Basic Principles of Solar Acoustic Holography

ASTR 500

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Outline

"Basic Principles of Solar Acoustic Holography"
C. Lindsey and D. C. Braun
2000

1. Introduction
2. Basic Principles of Computational Seismic Holography
3. The Computational Task
4. Subjacent Vantage Holography
5. An Example
6. Acoustic Modelling Based on Holographic Images
7. Phase-Sensitive Holography
8. Green's Functions
9. Summary

Overview

Drawing on principles in optics and optical holography: *Observe* the p-mode spectrum, and extract information without using (possible incorrect) models.

Comparing:

- simple acoustic-power
- phase-sensitive

Will eventually based solar models off of holographic signatures.

Propose "simple computational principles" to produce images from observations.

(Include some sort of eye diagram here?)

1.1

"Seismic holography" was applied to helioseismic data from SOHO. "New" (1998-1999) solar acoustic phenomena:

- 'acoustic moats' surrounding sunspots
- 'acoustic condensations' 10-20 Mm beneath active regions
- 'acoustic glories' surrounding complex active regions
- first helioseismic images of a flare

$\rightarrow$ solar cycle dependence of global p-modes! (which is ... ?)

Magnetic regions reflect p modes above the acoustic cutoff frequency, where the surface of the *quiet* sun ($\sim$ 10 G) acts as a nearly perfect absorber of incident acoustic radiation coming from the sun's interior.

1.2 The Basic Principle

The *phase-coherent* (what does this mean?) computational reconstruction of the *acoustic field* in the solar interior, so that *stigmatic images* (what are these?) of the sources of these disturbances can be produced.

Historical info here that might go in a pre-paper slide.

1.3

- Concept proposed in 1975 by Roddier
- Developed over the 1990s by Lindsey and Braun (current authors)
- Key to locating and examining fine structure as deep as possible.

1.4

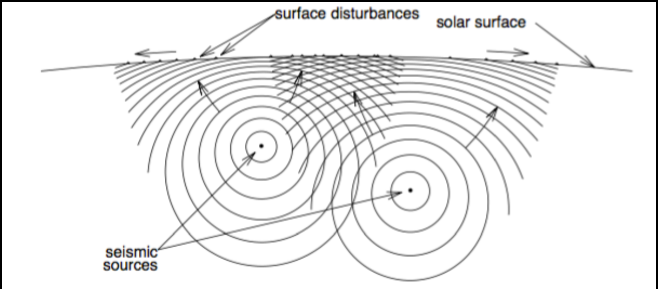
Seismology and tomography are not the same thing! Tomography is great for X-ray applications in the medical field, not so good for astronomical seismology; poor statistics and diffraction limited resolution. Holography is definitely not just another method of *modeling* stellar interiors, the images provide more of a basis for modeling techniques.

1.5

Helioseismic holography defined in terms of seismic imaging by phase-coherent reconstruction of the acoustic field into the solar interior. The terms ‘seismic imaging’ and ‘helioseismic imaging’ are applied in a broader context to include *partially* coherent acoustic signatures suggested to appear at the antipodes of far-side acoustic absorbers. ‘Holographic’ seismology applies to near side, far side, and everything in between.

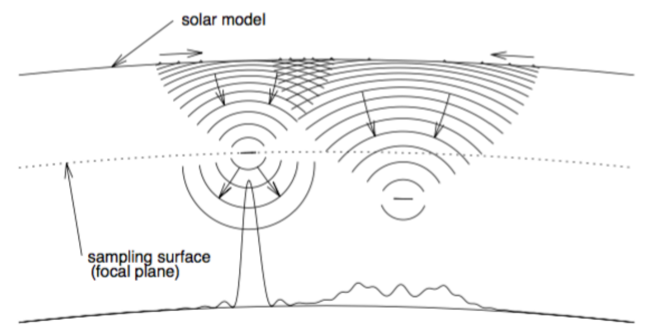
Part 2: Basic Principles of Computational Seismic Holography

2.1; Figure 1



- Well-defined acoustic sources
- All we see is the pattern of ripples at the surface, propagating from points directly *above* the sources.
- The waves are absorbed upon reaching the surface (accurate for $\nu > \sim 5.5$ mHz (what's the significance of this??)

