Prospects for Deep Interior Helioseismic Holography

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Abstract

Holographic seismic imaging of low-degree acoustic noise opens new prospects for solar interior diagnostics that are most encouraging. (1) Low-degree seismic holography is already giving us images of large magnetic regions on the far surface of the Sun, a utility with valuable space-weather forecasting and general synoptic applications. (2) Diffraction-limited imaging of low-degree noise over pupils covering most of the near solar hemisphere promises the most discriminating probe of the deep solar interior. (3) Earth-based helioseismic observations coordinated with seismic observations of the far side of the Sun at frequencies in the range 6–7 mHz would allow us to resolve local thermal and Doppler structure in the solar core with a resolution of 75 Mm. In order to take advantage of the superior spatial resolution offered by high-frequency waves, coordinated seismic observations of both near and far sides of the Sun are essential for the deep solar interior.

Local Helioseismology

Global helioseismology has given us a powerful utility for examining the thermal structure of the solar interior and mapping the flows therein. While comparisons between different modelling techniques have turned up some interesting ambiguities, the overall picture that p-mode diagnostics have given us suggests that we now know the thermal and flow structure of the subphotosphere down to the base of the convection zone reasonably well. However, the local thermal and flow structure in the radiative core of the Sun seems to be increasingly ambiguous and poorly resolved towards the nuclear-burning core. We think that we roughly understand the reasons. Because only relatively low-l modes penetrate to great depths, the spectrum of waves that are useful for deep interior diagnostics is limited, and statistics are therefore relatively poor. Because the sound speed increases strongly with depth, the wavelength of acoustic radiation at any given frequency is much greater deep in the solar interior. This imposes fairly strict practical limits on resolution, as a result of diffraction. For reasons that we will not try to elaborate here, the global diagnostics that have been applied to date fall substantially short of the basic diffraction limit imposed by standard acoustic optics. The purpose of this discussion is to recognize what we think are the basic principles that allow us to take the fullest advantage of the diagnostic utility offered by solar interior wave mechanics to give us seismic diagnostics of the highest quality and finest discrimination possible.

Problems that Confront Gravity-Wave Diagnostics

A considerable amount of interest has been expended on prospects for using gravity waves to study the structure and rotational dynamics of the radiative core of the Sun. Because these waves propagate very slowly in the radiative core, their wavelengths are short, resulting in a fine diffraction limit. However, this benefit comes at a severe cost. The gravity waves that penetrate deepest into the solar core are understood to have very low frequencies and propagate particularly slowly. This renders them exceptionally lazy tourists of the solar interior. While compression waves pass from the solar core to its surface in barely an hour, gravity waves take days or weeks to arrive just to the convection zone. Worse, when the disturbance does arrive at the base of the convection zone, nearly all of the acoustic flux incident thereinto is reflected back into the radiative core. The little acoustic power that tunnels through the convection zone seeps through it at an indefinitely sluggish rate, oozing to the surface perhaps months or years after it has probed the solar core. There are good reasons to suppose that gravity waves abound both in the deep solar interior and in the outer solar atmosphere. However, it would appear that what we see at the solar surface is predominantly locally generated and, for practical diagnostic purposes, decoupled from the deep solar interior.

Optimal Compression-Wave Diagnostics

While it would be dangerous to simply relax into the conclusion that gravity-wave diagnostics of the deep solar interior will never be practical, prospects for this avenue are presently discouraging. It is, nevertheless, possible to do seismic diagnostics of the deep solar interior, including the solar core, with much finer resolution than has been possible with global modeling based on compression waves. Indeed, this can be accomplished with familiar p-modes, by taking full advantage of the optical utilities generally offered by waves. We are therefore going to argue that it is in fact the familiar p-modes that are by far the most appropriate for seismic diagnostics of the deep solar interior. Indeed, it should be possible to secure remarkably fine discrimination of the thermal and flow structure of the tachocline and radiative interior, including the nuclear burning core, by applying standard optical techniques to compression waves.

Holographic Imaging

Because acoustic waves share the same basic wave-mechanical attributes of electromagnetic radiation, we can apply most of the same diagnostics to waves seen on the solar surface that standard optics applies to light, giving us phase-coherent images of the solar interior and far side. Helioseismic holography applied to SOHO-MDI observations has recently given us the discoveries of acoustic moats surrounding sunspots (see Fig 1), acoustic glories (Fig 2), which are conspicuous around large active-region complexes, apparent acoustic condensations 10–20 Mm beneath surface active regions, chromatic images of a large solar flare, and images of active regions on the far surface of the Sun (Fig 3).

