Implementation of Travel-Time Measurements in the HMI pipeline

S. Couvidat and the HMI Time-Distance Pipeline Team

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Three travel-time definitions we implemented:

Gabor Wavelet (Kosovichev & Duvall, 1997):

$$G = A \exp[-\delta\omega^2/4\ (\tau-\tau_g)^2] \cos[\omega_0(\tau-\tau_p)]$$

Gizon & Birch (2002):

$$X_{\pm}(\mathbf{r_1},\mathbf{r_2},t)= \int dt\ f(t')\ [C(\mathbf{r_1},\mathbf{r_2},t)-Cref(\Delta,t'-t)]^2$$

$$\tau_{\pm}(\mathbf{r}_1,\mathbf{r}_2) = \mathrm{argmin}_t\ \{X_{\pm}(\mathbf{r_1},\mathbf{r_2},t)\}$$

Gizon & Birch (2004):

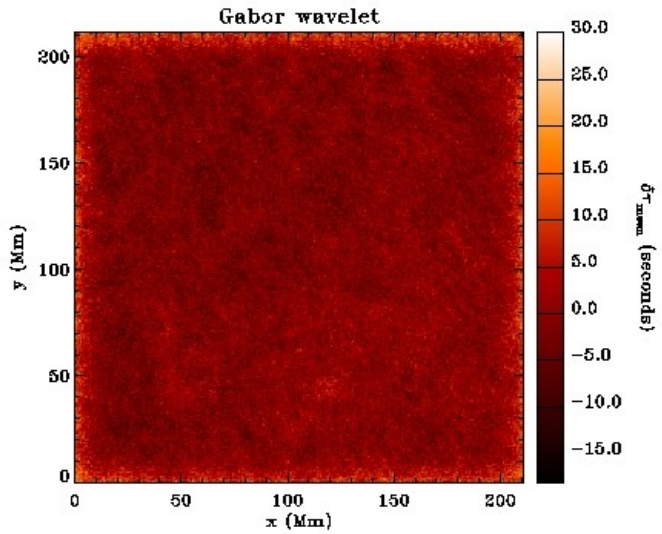
$$\tau_{\pm}(\mathbf{r}_1,\mathbf{r}_2) =$$

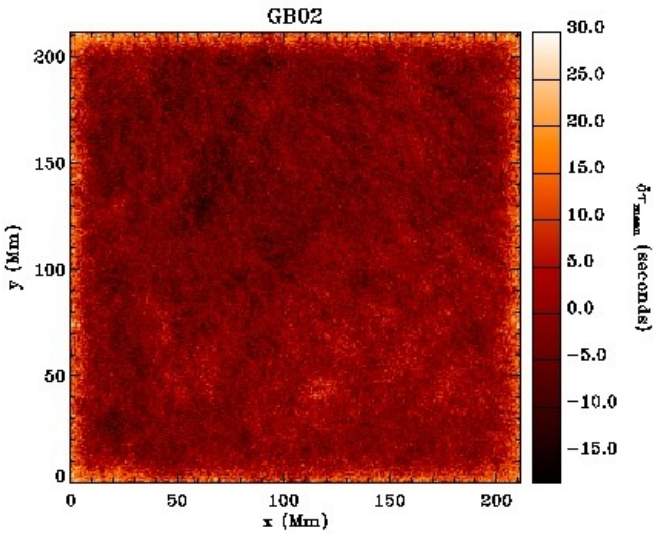
$$\int dt\ f(\pm t)\ \dot{C}_{ref}(\Delta,t)\ [C(r_1,r_2,t)-C_{ref}(\Delta,t)] \Big/ \int dt\ f(\pm t)\ [\dot{C}_{ref}(\Delta,t)]^2$$

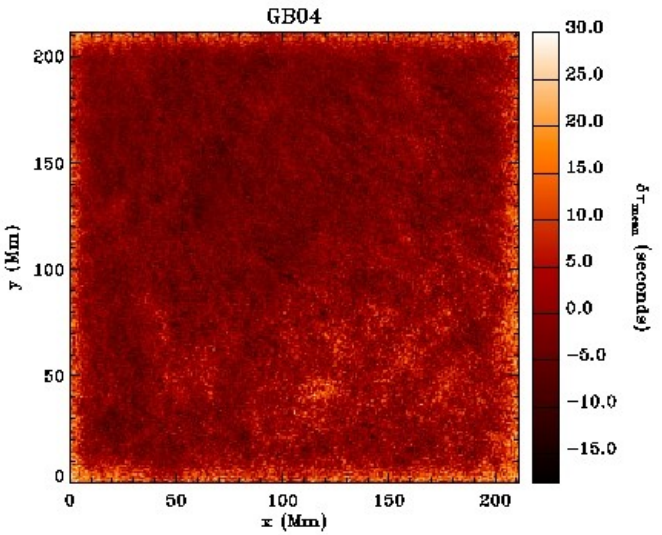
Implementation in C

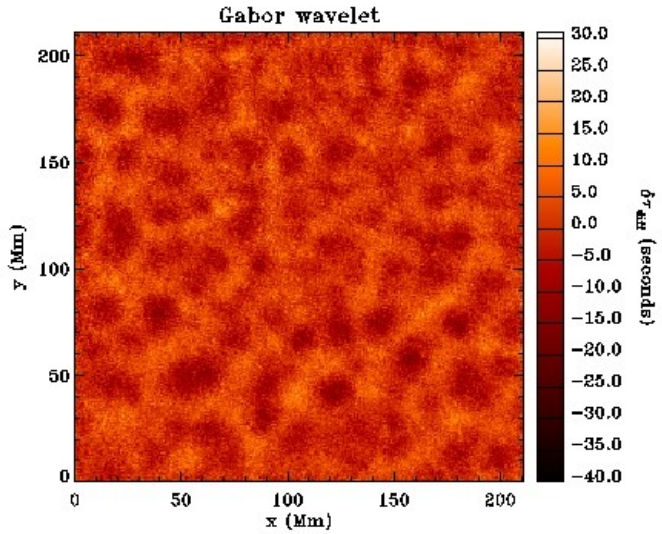
Comparison of tt definitions: Mean and Difference Travel Times in Quiet Sun (I)

