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SEISMIC IMAGING OF THE FAR HEMISPHERE OF THE SUN

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ABSTRACT

We apply phase-sensitive helioseismic holography to *Solar and Heliospheric Observatory*/Michelson Dopper Imager data to demonstrate how acoustic travel-time perturbations may be mapped over the entire portion of the Sun facing away from the Earth, including the polar regions. In addition to offering significant improvements to ongoing space weather forecasting efforts, the procedure offers the possibility of local seismic monitoring of both the temporal and spatial variations in the acoustic properties of the Sun over all of the far surface.

Subject headings: Sun: faculae, plages — Sun: helioseismology — Sun: interior — Sun: oscillations — sunspots

1. INTRODUCTION

Magnetic fields in solar active regions both absorb and scatter incident acoustic (*p*-mode) radiation (Braun, Duvall, & LaBonte 1988; Bogdan et al. 1993; Braun 1995; Fan, Braun, & Chou 1995). Prompted by these discoveries, helioseismic holography was developed as a general diagnostic basis for local helioseismology, with the purpose of imaging acoustic sources in the solar interior and on the far surface of the Sun (Lindsey & Braun 1990, 1997, 2000b; Braun et al. 1992). Lindsey & Braun (2000a) recently presented the first seismic images of active regions on the far surface of the Sun, obtained by an application of phase-sensitive holography to data from the Michelson Doppler Imager (MDI) on board the *Solar and Heliospheric Observatory* (*SOHO*; Scherrer et al. 1995). This approach exploited the acoustic travel-time anomalies recently discovered in plages and moats surrounding sunspots (Braun & Lindsey 2000). These anomalies are considerably more horizontally extended than the compact (and stronger) travel-time perturbations previously found in sunspots (Fan et al. 1995; Duvall et al. 1996; Chen et al. 1998). Large active regions are therefore readily apparent in seismic images reconstructed using observations of low-degree global *p*-modes that can propagate long distances through the Sun without significant loss of coherence. Since this first application of far-side seismic imaging, Duvall & Kosovichev (2001) have also mapped travel-time perturbations in active regions on the far side of the Sun in a tomographic perspective. To facilitate space weather forecasting, seismic images of the central portion of the solar far side have been produced nearly continuously since late 2000 by a synoptic program that applies phase-sensitive holography to "quick-look" medium-resolution data from MDI.[1] All of the seismic images of the far side have to date been limited to a region of the Sun within a heliocentric angle less than about 50° from the antipode of disk center (ADC). In this Letter, we demonstrate how holographic procedures may be employed to produce diffraction-limited images of the entire far surface (and poles) of the Sun.

The basic principle of helioseismic holography is the phase-coherent reconstruction of the acoustic field within the solar interior from *p*-mode disturbances observed on the near surface. The acoustic field at the surface, observed over a limited region, called the pupil, is regressed backward through a solar model to a focal point at some distant location to express the acoustic egression, H_+ (Lindsey & Braun 1997, 2000b). The egression is an incomplete but coherent estimate of the acoustic disturbance propagating *out of* the focal point. Its time-reversed counterpart, the ingression H_-, expresses acoustic disturbances propagating *into* the focal point (see § 3 of Lindsey & Braun 2000b). In acoustic power holography, egression power images are formed by integrating $|H_+|^2$ over time, providing a diagnostic sensitive to acoustic sources and absorbers. Phase-sensitive holography is accomplished by temporally correlating the ingression and egression time series. Temporal shifts in the peak of the correlation are used to infer *p*-mode travel-time deviations, δt, caused by the presence of thermal and magnetic perturbations.

In the Sun, the sound speed increases with depth so that acoustic waves emitted downward into the interior are refracted back up to the surface. Waves in the 2.5–4.5 mHz frequency range then undergo a specular reflection at the solar surface, penetrating back into the interior where they are eventually refracted back to the surface thousands of kilometers further from the source. These waves retain significant coherence after several such "skips" to the surface. Multiple-skip holography at these frequencies allows us to image active regions in pupils far separated from the focal point. Lindsey & Braun (2000a) employed "two-skip" phase-sensitive holography to produce the first images of the solar far side.

As Lindsey & Braun (2000a) point out, the two-skip far-side imaging procedures are only practical for regions within about 50° from the ADC. Figure 1*a* shows the perspective involved when seismic methods are applied to a focal point placed beyond this range. Since only one side of the required two-skip pupil is actually visible on the solar disk, the phase correlation between H_+ and H_- is insignificant, even while the ingression and egression, computed from the visible portion of the two-skip pupil, remain individually significant. Figure 1*b*, however, illustrates how a one-skip pupil and its three-skip specular reflection about the focus may be used to form images

[1] See http://soi.stanford.edu/data/farside.

