The measurement of the apparent phase speed of propagating disturbances

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See paper Yuan & Nakariakov 2012 A&A (submitted)

Introduction

AIA observation

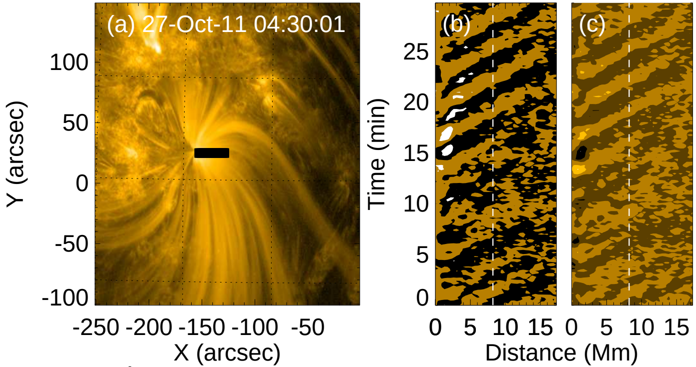

Figure: a) AIA 171 Å image on AR 11330. A cut was taken $C(s_m, t_k)$ as indicated with black bar. b) Running difference R_1 (R_2): $R(s_m, t_k) = C(s_m, t_k) - C(s_m, t_{k-l})$ with $l = 9$. c) D_1 (D_2):

$$D(s_m, t_k) = [C(s_m, t_k) - B(s_m, t_k)]/B(s_m, t_k), \text{ where } B(s_m, t_k) = \sum_{h=-N/2}^{N/2-1} C(s_m, t_{k+h})/N \text{ with } N = 50.$$

AIA image flux noise

$$
\begin{aligned}
\sigma^2_{\text{noise}}(F) &= \sigma^2_{\text{photon}}(F) + \sigma^2_{\text{readout}} + \sigma^2_{\text{digit}} + \sigma^2_{\text{compress}} \\
&+ \sigma^2_{\text{dark}} + \sigma^2_{\text{subtract}} + \sigma^2_{\text{spikes}}(F) \\
&= \sqrt{(1+0.25^2)\frac{F}{17.7} + 1.15^2 + 4 \times 0.5^2 + (0.0009F)^2} \\
&\approx \sqrt{2.3 + 0.06F}\ (\mathrm{DN}) \\
\sigma_{\text{photon}}(F) &= \sqrt{F/G_\lambda} \\
\sigma_{\text{compress}} &= 0.25\sigma_{photon} \\
\sigma_{\text{readout}} &= 1.15\,\mathrm{DN} \\
\sigma_{\text{digit}} &= 0.5\,\mathrm{DN} \\
\sigma_{dark} &= 0.5\,\mathrm{DN} \\
\sigma_{\text{subtract}} &= \sqrt{2 \times 0.5^2} = 0.7\,\mathrm{DN} \\
\sigma_{\text{spike}}(F) &= 0.006 \times 0.15F = 0.0009F
\end{aligned}
$$

ref.: Yuan & Nakariakov 2012, Aschwanden et al 2001, Boerner et al 2011

AIA image flux noise

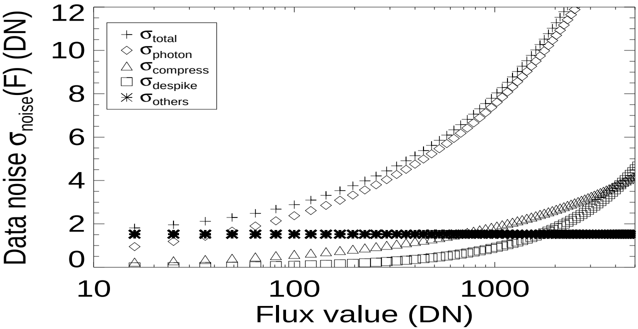

Figure: The data noise $\sigma_{noise}(F)$ (+) as a function of pixel flux F in AIA 171 Å images

Uncertainties in enhance time-distance plot

- Running difference plot:
  $\sigma(R(s_m, t_k)) = \sqrt{\sigma^2(C(s_m, t_k)) + \sigma^2(C(s_m, t_{k-9}))}$
- Background-removed time-distance plot:
  $\sigma(D(s_m, t_k)) = \sigma(C(s_m, t_k))/B(s_m, t_k)$

CFT method

- For $X(s_m, t_k)$, either R_1 (R_2) or D_1 (D_2)
- At each pixel, $X(s_m, *)$ is fitted with $A_s \cos(\omega_s t + \phi_s) + \delta_s$
- At each image (time), $X(*, t_k)$ is fitted with $A_t \cos(k_t x + \phi_t) + \delta_t$
- $V_p = \omega/k$ is obtained combining the average of the above fits.