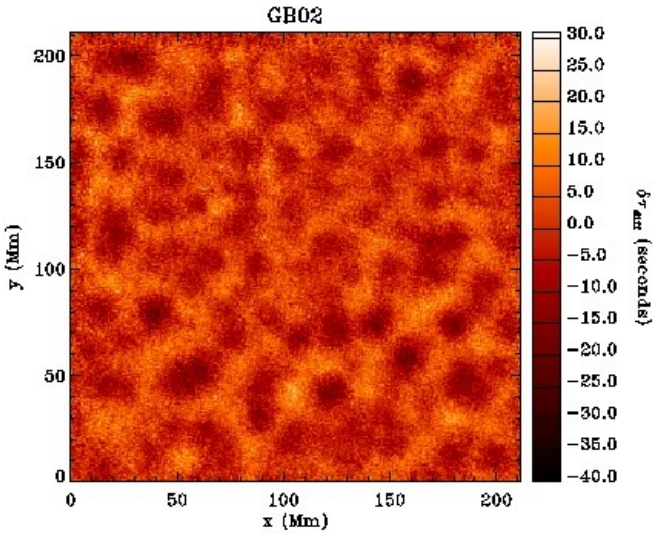
Δ= 6.2 Mm

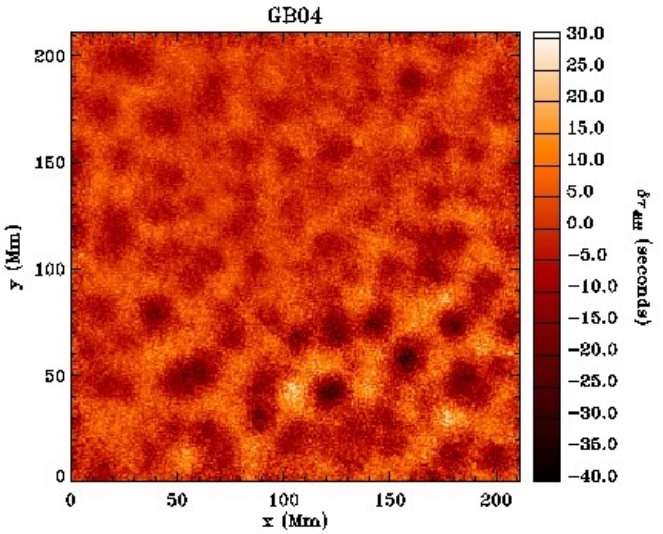






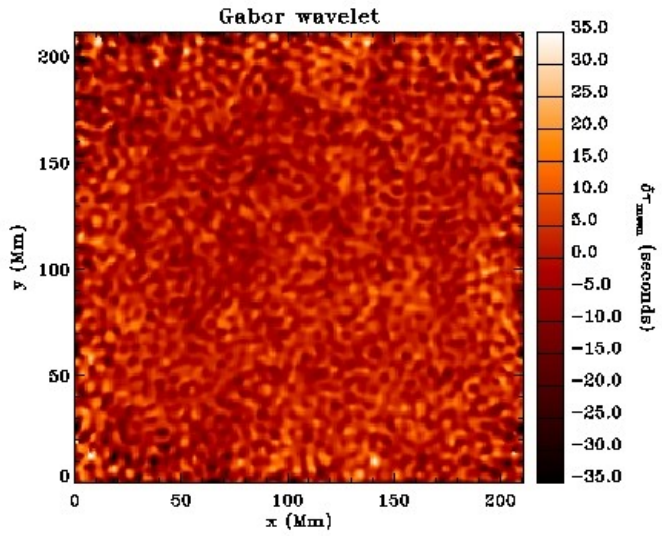


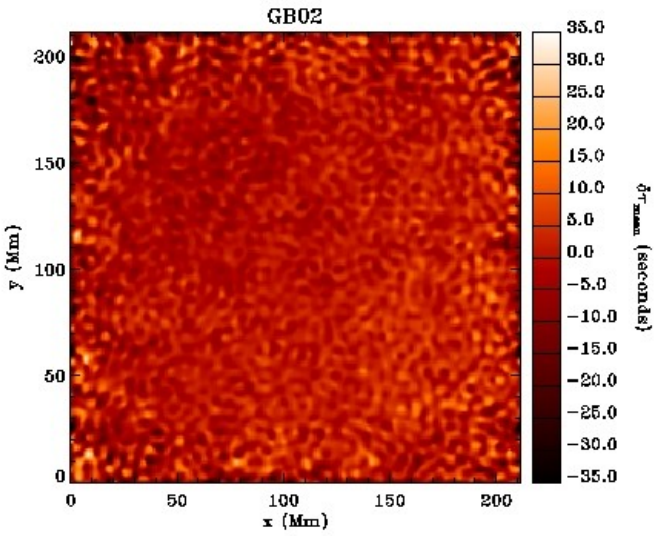


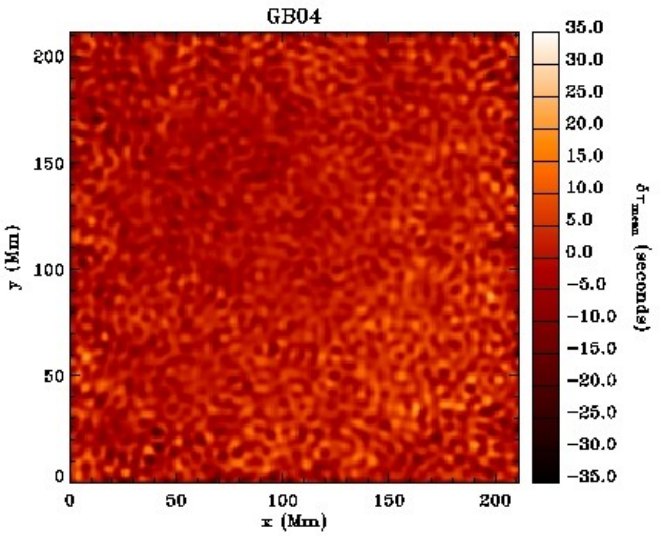


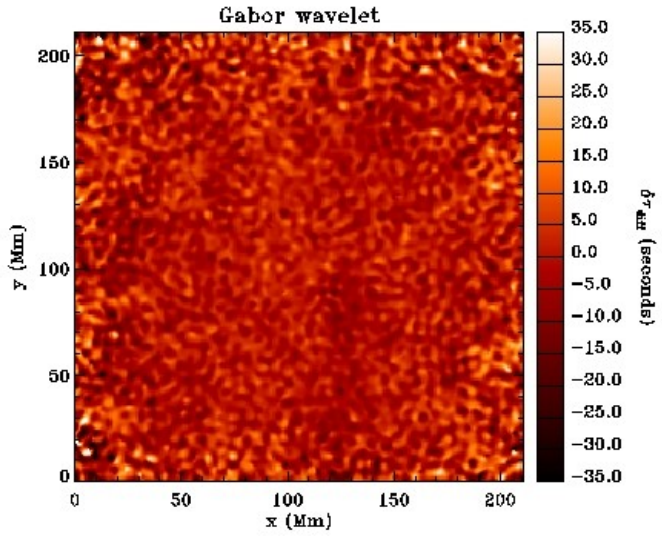
Mean and Difference Travel Times in Quiet Sun (II)

