

# Basic Principles of Solar Acoustic Holography

ASTR 500

Laurel Farris

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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

→ 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.

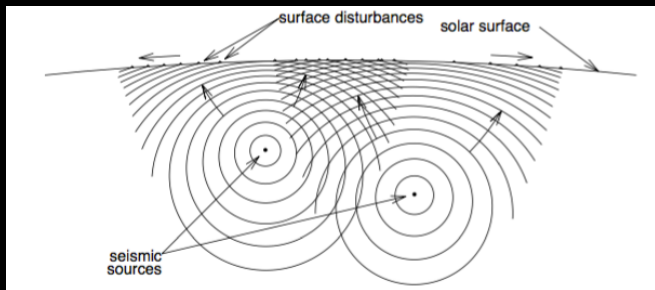
## 1.5

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.



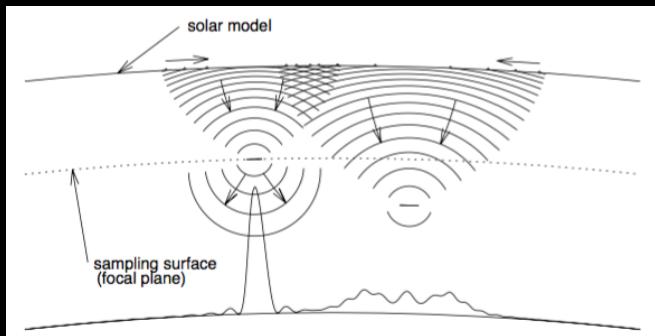
# Part 2: Basic Principles of Computational Seismic Holography

## 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??))

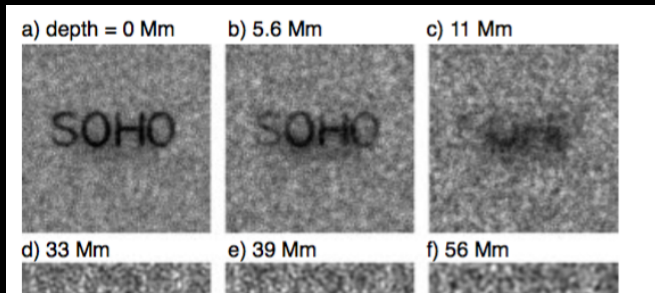
## 2.2; Figure 2



- ▶ 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 absorber 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 physical 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 similar 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
- ▶  $\psi$  - 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 incomplete, 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:

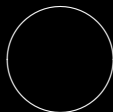
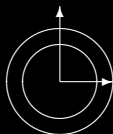
$$H_+(\mathbf{r}, z, t) = \int dt' \int_{a < |\mathbf{r} - \mathbf{r}'| < b} d^2 r' G_+(|\mathbf{r} - \mathbf{r}'|, z, t - t') \psi(\mathbf{r}', t')$$

$G_+$  - 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 reverse 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

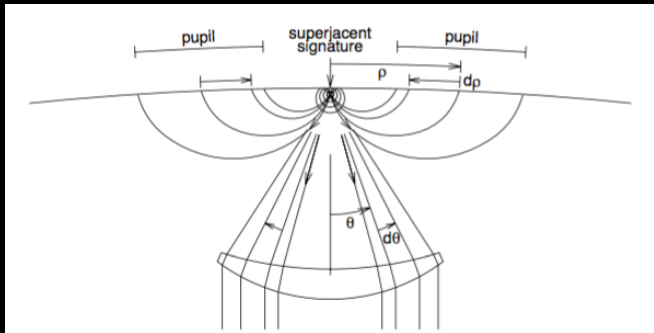
Start getting aberrations; some are easily corrected (e.g. spherical aberration, distortion, and curvature of field). Some however, are not (coma, primary astigmatism, and higher order aberrations) for large pupils that are needed to form deep focal planes (deep sources), or for imaging the far side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

## 3.8

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

# Part 4: Subjacent Vantage Holography

Figure 4





## 4.1

Previously: “*Superjacent* vantage Holography”. *Subjacent* 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.

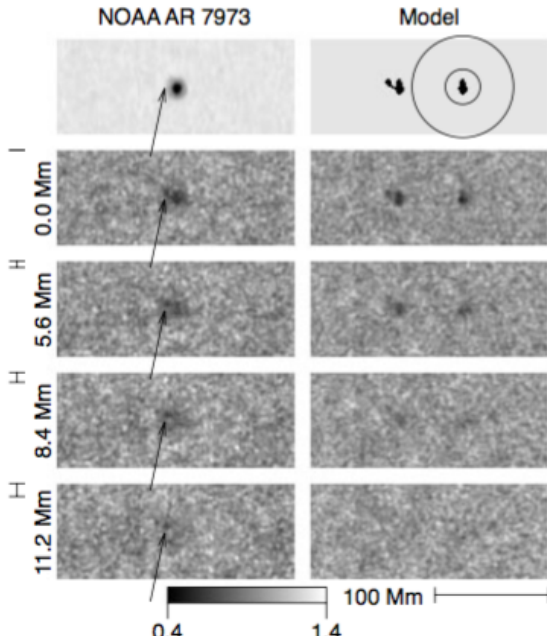
## 4.3

(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 physical terms such as:

