Compensated diffraction-limited imaging with adaptive optics at the GREGOR Solar Telescope

O. von der Lühe[1], L. Bielak[1,2], Th. Berkefeld[1]

GREGOR adaptive optics

GREGOR uses a conventional solar adaptive optics system (GAOS) with the deformable mirror at a conjugate of the entrance pupil. The wavefront sensor is based on the Hartmann-Shack principle working with arbitrary solar small scale structure within a quadratic field of 12 by 12 arcsec and a resolution of 0.5 arcsec/pixel for each sub-aperture. Windowing of the edges reduces the field to approximately 9 by 9 arcsec. GAOS compensates 130 Karhunen-Loève modes with a closed-loop bandwidth of 200 Hz. See also **poster 9909-78** .

Anisoplanatic imaging

The single lock point of the GAOS wavefront sensor delivers control of only a single line of sight. The best compensation is limited to an isoplanatic patch of about 10 arcsec (**Fig 1**). Nevertheless, an improvement of image quality is usually noticeable for much larger fields of several arcmin, because residual instrumental aberrations and strong ground layer turbulence are also compensated by GAOS.

The full diffraction limit can only be restored by using image restoration from short exposures which are sensitive to anisoplanatism. Proven methods are speckle imaging, phase diversity and blind deconvolution.

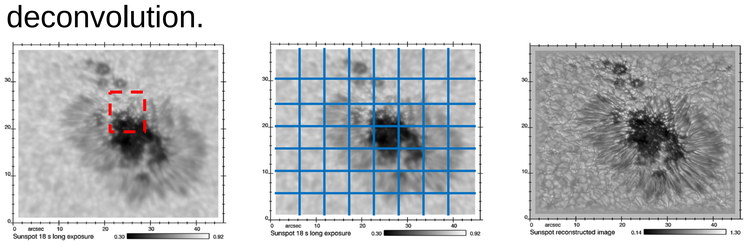

Fig. 1: anisoplanatism of solar adaptive optics. The AO lock point is indicated by the red square (left), the compensation is poorer elsewhere in the field. For reconstruction, areas smaller than the isoplanatic patch are separately processed (center). The result approaches the diffraction limit throughout the field (right).

Speckle Imaging

We use speckle imaging (**fig. 2**) to produce high resolution images of the solar surface from observations with the GREGOR Broad-Band Imager[1]. Between 50 to 200 short exposures (1 … 10 ms) are merged into a single reconstruction using the *Kiepenheuer Institut Speckle Imaging Package* (**KISIP**; [2])

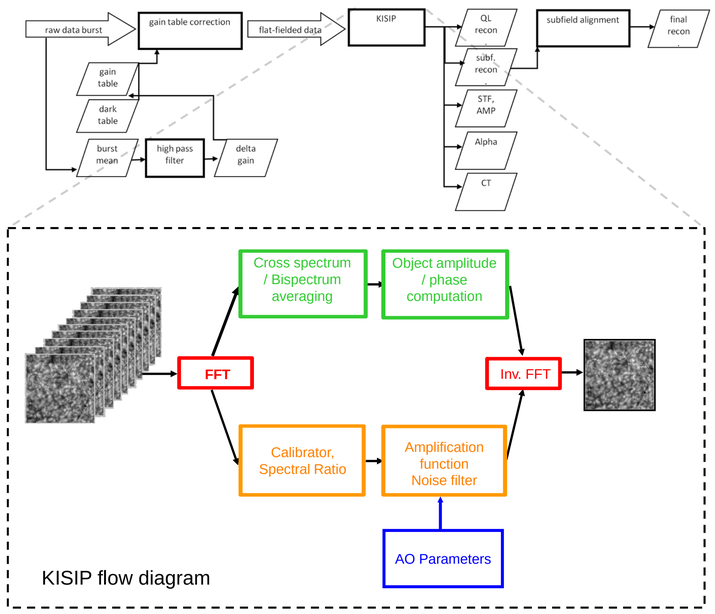

Fig.2 speckle imaging algorithm flow diagram. Top diagram: full procedure including flatfielding and subfielding. Bottom diagram: subfield reconstruction with KISIP. Average second or third order polyspectra are computed from bursts of short exposures to restore the Fourier phase of the reconstructed image. The Fourier amplitude is taken from the average power spectrum. A diagnostic derived from the input data is used to estimate the amplification function ("speckle transfer function"; STF), which depends on the quality of seeing, the telescope pupil shape and the characteristics of the adaptive optics system.

GREGOR STF Models

An STF library was computed which represent

- the central obscuration of the GREGOR pupil,
- a range of Fried parameters r_0 between 9 cm and 45 cm (r_0/D = 0.06 … 0.30),
- measured mode variance rejection characteristics of GAOS,
- distances from the AO lock point between 0 and 60 arcsec.