CFT method and its application

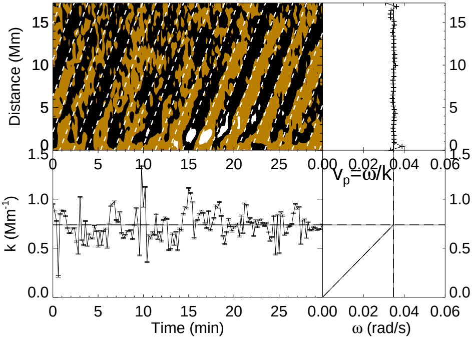

Figure: CFT application to R_1: $\omega = 0.0347 \pm 0.00002\,\mathrm{rad/s}$, $k = 0.738 \pm 0.002\,\mathrm{Mm}^{-1}$, $P = 181.2 \pm 0.1\,\mathrm{s}$, $V_p = 47.0 \pm 0.1\,\mathrm{km/s}$

DCF method and its application

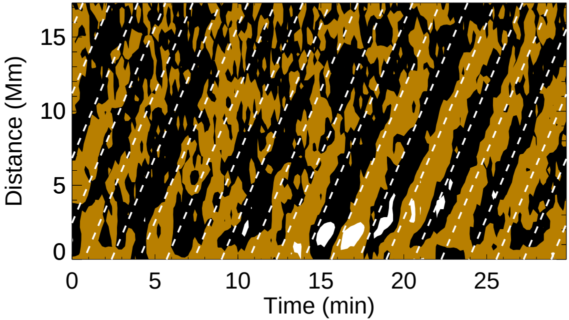

Figure: DCF application to R_1: $P = 240.7 \pm 0.7\,\mathrm{s}, V_p = 48.8 \pm 0.2\,\mathrm{km/s}$.

BSM methods

- A parametric model image is generated with $M_{V_p,P,\phi}(s_m,t_k)=\sqrt{2}RMS(X(s_m,t_k))\cos(\omega t_k-ks_m+\phi)$.
- The similarity is quantified as
$$L_p(M,R)=\left(\sum_{m=1}^{m=N_s}\sum_{k=1}^{k=N_t}|M(s_m,t_k)-X(s_m,t_k)|^2\right)^{1/2}.$$
- For each combination of $V_p\in[20,120]\,\mathrm{km/s}$, $P\in[150,200]\,\mathrm{s}$ and $\phi\in[0,2\pi]$, $L_p(M,R)$ is calcualted.
- Locating L_p^{min} in the parametric space, and selecting a set of 1% above minimum, We are able to get the mean values and their uncertainies.

BSM method and its application

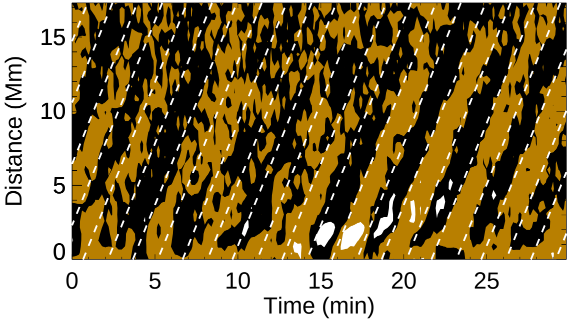

Figure: BSM application to R_1, $P = 180.0 \pm 1.8\,\mathrm{s}, V_p = 47.0 \pm 2.6\,\mathrm{km/s}$.

