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Horizontal to Vertical Displacement of Solar Oscillations

Jesper Schou

Max Planck Institute for

Solar System Research

schou@mps.mpg.de

tim larson

tplarson@sun.stanford.edu

Some Inconvenient Problems in Helioseismology

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- **Various systematic errors**
- **Surface effect - Model and observed frequencies disagree**
- **Mode visibilities are sometimes a bit off**
- **Observable (e.g. velocity and intensity) dependent center to limb effect**
- **The latter ones are related to what is known as mode physics**
  - Interactions between the modes and the convection near the surface play an important role!
- **Better theory and/or simulations needed**
  - Theory is extremely complicated
- **More direct observations**
  - Several attempts have been made to measure horizontal to vertical ratio
    - Schou+Bogart (1998), Rhodes+ (2001), Korzennik+ (2004), Woodard+ (2013), …
    - These indirect measurements have been difficult due to other physical effects and instrumental issues
  - So what to do?
    - Observe the same area from two directions – Directly gives two component of vector velocities
    - Key global helioseismology objective of PHI
  - Observing from two directions may also help with other issues

HMI vs. PHI

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- **Very similar instruments**
  - Same FeI 6173 line with roughly the same sampling of the line
  - PHI resolution is the same in arcsec for HRT, much less for FDT
  - Makes for almost identical observation heights and comparable data
- **8 hours of observations were taken on March 23, 2021**
  - Nominal 60 second cadence but a bit uneven
  - FDT continuum and 5 wavelengths in linear polarization all downlinked
  - First 20 taken off-tuned for calibration – 7.5 hours of useful data
- **Distance was 0.70AU**
  - Solar radius 386 pixels
  - Part of limb missing to accommodate long time series in available telemetry
- **PHI Carrington at disk center: (180.8°,+1.4°)**
- **HMI Carrington at disk center: (288.7°,-6.9°)**
- **Angle between spacecraft, as seen from the Sun, is about 108°**
  - So a substantial difference!
  - And a rather small overlap

Theory for H/V ratio – Plane Parallel

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- **What do we expect?**
- **Velocity from a simple wave is something like**
  - $\boldsymbol{V = Re\left(\xi(r)\exp(ikx - i\omega t + i\phi_0)\right)}$
  - V is total velocity, ξ is eigenfunction, r is radial position, k is horizonal wavenumber, x is horizontal position, ω is frequency, t is time, ϕ_0 is initial phase
- **If we look at a single point and assume a unit amplitude we get:**
  - Radial velocity $V_r=\cos(kx-\omega t+\phi_0)$
  - Horizontal velocity $V_h=c_t \sin(kx-\omega t+\phi_0+ \phi_h)$
  - ϕ_h is the phase relative to that from a simple theory. Ignored below.
  - $c_t=gk/\omega^2$ from an assumption of adiabatic and free surface
    - In principle c_t could have a different magnitude or be complex, but will only consider real here
  - $V_{obs} = A \cos(kx-\omega t+\phi_0+\phi')$
  - $\tan \phi' = c_t \cos \Delta\theta \tan \alpha$
    - Different for different observers, which is what will be exploited here.
    - Taking difference between different observers, ϕ_0 cancels out
  - α is observing angle from vertical and $\Delta\theta$ the horizontal angle between wave and observer
  - At the moment only ϕ' is used. Amplitude appears unusable due to PSF issues.

