FARSIDE HELIOSEISMIC HOLOGRAPHY: RECENT ADVANCES

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ABSTRACT

Both the Michelson Doppler Imager (MDI) and the Global Oscillation Network Group (GONG) programs have been calculating partial farside maps for some time, showing a high degree of agreement in detecting large active regions within approximately 45° around the antipode of the disk center. Recently, the full-hemisphere capability has been added to the farside pipelines of both instruments. We show here the capability of detecting large active regions and tracking them through out the full farside hemisphere by applying the technique to active region 10808. We also report on efforts underway to calibrate the farside signal in terms of equivalent magnetic field.

Key words: Sun; Helioseismic Holography; Far side; Active Regions .

1. INTRODUCTION

Until recently, the ever-changing magnetic activity on the solar surface could only be studied when the activity was on the side of the Sun facing the Earth. Helioseismic holography, developed by Lindsey & Braun [4], made it possible to map the magnetic regions on the non-visible or *farside* of the Sun.

Phase-sensitive seismic holography is based on the comparison of waves going in and out a particular point (termed *focus*) in the Sun. The waves propagating outward from the focus are called the egression and the waves converging towards the focus are called ingresion. An anomalie at the focus results in a phase shift between the ingression and egression, these are calculated from the wavefield observed in a *pupil* at the solar surface. In the case of farside seismic holography, the focus is located at the far hemisphere of the Sun, while the pupil is a circular surface surrounding the antipode of the focus point at the near side. Moving the focus point through the far surface of the Sun, and the corresponding near side pupil, maps of phase shifts (or time delays) can be constructed. Those areas with significant phase shifts are interpreted as regions with strong magnetic field.

Since the technique was applied in 2000 to SOHO/MDI [6], the method has proven to be capable of locating large regions of magnetic activity on the farside and tracking them before they emerge to face the Earth.

2. RECENT ADVANCES

The helioseismic holography principles were applied to the Michelson Doppler Imager experiment on the Solar and Heliospheric Observatory (SOHO/MDI) by Lindsey & Braun [6] and have since successfully led to the routine near-real-time imaging of the Sun's far side using SOHO/MDI, the results of which are available at http://soi.stanford.edu/data/farside.

In the last few years, the Global Oscillation Network Group (GONG), has developed the infrastructure needed to continuously calculate farside maps on a daily basis, coupling its efforts to the Michelson Doppler Imager (MDI) program. GONG is now continuously calculating farside maps of the Sun using the helioseismic holography technique. Each map, which is updated and displayed every twelve hours, uses a 24-hour-period of near-real-time images sent to Tucson from GONG's six worldwide network stations. The latest farside maps, along with archived maps, a movie and links of interest, can be found at http://gong.nso.edu/data/farside

Recently, the construction of far side maps has been improved by combining information from two different ray paths, as shown in figure 1. The ray paths are known as the 2-2 skippath and the 1-3 skip path. In the 2-2 skip path, the sound wave makes two skips both before and after encountering the sunspot. With the 1-3 skip path, the sound wave makes one skip before (or after) encountering the sunspot and three skips after (or before). As Figure 2 shows, the 2-2 skip path can provide information only about the inner $\pm 55°$ side, while the 1-3 skip path samples the angular range of about 50° to 90°. The combination of the two ray paths provides information over the entire far side hemisphere, with an overlap of about 5° that is used to normalize the two images.

Since full operation of the GONG far side pipeline began in August 2005, solar activity has been relatively low.

