Line-of-sight observables algorithms for HMI tested with *Interferometric BI-dimensional Spectrometer* (IBIS) spectro-polarimetric observations

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MDI-Like Algorithm

Fourier coefficients:

$$a_1 = \frac{2}{T}\int_{-\frac{T}{2}}^{+\frac{T}{2}} I(\lambda)\cos\left(2\pi\frac{\lambda}{T}\right)d\lambda \; ; \; b_1 = \frac{2}{T}\int_{-\frac{T}{2}}^{+\frac{T}{2}} I(\lambda)\sin\left(2\pi\frac{\lambda}{T}\right)d\lambda$$

$$a_2 = \frac{2}{T}\int_{-\frac{T}{2}}^{+\frac{T}{2}} I(\lambda)\cos\left(4\pi\frac{\lambda}{T}\right)d\lambda \; ; \; b_2 = \frac{2}{T}\int_{-\frac{T}{2}}^{+\frac{T}{2}} I(\lambda)\sin\left(4\pi\frac{\lambda}{T}\right)d\lambda$$

Gaussian Fe I line profile: $I(\lambda) = I_c - I_d \exp\left[-\frac{(\lambda-\lambda_0)^2}{\sigma^2}\right]$

Doppler velocity: $v = \frac{dv}{d\lambda}\frac{T}{2\pi}\,\mathrm{atan}\left(\frac{b_1}{a_1}\right)$

=> Calculated for LCP & RCP:
$V=(v_{LCP}+v_{RCP})/2$
$B=K(v_{LCP}-v_{RCP})$

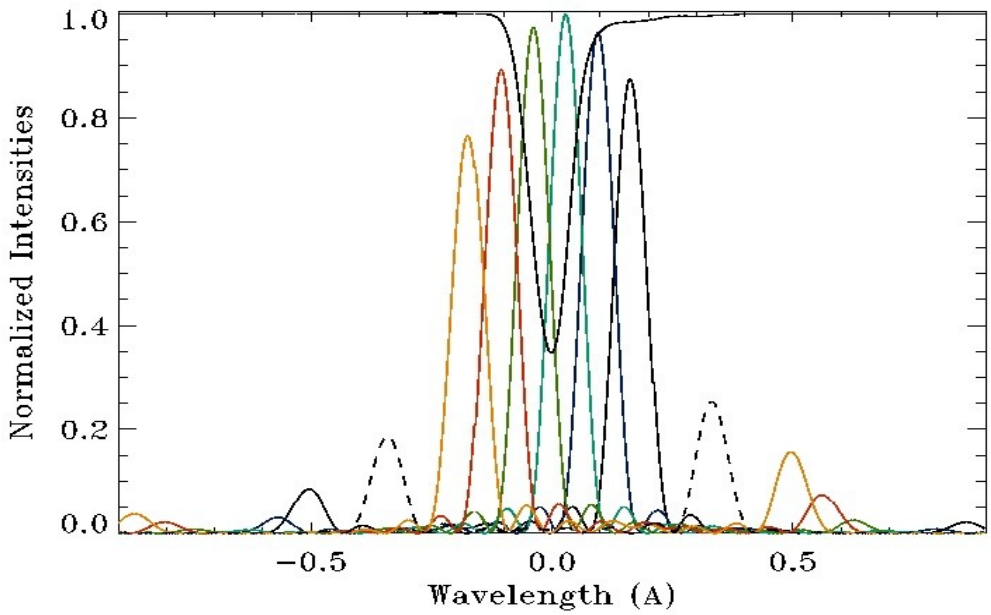
Linedepth: $I_d = \frac{T}{2\sigma\sqrt{\pi}}\sqrt{a_1^2+b_1^2}\exp\left(\frac{\pi^2\sigma^2}{T^2}\right)$

Linewidth: $\sigma = \frac{T}{\pi\sqrt{6}}\sqrt{\mathrm{alog}\left(\frac{a_1^2+b_1^2}{a_2^2+b_2^2}\right)}$

Implementation of MDI-Like Algorithm

Discrete estimate of Fourier coefficients:

$$a_1 \approx \frac{2}{6}\sum_{j=0}^{5} I_j \cos\left(2\pi\frac{2.5-j}{6}\right)$$



Example of HMI filter profiles for 6 wavelengths

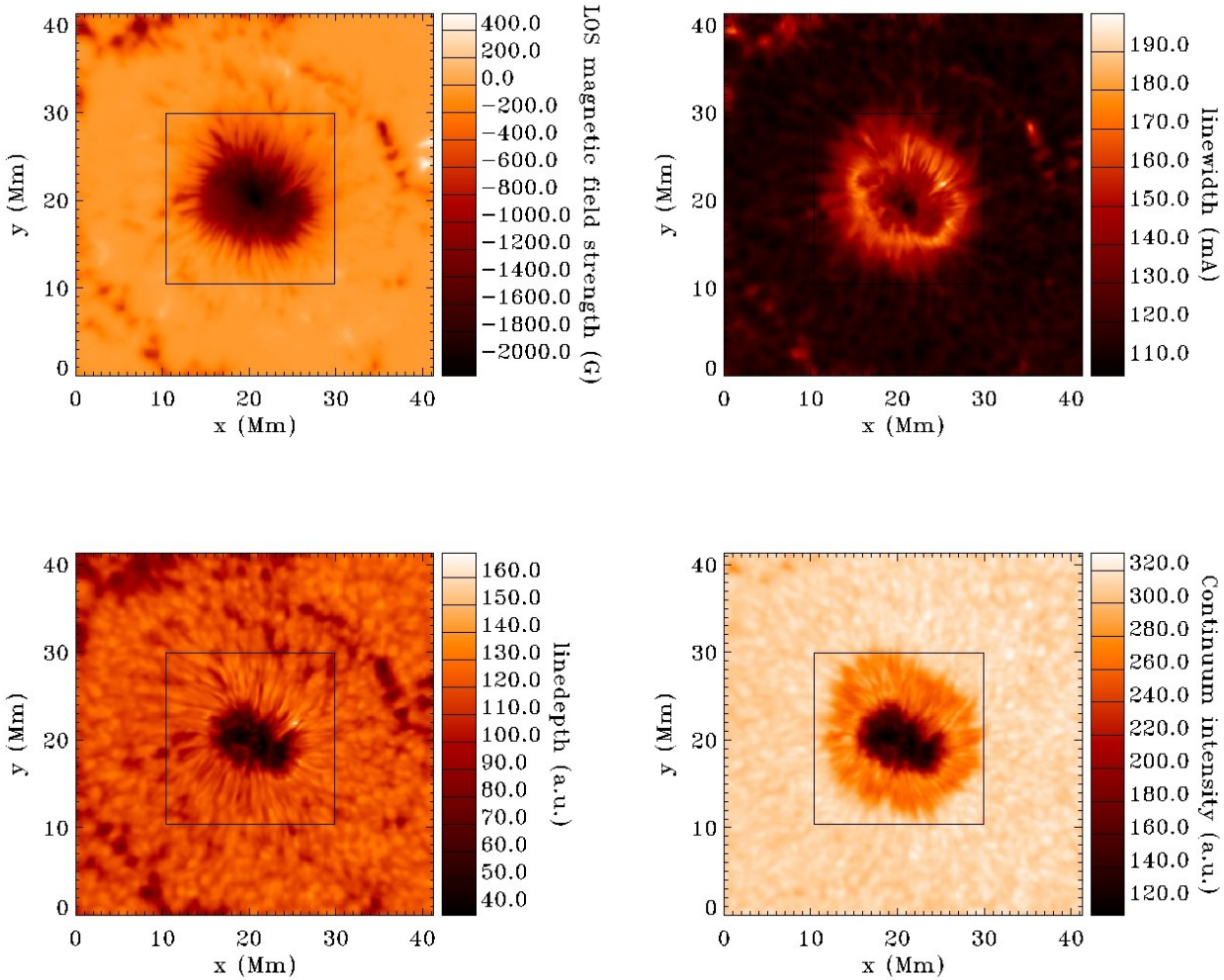
- discrete estimate of Fourier coefficients, HMI filters are not delta functions, Fe I line is not a Gaussian => need to correct velocities

- Calculation of look-up tables based on measured HMI filter profiles + Fe I line profile

- Polynomial correction based on OBS_VR

- For linewidth and linedepth, modifications compared to theoretical algorithm (x5/6 and 6/5)

