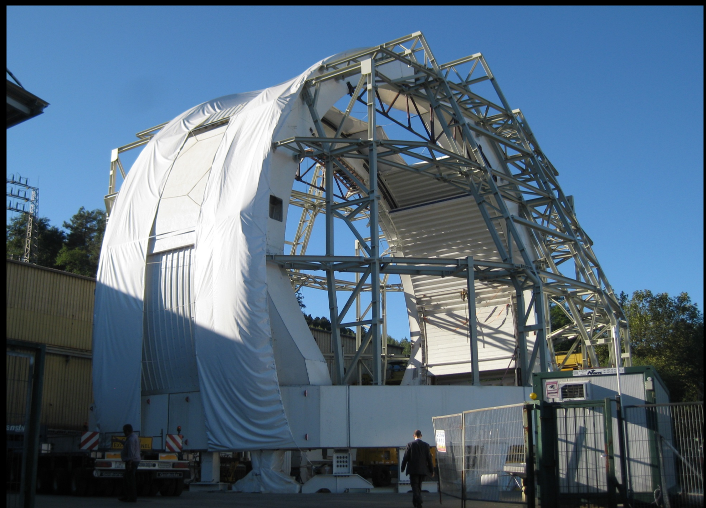
Solar-C and the new 4m class solar telescopes

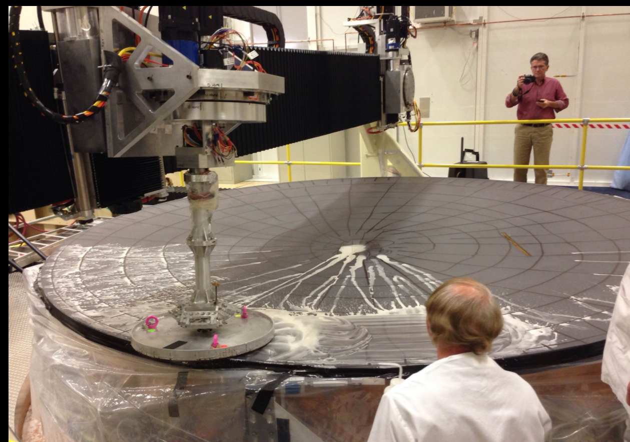
V. Martínez Pillet
National Solar Observatory

Outline

1. ATST/EST Status
2. Why 4m?
3. Science case: quiet sun magnetism
4. Solar Physics from space: opportunities
5. Solar-C & ATST

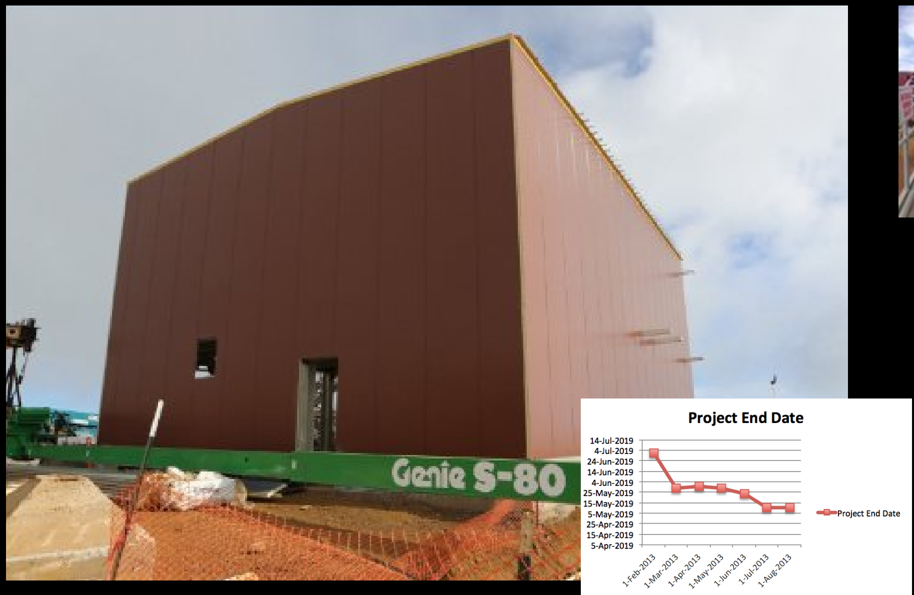
1.- ATST Status





<u>NSB approval of ATST revised project baseline</u>

Construction at the summit !



First generation of instruments

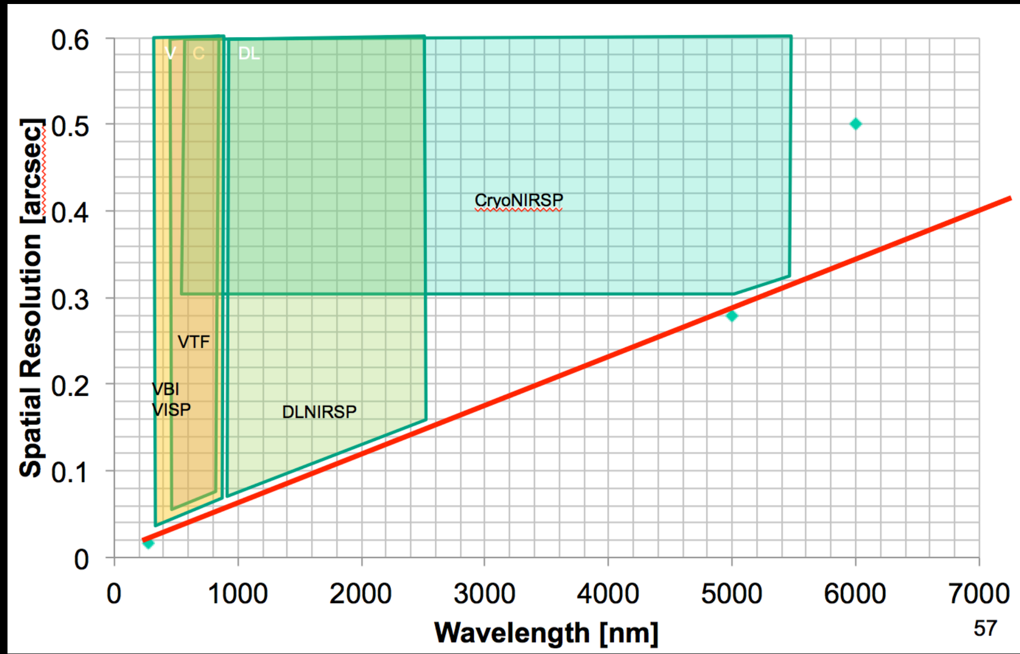
VBI (ROSA): Visible Broad band imager
- Wavelength range: 380–900 nm
- Spatial resolution: 0.03” @ Hα
- Spatial FOV: 2×2 $arcmin^2$
- Real-time speckle

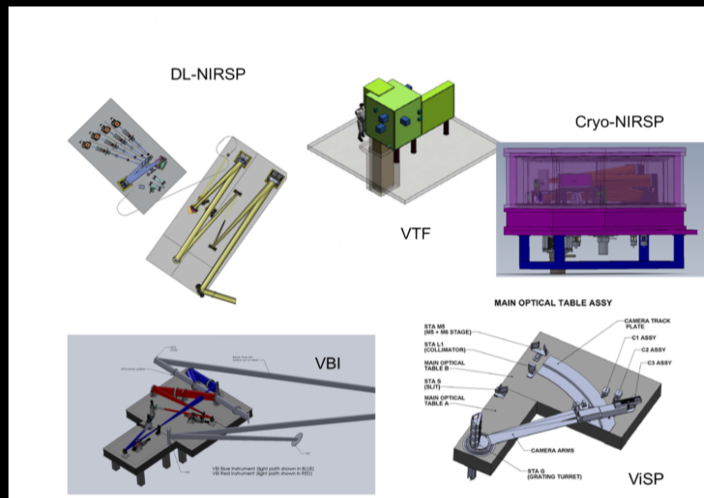
ViSP (SPINOR): Visible Spectropolarimeter
- Wavelength range: 380–900 nm
- Up to three lines simultaneously/fast reconfig (10 mins)
- Spatial resolution: 0.03”/pixel
- Spatial FOV: 2×2 $arcmin^2$
- Spectral Resolution: *R* ~ 3.5 pm at 630 nm