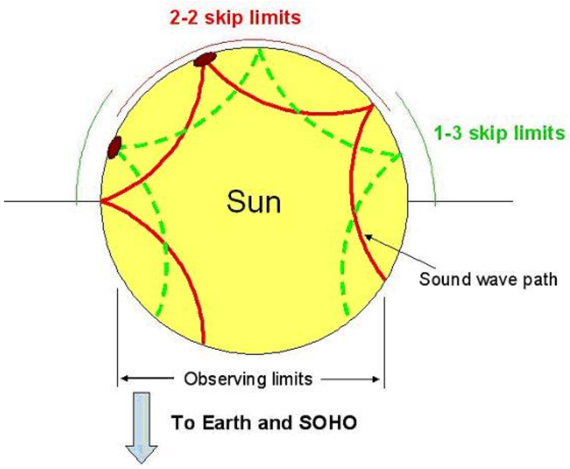

Figure 1. A schematic showing the ray paths for the 2-2 skip (solid red line) and 1-3 skip paths (dashed green line) for imaging the far side. The combination of the two paths provides an image of the full far side hemisphere.

However, the comparison between the calculated far side maps using the SOHO/MDI instrument and GONG for large active regions has been very successful. Figure 2 shows a comparison between a full hemisphere farside map calculated from a series of 1440 minunes of MDI Dopplergrams and the map calculated from the same series of GONG data. Active region NOAA10808 is positioned in the same location in both maps.

3. PREDICTION CAPABILITY

From the perspective of space weather, far side imaging has proven to be a useful tool for observing the appearance and evolution of large active regions on the non-visible disk of the Sun [4, 6, 2]. Since the improvement of the technique to allow for 1-3 and 3-1skip ray paths, the active regions can be tracked all the way from their dissapearance at the west limb of the Sun to their new appearence at the east limb. These large and/or long lasting active regions are often responsible for energetic phenomena such as strong flares or coronal mass ejections (CMEs).

Figure 3 shows a sequence of calculated far side maps using Global Oscillation Network Group (GONG) near-real time data from 2005 September 1 to September 7 which identified active region NOAA-10808 before it appeared on the front side of the Sun. The signal is clear and persistent through out the series of farside maps and the location coincide with that on the front side. NOAA AR10808 appeared at the east limb of the Sun on September 7 and produced a huge X-17 flare, one of the largest flares on record.

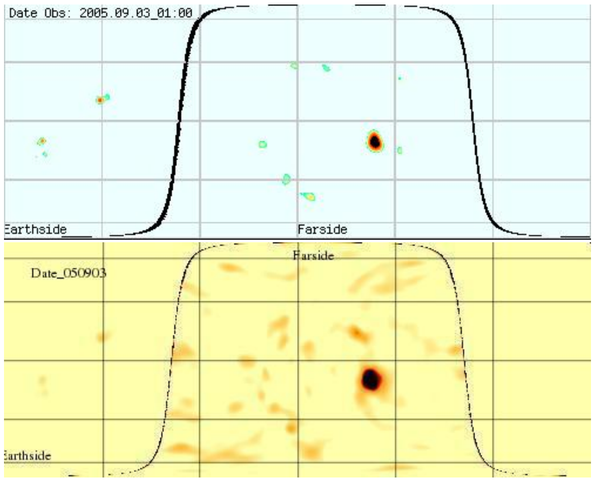

Figure 2. Comparison between MDI (top) and GONG (bottom) farside maps calculated using data from both instruments taken on September 3rd 2005. The signature of active region NOAA10808 is clearly visible in the same position in both maps. NOTE: The color tables used in these figures heavily suppress the noise in the farside calculated signal. To get a more realistic feel of the signal to noise ratio see figure 3.

4. CALIBRATING THE FARSIDE HELIOSEISMIC SIGNATURE

While the current far side maps show the existence and location of active regions, calibrating the far side signal in terms of area, magnetic field strength, or magnetic helicity would make far side imaging a more valuable tool.

Preliminary application of the phase-sensitive 2-2 skip holography method to almost four years of GONG data has produced maps of the central part of the non-visible solar far side. More than 200 candidate far side active regions have been identified. Figure 4 show a comparison between histograms constructed from far side phase-shift maps and front side magnetic field measurements. For the period analyzed, August 2001 to December 2003, the larger phase shifts are concentrated in the magnetic belts, as expected. The histograms in both cases confirm the presence of more magnetic activity in the southern hemisphere for this period of time. However, from the magnetogram data the southern hemisphere seems to present close to 30% more activity while the farside maps reflects only a 8% margin with respect to the northern hemisphere.