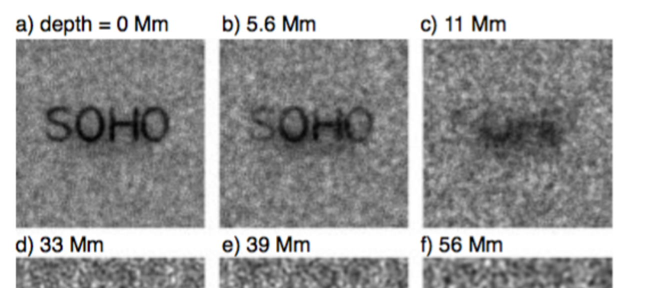
2.2; Figure 2



- Apply time-series of observations to model with no sources, sinks, or scattering (of what?)
- The observances are "seen" at the "pupil".
- Place the "focal plane" at the location of the sources, and get a diffraction-limited signature (left side of figure).
- If focal plane is above or below the source, we get an unfocused, diffuse profile (right side of figure).

2.3; Figure 3

- Simulation: random acoustic noise in model that contains alphanumeric absorbers at six different locations, from just below the surface to a depth of 56 Mm ($\sim \frac{1}{10}$ $R_\odot$).
- ‘acoustic stalactite’ of the aborber the de-focused plume.
- a diffuse ‘stalagmite’ appears closer to the absorber
- sharp, diffraction-limited silhouette at 56 Mm.
- depth diagnostics accomplished by focusing and de-focusing, rather than the appearance or disappearance that would be used in realistic phyiscal models.



2.4

Seismic holography is most certainly not a representation of solar acoustics in terms of ray optics. These are mechanical waves, not electromagnetic ones, though they have similiar behavior, such as interference and diffraction. Thus, it suffers from the same limitations as other helioseismological observations, and the same kind of optimization techniques used to extract information from coherent electromagnetic radiation can also be used here.

Part 3: The Computational Task

3.1

Two perspectives:

1. the “spectral”: the disturbance in terms of the normal modes of the medium
2. the “time distance”: closer to that of time-distance helioseismology

Terms used:

- space-time
- wavenumber-frequency

3.2

Given

- acoustic amplitude
- its derivative

can extrapolate the acoustic field anywhere in the interior! Although it's incomplete; we're getting a significant fraction, but not the entire interior. Future terminology:

- H - incomplete regression of the acoustic field
- ψ - Actual acoustic field

3.3: The space-time perspective

$\psi(\mathbf{r}', t')$ - acoustic field, secured at time t' and horizontal location $\mathbf{r}'$ regression is expressed by a formalism called the "acoustic egression", $H_+(\mathbf{r}, z, t)$, an imcomplete, but coherent assessment of the local acoustic disturbance that has emanated from the "focal point", $(\mathbf{r}, z)$, of the computation at time t based on its succeeding emergence at the overlying surface over the range of locations and time expressed by $(\mathbf{r}', 0, t')$. This can be expressed by an integral of the form:

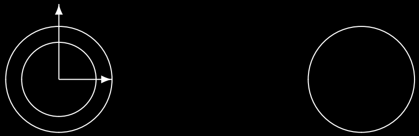
$$H_+(\mathbf{r}, z, t) = \int \mathrm{d}t' \int\limits_{a<|\mathbf{r}-\mathbf{r}'|<b} \mathrm{d}^2 r' G_+(|\mathbf{r}-\mathbf{r}'|, z, t-t')\psi(\mathbf{r}', t')$$

G_+ - Green's function that expresses how a single transient point disturbance propagates forward or backward in time between $(\mathbf{r}', 0, t')$ and $(\mathbf{r}, z, t)$.

3.4

H_- - acoustic ingression, time reverese of H_+. Describes waves coherently converging into a point, rather than from it. Replace G_+ by its time reverse:

$$G_-(|\mathbf{r}-\mathbf{r}'|, z, t-t') = G_+(|\mathbf{r}-\mathbf{r}'|, z, t'-t)$$



3.5

After computing H_+, square and integrate it to produce an egression power map over the time period in desired range. p-mode absorption in sunspots has already been confirmed this way!

3.6: The wavenumber-frequency perspective

- $\hat{\psi}(\mathbf{k}, \nu)$ - Fourier transform of $\psi(\mathbf{r}, t)$
- $\hat{G}_+(|\mathbf{k}|, z, \nu)$ - Fourier transform of $G_+(|\mathbf{r}|, z, t)$

From the convolution theorem:

$$\hat{H}_+(\mathbf{k}, z, \nu) = \hat{G}_+(|\mathbf{k}|, z, \nu), \hat{\psi}(\mathbf{k}, \nu)$$

Multiplication is computationally *faster* than convolution, so this perspective is used henceforth.