VTF (IBIS): Fabry-Perot tunable Spectropolarimeter
- Wavelength range: 520–860 nm
- Spatial resolution: 0.03”
- Spatial FOV: 1x1 $arcmin^2$
- Spectral Resolution: *R* ~3.5 pm at 630 nm

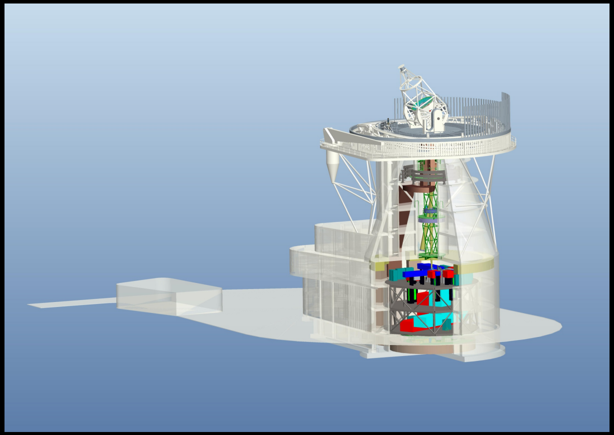
DL-NIRSP (FIRS): Diffraction Limited NIR Spectropolarimeter
- Wavelength range: 900–2300 nm
- Spatial resolution: 0.03-1”/pixel
- Spatial FOV: 2.4x1.8 $arcmin^2$

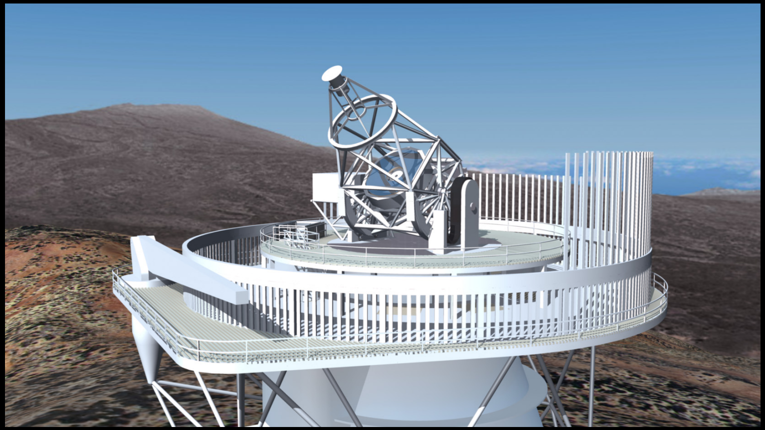
Cryo-NIRSP (CYRA): Cryogenic NIR Spectropolarimeter
- Wavelength range: 1000–5000 nm
- Spatial resolution: 1” (corona)
- Spatial FOV: 3x4 $arcmin^2$





EST (slide provided by M. Collados)





- Conceptual design finished
- Detailed design in progress (2013 - 2016)
- Construction Phase (2017 – 2022)

  (funding not approved yet)

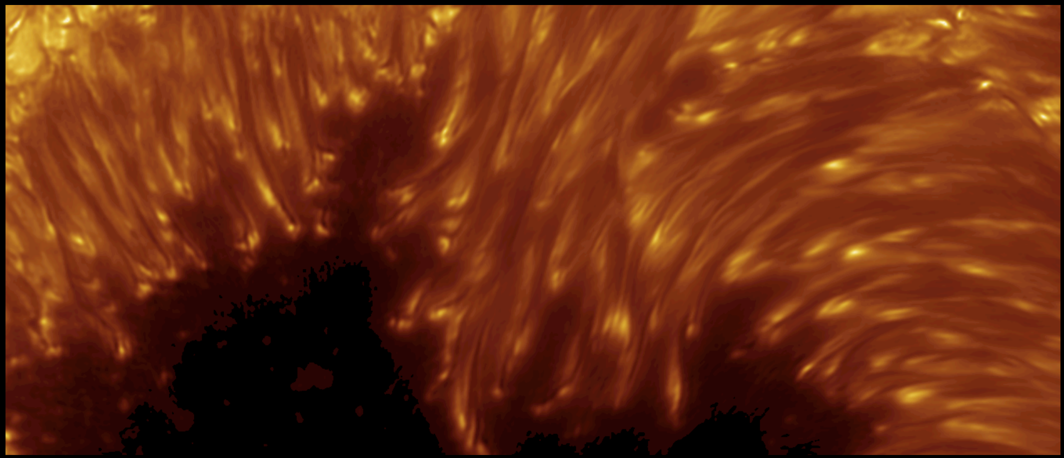
2.- Why 4m?

100 km is photon mean free path & H_p (scale height)

$$D = \frac{\lambda}{\phi}$$

100 km (ϕ ~0.1 arcsec) requires

$D \geq$ 1m



$$t_{\exp} \propto \frac{\phi / 2}{v_c}$$

→ 25 seconds. Polarimetry forces it to be 25/4 ≈ 6 s

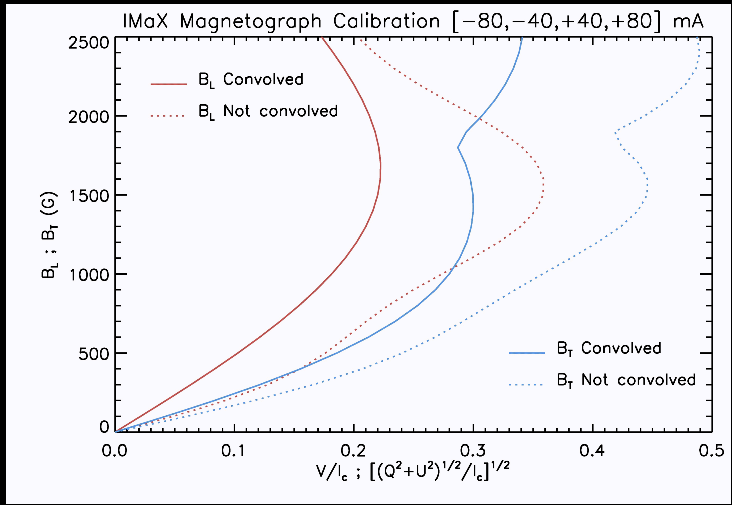
Science requires ***SNR* ≈10⁴** (m_o= -10.7 magnitudes/arcsec², $\phi_{px} = \phi / 2$)

$$D = \frac{SNR}{\sqrt{0.7N10^{-0.4m_{\circ}}\tau\Delta\lambda Q t_{\exp}\phi_{px}^2}}$$

→ $D \approx$ 4.6m

Forget the diffraction limit
(keep the photons!)

10^{-3}: requirement or performance?