Holographic images of front side active regions have suggested an approximately linear dependency of the observed travel-time perturbations with the log of the observed magnetic flux density [1]. However, our first attempts to calibrate the far side signal in terms of the magnetic flux have been inconclusive, mainly due to the evolution of the active regions in the time interval between acquisition of the far side map and appearance of the region on the front side. Figure 5 shows scatter plots of the

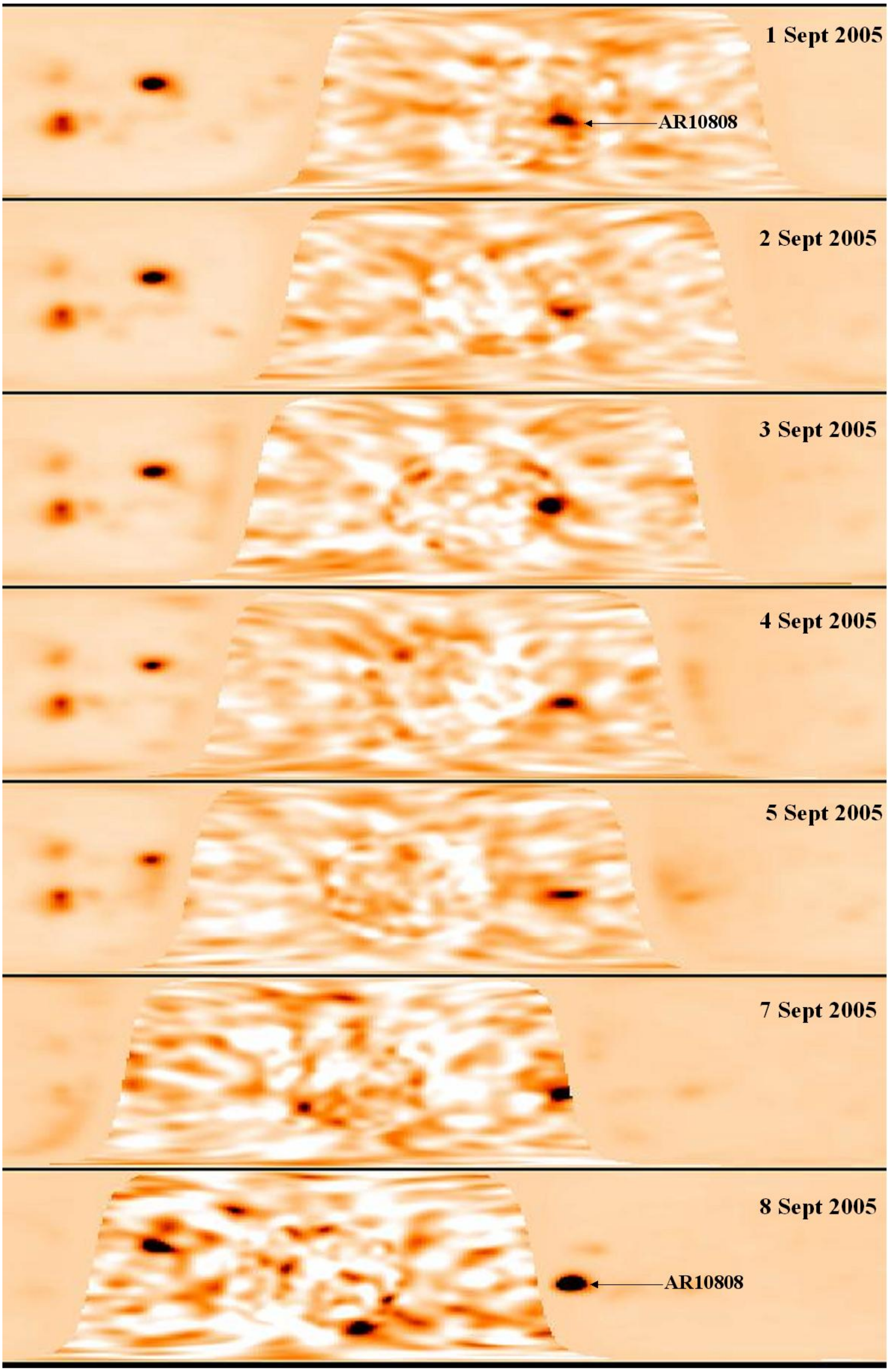

Figure 3. Seismic signature of NOAA AR10808 as it crosses the farside southern solar hemisphere from 2005 September 1 to September 7 when it emerged at the East limb of the Sun and produced the fifth most intense flare on record. The abscissa represents Carrington longitude. The ordinate of each image represents the sine of the solar latitude, over