Analysis of Pseudo-Lyapunov Exponents of Solar Convection Using State-of-the-Art Observations

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Abstract

The solar photosphere and the outer layer of the Sun's interior are characterized by convective motions, which display a chaotic and turbulent character. In order to further investigate those motions, we estimated the pseudo-Lyapunov exponents of the overshooting convection described by current state-of-the-art observations of the Sun's surface. In particular, we applied a method employed in the literature to estimate the pseudo-Lyapunov exponents, as well as another technique deduced from their definition, to the spectro-polarimetric data acquired with the ground-based Interferometric Bidimensional Spectrometer (IBIS) and Crisp Imaging SpectroPolarimeter (CRISP) instruments, and the space-borne Helioseismic and Magnetic Imager (HMI). Following previous studies in the literature, we computed maps of four quantities which were representative of the physical properties of solar plasma in each observation, and estimated the pseudo-Lyapunov exponents from the residuals between the values of the quantities computed at any point in the map and the mean of values over the whole map. We found that all the computed exponents hold negative values, which are typical of a dissipative regime, in contrast to previous results reported in the literature. We also found that the values of the estimated exponents increase with the spatial resolution of the data and are almost unaffected by small concentrations of magnetic field.

Theoretical background

The thermal convection is a non-equilibrium process which displays a chaotic and turbulent regime. The solar convection could be characterized by using the Lyapunov exponent Λ, which describe the dynamical or dissipative state of a physical system. The divergence between two initial slightly different initial states x and $x + \epsilon$ after n iteration is given by: $\epsilon(n) \sim \epsilon e^{\Lambda n}$. If Λ > 0 the system is chaotic; alternatively, if Λ < 0 the system is dissipative. There are few works on the Λ exponent of the solar convection in the literature: numerical MHD simulation (Steffen et al. 1995) and Lyapunov-like exponents evaluation (Hanslmeier et al. 1994).

Data sets and methods

- Multi-dataset analysis using by IBIS/DST, CRISP/SST and HMI/SDO
- Random sampling of the pixels to avoid the contamination of coherent spatial features
- λ exponents evaluation from δI_c, δv_c, δF, δA fluctuations

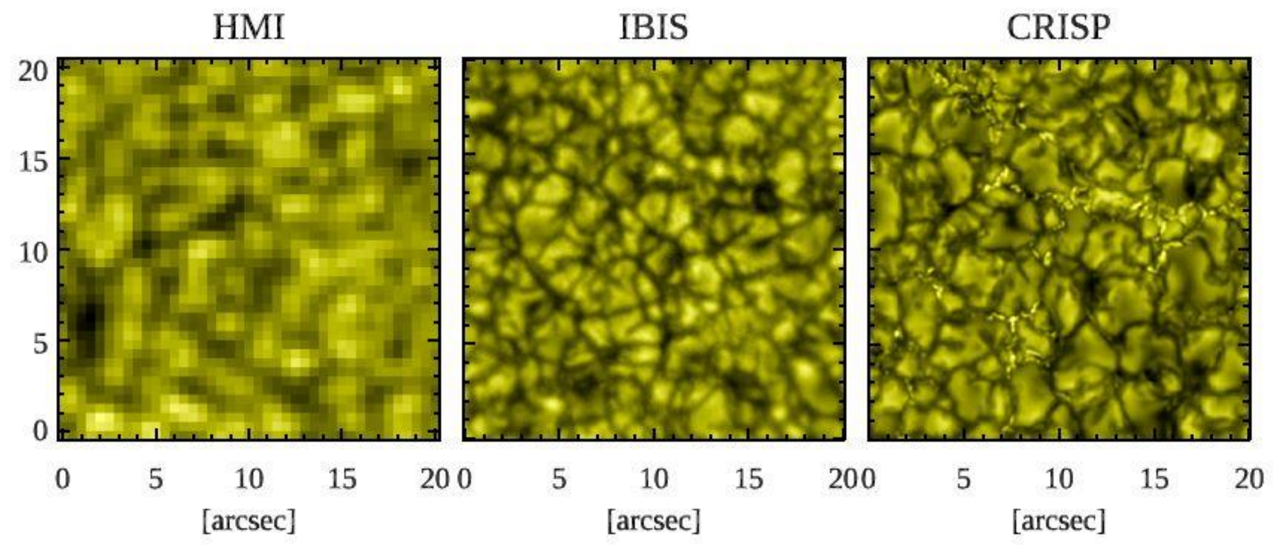

Figure 1: zoomed regions relevant to the 20''x20'' areas indicated at the center of each panel of Figure 2.

