Denoising Helioseismic Far-Side Images with Spatial and Temporal filters

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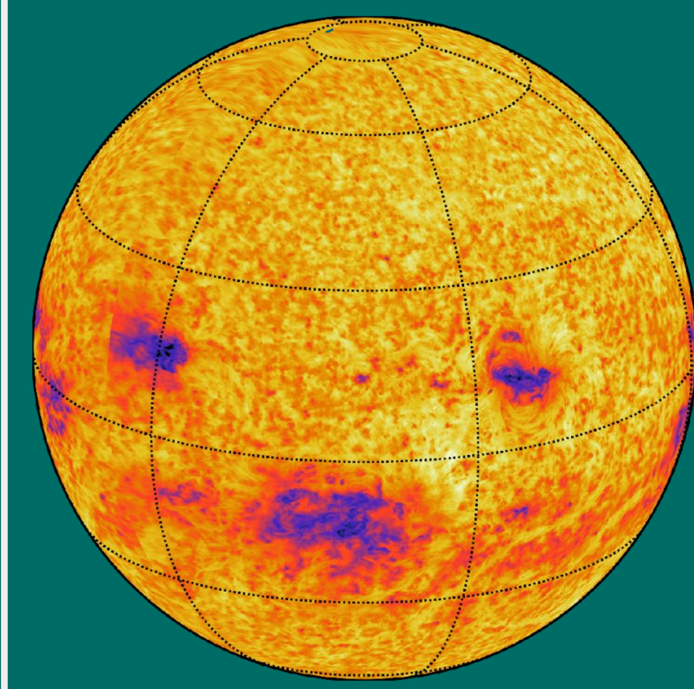
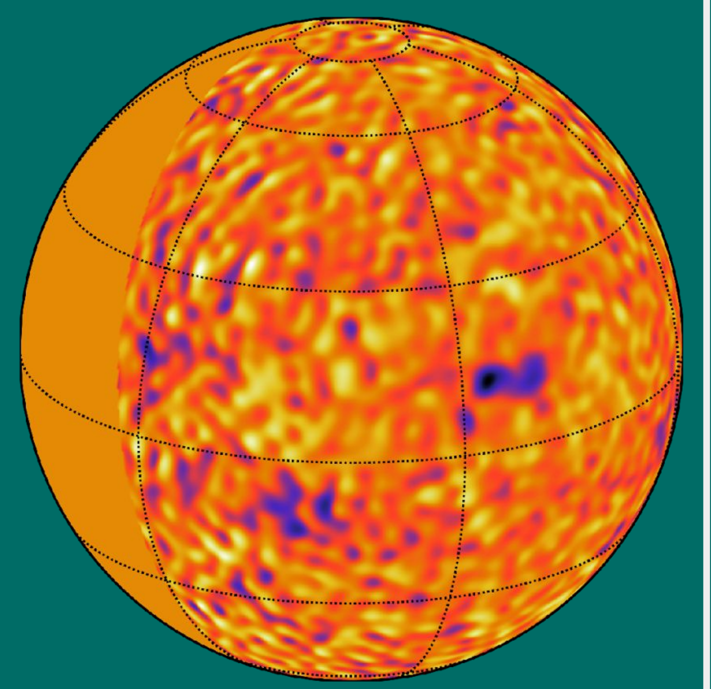
A. Rawat (rawat@mps.mpg.de)[1], D. Yang[1] & L. Gizon[1,2]

MAX PLANCK INSTITUTE FOR SOLAR SYSTEM RESEARCH

- Helioseismology can detect active regions on the Sun's far-side days before they rotate to the Earth's side, using solar acoustic oscillations.
- Recent advances in theoretical and computational helioseismology have improved far-side imaging, which enables **high-confidence detection** and daily tracking of **medium-size** active regions.



