The Acoustic Showerglass and Seismic Diagnostics of Active Region Subphotospheres

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Abstract

Efforts to reconstruct phase-coherent helioseismic images of active region subphotospheres confront us with disproportionate phase perturbations introduced by strong magnetic fields in the upper few hundred km beneath the photosphere. These phase perturbations have an effect similar to that of a shower glass in the electromagnetic spectrum, significantly impairing the coherence of waves from underlying acoustic anomalies. Helioseismic diagnostics based on a clear understanding of the acoustics of strong magnetic fields offer the possibility of a practical general model of the "acoustic showerglass" in terms of thermal structure and flows in the upper active region subphotosphere. Such a model can serve as the basis for a magnetic proxy that would facilitate an optical correction of the acoustic showerglass, significantly restoring the coherence of seismic images focused on thermal anomalies and flows 10–20 Mm beneath the photosphere. We are convinced that detailed hydromagnetic computations of subphotospheric acoustics are a major key to the control work needed for a realistic understanding of the structure and dynamics of active region subphotospheres.

I. Summary

A major obstacle that encumbers local seismic diagnostics of the shallow subphotospheres of strong active regions is relatively large phase shifts introduced by overlying surface magnetic fields. These phase shifts function as a sort of "acoustic showerglass" that impairs the coherence of acoustic waves impinging into the solar surface from below, degrading phase-coherent diagnostics such as time-distance correlation measurements and computational imaging of subsurface anomalies derived by phase-coherent seismic reconstruction.

Statistics of the "local control correlations,"

$$C_+ \;=\; \langle H_+ \, \psi^* \rangle_{\Delta\nu},$$

and

$$C_- \;=\; \langle \psi \, H_-^* \rangle_{\Delta\nu},$$

for the coherent acoustic egression and ingression, respectively, focused at the solar surface (see Fig 1a), allow us to relate showerglass phase shifts to surface magnetic fields. Maps of the local control correlations, and of the egression-ingression correlation,

$$C \;=\; \langle H_+ \, H_-^* \rangle_{\Delta\nu},$$

focused over a range of depths beneath the photosphere, show signatures consistent with an active region acoustic anomaly that is predominantly superficial. The local *ingression*

control correlation exhibits a phenomenon we call the "penumbral acoustic anomaly," characterized by a conspicuous increase in phase in regions of inclined magnetic field. The penumbral acoustic anomaly appears to be consistent with hydromechanical interactions between acoustic waves with magnetic fields in the photosphere and shallow-subphotosphere that involve mode conversion and acoustic absorption (Cally & Bogdan 1993, Cally 2000).

We have developed a rough proxy to represent showerglass phase errors as a function of the square magnitude of the vector magnetic field at the solar surface, inferred from cospatial line-of-sight MDI magnetograms. We apply the proxy to correct *SOHO*/MDI observations and use phase-correlation seismic holography to image the underlying 5–10 Mm subphotosphere. The corrected phase maps show no significant evidence for sound-speed anomalies beneath 5 Mm.

Results of this study suggest that more careful modeling of the acoustic showerglass will lead to greatly improved seismic diagnostics of active region subphotospheres. Detailed hydromechanical computations of acoustics models of active region subphotospheres are also needed to facilitate the interpretation of showerglass-corrected holographic signatures.