the range -90(south pole) to +90(north pole) The farside maps are overlaid on top of the daily GONG magnetograms that have been smeared to present a similar resolution to that of the farside maps. The last image of the sequence shows the active region 10808 already on a front side magnetogram.

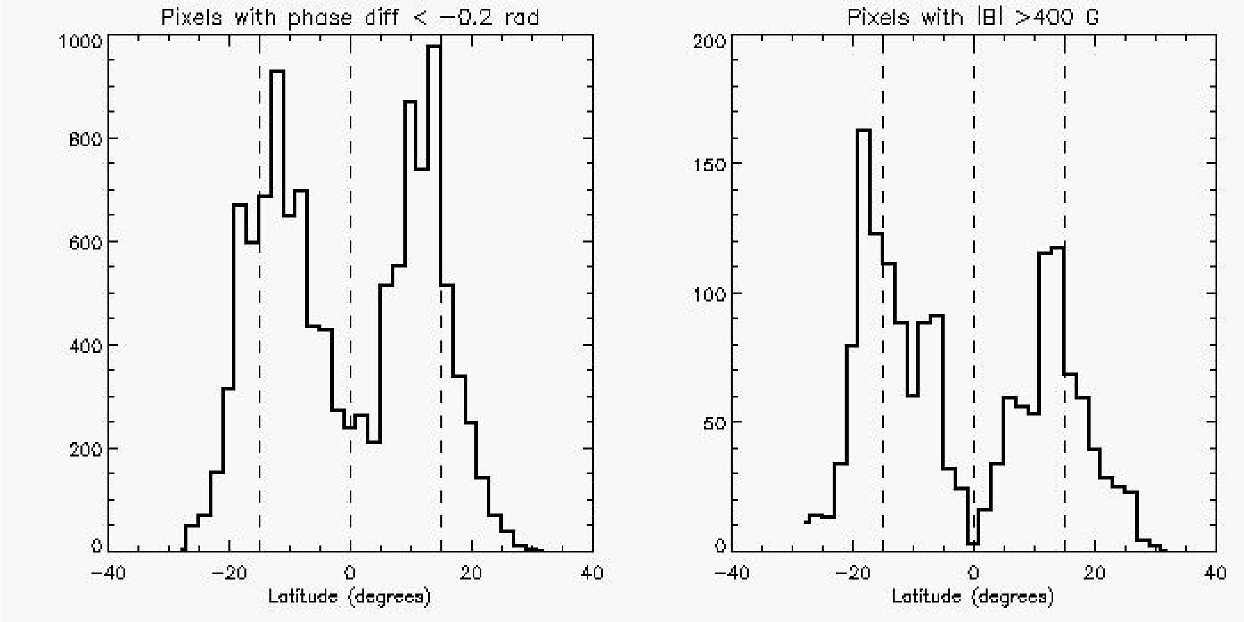

Figure 4. Histograms of phase difference (from farside maps, left) and magnetic index (Kitt Peak magnetograms, right) versus latitude. The data used spans from August 2001 to December 2003. The larger phase shifts are concentrated in the magnetic belts, as expected.

phase shift versus the square of the magnetic field measured half rotation later on the front side of the Sun for two different Carrington rotation. Although there seems to be some correlation for bigger phase delays, a more careful analysis is needed to further understand the correlations.

