A comparison of solar image restoration techniques for SST/CRISP data

Mats Löfdahl

Institute for Solar Physics
Stockholm University

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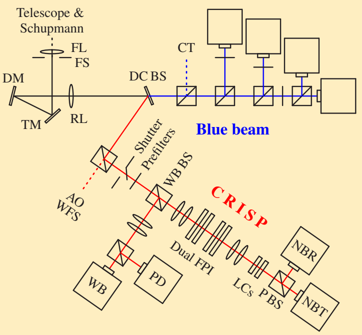
A SOLARNET project

1. CRISP image formation
2. Image restoration
3. Preliminary data and processing
4. Plans

WP 50.1.3 Image restoration

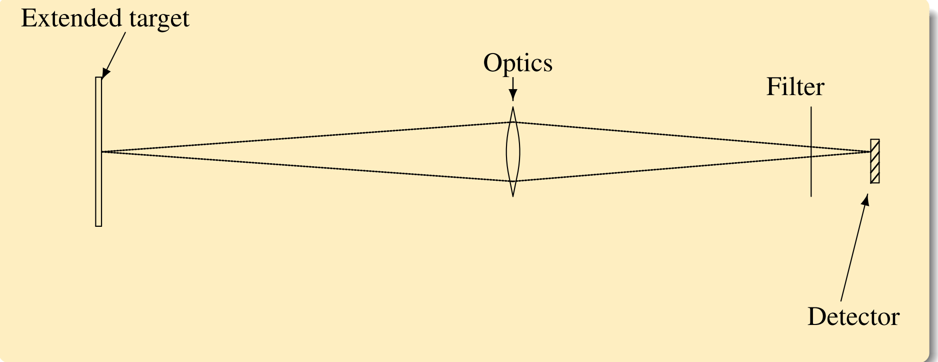
"improving the accessibility and characterization of both speckle and MFBD-based methods"

CRISP setup



- All cameras synchronized through common shutter
- Prefilter before WB BS $\Rightarrow$ NB is within WB
- FPIs in telecentric setup
- WB and NB re-imaging systems make identical beams on cameras
- PD data collected, but PD camera has problems

Image formation



- Telescope and detectors
- Ground layer seeing
- Various optical calibrations
- Scattering
- High altitude seeing
- CRISP optics
- Instrumental polarization

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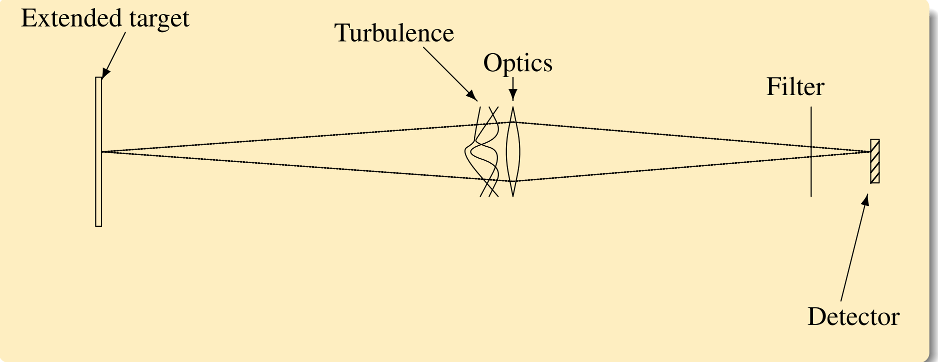

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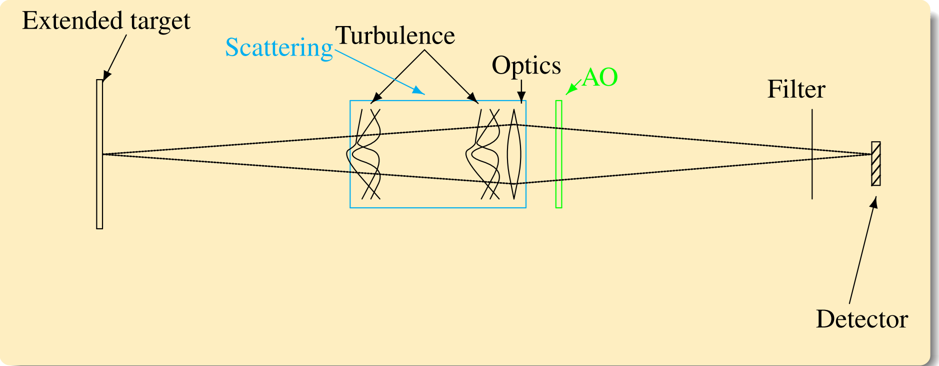