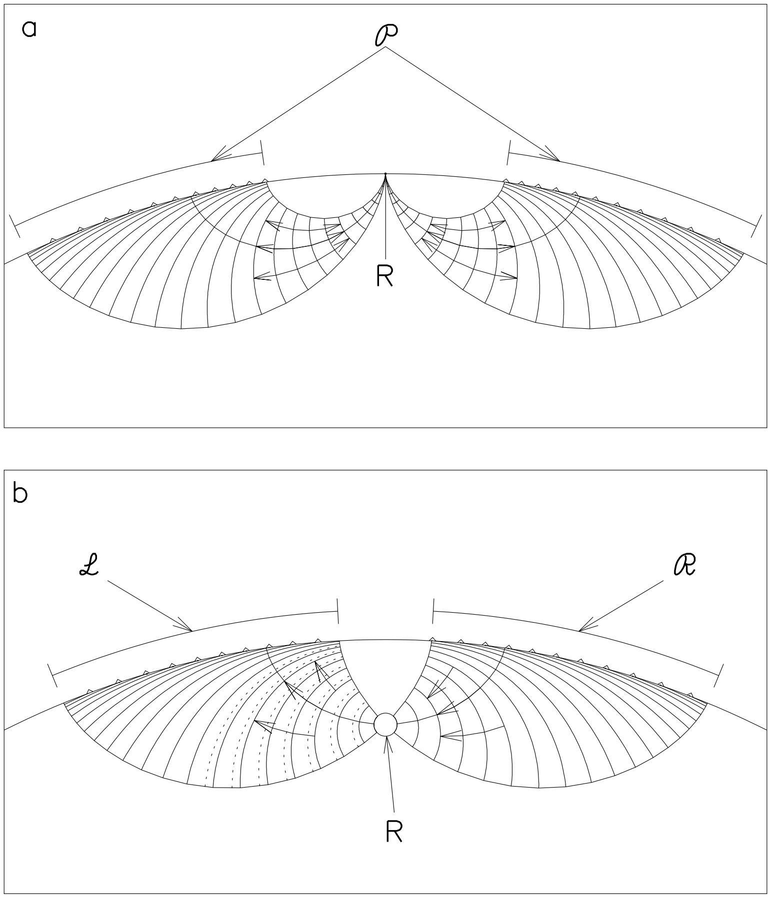

Fig 1: Conceptual diagrams illustrating (a) subjacent-vantage seismic holography of a relatively shallow focal point, **R**, from an extended pupil, $\mathcal{P}$, and (b) lateral-vantage holography of a significantly submerged focal point, **R**. The subjacent vantage, with **R** located at the solar surface, can be used to compare the magnetic field, **B**, at **R** with the acoustic disturbance to and from $\mathcal{P}$, thereby to assess phase errors introduced as the acoustic disturbance passes through the underlying showerglass. The lateral vantage is used to reconstruct coherent phase-correlation images of submerged acoustic anomalies through the showerglass.