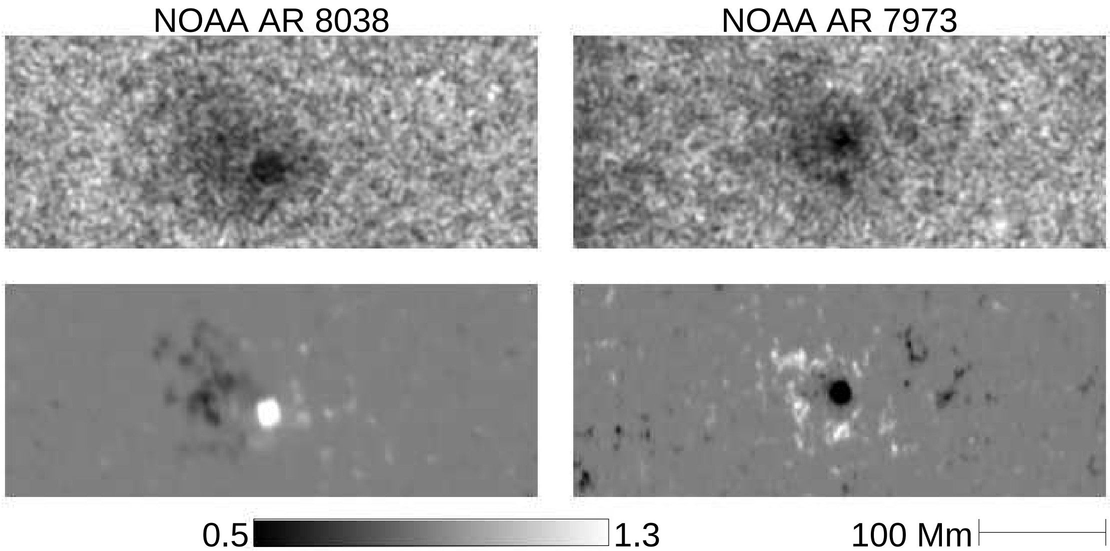

Figure 1: Egression-power maps in the 2.5–3.5 mHz band show acoustic moats surrounding sunspots in active regions NOAA AR 8038 on 1997 May 10 (upper left) and NOAA AR 7973 on 1996 June 25 (upper right). Concurrent magnetograms (bottom) are taken from the Kitt Peak Vacuum Telescope (National Solar Observatory).