- ▶ acoustic emissivity
- ▶ acoustic opacity
- ▶ refractivity
- ▶ flow velocity

## 6.2

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

# 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. ?

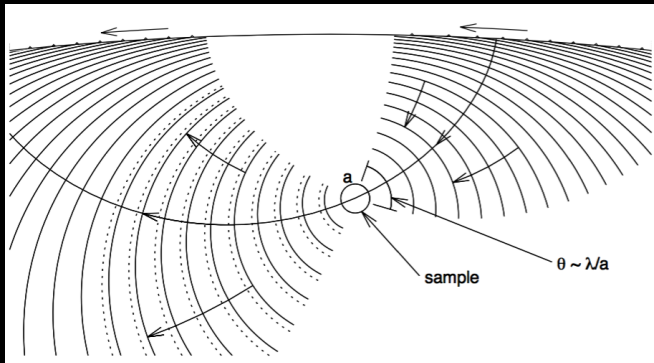


## 7.3

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



# Part 8: Green's Functions

# 8.1

Green's function:

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

Characterizes the acoustics of the solar *model* to which helioseismic observations,  $\psi(\mathbf{r}', t')$ , are applied to accomplish acoustic regressions.

Computational is a broad, flexible diagnostic, not intended for any one particular model.

Outlining intuitive concepts used to fashion Green's Functions appropriate for practical diagnostic applications.

## 8.2

Acoustic formalism:

- ▶ Field,  $\psi$  is normalized wrt energy flux
- ▶ Solar interior acoustics (in the absense of sources and sinks) is *time-reversal invariant*

Given these two conditions, the same Green's functions characterize the propagation both forward and backward in time between surface  $(\mathbf{r}', 0, t')$  and source  $(\mathbf{r}, z, t)$

## 8.3: Dispersionless acoustics

Pulse propagates in the form of a *wavefront*. Surface location,  $\mathbf{r}'$  responds with ripple characterized by the same infinitely sharp temporal profile as the source, but properly attenuated. The Green's function is invariant with respect to both time and horizontal translation.

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

## 8.4

## 8.5

$T$  (travel time) and  $f$  (amplitude of pulse) both depend strongly on the sound speed variation with depth. Derive  $\Gamma$  (optimal optical path) that satisfies Fermat's principle.

Obtain  $T$ !

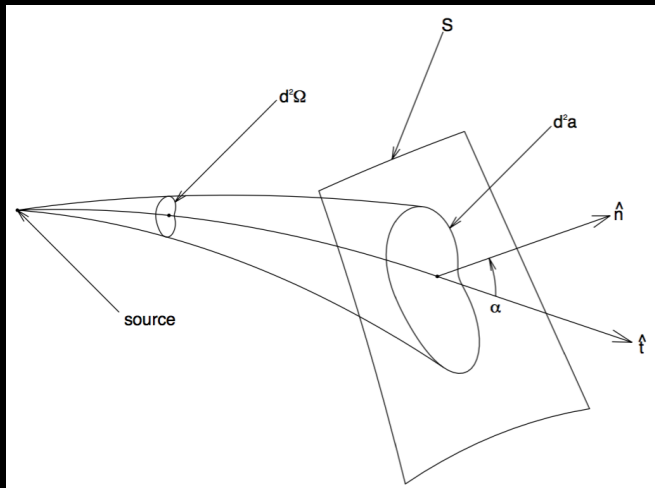


## 8.6

Obtain  $f$ ; acoustic flux must be in proportion to solid angle subtended by the optical paths leading to the boundary of the surface element.

Acoustic energy flux density:  $cf^2$

Figure 7



## 8.7

- ▶  $\nu > 5.5$  mHz absorbed by photosphere upon first encounter after leaving source.
- ▶  $\nu < 4.5$  mHz reflected from the specular (“mirror-like”). In this case the Green’s function is characterized by a sum of  $n$  components, where each  $n$  is a “skip”, or reflection from the photosphere (include diagram)

## 8.8

Multiple-skip holography: Two branches

1.  $\rho$  decreases as  $\theta$  increases
2.  $\rho$  increases after reaching a minimum as  $\theta$  continues to increase toward  $180^\circ$ .