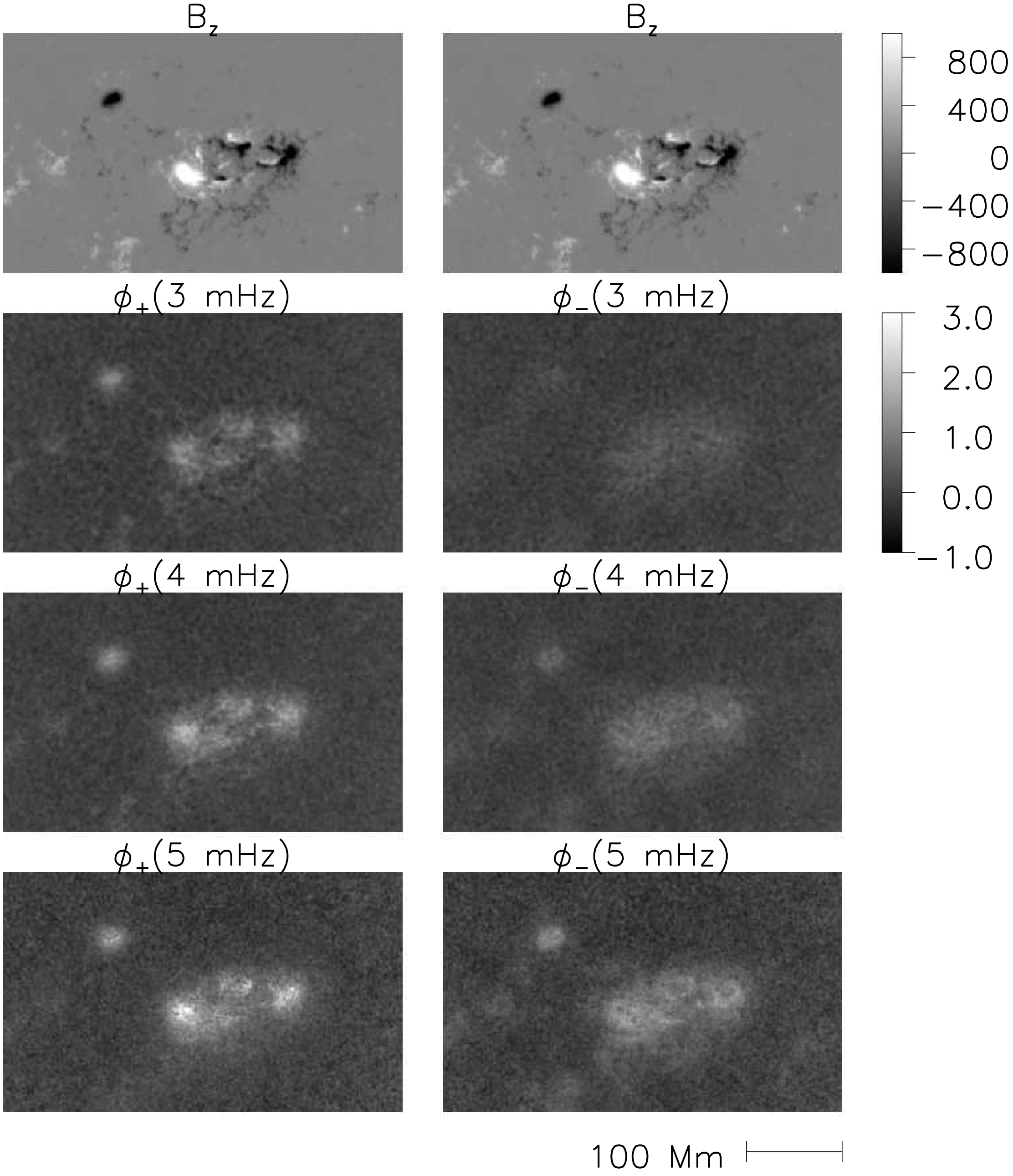

Fig 2: The phase asymmetry. The local control correlation, $C_{+} = \langle H_{+}\ \psi^{*}\rangle_{\Delta\nu}$, for the acoustic *e*gression departs significantly from the local control correlation, $C_{-} = \langle \psi\ H_{-}^{*}\rangle_{\Delta\nu}$, for the acoustic *in*gression in a strong magnetic region (NOAA AR 8179, 1998 March 15 11:00–35:00 UT). This, effect, discovered by Duvall et al. (1996) and sometimes attributed to flows, must be the result of an interaction between compression waves and magnetic regions that discriminates between temporal directions (past and future). We believe that the phase asymmetry in the 2.5–4.5 mHz spectrum is largely the signature of a strong absorbing interaction between compression waves and magnetic fields in the shallow subphotosphere (Cally & Bogdan 1993, Cally 2000).