Deep Water Wave

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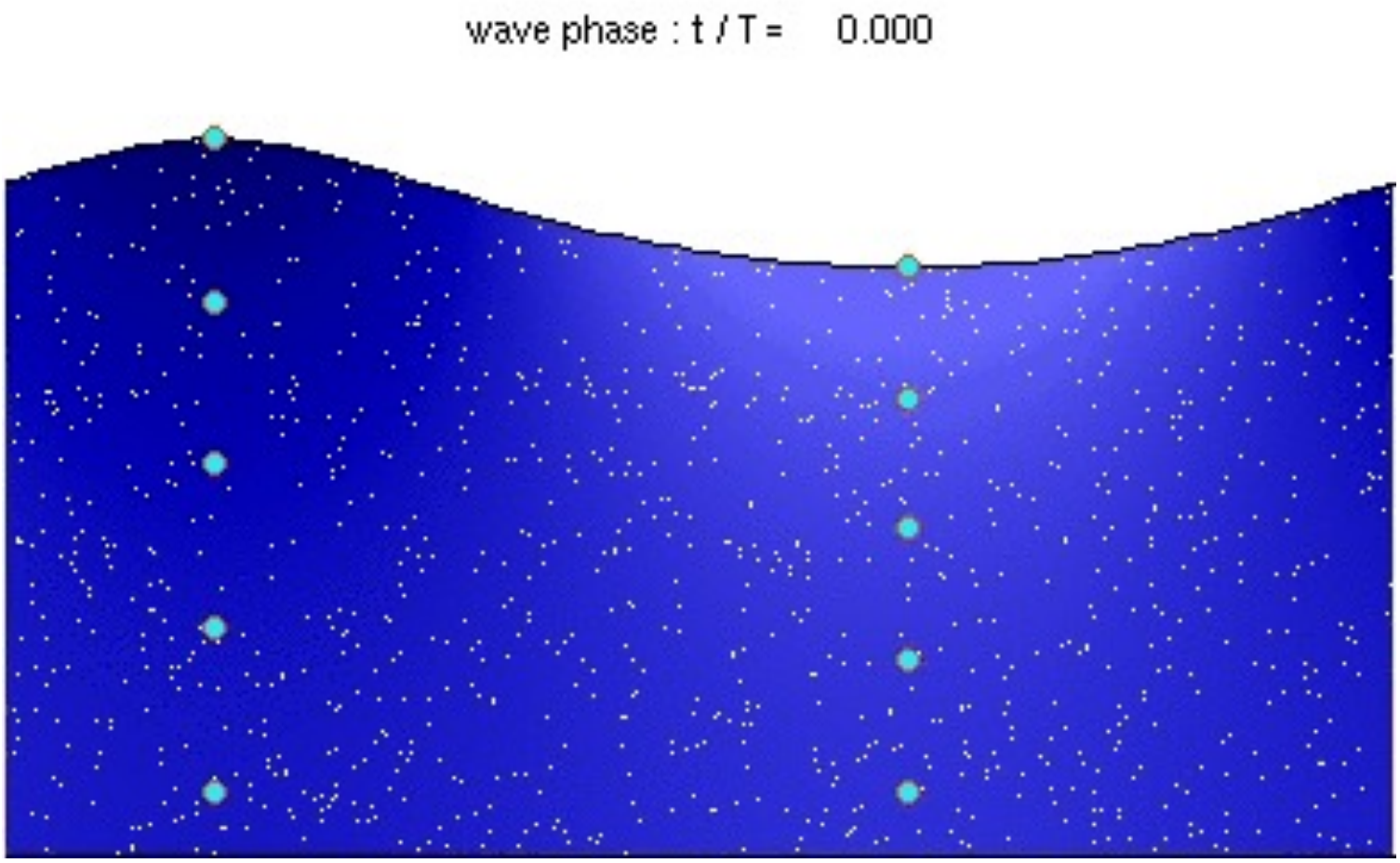
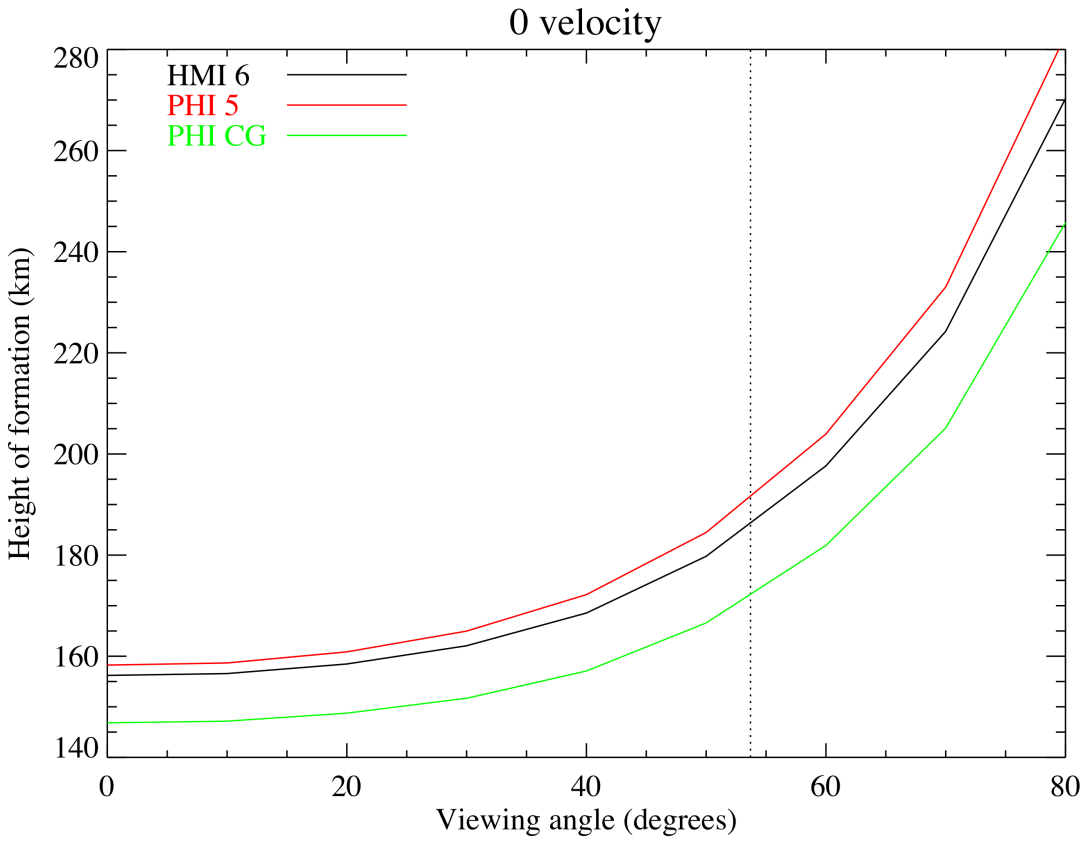


From Wikipedia

Data Analysis

- **Calculate Dopplergrams**
  - Use MDI-like algorithm on the 5 filtergrams across the line
  - Calibrate based on RT on MURaM cube
  - Undistort
- **Get image geometry from intensity filtergram**
  - Undistort and limb find to get center and radius. Correct center time.
  - Tweak P-angle (0.36°) based on what appears to fit
  - Correct Carrington longitude (for light travel time, as current keywords are wrong)
  - Ingest into DRMS at MPS
- **Track 15° PHI and HMI cubes with mtrack at various locations – with bug fixed**
  - Interpolate PHI times to HMI times taking into account light travel time difference
- **Circularly apodize, 3D FFT and remap to (k,θ,ω) (ring analysis)**
- **Compute cross spectrum, interpolate to ridges and from that the phase shift**
- **Fit phase to obtain c_t, orthogonal term and phase (time) error along ridges**
  - Unfortunately c_t and the orthogonal term are near degenerate with image offsets
    - Which leads to complications