Table 1: ground- and space-based data sets used for the analysis.

Telescope	Instrument	Spectral Coverage	Time Coverage	Time Cadence	Spatial Resolution
DST	IBIS	Fe I 617.3 nm	1 May 2015 14:18–15:03 UT	48 s	0.16″
SST	CRISP	Fe I 630.15 nm	25 May 2017 09:30–09:40 UT	-	0.13″
SDO	HMI	Fe I 617.3 nm	1 May 2015 14:24 UT 25 May 2017 09:36 UT	-	1″

Results with time evolution estimation

Further estimation based on a more accurate definition of the Λ exponents, which accounts for the time evolution of the quantities analysed at each image pixel

- Confirmation of the negative values from all considered quantities
- Clear trend towards smaller values when increasing the time elapsed between the compared observations

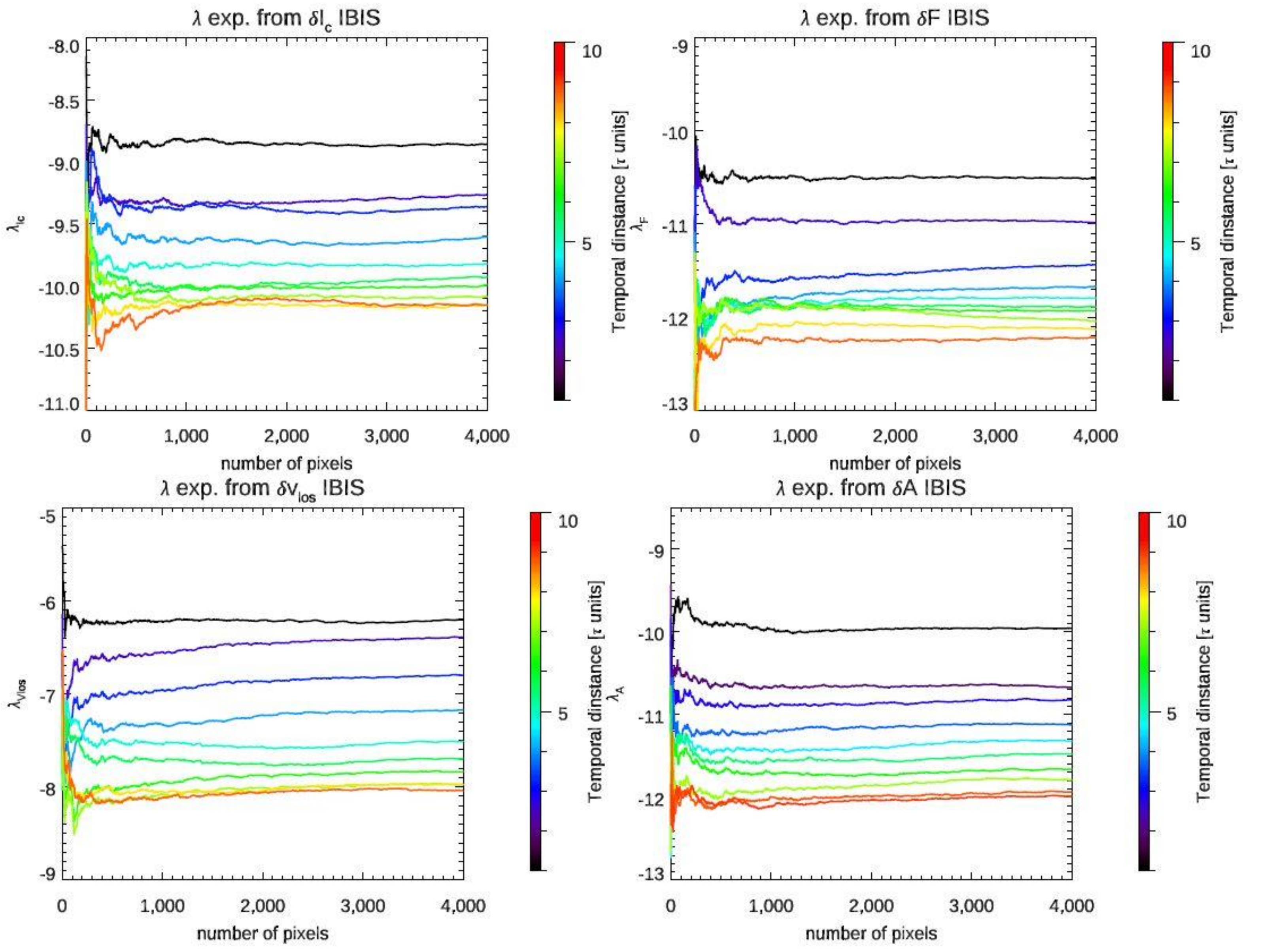

Figure 3: λ exponents evaluated from δI_c, δv_c, δF, δA residuals between maps derived from observations taken at different times.

Conclusions

- We found negative values (dissipative regime)
- Strong dependence on spatial resolution
- Mostly unaffected by weak magnetic fields concentrations
- Further new estimates based on more accurate definition of λ exponents

Results of Pseudo-Lyapunov exponents estimation

- Negative values (dissipative regime) from all parameters in contrast to previous results in the literature
- Strong dependence on spatial resolution (less dissipative regime at small spatial scales)
- Less noisy behaviour at the smallest spatial scales and more stable convergence wrt previous results in the literature