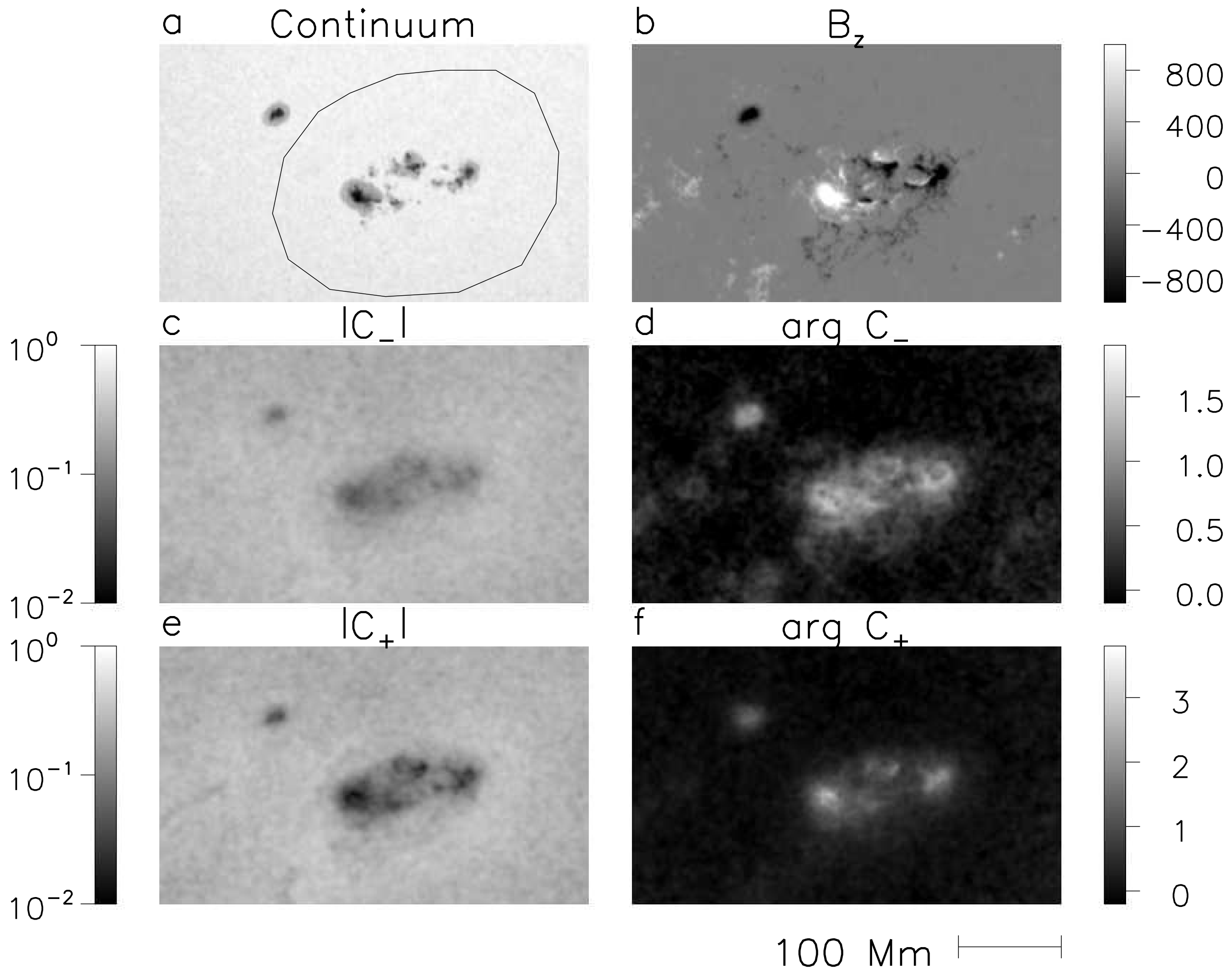

Fig 3: The penumbral acoustic anomaly. The local control correlation, $C_- = \langle\psi\ H_-^*\rangle_{\Delta\nu}$ for the acoustic ingression (NOAA AR 8179, same as above) shows a disproportionate phase shift in regions in which the magnetic vector, $\mathbf{B}$, is tilted, as it is in the penumbrae and near outskirts of sunspots. Maps of the phase of C_- (Frame d) therefore tend to show ring-like enhancements surrounding large sunspots.