Observing Height



Tracking Locations

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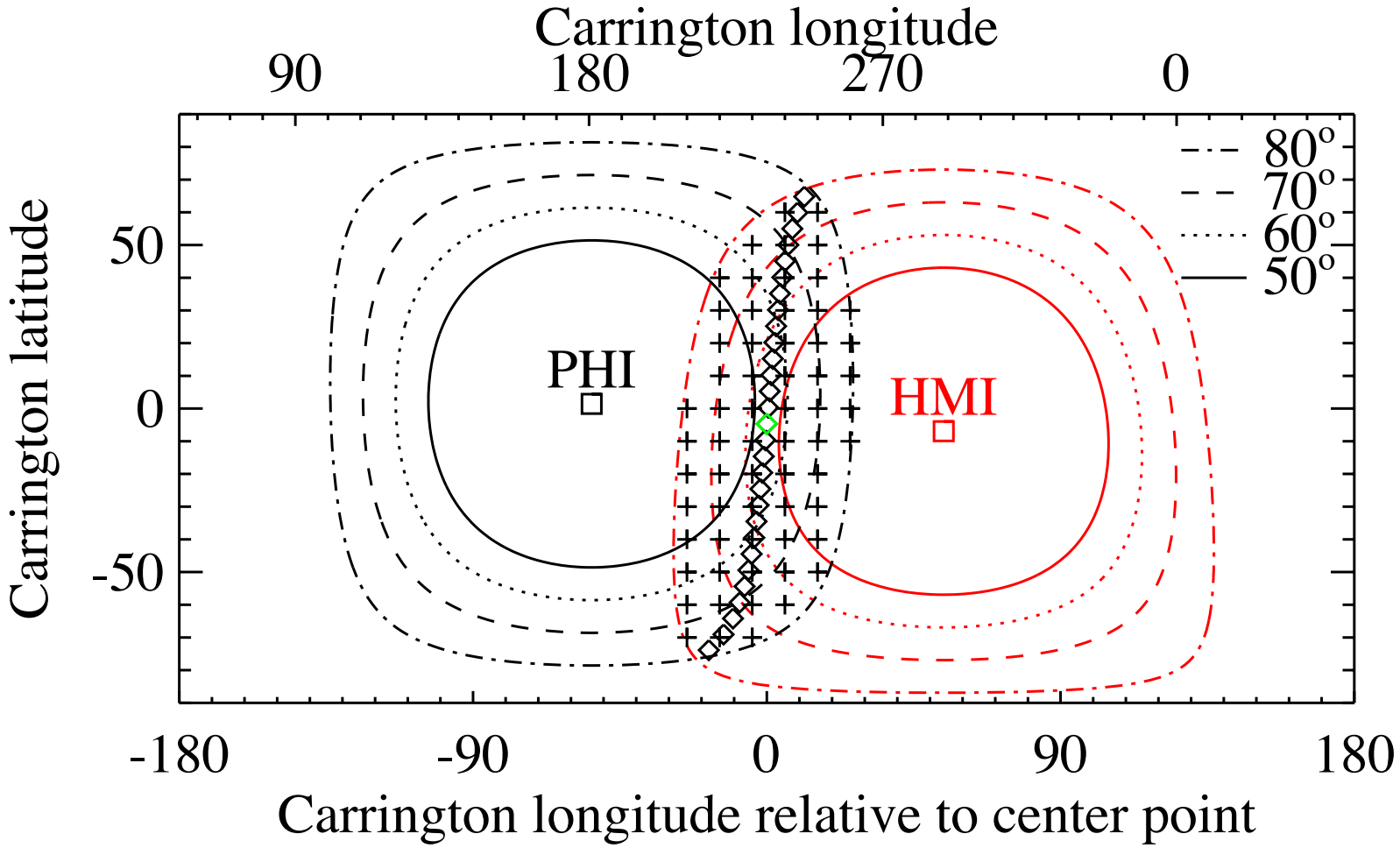
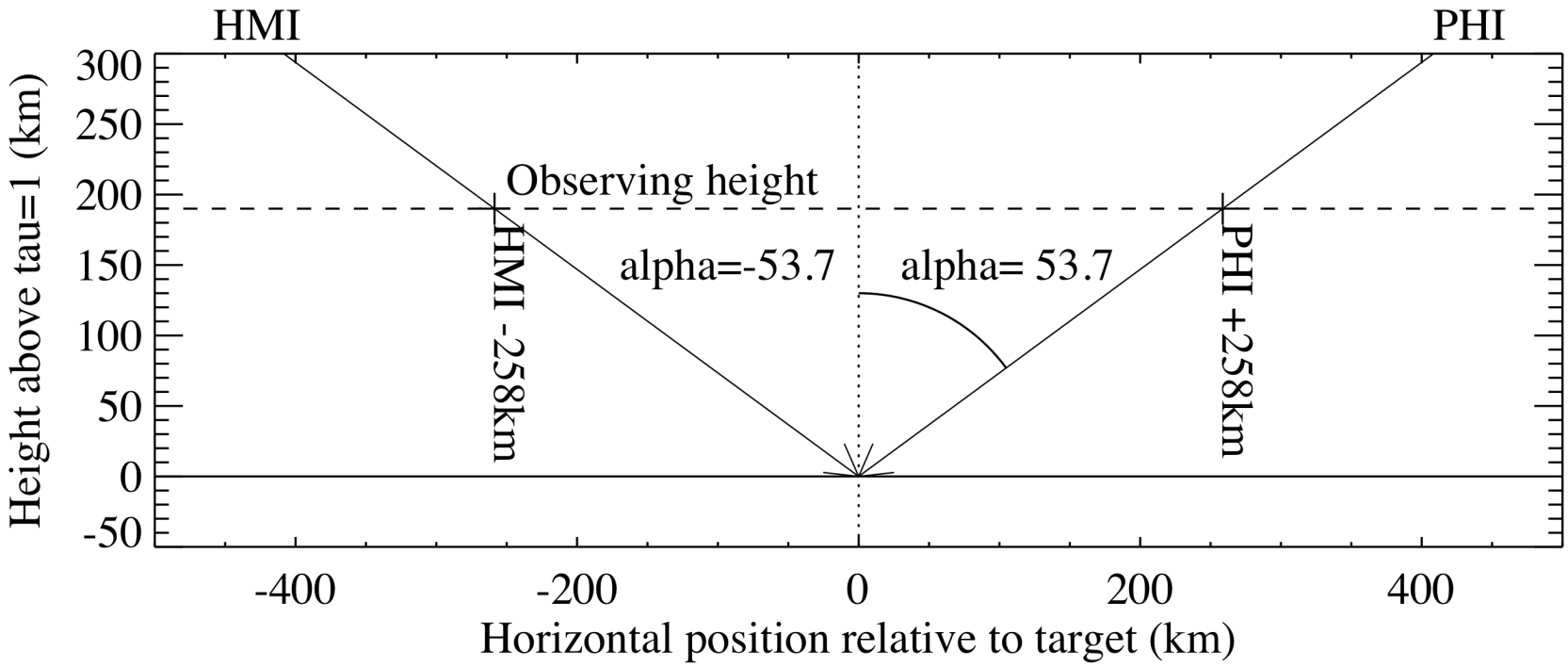


