THE SHOWERGLASS EFFECT IN SEISMIC DIAGNOSTICS OF ACTIVE REGION SUBPHOTOSPHERES

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ABSTRACT

A major obstacle that encumbers local seismic diagnostics of the shallow subphotospheres of strong active regions is phase errors introduced by overlying surface magnetic fields. These errors function as a sort of "acoustic showerglass" that obscures subphotospheric acoustic anomalies, scrambling computational images of these derived by phase-coherent seismic reconstruction. We develop a proxy based on the surface magnetic field to correct the showerglass phase errors and image acoustic scatterers beneath it. Preliminary applications of this correction give us signatures that appear to signify strong, sharply outlined acoustic anomalies 3–9 Mm beneath large growing active regions. Correction of the showerglass correction appears to be important, if not essential, for diffraction-limited diagnostics of acoustic anomalies in the shallow subphotospheres of strong active regions.

Key words: local helioseismology; helioseismic holography.

1. INTRODUCTION

Over the past decade helioseismology has begun to focus on solar interior diagnostics from the local perspective, now recognized as "local helioseismology." A major subject of interest to local helioseismology has been physical anomalies in the subphotospheres of active regions (e.g. Braun et al., 1992; Duvall et al., 1996). The interaction of active regions with acoustic waves in the *p*-mode spectrum is now well established. Active regions are known to exhibit strong absorption of solar interior *p*-modes that reflect from them (Braun, 1995) and to reduce travel times by up to a minute as compared to waves that reflect from the quiet solar photosphere (Braun, 1995; Fan et al., 1995; Duvall et al., 1996; Kosovichev, 1996; Hindman, 2000). Computational holographic images of active regions show "acoustic moats" surrounding large sunspots (Lindsey & Braun, 1998; Braun et al., 1998), and "acoustic glories," stochastic regions of enhanced high-frequency acoustic emission surrounding large, growing magnetic regions (Braun & Lindsey, 1999; Donea, Lindsey & Braun, 2000). These acoustic phenomena seem to be relatively superficial, characterizing the medium within a few Mm of the base of the active region photosphere (Braun & Lindsey, 2000a).

One of the major diagnostic utilities that local helioseismology borrows from electromagnetic applications is what can be regarded as the "optical perspective." The optical perspective is the basis of computational seismic holography, a diagnostic based on phase-coherent siesmic imaging of the solar interior acoustic field that is very much the analogy of the function of our eyes and other optical accessories with respect to light and other electromagnetic radiation. While it would be a dangerous mistake to suggest that local helioseismology *is* computational acoustic optics, we believe that the optical perspective is critical to local solar interior diagnostics, and that fundamental diagnostic limitations imposed by elementary optics are bound to apply to helioseismic diagnostics in general. A simple example is that of the effects of diffraction, which limits spatial discrimination of compact subphotospheric anomalies in the same way that optical diffraction limits the resolution of an optical microscope. As far as we are presently aware, the diffraction limit is fundamental to wave mechanics, and cannot be circumvented in practical terms by known alternative diagnostics.

The purpose of this report is to address the diagnostic impact of seismic phase errors introduced at the solar surface by magnetic fields. We propose to quantify the phase errors and establish the need for a magnetic proxy to correct them . This analysis will be expressed essentially in terms of the optical perspective.

The basic principle of computational siesmic holography is to extrapolate the surface acoustic field into the solar interior, into the neighborhoods of local acoustic anomalies. This is accomplished either forward or backward in time by computing fields of the form

$$H_\pm(\mathbf{r},\ \nu) \ = \ \int_\mathcal{P} d^2\mathbf{r}'\ G_\pm(\mathbf{r},\ \mathbf{r}',\ \nu)\ \psi(\mathbf{r}',\ \nu), \quad (1)$$