IBIS Data

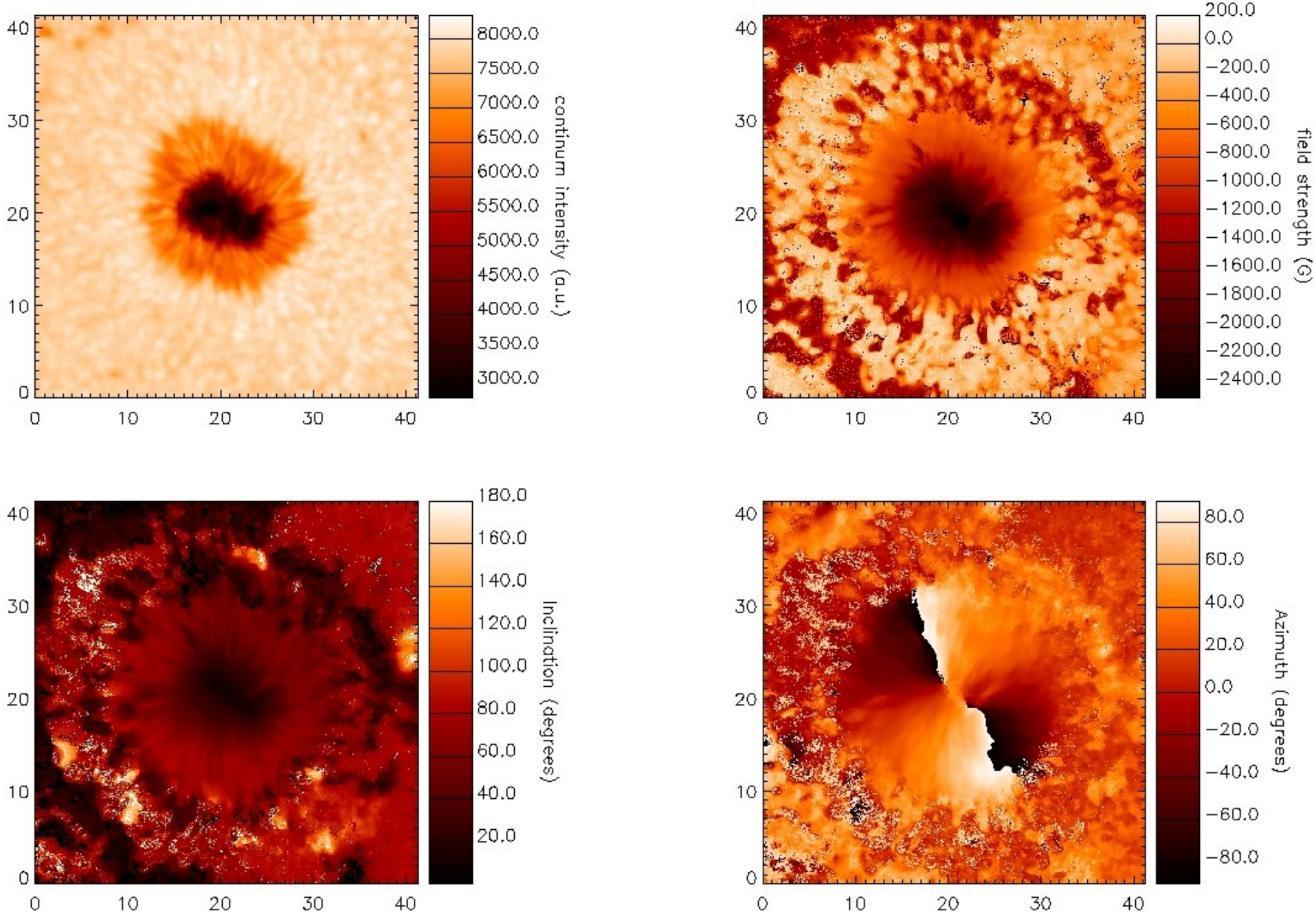


Situation maps: LOS magnetic field strength, linewidth, linedepth, and continuum intensity returned by MDI-like algorithm

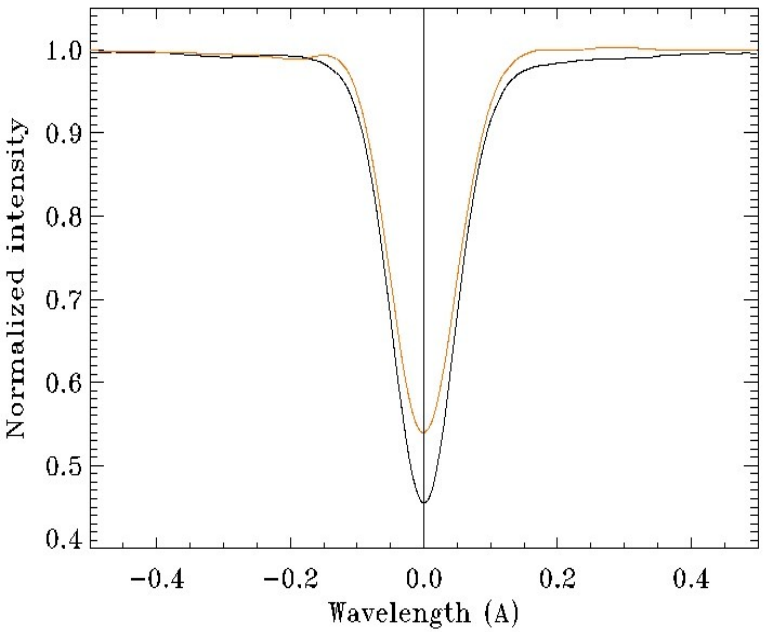
- data from IBIS instrument installed on Dunn Solar Telescope (Sacramento Peak, NM)
- image scale 0.165”/pixel
  spectral resolution 25 mA
- full Stokes vector (I,Q,U,V) at 23 wavelengths across the Fe I line at 6173 A, cadence of 47.5 s
- data used in Rajaguru et al. (2010)
- NOAA AR 10960, on June 8, 2007
- only 1 hour selected (for best seeing), and Milne-Eddington (M-E) inversion of full vector magnetic field performed on the averaged data
- the full hour is averaged prior to calculating “HMI-like intensities” and applying the observables algorithms

Milne-Eddington Inversions

(performed by K. Sankarasubramanian)