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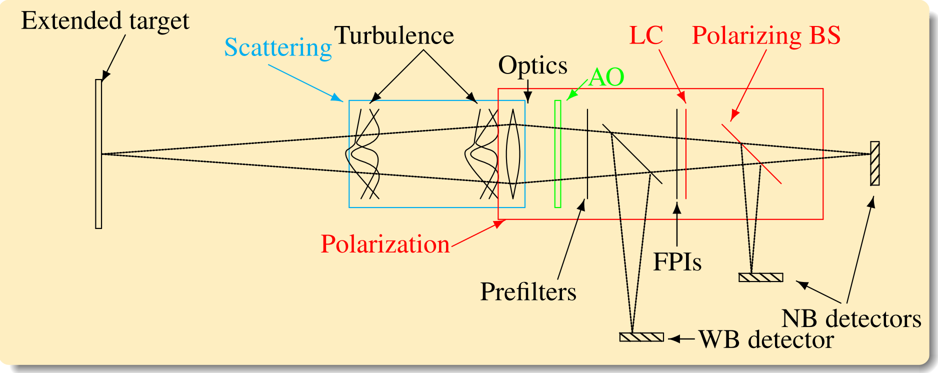

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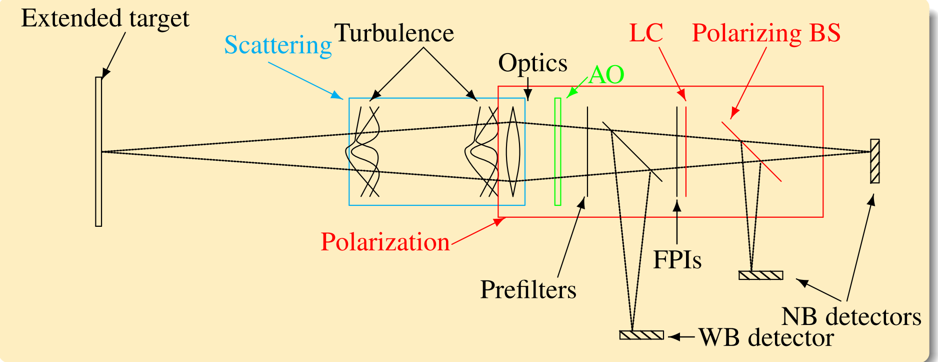

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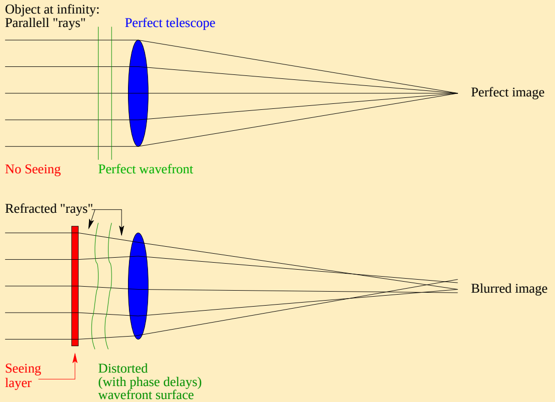
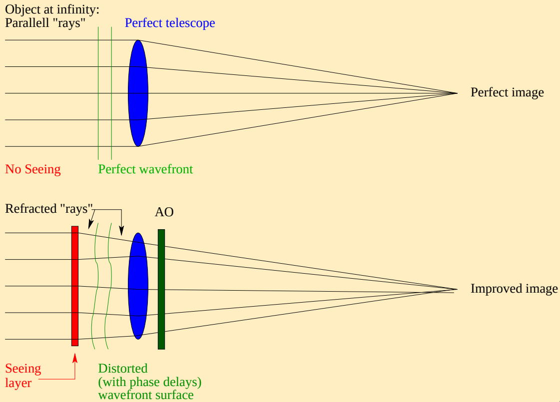
Seeing – ground layer



- Distorts wavefront
- Space invariant (isoplanatic)
- Kolmogorov statistics
- Fried's $r_0 \propto \lambda^{6/5}$
- Wavefront RMS: $\sigma_\phi \propto (D/r_0)^{5/6} \propto D^{5/6}/\lambda$
- Strehl ratio: $s \approx \exp\{-\sigma_\phi^2\}$
- $t_{\text{exp}} \lesssim 10$ ms
- $t_{\text{decorr}} \approx 50$ ms
- AO flattens wavefront
- AO modifies statistics

Seeing – ground layer with AO



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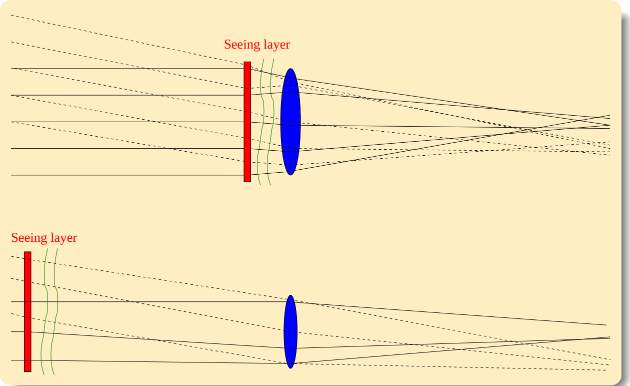
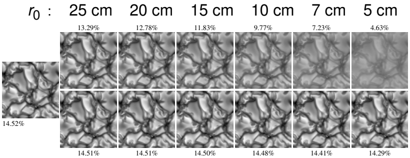
Seeing – high altitude



- Anisoplanatic
- Geometric distortions
- Space variant blurring
- Space invariant AO residuals
- Space variant statistics after AO correction

CRISP/SST straylight

Perfect correction of 36 KL modes restores resolution but not contrast



Can be compensated for by use of atmospheric statistics!