We constructed a model to generate short exposure point spread functions using numerical phase screens which a structure function for Kolmogorov statistics (**fig. 3**). The turbulence distribution with height was modeled with a ground layer and a single high altitude layer at 10 km. The high altitude contribution to r_0 was set to a constant value of 100 cm while the ground layer contribution was varied to produce the desired range of Fried parameters. Amplitude effects due to Fresnel propagation were neglected. Between 100 and 400 phase screen realizations were used to compute mean long exposure and speckle transfer functions from the Fourier transform of the phase screens

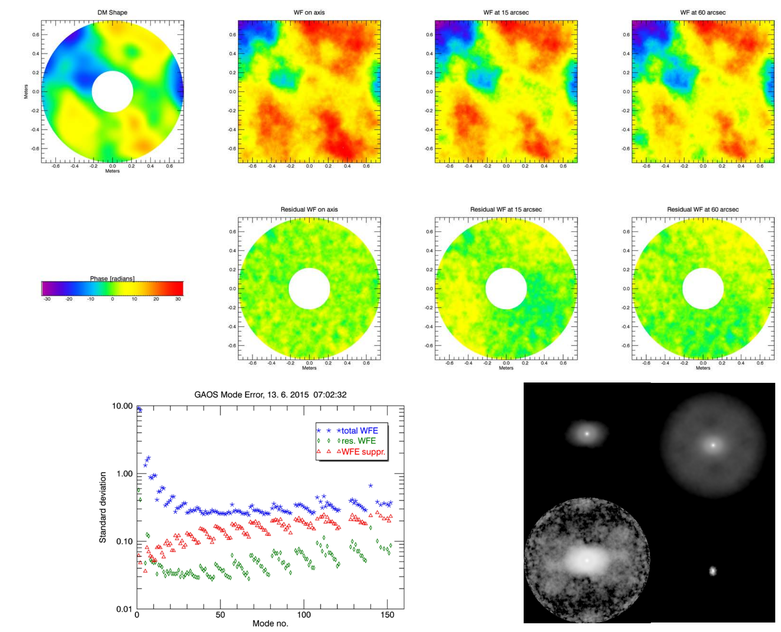

Fig.3 top row: shape of the GAOS deformable mirror and input phase screens at 0, 15 and 60 arcsec distance from the lock point. Center row: residual phase at 0, 15 ad 60 arcsec distances. Bottom row left: GAOS mode suppression; right: sample model output showing long exposure TF and STF (top left and right), spectral ratio (LTF^2/STF) and average PSF for r_0 = 12 cm at 10 arcsec off lock point.

First Results

We compare the reconstruction obtained using the GREGOR STF model with the reconstruction using an STF model for a telescope pupil without central obstruction ("VTT model"; **fig. 4**).

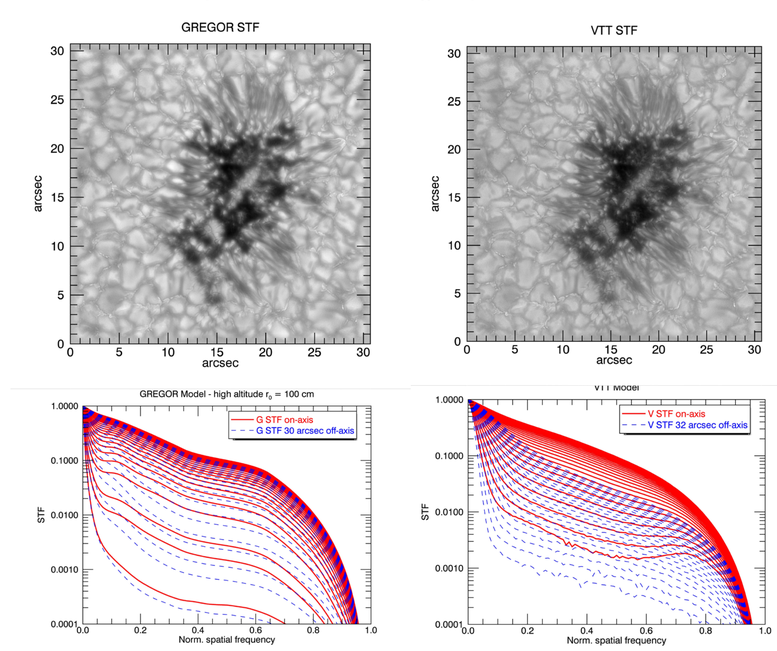

Fig.4. Top: sample reconstructions of the spot AR11757 observed on May 31, 2013. Left: this work, right: earlier STF models. The STF model libraries are shown in the bottom row. The new models produce a higher contrast at mid frequencies which emphasize solar granulation. This is caused by the proper representation of the GREGOR central obscuration.

[1]Kiepenheuer-Institut für Sonnenphysik
Schöneckstraße 6
79104 Freiburg
Germany

[2]Department of Radiology
University Medical Center Freiburg
Breisacher Straße 60a
79106 Freiburg, Germany

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