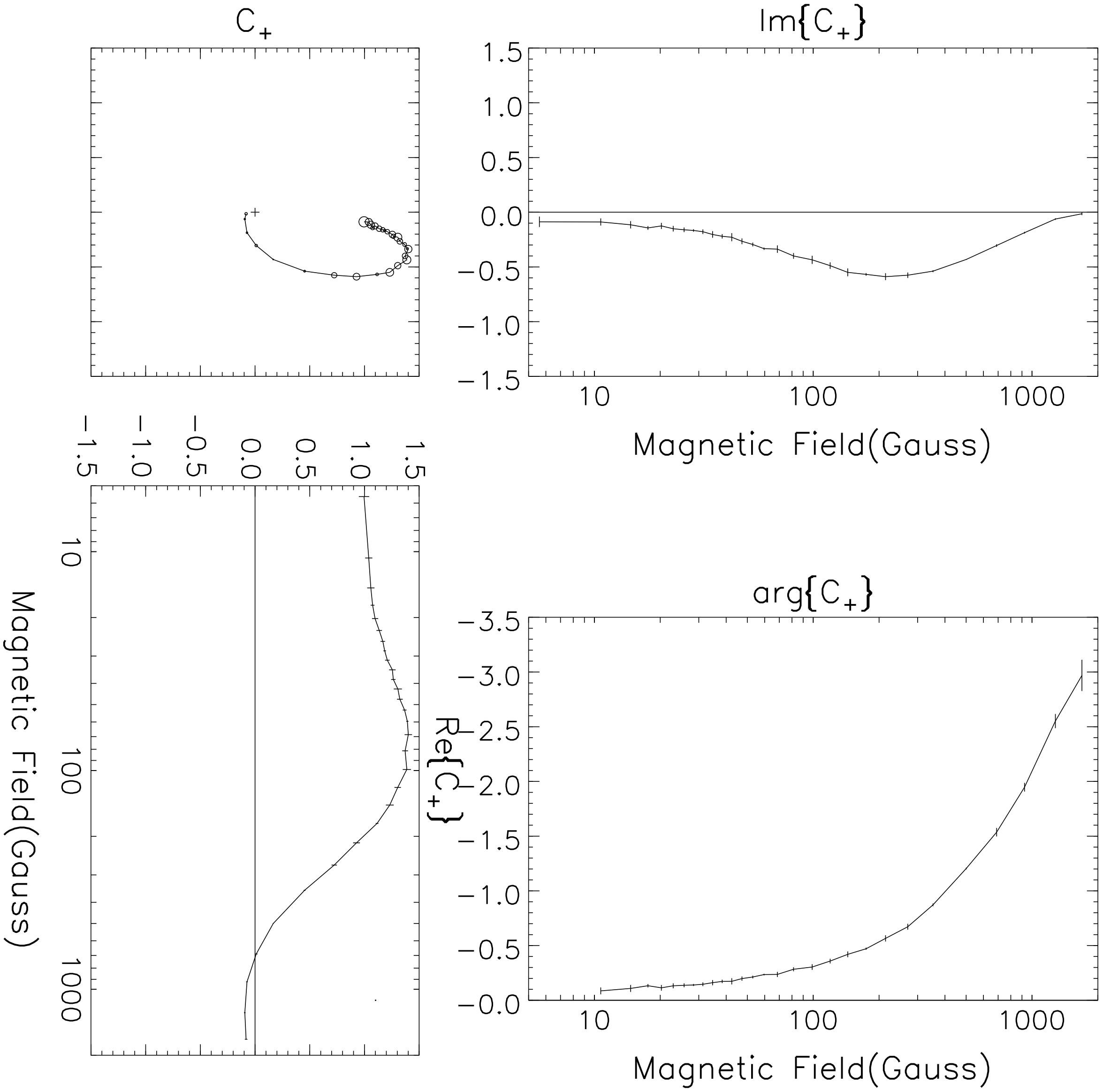

Fig 4: Diagnostic plots of of the local egression control correlation, $C_+ = \langle H_+ \, \psi^* \rangle_{\Delta\nu}$, as a function of the magnitude, B, of the magnetic field at the focal point over the region enclosing AR 8179 indicated by the contour drawn in Fig 3a. Top left panel shows the locus of C_+ in the complex plane over magnetic fields, B, ranging from 5 G–2 kG. Bottom left panel shows the real part of C_+ plotted as a function of B. Top right and lower right panels show the imaginary part of C_+ and the argument of C_+ (in radians), respectively, plotted as functions of B.

