The Stanford Synoptic Seismic Monitor
of the Sun’s Far Hemisphere

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Seismic Maps of the Sun's Far Hemisphere
Derived from Observations by
The Helioseismic and Magnetic Imager
aboard the
Solar Dynamics Observatory

1. Background

This article describes the Seismic Monitor of the Sun’s Far Hemisphere operating at the Joint Science Operations Center at Stanford for The National Aeronautics and Space Administration’s (NASA’s) Solar Dynamics Observatory (SDO), launched in February of 2010. This monitor is a data product computed from Doppler observations by the Helioseismic Magnetic Imaginer (HMI) aboard the SDO, to give us twice-daily seismic maps that identify and accurately locate moderate-to-strong active regions in the Sun’s far hemisphere. The work leading to the operational monitor posted began in the late 1990s, supported by NASA and NSF contracts, long before the advent of the SDO. Since the advent of SDO, it has been supported by NASA contracts NNH10CD50C, NNH11AQ241, NNX15AN51G and 80NSCC18KO063; and by NOAA SBIR contracts WC-133R-15-CN-0076 and WC-133R-16-CN-0116 to NorthWest Research Associates (NWRA) with subcontracts to the Global Oscillations Network Group (GONG) of the National Solar Observatory (NSO) and to the Joint Science Operations Center (JSOC) for the SDO project at Stanford University.

The data products described here are the fruit of work done by many contributors, among them the following: C. Lindsey, D. C. Braun and J. Werne at NWRA, F. Hill, I. González Hernández and T. Wentzel at NSO/GONG, M. Rempel at NCAR/HAO, and J. Zhao, P. Scherrer and R. Bogart at the SDO JSOC, at Stanford. It also includes international collaborators P. Cally and A.-C. Donea at Monash University, in Melbourne, Australia. It is especially, and unequivocally, the love-labor of the late Irene González Hernández, who can be fairly credited with taking seismology of the Sun’s far hemisphere from the precarious experimental proposition it was at the turn of the century, confronting head-on the intimidating array of technical and quality-control problems hidden within its bilge and making it the practical, reliable, synoptic program it is today with a growing audience of applications in space-weather forecasting.

2. Brief History

Informal discussions of the possibility of imaging solar activity in the Sun’s far hemisphere go back to the late 1980s between Douglas Braun, Thomas Duvall and Barry LaBonte, largely motivated by their ground-breaking work on sunspot seismology (Braun, Duvall & LaBonte 1988). This concept was formally introduced into the scientific literature by Lindsey & Braun (1990), and was a basis for the development of “helioseismic holography” (Lindsey & Braun 1990; Braun et al. 1992; Lindsey 1996; Lindsey
& Braun 1997, 2000b) as a diagnostic for this and other diagnostic applications. The first successful imagings of active regions in the Sun’s far hemisphere were reported by Lindsey & Braun (2000a) and Braun & Lindsey (2001), applying computational seismic holography in a spherically symmetric medium to helioseismic observations from the Michelson Doppler Imager (MDI) aboard the Solar Heliospheric Observatory (SoHO). These led to the fairly prompt establishment of synoptic far-side monitors, first applied to low-resolution helioseismic observations by SoHO/MDI, and soon after to Doppler observations by the Global Oscillations Network Group (GONG) (González Hernández et al. 2007, 2008).

The advent of the SDO/HMI became a third resource for the far-side seismic monitor soon after the SDO was launched, in February of 2010. This was implemented by NSO/GONG PI González Hernández with the help of R. Bogart at Stanford’s SDO/JSOC. It was upgraded and modernized over the remainder of 2010 and remains in operation today, producing twice daily synoptic seismic maps that identify and accurately locate moderate-to-strong active regions in the Sun’s far hemisphere.

The development of practical applications of seismic mapping of activity in the Sun’s far hemisphere since the first successful maps of the Sun’s far hemisphere, at the turn of the century, have been significant. We will proceed here with a description of the individual data products the far-side seismic monitor is now delivering and the applications for which it is intended to serve.

3. The Basic Data Product

The software that computes the data projects delivered by the far-side seismic monitor is available upon request to C. Lindsey clindsey@cora.nwra.com for implementation on single CPU’s running on linux. Because a large part of the data-processing task is condensing something like 32 GB of Doppler observations archived on the DRMS, twice daily It may not be practical to run the entirety of this operation on other than JSOC hardware, since this entails the telemetry for transferring JSOC observations to some other machine to repeat a condensation that has already been done at the JSOC. The software that computes the helioseismic images from the condensed data, also a standard JSOC data product, runs in about 15 minutes on a single linux or Mac CPU.