LOS Observables Algorithms Tested With HMI intensities Simulated From IBIS data

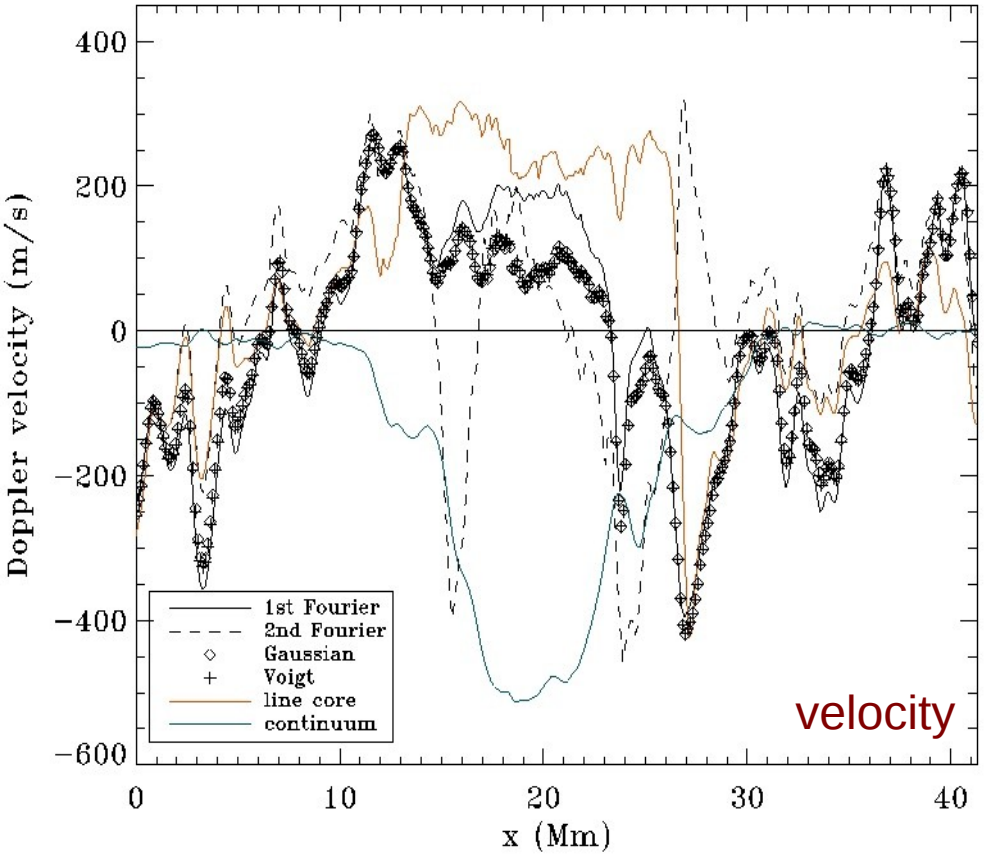


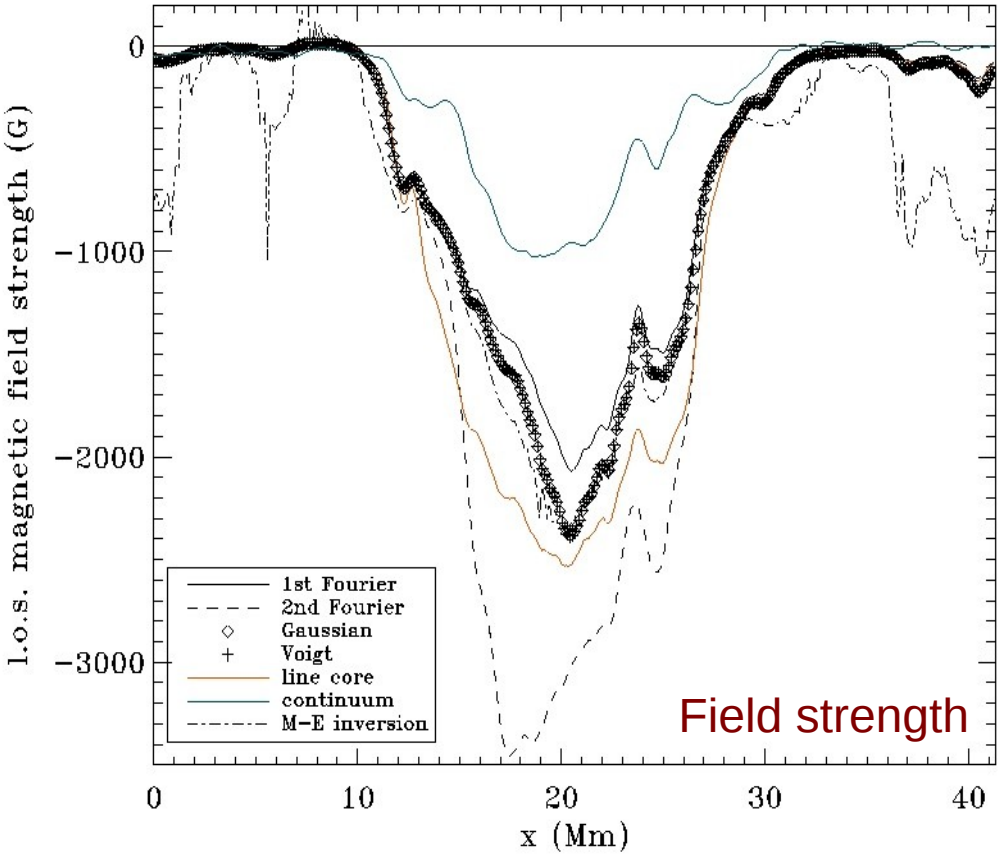
Reference Fe I line used to compute the look-up tables (in orange), vs. Fe I line from Kitt Peak Atlas (in black)

- 1st Fourier-coefficients MDI-like algorithm
- 2nd Fourier-coefficients MDI-like algorithm
- least-squares fit with Gaussian profile
- least-squares fit with Voigt profile (analytical profile from Tepper Garcia (2006) with *a=0.225*)

Comparison of the Different Algorithms

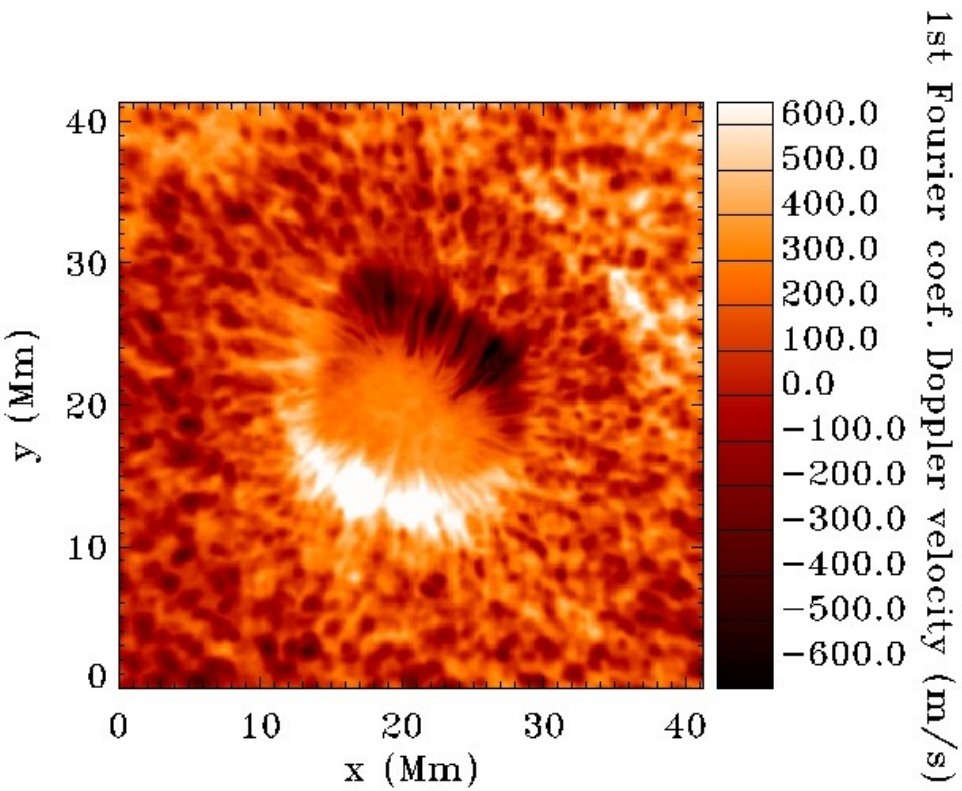
Cut at the latitude crossing the middle of the sunspot