Sources

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Scharmer et al. (2011): Most straylight ∼1” wide.

Löfdahl & Scharmer (2012): Ghost images (∼1%), post-focus scattering (∼0.1%, 30”), DM high-order (fixed)

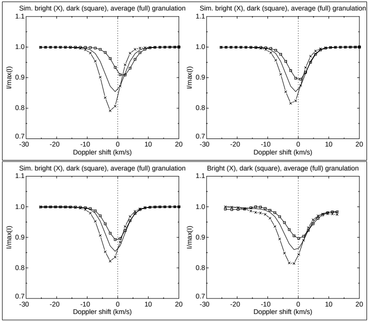
Scharmer (priv. comm.): Anisoplanatism (∼50%, depends on r_0 at high altitude and zenith distance)

Löfdahl (submitted): Scattering in atmosphere and telescope ($\lesssim$2%, 1’)

Scharmer et al. (in prep): Now 25% straylight?

CRISP/SST straylight

Match 5380 C I line profiles by degrading synthetic data with 60% straylight, 1″.2 wide.



Straylight amount also constrained by umbral intensity.

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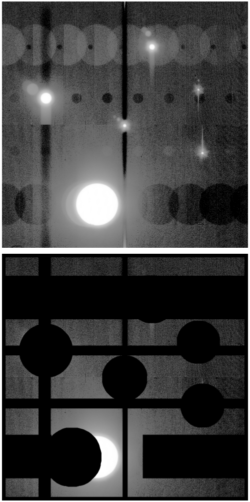
CRISP/SST straylight

Post focus straylight: target with 6 holes at primary focus



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CRISP/SST straylight

Modest assumptions:

- 1 meter telescope
- $r_0 = 50$ cm at $h = 8$ km
- 60° zenith distance
- Short exposures

Dramatic conclusions:

- Isoplanatic angle $1\overset{''}{.}3$
- Strehl ratio 0.44!

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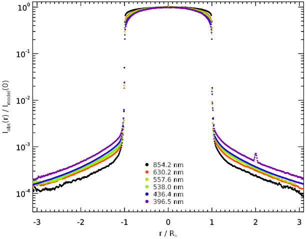
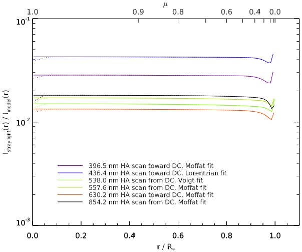
CRISP/SST straylight

Drift scans with science cameras, fit limb darkening + straylight PSF





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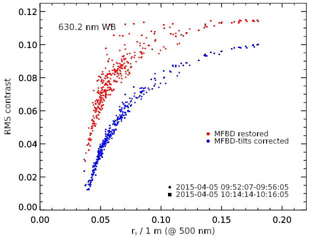
CRISP/SST straylight

Replaced AO and tip-tilt mirrors before 2015 season. Granulation at disk center, 630.2 nm Fe I, 11.5% RMS contrast.

MHD: should be 14.5%



Don't expect image restoration to deliver MHD contrasts!

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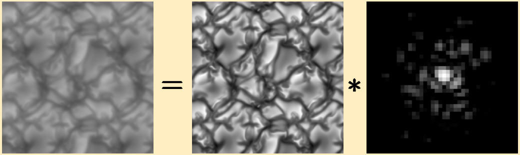
Image restoration

Convolution: $d_i = f * s_i$



- Atmosphere convolves object f with PSFs s_i
- We need to deconvolve images d_i (implicitly or explicitly)
- But we don't know the PSFs!

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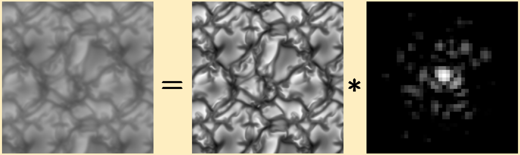
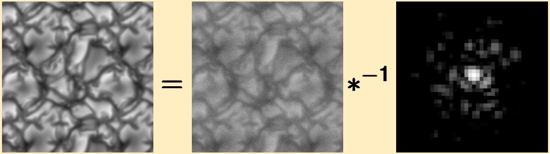


Deconvolution: $f = d_i *^{-1} s_i$



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Two methods, key steps

Multi-Frame Blind Deconvolution (MFBD)