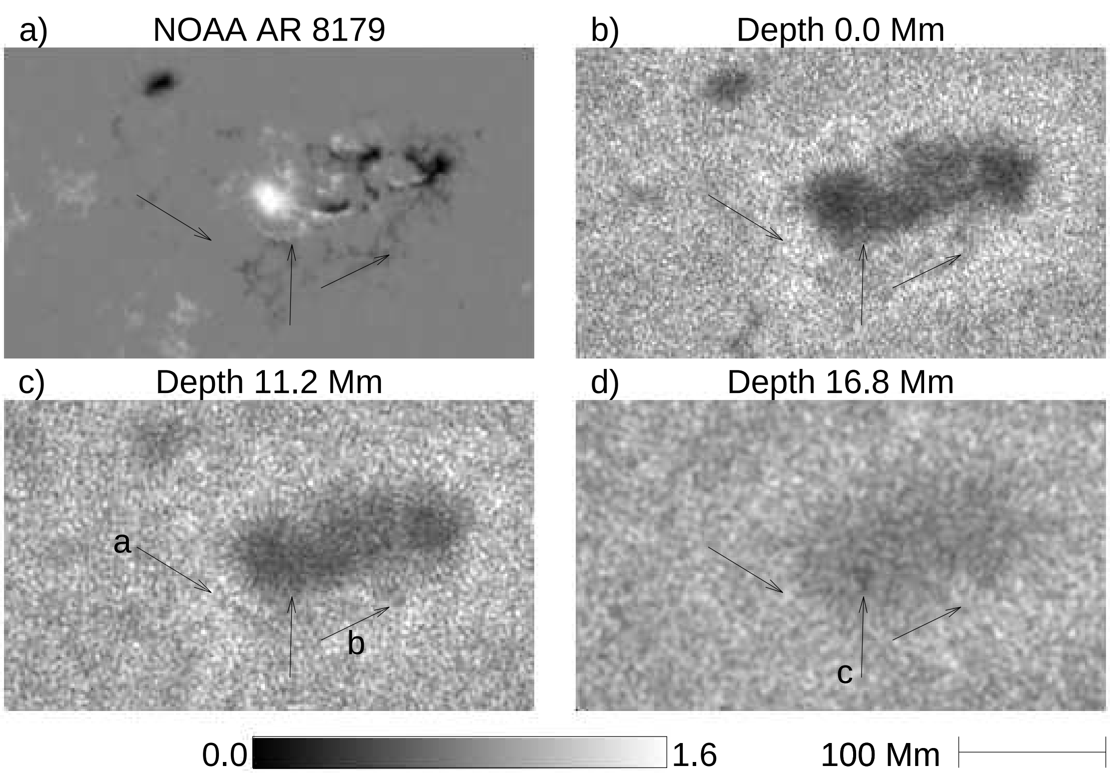

Figure 2: Egression power map at 5 mHz (Fig 2b) of NOAA AR 8179 on 1998 March 16.0 show enhanced acoustic power, i.e. an "acoustic glory," emanating from the quiet Sun surrounding the magnetic region. When the focal plane is submerged to 11.2 Mm (Frame c) apparent "condensations" appear, indicated by arrows a and b. At 16.8 Mm (Frame d) an apparent condensation is indicated by arrow c. Frame a shows a Kitt Peak magnetogram of the region.

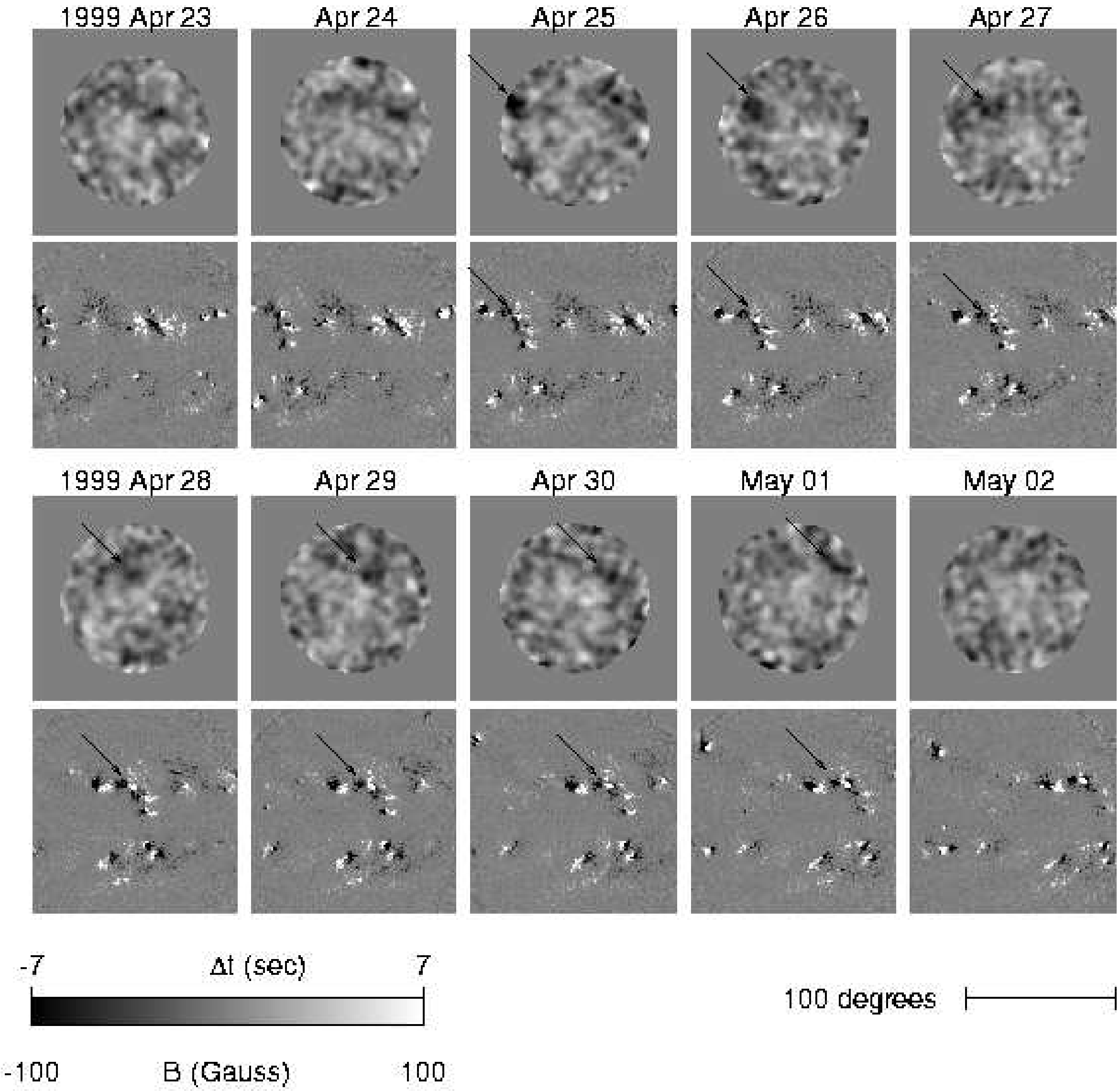

Figure 3: Holographic images of active regions marching across the far side of the Sun (top frames) are compared with near-side magnetogram (Kitt Peak Vacuum Telescope, National Solar Observatory) made two weeks later, when these (along with newly emerged regions) were visible on the near side of the Sun.