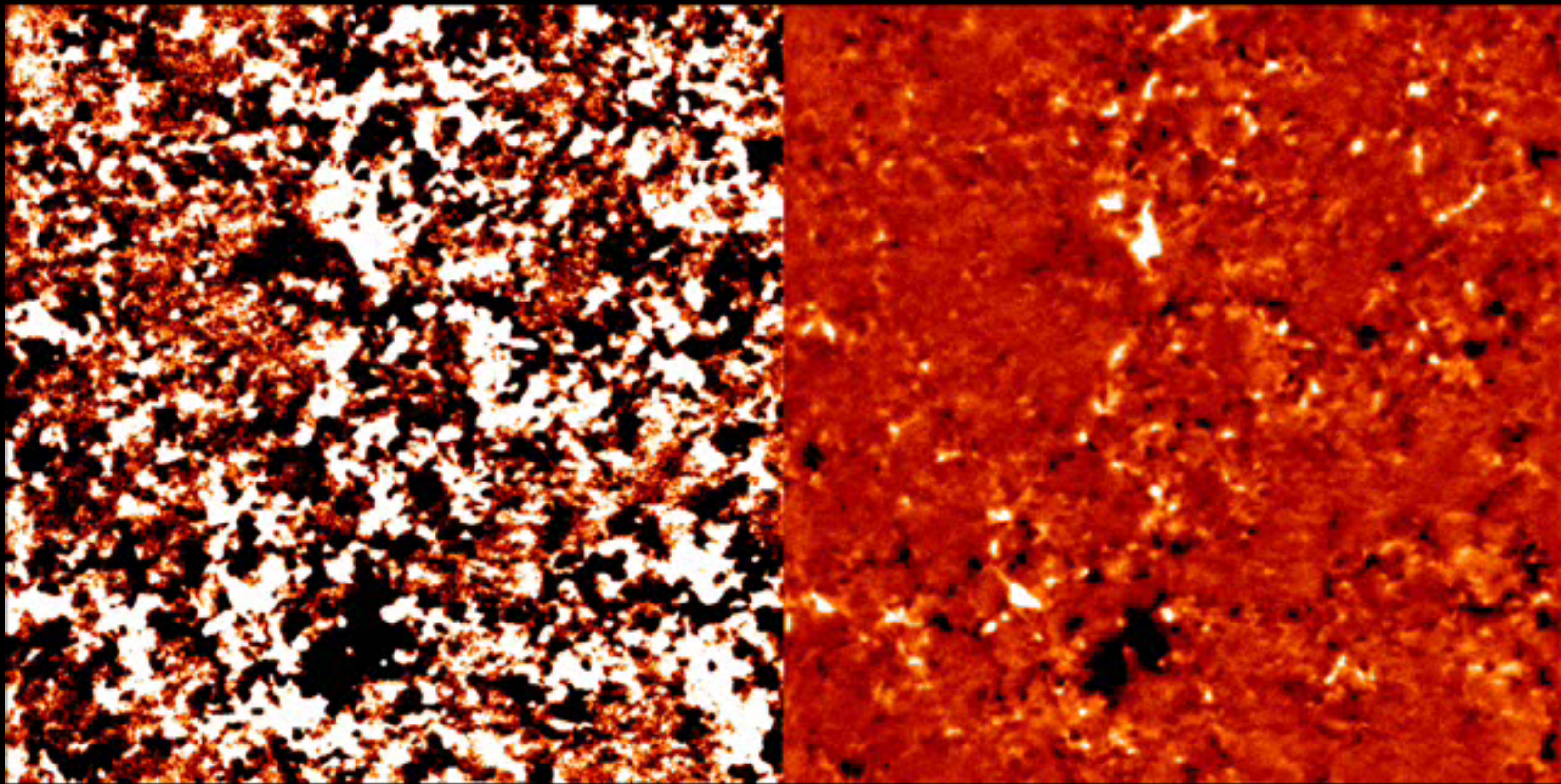


$$B_{LON}(G) = 4759 \frac{V}{I_c}$$

$$B_{TRA}(G) = 2526 \left[\frac{\sqrt{Q^2 + U^2}}{I_c} \right]^{1/2}$$

- 10^{-3} sensitivity gives a B_{LON} sensitivity of 5 G
- 10^{-3} sensitivity gives a B_{TRA} sensitivity of 80 G
- This provides a fundamentally *biased* view of solar magnetism
- To have a 5 G sensitivity in B_{TRA} we need to reach 4 10^{-6}
- The Sun doesn't know anything about 10^{-3}…

We are starting to explore the 10^{-4} limit

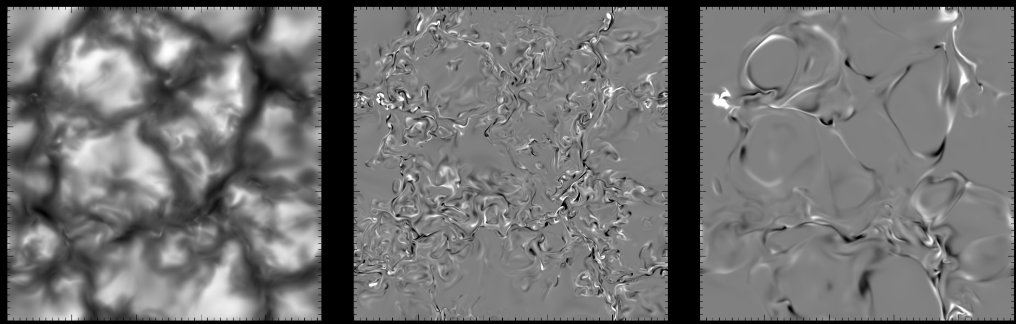


$\pm 5\ 10^{-4}$

$\pm 5\ 10^{-3}$

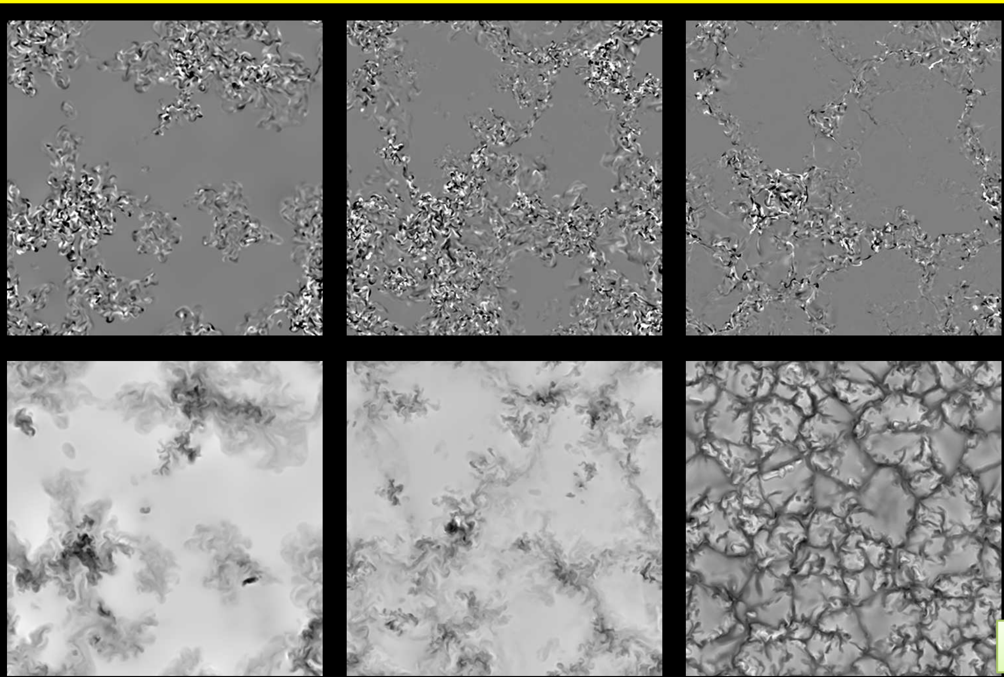
3.- Science Case: Quiet Sun magnetism

25 G **3 G**



Intergranular lanes filled with SSD fields

Vogler et al 2007



The dynamo-generated field is associated with the downflows in the deeper parts of the domain and thus exhibits a 'mesogranular' pattern at the surface.

