Understanding and Modeling the Effects of Observational Gaps on Solar P-mode Oscillations

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Outline

- Helioseismology and P-mode oscillations
- GONG network and the GONG pipeline
- Creation of data set
- Correction of Mode parameters
- Application of corrections to solar cycles 23 and 24
- Investigation of Correlation values for parameters
Helioseismology

- Uses waves that propagate through the Sun to determine features of the interior of the Sun
- Millions of waves at any given moment
- Waves travel to different depths
  - Can probe different depths of the Sun with different waves
- Different types of waves
  - P - modes
  - G - modes
  - F - modes

http://soi.stanford.edu/press/agu05-98/background.html
What are p-mode oscillations?

- Sun acts as a resonant cavity for sound waves
- Observed through Doppler shift
- Waves can be described by Spherical Harmonics and quantum numbers
  - $\ell$ = angular degree - # of wavelengths along circumference
  - $n$ = radial order - # of vertical wavelengths along radius of sphere
  - $m$ = azimuthal order - # of nodal lines that intersect the equator
    - $-\ell < m < \ell$
- We are looking at low and mid angular degree
  - $\ell$ = 0-3 = low degree
  - $\ell$ = 4-150 = mid degree

https://gong.nso.edu/info/helioseismology.html
https://nisp.nso.edu/solar_interior_contd
How do we observe the oscillations?

- **Ground Observation**
- **GONG (Global Oscillation Network Group)**
  - 6 stations across the world placed to get the highest possible coverage of observations
  - Goal is to get observations 100% of time
  - Failure to do so lies with weather, instrument failure, etc.
  - Usual coverage lies around 75-85% duty cycle (observation percentage)

How do we know if the data we are getting is accurate if we do not observe all the time?
Initial Analysis of Oscillations

- Time series are gathered
  - GONG separates data into 36 day periods (GONG Months)
  - Overlapping 3 GM time series by one month
- Fourier Transform is applied to time series to acquire Power Series
- Amplitudes, Frequencies, and widths are then fitted to this power series
  - Standard GONG pipeline
  - Symmetric Lorentzian Profiles fit to power series
Why is this all important?

- Important to understand how we need to correct the mode parameters
- Frequency is related to rotation of solar interior and oblateness of the Sun
- Amplitude and width are related to Energy and Energy Rate of Oscillations
- Describes structure of Solar Interior
What are we doing?

- Took 3 month set with about 93% duty - Reference Set
  - GONG month 138 - Solar minimum activity → 10/1/08 - 1/16/09
- Inserted observation gaps in the data from 30 other GMs to modify the duty cycle
  - 108 sets of 3 month periods of the same data with random gaps inserted
- Now the goal is to understand how these gaps affect the original data (frequency, amplitude and line width)
  - For all low - mid degree modes ($\ell = 0 - 150$)
Frequency

- Frequency range between 1500 - 4500 μHz
- Linear relationship between duty cycle and frequency
- All quantities are calculated with the reference times series (3 GONG Month series centered on GONG Month 138))
- First plotted single modes to see what the correction would look like
- Then extended to all modes (about 2200 modes)
Wanted to be able to correct our values using our slopes

- Plotted 100 - Duty against Frequency diff (y intercept would be value at 100% duty cycle)
- Fitted a best fit line for each mode by forcing the intercept of the line to be 0.
- Now had a list of slopes for each mode
- Slopes were very small - did not expect much change in frequency with duty cycle.
Mode Amplitude

- Now wanted to extend what we did for frequency to amplitude
- For a given mode, amplitudes vary by a much larger amount than for frequency
  - Did not make sense to do a difference with reference GM - normalization makes more sense
  - Large range of values for amplitude for a single mode over many GONG months
- Found best fit line for each mode for amplitude
  - Plotted amplitude against 100 - Duty cycle
  - Forced intercept to be 1 - At 100% duty cycle the normalized amplitude should be 1
- Much larger slopes than those found for frequency
  - Expect to see much more dependence on duty cycle
  - Majority of slopes were negative - Amp increases with duty cycle
Line Width

- **Repeat of Mode Amplitude**
  - Normalization of width with reference GONG month.
  - Same fitting method - fixed intercept at 1