Phase-Correlation Imaging

Acoustic moats and acoustic glories (Figs 1 and 2) are examples of seismic absorbers and emitters, which are clearly seen in simple acoustic-power images of active regions. These are relatively superficial phenomena, and it is in the shallow subphotosphere where essentially all of the acoustic noise that comprises the p-modes is thought to be generated. While it is still too early to make a definitive judgement, we know very little to encourage the prospect of substantial acoustic emission from the deep solar interior, nor of any mechanisms that would result in substantial acoustic absorption. However, it is now clear that the deep solar interior contains thermal structure and flows that will render themselves clearly in seismic phase-correlation images.

Phase-correlation seismic holography (see Lindsey and Braun 2000b, Braun and Lindsey 2000) is accomplished by comparing waves converging into a focal point, as represented by any particular pixel in the image, with waves coherently diverging from it. This scheme recently gave us the first maps of active regions on the far surface of the Sun (Lindsey and Braun 2000a). The basic wave configuration representing phase-correlation imaging of an acoustic sample at the depth of the solar tachocline, for example, is illustrated in Fig 4. The diagnostic recognizes acoustic waves from an "ingression pupil" (upper right surface of the Sun) focused into an acoustic sample represented by a small circle (upper middle). These waves proceed through the focal point to arrive into an "egression pupil" (upper left surface of the Sun) with a phase shift predominantly caused by refractive and Doppler effects imposed by the sample. By phase-correlating the egression and ingression amplitudes, and comparing the result with a similar phase correlation derived by swapping the ingression and egression pupils, it is fairly straightforward to model the refractivity and motion of the medium in the close neighborhood of the focal point.

It is intesting to reflect that the wave modes illustrated in Fig 4 are essentially the same as those which render the far-side images shown in Fig 3 when both ingression and egression trajectories are extended to two skips and the focal point is situated on the far surface. We are convinced that phase-correlation seismic holography, or its equivalent, is fundamental to the detection of local siesmic structure deep in the solar interior. Phase-correlations statistics are particularly needed for diagnostics of flows, which we know exist deep in the solar interior, and for local thermal variations, whose existences we suspect.