Viewing Geometry for Center Position



Measured Effect With Various Shifts

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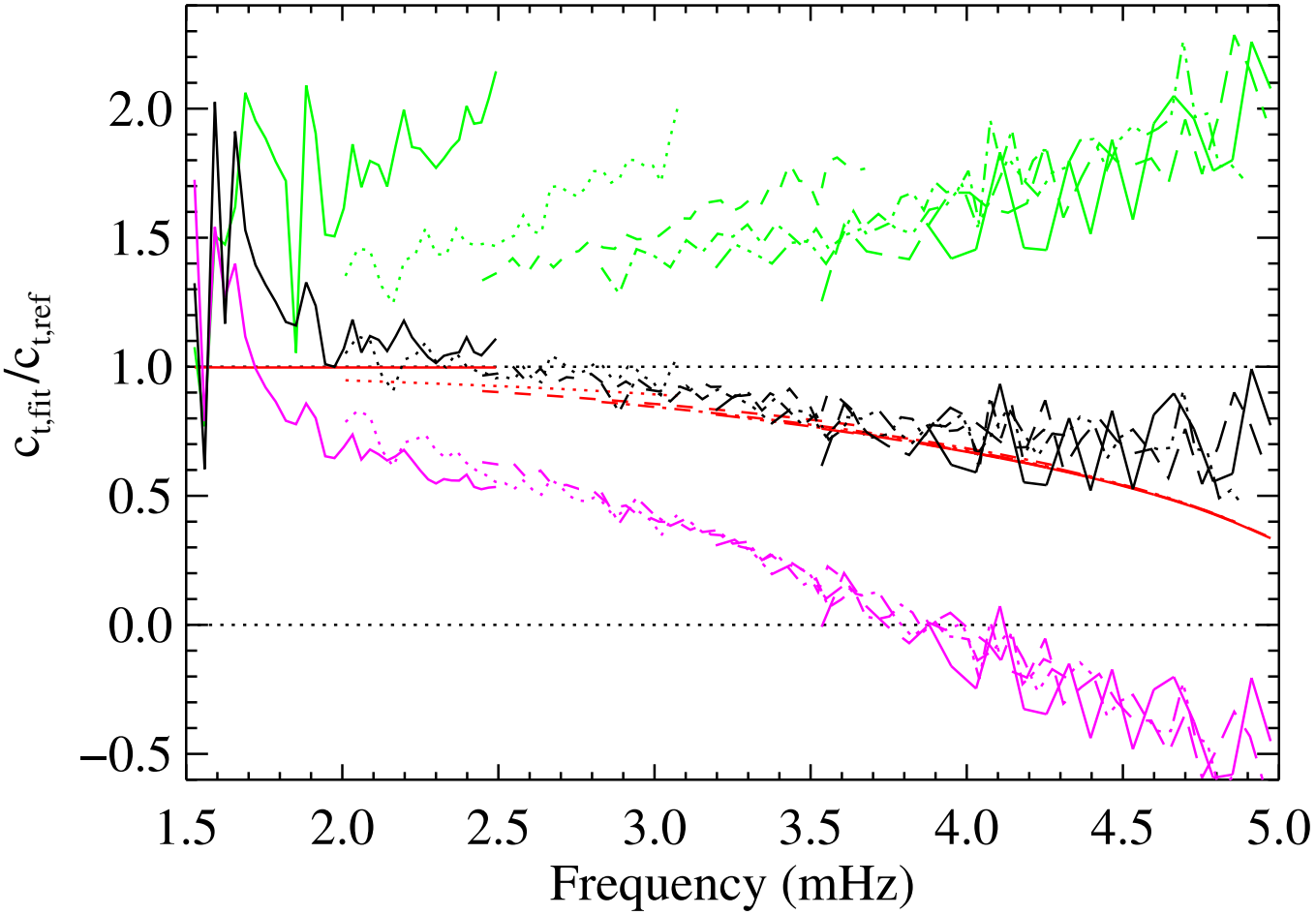

Various Viewing Angles

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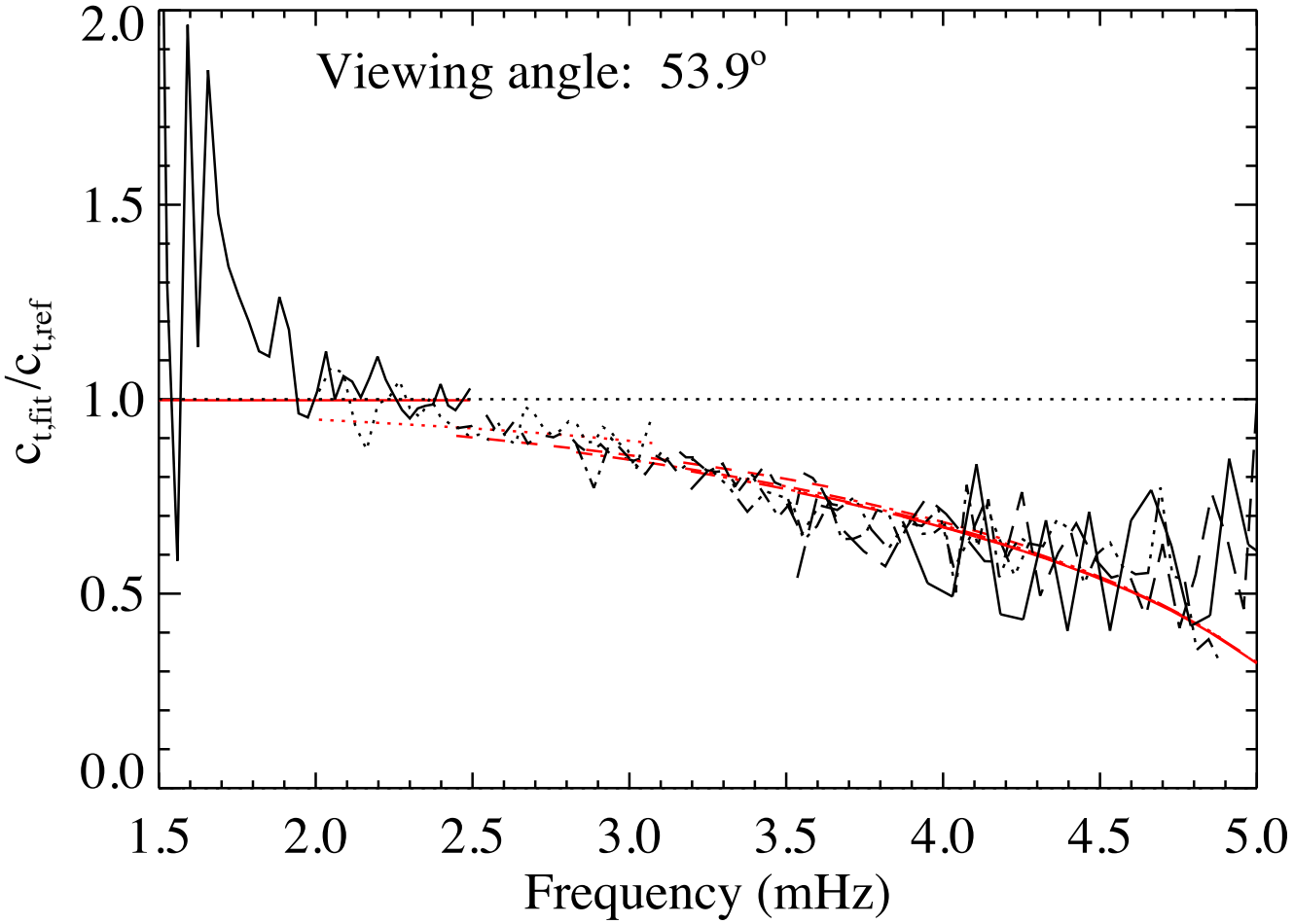