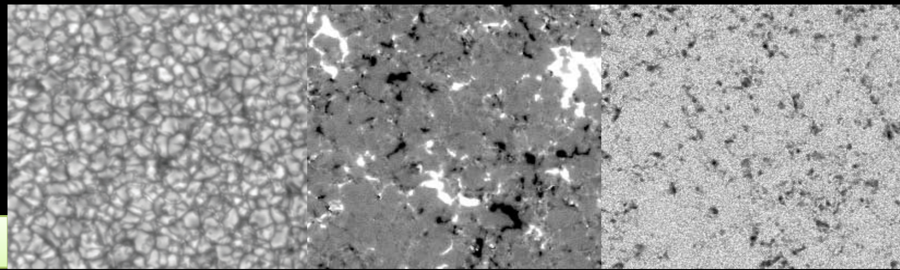
Schussler et al 2013

Quiet Sun magnetism: Hanle vs. Zeeman

- Hinode/SP has mapped QS magnetic fields with unprecedented spatial resolution (0.3 "), polarimetric sensitivity (10^{-3}) and spectral coverage.
- Much debated in the last years: noise and its impact

$$\left\langle \frac{|B_T^{app}|}{|B_L^{app}|} \right\rangle \approx 5$$

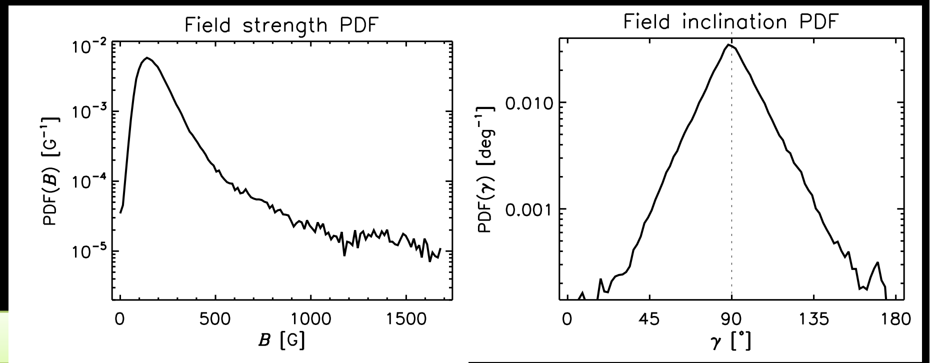
Lites et al. 2008



- Hinode/SP at **<u>10^{-4}</u>** obtains (67 s):

$$\left\langle \frac{|B_T|}{|B_L|} \right\rangle \approx 3.1$$

Orozco Suarez et al. 2012

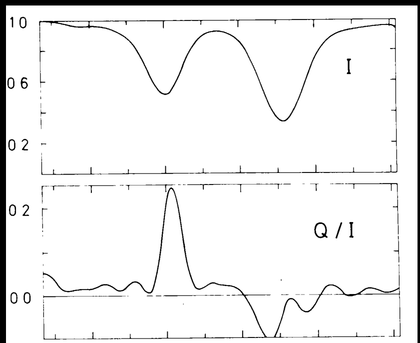


- 30% of the pixels with clear Q and U signals, ME inversions
- QS fields: <u>hectogauss (220 G)</u>, <u>transverse</u>, r<u>andom orientations</u>
- Long integration times result in larger inclinations

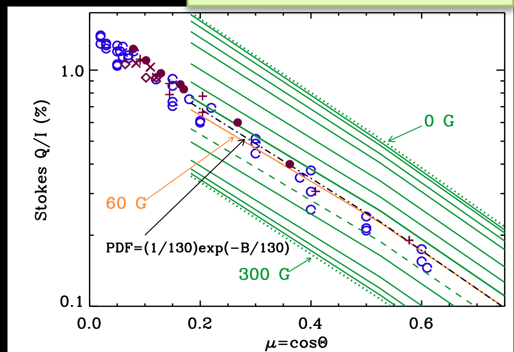
$$\tan\gamma = \sqrt{2}\tan\gamma_{real}$$

Quiet Sun magnetism: Hanle vs. Zeeman

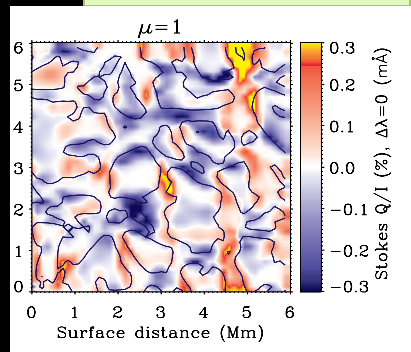
- Hanle "hidden" turbulent fields (Stenflo, Faurobert-Scholl, etc.): >10 G
- Small signals observed with no spatial resolution and long integrations
- Measurements typically made at <u>**10^{-4}**</u>. Interpretation is model dependent.
- Sr I 4607 Å, C_2 5140 Å molecular lines.



Stenflo 1982



Trujillo Bueno et al. 2004



Trujillo Bueno et al. 2007

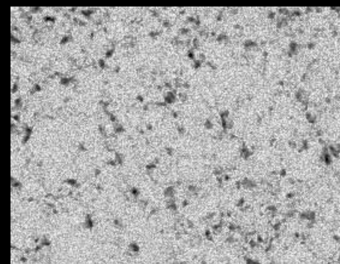
- Average field is <u>$<|B|>\approx$ 130 G</u>. Granules 10 G & interganular lanes > 200 G.
- Non vertical (isotropic), hectoGauss fields needed for Hanle depolarization.

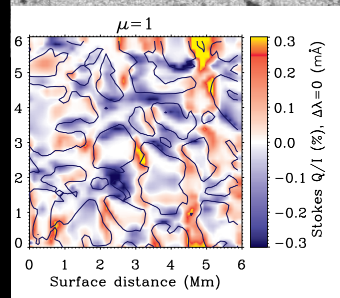
Hinode/SP Quiet Sun (Zeeman) fields ≅ Hidden turbulent (Hanle) fields ?

Quiet Sun magnetism: Hanle vs. Zeeman

- Urgent: Similarities between the Zeeman QS and Hanle QS fields?
- Shed light into their origin: Small-Scale Dynamo (non-helical)
- Average properties are similar: there must be a relation
- Zeeman-inferred QS fields are episodic (mesogranular)
- Hanle-inferred QS fields are pervasive in time and space (microturbulent?).
- Resolve Hanle QS fields: A target for large aperture solar telescopes.

- 10^{-4} sensitivity in Stokes Q & U
- Spectral resolution 50 mÅ
- Resolve granular evolution (tens of seconds).
- Resolve granulation (Hinode resolution may be OK)
- Zeeman (5250 Å) and Hanle (Sr & C_2) lines simultaneously
- In the blue !





4.- Solar Physics from space: opportunities

<u>CDS</u> (Coronal Diagnostic Spectrometer)

<u>EIT</u> (Extreme ultraviolet Imaging Telescope)

<u>GOLF</u> (Global Oscillations at Low Frequencies)

<u>LASCO</u> (Large Angle and Spectrometric Coronagraph)

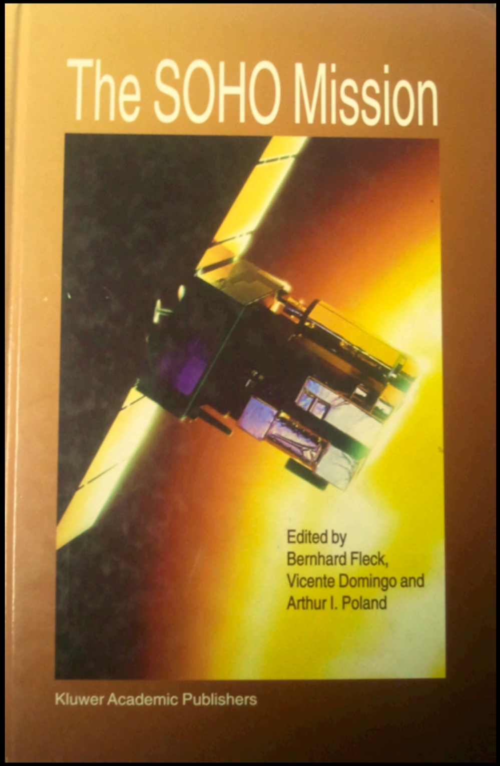
<u>MDI</u> (Michelson Doppler Imager)

<u>SUMER</u> (Solar Ultraviolet Measurements of Emitted Radiation)

<u>SWAN</u> (Solar Wind Anisotropies)

<u>UVCS</u> (Ultraviolet Coronagraph Spectrometer)

<u>VIRGO</u> (Variability of Solar Irradiance and Gravity Oscillations)