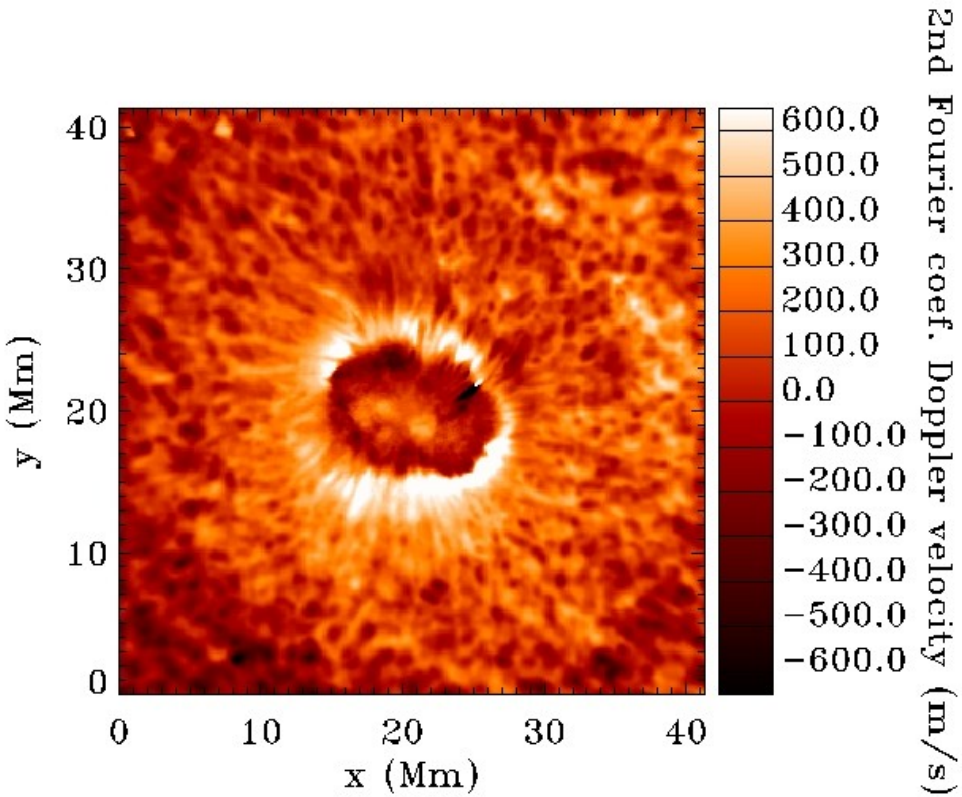


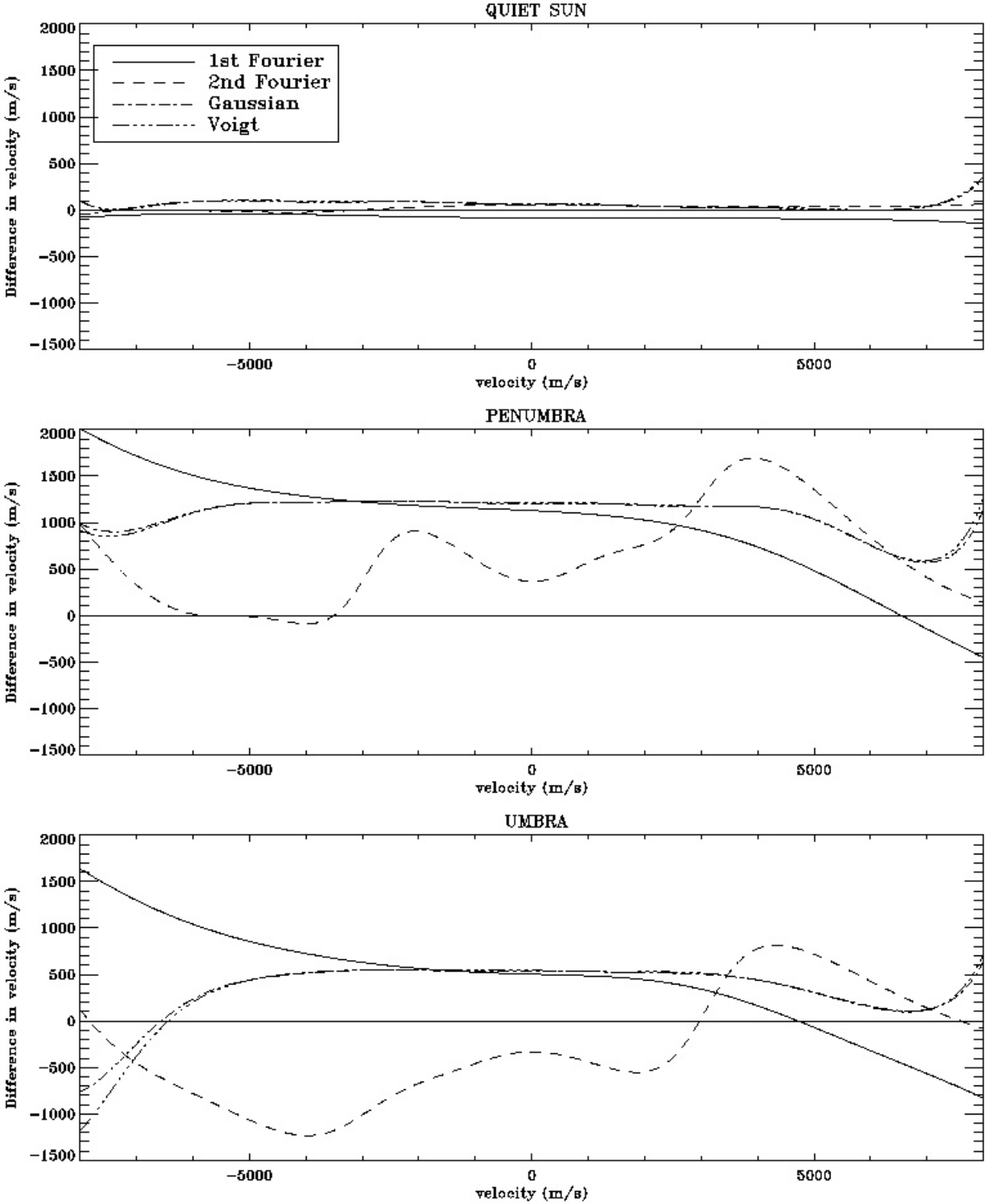


- Line-core velocity is defined by the location of the minimum of intensity of the Fe I line
- different algorithms are expected to be sensitive to different heights in the solar atmosphere (e.g. Fleck et al. 2011)
- 2nd Fourier coeff. algorithm behaves differently

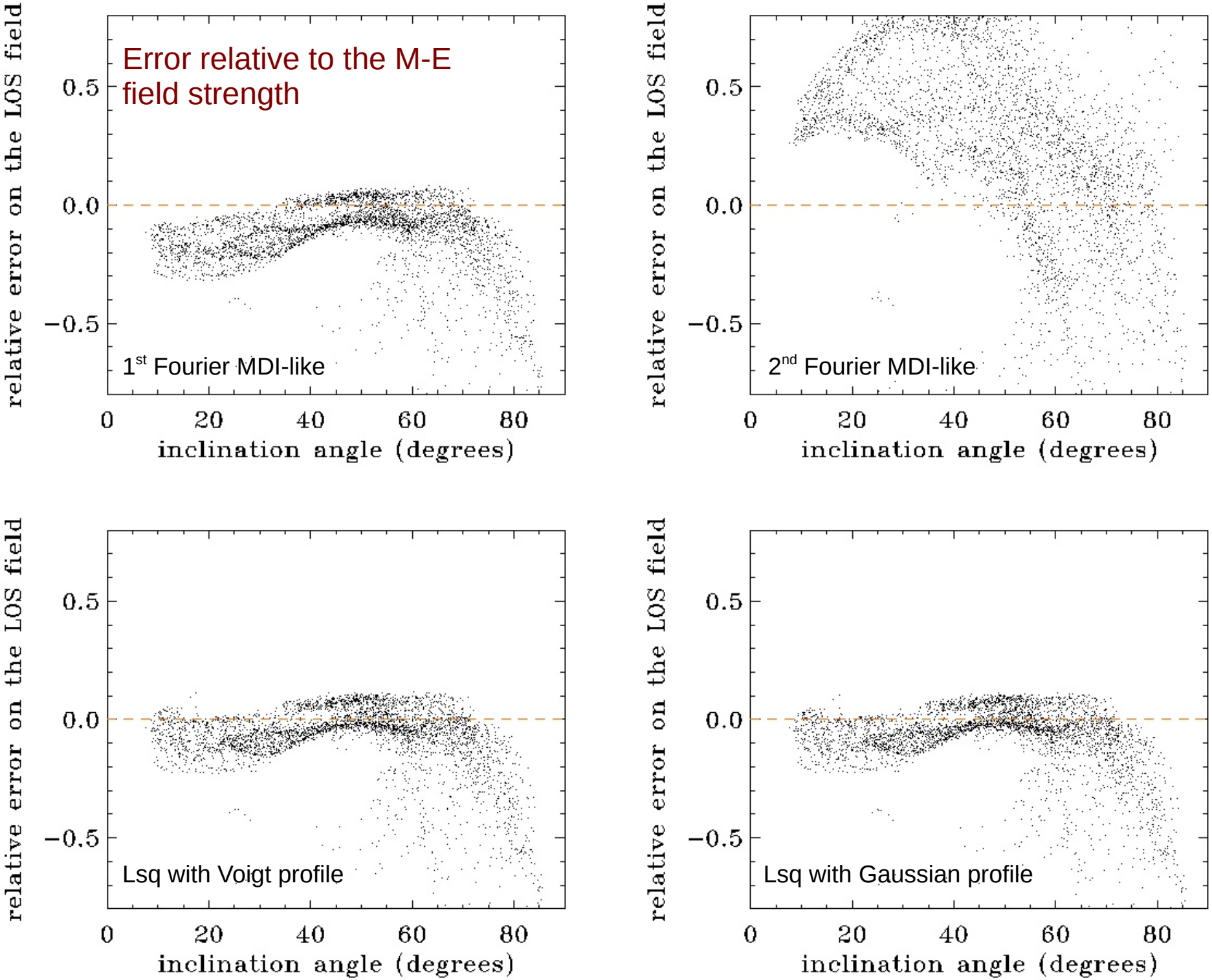
Doppler velocities obtained by 1st and 2nd Fourier-coefficients MDI-like algorithm:

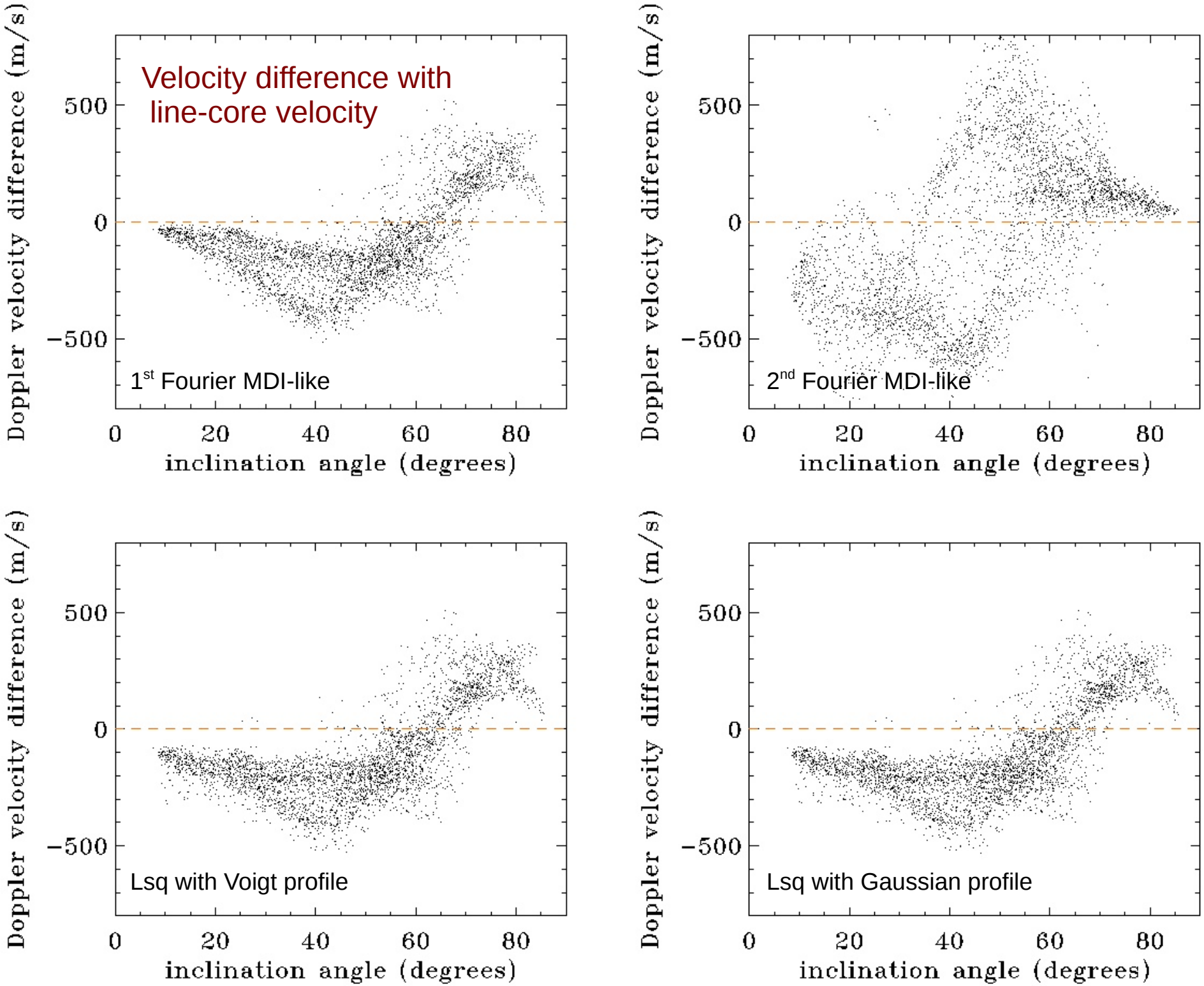


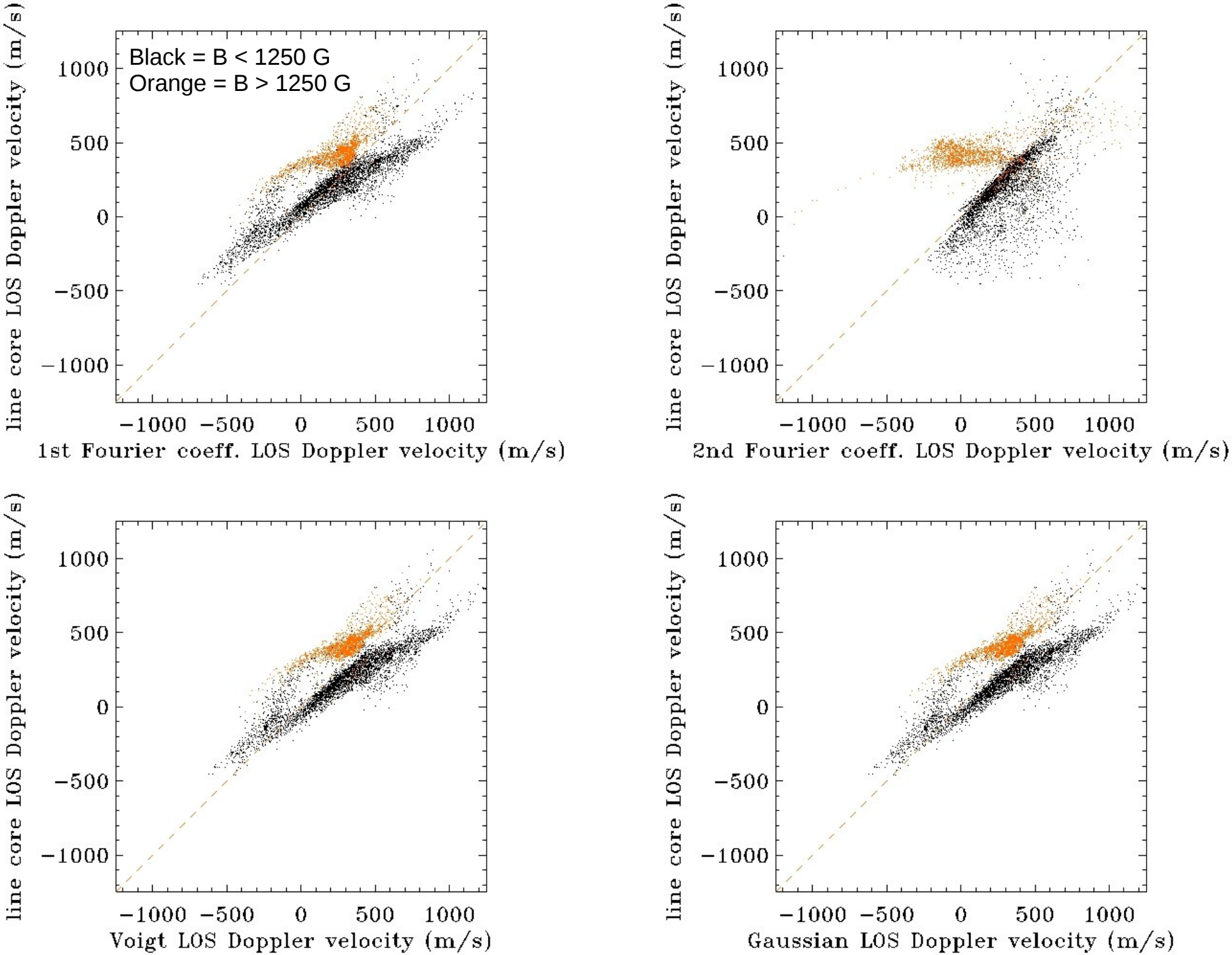


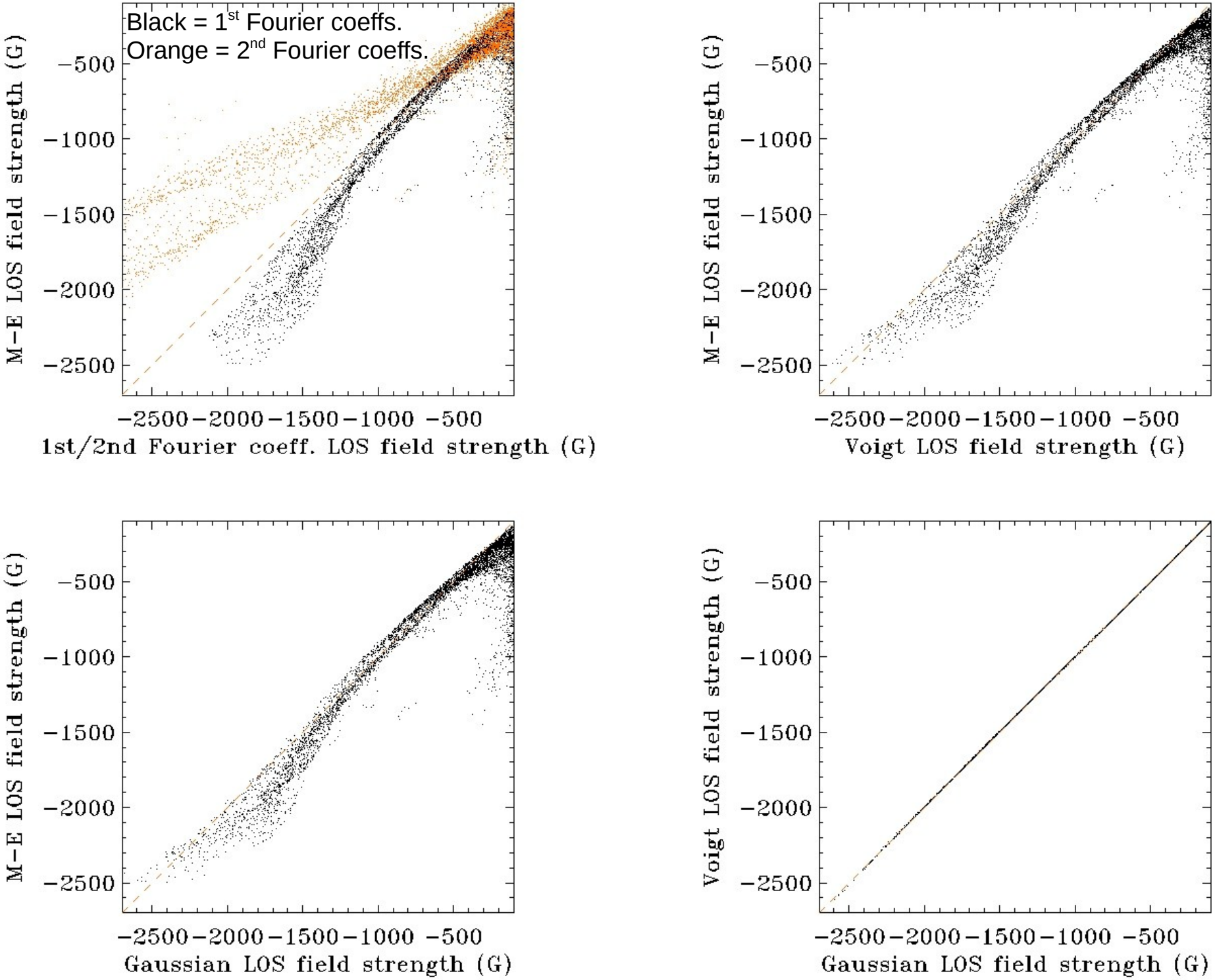


- Doppler shifts simulated on 1h-averaged LCP profiles from IBIS at three locations
- for each Doppler shift, the HMI intensities are simulated, and the observables algorithms are applied
- 2nd Fourier coefficients algorithm behaves differently from other algorithms in sunspot