STEREO/EUVI far-side map

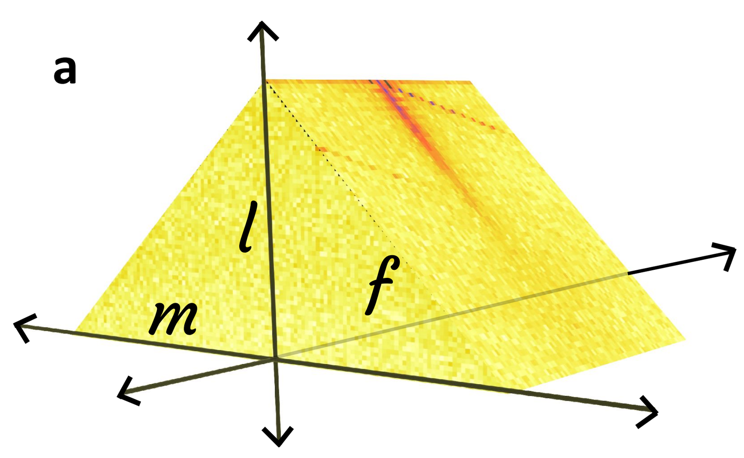


Helioseismic far-side image + near-side window

- These far-side images, however, suffer from **substantial noise.** This noise is primarily due to the stochastic nature of these solar oscillations.
- Application of **low pass filters** to the seismic phase in **spectral space** can reduce unwanted noise and quiet-Sun signatures, thereby improving the detectability of the active region signals.

Characterizing Far-Side Images in Spectral Space

1. 109-day segments from a 10-year time series of far-side images of the 24th solar cycle, mapped in the Carrington frame, were transformed into the spectral domain with a frequency resolution of 0.1μHz. To analyze spatial characteristics, spherical harmonics were used to decompose variations into **degrees (*l*) and orders (*m*)**. Finally, the power spectrum was calculated.
2. A fit for lower spherical harmonic degrees (*l*=0,1,2) was removed. These degrees represent the background having high spectral leakage into high-degree modes.
3. Each segment data cube with the three parameters was averaged over 2 years of data from active and quiet periods.
4. These were then averaged over the 3 parameters to study power distribution across different scales and frequencies. This helps to get rough estimates of *l*, *m*, and υ.



