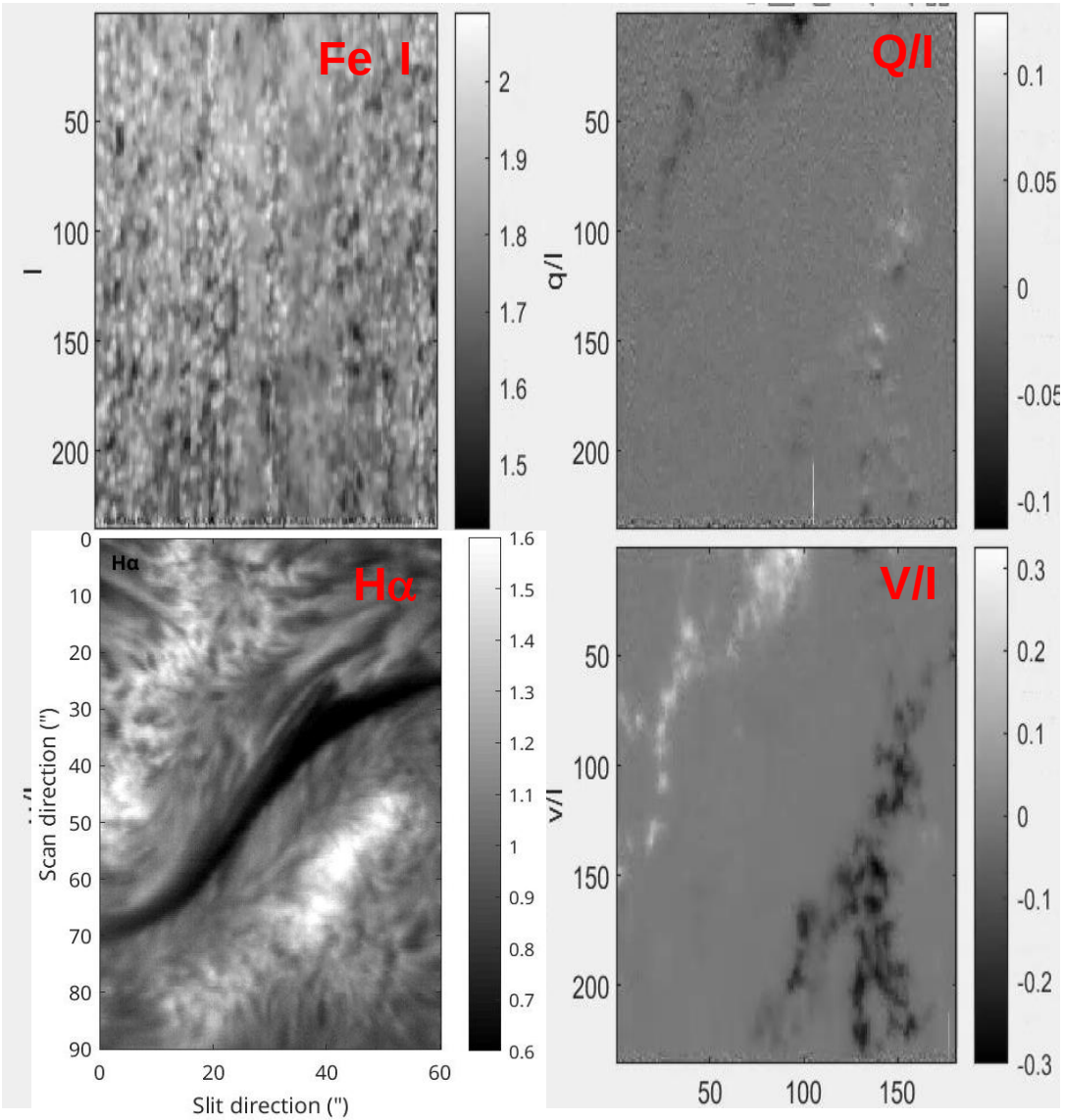
- **THEMIS ARMagMap_THEMIS project for ESA Safe Safety program ⇒ initiate transformation of THEMIS toward service mode for SW**
- **Dedicate a portion (10%) of THEMIS operation time**
  - THEMIS is reaching maturity: instrumental developments are diminishing.
  - Many sub-systems have been simplified in the past years: reduce the need for extensive maintenance
  - ➔ longer operative availability period expected
- **Production of standardized data products**
  - Reflection toward a standard set-up for THEMIS
    - Standard MTR2 set-up: e.g. Hα & Fe I doublet @6302 A
    - Standard cameras set-up
    - Standard scanning methodology: orientation, FOV, step, cameras
    - Usage of IBIS 2.0 to be discussed with Italian partners
  - Design of automatic data analysis & data distribution, interoperability pipelines & soft
    - Collaborate with expert French SNOs from ANO6