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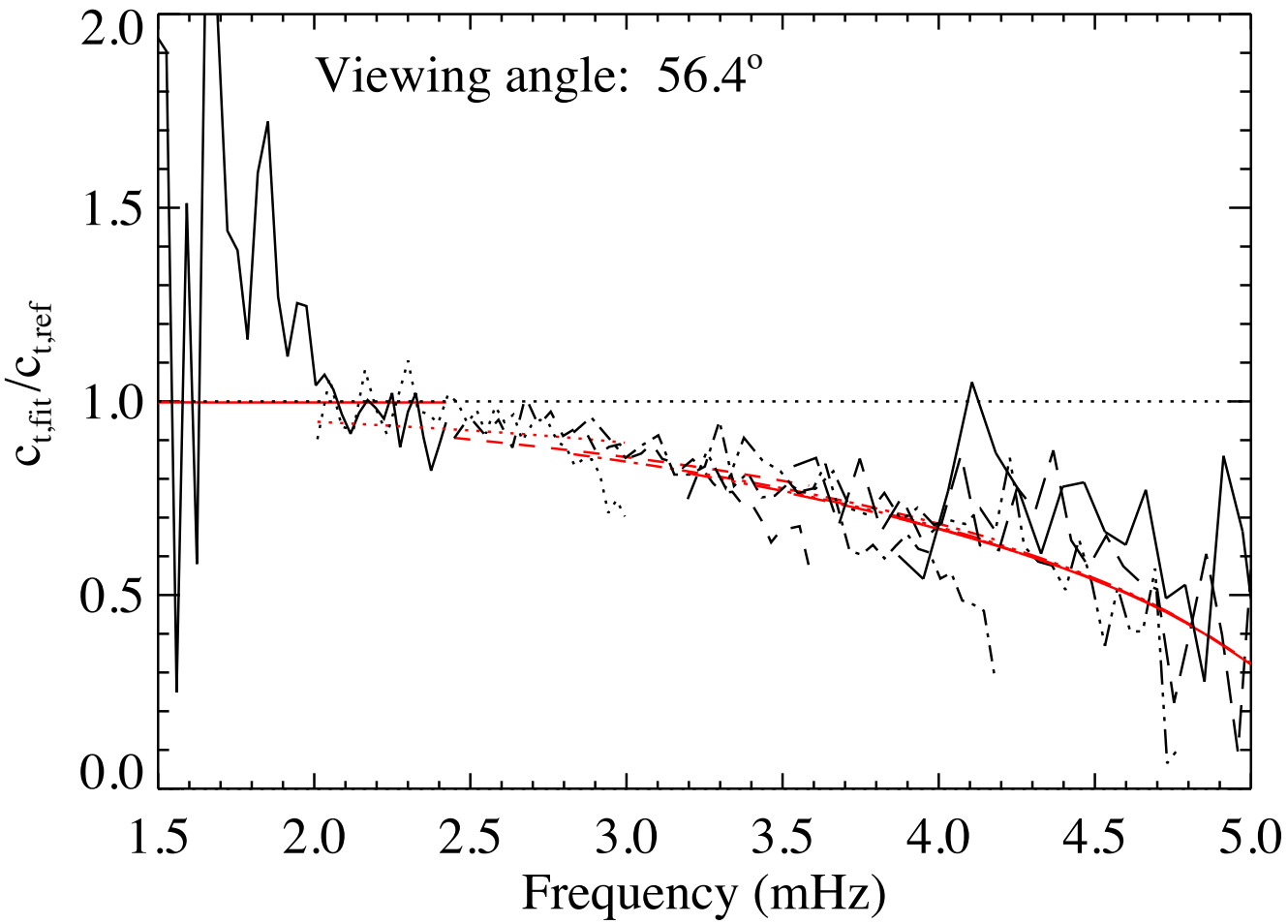

