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A novel technique for magnetic flux emergence diagnostics on the Sun

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1. Introduction

- Helioseismology allows us to analyse solar surface via oscillations of surface gravity waves: fundamental mode (*f*-mode).
- ***f*-mode is diagnostic for plasma flows and turbulent magnetic field structures** generated from magnetic flux advected from solar interior.[1,2]
- Previous studies found potential ***f*-mode enhancements a few days prior to t_0,** the time of flux emergence [3,4]
- At times **$t > t_0$, *f*-mode is quenched** (as previously theorised).
- However these methods suffer from selection biases and key dependencies in background and heliocentric angle which affect the *f*-mode signal.
- Here, we **create a novel method that eliminates the background dependence and normalises observations of interest using a time-dependent flat-field (FF).**

2. Flat-field (FF) algorithm

- Use data products generated from *mtrack** applied to full-disk line-of-sight maps from Heliospheric Magnetic Imager (HMI) dopplergrams, using cylindrical plate carrée projection[5]
- **Korpi-Lagg+ 2022 pipeline[6]**, for full *mtrack* computation**,** calculates k-ν maps for each 4-hr observation with resolution 0.05°, with solar lon/lat range $\boldsymbol{\lambda}_\odot$, $\boldsymbol{\psi}_\odot$ = ±82.5 °, ±75 ° producing full-disk 21x19 grid with 15° patches.
- **Algorithm can be summarised as follows:**

1) **Point selection and patch tracking:**

- Use k-nearest neighbours (KNN) computation to find closest 4 k-ν maps to any ($\boldsymbol{\lambda}_\odot$, $\boldsymbol{\psi}_\odot$) point.
- Use $\boldsymbol{\lambda}_\odot$ and Snoddgrass and Ulrich (1990) empirical model to calculate solar rotation per 4-hr (i.e., track point for each observation)

2) **FF calculation:**

- Average over all k-ν maps at ($\boldsymbol{\lambda}_\odot$, $\boldsymbol{\psi}_\odot$) which follow the quiet Sun criterion[6] $B_{\mathrm{RMS}} \leq 20$ G
- Quiet maps are also subjected to thresholding on average wave power criterion to account for instrumental background (see Figure 1).
- Split into 4-hr intervals to remove 24-hr periodicity.

3) **Calculation of *f*-mode power:**

- Use a patch to locate sensible *f*-mode region from dispersion relation (see Figure 2).
- Normalise each observation at time *t* with associated FF, FF(*t*).
- Average over patch to find normalised f-mode power, or $\mathcal{F}_r$.