Error relative to the M-E field strength
1st Fourier MDI-like
2nd Fourier MDI-like
Lsq with Voigt profile
Lsq with Gaussian profile
relative error on the LOS field
inclination angle (degrees)
0.5
0.0
−0.5
0
20
40
60
80


Velocity difference with
line-core velocity
1st Fourier MDI-like
2nd Fourier MDI-like
Lsq with Voigt profile
Lsq with Gaussian profile
Doppler velocity difference (m/s)
inclination angle (degrees)
500
0
−500
0
20
40
60
80

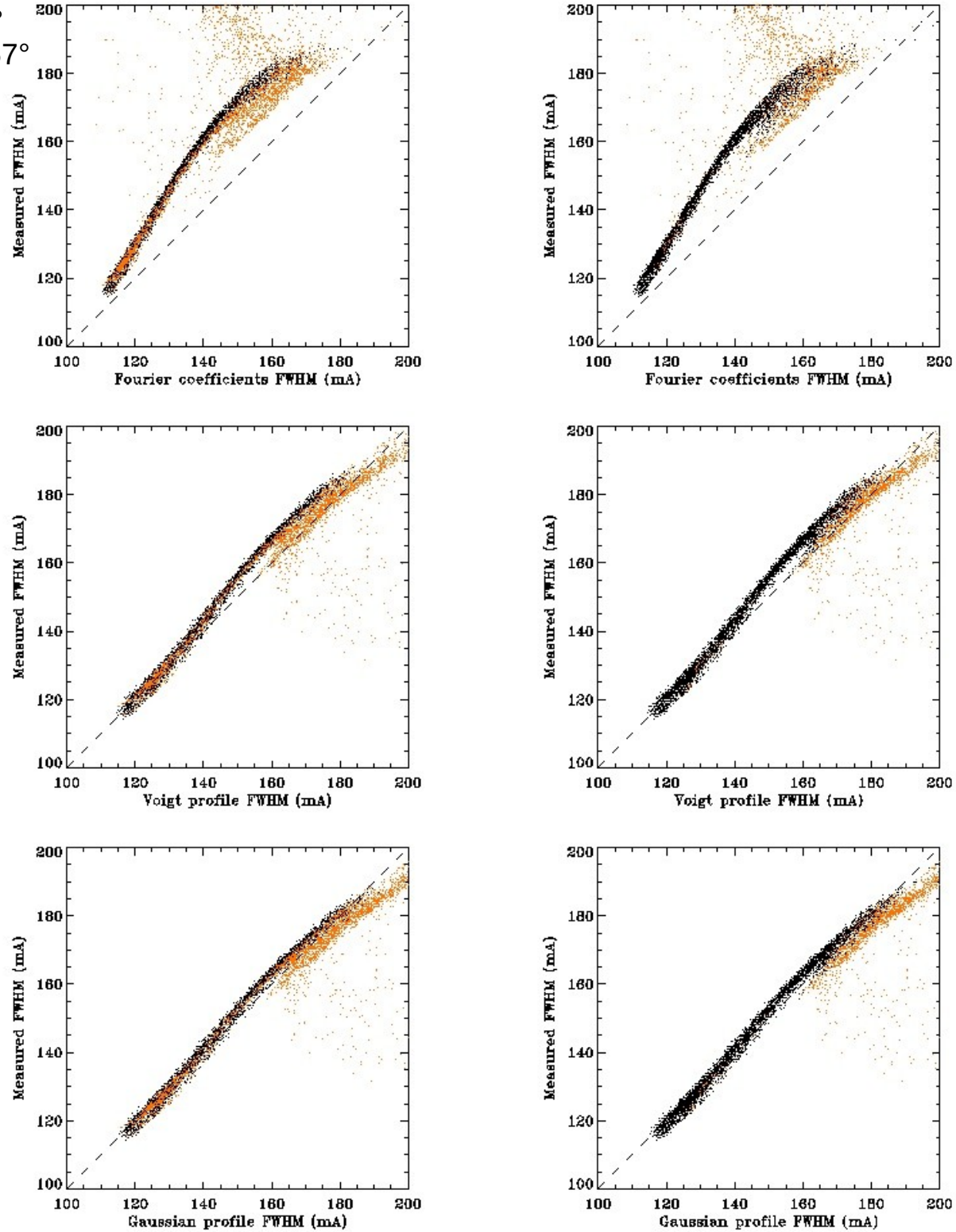

Black = B < 1250 G
Orange = B > 1250 G
line core LOS Doppler velocity (m/s)
1st Fourier coeff. LOS Doppler velocity (m/s)
2nd Fourier coeff. LOS Doppler velocity (m/s)
Voigt LOS Doppler velocity (m/s)
Gaussian LOS Doppler velocity (m/s)
1000
500
0
−500
−1000


Black = 1st Fourier coeffs.
Orange = 2nd Fourier coeffs.
M−E LOS field strength (G)
1st/2nd Fourier coeff. LOS field strength (G)
Voigt LOS field strength (G)
Gaussian LOS field strength (G)
Voigt LOS field strength (G)
−500
−1000
−1500
−2000
−2500

Black = inclination > 57°
Orange = inclination < 57°

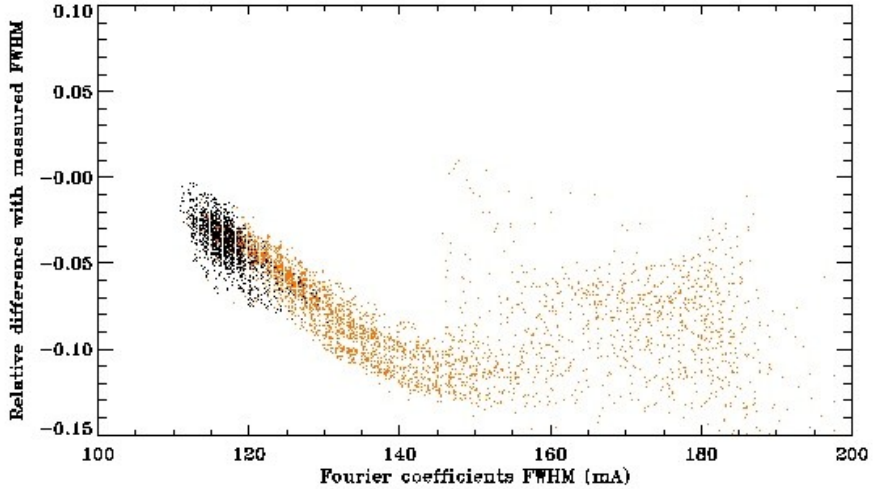
Black = field < 1250 G
Orange = field > 1250 G

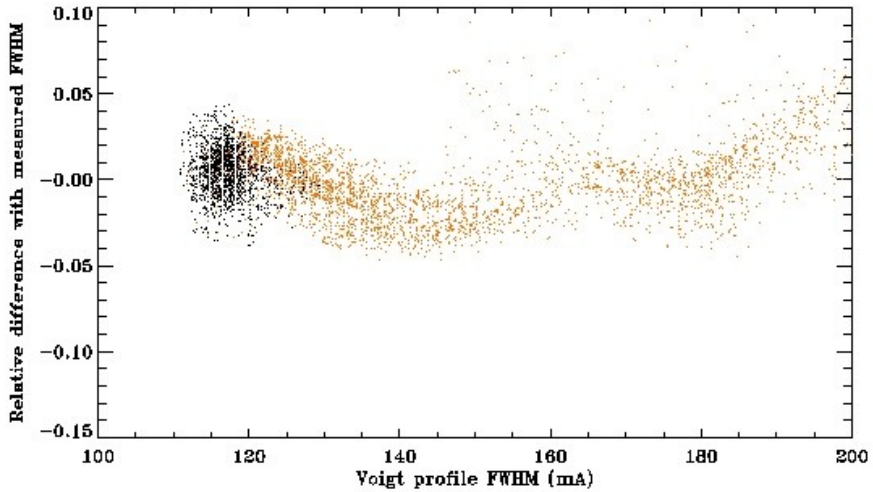
Linewidth

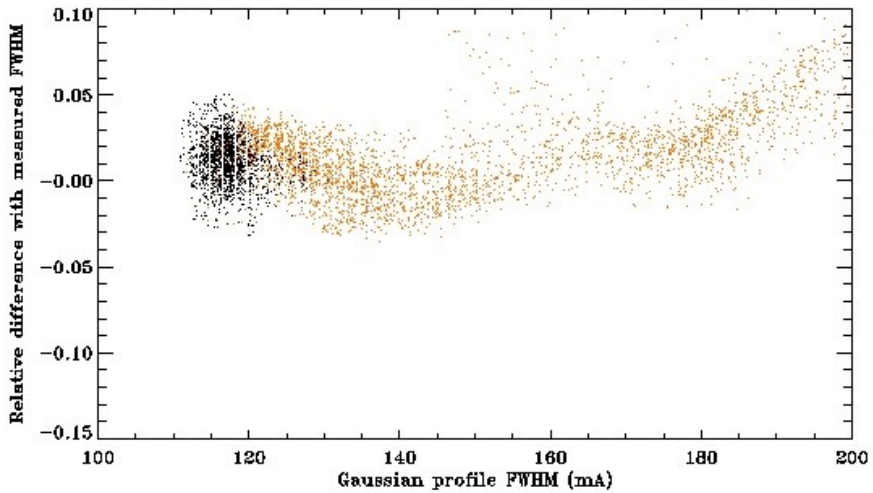


Black = field < 50 G
Orange = field > 1250 G

Relative difference between FWHM returned by the observables algorithms and the actual FWHM