Figure 8

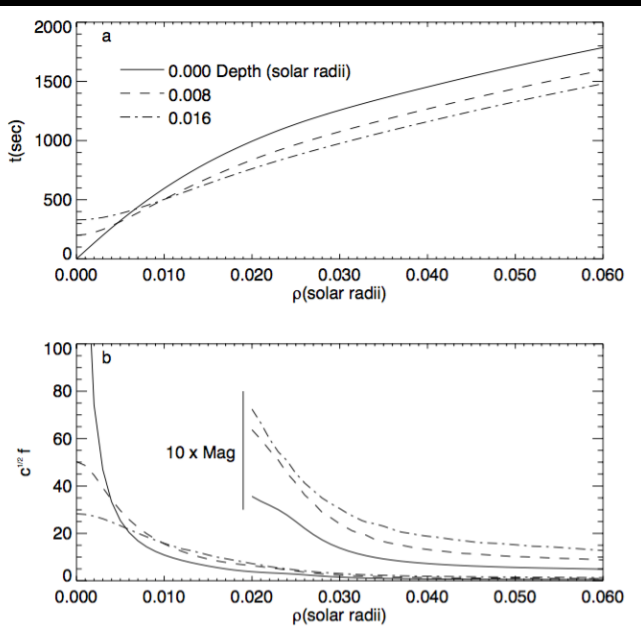
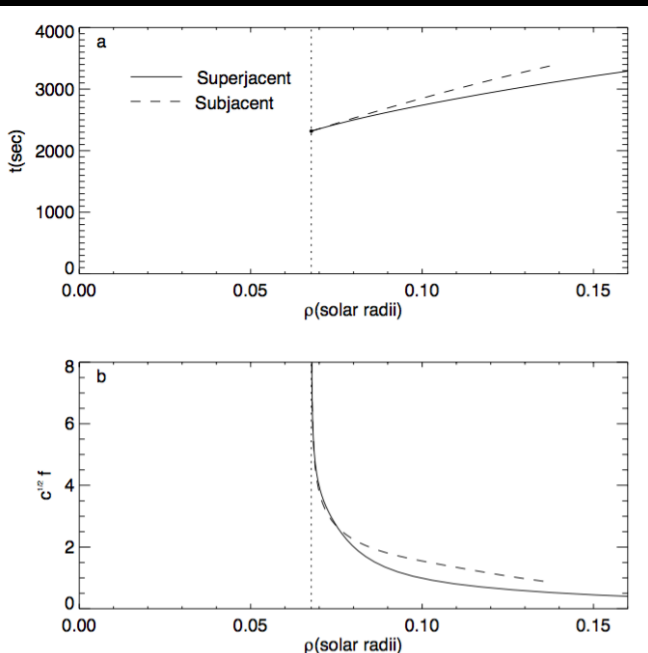


Figure 9



## 8.10: Dispersion

In reality, acoustic waves are *significantly* dispersed near the photosphere.

## 8.9



# 8.11

## 8.12

## 8.13

## 8.14

Figure 10

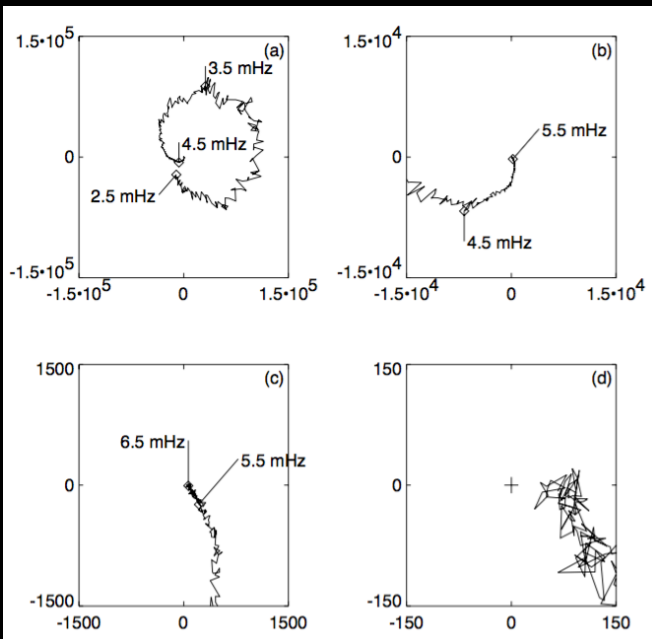
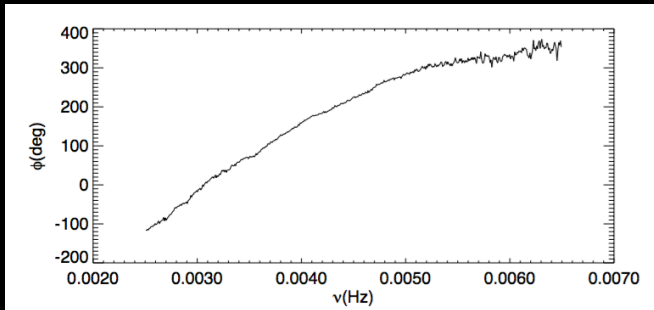


Figure 11



# Part 9: Summary