*http://hmi.stanford.edu/teams/rings/modules/mtrack/v25.html

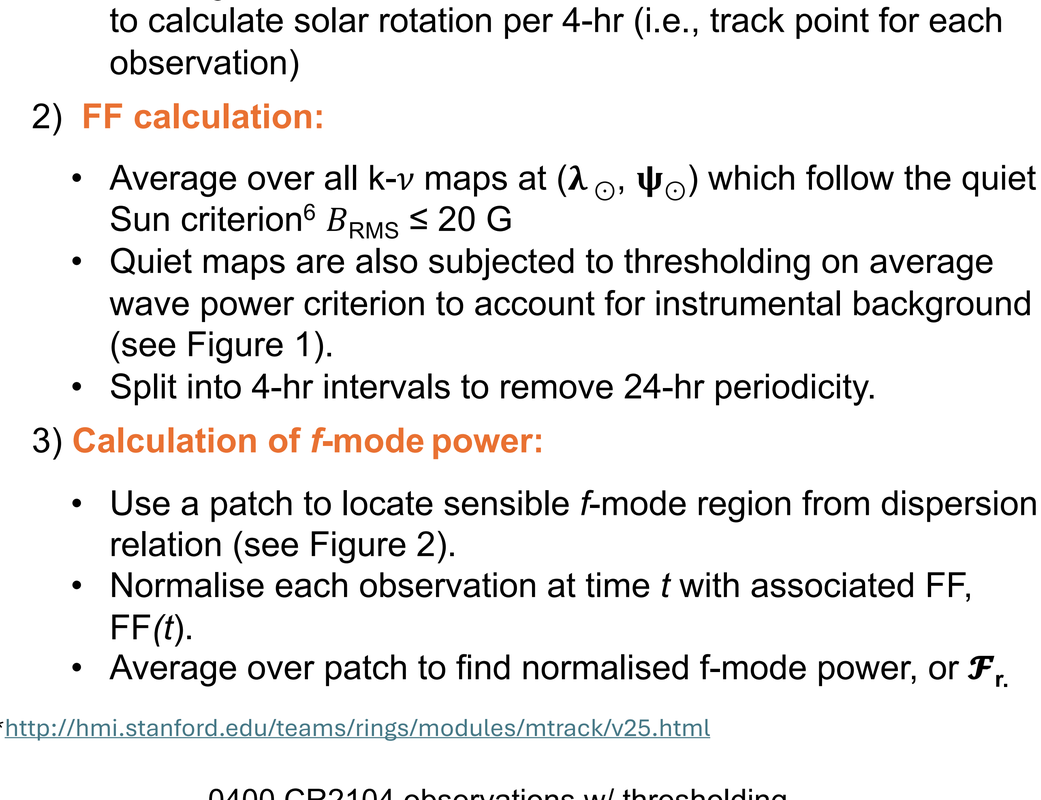
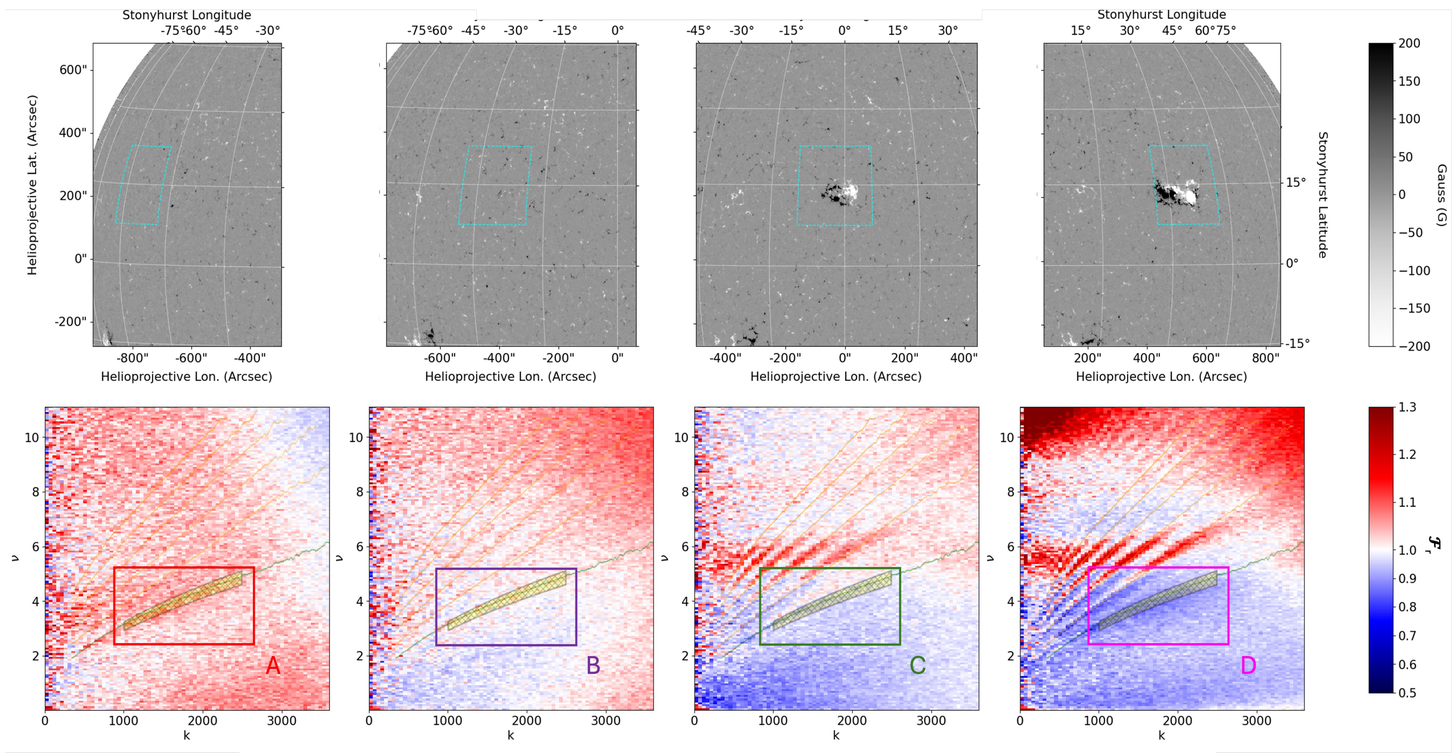


Figure 1: Labelled example of k-ν FF map, using 0400 observations which follow threshold (over 28 day interval). Colour bar = power at each HMI pixel.



