Local helioseismology

Observe deviations from “quiet” Sun cross-correlations, amplitude, ring shape, linewidths, frequency....

Infer properties of the solar interior

Fourier Transform
Theoretical tools for local helioseismology

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Outline

• **Introduction**
  Forward & inverse problem
  Assumptions of linear inversions
  Strong perturbations: an example
  Simple Models

• **The way forward: Numerical simulations**
  Background models
  Waves
  Sunspot models
  Simulation codes

• **Results from SLiM**
  Comparisons to observations
  Subsurface
  Wavepacket vs XC

• **Discussion**

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Introduction: forward & inverse

- **The forward problem**
  Solar model (+ heterogeneity)
  Calculate the wave field
  Extract desired quantity e.g. travel time, amplitude, phase shift

- **The inverse problem**
  Observe the wave field
  Calculate the desired quantity
  Compare to predictions of a model
Introduction: linear inversions

- **Linear Inversions**

\[ \delta O_i = \sum_{\alpha} \int d^3r K^i_{\alpha}(r) \delta q_{\alpha}(r) \]

- **Assumptions**
  - background perturbation is constant in time
  - the background perturbation is small

- **Forward task** is to calculate the kernels for any type of measurement

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Introduction: an example

- **Sunspots: large perturbations**
  - absorb wave energy, cause phase shifts

- Serious differences in helioseismic results for sound speed inversions
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![Graph showing wave-speed perturbation vs height](image-url)

- Phenomenological model (Fan et al. 1995)
- Nested magnetic cylinders (Crouch et al. 2005)
- 1Dx Ring diagram inversion (Gizon et al. 2009)
- Time–distance inversion (Gizon et al. 2009)
- Semi-empirical model (Cameron et al. 2009)
- Radiative MHD simulation (Rempel et al. 2009)

Gizon et al (2010)
Introduction: simple models

- Magnetic field effects on the waves are significant and should be accounted for (Bogdan; Cally; Crouch; Hanasoge; Khomenko;...)

Useful physics, but not realistic.
Numerical simulations

- Realistic physical simulations: Rempel et al 2009
  - computationally expensive
  - include full physics

- Linearised simulations: Cameron; Hanasoge; Khomenko; Parchevsky; Shelyag
  - faster to compute
  - require stable background model
  - free to alter individual background quantities
Simulation Ingredients

- Solar background model
Simulation Ingredients

- **Solar background model**
  Must be *stable against convection*

\[
\frac{N^2}{g} > 0 \quad \frac{N^2}{g} = \frac{1}{c^2 \rho} \left( \frac{dp}{dz} - c^2 \frac{d\rho}{dz} \right)
\]

Parchevsky & Kosovichev 2007: when this condition is not met then the value is replaced with zero

Shelyag *et al* 2008: adjust both pressure and density using the equation of state for an ideal gas to maintain \( \Gamma_1 = 5/3 \), making sure sound speed doesn’t change too much

Cameron *et al* 2007: not in hydrostatic equilibrium

\[
\frac{dp}{dz} = \max \left[ \frac{dp}{dz}, c^2 \frac{d\rho}{dz} \right]
\]

- **Solar-like eigenmodes**
  - Schunker *et al* 2010 modify the sound speed
Simulation Ingredients

- Solar background model
- Model of solar sources or an initial condition
- Wave attenuation

Gizon & Birch (2002)
- Solar background model
- Model of solar sources
- Sunspot model: axisymmetric

Khomenko & Collados (2008)
Hanasoge (2008)
Moradi & Cally (2008)
Cameron et al (2010)
Simulation ingredients: sunspot

- Our sunspot: semi-empirical umbra, penumbra, stable background model
- Designed to match observed sunspot AR9787
Simulation ingredients: sunspot

- Our sunspot: semi-empirical umbra, penumbra, stable background model
- Designed to match observed sunspot
Simulation Ingredients

- Solar background model
- Model of solar sources
- Sunspot model
- Simulation code:
  - IAC MHD Code (Khomenko)
  - SAC (Shelyag)
  - SLiM (Cameron)
  - SPARC (Hanasoge)
Simulations ingredients: SLiM

• **Semi-spectral Linear MHD**
  Cameron, Gizon & Daiffallah (2007)
  Cameron, Gizon & Duvall (2008)

\[
\rho (\partial_t + \gamma) \frac{2}{\partial_t} \xi = -\nabla p' + \rho' g \hat{z} + \frac{1}{4\pi} (J' \times B + J \times B')
\]

\[
\begin{align*}
\rho' &= -\nabla \cdot (\rho \xi) \\
p' &= c^2 (\rho' + \xi \cdot \nabla \rho) - \xi \cdot \nabla p \\
B' &= \nabla \times (\xi \times B) \\
J' &= \nabla \times B'
\end{align*}
\]

• **Sponge layers**
SLiM results: wavepacket vs XC

quiet Sun

sunspot
SLiM results: sunspot simulations

XC time lag

Observations

SLiM

Uz, time

f

p1

p2
SLiM results: sunspot simulations

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SLiM results: sunspot simulations

phase difference between
sunspot and quiet Sun
curves for Observations
(points) & SLiM (curve)
SLiM results: sunspot simulations

\[ \sqrt{\rho U_x} \]

Different subsurface structure
Discussion

- Two ways: linear inversions and forward numerical modelling
- Linear inversions: mostly understood as long as the perturbations to the background are small
- Numerical simulations are a useful tool to study the interaction of solar waves in general background including magnetic models of sunspots
- This is currently the only practical way to get realistic/quantitative interpretation of seismic observations
- SDO/HMI will help: vector fields, higher res.