The SDO/HMI Seismic Monitor of the Sun’s Far Hemisphere

Prologue

This article describes the Seismic Monitor of the Sun’s Far Hemisphere operating at the Joint Science Operations Center at Stanford serving the Solar Dynamics Observatory (SDO). The monitor is a data product of the Helioseismic Magnetic Imaginer aboard the SDO, computing twice-daily seismic maps of moderate-to-large active regions in the Sun’s far hemisphere. The work leading to the operational monitor began before the SDO was launched, in February of 2010. The work for this project was done over the past five years under NASA contracts to NWRA and NSO/GONG that include, most recently, NNH10CD50C, NNH11AQ241. The direct object of these contracts has been the implementation of parallel-processing facilities that have reduced the turn-around time of computational seismic holography from several hours to a few minutes. This gives us the benefit of publishing a seismic map of the Sun’s far hemisphere a few hours earlier than before. However, it has had the much greater benefit of facilitating diagnostics on a massive scale, the quick turn-around times allowing parameter based upon educated judgments between successive tests not possible on such a short time scale with single CPU devoted to each seismic computation.

The data product described here is the fruit of work done by many contributors, among them the following: C. Lindsey, D. C. Braun and J. Werne at NWRA, in Boulder, F. Hill and I. González Hernández at NSO/GONG, in Tucson, and M. Rempel at NCAR/HAO, in Boulder. 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.

Brief History

The project described here has been a collaboration between NorthWest Research Associates’ (NWRA’s) Colorado office, in Boulder, and the Global Oscillations Network Group (GONG) of the National Solar Observatory (NSO) in Tucson. Most recently, the work has been conducted under NASA Contract NNH10CD50C to NWRA, and NNH11AQ241 to NSO/GONG. However, the collaboration goes back years before these contracts, indeed, into the previous century, and in practice has not observed a boundary between separate contracts.

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 solar activity in the 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 Solar Dynamics Observatory (SDO) with its Helioseismic Magnetic Imager (HMI) became a third resource for the seismic monitor of the Sun’s far hemisphere, and this was implemented by NSO/GONG PI González Hernández with the help of Rick Bogart at Stanford’s Joint Science Operations Center (JSOC). This system has remained in operation over the term of SDO. The “preprocessing” computations have been run at the JSOC. The spherical-seismic-holography computations have been applied to these in Tucson, running on GONG hardware, and the resulting far-side maps published on the GONG website and by the Virtual Solar Observatory (VSO).

The most recent work in seismology of the Sun’s far hemisphere has focused upon the adaptation of the algorithm for computational seismic holography in a spherical environment to run on multiple processors in parallel, both on hardware at NWRA and NSO/GONG and on the Data Records Management hardware of the Joint Science Operations Center (JSOC) at Stanford. By far the pre-eminent application of this software has been, and so far remains, the seismic monitor of activity in the Sun’s far hemisphere, a standard data product of the SDO, and this has been the singular practical focus of the project in terms of nominal testing. This software is now running on the DRMS and delivering high-quality seismic maps of the Sun’s far hemisphere with a 12-hour cadence. These computations have been backdated to the beginning of 2011.

The practical value of the parallel processing has not been so much the ability to produce images of the Sun’s far hemisphere more quickly as other diagnostic benefits. Forecasting on time scales consistent with active regions that will rotate into view in up to two weeks is not significantly encumbered by computations that would run in two hours on a single CPU, as opposed to 15 minutes on a cluster, and the total computational labor is the same. The major value of the parallel computations has been the ability to run the algorithm diagnostically in a large variety of different contexts, view the results with a greatly reduced turn-around time, and formulate further diagnostics on a timely schedule to deliver further insight. The results of these diagnostic tests have been considerable improvements in the quality of the far-side monitor we now have, leading to a greater reliability in the identification of active regions presently in the Sun’s far hemisphere, lowering the detection threshold, and allowing us to identify many more active regions than we could before. The improvements opened by this new facility now appear
to be far from exhausted.

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 major data product the far-side seismic monitor is now delivering and the applications we know to be drawing upon this product.

In a technical context, we distinguish between the working software that computes the data product published by the far-side seismic monitor and the domain of data products it delivers. The software that computes the data projects delivered by the far-side seismic monitor is publicly available upon request to C. Lindsey at clindsey@cora.nwra.com for implementation on parallel-processing systems compatible with JSOC hardware. 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 is usually not practical to run the entirety of this operation on other hardware, since this would entail the telemetry for transferring these data to some other machine to repeat a condensation that has already been done at the JSOC. Because of this, the remainder of this article will focus upon a description of the data product the far-side seismic monitor presently publishes, i.e., seismic maps of magnetic regions in the Sun’s far hemisphere. Interest in acquiring the software, using it for further development, or applying it to other purposes is nevertheless welcome.