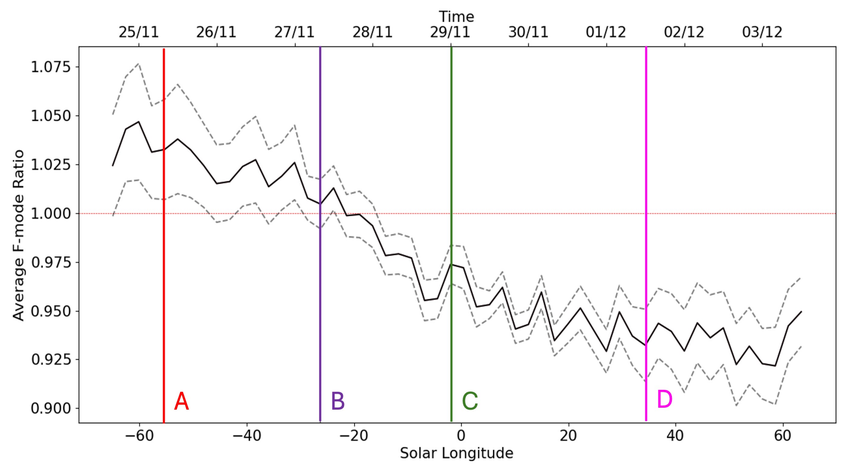


Figure 2: Plot showing four HMI images of the patch (cyan) tracking AR11130 across the disk. A = beginning, t < t_0; B = t_0 **this study;** C = National Oceanic and Atmospheric Administration (NOAA) t_0 and D = t > t_0 during observation interval with k−ν diagram at each location using the FF method and the time evolution of $\mathcal{F}_r$ (colour bar) with RMS error.

3. Interpretation of $\mathcal{F}_r$

- **$\mathcal{F}_r > 1$:** enhancement of *f*-mode – caused by cavity size decreasing as flux approaches surface.
- **$\mathcal{F}_r < 1$:** quenching of *f*-mode – caused by strong surface fields (large scale and turbulent) making region more rigid, inhibiting oscillations
- **$\mathcal{F}_r \sim 1$:** unchanged behaviour from average, typical for undisturbed quiet Sun.

4. FF method key conclusions

- **FF method results compatible with theory[1,2] (see Figure 2 example).**
- **Choice of t_0 critical for interpreting *f*-mode behaviour** – previous studies likely observed intervals of 'higher quenching' opposed to true enhancements.
- **Categorise behaviours using $\mathcal{F}_r$ (see Figure 3):**

(1) Quiet Sun (**QS** or **$\mathcal{F}_r \sim 1$**);
(2) Populated region (**PR**; flux already emerged, or **$\mathcal{F}_r < 1$**);
(3) Emerging active regions (**QS/PR** – behaviour shown in Figure 2);
(4) Exceptional regions (**ER;** regions that exhibit behaviours outside these regimes, e.g., coronal holes: CHs)

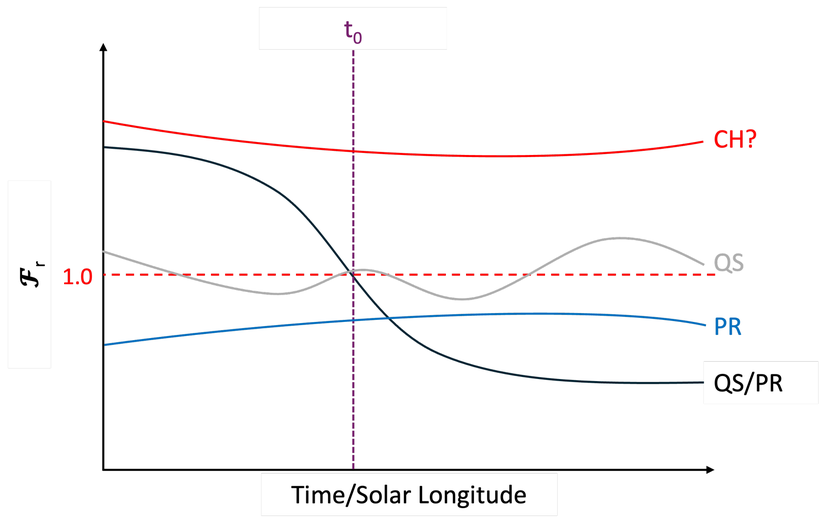


Figure 3: Schematic for general behaviours categorised by FF method. Labels can be utilised for machine learning/prediction purposes?

5. Next Steps

- Find a method and suitable parameter to utilise this for machine learning and prediction capabilities (Figure 3), and accurate diagnostics of time evolution.
- Compare with numerical modelling of magnetic flux advected to surface.
- **Paper in advanced preparation – publication soon!**

References:
[1] Duvall+ 1998, ApJ 505, L55, DOI: DOI 10.1086/311595; [2]Felipe+ 2012 *ApJ* 757 148 DOI: 10.1088/0004-637X/757/2/148; [3]Singh+ 2016 *ApJ* 832 120 DOI:10.3847/0004-637X/832/2/120; [4]Waidele+ 2023 Sol. Phys. 298 30 DOI: 10.1007/s11207-023-02124-7; [5]Thompson 2006 A&A 449, 791-803 DOI: 10.1051/0004-6361:20054262; [6]Korpi-Lagg+ 2022 A&A 665, A141 DOI: 10.1051/0004-6361/202243979