Synoptic maps constructed from farside maps compared to those of the front side magnetograms are presented in figure 6. Although the location of large active regions on the far side of the Sun seems to agree very well with the front side observations (see figure 6), the calibration of the signal in terms of magnetic parameters needs further investigation.

Table 1 presents the maximum area, maximum number of spots and clasification of the large active regions in the synoptic maps shown in figure 6 (data from www.solarmonitor.org). Notice that for this particular subset of active regions, the ones identified by the far side technique are the larger, more complex ones, which are also the ones more likely to produce large flares. The farside active regions are named using a new notation FSXXXX, where FS stands for Far Side and XXXX is a number. The choice of numeration has been done based on estimations of the maximum number of farside active regions that could be calculated if the available medium-resolution helioseismic data, dating back to 1995 for GONG and 1996 for MDI, where to be analysed. As the farside detection of magnetic activity progresses, the name of the active region on the farside would ideally coincide with that of the NOAO naming on the front side, and would stay the same for active regions that span several Carrington rotations.

To aim in the calibration process, we will use a numerical model that allows waves to propagate within a spherically stratified domain from which the wave field can be analyzed. The code has been written as part of Shravan Hanasoge s Ph.D. thesis (Stanford University). It follows MPI and OpenMP parallel standards, and employs spherical harmonic analyses of horizontal variations, compact finite differencing in the radial direction and an optimized Runge-Kutta explicit time stepping scheme [3]. Figure 7 shows a snapshot of the simulated velocity field covering most of the solar disk and a power map of approximately 29 hours of simulated data where the artificial *sunspot* can be seen.

5. CONCLUSIONS

Helioseismic holography applied to the far surface of the Sun has demonstrated to be a useful predictive tool for space weather. As of today, the technique is able to detect the presence and to locate large active regions in the nonvisible disk with reasonable degree of accuracy. However the calibration of the holographic signal, namely the phase shift, in terms of magnetic parameters such as the area, the magnetic field strength and other morphological aspects of the identified region is still the object of a much careful investigation.

Farside holography relies on ongoing research aimed at understanding the physical aspects of seismic holography when applied to magnetic anomalies in the front side of the Sun. The recent improvements in artificial data will also provide an unprecedent opportunity to further in-