The computations for the far-side seismic monitor are now running on the Data Records Management System (DRMS) of the SDO/JSOC. It analyzes 31-hour time series of HMI Doppler observations twice daily to produce “seismic-crosscorrelation-phase” maps of the Sun’s far hemisphere, each representing seismic crosscorrelations over a 24-hr period. These maps are published as public domain on the website “http://jsoc.stanford.edu/data/farside”. The correlations on which these maps are based discriminate the acoustic field observed by SDO/HMI in terms of two components. The first is a component representing seismic waves traveling from the near hemisphere to a field of specific locations in the far hemisphere. The second component is the returning echo of the first. The field representing the correlation between the two has a phase that is sensitive to the presence of magnetic regions.
Figure 1. Composite maps of the Sun’s far hemisphere (amber) and the line-of-sight magnetic field (blue-gray) show NOAA AR11498 passing the far-side meridian (top), approaching the east limb (middle), and rotating into direct view (bottom) in the near hemisphere. The phase correlation signature is rendered in terms of the travel time perturbation, $\tau$, encountered by the echo from a magnetic region as compared to the quiet Sun.
The algorithm simply maps this phase as a function of location in the Sun’s far hemisphere. It is customary to represent this phase shift in terms of an equivalent travel time perturbation, \( \tau \). Figure 1 shows samples of the standard 24-hr far-side data product over the period 2012-May-25 (top) to -June-02 (bottom). NOAA AR11498 is seen passing the far-side meridian (top), approaching the east limb (middle), and rotating into direct view (bottom) in the near hemisphere. The phase shift of the seismic correlation described above is equivalent to a reduction of \( \sim 12 \) sec in the \( \sim 7\)-hr round-trip travel-time enjoyed by the echo returning from AR11498, a result of active-region structure that Braun & Lindsey (2000) propose to characterize in terms of an “acoustic Wilson depression.”

The reason for the 31-hr time series is the approximately 3.5-hour acoustic travel time from near to far hemisphere, and the same for the returning echo, the period over which the acoustic radiation traveling toward the focus in the far hemisphere and its echo correlate is reduced by the 7-hour round trip. Each far-side map, then, represents a correlation over a duration of \( 31 - 7 = 24 \) hr.

4. Cumulations of the Far-Side Seismic Signature

Greater sensitivity can be attained at the expense of temporal resolution by averaging the helioseismic signature over several days. For a considerable domain of purposes, the gain in sensitivity more than makes up for the loss in temporal resolution. A considerable quantity of magnetic flux can emerge into the solar photosphere in just hours, and this will not be readily apparent in 5-day cummulations of the helioseismic signature. However, once a large magnetic flux has emerged into the photosphere, however suddenly, it does not appear in the character of solar magneto-convection then to retract it, nor to otherwise abscond it except through diffusive processes that operate over a period of days. For a broad range of forecasting purposes, then, in which a newly emerged region will not be directly visible for days—but its conduct, once visible, is the subject of concern for some time thence, a 5-day cumulation of the helioseismic signature can be highly informative, clearly showing active regions whose travel-time deficit is of order 6 seconds.

Indeed, given the demographics of magnetic regions—a population that rapidly increases with decreasing magnetic flux, the cumulations greatly enhance the number of active-region signatures that can be regarded as securely bona fide. Figure 2 shows a sequence 5-day cummulations (composite with near-side magnetic maps) over a 15-day period at 3-day intervals. NOAA AR11890 is seen crossing the east limb into direct view at \( \sim 2013-11-02.5 \) to release a large number of C- and M-class flares over the succeeding three days. A smaller active region, FS-062W18S (see table on page 7) is rotating into view on 2013-11-10.0, while large active regions FS-034W06N and FS-006W11S approach limb crossings in 2.4 and 4.8 days, respectively.
Figure 2. Composite near-side magnetic and 5-day cumulative far-side seismic maps of the Sun over a 15-day period beginning with the most recent at the top.
5. The Strong Active Region Discriminator (SARD)

The frame with the dark blue background below identifies seismic signatures sufficiently strong to suggest that the associated active regions may have a potential impact on space weather at Earth. The signatures are given numerical designations (right color bar) in the order of their first recognition by the SARD.

![Graph and table showing solar activity and designations.]