Model fit to image data

1. Image formation model: image = object $*$ PSF + noise, PSF $\Leftarrow$ pupil phase = wavefront shape
2. Parameterize pupil phase
3. Constrain phase parameters using multiple exposures, phase diversity, etc.
4. Fit estimated object $*$ PSFs to observed images by minimization of error metric.
5. NB data included in model, more constraints $\Rightarrow$ Multi-Object MFBD

Speckle Interferometry (SI) + Deconvolution (SD)

WB object Fourier amplitude:

1. Estimate r_0 from statistical sample
2. Atmospheric (+AO) model $\Rightarrow$ TF
3. Correct average Fourier amplitudes for TF

WB object Fourier phase:

1. Differential phase information that does not average to zero.
2. Build phase estimate from Fourier domain origin.

NB Speckle Deconvolution (SD):

1. Restored WB image + original WB data $\Rightarrow$ PSFs
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Has it been done before?

Previous comparisons

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Puschmann & Beck 2011: VTT GFPI data, MOMFBD and Göttingen SI+SD

Bellot Gonzalez et al. 2014: Real and simulated VTT data, MOMFBD and Speckle (SOLARNET milestone)

Hoch 2014: Simulated and real GREGOR data, KISIP and MOMFBD

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Two methods, algorithms and software

Speckle

- KISIP – Speckle Interferometry (von der Lühe 1987), current C++ implementation (Wöger).
- AO corrected calibrations for Zernike modes (Wöger 2007), now more general program exists.
- Decorrelation model for Zernike modes (Molodij 1997), now generalizing this for arbitrary modes ("Soon, don't worry").
- Speckle Deconvolution: (Keller & von der Lühe 1992), current IDL implementation (Mikurda 2006)

MOMFBD

- ○ Phase Diversity (Löfdahl & Scharmer 1994)
- ○ MFBD algorithm (Löfdahl 2002)
- MOMFBD – Multi-Object and C++ implementation (van Noort et al. 2005)

Two methods, potential problems

Speckle

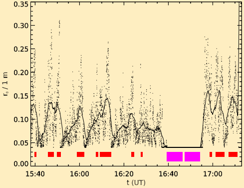
- Kolmogorov statistics true?
- AO correction modifies statistics – how well do calibrations work?
- Anisoplanatism – more calibrations
- ...

MFBD

- Model mismatches
- Fit depends on data quality and object contrast
- Compensation for high-order wavefront modes
- Anisoplanatism
- ...

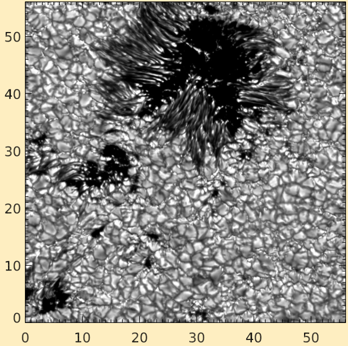
CRISP data from 2015-04-05

r_0: variable seeing

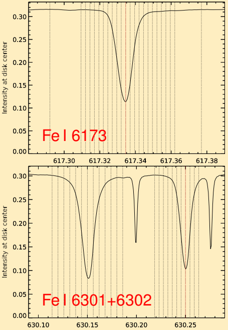


Data collected (■) during r_0 peaks

AR 12320 in late PM

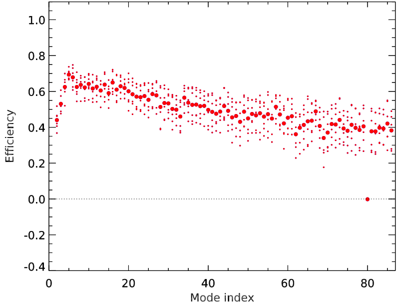


Fe I 6173, 6301+6302



Polarimetric scans in three Fe I lines

AO calibration data

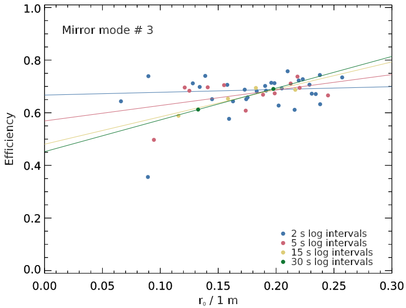


5 s log file intervals

Efficiencies

- 2 AO log files, each 30 s
  - Granulation at disk center
  - Variable seeing
  - DM voltages @ 2 kHz
  - SH shifts @ 2 kHz
- $\beta_i = \sqrt{\sigma^2_{i,\mathrm{res}} \Big/ \sigma^2_{i,\mathrm{orig}}}$
- Variation around mean for low order modes
- r_0 dependence for higher order modes