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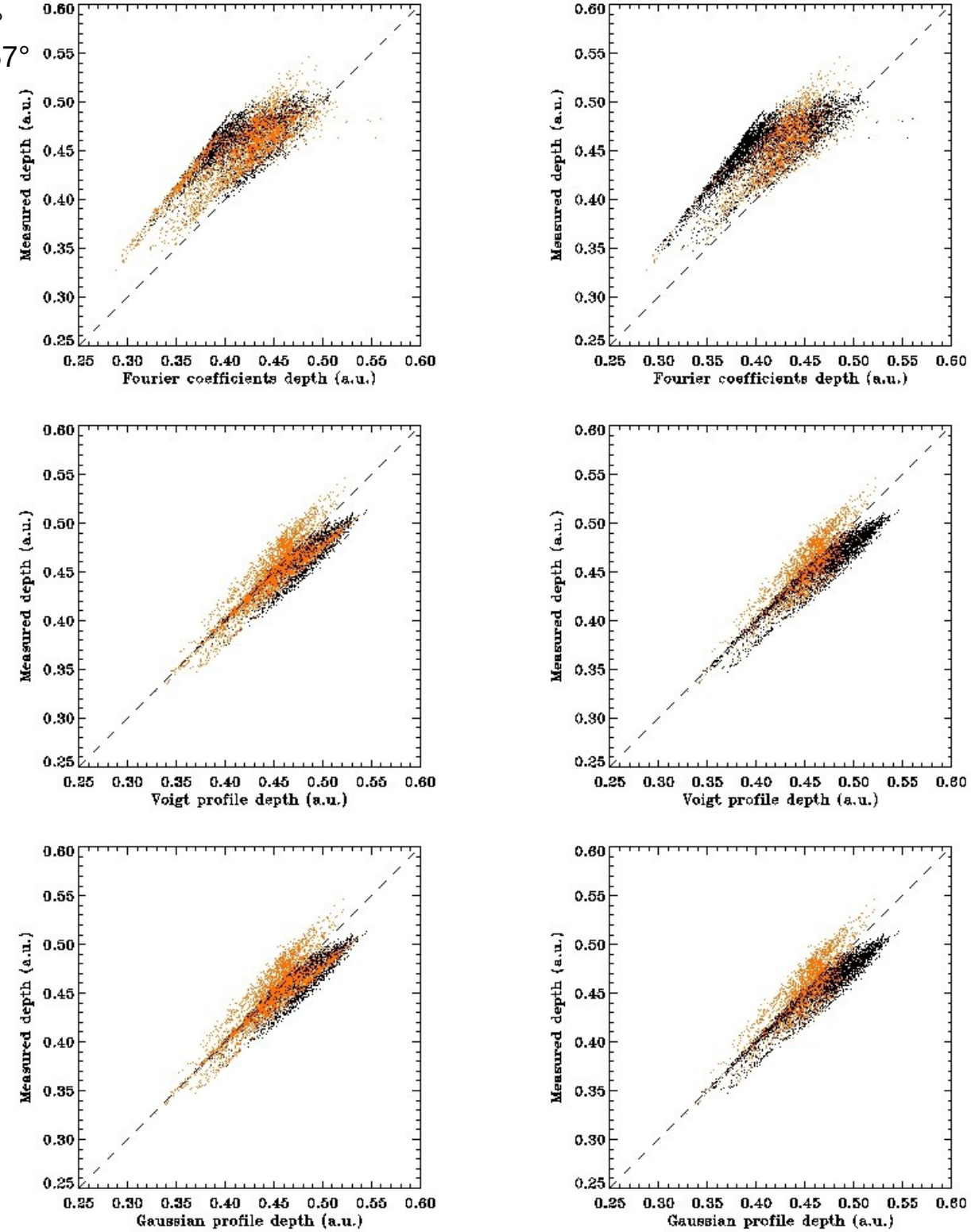
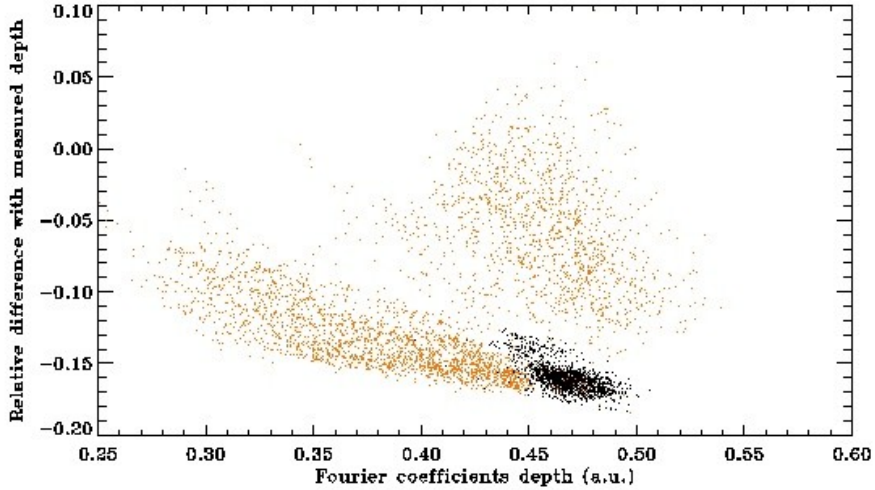
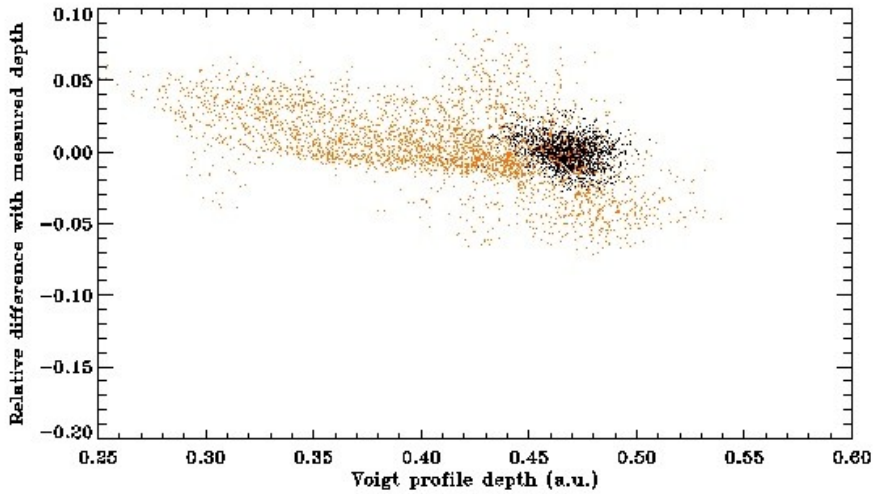
Linedepth

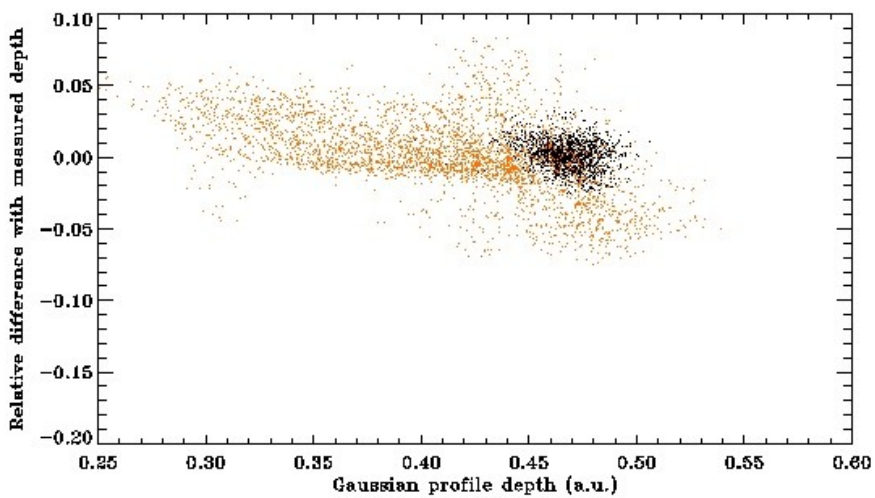


Black = field < 50 G
Orange = field > 1250 G

Relative difference between linedepth returned by the observables algorithms and the actual linedepth