where $\psi(\mathbf{r}', \nu)$ represents the complex amplitude of the surface acoustic field at frequency ν and surface location $\mathbf{r}'$, and $G_\pm(\mathbf{r},\ \mathbf{r}',\ \nu)$ represents the Green's function that propagates an acoustic disturbance at $\mathbf{r}'$ to the "focal point," $\mathbf{r}$, in an acoustic model devoid of anomalies. In these computations, $\mathbf{r}'$ ranges over a region $\mathcal{P}$ called the "pupil" of the computation (see Lindsey & Braun, 2000). The focal point, $\mathbf{r}$, of the computation most conveniently ranges over any submerged "focal plane" chosen by the analyst or a range of such planes covering depths of particular interest. The forward extrapolation, H_-, in time is called the "acoustic ingression," whereas the time-reverse, H_+, is called the "acoustic egression." In practice, maps of the egression power, $|H_+(\mathbf{r},\ \nu)|^2$, show clear signatures of compact acoustic emitters or absorbers, the latter rendered as silhouettes, when these occur at or near the depth the focal plane.

Anomalous acoustic absorbers are well established in association with active regions, and even anomalous emission at relatively high frequencies. These show up clearly as silhouettes in egression-power maps. However, these seem to be quite superficial, and there is little evidence for the existence of either strong acoustic emitters or absorbers more than about a Mm beneath the solar photosphere. Besides these, the two most familiar prospective local acoustic anomalies recognized by local helioseismology are those characterized in terms of (1) "sound-speed" anomalies and (2) flows, to which we also refer as "Doppler anomalies." These anomalies, which act as scatterers, are invisible to simple acoustic power holography for lack of contrast. They simply replace acoustic radiation that they block by radiation scattered from some other direction. However, because these anomalies shift the phase of radiation passing through them, they can be clearly rendered by phase-correlation statistics. These are recognized by the terms "time-distance helioseismology" and "phase correlation holography." Efforts to model subphotospheric sound-speed and Doppler anomalies based on time-distance helioseismology include Duvall et al. (1996); Kosovichev (1996); Zhao, Kosovichev & Duvall (2001). The optical variation of this diagnostic, phase-correlation holography, is based on maps of the correlation

$$C(\mathbf{r}, z) \ \equiv \ \langle H_+(\mathbf{r}, z, \nu)\ H_-^*(\mathbf{r}, z, \nu)\rangle_{\Delta\nu}, \quad (2)$$

averaged over an appropriate range, $\Delta\nu$, in frequency.

A compact submerged acoustic scatterers will generally show a strong localized signature in $C(\mathbf{r}, z)$ when the focal plane of the computations is at the same depth, z, as the scatterer. When the focal plane is moved substantially above or below such an anomaly, the signature becomes defocused, and therefore diffuse, but does not otherwise entirely disappear. It is important to keep in mind the distinction between the forgoing exercise of extrapolating the acoustic field from the solar surface and modeling of the various acoustic anomalies that contribute to the acoustic signatures. Indeed, the holographic extrapolation expressed by equation (1) is based on the assumption that no such anomalies exist. While we believe that the problem of inverting holographic signatures to derive models of acoustic anomalies in terms of sound-speed and Doppler perturbations is straightforward under realistic conditions, we will not attempt to prescribe how to do this here. We are convince that the basic diagnostic requirements for physical modeling of acoustic anomalies are essentially the same as those for coherent holographic signatures—even if modeling is to be based on principles that circumvent holographic signatures.

We will now proceed with a brief summary of some elementary practical considerations that confront modeling of phase anomalies based on optical signatures.

1.1. The Born Approximation

Holographic diagnostics of a local anomaly are essentially based on how the anomaly shifts the phase of radiation that encounters it, as compared with the phase with which the radiation would have arrived at the surface if the anomaly had been absent. If the radiation arrives at the solar surface with a scrambled phase because it has passed through a swarm of other intervening anomalies, then the analyst is confronted with the basic problem of trying to "see" through a cloud or a fog bank. For purposes of seismic diagnostics of active region subphotospheres, we will say that the "Born approximation" is satisfied if a substantial fraction of acoustic radiation propagates from the focal plane of the acoustic extrapolation to the solar surface without undergoing further significant scattering. This means that the phase errors are kept comfortably less than a radian for a usable fraction of the radiation.