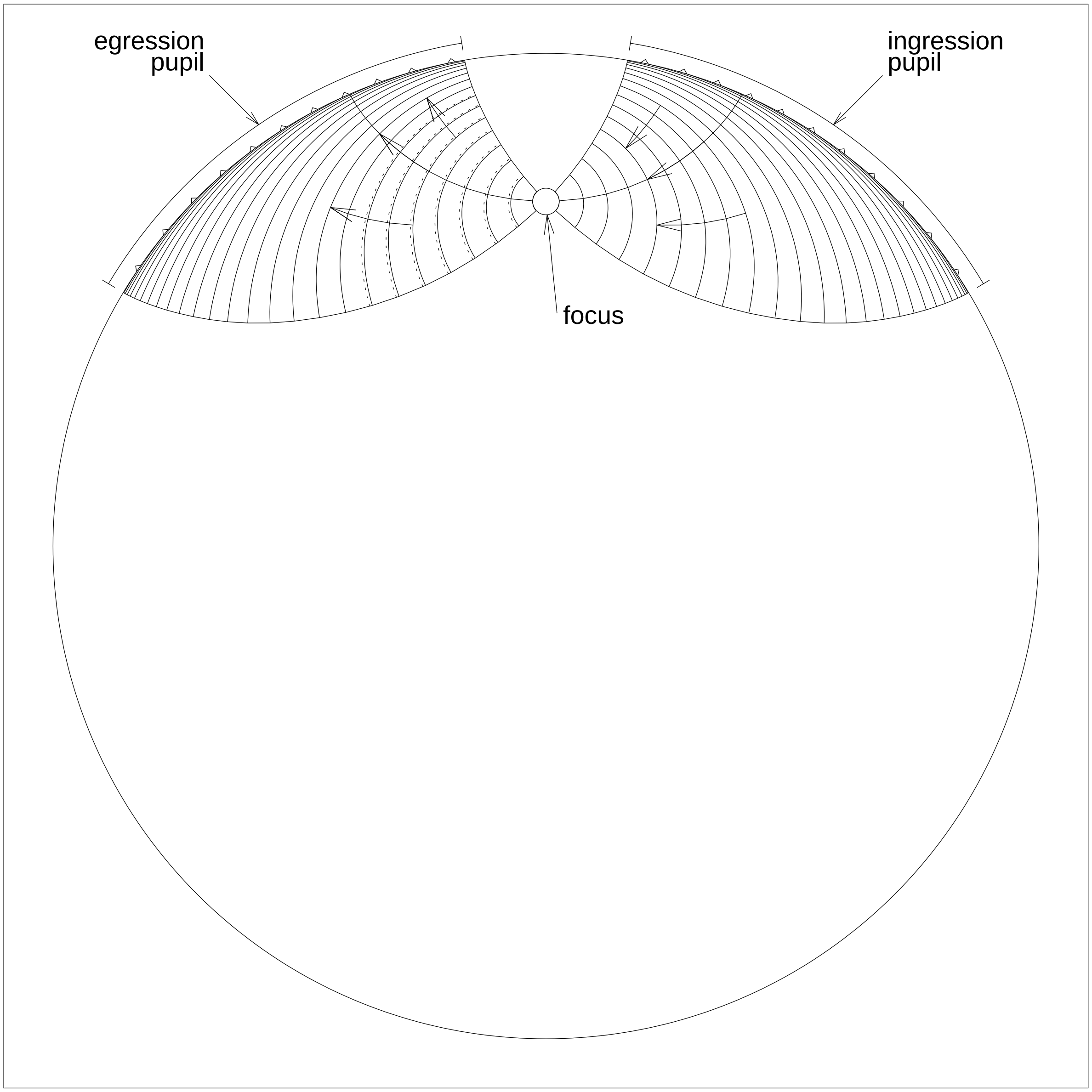

Figure 4: Wave configuration for phase-correlation imaging of the tachocline. Waves converging into an acoustic sample (small circle at top middle) from an ingression pupil (top right surface of Sun) are phase correlated with waves emanating from the sample to arrive into the egression pupil (top left surface of Sun).

The Optical Perspective

At this point we will undertake to emphasize three points that we think will make it fairly clear what is needed to secure the best deep interior diagnostics that solar acoustics can offer:

(1) The diffraction-limited resolution for acoustic diagnostics at any given frequency becomes poorer with increasing depth. Roughly speaking, the diffraction limit is the wavelength,

$$\lambda = c(z)/\nu, \tag{1}$$

where $c(z)$ is the speed of sound at depth z, and ν is the frequency.

(2) The finest resolution for any given depth is offered by the highest frequencies, a benefit that is evident by equation (1), above.

(3) The solar surface efficiently absorbs high-frequency waves, a point emphasized by Duvall et al. (1993) and illustrated here by Fig 5. Phase-correlation seismic holography at frequencies above 4.5 mHz must therefore depend on single-skip diagnostics.

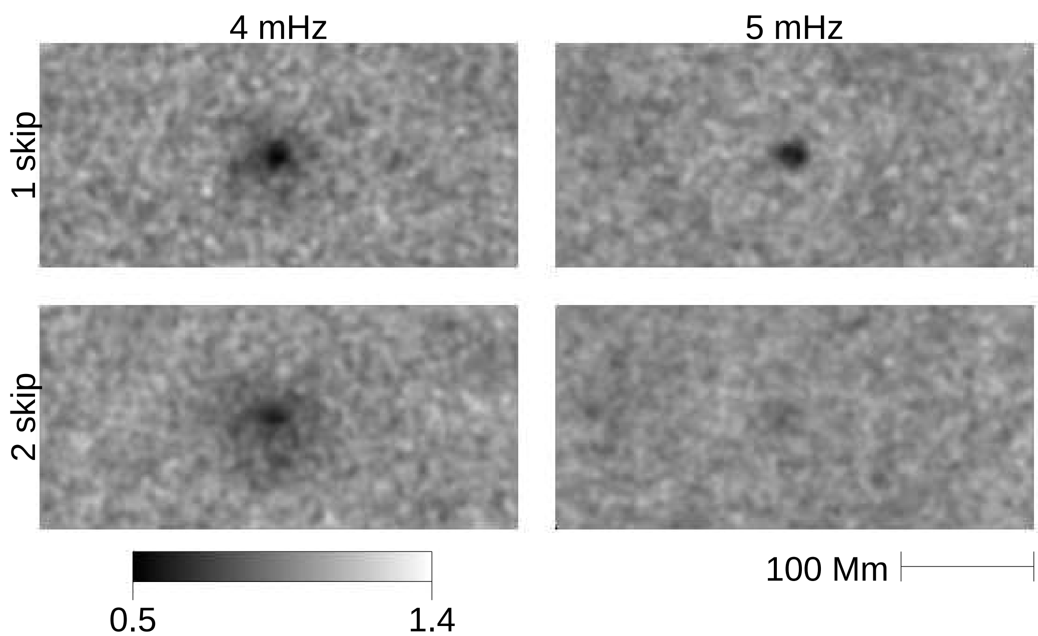

Figure 5: Single skip (upper row) and double-skip (lower) egression power maps of NOAA AR 7973 (1998 June 25) are computed in 1 mHz passbands centered at 4 mHz (left column) and 5 mHz (right).