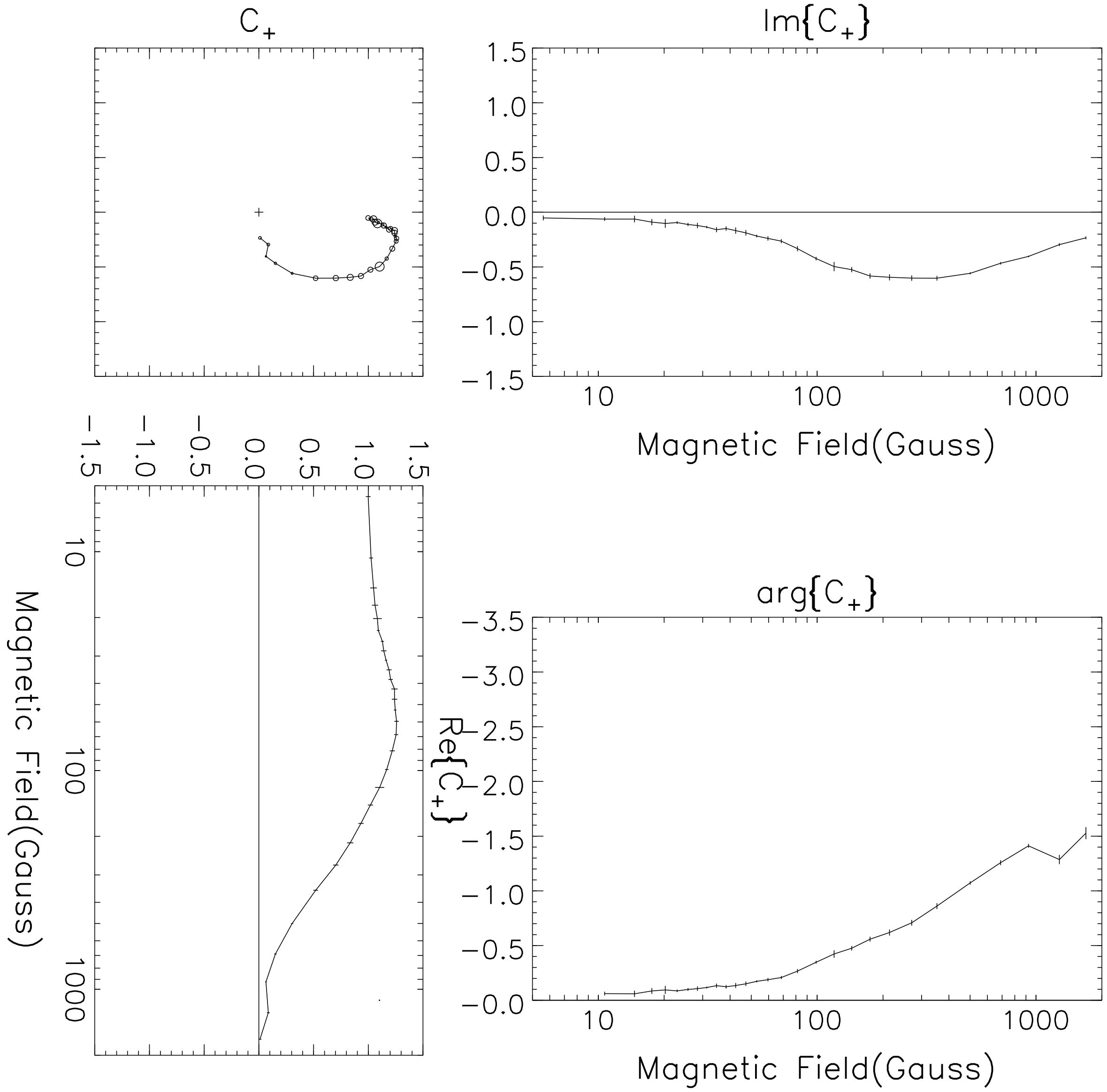

Fig 5: Diagnostic plots of of the local ingression control correlation, $C_- = \langle\psi\ H_-^*\rangle_{\Delta\nu}$. See Fig 4 for details.

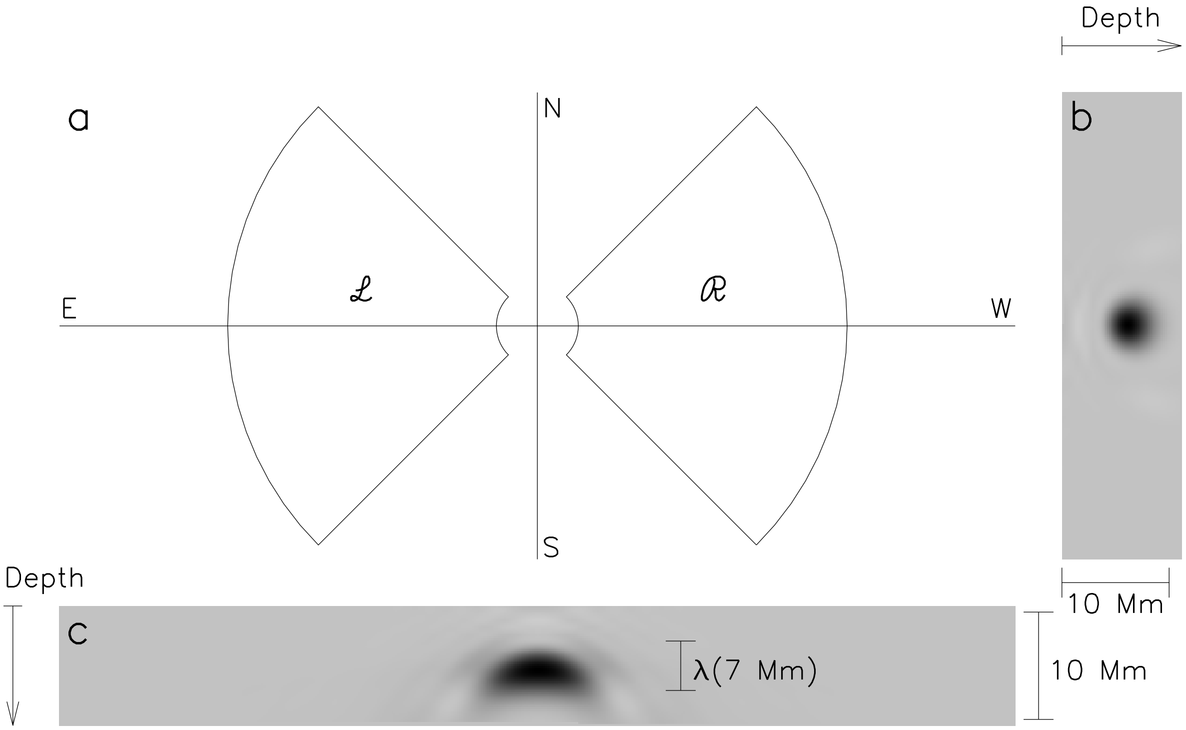

Fig 6: Pupil configuration for phase-correlation holography in the lateral vantage (Frame a, see also Fig 1b) with focus 7 Mm beneath the photosphere. Gray-tone frames, b and c, show the sensitivity of the phase correlation, $C = \langle H_+ \, H_-^* \rangle_{\Delta\nu}$, to a localized acoustic anomaly for 5 mHz acoustic radiation. λ(7 Mm) indicates the wavelength c/5 mHz at depth 7 Mm.