The function of a showerglass is to introduce stochastic phase variations in excess of a radian such that modeling based on the Born approximation is prohibitive. In the practical realm, it appears that modeling of any sort is prohibitive when the Born approximation is thoroughly violated. We have generally been forced to treat the problem of diagnostics through a showerglass as hopeless, at least within the confines of the optical context. We either must resort to extra-optical resources to remove the showerglass or flatten it (the function of windshield wipers, for example) or defer to an alternative diagnostic that is not encumbered with prohibitive phase errors.

1.2. Assessing the Phase Errors

Consider acoustic radiation impinging from the solar interior upward into the photosphere. How is the phase of that radiation shifted if a magnetic field is imposed at the surface? To make an assessment of this, we compute acoustic extrapolations, $H_-(\mathbf{r},\nu)$ and $H_+(\mathbf{r},\nu)$, integrating over pupils that are confined, as substantially as possible, to the quiet Sun, and whose focal points are located also at the surface but in regions with various magnetic field strengths. We then examine the respective correlations between $H_\pm$ and the local amplitude, ψ, at $\mathbf{r}$:

$$\mathcal{C}_\pm(\mathbf{r},\ \nu) \ = \ \langle H_\pm(\mathbf{r},\ \nu)\ \psi(\mathbf{r},\ \nu)\rangle \qquad (3)$$

Statistics of these correlations are plotted in Figure 1. In this exercise, we did not attempt to confine the pupil to regions of quiet Sun. As a result, the statistics plotted in Figure 1 may be somewhat of an underestimate of the actual phase errors. In any case, the phase errors plotted in Figure 1 strongly suggest that fields in the neighborhood of 200 Gauss are sufficient to endanger the Born approximation.

The differences between the phases of $\mathcal{C}_+$ and $\mathcal{C}_+$ are substantial, and consistent with travel time asymmetries previously reported by Duvall et al. (1996). They and other authors proposed that the travel-time asymmetries are the Doppler signature of rapid downflows beneath magnetic regions (Kosovichev, 1996). There is some question as to whether the phase inequality could be the result of other, non-Doppler effects. While this is an important issue, we do not propose to address this question here. In either case, it is evident (Braun, 1997) that the phase inequality is, at least in large part, a relatively superficial phenomenon, originating within a few Mm beneath the photosphere, and that it is significant over a broad range of frequencies for moderate or greater magnetic fields. On that basis we will proceed here to treat it as part of the acoustic showerglass with more of a regard at present for the problem of seeing beneath it than for settling its origin in physical terms.

Figure 2 shows egression phase errors for NOAA AR 8179 mapped in projected relief as prescribed by the egression phase plot in Fig 1a (solid curve).

The acoustic showerglass is only significant for diagnostics of the relatively shallow subphotospheres of strong magnetic regions. For these diagnostics relatively compact pupils are needed, which cannot avoid the overlying surface magnetic regions.

1.3. Correcting the Phase Errors

The correction of the showerglass by use of the magnetic proxy is fairly straightforward in principle. The observed local acoustic amplitude, ψ, at the solar surface is multiplied by the reciprocal of the correlation between egression, H_+, and local acoustic amplitude, ψ, as expressed by the magnetic proxy shown in Fig 2a. The egression is then computed as if this would be the amplitude observed if there were no showerglass. The local acoustic amplitude is likewise multiplied by the reciprocal of the magnetic