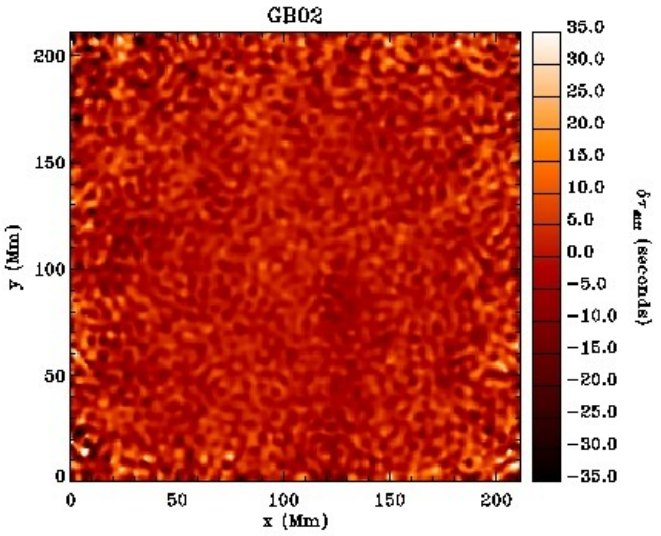
Δ= 30.55 Mm

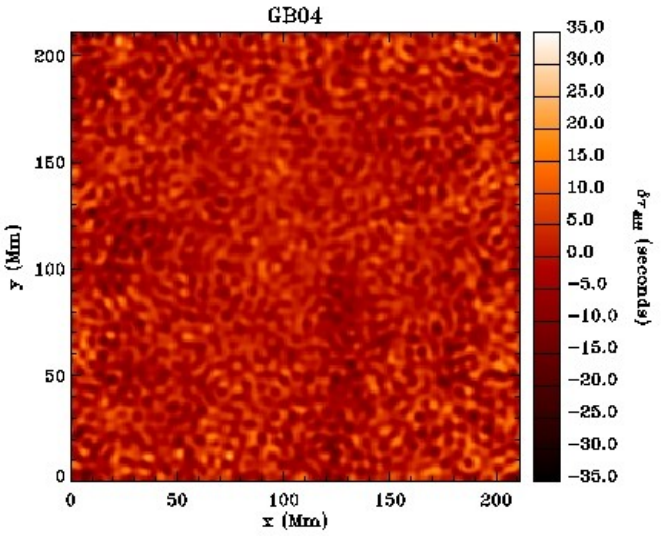




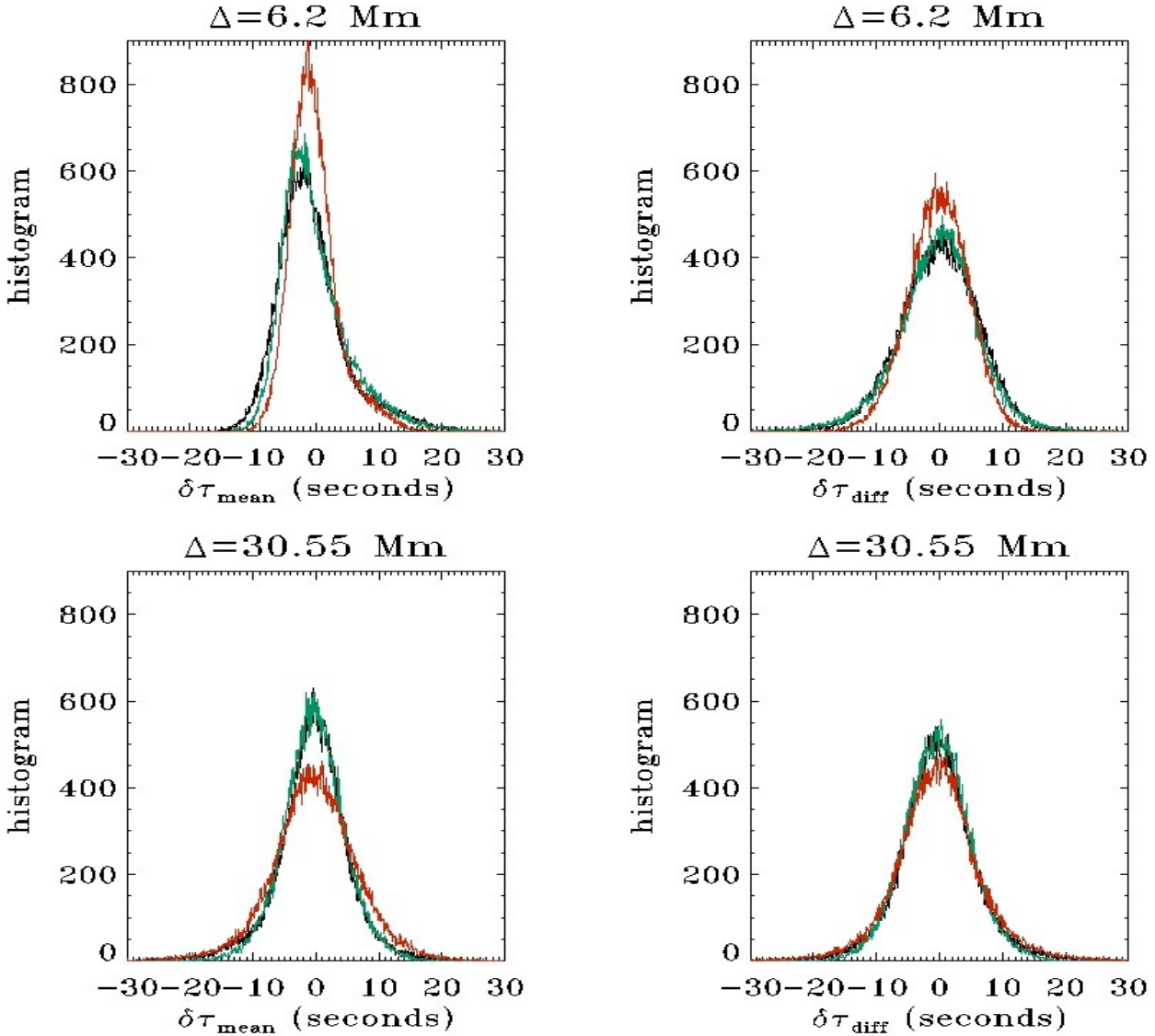








Mean and Difference Travel Times in Quiet Sun (III)



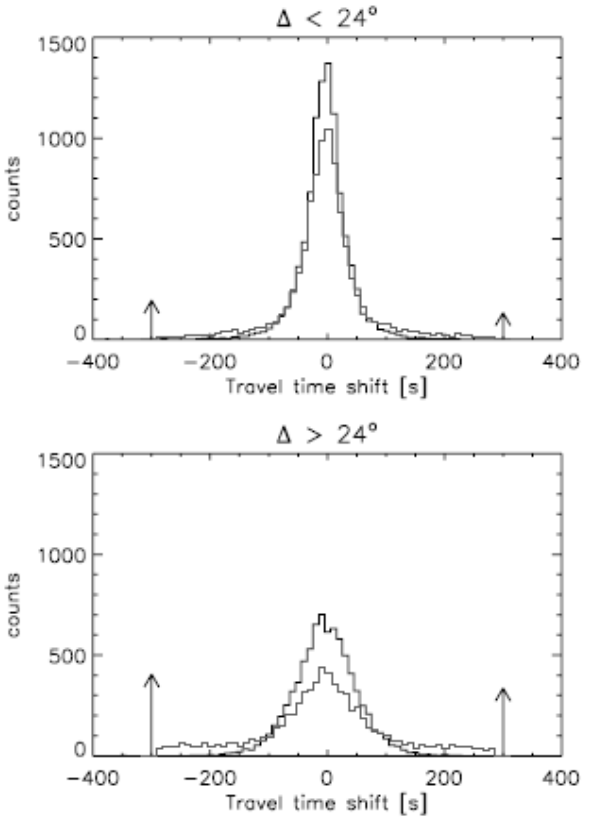
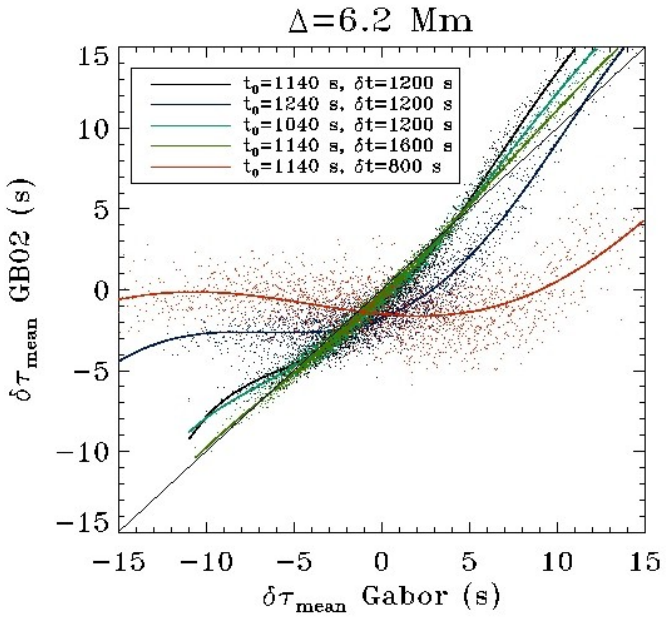


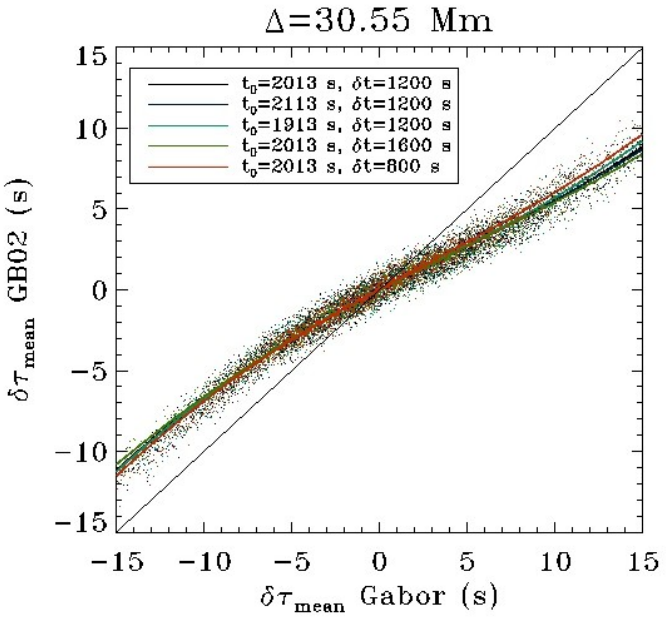
Fig. 6 Histograms for travel-time shifts measured by the Gabor-wavelet fit (grey) and the one-parameter fit (black) applied to north-south data; $T = 72$ h. *Top*: Measurements for distances lower than 24°. The total number of measurements is 9667. *Bottom*: Measurements for distances larger than 24°. The total number of measurements is 8036. In both cases the number of outliers produced by the Gabor-wavelet fit are indicated by arrows at the bins −300 s and 300 s, resp. The total number of outliers is 327 for $\Delta < 24°$ and 741 for $\Delta > 24°$.