- **Majority of slopes were positive**
  - Width decreases with increasing duty cycle

\[ n = 10, \ell = 55 \]
Extending to all GONG Months

- Now had slopes for each mode parameter
- Goal to correct all GONG months with slopes found for each mode parameter
- $\nu_{n,l} = -m_{n,l}(100 - D) + \nu_{n,l}$
- $\Gamma_{n,l} = -m_{n,l}(100 - D) + \Gamma_{n,l}$
- $A_{n,l} = -m_{n,l}(100 - D) + A_{n,l}$
  - $\Gamma$ and $A$ must be normalized first
- Equations return values normalized with old reference
  - Reference GM is also corrected through this method
- Multiply normalized values by old reference, and then renormalize by new reference
- Take mean over all modes for each GONG month
Corrected Frequency

\[ \rho_c = 0.893 \]
\[ \rho_u = 0.886 \]
Corrected Amplitude

**Corrected Values**

**Uncorrected values**

\[
\rho_c = -0.676 \\
\rho_u = -0.615
\]
$\rho_c = 0.746$
$\rho_u = 0.576$
Corrected Energy and Energy Rate

\[ \rho_c = -0.5125 \]

\[ \rho_c = 0.3004 \]
Comparison of Correlation Values
## Comparison of Correlation cont.

<table>
<thead>
<tr>
<th>ν Range [μHz]</th>
<th># of Modes</th>
<th>ν ρ</th>
<th>ν p value</th>
<th>A ρ</th>
<th>A p value</th>
<th>Γ ρ</th>
<th>Γ p value</th>
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</thead>
<tbody>
<tr>
<td>1500 - 2000</td>
<td>286</td>
<td>0.32</td>
<td>&lt; 10⁻¹⁰</td>
<td>-0.56</td>
<td>&lt; 10⁻¹⁰</td>
<td>0.42</td>
<td>&lt; 10⁻¹⁰</td>
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<td>2000 - 2500</td>
<td>319</td>
<td>0.58</td>
<td>&lt; 10⁻¹⁰</td>
<td>-0.68</td>
<td>&lt; 10⁻¹⁰</td>
<td>0.54</td>
<td>&lt; 10⁻¹⁰</td>
</tr>
<tr>
<td>2500 - 3000</td>
<td>314</td>
<td>0.60</td>
<td>&lt; 10⁻¹⁰</td>
<td>-0.91</td>
<td>&lt; 10⁻¹⁰</td>
<td>0.76</td>
<td>&lt; 10⁻¹⁰</td>
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<tr>
<td>3000 - 3500</td>
<td>329</td>
<td>0.74</td>
<td>&lt; 10⁻¹⁰</td>
<td>-0.92</td>
<td>&lt; 10⁻¹⁰</td>
<td>0.85</td>
<td>&lt; 10⁻¹⁰</td>
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<tr>
<td>3500 - 4000</td>
<td>345</td>
<td>0.85</td>
<td>&lt; 10⁻¹⁰</td>
<td>-0.28</td>
<td>1.6 x 10⁻⁵</td>
<td>0.64</td>
<td>&lt; 10⁻¹⁰</td>
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<tr>
<td>4000 - 4500</td>
<td>309</td>
<td>0.55</td>
<td>&lt; 10⁻¹⁰</td>
<td>0.33</td>
<td>3.7 x 10⁻⁷</td>
<td>-0.13</td>
<td>0.06</td>
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<td>1500 - 3500</td>
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<td>0.72</td>
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<td>-0.86</td>
<td>&lt; 10⁻¹⁰</td>
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<td>1500 - 4500</td>
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<td>0.89</td>
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<td>-0.68</td>
<td>&lt; 10⁻¹⁰</td>
<td>0.74</td>
<td>&lt; 10⁻¹⁰</td>
</tr>
</tbody>
</table>
Summary

- Oscillation Frequencies independent of duty cycle
- Amplitude and line width have large dependence on duty cycle
  - Necessary to correct parameters after passing through standard GONG pipeline
  - Energy is much higher than observed
- Frequency has maximum correlation with $F_{10.7}$ radio flux in the 3500 - 4000 $\mu$Hz range
- Amplitude and line width both have maximum correlation in the 3000 - 3500 $\mu$Hz range
Possible Future Work

- Why is Frequency correlation higher in a range we do not expect it to be?
- What is the big jump in the energy rate during solar cycle 23?
- Investigate difference between solar cycles 23 and 24 further
  - Correlation values for cycle 24 are higher than those for 23
Acknowledgements

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