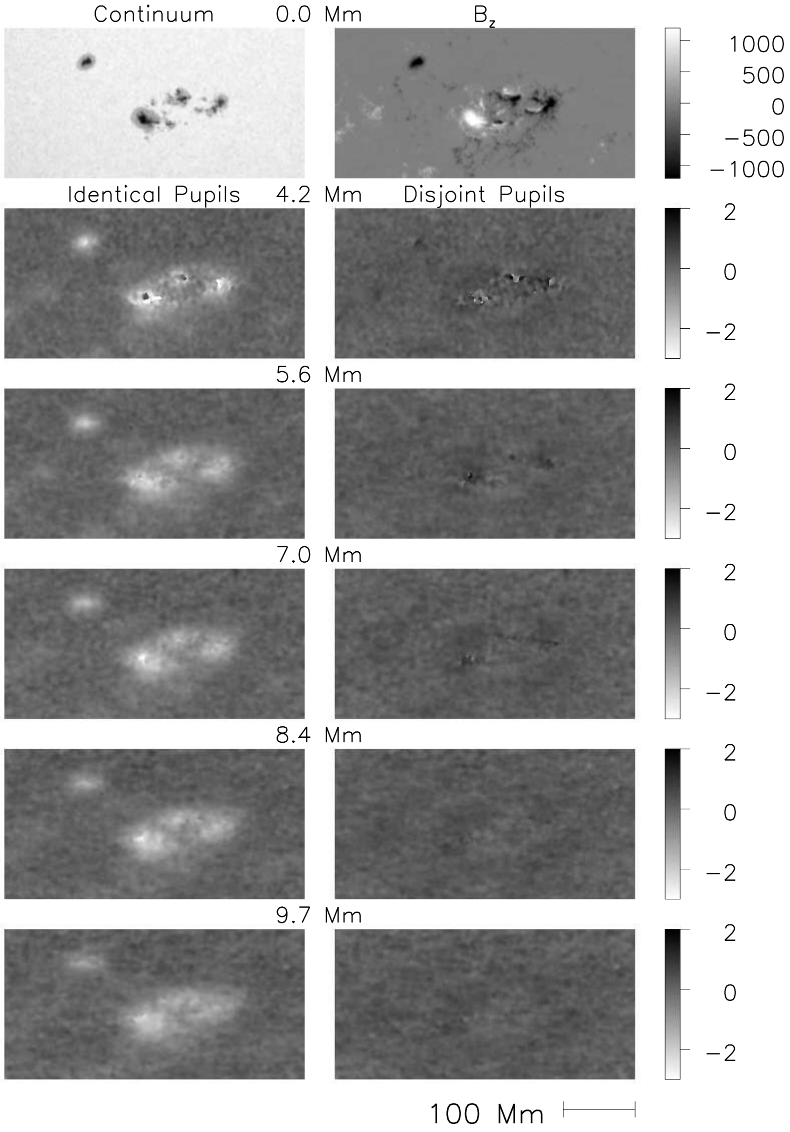

Fig 7: Lateral vantage phase-correlation holography of AR 8179 with no correction for the acoustic showerglass (left column) and with a phase correction determined by a proxy based on the square magnitude, B^2, of the magnetic field (right column). The uncorrected phase correlation signatures seen in the left column appear to be predominantly the result of a superficial acoustic anomaly equivalent to a magnetic depression of the photosphere up to 250 km in sunspot umbrae. A considerable fraction, possibly the entirety, of the residual signatures seen in the right column can be attributed to errors in the proxy.

II. References

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Cally, P. S. & Bogdan, T. L. 1993 *Ap. J.* **402**, 721.

Duvall, T. L. Jr., D'Silva, S., Jefferies, S.M., Harvey, J. W. & Schou, J. 1996 *Nature* **379**, 235.