SOHO mission book (531 pages)

Measure magnetic fields at all heights

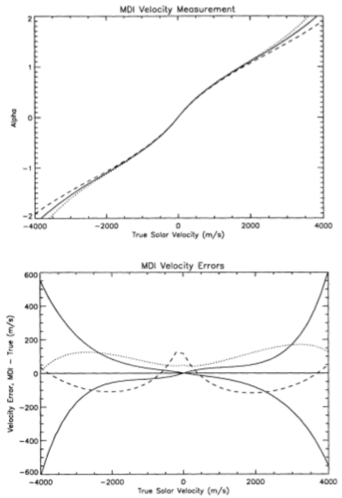


Fig. 12. The upper panel shows α versus velocity calculated for a nominal line profile (solid) and for lines 25% broader (dashed) and narrower (dotted). The lower panel shows velocity error versus velocity for a reasonable range of solar line profile and filter variations. The solid curves show the velocity error with perfect filters but line profiles that are 25% broader or narrower than the profile used to construct the velocity lookup table. The dashed line shows the effect of mistuning of the Michelsons, -10 mÅ for M1 and +30 mÅ for M2. The dotted curve shows the effect of a Lyot central wavelength shift of +75 mÅ relative to the nominal line center at zero velocity.

line depth to an accuracy of about 5% over the variation of line profiles and velocity considered above.

The continuum intensity is computed using all five filtergrams:

$$I_c = 2F_0 + I_{\text{depth}}/2 + I_{\text{ave}}$$

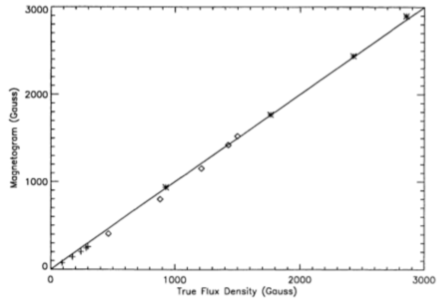


Fig. 13. Plot of modeled MDI magnetogram signal vs. true flux density, for umbral profiles (asterisks), penumbral profiles (diamonds), and plage profiles (plusses). The solid line is simply y=x.

where I_{ave} is the average of the other 4 filtergrams, F_{1-4}. The components of this sum have cancelling systematic errors as a function of solar velocity, so the result is a continuum image free from Doppler crosstalk at the 0.2% level.

A longitudinal magnetogram is constructed by measuring the Doppler shift separately in right and left circularly polarized light. The difference between these two is a measure of the Zeeman splitting and is roughly proportional to the magnetic flux density: the line-of-sight component of the magnetic field averaged over the resolution element. Figure 13 shows simulations of this magnetogram signal for sunspot and plage conditions, with various field strengths, inclination angles, and filling factors. These simulations use the same thermal line parameters in the magnetic and non-magnetic components. Differences cause an additional weighting factor of the unsplit equivalent width times continuum intensity (Rees and Semel, 1979).

The remaining observables are derived by ground processing of continuum images. Horizontal velocities are measured by local correlation tracking of granulation in high resolution images (November *et al.*, 1987; Title *et al.*, 1986; Bogart *et al.*, 1988). Feature tracking algorithms may also be used on continuum and line depth images (Strous, 1994). The limb figure (both limb position and slope of the limb darkening) as a function of azimuthal angle

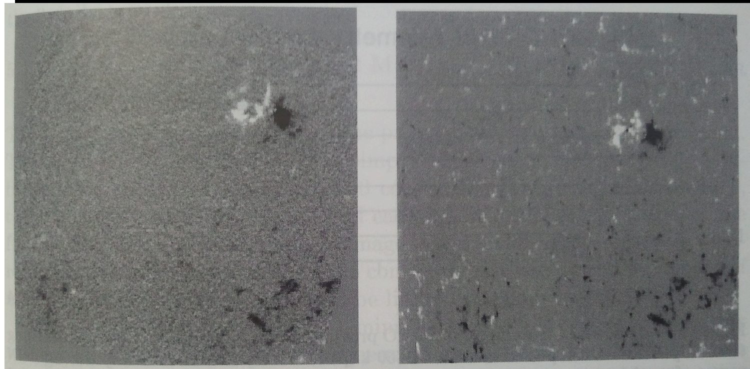
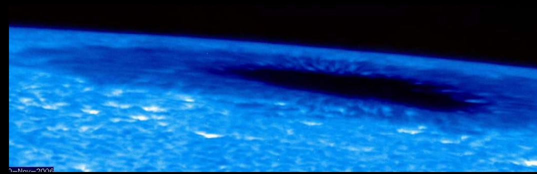


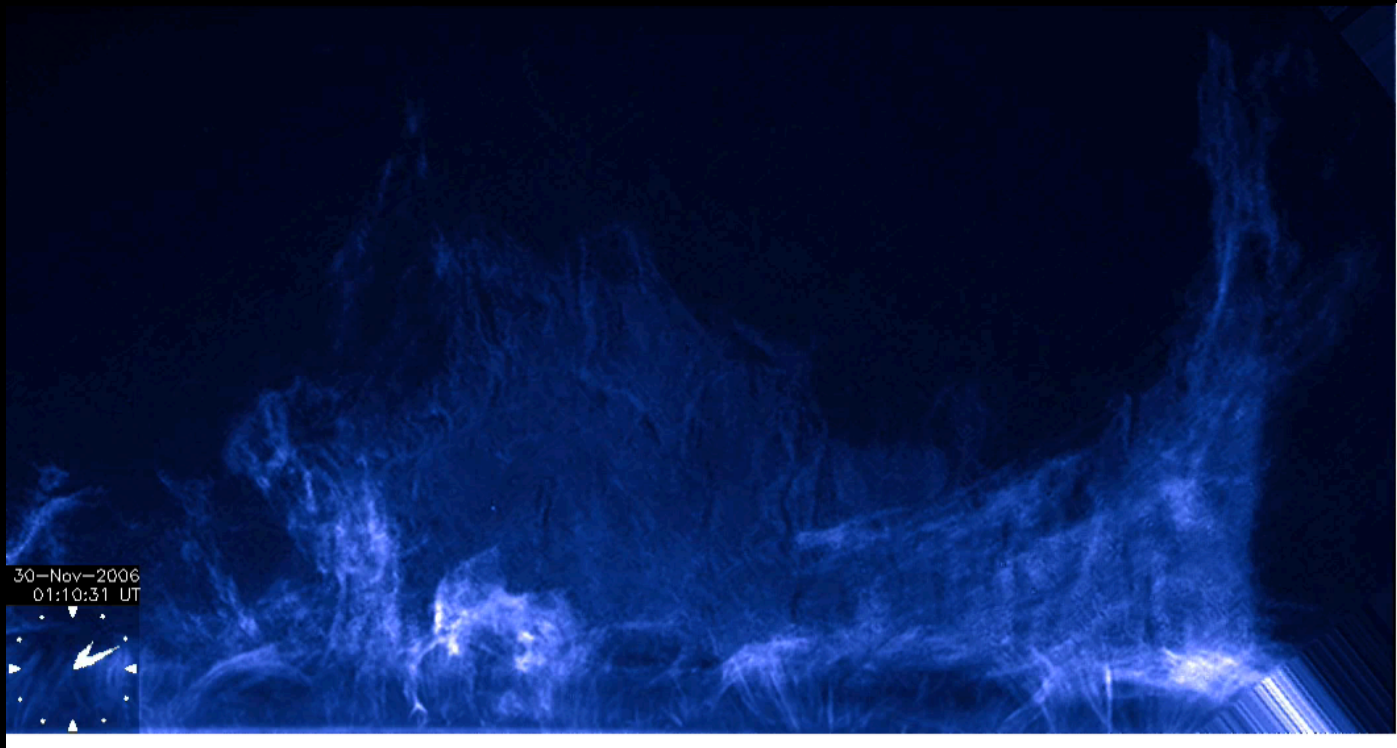
Fig. 18. High resolution magnetograms (MDI (left) & KPNO (right), taken several hours apart on 22 April 1994).