Figs 6–8 show pupil configurations for phase-sensitive imaging of acoustic samples at depths ranging from the outer limit of the nuclear-burning core (Fig 6) to its center (Fig 8). All of the wave diagrams in this presentation, including that representing phase-correlation diagnostics of the tachocline (Fig 4) are computed for a frequency of 6 mHz, and the diffraction limit for that frequency is represented by the diameter of the circle representing the focal point. Given a Sun-center sound speed of 0.5 Mm/s and a wave period of 150 s, the reader may confirm a diffraction limit in the solar core of order 0.5 Mm/s·150 s = 0.75 Mm. It should be clear that phase-correlation imaging of acoustic samples in the nuclear-burning core (Figs 6–8) requires simultaneous helioseismic observations from both the near and far sides of the Sun, since an acoustic egression integrated over any pupil on the near side will substantially correlate only with an ingression integrated over a conjugate pupil on the far side.

It is possible to do phase-correlation imaging of the solar tachocline (Fig 4) at near-equatorial latitudes and near-meridian longitudes with earth-based observations alone. Since the Sun rotates, all longitudes can eventually be covered in a single solar rotation. However, simultaneous helioseismic observations substantially covering both the near and far sides of the Sun would allow us to monitor the tachocline at all latitudes and longitudes continuously, giving us much more complete coverage and far superior statistics.

Conclusion

The critical point of this discussion is that helioseismic imaging of the far solar surface should be regarded as essential for high-quality diagnostics of the deep solar interior. Indeed, the possibility of monitoring the far side of the Sun with MDI-quality observations promises some remarkably interesting science that cannot be accomplished by any other avenue.

References

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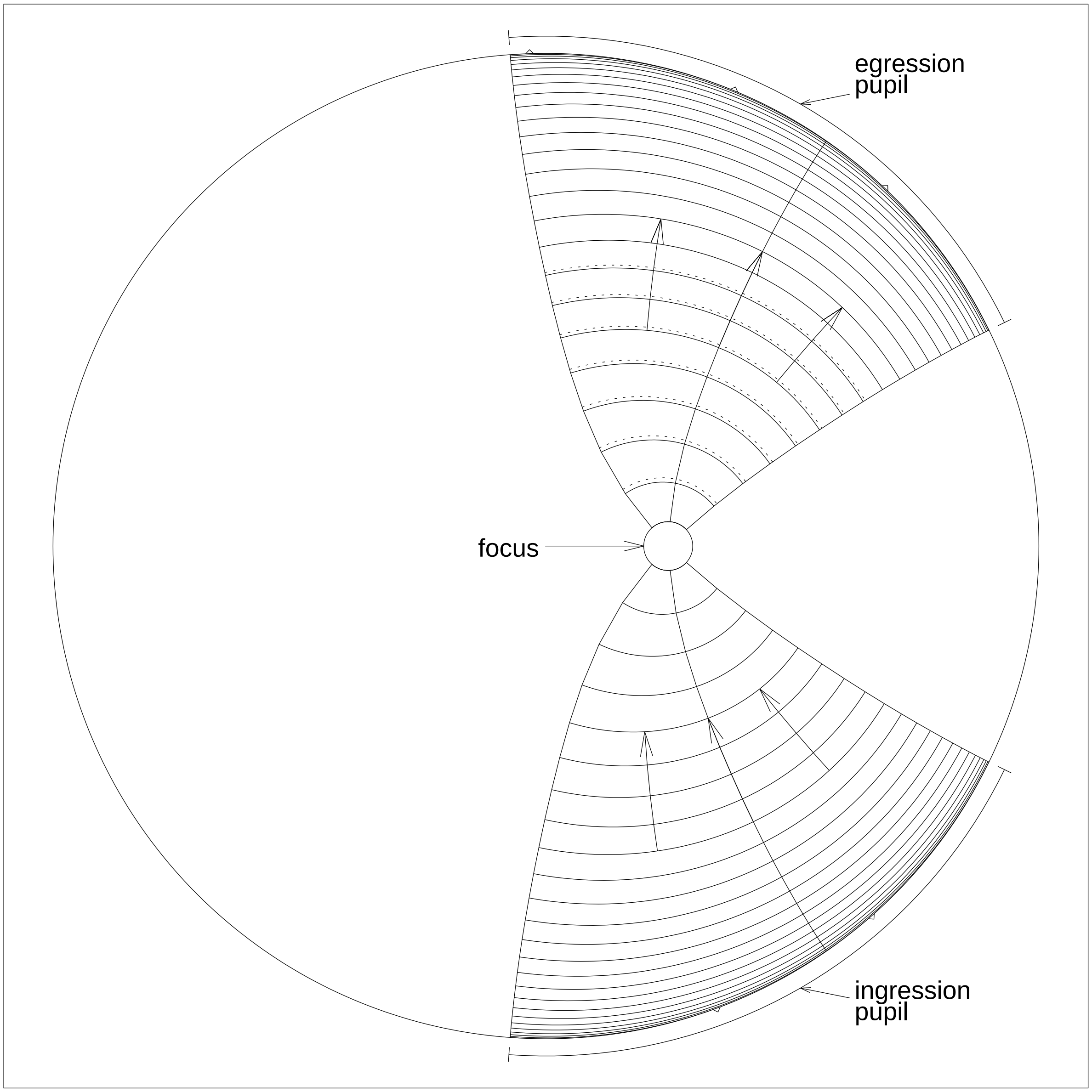