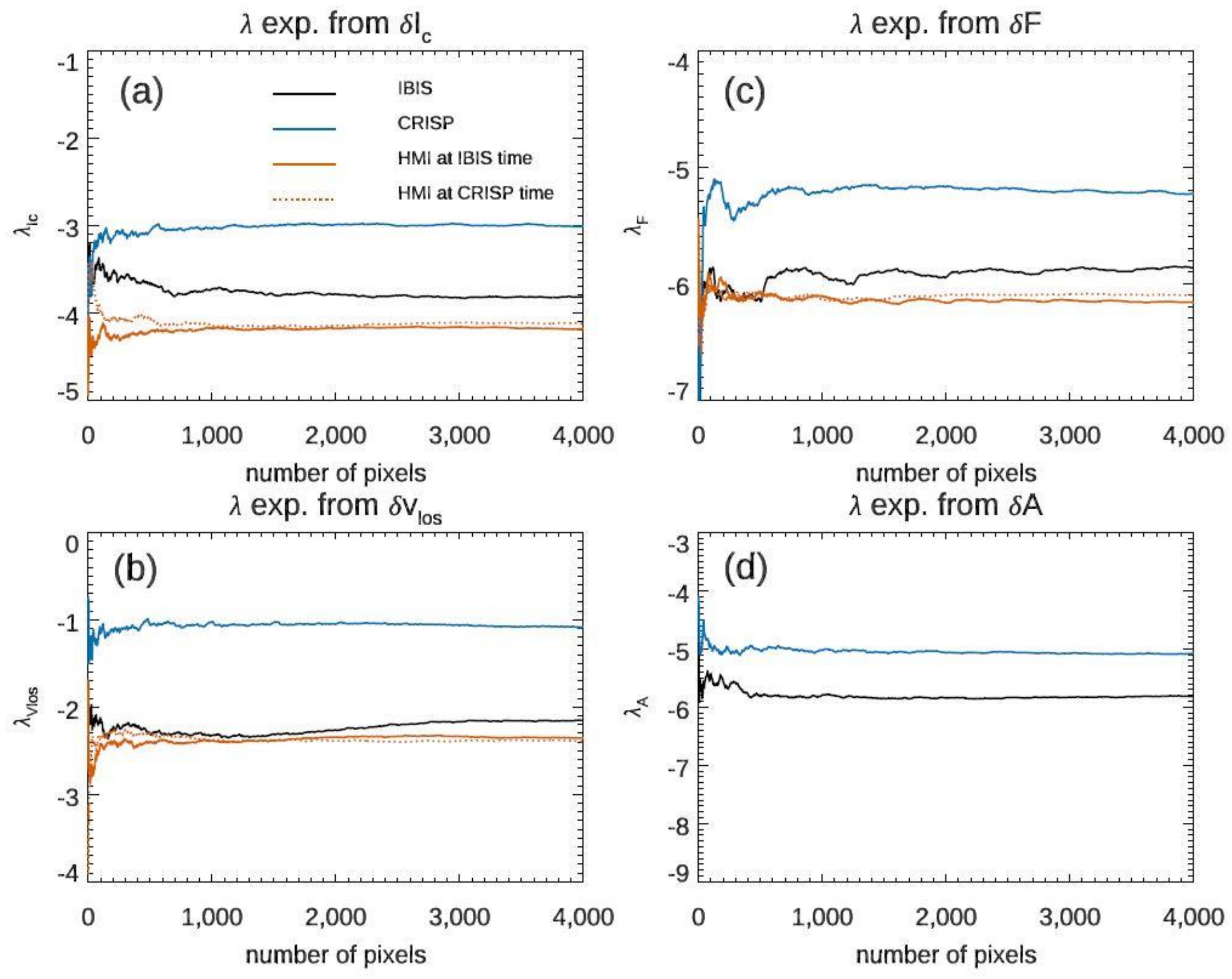

Figure 2: λ exponents evaluated from δI_c, δv_c, δF, δA fluctuations for IBIS, CRISP and HMI data sets.

Further analysis

Analysis of the dependence on spatial degradation with gaussian filtering

- Confirmed dependence of λ exponents on spatial resolution