SOHO/MDI magnetograms described in 1 paragraph and 1 image

CaII H imaging: a Hinode success story

$$r_0 = 0.185\lambda^{6/5}\cos^{3/5}\zeta\left[\int\left(C_n^2(h)dh\right)\right]^{-3/5}$$



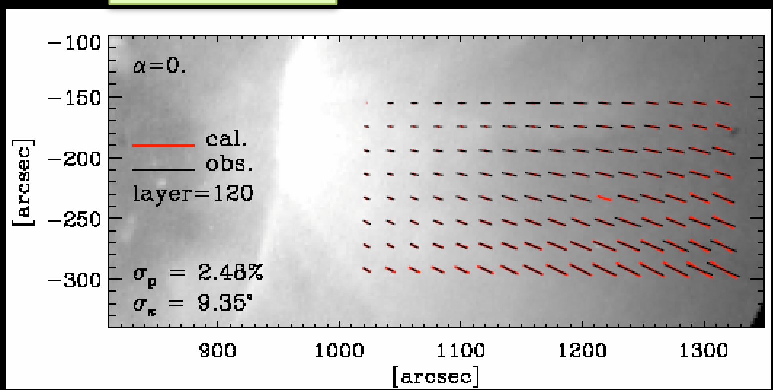


The blue is hard from the ground: AO has a much harder job

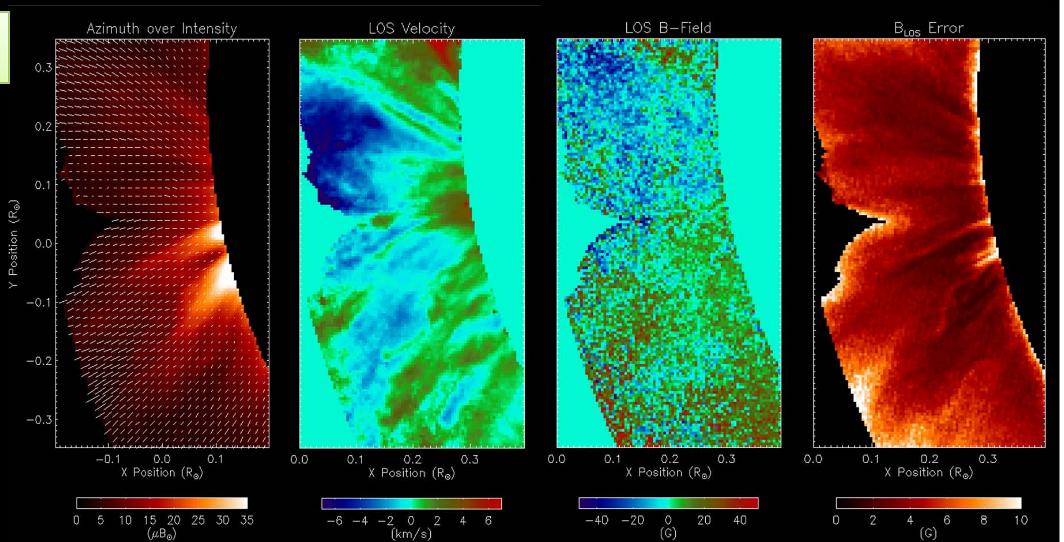
Measuring ***B*** at the TR & Corona: Off Disk

- P. Cargill@ISSI (2008) "moderate" optimism on Coronal field measurements:
  - *`the generality of the sole SOLARC published result is unclear´*
  - *`work needs to be done on both the details of the atomic physics, and how any observations would be interpreted [ref. Hanle]´*
- <u>Both have happened to a large extent</u>
- Forbidden line FeXIII 10747 Å <u>off disk,</u> Hanle saturated. Stokes V from Zeeman
- 10^{-4} was needed for observations with arcsecs (t_{exp} minutes !)
- Efforts in Sac Peak+SOLARC+CoMP → ATST (High Resolution)

SOLARC

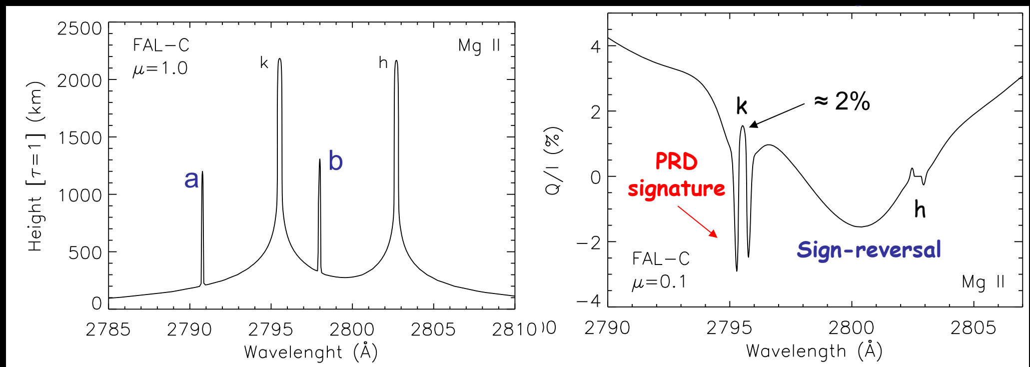


CoMP

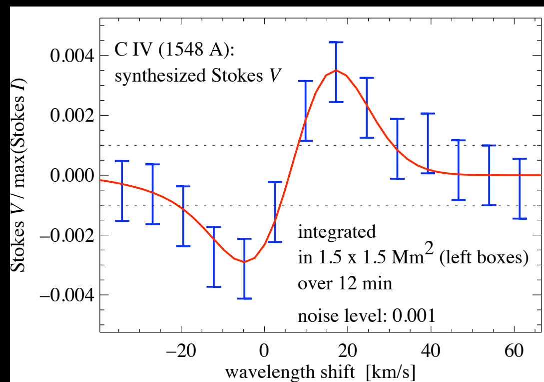


Measuring ***B*** at the TR & Corona: On Disk

- The list of valid windows to observe TR and Coronal fields is increasing rapidly
- UV: **space observations**
- Scattering polarization, Hanle effect, 3D transfer, PRD, etc included in modeling.
- Outside Hanle saturation, full vector measurements are possible
- On-disk measurements are possible (off-disk proved by SUMER/SOHO)
- MgII h & k line (2795 Å): upper chromosphere & TR. Stokes V expected large. k line sensitive to Hanle effect: 10-100 G fields.
- C IV (1548 Å): Transition region. Stokes V measured in the past.
- Need better than 10^{-3} for reliable diagnosis.