3.7

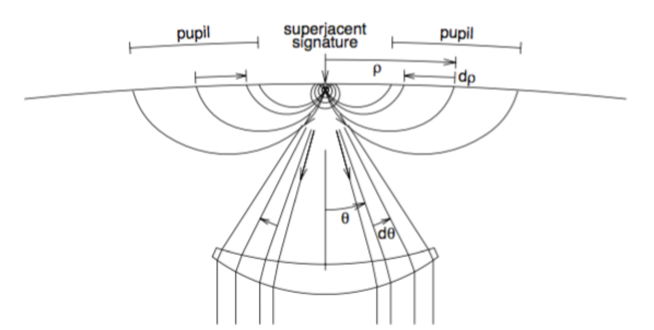
Start getting aberrations; some are easily corrected (e.g. spherical aberration, distortion, and curvature of field). Some however, are not (coma, primary astigmatism, and higher order aberrations) for large pupils that are needed to form deep focal planes (deep sources), or for imaging the far side of the sun. In this case, the aforementationed wavenumber perspective cannot be used.

3.8

$$\check{H}_+(\mathbf{r}, z, \nu) = \int\limits_{a<|\mathbf{r}-\mathbf{r}'|<b} \mathrm{d}^2 r' \check{G}_+(|\mathbf{r} - \mathbf{r}'|, z, \nu)\check{\psi}(\mathbf{r}', \nu)$$

Part 4: Subjacent Vantage Holography

Figure 4



4.1

Previously: "*Super*jacent vantage Holography". *Sub*jacent vantage holography is when the inner radius, a, of the pupil annulus is much greater than the depth of the focal plane (where the source is). This usually applies to quiet sun areas, whereas the superjacent vantage applies to active regions.

4.2

In contrast to normal optics, the diffraction limit is set by how compact the inner radius is.

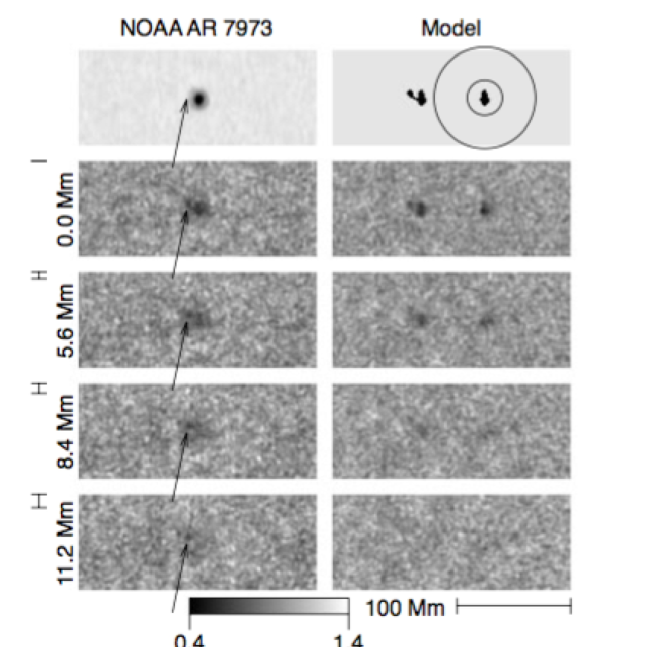
4.3

(Explains which panels in figure 3 are sub or superjacent)

Part 5: An Example

5.1

Figure 5



5.2

5.3

5.4

5.5

Fundamental limitation: As sound speed increases with depth, wavelength *increases*, which results in a coarser diffraction limit at any frequency.

Part 6: Acoustic Modeling Based on Holographic Images

6.1

Applying phase-sensitive holography to models: Flexible procedures, such as inversions, would characterize the acoustic environment in pysical terms such as:

- acoustic emissivity
- acoustic opacity
- refractivity
- flow velocity

6.2

$$\langle |H_+(\mathbf{r}, z)|^2 \rangle = \int \mathrm{d}^2\mathbf{r}' \int \mathrm{d}z' g^{-1}(|\mathbf{r} - \mathbf{r}'|, z, z') S(\mathbf{r}', z')$$

Part 7: Phase-Sensitive Holography

7.1

7.2

The need for phase-sensitive holography is two-fold:

1. straight-forward quantitative probe of refractive anomalies that we expect from thermal perturbations
2. ?