<table>
<thead>
<tr>
<th>Designation</th>
<th>Centroid Lon (degree)</th>
<th>Centroid Lat (degree)</th>
<th>Strength</th>
<th>ETA at E Limb (yyyy-mm-dd.d)</th>
<th>Days from E Limb</th>
</tr>
</thead>
<tbody>
<tr>
<td>FS-2013-45</td>
<td>61.6</td>
<td>-16.0</td>
<td>511</td>
<td>2013-11-10.3</td>
<td>0.3</td>
</tr>
<tr>
<td>FS-2013-42</td>
<td>33.0</td>
<td>6.6</td>
<td>1646</td>
<td>2013-11-12.3</td>
<td>2.3</td>
</tr>
<tr>
<td>FS-2013-44</td>
<td>1.1</td>
<td>-13.0</td>
<td>1098</td>
<td>2013-11-14.8</td>
<td>4.8</td>
</tr>
</tbody>
</table>

Figure 3. Five-day cumulative map of the Sun’s far hemisphere (top yellow), and the line-of-sight magnetic field in the near hemisphere (blue) serves to define “large active regions” in in the far hemisphere, color coded in the middle frame and tabulated in the underlying table.
6. What Do the Helioseismic Maps Tell Us?

An rough intuitive grasp of the utility the seismic maps can offer us for space-weather forecasting can be gotten by comparing the images below:

![Helioseismic Maps](image)

Figure 4. Standard seismic map of the far hemisphere (top frame) on 2014-11-05.0 is compared with SDO/HMI visible intensity (middle left), line-of-sight magnetic (middle right) and AIA intensity maps of the near hemisphere in 1,700 Å(bottom left) and He I 304 Å(bottom right) on 2014-11-17, active regions designated “FS-101” and “FS-103” were in direct view from Earth. The total He I 304 Å attributed to FS-101 and FS-103 exceeds the entirety of the quiet Sun at solar minimum.
6.1 Relationship Between Helioseismic Signatures and EUV Intensities

Direct EUV observations of the Sun’s far hemisphere from NASA’s twin STEREO spacecraft have made it possible to compare the EUV brightnesses with the helioseismic signatures concurrently. This is the subject of Liewer, Qiu & Lindsey (2017). They evaluate the reliability of seismic signatures for a set of active regions selected from STEREO EUV (He II 304 Å) observations and plot the relationship between the strengths, $S$, of the helioseismic signatures and the EUV brightnesses, $J$, where the former, $S$, were significant. Their analysis finds (1) that the helioseismic signatures miss many active regions that show significant EUV emission, and (2) a large variation in EUV intensities that have significant helioseismic signatures. The latter show instances of different active regions whose helioseismic strengths, $S$, are very similar showing intensities, $J$, varying factors up to about six. Nevertheless, there appears to be a fairly sharp threshold in EUV intensity separating active having significant helioseismic signatures and those that do not.

Figure 5. Plot of a sample of He II 304-Å intensities, $J(AR)$, of active regions in the Sun’s far hemisphere and and the maximum strength, $S$, reached by their respective helioseismic signatures.
Liewer, Qiu & Lindsey (2017) recognize a possible bimodality in their distribution in $(S, J)$ that is most interesting. This suggests two distinct classes of active regions that have significant seismic signatures, one of which tends to be about twice as emissive as the other.

Liewer, Qiu & Lindsey (2017) are aware of the concern, stated in the Phase-2 Proposal (whose further development is summarized in §3.2, above), that the onset of the growth of the helioseismic is delayed and its decay expedited by saturation and diffusion, respectively. In response, they plot the maximum EUV brightnesses against the maximum seismic signature. The result is a significantly tighter distribution, but, nevertheless, one in which the same helioseismic signature can be correlated with maximum EUV intensities that typically vary by a factor of three.

6.2 Relationship of Seismic Sensitivity to Magnetic Fields in the Far Hemisphere

Neither the STEREO spacecraft nor any other have a magnetometer that can view any significant part of the Sun’s far hemisphere, hence, concurrent helioseisic and magnetic comparisons are not yet possible. It is possible to compare helioseismic signatures with magnetic signatures days later, after the magnetic regions have rotated into the near hemisphere (e.g., Figure 4, above). While this is very useful, active regions generally evolve considerably in the time taken to rotate from the far hemisphere to a favorable longitude from Earth vantage. So, while not throwing away the comparison between the far- and near-side signatures, we have capitalized upon our ability to seismically image active regions in the near hemisphere just as we do the far. This allows us to look at helioseismic, magnetic and EUV images—from HMI, HMI and AIA, respectively—all at the same time. It has the added advantage that helioseismic signatures in the near hemisphere have significantly finer spatial resolution, hence greater signal-to-noise, giving our statistics proportionately greater weight. Figure 6 shows a sample.