Figure 6: Wave configuration for phase-correlation imaging of the outer limit of the nuclear-burning core. The diameter of the acoustic sample at the focus represents the diffraction limit for 6 mHz acoustic radiation.

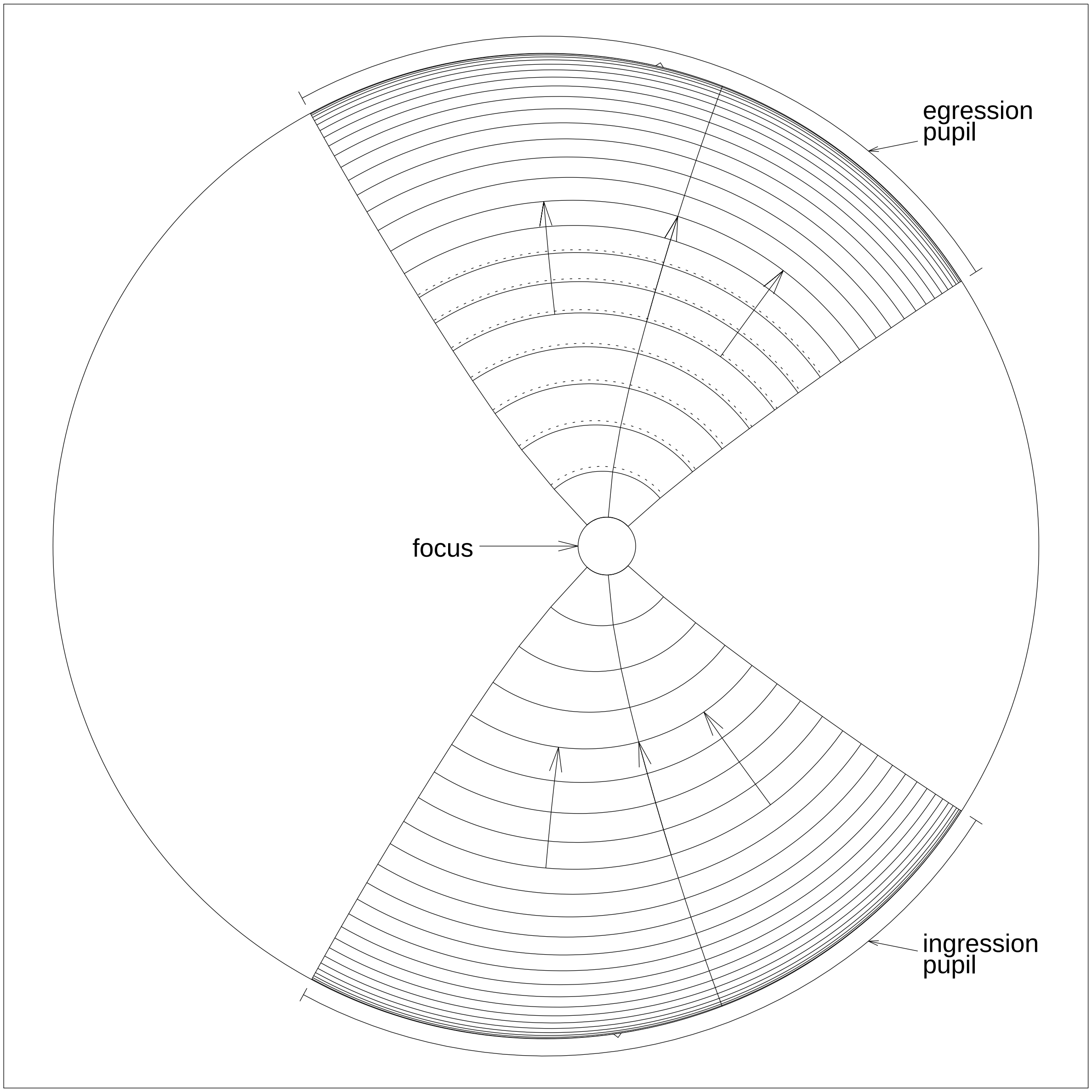