7.3

Visualize phase-sensitive holography in terms of a *gedanken experiment*.

- No phase-shift
- Phase-shift:
  - $\Delta n = \Delta c/c \rightarrow$ refractive perturbation
  - $\Delta t \sim a\Delta n/c \rightarrow$ time delay
  - $\Delta\phi \sim 2\pi\nu a\Delta n/c \rightarrow$ phase shift

Figure 6

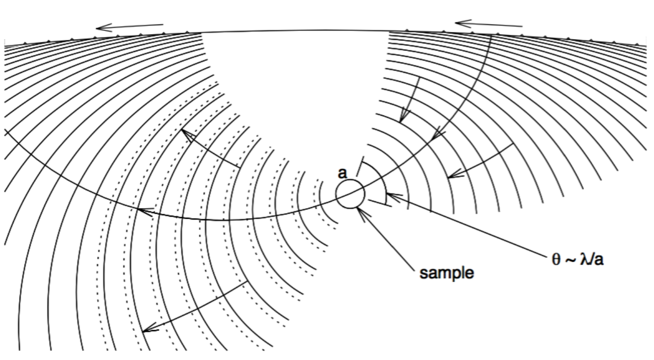


Figure 7

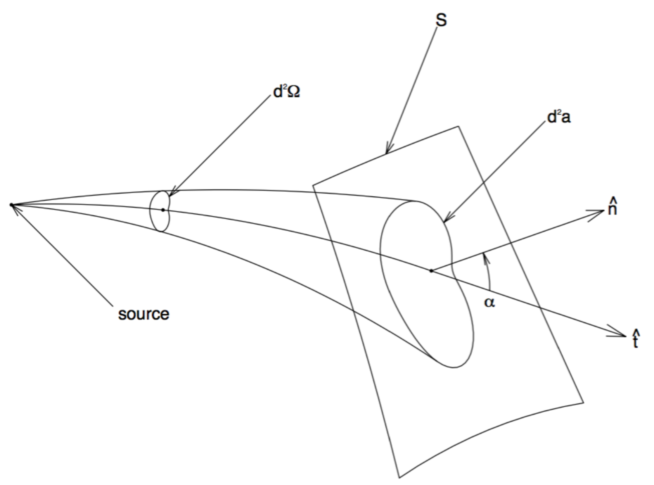
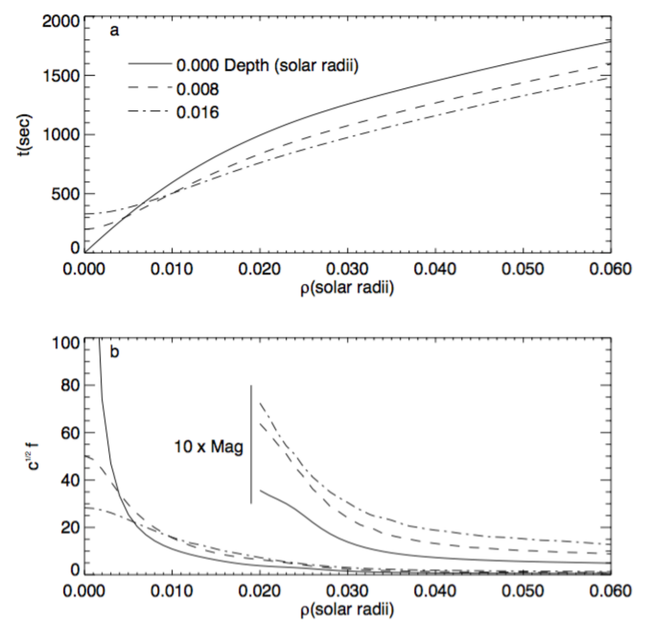
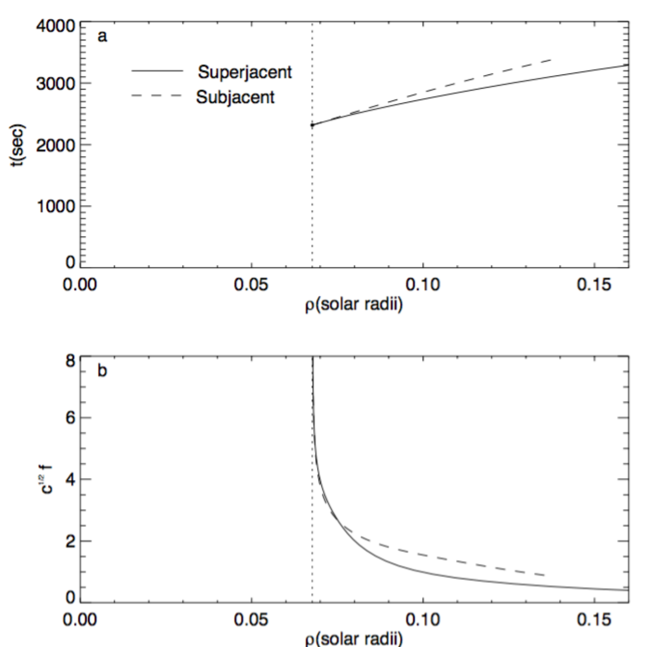