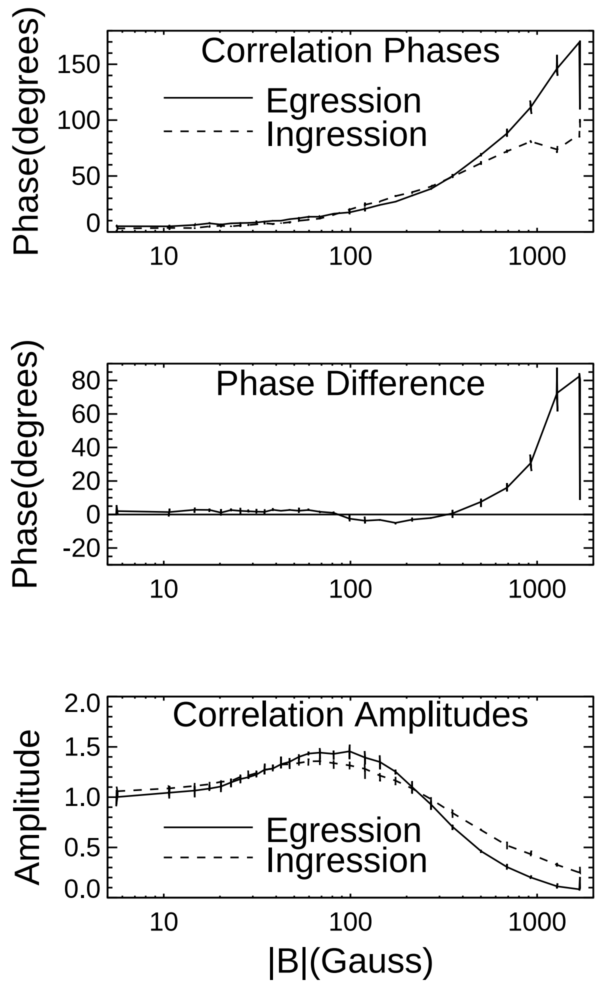

Figure 1. Correlations $\mathcal{C}_\pm$ between acoustic egression, H_+, (acoustic extrapolations backward in time) and ingression, H_-, (forward in time) and local acoustic amplitude, ψ, as functions of the magnitude of the surface magnetic field. The foregoing statistics were derived from helioseismic observations by SOHO/MDI of NOAA AR 8179 over the 24 hr period beginning on 1998 March 15 in the 4.5–5.5 mHz spectrum, and on line-of-sight magnetic observations also by the MDI instrument in the same timeframe. The full vector magnetic fields were reconstructed from the line-of-sight component under the assumption that the overlying magnetic field is the gradient of a potential. Panel a shows the phases, $\arg\{\mathcal{C}_\pm\}$, *of the correlations. Panel b shows the difference in the phases plotted in Panel a. Panel c shows the amplitudes of the respective correlations.*

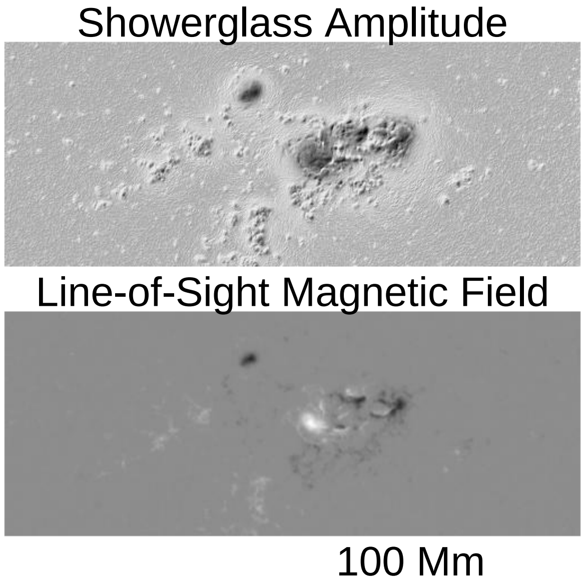

Figure 2. The acoustic showerglass for NOAA AR 8179. Panel a shows a map of the vertical magnetic field taken from SOHO/MDI on 1998 March 15 at 16:00 UT. Panel b shows a projected relief map of the egression correlation phase errors as prescribed by the curves plotted in Figure 1.

proxy of the ingression-local amplitude correlation before the ingression is computed. We then proceed as prescribed by equation (2) to make correlation maps of the subphotosphere.

A careful analysis comparing phase-correlation maps over a range of depths with and without the showerglass correction is under preparation for a forthcoming publication (Lindsey & Braun, 2002). The method used is an adaptation of that summarized above. Results at this point are preliminary, and we will only summarize them here. Correction of the acoustic showerglass in large active regions generally renders a considerable degree of fine detail in correlation maps up to 9 Mm in depth that is not substantially visible without the correction. Figure 3 shows an example: a showerglass corrected phase-correlation map of the egression-ingression correlation, C, of NOAA AR 8179 at depth 5 Mm. The active region signature at this depth is characterized by a strong seismic signature with a fairly sharp boundary spanning approximately 160 Mm from east to west and 65 Mm from south to north. The correlation between the C and the overlying surface magnetic field is actually quite weak on a fine scale. The acoustic signature extends far outside of the sunspots the east and west ends of the active region, and otherwise offers minimal acknowledgment of their existence.