There are two primary questions:

1) What is the basic relationship between helioseismic signatures, $H$, and the magnetic flux distributions that elicit them?

2) How does the sensitivity of the seismic signature, $H$, to magnetic fields, $B$, vary with location in the far hemisphere?

The practical diagnostic theme in the first is, what can we learn about seismic signatures in the near hemisphere where we can see them concurrently with the magnetic fluxes that elicit them? The analogous theme in the second is, how might this sensitivity change in the far hemisphere where we cannot compare the two directly? The way the diagnostic works in the far hemisphere is sufficiently different from its near-hemisphere counterpart that we cannot realistically apply the former directly to the latter without further control. The second question is the subject of the Third Interim Progress Report, and is reviewed in §3.2. Our work on the first question has yet to be reported. We describe this now in §3.1, directly below:
6.2.1 Measurement of Seismic Sensitivity in the Near Hemisphere

Figure 7 shows a scatter plot of the 2-D association between (1) and (2) for AR11158 as mapped in Figure 6, above, in which the mean square magnetic field, $\langle |B|^2 \rangle$ (abscissa), is taken as a proxy for the local magnetic pressure. Here, we have extrapolated the vector magnetic field, $B$, from its line-of-sight component, $B_{\text{los}}$, mapped in the upper right panel of Figure 6 assuming that the coronal field is the gradient of a potential (i.e., a variation of the classical Neumann problem).

The seismic signature, $H$, is seen to be a highly non-linear function of $\langle |B|^2 \rangle$. It is most differentially sensitive to variations in weak magnetic fields and saturates sharply as the magnetic pressure exceeds 300 Gauss, i.e., magnetic pressures in excess of 4,000 dyne/cm$^2$. We think we broadly understand this in terms of a simple model that attributes the travel-time deficit that constitutes the helioseismic signature to the active-region photosphere being effectively depressed by local magnetic pressure, $B^2/(8\pi)$ (Lindsey, Cally & Rempel 2010). Because the gas pressure opposing the depression increases rapidly (approximately exponentially) with depth, the depression rapidly saturates as the magnetic pressure increases.
The actual relationship prescribed by our model fits the helioseismic signature, $\mathcal{J}$, to the function

$$\mathcal{J} \equiv h_0 \ln \left(1 + \frac{\langle |B|^2 \rangle}{B_0^2}\right)$$

(1)

of $\langle |B|^2 \rangle$, with $h_0 = -13.0$ sec, and $B_0 = 75$ Gauss, where “$\langle \ldots \rangle$” signifies the mean value of the contents of the brackets over a spatial-resolution element. Figure 8 shows a scatter plot of $\mathcal{J}$ prescribed by equation (1) applied to $\langle |B|^2 \rangle$ (ordinate), derived from the line-of-sight magnetic map shown in the upper-right panel of Figure 6, where the abscissa is now the helioseismic signature shown in the upper-left panel of Figure 6.

A model of seismic signatures in the far hemisphere can be formulated by smearing both $\mathcal{J}$ and $\langle |B|^2 \rangle$ to the spatial resolution of the far-hemispheric seismic maps. When this is

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Figure 7. Scatter plot of values of the helioseismic signature (ordinate) of AR11158 mapped in the upper-left panel of Figure 6 against the square magnetic field, $\langle |B|^2 \rangle$ (abscissa) of the same, derived by solving the Neumann problem for the line-of-sight component of the magnetic field mapped in the upper-right panel of Figure 6.
done, the points plotted in Figure 7 condense tightly about a nearly linear locus,

\[ J = h_0 \langle |B|^2 \rangle, \quad (2) \]

(Figure 8), in which \( h_0 = (4.0 \pm 0.05) \times 10^{-4} \text{ sec/Gauss}^2 \).

Figure 8. Scatter plot of values of the helioseismic signature imaged in the upper-left frame of Figure 6 (abscissa) and that prescribed by equation (1) applied to \( \langle |B|^2 \rangle \) (ordinate). The latter has been derived from the line-of-sight magnetic field imaged in the upper-right frame of Figure 6 assuming that the vector magnetic field, \( B \), of which it is a component, is the gradient of a potential above the photosphere. The conformation of the latter to the former can be taken as a gauge of how well equation (1) represents the effect of local magnetic fields on helioseismic travel-time perturbations, and, accordingly, how good a proxy the helioseismic signature is to local magnetic pressure.