Figure 8



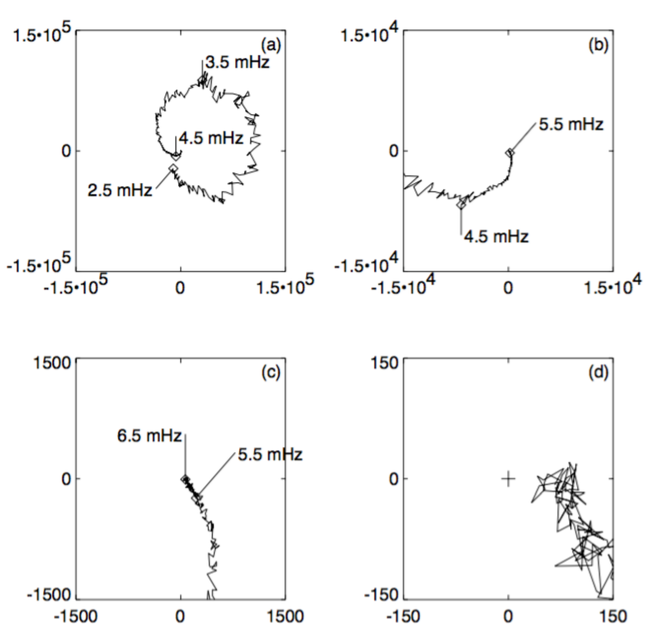
a
0.000 Depth (solar radii)
0.008
0.016
t(sec)
2000
1500
1000
500
0
0.000
0.010
0.020
0.030
0.040
0.050
0.060
ρ(solar radii)
b
10 x Mag
$c^{1/2}$ f
100
80
60
40
20
0
0.000
0.010
0.020
0.030
0.040
0.050
0.060
ρ(solar radii)

Figure 9



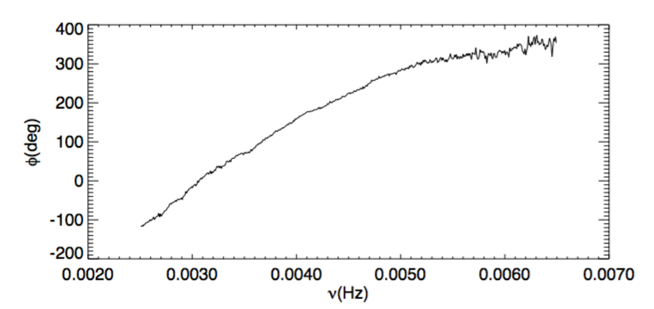
a
Superjacent
Subjacent
t(sec)
4000
3000
2000
1000
0
0.00
0.05
0.10
0.15
ρ(solar radii)
b
$c^{1/2}$ f
8
6
4
2
0
0.00
0.05
0.10
0.15
ρ(solar radii)

Figure 10



(a)
3.5 mHz
4.5 mHz
2.5 mHz
1.5•10^5
0
-1.5•10^5
(b)
5.5 mHz
4.5 mHz
1.5•10^4
0
-1.5•10^4
(c)
6.5 mHz
5.5 mHz
1500
0
-1500
(d)
150
0
-150

Figure 11



400
300
200
100
0
-100
-200
φ(deg)
0.0020
0.0030
0.0040
0.0050
0.0060
0.0070
ν(Hz)