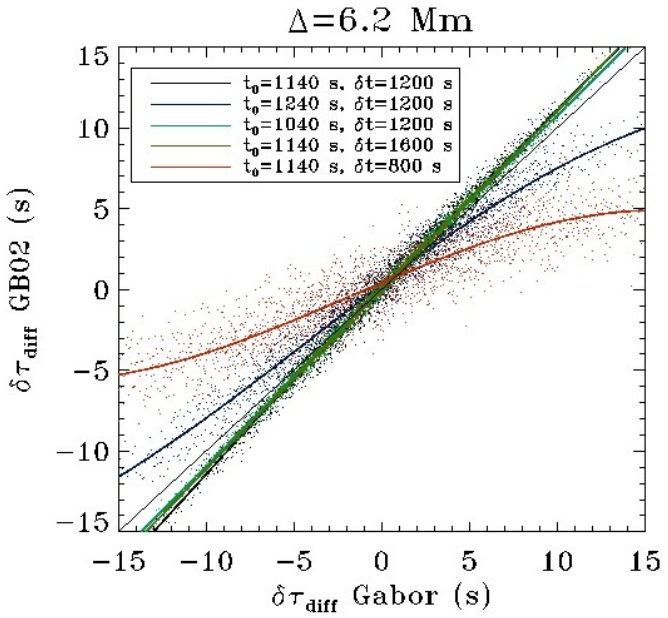
Roth, Gizon & Beck, AN 328, 215 (2007)

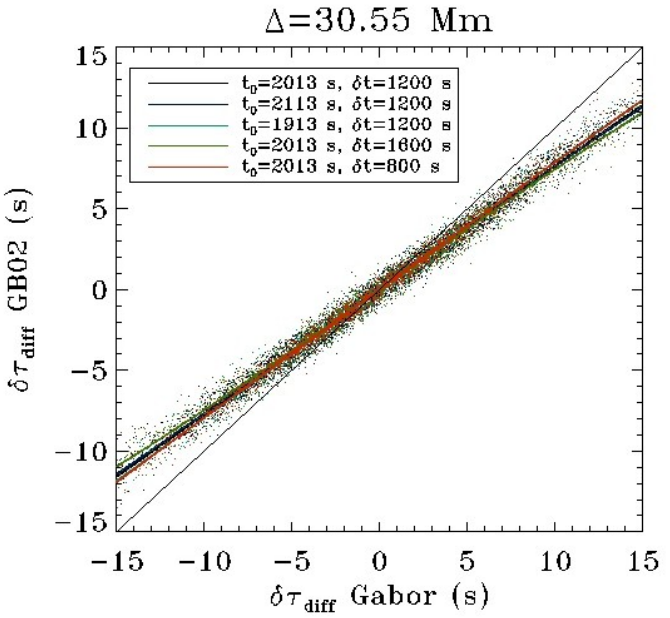
Black = GB02, Green= GB04, Red= Gabor

Mean and Difference Travel Times in Quiet Sun (IV)

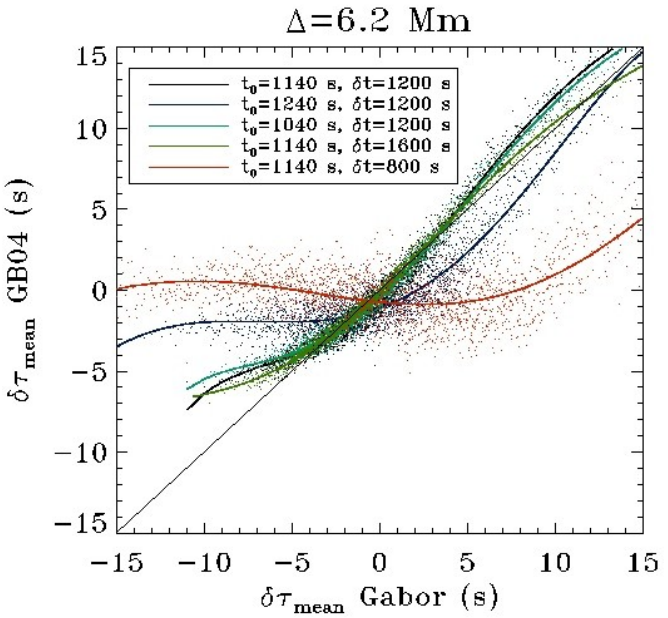


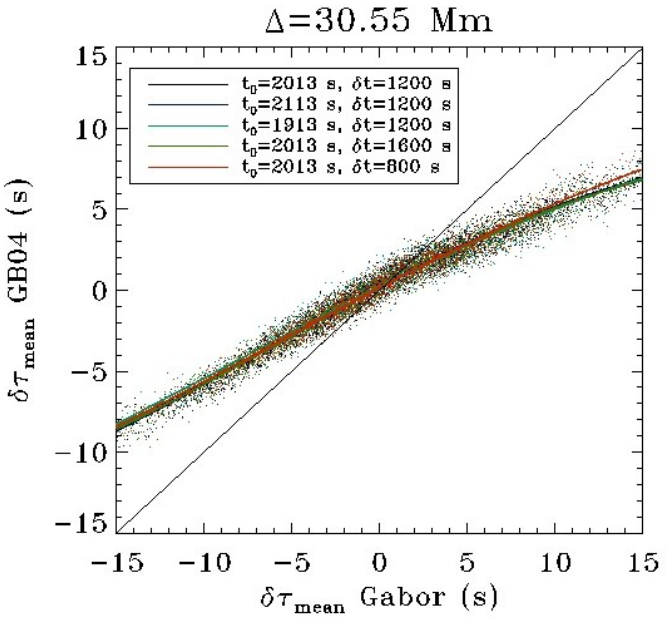


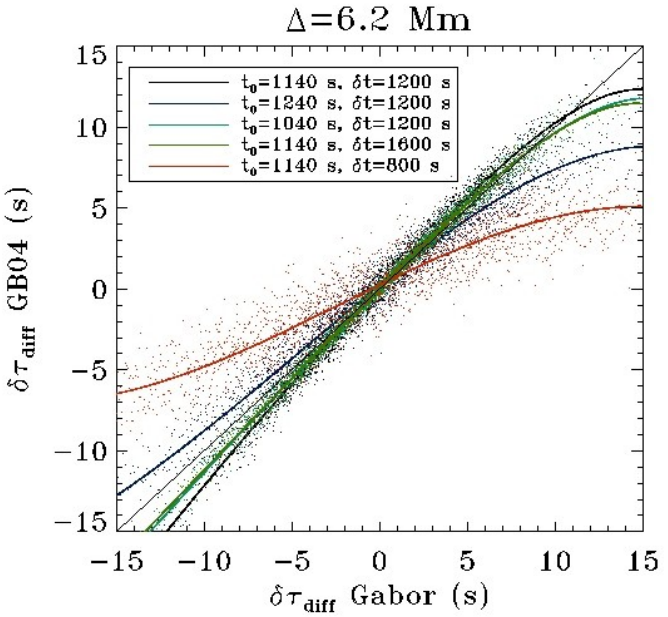


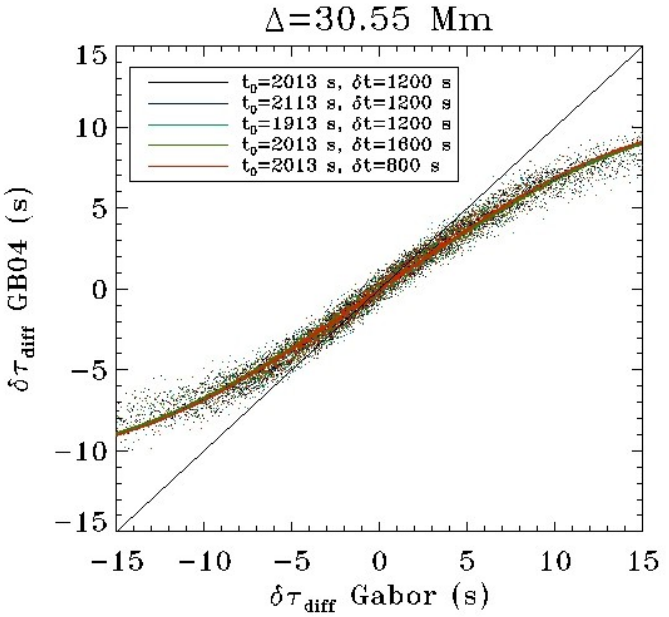


Mean and Difference Travel Times in Quiet Sun (V)