In practice, the data product has been a major part of tests that were essential in the development of a workable system. And, because the applications are highly specialized, knowledge of the data product appears to be far more useful to the public than instruction in how to run the computations oneself. Moreover, the quality of the data product says as much as we can presently say otherwise about the quality of the software itself.

The Data Product

The new far-side seismic monitor is now running on the DRMS 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. 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. Composite maps of the Sun’s far hemisphere (yellow) and the line-of-sight magnetic field (blue) 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.
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.

Improvements in the Far-Side Seismic Signature

A number of changes in the algorithm have been implemented to improve the sensitivity of the far-side seismic signature. These have been described in the quarterly reports. For this final report, we review a major one, which has been implemented in the HMI far-side pipeline. (This has yet to be implemented in the GONG pipeline, due to telemetry limitations that will soon be relieved.) In the original implementation of the far-side algorithm, for both SOHO/MDI and GONG, and even for SDO/HMI until recently, the spherical-holography algorithm has been applied to low-resolution Doppler maps, whose dimensions were something like $200 \times 200$ pixels. The limited resolution was basically a result of limited computing resources, which is still a practical issue, since the resources required go as the fourth power of the spatial resolution attempted (bearing in mind that whatever the observation offer, this is eventually limited by diffraction). But, there was also a limit imposed by telemetry of the image from the spacecraft, as well as from the individual GONG sites. The main problem with the low-resolution images was the damage caused by foreshortening approaching the solar limb.

In principle, this problem could have been solved by Postel projecting the high-resolution images made by the MDI and the GONG++ instrument before condensing them to a coarser resolution, aboard the SOHO spacecraft or at the GONG observing sites, respectively. This required computing resources exceeding those on both the SOHO spacecraft and the GONG observing sites at the time. For HMI, both telemetry and computing resources are plentiful for this purpose, as is the resolution of the Dopplergrams to which the Postel projections are applied. Figure 2 shows the resulting improvement, about a factor of two in signal to noise.
Figure 2. Comparison between seismic maps of AR11498 in the Sun’s far hemisphere (see arrow) computed from helioseismic observations coarsely sampled then Postel-projected (left frame) and a high-resolution Postel projection that is coarsely sampled (right frame) for the wave-optical computation that forms the seismic image.

**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 cumulations 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 such as that shown in Figure 3, below, can be highly informative, clearly showing active regions whose travel-time deficit is of order 6 seconds.
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 the far hemisphere, color coded in the middle frame and tabulated in the underlying table.
Figure 4. Five-day composite near-side magnetic and far-side 5-day cumulative seismic maps of the Sun over a 15-day period beginning with the most recent at the top.
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 4 shows a sequence 5-day cumulations (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 \(~2013-11-02.5\) 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.

**Applications of Far-Side Seismic Imaging**

The range of applications of seismic imaging of the Sun’s far hemisphere is far beyond what can be summarized in this report. We summarize here applications that have undergone rapid development in about the past five years.

*Solar UV Irradiance Forecasting.*

Fontenla et al. (2009) established the utility of seismic mapping of the Sun’s far hemisphere as a resource whereby to account for the contribution to the solar UV irradiance of large, newly emerged active regions in the Sun’s far hemisphere rotating into view from Earth. The need for these forecasts is largely based upon the role of the solar UV flux in inflating the terrestrial ionosphere and exosphere, and the strong effect this has on orbital decay rates of spacecraft and space junk.

Development of a synoptic forecasting system that incorporates helioseismic signatures of active regions in the Sun’s far hemisphere has proceeded under support from the Air Force Research Laboratory (AFRL), first under the MURI (Multiple-University Research Initiative) program, and subsequently under support of other AFRL resources (see Fontenla et al. 2011). Because active regions with similar magnetic indices can have considerably different UV emissivities, and this varies considerably over the UV spectrum, these forecasting systems also incorporate observations, by SOHO/SWAN, of Ly-\(\alpha\) radiation from far-side active regions back-scattered from the interplanetary medium on the far side of the solar system. The back-scattered radiation offers a more accurate quantification of the UV emissivity of a given active region but a very coarse appraisal of its location. The significant role of the helioseismic maps in irradiance-forecasting, then, is the accurate location of the SWAN sources.