AO calibration data



Low order mode

Efficiencies

- 2 AO log files, each 30 s
  - Granulation at disk center
  - Variable seeing
  - DM voltages @ 2 kHz
  - SH shifts @ 2 kHz
- $\beta_i = \sqrt{\sigma^2_{i,\mathrm{res}} \Big/ \sigma^2_{i,\mathrm{orig}}}$
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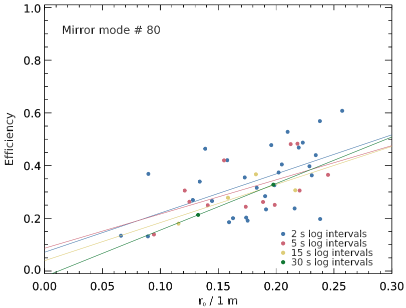
AO calibration data



High order mode

Efficiencies

- 2 AO log files, each 30 s
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  - Variable seeing
  - DM voltages @ 2 kHz
  - SH shifts @ 2 kHz
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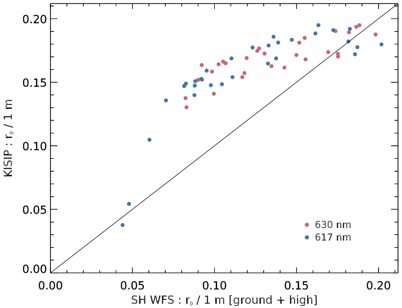
- r_0 dependence for higher order modes

AO calibrations

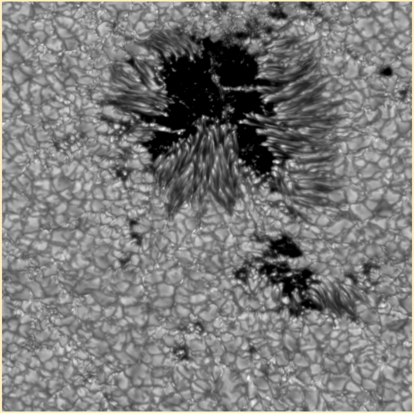


Processed using VTT calibrations

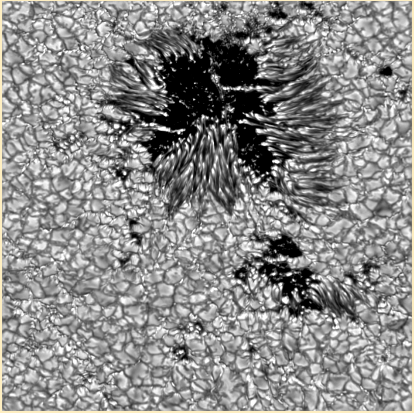
- Not using SST calibrations yet.
- Not as wrong as you might think (self-correcting to some degree) but still not satisfactory.
- No proper model for decorrelation with distance from lock point yet.

2015-04-05 15:39, WB 6302

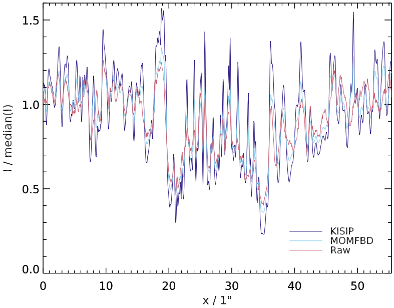
MOMFBD



Speckle Interferometry



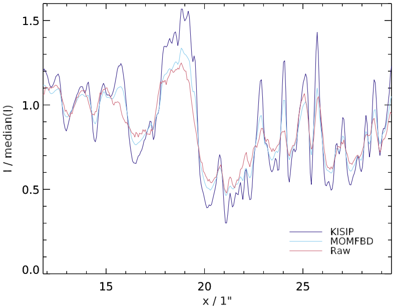
Restored contrast



Single pixel row through lower part of spot

- Much higher contrast in speckle restored image
- Resolution about the same
- Speckle contrast varies with r_0
- Wrong calibrations but needs to be looked out for

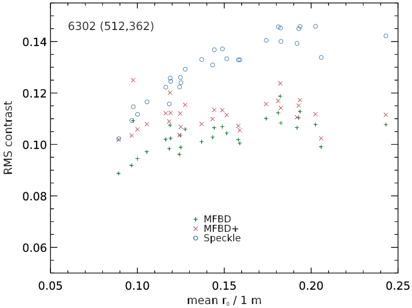
Restored contrast



Zoom in a bit

- Much higher contrast in speckle restored image
- Resolution about the same
- Speckle contrast varies with r_0
- Wrong calibrations but needs to be looked out for

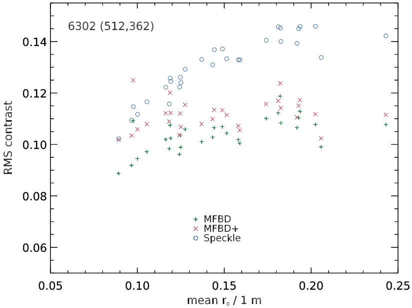
Restored contrast



RMS contrast measured in granulation below the spot

- Much higher contrast in speckle restored image
- Resolution about the same
- Speckle contrast varies with r_0
- Wrong calibrations but needs to be looked out for