This model is radically different from that proposed by González Hernández, Hill & Lindsey (2007), who, motivated by the same understanding as that stated in §3.1, that the helioseismic signature is subject to strong saturation, fit their samples of \( \langle B_{\text{los}} \rangle, H \) at far-hemispheric resolution directly to the profile prescribed by equation (1). In fact,
the scatter in the samples of $(\langle B_{\text{los}} \rangle, H)$ Hernández, Hill & Lindsey (2007) analyzed (Fig 8 of their study) was so broad that either form would most prospectively have fit the samples acquired about as well as the other. The major advantage of the form prescribed by equation (2) appears to be simply that of simplicity.

Figure 9. Reproduction of the scatter plot shown in Figure 6 in which both the helioseismic signature, $H$, (ordinate) and the mean square magnetic field, $\langle |B|^2 \rangle$ (abscissa) have been smeared by a Gaussian of radius of $5^\circ$ of arc on the solar surface, to match an approximately $16^\circ$ ($190$ Mm) spatial resolution of seismic maps of the Sun’s far hemisphere.

The reasons for the large scatter in the samples $(\langle B_{\text{los}} \rangle, H)$ analyzed by Hernández, Hill & Lindsey (2007) were (1) a delay of several days between the registration of the helioseismic signatures and the subsequent magnetic ones, (2) the unmatched spatial resolution between the maps of $H$ and $\langle B_{\text{los}} \rangle$, and (3) the line-of-sight component of $\langle B \rangle$ being used in place of $\langle |B|^2 \rangle$ (noting that the former passes through zero at strong magnetic neutral lines where the latter [hence the helioseismic signature] remains strong.
While the parameter $h_0$ in equation (3) is generally quite definite for any particular active region, it is generally less for a strong, compact active region than for a weak, diffuse one, and even for the same active region as the active region evolves from the first to the second. This is the subject of §6.2.2.

6.2.2 Locational Dependence of Seismic Sensitivity to Magnetic fields

Active region signatures undergo considerable changes during their transit across the far hemisphere. Without knowing how the sensitivity of the helioseismic signatures vary with location in the far hemisphere, we cannot between actual evolution of an active region from one day to the next and the active region simply moving from a location of lesser or greater sensitivity than that at its location the previous day.

To address this question, we assume, based upon symmetry, the sensitivity to be a function of radial distance from the antipode of disk center. We first examined statistics of helioseismic-strength profiles of large active regions transiting the far hemisphere, hence at a selection of radial distances from anti-disk center. It transpired that the variations in these profiles were large enough that the mean helioseismic-strength profiles were too noisy for a satisfactory determination of the relative sensitivity profile. We therefore resorted to a statistical analysis of much weaker variations in the helioseismic signature of which there were many more, indeed, several thousand. The results, plotted in Figure 10, were more stable than expected.
Figure 10. Sensitivity of the Stanford JSOC seismic monitor of the Sun’s far hemisphere as a function of angle, $\rho \equiv |\rho|$, along the solar surface from the antipode of solar disk center as if viewed from Earth.

Because of this, we now believe that larger-than-expected variations in the strengths of helioseismic signatures as they transited the far hemisphere are a signature of unexpectedly strong evolution in the basic helioseismic properties the active regions as they grow to their prime and subsequently decay. This is the subject of §6.2.3

6.2.3 The Temporal Profiles of Helioseismic Signatures

One of the features that confronted our initial efforts to calibrate helioseismic signatures to the EUV radiation they emitted was a remarkably large spread in the EUV intensities that could accompany helioseismic signatures in a narrow range of values, a range of about a factor of six from minimum to maximum. Eyeball estimates of individual temporal profiles, while indefinite, suggested that this may be due to both an anomalous delay in the initial growth of the helioseismic signature and an anomalously rapid decay thereafter. Liewer, Qiu & Lindsey (2017) show individual instances suggesting the latter trend (Panels b and c of Figure 9 of their study).