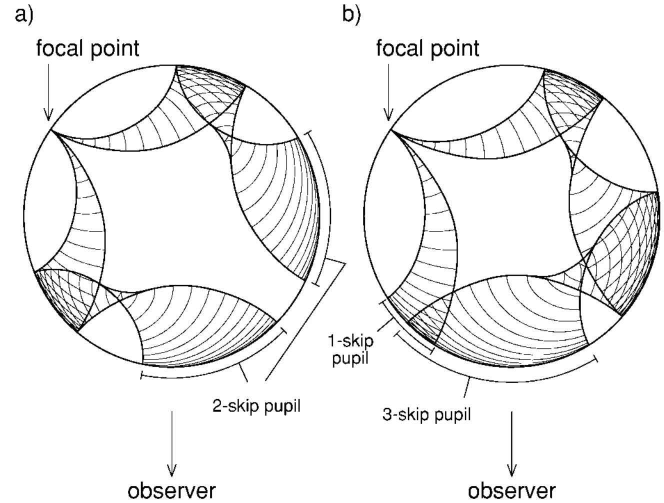

FIG. 1.—Far-side imaging for focal points significantly away from the ADC, showing (*a*) the limitations of using two-skip correlations and (*b*) the advantages of using one/three-skip correlations. Both panels show cross sections of the solar interior, as viewed from above the north pole of the Sun. Wave fronts emanate from a far-side point source (focal point), located at 55° from ADC, at intervals of 286 s within a corridor of trajectories reflecting a number of times from the solar surface to arrive at the near side. To avoid clutter in the diagram, the pupils illustrated in (*b*) are actually narrower than those used in the data analysis.

at this location of the focal point. Ingressions and egressions, coherently summed over the observed portions of the three- and one-skip pupils, should give rise to favorable correlations with the focal point placed close to or even directly on the solar limb. This idea was independently conceived by P. Scherrer (2000, private communication). A noteworthy feature of the perspective illustrated in Figure 1*b* is that the *p*-modes undergo the same number of reflections at the surface (three in this case) between the egression and ingression pupils as modes of comparable wavenumber employed in the two-skip computations. This appears to be critical since tests have indicated that increasing the total number of skips produces an undesirable degradation in the correlations. A combination of the two different methods illustrated in Figure 1 may be employed to yield images spanning the entire far surface of the Sun. This provides the principal motivation for the computations discussed below.

2. DATA ANALYSIS AND RESULTS

A 4 day interval of full-disk MDI Dopplergrams, obtained between 1999 April 22 and 25, was selected for the analysis. For each 24 hr interval of data, preliminary reduction consisted of (1) removing the spatial gradient in the Dopplergrams due to solar rotation, (2) remapping the Doppler signal to a Postel's projection tangent to the Carrington disk-center coordinate at noon UT, (3) de-trending each remapped pixel with a linear function in time, (4) Fourier-transforming the data in the temporal domain and extracting the signal between 2.5 and 4.5 mHz, and (5) collapsing by pixel summation in the spatial domain to a sampling resolution of $(0.016\ \mathrm{rad})^2$. For holographic applications with large pupils, we use the formalism expressed by equation (4) in Lindsey & Braun (2000b). The Green's functions in that formalism were computed from a solar model and correspond to acoustic waves propagating one, two, and three skips