XUV observations from STEREO offers a valuable resource for comparing far-side helioseismic signatures with coronal emissivity both in “real-time” and “real-place.” This utility, being developed by Liewer et al. (2012), shows a broad range of emissivities from regions that have similar seismic signatures. STEREO will continue to have full coverage of the Sun’s far hemisphere until 2019, provided it continues operation for this period.
**Forecasting the Global Solar Magnetic Index.**

The large variation in UV emissivities for strong helioseismic signatures appears to apply in a very similar way to the relationship with magnetic flux. Fontenla (2013, private communication) notes that the near-side correlation between magnetic flux and UV emissivity is not very strong. Our present understanding of helioseismic signatures suggests a much tighter relationship to magnetic flux than to UV emissivities (see, for example, Lindsey, Cally & Rempel 2012). This relationship has yet to be physically characterized or statistically quantified, but is the basis of a magnetic calibration of far-side helioseismic signatures by González Hernández, Hill & Lindsey (2007). The larger role of solar activity in solar variability motivates the recognition of a “global magnetic index” as a major element of our characterization of global solar structure. This global characterization includes helioseismic qualities, such as the “acoustic solar radius” (see González Hernández et al. 2009). The solar magnetic index is also a critical to our understanding of the variation of p-mode frequencies with the solar cycle.

The global magnetic index, while it may have a helioseismic characterization, yet to be established, must rely upon magnetic observations in the mean time. That magnetograms presently have access to only half of the Sun’s surface opens another attractive role for seismic observations of the Sun’s far hemisphere. This new role is introduced and developed by González Hernández et al. (2013).

**Coronal Magnetic-Field Forecasting.**

Carl Henney and Nick Arge, at AFRL, have developed a scheme for reconstructing models of the coronal magnetic field based upon line-of-sight magnetic observations of the photosphere. This undertaking is complicated by the lack of magnetic observations of the far hemisphere. A large part of the magnetic field in the far hemisphere can be accurately extrapolated by applying our understanding of flux-transport dynamics to magnetic observations made before rotation across the west limb of the Sun, hence the name “Air Force Data Assimilative Photospheric Flux Transport” (ADAPT) for the forecasting tool under development (see Arge et al. 2009).

Even the best of our present understanding of magnetic flux transport takes no account of flux emerging unseen in the far hemisphere. Seismic monitoring of the Sun’s far hemisphere, then, once again, offers a very promising resource whereby to secure a grip this major missing element. It has to be born in mind that the polarity of the emerging magnetic flux to be considered is crucial to the coronal-field configuration, and the seismic signatures are insensitive with respect to polarity. However, Henney et al. recognize that the relatively large active regions detected by the seismic monitor tend strongly to conform to Hale’s polarity law. The far-side seismic signatures, then, are recognized as an important element in coronal magnetic forecasting whose promise improves considerably with improved seismic sensitivity.
Outstanding Issues.

Further Improvements in Sensitivity.

Resources for further improvement in the sensitivity of far-side seismic signatures have been identified in the project that, for have yet to be implemented in either the HMI or GONG pipelines, for lack of sufficient time:

1. Inclusion of $2 \times 3$-skip correlations in the far-side seismic statistics, and

2. A realistic approximation to the Green’s function at the antipode of the focus that takes account of diffraction. The pupil in the $2 \times 2$-skip algorithm, which maps the far hemisphere out to $\sim 30^\circ$ from the antipode of disk center is encumbered with a “doughnut hole” within about $6^\circ$ of the antipode of the focus. The reason for this has been that the method we presently use to estimate the amplitude of waves emanating from a source at the focus, i.e., the Green’s function, (Lindsey & Braun 2000a), is based upon the ray approximation, and this manifests a singularity at the focus, which the pupil must avoid. We now have the formalism to represent the antipodal signature properly as an analytic diffraction spike. This allows us to eliminate the doughnut hole, to capture ripples that pass through the antipode and continue to the diametrically opposite side of the pupil, i.e., to ripples that have traveled a full $218^\circ$ from the focus instead of only $174^\circ$. This refinement inwardly extends the spatial spectrum of both the $2 \times 2$- and $3 \times 3$-skip advantages considerably.

Magnetic Calibrations.

The magnetic calibration of helioseismic signatures worked out by González Hernández, Hill & Lindsey (2007) appears to have been made obsolete by the increased sensitivity of the spherical-holography algorithm developed in the last three years. However, resources for further increases in sensitivity have been identified, and we expect them to be implemented in due time. So, maintaining a magnetic calibration will likely be somewhat of an ongoing process in the future.

Recent Publications

The nature of the project has involved the PIs and their collaborators in a broad variety of investigations that focus on the nowcasting of activity in the Sun’s far hemisphere and the use of this in the forecasting of activity in the near hemisphere. The following publications describe research based heavily seismic imaging of the Sun’s far hemisphere in the past three years. Additional relevant publications cited in the following “Reference” section describe other research important in motivating the far-side synoptic seismic monitor.


Other References


González Hernández, I., Lindsey, C., Braun, D. C. & Hill, F. 2008 “Combining Far-Side Maps from MDI and GONG to Improve the prediction Capability,” AGU SMSP41A, 04G.