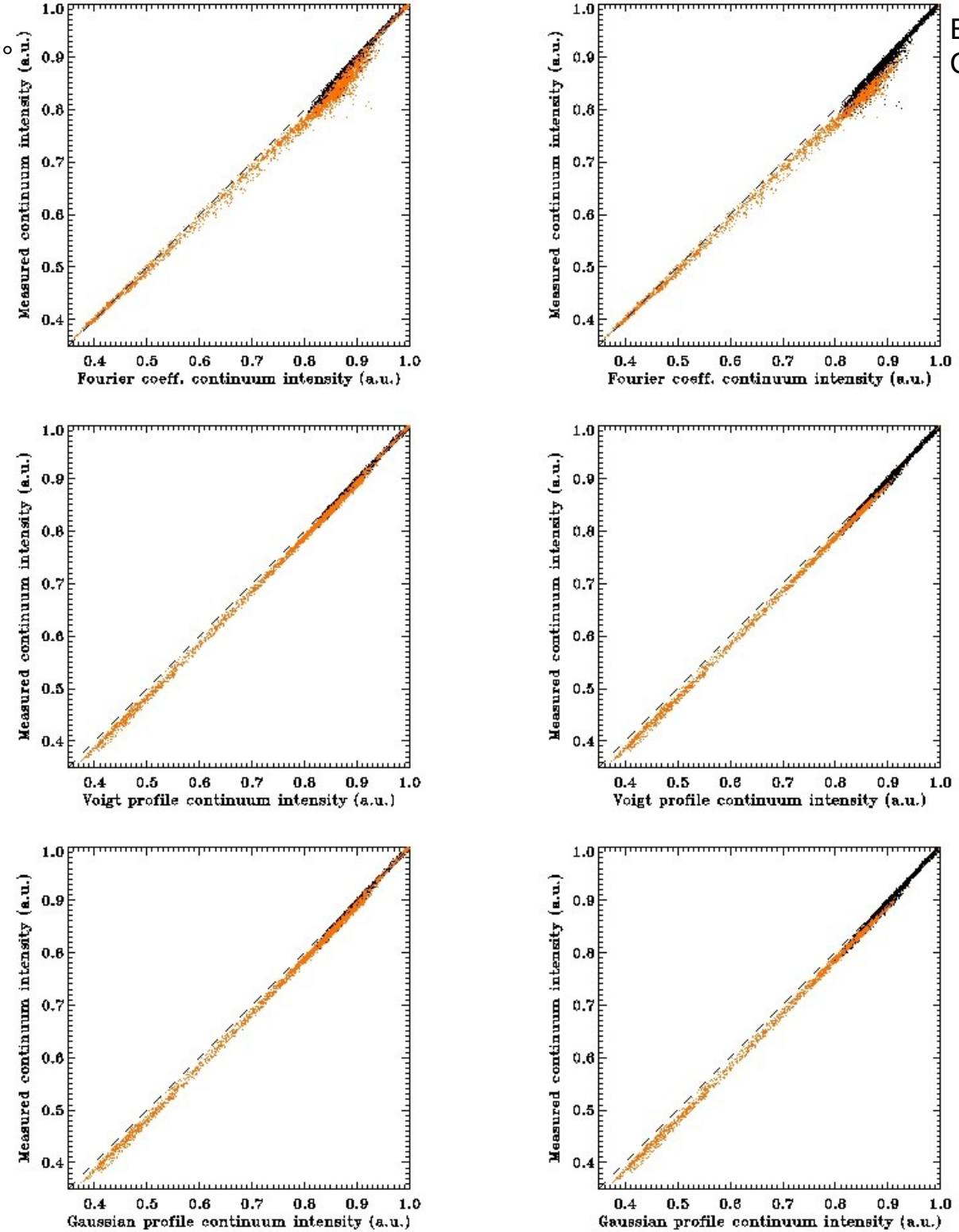




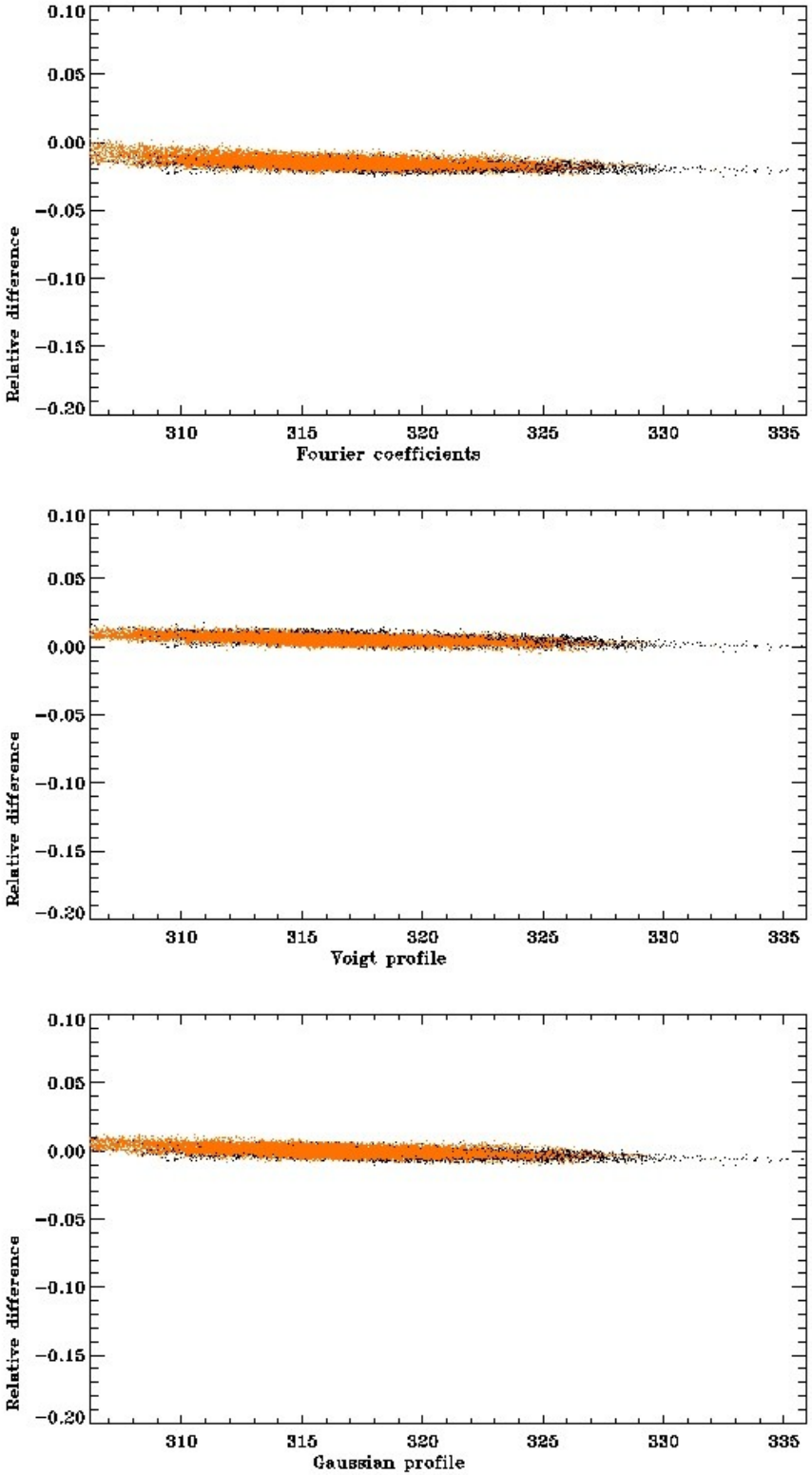
Black = inclination > 57°
Orange = inclination < 57°

Black = field < 1250 G
Orange = field > 1250 G

Continuum intensity



Relative difference between continuum intensity returned by the observables algorithms and the actual intensity



Conclusions

- NOAA AR 10960 observed on June 8, 2007 by IBIS (following proposal by R. Wachter et al.)
- HMI-like intensities were calculated from IBIS data, or from simulated Doppler-shifted Fe I line profiles
- 4 different observables algorithms were applied to these intensities, to derive Doppler velocity, l.o.s. field strength, linewidth, linedepth, and continuum intensity
- least-squares fits are the most accurate algorithms, as expected (Gaussian or Voigt profiles return similar results)
- 2nd Fourier-coefficients MDI-like algorithm is the least accurate algorithm
- 1st Fourier-coefficients MDI-like algorithm (currently implemented) underestimates the field strength in the sunspot (~20%), underestimates the linewidth (~3% in quiet Sun, up to ~15% in sunspot), and underestimates the linedepth (~16% in quiet Sun, less in sunspot)
- a proposal has been sent to NSO for simultaneous observations between HMI and IBIS