While the statistical weight of the profiles we have are insufficient to support a model to thoroughly clarify this supposed behavior, the relations expressed by equations (1) and (2) based upon our seismology of the near hemisphere offer a model that is both attractive and consistent with the statistics we do have: This is based upon the understanding that once magnetic flux is fully emerged, its evolution from thence is then subject to simple diffusion (Wang, Nash & Sheeley 1989). Hence the general area, $A$, over which the flux, $\Phi$, of either polarity is spread is proportional to the time, $t$, elapsed from that at which $A$ would extrapolate linearly back to nil. So, then, the mean magnetic flux density, $\langle |B_z| \rangle$, over $A$ decays in general portion to $1/A$, hence $1/t$, while the strength, $S$, of the helioseismic signature, an integral of $H^\dagger$ over area, is seen to be

$$S = \langle H \rangle A \propto \langle |B|^2 \rangle A \propto \frac{\Phi^2}{A^2} A = \frac{\Phi^2}{A} \propto \frac{1}{t}. \quad (3)$$

According to the model expressed by equation (2), then, the diffusive spreading of the magnetic flux with time is decidedly erosive of the strength of its helioseismic signature.

Extending the line of reasoning applied directly above to equation (2) back to equation (1) leads to a heliosiemic strength, $S$, that is also suppressed early in the emergence of new flux, for a different reason: the strong saturation of the helioseismic signature for fields exceeding about 300 Gauss, as seen in Figure 7. Newly emerged flux is compacted into intense concentrations in which the value of $H$, because of the foregoing saturation, is insufficient to make up for the loss in area, $A$, over which the flux distribution extends. This leads to $S$ taking the form

$$S = S_0 \frac{t}{t_0} \ln \left(1 + \frac{t_0^2}{t^2} \right). \quad (4)$$

† In the Second Interim Progress Report of the Phase-1 Project the helioseismic signature is expressed as $\Delta \phi$ (see equation [1] therein).
Figure 11 plots this in terms of the maximum value, $S_{\text{max}}$, reached by $S$ and the time, $t_{\text{max}}$, at which it reaches said maximum.

![Model Evolution of Helioseismic Signatures](image)

Figure 11. Temporal profile of the evolution of the strength, $S$, of a helioseismic signature according to a model of the effect of (1) saturation (see equation [1]) on strong magnetic fields when the region is newly emerged and (2) eventual diffusive spreading of the magnetic flux as the region ages.

Based upon the prevalence of active regions that have emerged just before crossing the Sun’s eastern limb without manifesting a significant helioseismic signature, we estimate $t_{\text{max}}$ to be of the order of two days.

### 6.2.4 Solar Cycle Dependence of the Background Offset in the Helioseismic Signature of the Quiet Sun

We have found that the helioseismic signature of the quiet Sun varies significantly over the solar cycle. The variation is of a sort that suggests that the solar radius at solar maximum is $\sim 6.5$ km less than at solar minimum. Figure 11 shows this profile over most of cycle 24.

The top panel of Figure 12, shows our determination of the seismic offset over most of Cycle 23 (top frame). This was compared with various aspects of the magnetic field over the concurrent near hemisphere. The bottom panel of Figure 12 plots the square line-of-sight magnetic field over the near hemisphere up to $75^\circ$ from disk center, i.e., the nominal pupil of the far-side seismic monitor. In principle, it might be possible by any number of avenues to combine a series of profiles such as that shown in the bottom frame of Figure 12 to conform to the helioseismic signature. However, it is doubtful to us that this would be stable in such a way as to conform similarly in subsequent solar cycles.
While the magnetic field in the near hemisphere may have a significant effect upon it, we are more inclined to believe that the seismic offset in the far hemisphere is also influenced by other significantly independent factors that have yet to be identified. While this is disappointing to the desire for an easy, accurate correction of the seismic offset from one cycle to the next, this is a much more interesting outcome scientifically.

As an alternative to the magnetic proxy, the offset for any solar rotation can be extrapolated with satisfactory accuracy from immediately preceding seismic offsets. Because the offset has prospective scientific value, and is a true signature of conditions that characterize the solar seismic environment, we do not propose at this point to remove it from the seismic maps. What is needed for space-weather forecasting on time scales of the order of the transit time of activity across the far hemisphere is to correct the threshold for the recognition of strong active regions by the SARD. This will be one of a series of upgrades planned for the SARD in cycle 25.

Figure 12. The quiet-Sun seismic offset within a circle of 18° radius centered in the far hemisphere from Earth vantage is plotted (top frame) for solar cycles 2411 to 2499. For comparison, the square line-of-sight magnetic field integrated inside of a circle of 75° radius centered in the near hemisphere is plotted in the bottom frame.
8. References