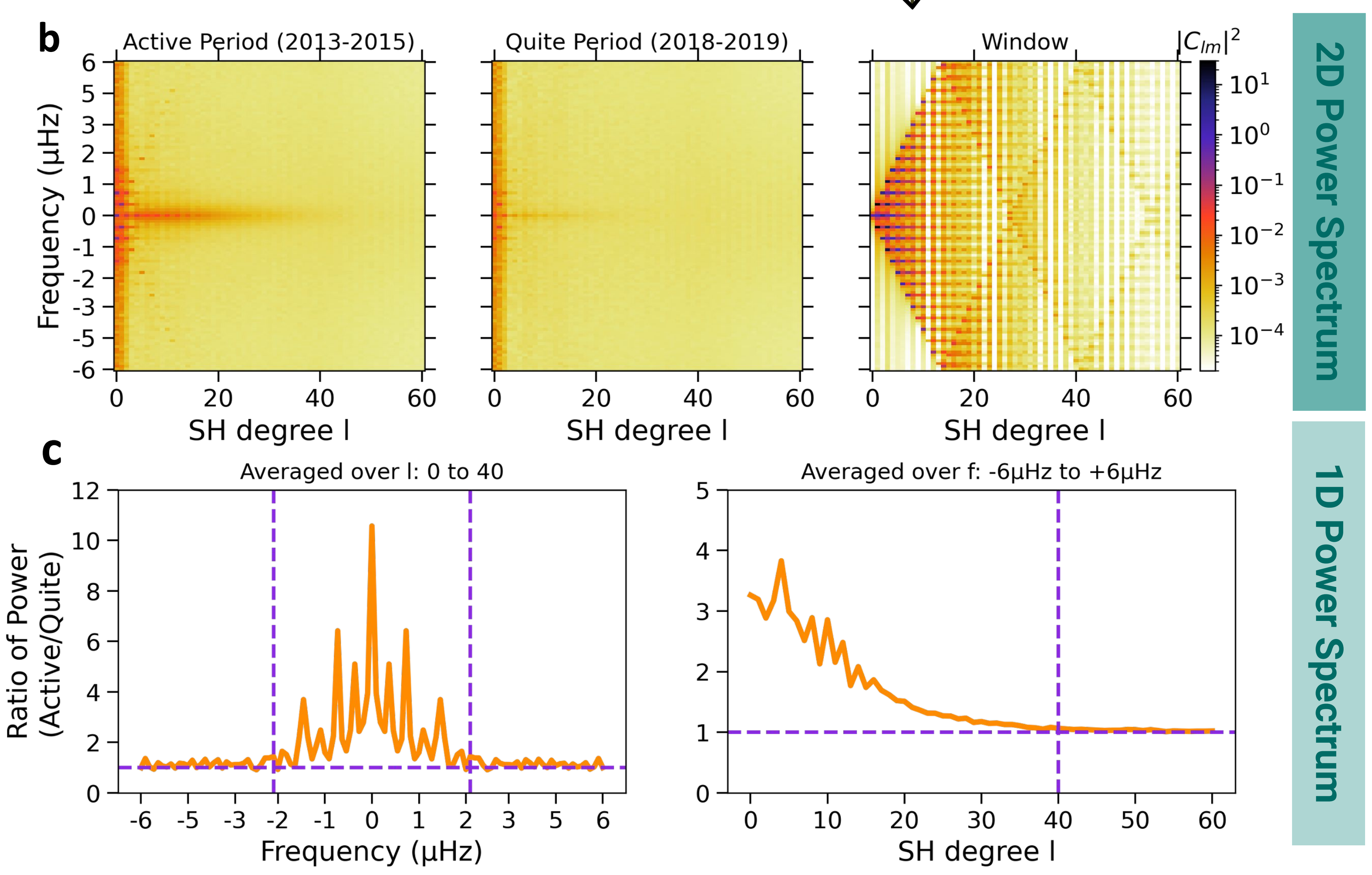


Fig 1: a) Illustrative 3D power spectrum b) 2D power spectrum averaged over all m's for active, quiet and near-side window c) Power distribution over a signal parameter only. Indigo lines show filter limits for separating signals from noise.

Spectral filter in υ & *l*

A preliminary filtering process was applied in υ and *l*. The limits for this filtering were determined based on the analysis presented in Fig 1c i.e.

- *l* > 40
- υ > 2.286 μHz

in spatial and frequency domains respectively. This effectively removes surface features smaller than **100 megameters (Mm)** and temporal evolution scales faster than **5 days**.

