What Can We Learn about the Solar Subsurface Large Scale Flows from Accurate High-Degree Modes Frequencies?

Helas VI — SOHO 28 — SPACEINN
Göttingen, GE

S.G. Korzennik

Harvard-Smithsonian Center for Astrophysics, USA.

September 2014

Contributors: A. Eff-Darwich (ULL, IAC)
T. Larson (Stanford)
M.C. Rabello-Soares (UFMG)
J. Schou (MPS)
Introduction

- High degrees “problem”:
  - modes blend into ridges ($\ell > 200$, for p-modes, $\ell > 300$ for f-modes),
  - ridge characteristics ($\nu, A, \Gamma, \alpha$) are not the mode characteristics.

- Methodology
  - Fit ridges ($100 \leq \ell \leq 1000$),
  - Use multi-taper estimator (to reduce realization noise).
  - Apply a ridge to mode correction, based on best possible model of mode blending - dominated by the effective leakage matrix.
  - Iterate on model input parameters to best match observations.
  - Use the $100 \leq \ell \leq 300$ overlap for validation.
Coverage in the \((\ell, \nu)\) Plane

- Red dots: low and intermediate degrees: fitting resolved modes.
- Black circles: high degrees modes: ridge fitting.
### Data Sets Analyzed

<table>
<thead>
<tr>
<th></th>
<th>2001 90 day long</th>
<th>2002 98 day long</th>
<th>2010 67 day long</th>
</tr>
</thead>
<tbody>
<tr>
<td>MDI</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>GONG</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HMI</td>
<td></td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

- All epochs correspond to MDI *Dynamics* epochs.
- Can extend the time series for HMI & GONG.
Comparison with Resolved Modes

<table>
<thead>
<tr>
<th>Year</th>
<th>Instrument</th>
<th>$\Delta \nu$ [(\mu\text{Hz})]</th>
<th>$\Delta \nu/\sigma_\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2001</td>
<td>MDI</td>
<td>$-0.220 \pm 0.673$</td>
<td>$-0.880 \pm 2.182$</td>
</tr>
<tr>
<td>2002</td>
<td>MDI</td>
<td>$-0.298 \pm 0.966$</td>
<td>$-0.862 \pm 2.631$</td>
</tr>
<tr>
<td></td>
<td>GONG</td>
<td>$0.176 \pm 0.769$</td>
<td>$0.517 \pm 2.416$</td>
</tr>
<tr>
<td>2010</td>
<td>MDI</td>
<td>$-0.088 \pm 1.087$</td>
<td>$-0.077 \pm 2.766$</td>
</tr>
<tr>
<td></td>
<td>GONG</td>
<td>$0.748 \pm 1.186$</td>
<td>$2.751 \pm 2.411$</td>
</tr>
<tr>
<td></td>
<td>HMI</td>
<td>$0.269 \pm 0.616$</td>
<td>$0.880 \pm 2.044$</td>
</tr>
</tbody>
</table>

- Mean and standard deviation of
  - frequency differences, and
  - frequency differences normalized by their uncertainties,
  between estimated mode frequencies derived from ridge fitting and coeval resolved mode frequencies measurements,
- for the $100 \leq \ell \leq 200|300$ overlapping range.
Circles: frequency differences; dots: ridge to mode correction

Differences are small, clustered near zero, with no discernible trends, and much smaller than the correction itself.

The largest scatter is seen for the f-mode below $\ell = 250$ or so.
Similar plot for MDI, GONG and HMI 2010.
GONG comparison shows a larger bias ($2.8\sigma$)
Scatter for the f-mode remains large even above $\ell = 250$.
Is this the result of using a shorter time series? (67 versus 90 or 98 days).
Comparison at High Degree between Data Sets

<table>
<thead>
<tr>
<th>Year</th>
<th>Instruments</th>
<th>$\Delta \nu$ [(\mu)Hz]</th>
<th>$\Delta \nu / \sigma_\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>GONG – MDI</td>
<td>$-0.222 \pm 0.460$</td>
<td>$-1.317 \pm 1.470$</td>
</tr>
<tr>
<td>2010</td>
<td>GONG – MDI</td>
<td>$-0.982 \pm 0.934$</td>
<td>$-4.260 \pm 2.770$</td>
</tr>
<tr>
<td></td>
<td>HMI – MDI</td>
<td>$-0.655 \pm 1.117$</td>
<td>$-2.162 \pm 1.572$</td>
</tr>
</tbody>
</table>

- Mean and standard deviation of
  - frequency differences, and
  - frequency differences normalized by their uncertainties,
- between estimated mode frequencies derived from ridge fitting for different instruments and coeval epochs, with respect to MDI values.
Comparison of $\nu$, $\Gamma$, & $\alpha$, 2002
By contrast with the 2002 data, the frequency comparison shows a variation with degree, and some dependence on frequency.
Comparison of Clebsch–Gordan Coefficients

- Color dots: coefficients derived from ridge fitting.
- Black crosses: coefficients derived from coeval resolved mode fitting.

⇒ Large offset between ridge and mode estimate, and between instruments.
Comparison at High Degree between Data Sets

- Color circles: coefficients derived from mode estimates, after correcting ridge fitting results.
- Black crosses: coefficients derived from coeval resolved mode fitting.

⇒ Despite *horns*, both the offset high degree and mode estimate, and between instruments has vanished - no *ad hoc* fudging.
Rotation Inversions

- Inversion model grid (semi uniform in radius and latitude),
- shown in cartesian coordinates.


S.G. Korzennik (CfA) What Can We Learn from High-Degree Modes? Sep 2014 13 / 21
Averaging Kernels

- Kernels for inversions using or not high degree modes (left vs right)

- Target location: black cross-diamond symbols,
- Kernel center of gravity and width: green crosses and circles.
- Inversion grid: black dots.
Averaging Kernels (Cont’d)

- Top 10%

S.G. Korzennik ( CfA )  What Can We Learn from High-Degree Modes?  Sep 2014
Ratio of $\Gamma_{ak}$ and differences $\Lambda$, for rotation inversions using or not high degree modes.

$$\Gamma_{ak} = \int K_a^2(r, \phi)D^2(r, \phi)drd\phi / \int K_a^2(r, \phi)drd\phi$$

$$\Lambda^2 = (r_t - r_c)^2 + ((\phi_t - \phi_c)/(\pi/2))^2$$

where $D^2 = (r - r_c)^2 + ((\phi - \phi_c)/(\pi/2))^2$, and $(r_c, \phi_c)$ is an estimate of the center of gravity of the averaging kernel main peak; and $(r_t, \phi_t)$ is the inversion target location on the solution grid.
Rotation Rate in the Outer 10% of the Solar Interior

- after subtracting a differential rotation profile, inferred using or not high degree modes (right and left panels).

**Note**

- (a) the “torsonial oscillations” signal stands out more clearly when including high degrees, and
- (b) the profiles are quite different in the top 5%, esp. at high latitudes.
Medium-$\ell$ Only
High- and Medium-$\ell$
Conclusions

- Can use ridge values to estimate mode parameter.
- Discrepancies remain, likely due to short time series, error in PSF, ...
- GONG, MDI & HMI overlap can be leveraged to resolve this.
- Inclusion of high degree splittings affects solution in the top 10%, and alters the solution in the top 5%.
- Should produce and use high-degree mode estimates on a regular basis.

Tables are available at
https://www.cfa.harvard.edu/~sylvain/research/
under
https://www.cfa.harvard.edu/~sylvain/research/tables/HiL/