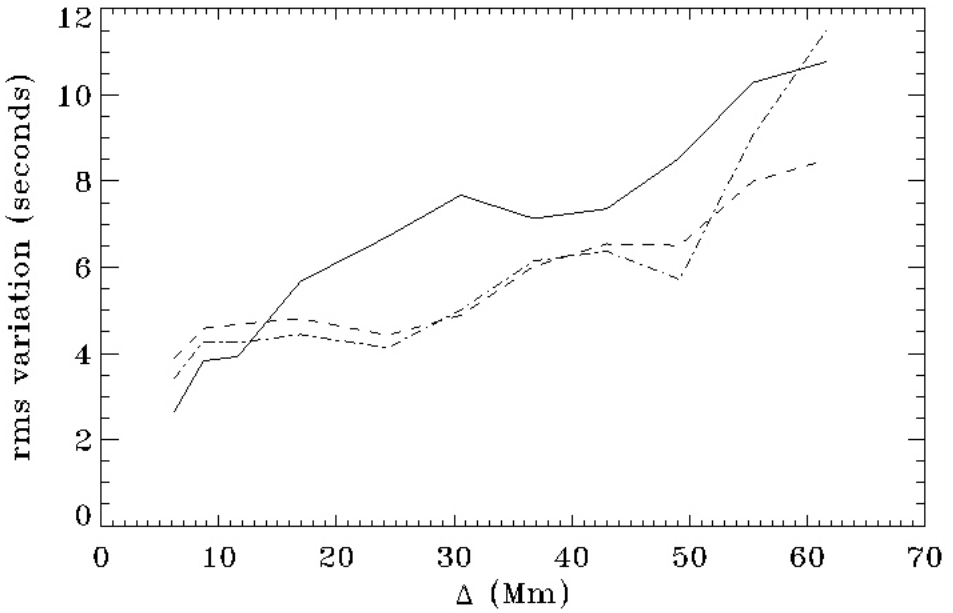


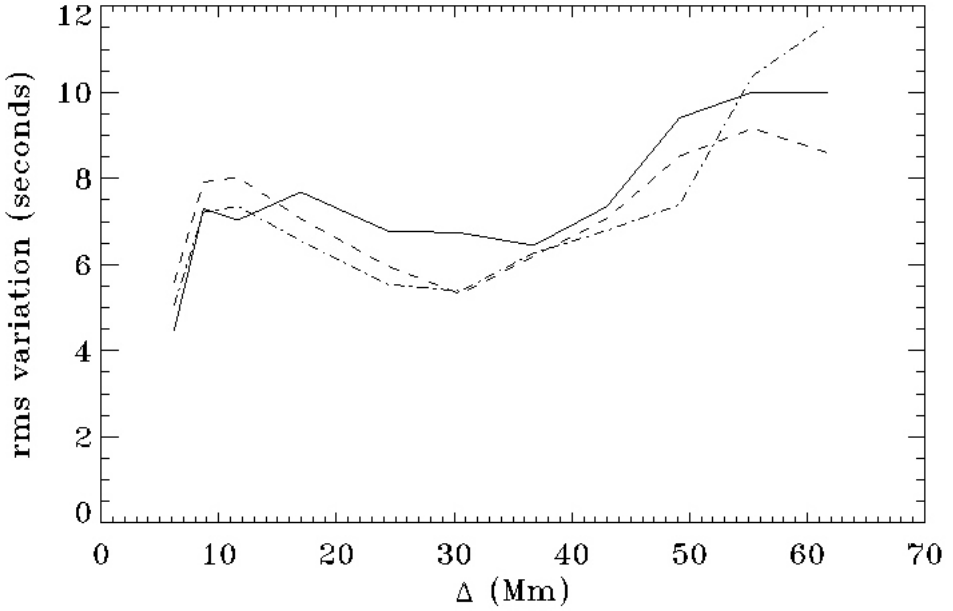




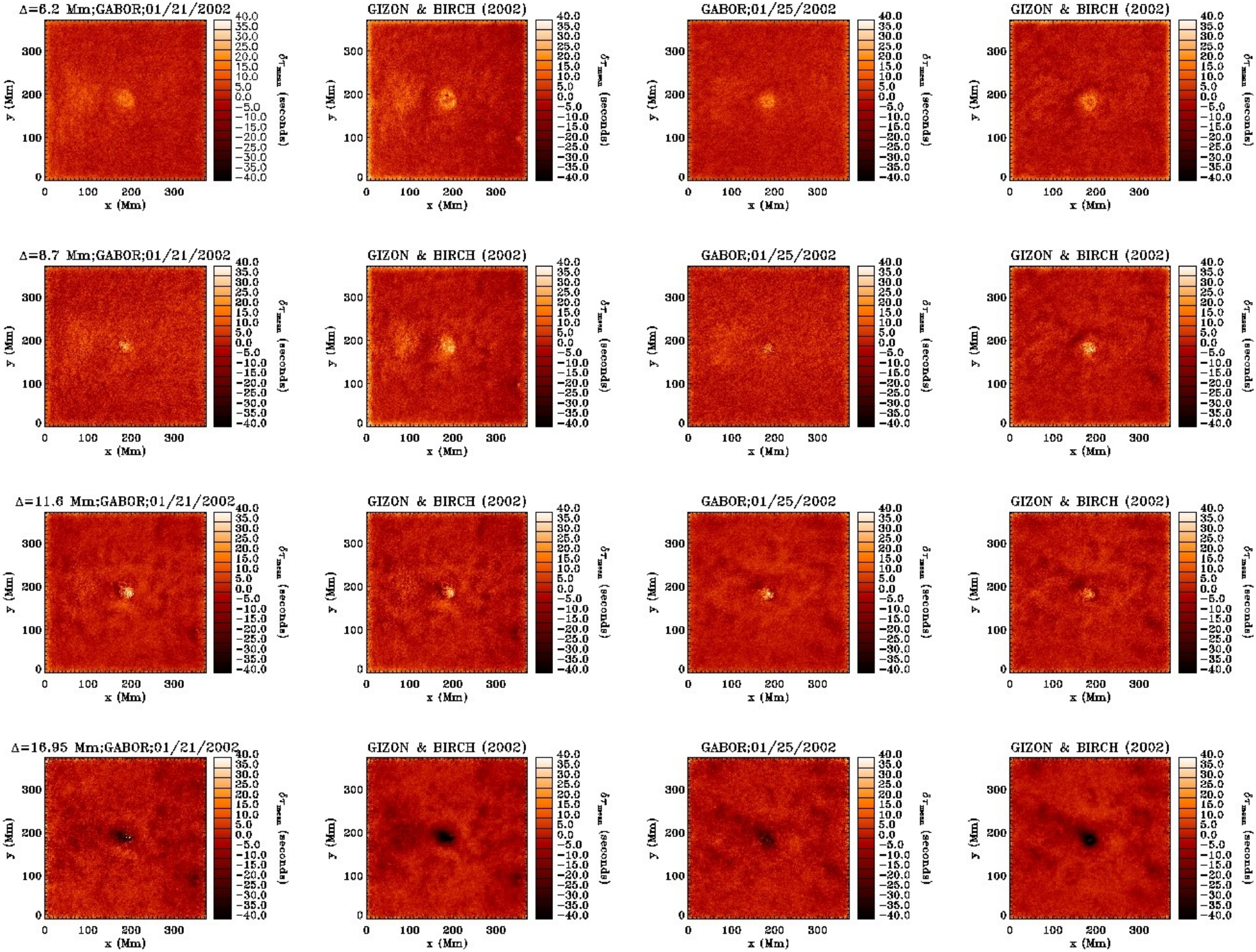
Mean and Difference Travel Times in Quiet Sun (VI)