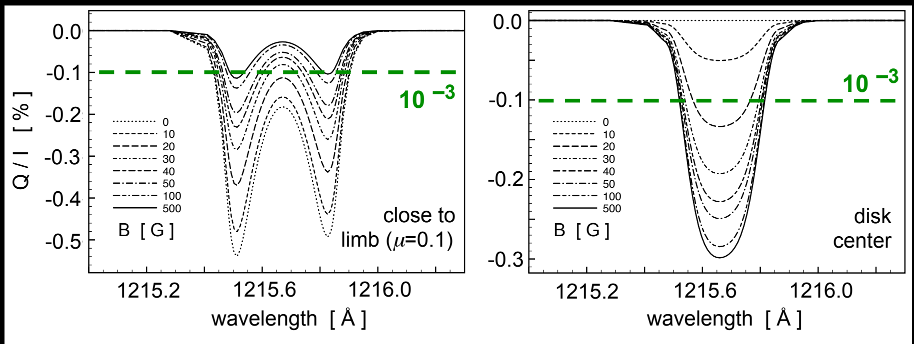
Trujillo Bueno's group

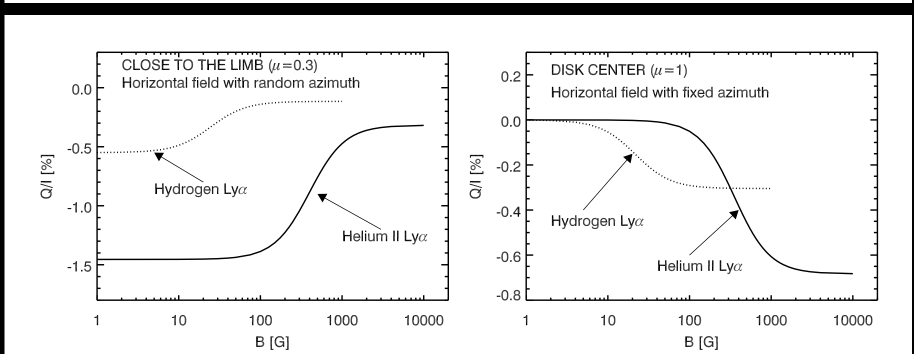


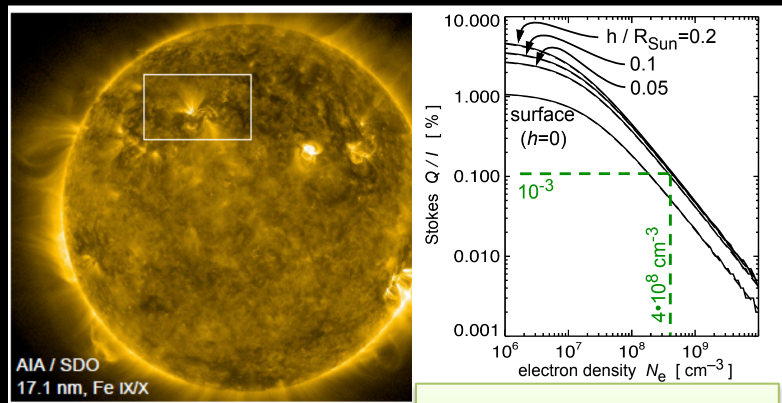
H. Peter (2012)

Measuring ***B*** at the TR & Corona: On Disk

- HI Lyα (1215 Å) off disk will provide full vector in the range 10-100 G for 1 R_{sun}
- HI Lyα (1215 Å) on disk transition region: full vector in the range 10-100 G
- HeII Lyα (304 Å) on disk transition region: full vector in the range 100-1000 G
- Fe X (174 Å): on disk. Hanle saturation but orientation can be obtained.
- Japanese led **CLASP** effort



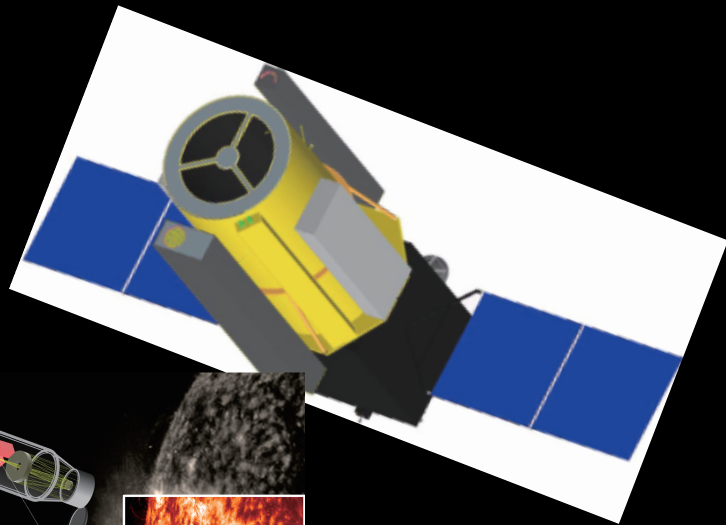


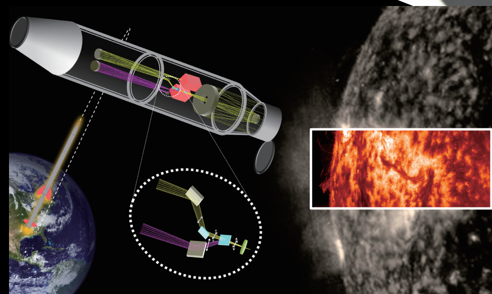


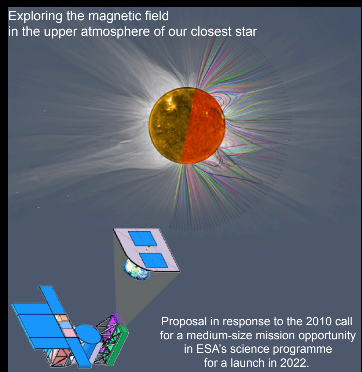
Manso Sainz's idea

Trujillo Bueno et al.

How do we best combine Solar Physics efforts?







5.- Solar C & ATST

Observing Modes of ATST: DST, Hinode, AIA

Access Mode	Service Mode	Facility Mode
PI present Dedicated time PI runs facility Proprietary data	PI at remote site Dynamic scheduling RA runs queue Open data policy	No PI Dynamic scheduling RA selects program Open data policy
Install New Instrument Inst. Scientist Training	Nominal Science Mode	Unscheduled Time Test/Develop new Programs Poor weather/seeing
~ 10%	~ 80%	~10% ??

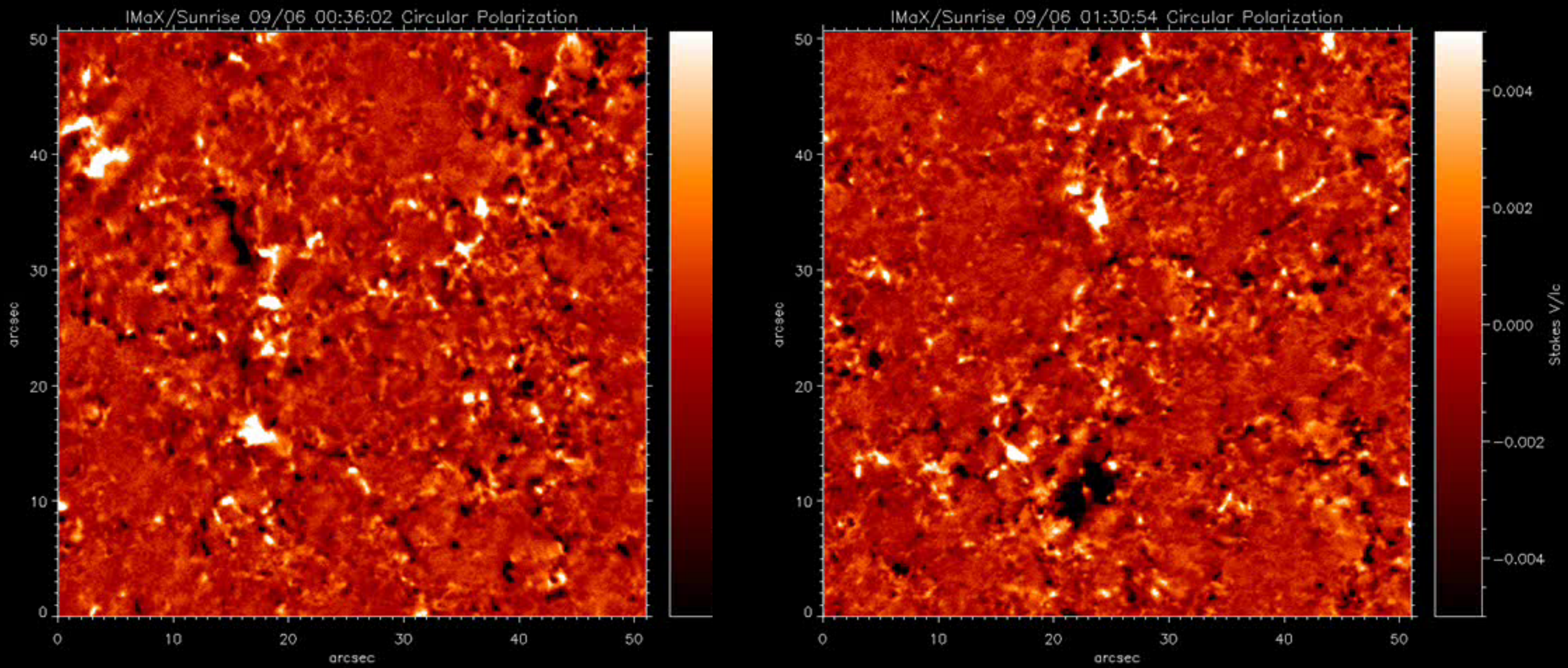
ATST operates ~ space missions: ATST+Solar-C common TAC?