Phase correlation maps of the subphotospheres of isolated sunspots generally show a somewhat less horizontally extended anomaly than that of a large active region, with radii ranging from 20–30 Mm. However, this extension is invariably far outside the outer boundary of the penumbra of the sunspot. An

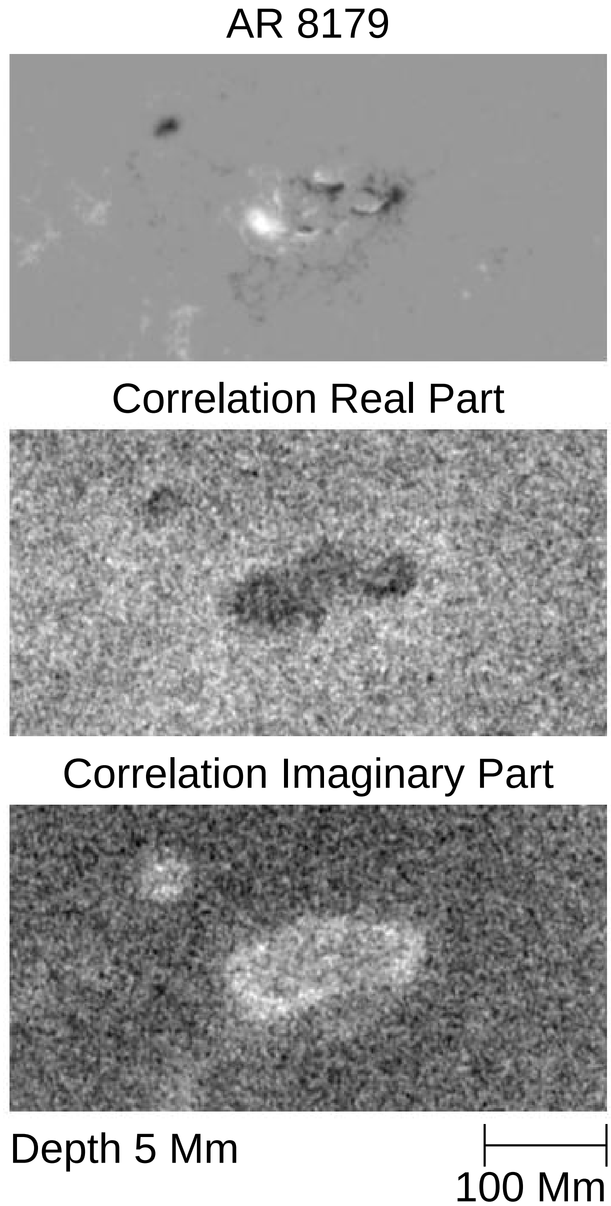

Figure 3. Phase correlation map of AR 8179 at depth 5 Mm computed after application of showerglass phase and amplitude correction. The top frame shows a magnetograph of the region. The underlying two frames show the real and the imaginary parts of the correlation function, respectively, integrated over the frequency range 4.5–5.5 mHz and over the 24-hr period beginning on 1998 March 15, 11:00 UT.

example is seen to the isolated sunspot (NOAA AR 8185) north-east (above and to the left) of AR 8179 in Figs 3b and 3c.

Preliminary control computations to determine the signature of a superficial anomaly are accomplished by moving the showerglass correction to a region of quiet Sun and computing the correlation maps as before. The result is a signature that is discernible at 8.4 Mm, but far out of focus and diffuse. The relative sharpness of detail in the correlation map shown in Fig 3b suggests that a considerable part of the acoustic signature appearing in Figs 3b and 3c is due to sharply defined acoustic anomalies in the neighborhood of that depth.

Figure 4 shows egression-ingression correlation maps of NOAA AR 9169 at depth 8.4 Mm with and without the showerglass correction. The active region signature in Fig 4b shows a strong seismic signature with point-like condensations and other fine detail in the near periphery of a large sunspot at the east (right) side of the active region (lower middle of frame). These details are essentially invisible when the phase correction of the showerglass is removed (Fig 4c), and still further suppressed if the amplitude correction also is omitted.