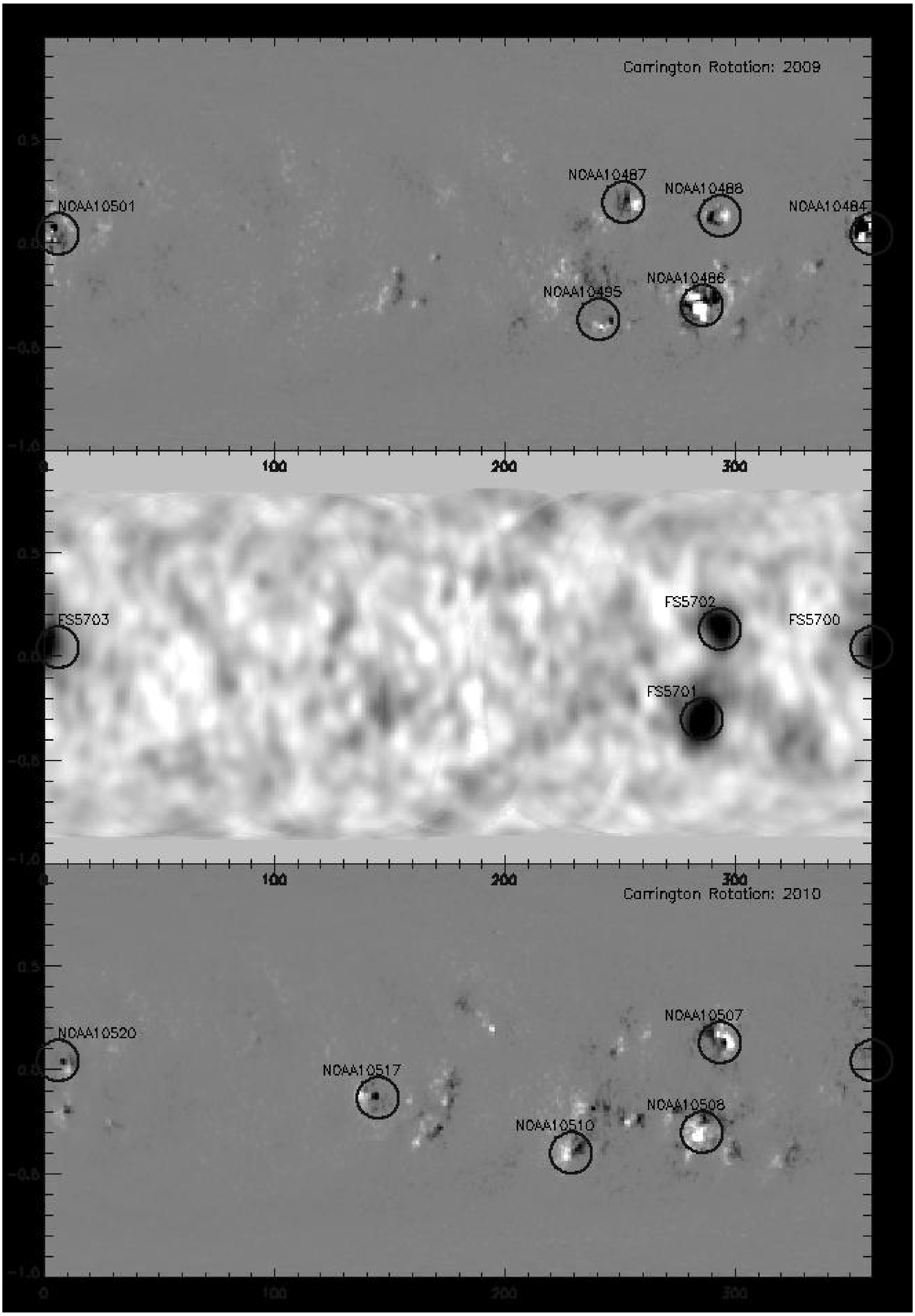

Figure 6. Comparison between synoptic maps constructed from farside calculated images (top) with the previous Carrington Rotation 2009 frontside synoptic maps from magnetograms (bottom, Kitt Peak). The four active regions clearly visible in the farside synoptic maps (FS5700, FS5701, FS5702 and FS5703) coincide with large and complex active regions on the front side (NOAA-10484, 10486, 10488 and 10501). The circles for these four regions are situated at the same location in the three maps. Two of these active regions produced the large Halloween flares of 2003. Not all the active regions identified on the front side however are visible in the farside maps. The analysis of particular cases will help to identify criteria in order to calibrate the farside signature as a function of magnetic parameters.