Example of intensity image (top) and Blos map (bottom) from THEMIS MTR2 **(Gelly & Bommier)**



ESA Safe Safety ARMagMap_THEMIS project

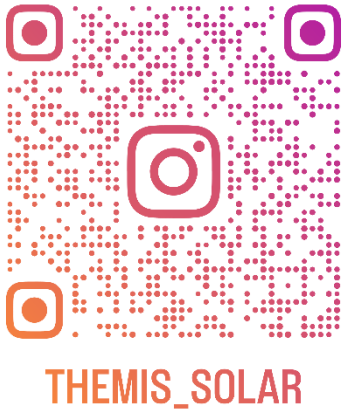
- **Production of datasets of interest for SW : high-resolution, vector magnetograms of eruptive regions (active regions, filaments, …)**
  - Provide first order handedness of filaments: relevant for the estimation of B_z orientation of CMEs → improvement prediction of their geoeffectiveness.
  - **Added value of spectroscopic measurements (better quality magnetogram)** → better magnetic inversions → better extrapolation of coronal magnetic field.
  - **Provide "zoomed", i.e. higher-resolution magnetic information on potentially eruptive structures** → better extrapolation of coronal magnetic field.
  - higher-fidelity coronal B reconstruction → improved characterization on magnetic properties of source regions **→ better advanced prediction of eruptions**
- Complement existing spatial datasets.
  - Improve reliability of magnetic measures thanks to comparison with spatial data sets
- Reduce actual exclusive reliance on non-EU magnetograms

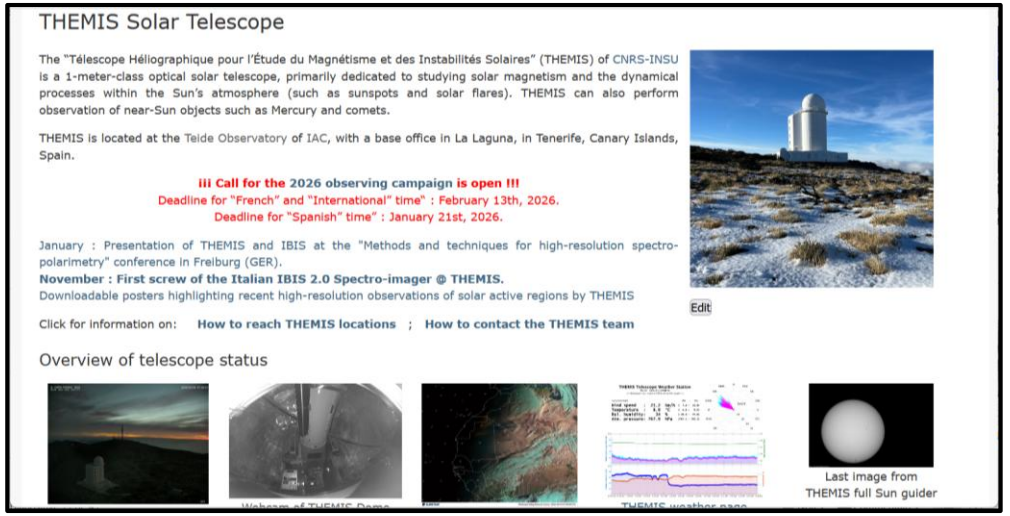


THANKS FOR YOUR ATTENTION

FSLAC International Research Lab.

- New THEMIS website:
  - Feedbacks welcomed
- New Instagram account
  - Follow us @themis_solar
- Downloadable posters on THEMIS highlights





https://www.themis.iac.es