BSM method and its application to regularised image

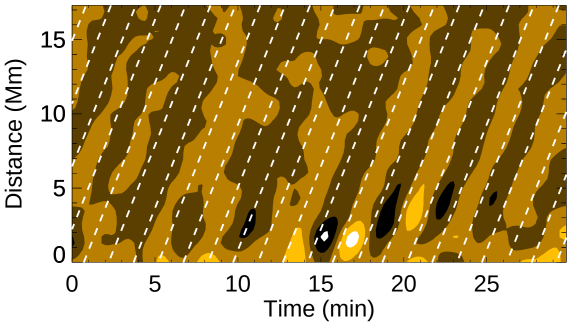

Figure: BSM application to R_1^σ, $P = 180.0 \pm 1.0\,\mathrm{s}, V_p = 48.0 \pm 1.3\,\mathrm{km/s}$.

Comparison of the measurements

Table: A comparison of the measured results of CFT, DCF and BSM methods

		CFT	DCF	BSM
R_1	P (s)	181.2 ± 0.1	240.7 ± 0.7	180.0 ± 1.8
	V_p (km/s)	47.0 ± 0.1	48.8 ± 0.2	47.0 ± 2.6
R_2	P (s)	179.7 ± 0.2	177.2 ± 0.9	178.0 ± 2.0
	V_p km/s	48.1 ± 0.3	65.8 ± 0.3	49.0 ± 4.5
R_1^σ	P (s)	...	...	180.0 ± 1.0
	V_p km/s	...	...	48.0 ± 1.3
R_2^σ	P (s)	...	...	180.0 ± 1.0
	V_p (km/s)	...	...	50.0 ± 2.6
D_1	P (s)	180.0 ± 0.1	198.9 ± 0.7	180.0 ± 1.0
	V_p (km/s)	45.8 ± 0.2	44.5 ± 0.2	47.0 ± 1.4
D_2	P (s)	180.0 ± 0.2	250.5 ± 2.2	178.0 ± 1.0
	V_p km/s	48.6 ± 0.4	51.4 ± 0.5	49.0 ± 2.8
D_1^σ	P (s)	...	...	180.0 ± 1.0
	V_p km/s	...	...	48.0 ± 1.3
D_2^σ	P (s)	...	...	180.0 ± 0.9
	V_p (km/s)	...	...	50.0 ± 2.3

Comparison of the measurement

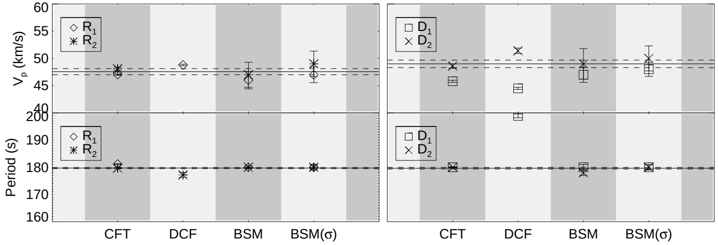

Figure: A Comparison of the measurement CFT, DCF, BSM and its application to regularised images BSM(σ).

Comparison of the measurement

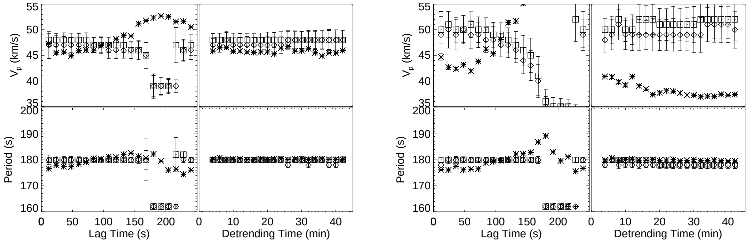

Figure: The meaurement of R_1 and D_1 as functions of lag time and detrending time respectively (left panels), and those of R_2 and D_2 (right panels). The measurements of CFT, BSM and BSM (σ) are plotted with $\ast$, $\diamond$ and $\square$ respectively.

Conclusion

- CFT, DCF and BSM are valid and robust methods to meaurement the phase speed of propagating disturbances.
- CFT, DCF and BSM are in general more robust in measuring background removed samples than running differences.
- Samples with longer valid detection lengh are more suitable for the above methods. They sustain more variability of lag time and detrending time.