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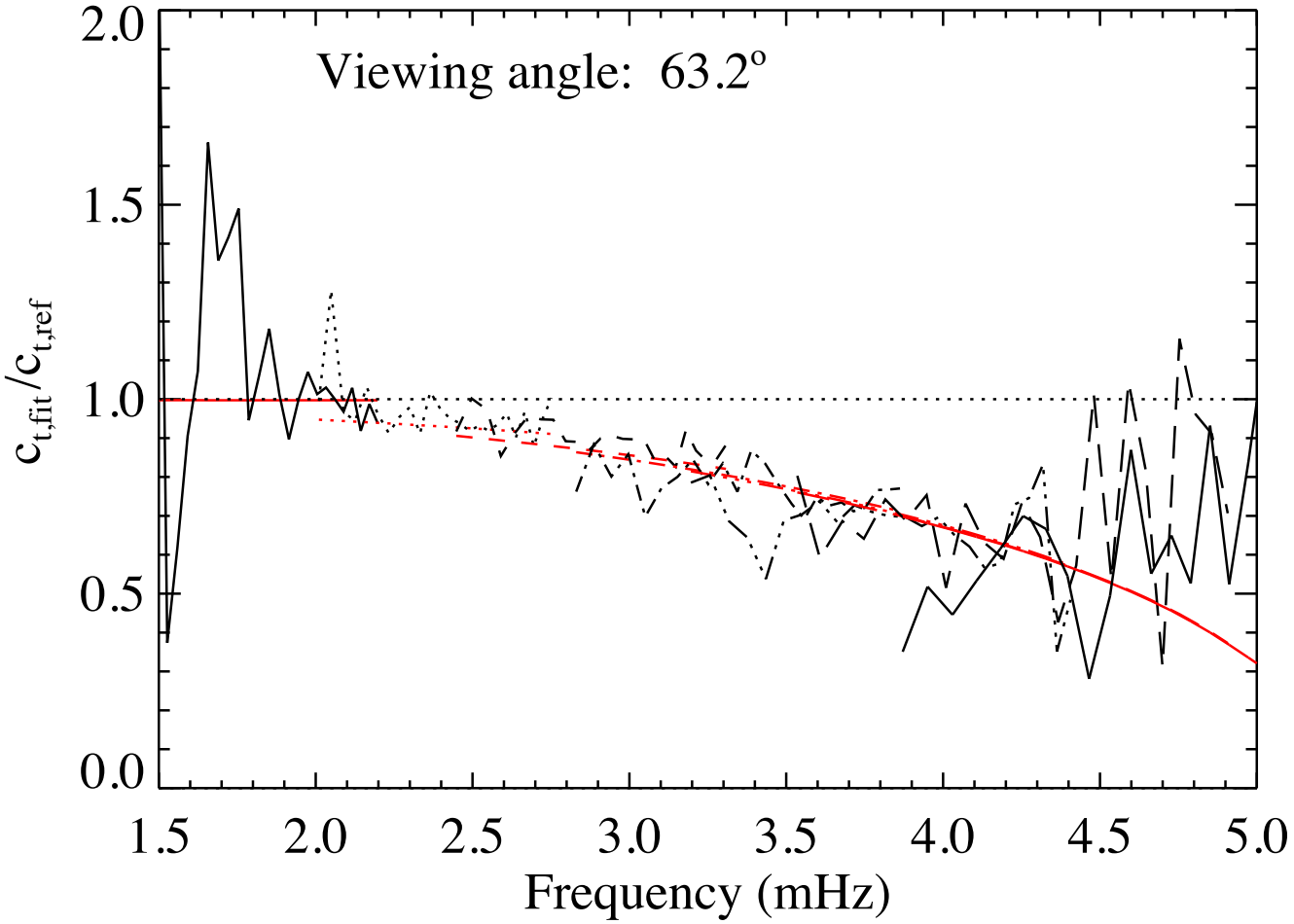