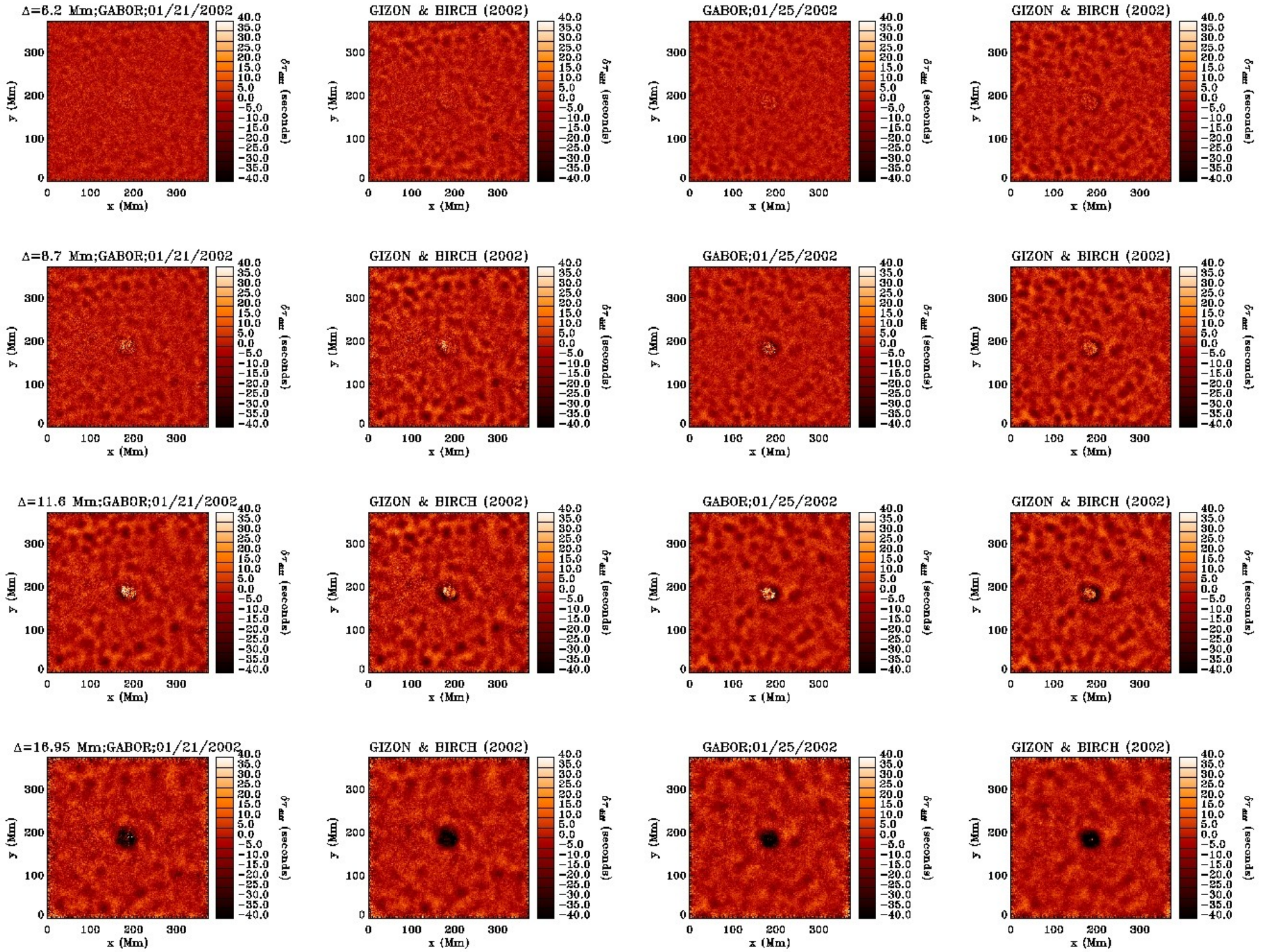
Solid = Gabor,
dashed= GB02,
dash-dotted= GB04
upper=mean,
lower=difference