Table 1. Active regions

Front Side AR	Area (max)	n^o Spots (max)	Hale/McIntosh	Far Side AR
NOAA10484	1750	69	$\beta\gamma\delta$ / Ekc	FS5700
NOAA10486/508	2200	108	$\beta\gamma\delta$ / Fkc	FS5701
NOAA10487	280	23	β / Dao	
NOAA10488/507	1750	61	$\beta\gamma\delta$ / Fkc	FS5702
NOAA10495	220	16	β / Dso	
NOAA10501/520	410	26	$\beta\gamma\delta$ / Dki	FS5703
NOAA10510				
NOAA10517				

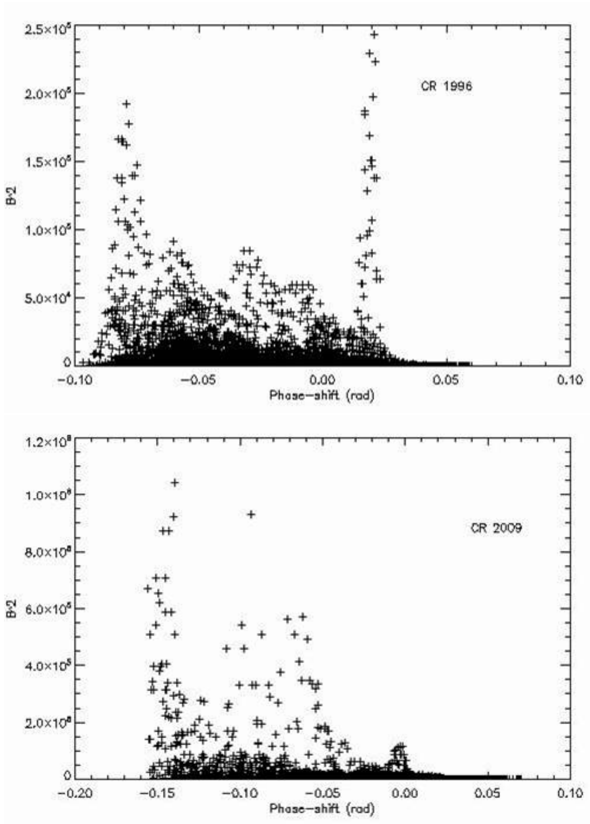

Figure 5. Scatter plots of phase-shifts from the synoptic maps constructed from far side calculated images (Carrington Rotation 2009, left, and 2000, right) versus the square of the magnetic flux of the front side synoptic maps from magnetograms (Kitt Peak). The front side magnetograms are taken 1/2 rotation after the far side maps are calculated.

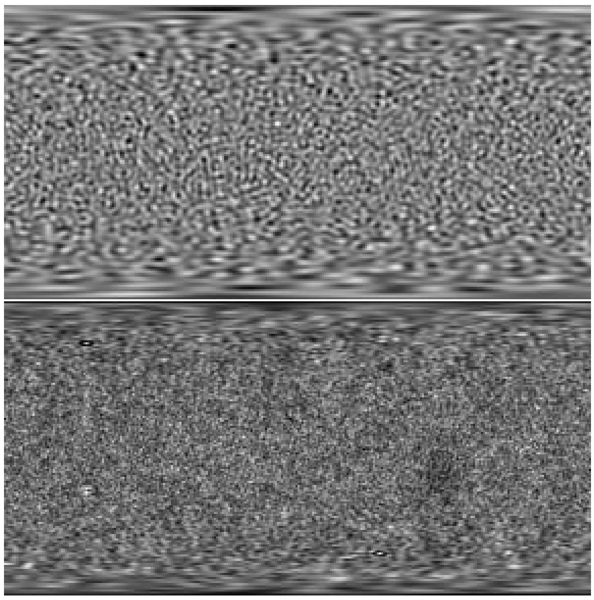

Figure 7. Artificial data.The top panel shows the radial component of the velocity field at the surface for a particular time. It covers 360° in longitude and 89° in latitude. The bottom panel shows a power map calculated using approximately 29 hours of the artificial data. The sunspot can be seen south of the equator in the right-hand half of the far side. It has been simulated by increasing the sound speed by approximately 10% over 1Mm in depth and 25° to 40° in angular extent.

vestigate how the different physical anomalies affect the seismic holography signal.

Continuous synoptic farside maps calculated from MDI and GONG are available on line on a near-real-time basis.

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