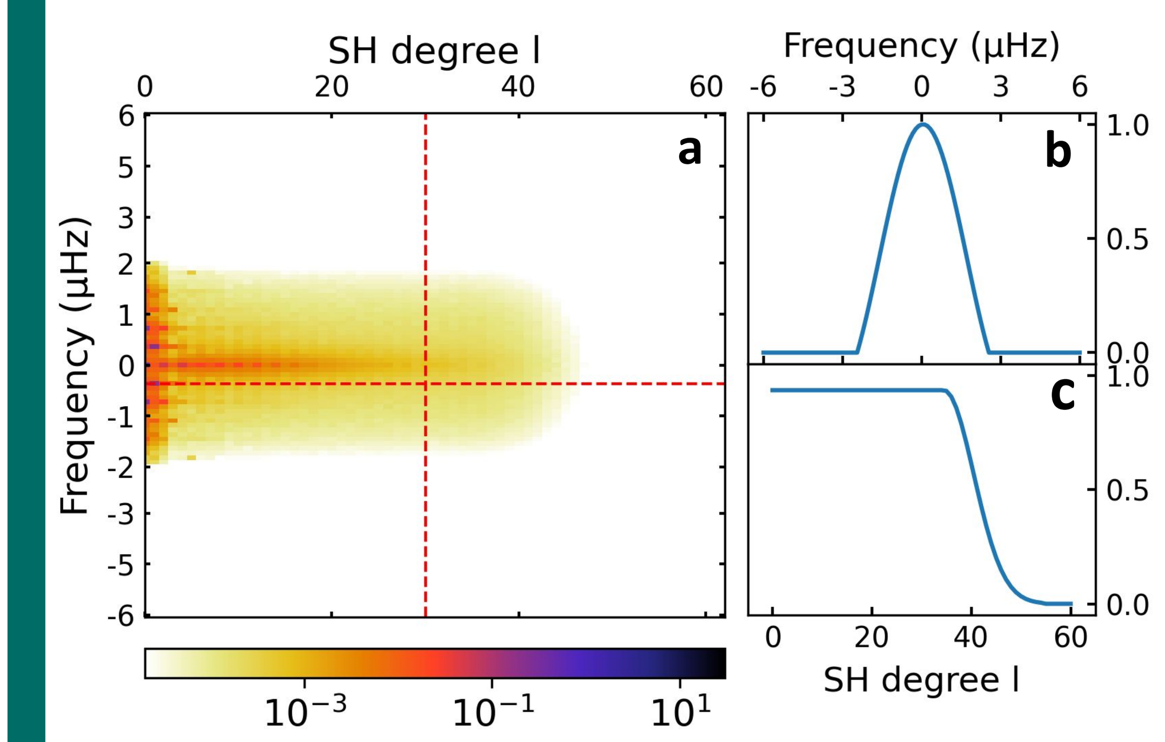


Fig 2: a) Filtered power spectrum for Fig 1d active period b) Lanczos filter in frequency υ c) Gaussian filter in spherical harmonic degree *l*.

Detection Statistics

The **ROC curve** is used to assess the filter's effectiveness. The diagonal line represents the performance of a random classifier. The more the curve bends from the diagonal, the better the filter performs. Even with preliminary filtering, there is an **improvement in the detection** of active regions. The true positive rate not reaching 1 may be due to an overestimation in the algorithm for detecting smaller active regions in HMI magnetograms which needs to be taken care of in the future.