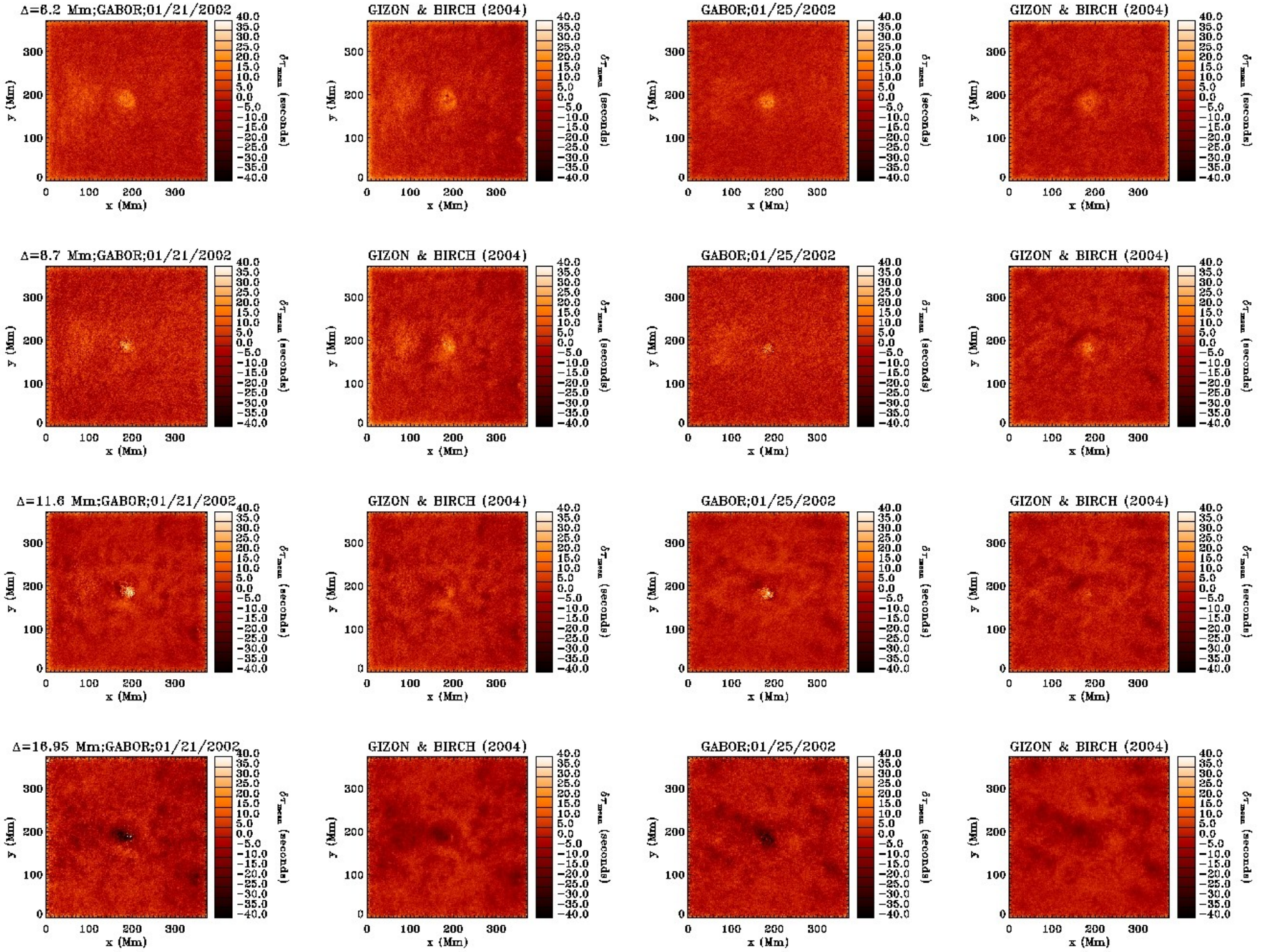


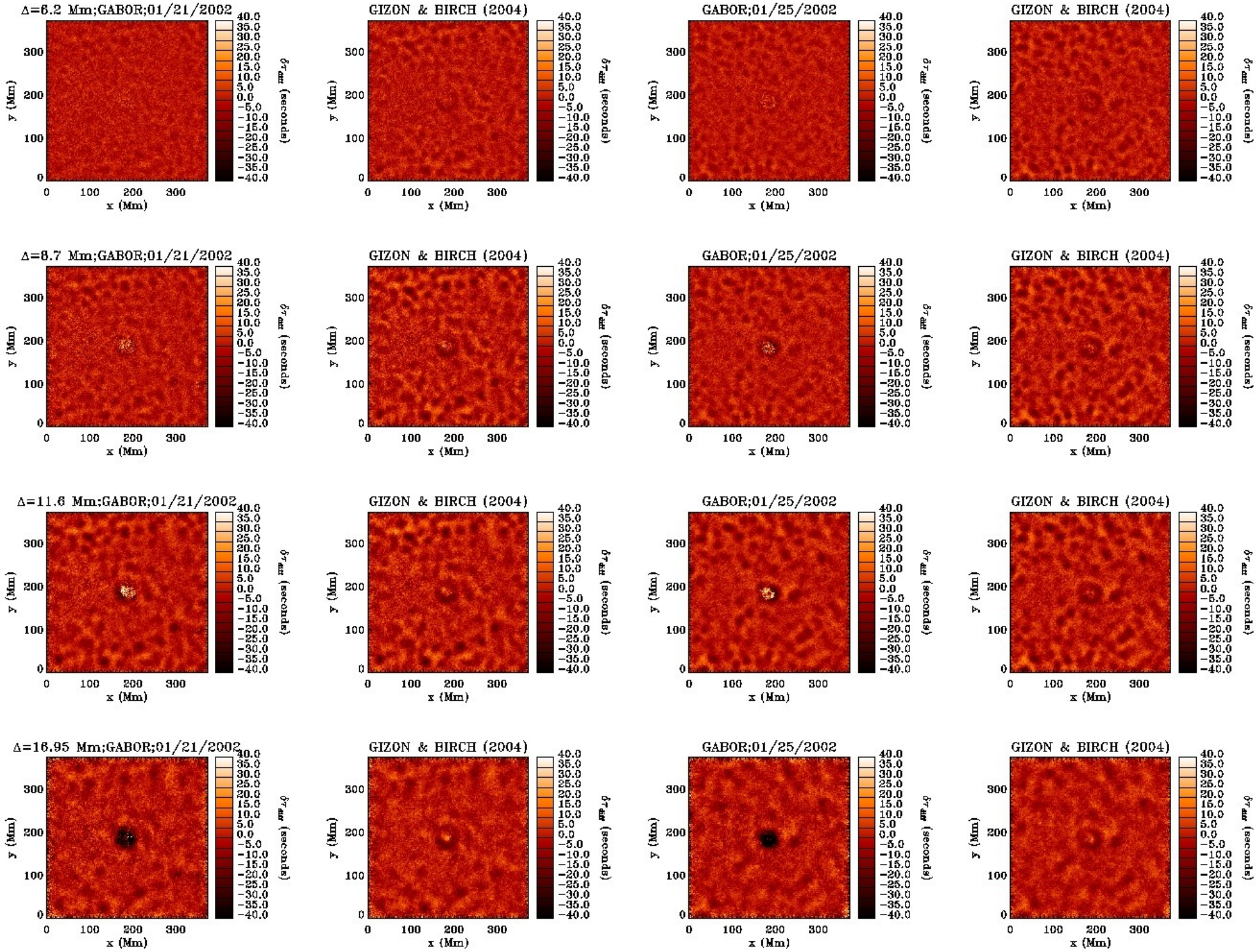


Mean and Difference Travel Times in Active Region NOAA 9787


Δ=6.2 Mm;GABOR;01/21/2002
GIZON & BIRCH (2002)
GABOR;01/25/2002
GIZON & BIRCH (2002)
Δ=8.7 Mm;GABOR;01/21/2002
GIZON & BIRCH (2002)
GABOR;01/25/2002
GIZON & BIRCH (2002)
Δ=11.6 Mm;GABOR;01/21/2002
GIZON & BIRCH (2002)
GABOR;01/25/2002
GIZON & BIRCH (2002)
Δ=16.95 Mm;GABOR;01/21/2002
GIZON & BIRCH (2002)
GABOR;01/25/2002
GIZON & BIRCH (2002)
y (Mm)
x (Mm)
δT_meas (seconds)


Δ=6.2 Mm;GABOR;01/21/2002
GIZON & BIRCH (2002)
GABOR;01/25/2002
GIZON & BIRCH (2002)
Δ=8.7 Mm;GABOR;01/21/2002
GIZON & BIRCH (2002)
GABOR;01/25/2002
GIZON & BIRCH (2002)
Δ=11.6 Mm;GABOR;01/21/2002
GIZON & BIRCH (2002)
GABOR;01/25/2002
GIZON & BIRCH (2002)
Δ=16.95 Mm;GABOR;01/21/2002
GIZON & BIRCH (2002)
GABOR;01/25/2002
GIZON & BIRCH (2002)
x (Mm)
y (Mm)
δτ_aux (seconds)


Δ=6.2 Mm;GABOR;01/21/2002
GIZON & BIRCH (2004)
GABOR;01/25/2002
GIZON & BIRCH (2004)
Δ=8.7 Mm;GABOR;01/21/2002
GIZON & BIRCH (2004)
GABOR;01/25/2002
GIZON & BIRCH (2004)
Δ=11.6 Mm;GABOR;01/21/2002
GIZON & BIRCH (2004)
GABOR;01/25/2002
GIZON & BIRCH (2004)
Δ=16.95 Mm;GABOR;01/21/2002
GIZON & BIRCH (2004)
GABOR;01/25/2002
GIZON & BIRCH (2004)
y (Mm)
x (Mm)
δτmean (seconds)

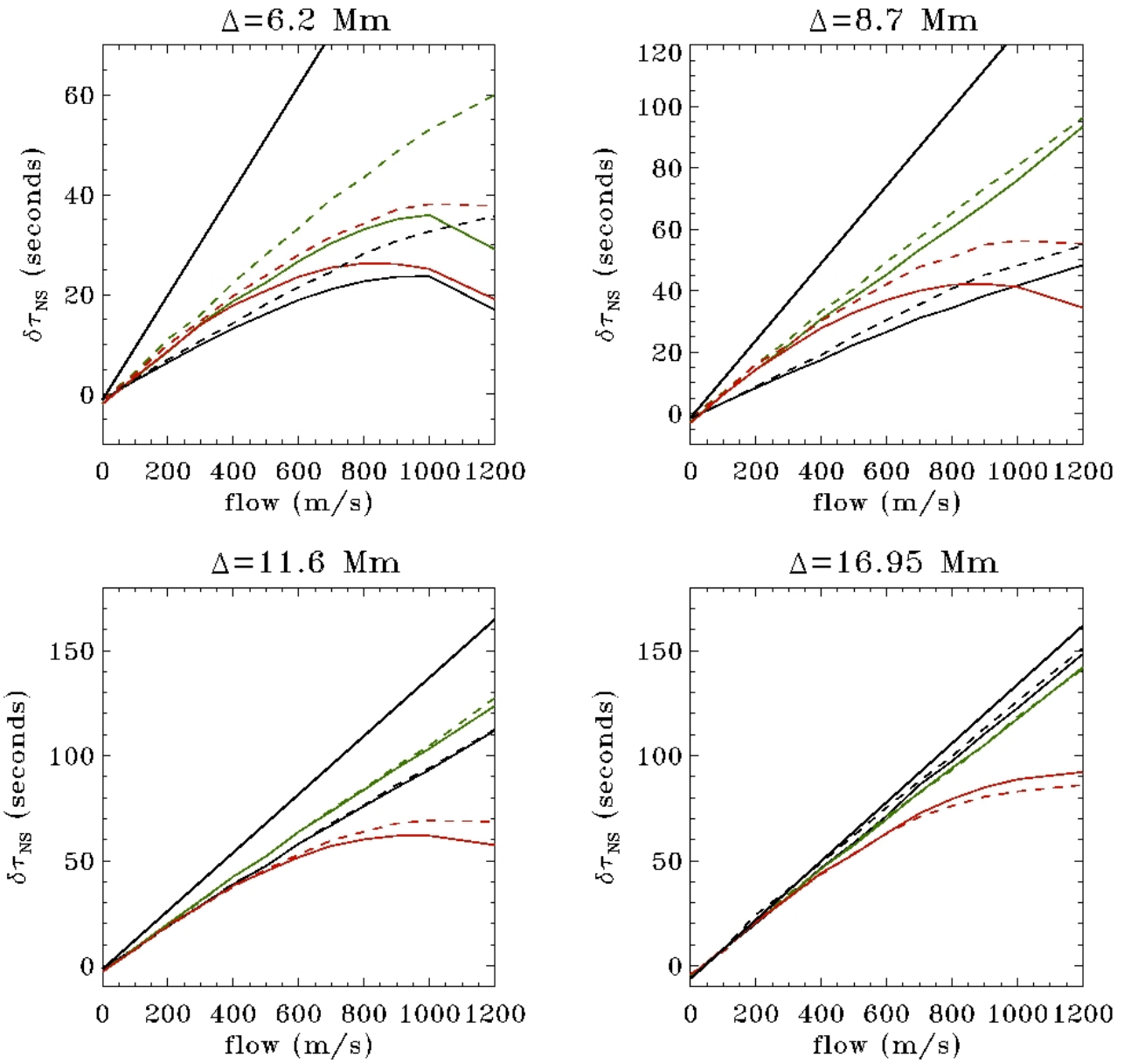

Δ=6.2 Mm;GABOR;01/21/2002
GIZON & BIRCH (2004)
GABOR;01/25/2002
GIZON & BIRCH (2004)
Δ=8.7 Mm;GABOR;01/21/2002
GIZON & BIRCH (2004)
GABOR;01/25/2002
GIZON & BIRCH (2004)
Δ=11.6 Mm;GABOR;01/21/2002
GIZON & BIRCH (2004)
GABOR;01/25/2002
GIZON & BIRCH (2004)
Δ=16.95 Mm;GABOR;01/21/2002
GIZON & BIRCH (2004)
GABOR;01/25/2002
GIZON & BIRCH (2004)
x (Mm)
y (Mm)
δτ_aw (seconds)

Comparison of north-south difference travel times through horizontal flows added to a simulation of the solar convection

(S. Couvidat & A. Birch)

- Simulation of Stein, Nordlund, Georgobiani, & Benson (already used in local helioseismology by, e.g., Braun et al. (2007), Zhao et al. (2007), Georgobiani et al. (2007)
- power spectrum close to MDI
- 96x96x20 Mm^3
- 8.5 hours of data
- dx=0.384 Mm, dt=60 s
- added steady southward uniform flows to the vertical velocity maps, using shift theorem in Fourier domain; 12 flow velocities
- worked with acoustic modes only (Jackiewicz et al., 2007, studied f-mode case)
- time-distance analysis performed with 2 kind of filters (“standard” ---values from T. Duvall--- and “broad” ---FWHM x4---) for 4 distances source-receiver