Restored contrast

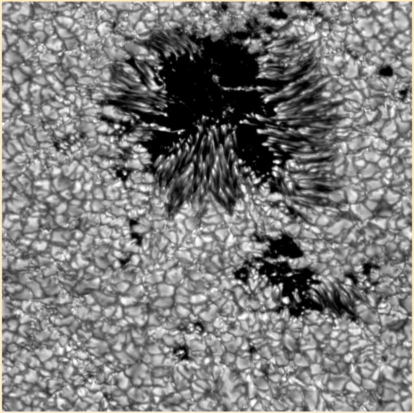


RMS contrast measured in granulation below the spot

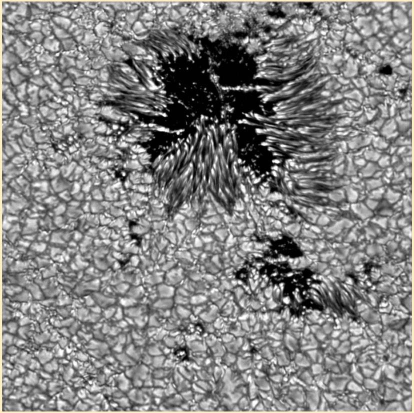
- Much higher contrast in speckle restored image
- Resolution about the same
- Speckle contrast varies with r_0
- Wrong calibrations but needs to be looked out for