Effects on Inversions

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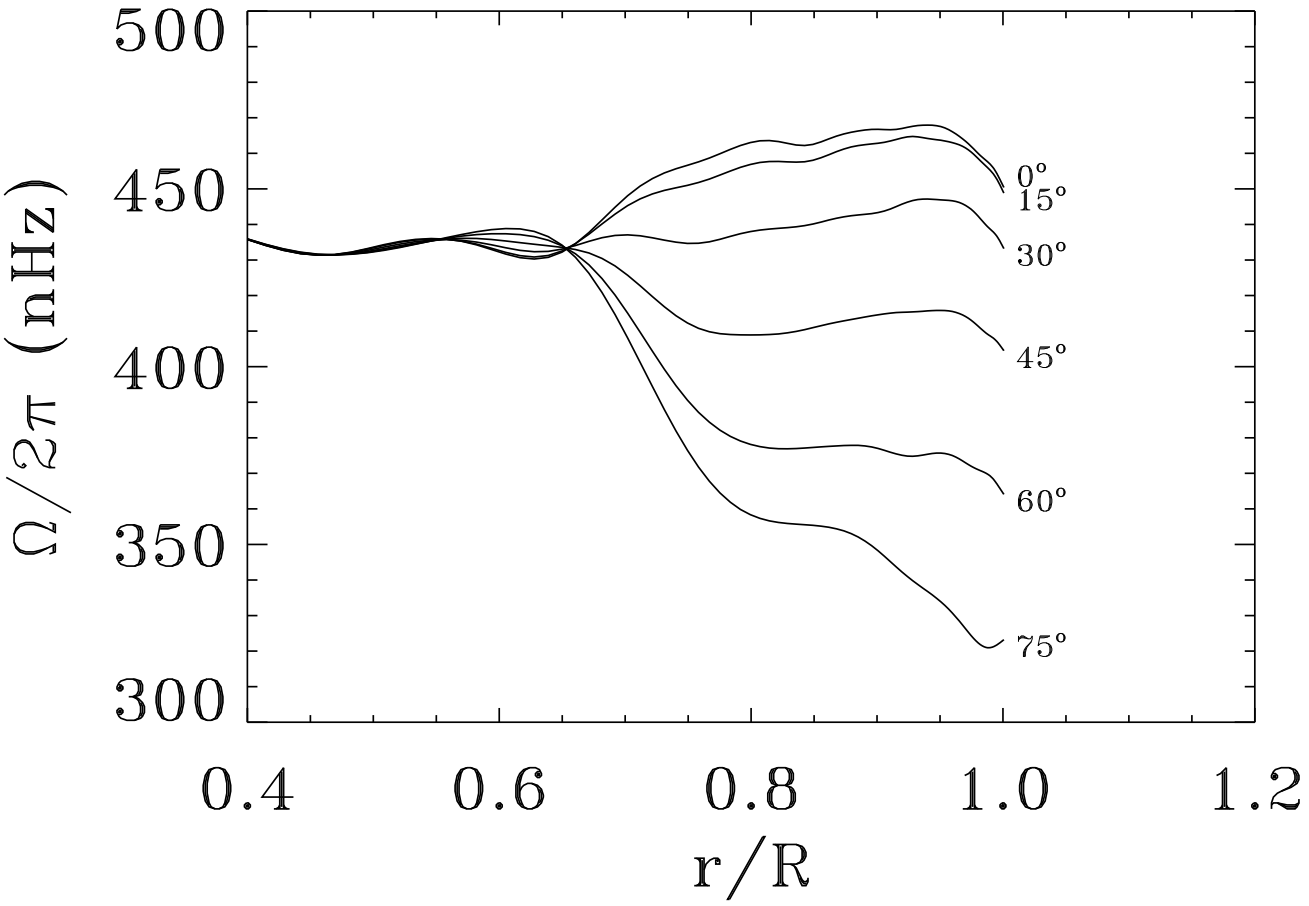
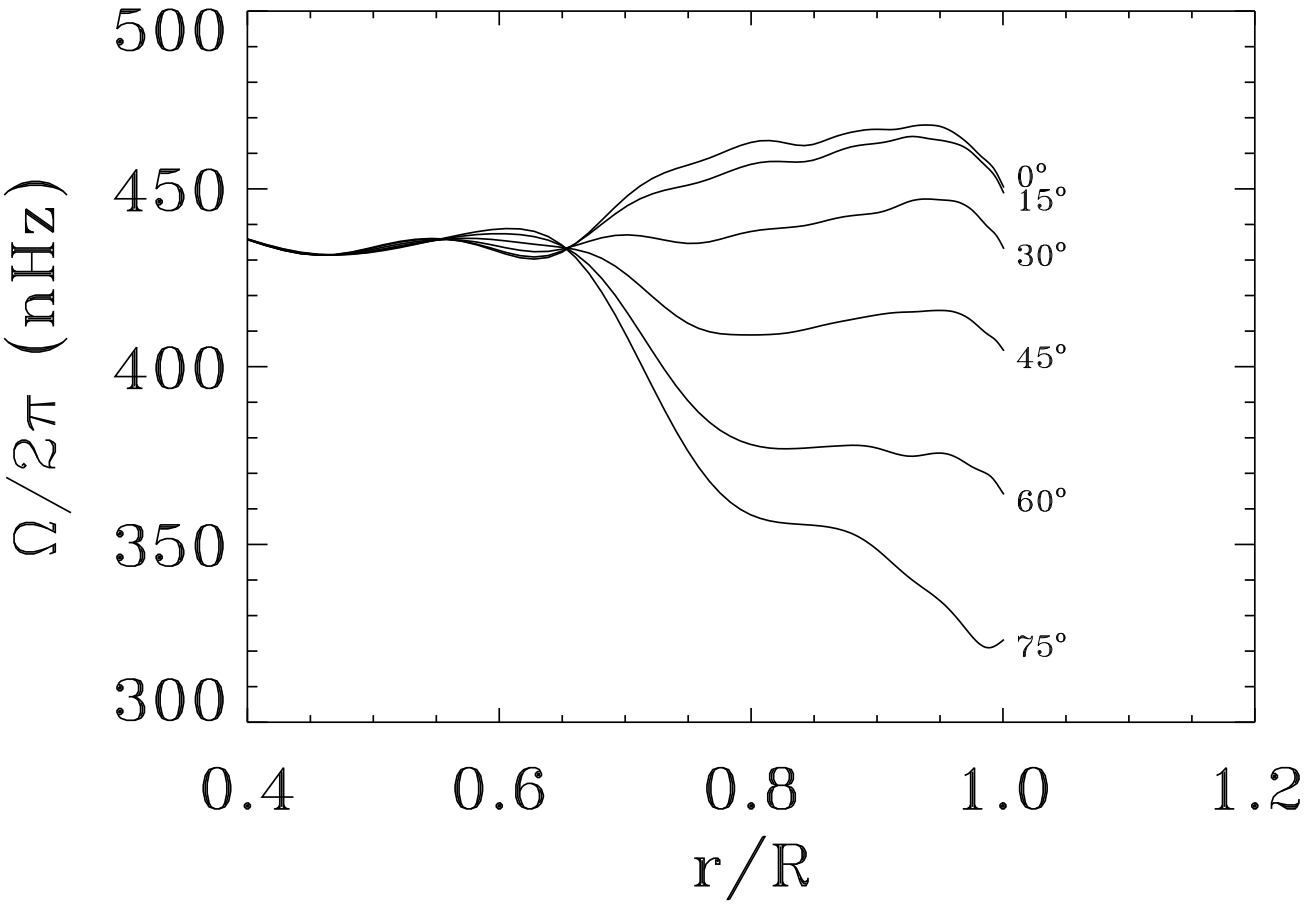
- **We now know that the simple model is wrong**
- **Does changing to the better model make a difference?**
- **So we peakbagged a 72 day HMI time series with both models**
  - And ran a 2D inversion