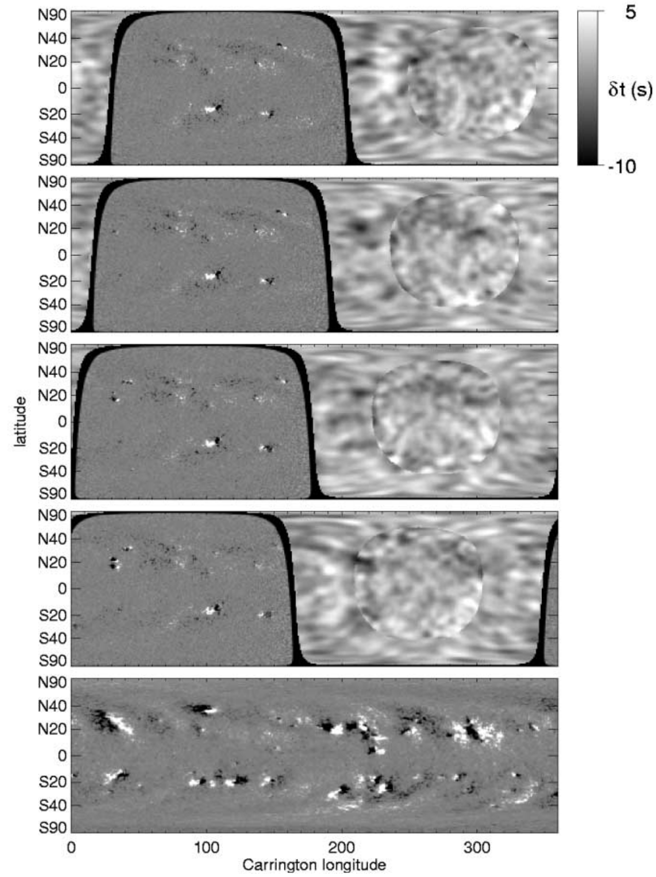

FIG. 2.—Composite images of the near-side magnetic flux density and far-side acoustic travel-time perturbations for the 4 days spanning 1999 April 22–25 (*top four panels*, proceeding downward). The circular discontinuities apparent around the center of the far-side images divide the two-skip correlations, computed within 48° of the ADC, from the one/three-skip correlations computed outside. The bottom panel shows a synoptic magnetogram for the subsequent Carrington rotation (1999 May 1–28).

from the focal point. It is important that these computations take proper account of dispersion near the solar surface.

Optimal pupils for each focal-point position were determined by requiring that each pixel in the egression pupil and the conjugate pixel in the ingression pupil be situated within a heliocentric angle of 75° from disk center as viewed by *SOHO*. (The "conjugate" is the pixel in the ingression pupil that is maximally illuminated by radiation emanating from the egression pixel after passing through the focal point and undergoing specular reflections at the surface.) The pupils span the ranges 57°–115°, 115°–172°, and 172°–344° from the focal point, for one, two, and three skips, respectively. At a frequency of 3.5 mHz, these pupils sample waves with spherical harmonic degrees l of up to $l \approx 40$, which imposes a diffraction limit of $\sim$10°. All correlations between egressions and ingressions were corrected for the effects of dispersion according to § 8.2 of Lindsey & Braun (2000b).

Figure 2 shows the travel-time perturbations computed for each of the 4 days in a longitude–sin (latitude) projection. The seismic images cover the entire far hemisphere of the Sun, extending approximately 3° *beyond* the limb onto the front side. Also shown is the line-of-sight magnetic flux density observed on the near side by MDI. The magnetic flux density is only shown for heliocentric angles up to 85° from (the near-side) disk center, thereby avoiding the artifacts in magnetograms that