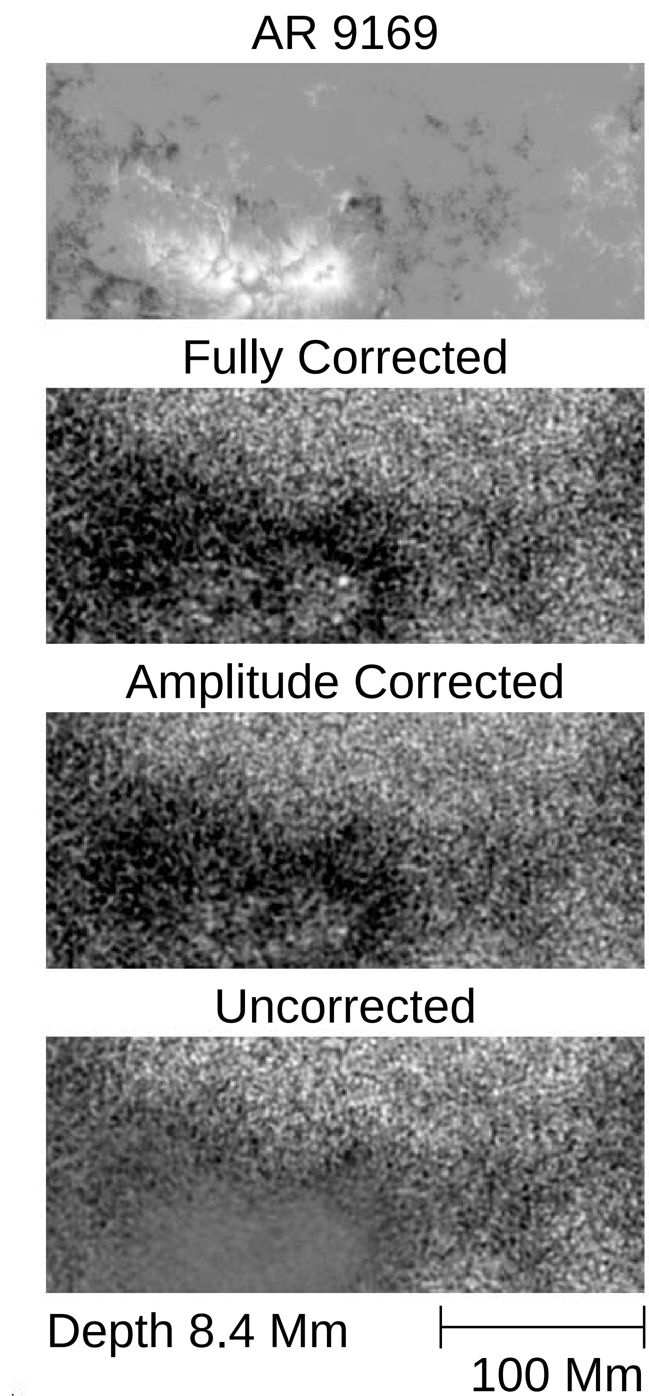

Figure 4. Correlation amplitude of AR 9169 at a depth of 8.4 Mm computed with and without the showerglass correction. Panel a shows a magnetograph of the region. Panel b shows the real part of the complex correlation amplitude, $C(\mathbf{r}, 8.4\ Mm)$, integrated over the 4.5–5.5 mHz frequency band and over the 24-hr period beginning on 2000 September 23, 13:00 UT. Panel c shows the same with the phase correction of the showerglass removed. Panel c shows the correlation map with neither a phase correction nor an amplitude correction.