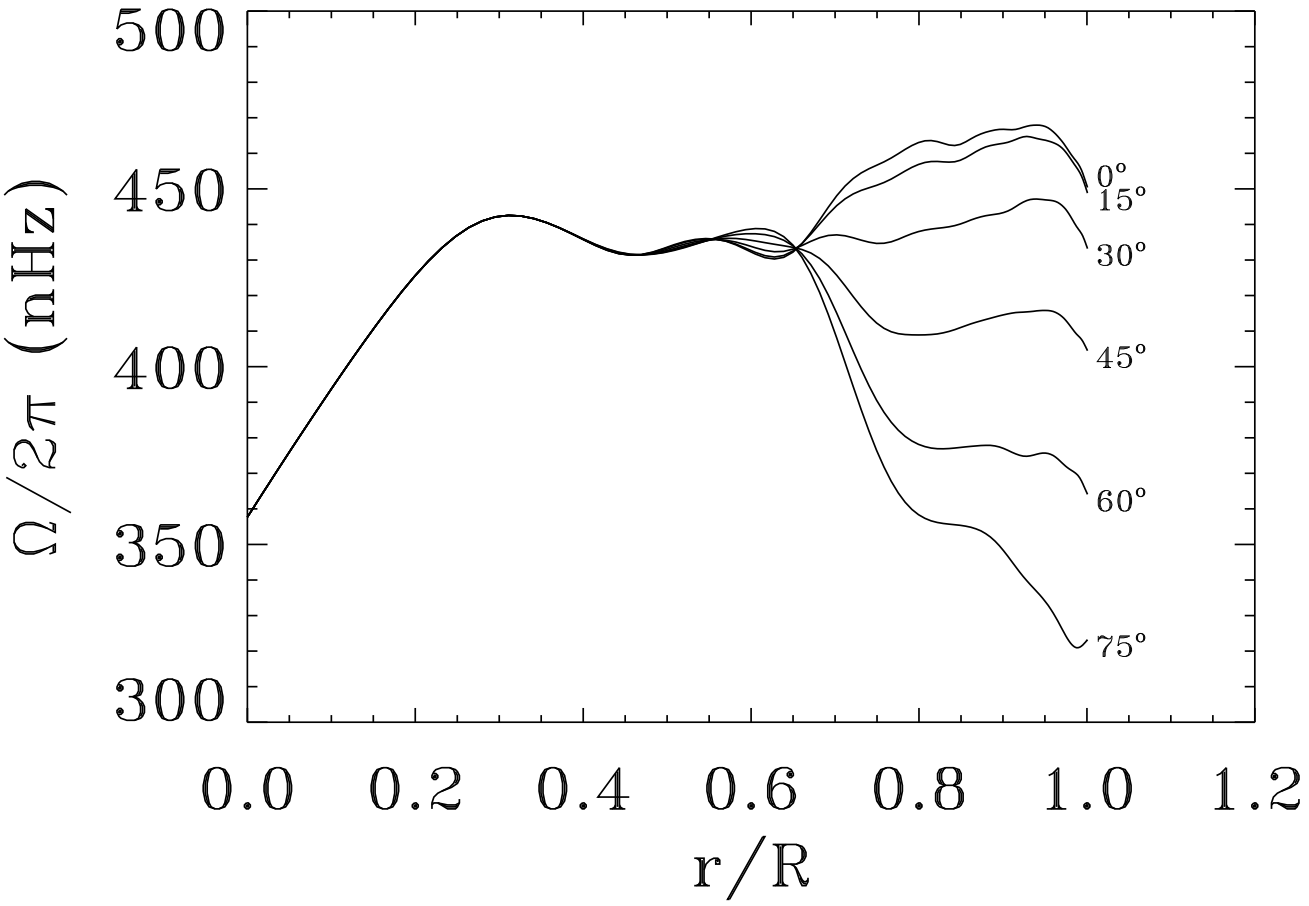
Effect on Inversions - Original



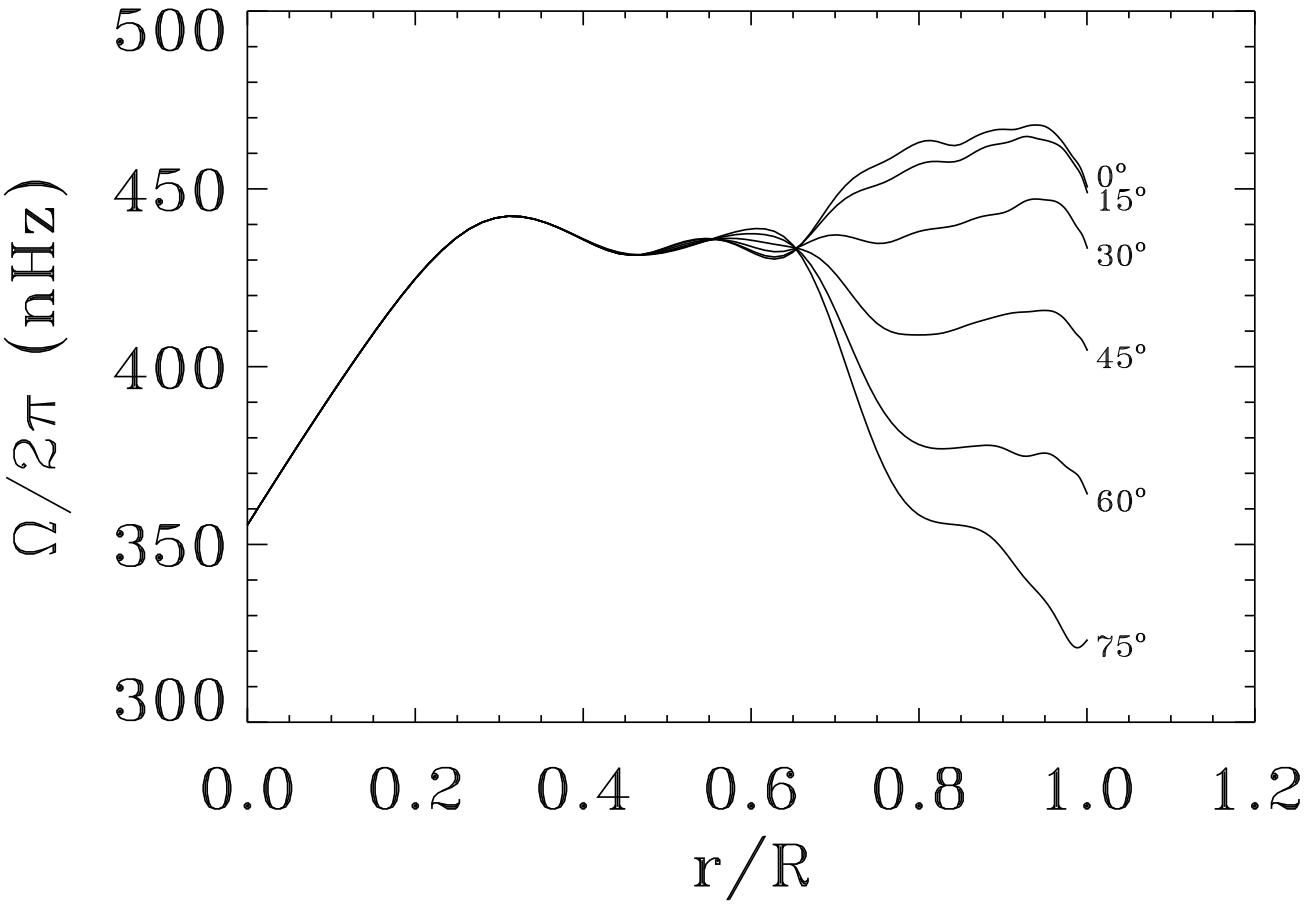
Effect on Inversions - New



Effect on Inversions - Original



Effect on Inversions - New



Conclusion

- **The horizontal to vertical ratio can be measured**
- **Results agree quite well with theory**
  - But not with simple theory
    - So don't use it!
  - Phase appears close to zero (ratio is real)
  - Likely part of center to limb effect
- **Effect on global mode seismology appears to be modest**
- **To do:**
  - Understand origin of systematics and adjustments
  - New dataset has been taken, but angle is quite small
    - Could be interesting as here may me a height depemndence
- **Study of waves in granulation**
  - https://ui.adsabs.harvard.edu/abs/2015A%26A...580L..11S/abstract
  - Dataset of quiet Sun with better resolution of HMI taken
- **Lots of fun ahead!**