Analysis of the effects of weak magnetic fields (magnetic and quiet sub-FoVs selected using CP circular polarization maps)

- λ exponents mostly unaffected by weak magnetic fields

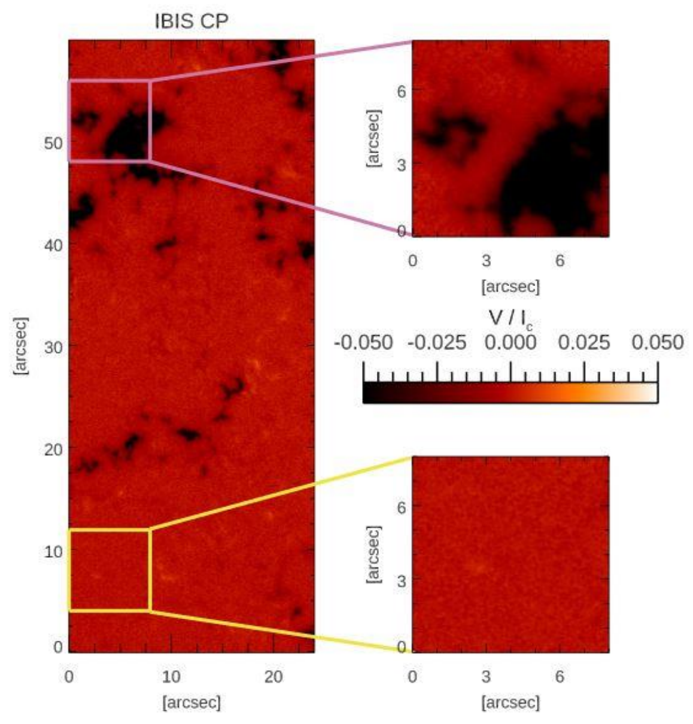

Figure 4: CP map of IBIS data set and selected magnetic and quiet sub-FoVs.