1.4. Conclusions

It is evident that the effects of phase and amplitude errors introduced by strong surface magnetic fields degrade the coherence of acoustic radiation from subphotospheric acoustic anomalies. We have begun to explore the use of the photospheric magnetic field as a proxy for phase errors imposed by the acoustic showerglass. The proxy we have introduced here is relatively crude, but suggests that a realistic magnetic proxy is practical. It should be kept in mind that the assessment of the showerglass errors plotted in Figure 1 include anomalies that are submerged considerably beneath the photosphere along with the effects of the magnetic field at the extreme surface. The magnetic proxy presented here therefore removes not only the phase errors due to the showerglass but includes a sort of overall average of what lies beneath the showerglass when the phase errors are measured. At the same time, contamination of the pupil by magnetic regions during the error measurements may result in an underestimate of the actual errors. The function of the correction applied in this exercise is more rather that of replacing the showerglass with glass that is relatively flat but of an unknown thickness than that of removing the showerglass entirely. It simply makes it possible to see through the showerglass, thereby to reconstruct sharp images of underlying local structure that was otherwise obscured by the strong stochastic surface anomalies.

Figure 5 shows a plot of the phase of the correlation signature imaged in Figure 3 along the north-south direction in a strip 10 Mm wide that crosses

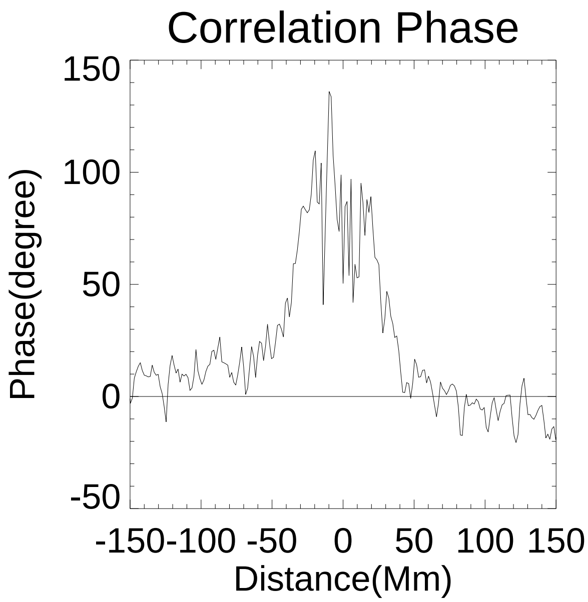

Figure 5. The phase of the correlation signature, C, of AR 8179 along the north-south direction in a 10 Mm wide strip that crosses the sunspot on the east end of AR 8179. The left of the plot represents south of the sunspot, at abscissa zero, with the right representing north.

the sunspot on the east end of AR 8179. The phase difference between the active region and the quiet Sun is approximately 80°. At 5 mHz, this is the equivalent to a time delay, Δt, of -44 s. The acoustic travel time in the quiet-solar subphotosphere, from the surface to a depth of 5 Mm and back is estimated at 1070 sec. This suggests a general enhancement, Δc, over the ambient sound speed, c, of order

$$\frac{\Delta c}{c} \;=\; -\frac{\Delta t}{T} \;=\; 0.04. \tag{4}$$

Statistical comparisons by Braun & Lindsey (2000b) of regions with the same surface magnetic field inside and outside of acoustic moats suggest one-way travel-times approximately 4 s shorter for roughly vertical paths through the moat anomaly to the solar surface. An estimate similar to that above gives a fractional sound-speed excess, $\Delta c/c$, of only 0.01 for acoustic moats if the anomaly is confined to a depth of 10 Mm. The discrepancy suggests that the phases plotted in Fig 1a are somewhat of an underestimate of the actual phase errors introduced by magnetic regions, and that a significant part of the phase signature plotted in Fig 5 is residual from the showerglass. This is a possible result of contamination of the pupil with magnetic regions when the phase errors plotted in Fig 1a were measured.

In summary, then the shower-glass corrected correlation maps suggest the existence of horizontally extended acoustic anomalies underlying large active regions with sharply defined boundaries 20 Mm or more outside of large sunspots. These anomalies show considerable stochastic fine structure particularly underlying the peripheries of the sunspots. The acoustic signatures we find, together with published statistics of phase anomalies that characterize acoustic moats, are roughly consistent with a fractional sound-speed enhancement of order 1% over the depth range 3–9 Mm. This assessment should be regarded as tentative. A careful examination including further control work is needed to judge whether such an interpretation is realistic.

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