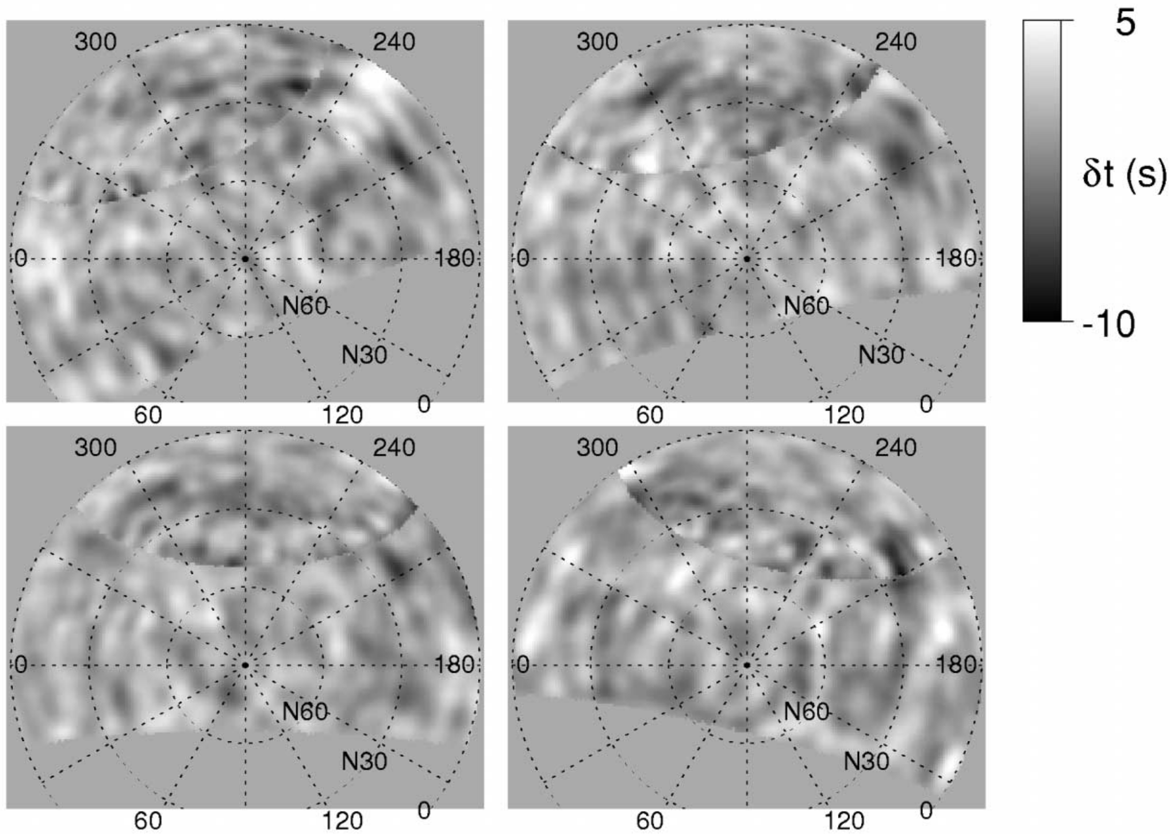

FIG. 3.—Acoustic travel-time perturbations in a Postel's projection centered on the north pole of the Sun and extending outward to the equator. The 4 successive days are shown proceeding left to right and top to bottom. The acoustic perturbations shown here cover the entire far hemisphere and extend approximately 20° beyond the limb onto the near side of the Sun. Selected latitudes and Carrington longitudes are indicated with a dotted grid.

often appear at the limb. In the far hemisphere, active regions are characterized by a reduction of up to 10 s in the one-way acoustic travel time. At least two active regions are visible on the far hemisphere. On 1999 April 22 (*top panel*), one of these (at Carrington longitude 210°) is clearly visible just a few degrees behind the limb.

Measurements of the rms of the travel-time perturbation as a function of the ADC angle were made to assess the quality of the far-side images. It was found that the rms for both the two-skip and the one/three-skip travel-time maps were comparable (rms ≈ 3.5 s) at an ADC angle of 48°. In the two-skip correlations, the rms falls off to ≈ 2 s as one approaches the ADC. A similar decrease in the rms is observed in the one/three-skip correlations as one approaches the limb. Averaging two-skip and one/three-skip correlations near 48° should reduce both the noise and the discontinuity appearing in this location. A smearing of the images, due to diffraction effects, in a direction perpendicular to the limb becomes noticeable at ADC angles approaching and surpassing 90°.

3. DISCUSSION

The application of helioseismic holography to the entire far hemisphere offers obvious enhancements to existing space weather forecasting efforts. It is noteworthy that the two regions most visible on the far side during the 4 days examined developed into significant centers of magnetic activity, as shown in the synoptic magnetogram (the bottom panel of Fig. 2) that illustrates the solar rotation over the following month. Synoptic images like those shown here will significantly improve our ability to forecast the appearance of large active regions up to 2 weeks in advance. Routine imaging of the entire hemisphere will also allow the detection of active regions that may emerge just a few days or less before they rotate into view.

Local helioseismic observations of the complete far hemisphere are also important for diagnosing and interpreting temporal variations in the acoustic properties of the Sun. Many studies performed over the past decade have provided evidence that the solar cycle variations of global *p*-mode frequencies are due to near-surface magnetic fields (e.g., Goldreich et al. 1991; Evans & Roberts 1992; Dziembowski & Goode 1997; Howe, Komm, & Hill 1999; Dziembowski, Goode, & Schou 2001). Braun & Lindsey (2000) have proposed that the global frequency variations are consistent with the sound travel-time reductions in active regions (primarily plages) that they and others have detected using local helioseismic analyses (Braun & Lindsey 2000; Hindman et al. 2000). This suggestion is similar to that put forth by Cunha, Brüggen, & Gough (1998), who considered only sunspots. It is now widely recognized that surface effects will need to be carefully appraised and removed in order to unambiguously detect signatures in the solar cycle variation of global frequencies caused by deeper perturbations. Gough (2001) has recently pointed out the importance of monitoring the temporal variations of the acoustic properties of the complete solar surface for a proper interpretation of the low-degree *p*-mode frequencies that sample the core of the Sun. It is certain that applications of both global and local helioseismic techniques will be necessary to fully address these issues.

Local diagnostics like those demonstrated here also make possible direct helioseismic studies of the polar regions. Figure 3 shows seismic images in a Postel's projection centered on the north pole of the Sun. Woodard & Libbrecht (1993) found a significant polar component to the 11 yr variation in global mode frequencies and suggested a relation to polar faculae (e.g., Sheeley 1991). Direct seismic imaging of acoustic perturbations near the poles, and indeed over the entire surface of the Sun, offers considerable diagnostic advantages over measurements of frequencies alone, which do not have any practical azimuthal or north/south hemisphere discrimination.

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