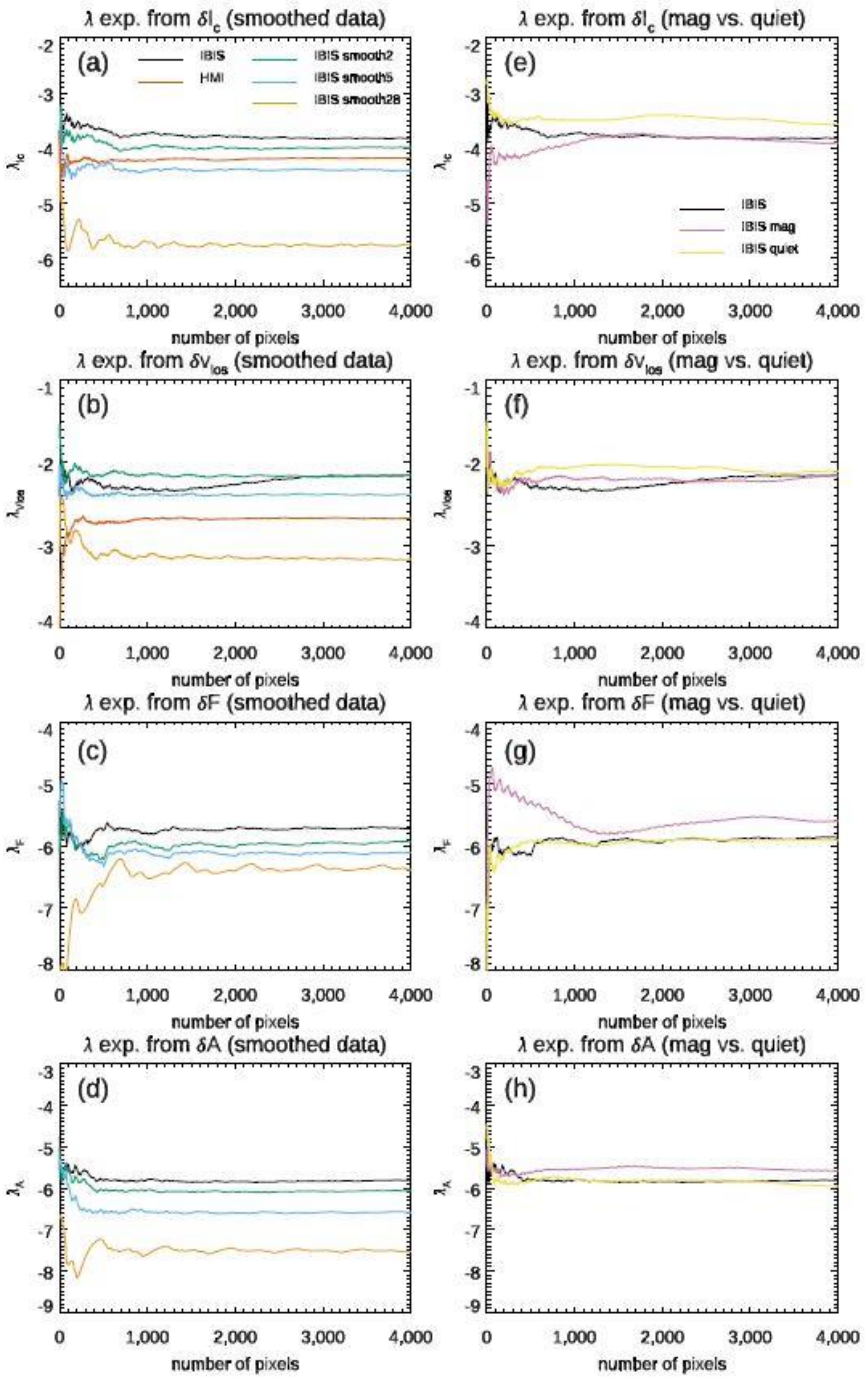

Figure 5: λ exponents evaluated from δI_c, δv_c, δF, δA fluctuations for IBIS smoothed data (left column) and in magnetic and quiet sub-FoVs.

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