2015-04-05 15:39, NB line core 6301 − 700 mÅ

MOMFBD scaled separately

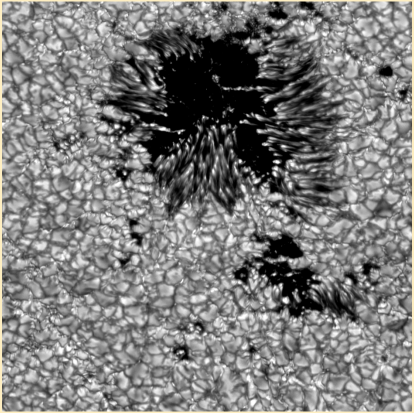


Speckle Deconvolution

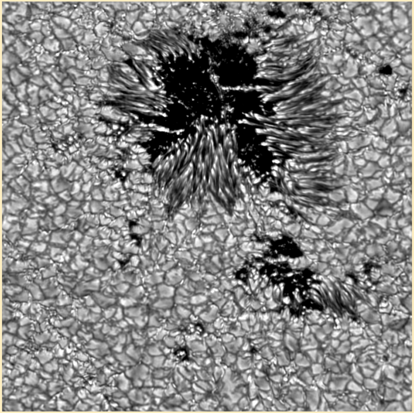


2015-04-05 15:39, NB line core 6301 – 342 mÅ

MOMFBD scaled separately

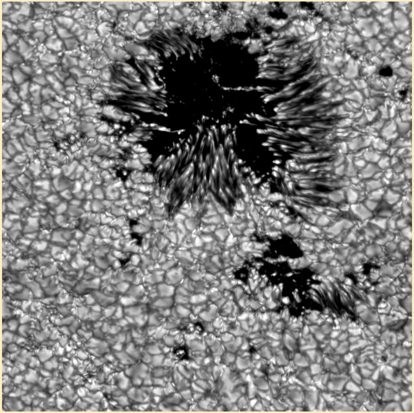


Speckle Deconvolution

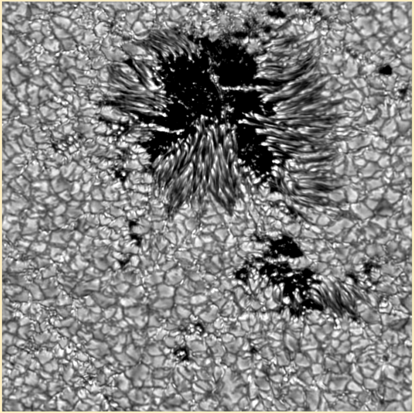


2015-04-05 15:39, NB line core 6301 – 304 mÅ

MOMFBD scaled separately

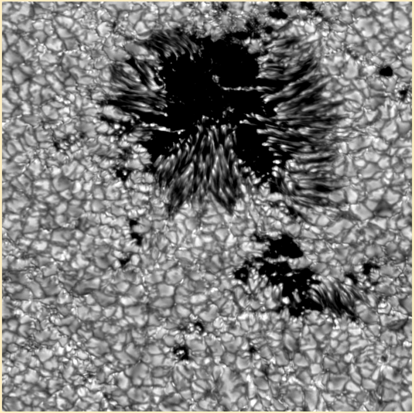


Speckle Deconvolution

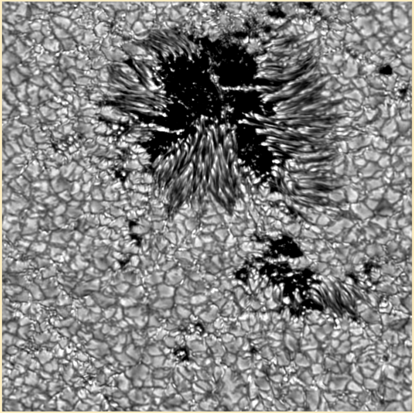


2015-04-05 15:39, NB line core 6301 – 266 mÅ

MOMFBD scaled separately

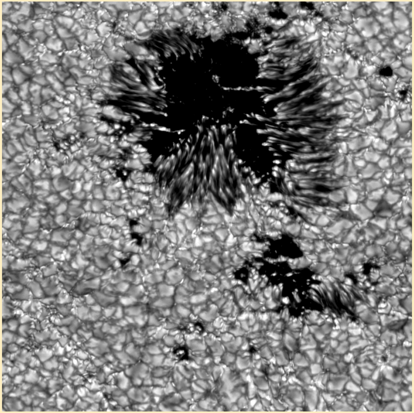


Speckle Deconvolution

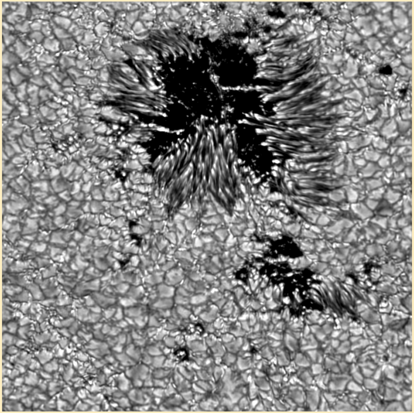


2015-04-05 15:39, NB line core 6301 – 228 mÅ

MOMFBD scaled separately

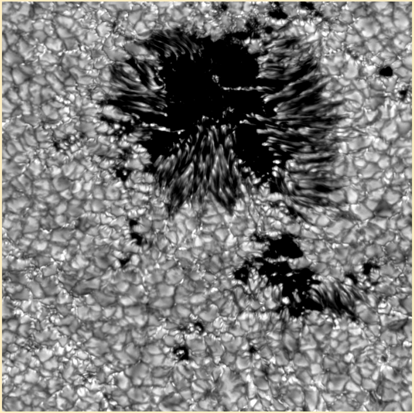


Speckle Deconvolution

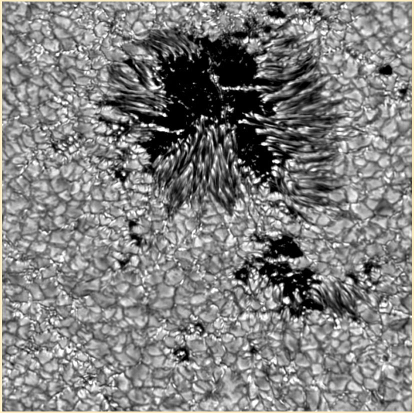


2015-04-05 15:39, NB line core 6301 − 190 mÅ

MOMFBD scaled separately

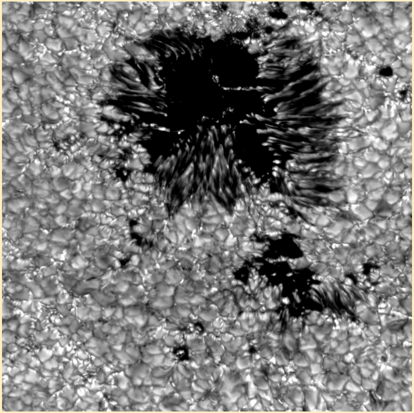


Speckle Deconvolution

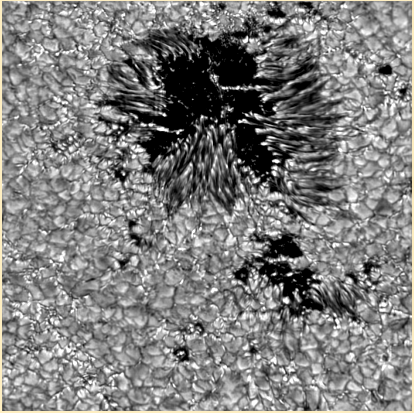


2015-04-05 15:39, NB line core 6301 – 152 mÅ

MOMFBD scaled separately

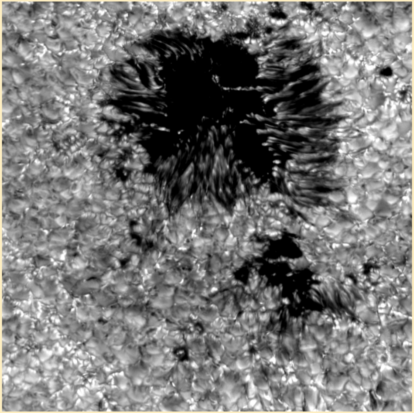


Speckle Deconvolution

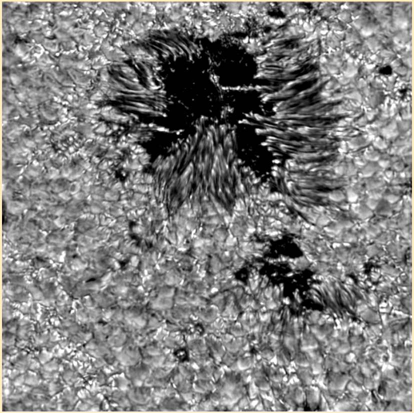


