HELIOSEISMIC IMAGING OF SUNSPOTS AT THEIR ANTIPODES

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Abstract. Recent work by Braun, Duvall, and LaBonte has shown that sunspots absorb helioseismic waves. We propose that sunspot absorption causes a seismic deficit that should be imaged at the antipode of the sunspot. If these images are observable, it should be possible to produce seismic maps of magnetic regions on the far side of the Sun. This possibility opens a broad range of synoptic and diagnostic applications. Diagnostic applications would include lifetimes of higher-frequency modes, and possibly rotation of the solar interior and detection of subsurface magnetic structure. We outline elements of the theory of seismic imaging and consider some applications. We propose the extension of acoustic holography to solar interior diagnostics in the context of antipodal imaging.

1. Introduction

Recent work by Braun, Duvall, and LaBonte (1987, 1988) has shown the surprising result that sunspots absorb a substantial fraction of the seismic energy that encounters their cross-section. They find that wave modes, expressed in cylindrical coordinates centered about the sunspot, show considerably more energy flowing into them than out. This phenomenon is so striking that the presence of the sunspot is manifest in wave motion even when the sunspot itself is outside the region observed (Braun, 1988). We propose that the effects of this seismic absorption will manifest themselves at the antipode of the sunspot as a deficit in seismic power. The basic idea is that the spherical symmetry of the Sun as a wave-propagating medium should result in coherent focusing of the seismic energy deficit generated by the sunspot at the antipode. Ideally, this would mean that solar $p$-modes, properly analyzed, could provide us with a sort of seismic absorption map of the far side of the Sun.

It is important to understand that the seismic focusing we are considering is not direct refractive focusing of rays from the source to the antipode by the solar interior. Indeed, the refractive properties of the interior do just the opposite and result in the further divergence of rays emanating from a point, whereby most rays are turned prematurely back to the surface. The attainment of a focus depends on the seismic energy being trapped under the surface, repeatedly reflected back inward at each arrival to the surface, for sufficient time for each ray to explore the solar interior extending to the antipode. We will say that the ray trajectory walks around the Sun under its surface, where each

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encounter with the surface and reflection back into the solar interior is given the analogy of a single step. In a non-dissipative medium this walk carries seismic energy to the other side of the Sun, where spherical symmetry of the Sun results in its eventual coherent convergence at the antipode.

The quality of the resulting image is not as fine as that of a well-designed acoustic lens. Even in the ideal case of a non-dissipative non-rotating medium with perfect spherical symmetry, the point-source response function has broad wings that will degrade contrast. However, the sharpness of the core of the response profile is limited only by the availability of short-wavelength seismic waves to be absorbed by the sunspot and by the spatial resolution of the observations. Given reasonable signal to noise, it should be possible, in principle, to reconstruct the structure of the source to this resolution.

Antipodal imaging has already found terrestrial applications. Rial (1978) and Rial and Cormier (1980) analyzed the seismic image formed in the neighborhood of the antipode, in Europe, of an earthquake with epicenter in New Zealand. Butler, Brocher, and Rial (1986) suggest a variation of those measurements that would take advantage of occasional nuclear tests.

Besides the obvious synoptic utility of detecting sunspots or plage on the far side of the Sun, seismic focusing may offer useful interior diagnostic techniques. We propose the following possibilities:

(1) \textit{P-Mode Lifetimes}

The strength and contrast of seismic images will depend on the lifetimes of the modes that contribute to the image. Thus, image contrast can provide a useful diagnostic of the lifetimes of various \textit{p}-modes, particularly those that suffer considerable attenuation in only a single trip to the antipode.

(2) \textit{Solar Rotation}

Differential rotation should cause observable aberrations in seismic images at the antipodes of point sources. Observations of these aberrations may, thus, contribute to diagnostics of subsurface rotation.

(3) \textit{Other Sources and Sinks}

Seismic imaging of sunspots onto a region of quiet Sun may show us seismic qualities at a quiet antipode that are difficult to detect in the presence of sunspots and magnetic fields. Magnetic regions, for example, seem to suppress the local surface manifestation of a wave (i.e., the surface velocity- or brightness-amplitude) independent of whether they actually absorb wave energy. This superficial manifestation is eliminated at a quiet antipode, so a seismic deficit there assures us that wave energy has been absorbed. It is possible that antipodal imaging will reveal other localized seismic sinks, even perhaps sources, besides surface magnetic regions themselves.