Figure 7: Wave configuration for phase-correlation imaging of the nuclear-burning core (radius 0.125 $R_\odot$).

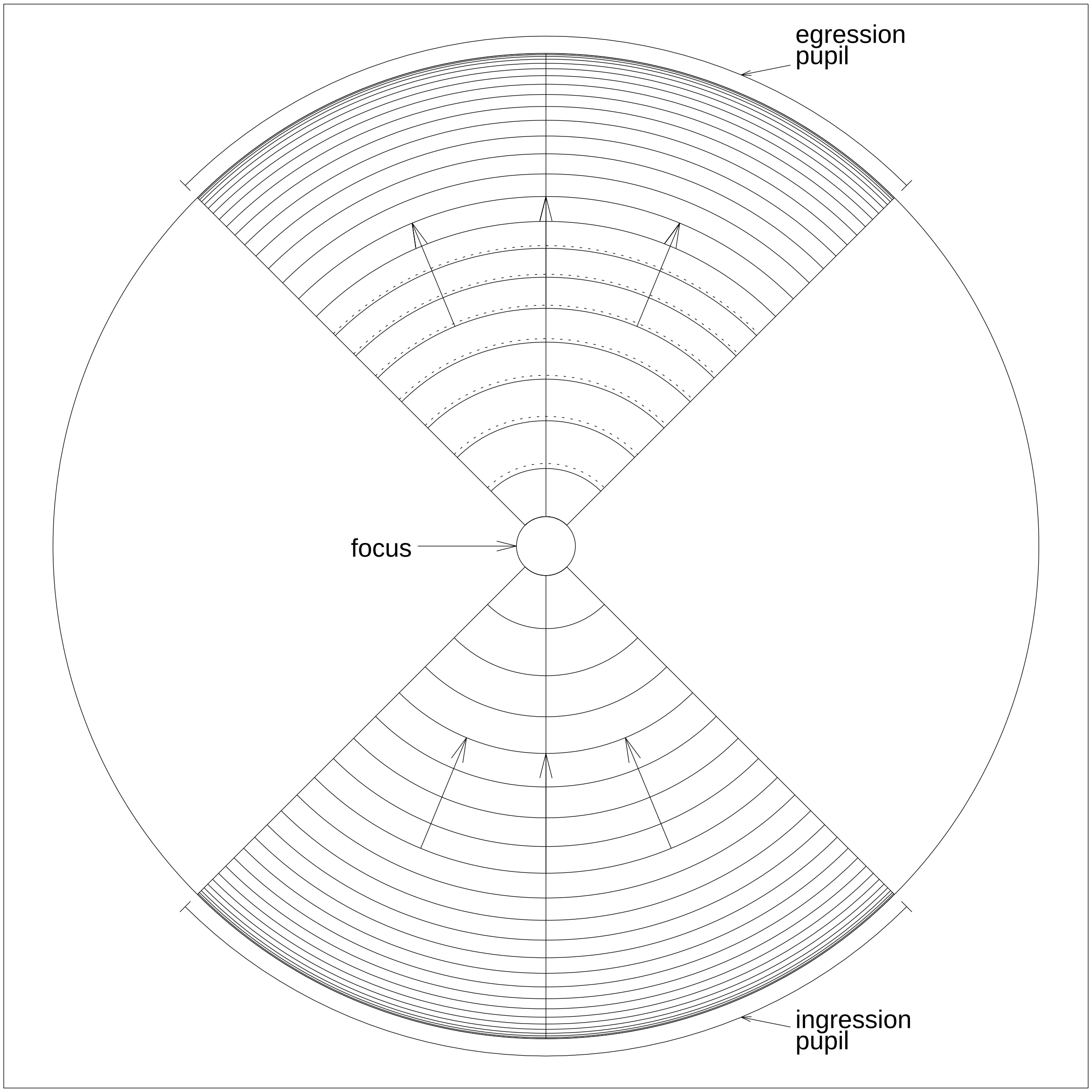

Figure 8: Wave configuration for phase-correlation imaging of Sun center.