2015-04-05 15:39, NB line core 6301 − 114 mÅ

MOMFBD scaled separately

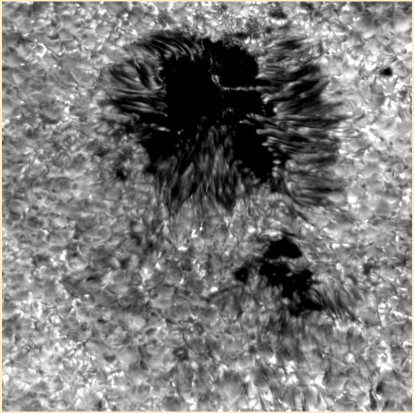


Speckle Deconvolution

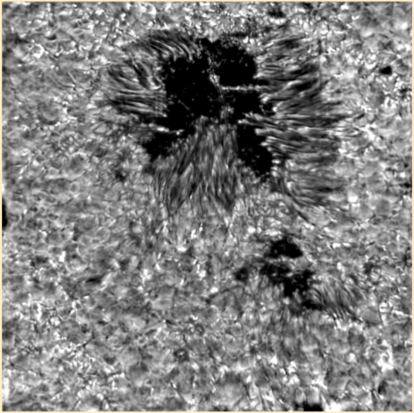


2015-04-05 15:39, NB line core 6301 – 076 mÅ

MOMFBD scaled separately

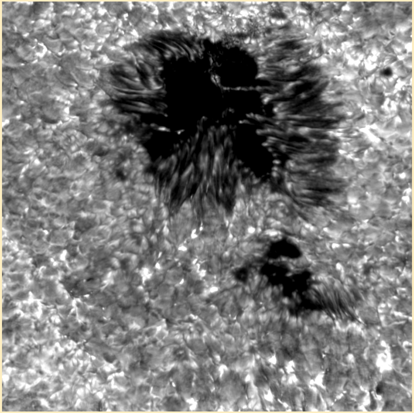


Speckle Deconvolution

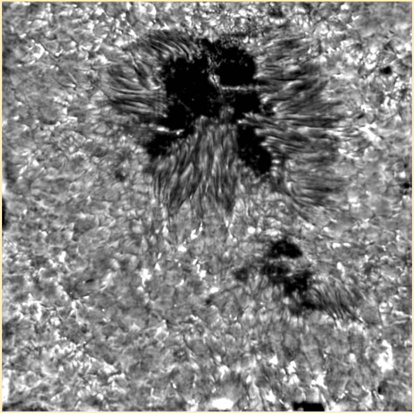


2015-04-05 15:39, NB line core 6301 – 038 mÅ

MOMFBD scaled separately

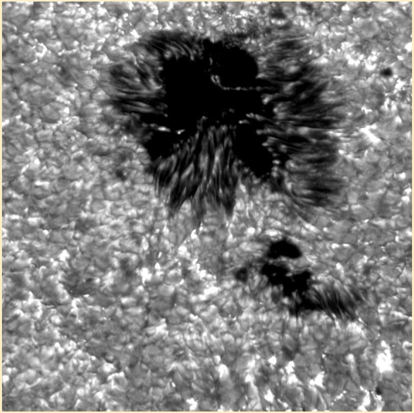


Speckle Deconvolution

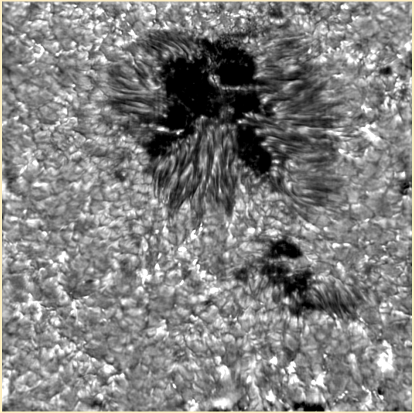


2015-04-05 15:39, NB line core 6301 + 000 mÅ

MOMFBD scaled separately



Speckle Deconvolution



Conclusions

- Integrate KISIP and SD into CRISPRED
- We want to compare "state of art", only quick code changes $\Rightarrow$ make processing that is not *core algorithm* more similar. (Subfield size, mosaicking, noise filtering, etc.)
- Initial comparisons of several versions of restored images
  - Speckle with different calibrations?
  - MOMFBD different numbers of modes, different NB weights?
  - Phase Diversity?
- Speckle vs. MOMFBD: contrasts and power spectra, PSFs, line profiles
- For a few selected scans:
  - Atmospheric inversions
  - Evaluate artifacts that matter for interpretation