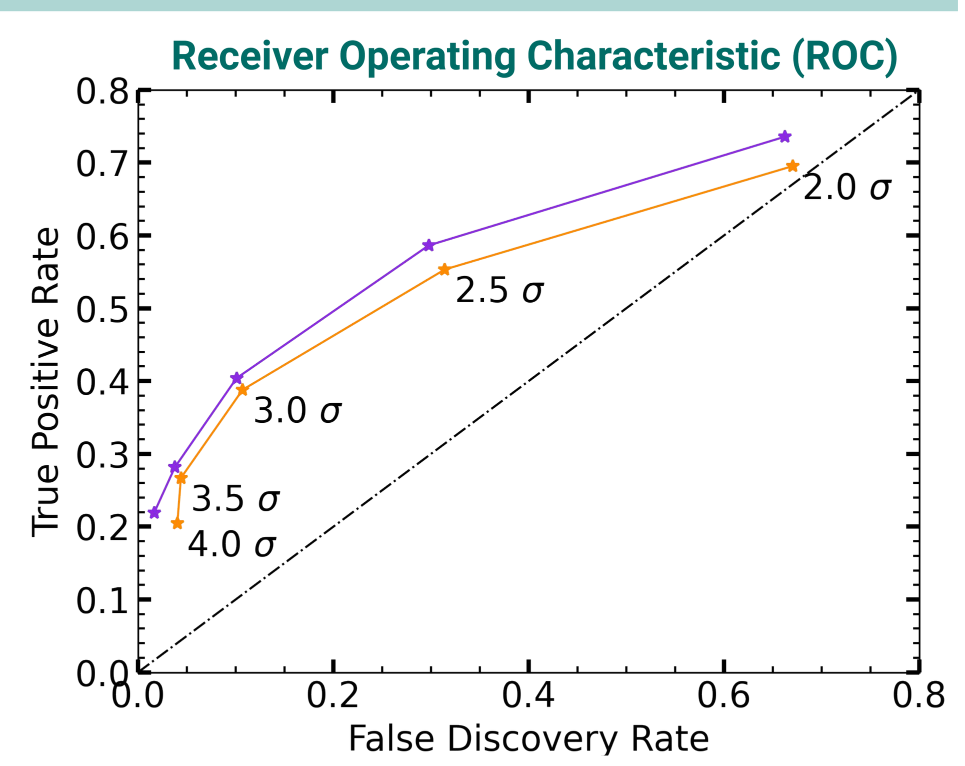


Fig 3: The ROC curves for two filters. The orange curve represents the current best filter, which utilizes a 3-day moving average in time and Gaussian smoothing in space. The indigo curve corresponds to the current filter.

Outlook: Directional Dependence

The third parameter, **spherical harmonic order *m***, can also play a crucial role in eliminating artifacts from the data. To do this, excess power is certain m's, if present, would be investigated. This could also give insight into the hypothesized **active longitudes** of the Sun. Therefore, by carefully selecting and applying filters based on the power distribution of *m*, we can effectively remove more unwanted noise.

The denoised dataset will provide over 10 years of data on active region (AR) evolution, serving as a valuable resource for their analysis.

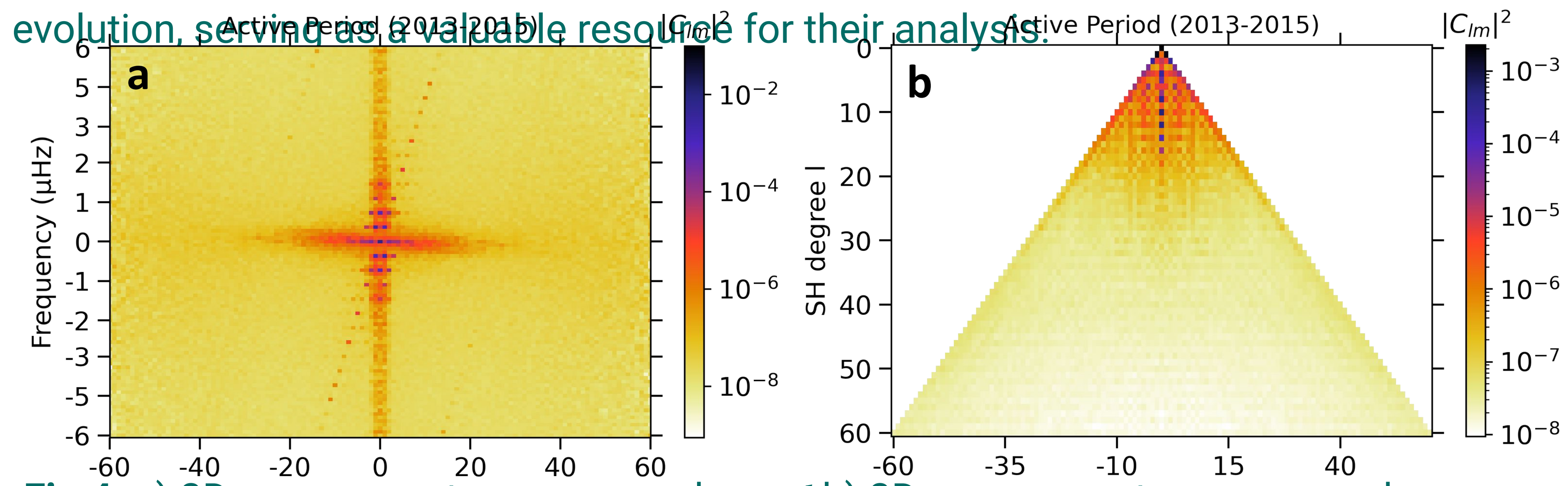


Fig 4: a) 2D power spectrum averaged over *l* b) 2D power spectrum averaged over υ

Affiliations

[1] Max-Planck-Institut für Sonnensystemforschung, 37077 Göttingen, Germany

[2] Institut für Astrophysik und Geophysik, Georg-August-Universität Göttingen, 37077 Göttingen, Germany

References

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