Conclusions

1. ATST construction is running at full speed: 2019
2. Spectropolarimetry will do lots of science above the diffraction limit.
3. Keep emphasizing observations of the vector magnetic field
4. The blue side of the spectrum will always be hard from the ground
5. Maximize collaborations among major projects
6. Solar-C+ATST common Time Allocation Committee?

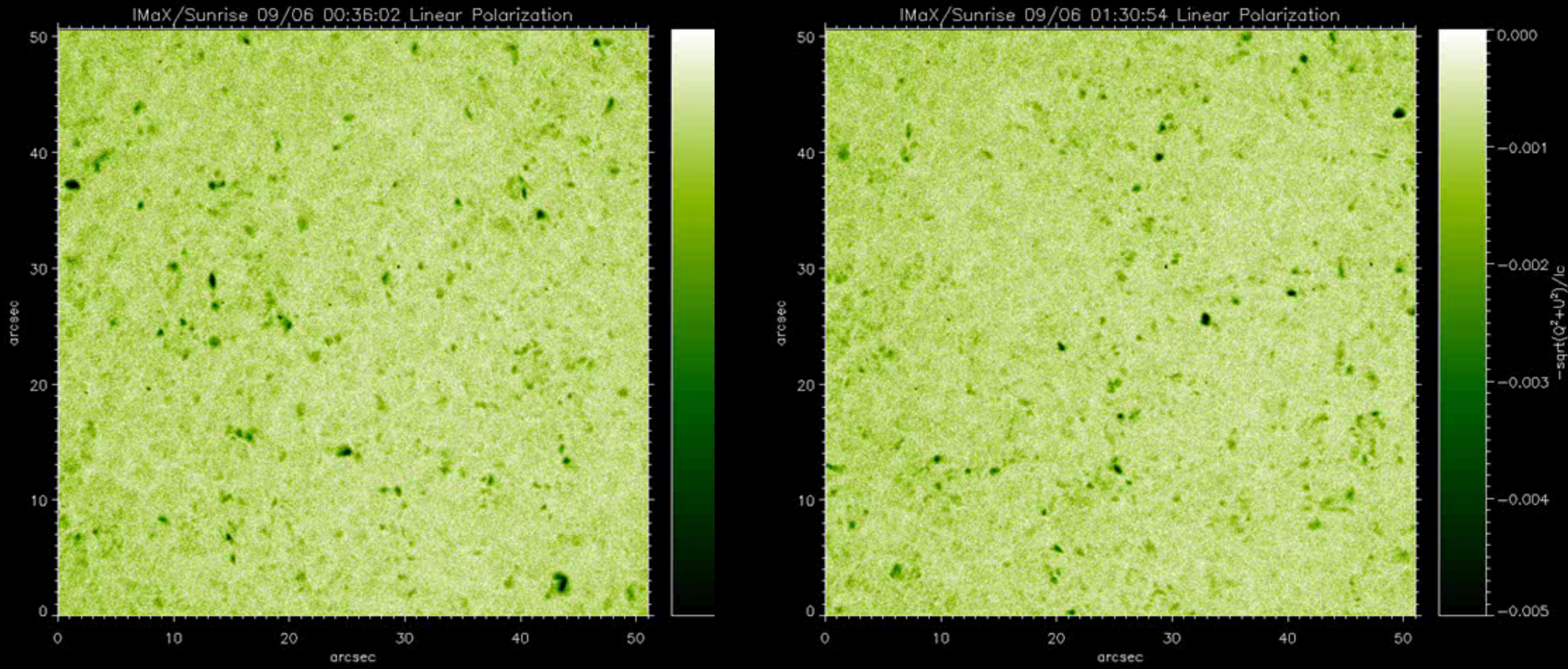
有難う 御座います

We are starting to explore the 10^{-4} limit



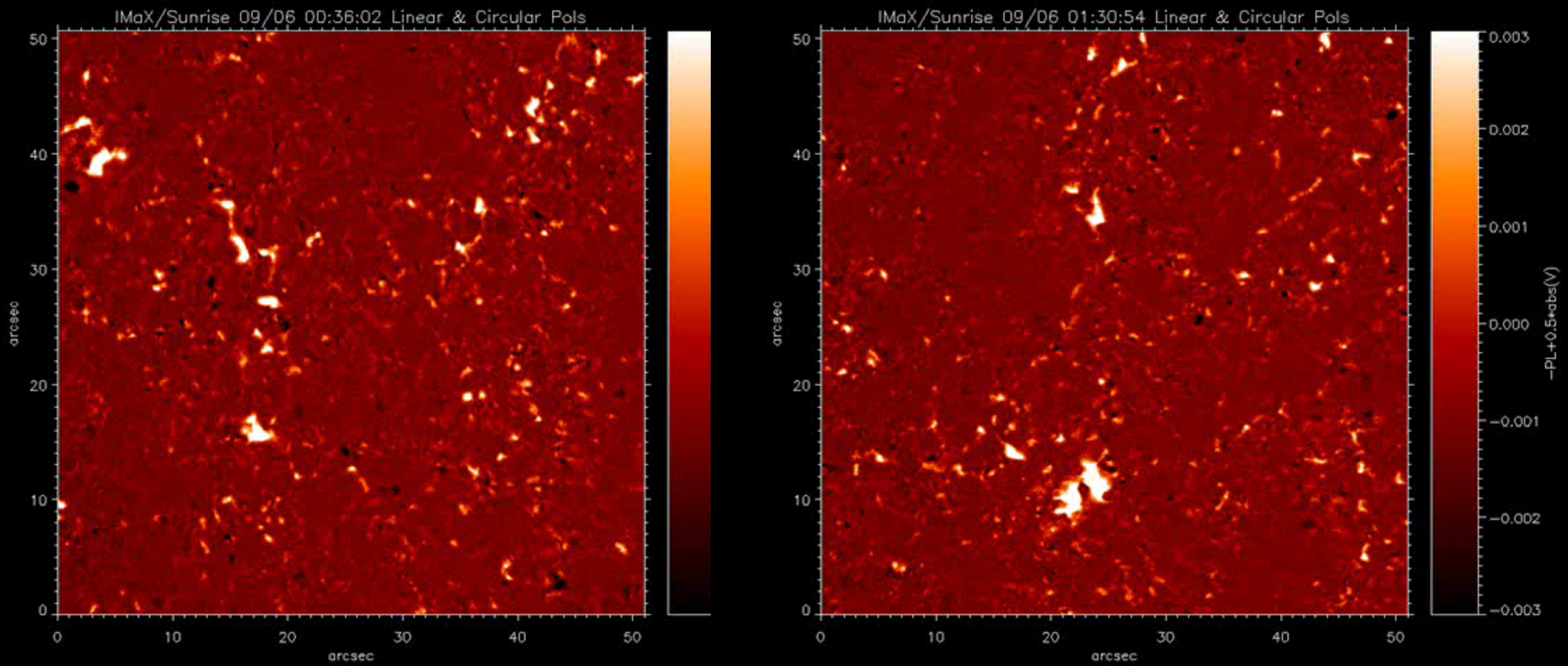
From a mixed-polarity field filling the interiors of supergranular cells to…

We are starting to explore the 10^{-4} limit



...fields with a dominant transverse component evolving in granular timescales

We are starting to explore the 10^{-4} limit



Network persists, internetwork evolves with granulation and has granular-size loop-emergence as a key ingredient