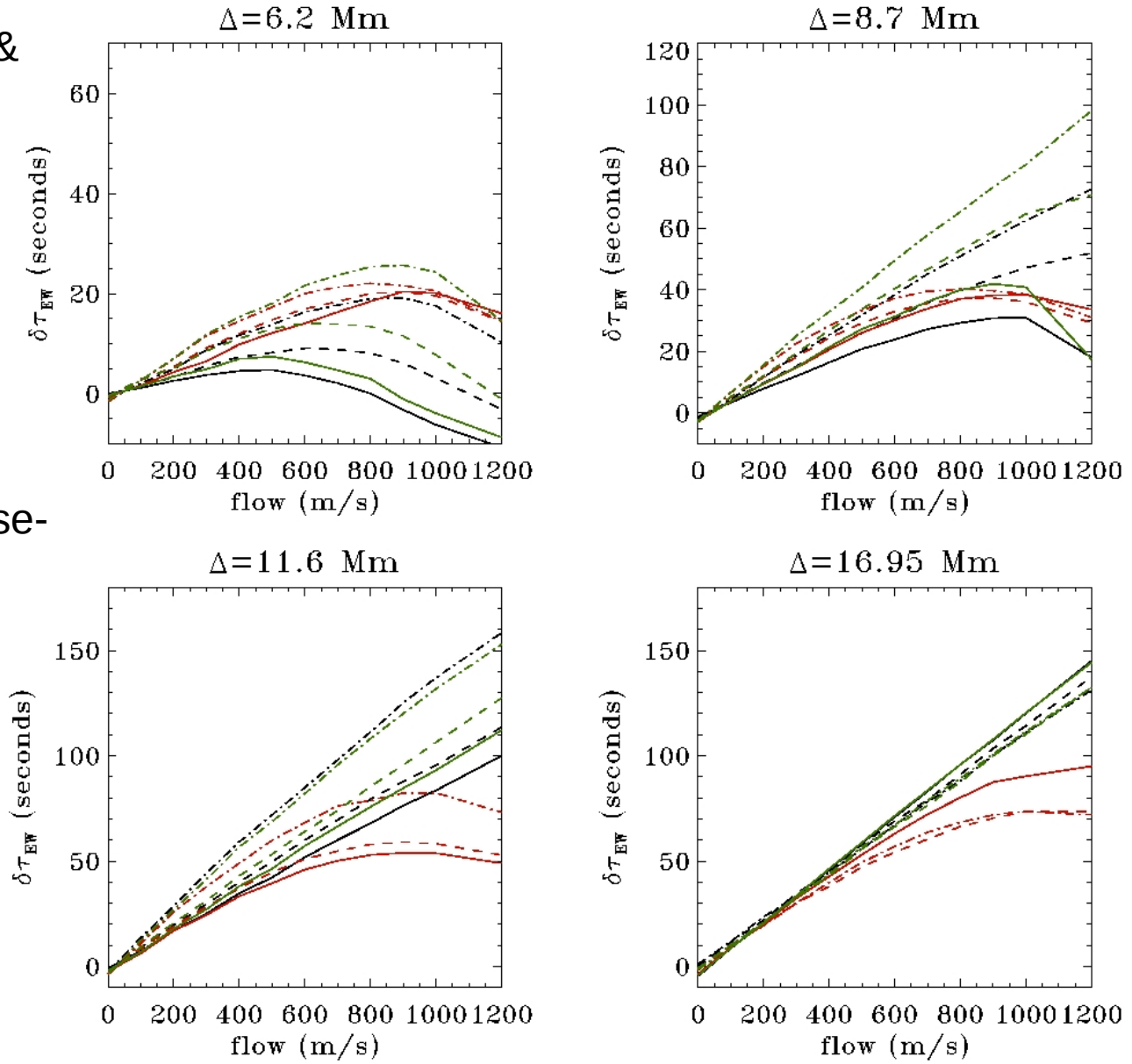
North-South travel-time difference in presence of flows (I)



North-South travel-time difference in presence of flows (II) : frequency dependence

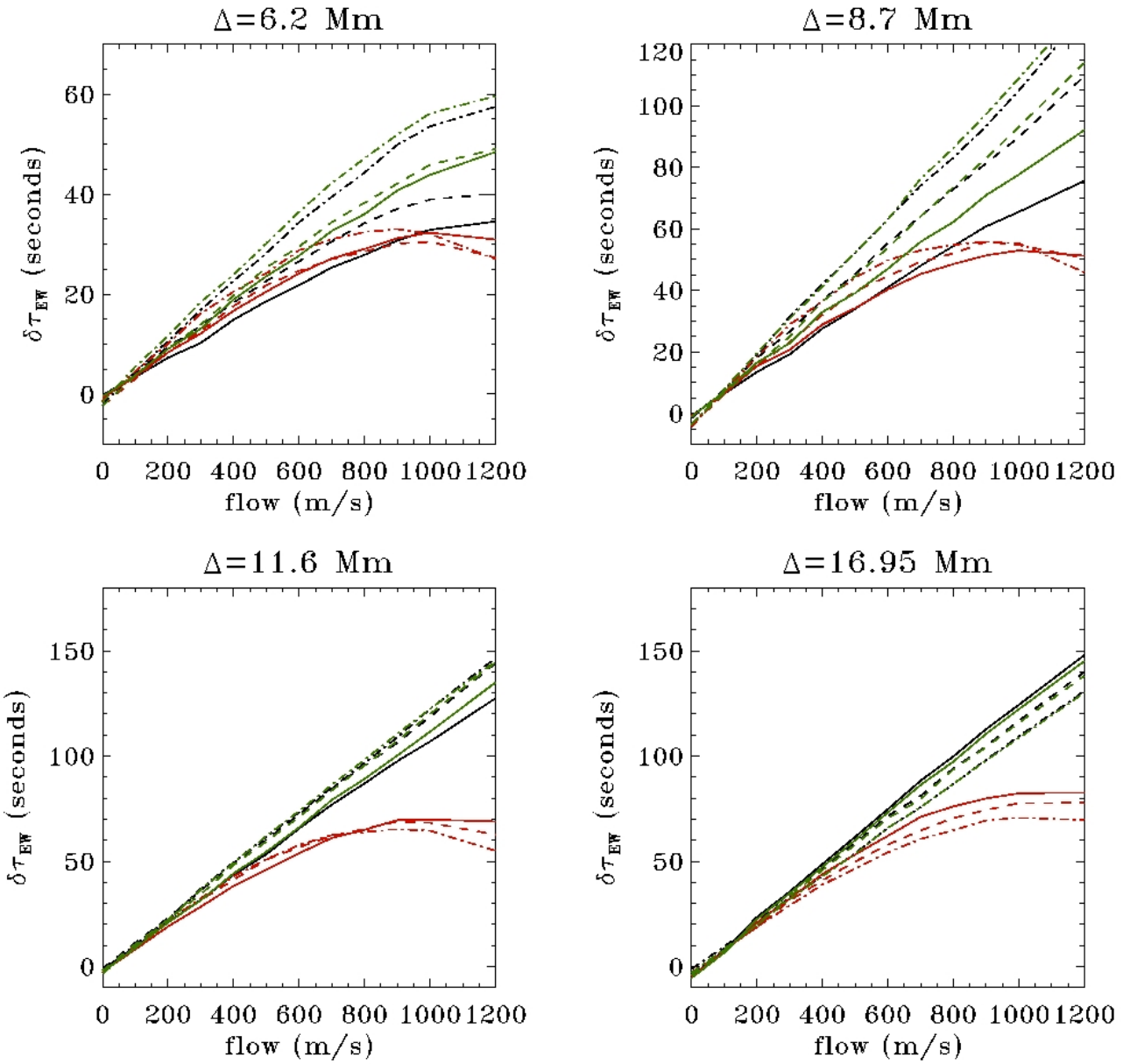
Following Braun & Birch (2006)

Standard phase-speed filters



North-South travel-time difference in presence of flows (III) : frequency dependence

Broad phase-speed filters



Conclusion

- in quiet Sun the three definitions give very similar results
- in active region, Gabor and GB02 give similar results after cross-covariances have been normalized
- GB04, even with normalization, seems inadequate for active regions
- if phase-speed filters are too narrow, Gabor and GB02 can return time differences not linear in the flow strength
- GB04 is never linear in the flow strength