TIME-DISTANCE IMAGING OF SOLAR FAR-SIDE ACTIVE REGIONS

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Received 2007 April 13; accepted 2007 June 13; published 2007 July 18

ABSTRACT

It is of great importance to monitor large solar active regions on the far side of the Sun for space weather forecasting, in particular, to predict their appearance before they rotate into our view from the solar east limb. Local helioseismology techniques, including helioseismic holography and time distance, have successfully imaged solar far-side active regions. In this Letter, we further explore the possibility of imaging and improving the image quality of solar far-side active regions by use of time-distance helioseismology. In addition to the previously used scheme with four acoustic signal skips, a five-skip scheme is also included in this newly developed technique. The combination of both four- and five-skip far-side images significantly enhances the signal-to-noise ratio in the far-side images and reduces spurious signals. The accuracy of the far-side active region imaging is also assessed using one whole year’s solar observation.

Subject headings: Sun: helioseismology — Sun: oscillations — sunspots

1. INTRODUCTION

Being able to detect a large solar active region before it rotates into our view from the Sun’s far side and to monitor a large active region after it rotates out of our view into the far side from the Sun’s west limb is of great importance for space weather forecasting (Schrijver & DeRosa 2003). Using the helioseismic holography technique (for a review, see Lindsey & Braun 2000a), Lindsey & Braun (2000b) mapped the central region of the far-side Sun by utilizing double-skip solar acoustic signals visible in the near side of the Sun but originating from or arriving into the targeted far-side area. Then, Braun & Lindsey (2001) further developed this technique to map the near-limb and polar areas of the solar far side by combining acoustic signals visible in the near side after single and triple skips on either side of the targeted far-side area. These efforts have made monitoring active regions of the whole back side of the Sun possible, and daily solar far-side images have become available using Solar and Heliospheric Observatory Michelson Doppler Imager (SOHO MDI; Scherrer et al. 1995) and Global Oscillation Network Group (GONG; Harvey et al. 1996) observations. That the far-side active regions are detectable by phase-sensitive holography (Braun & Lindsey 2000) is mainly because low- and medium-l (l is the spherical harmonic degree) acoustic waves manifest an apparent travel time deficit in solar active regions, and it is these travel time anomalies that far-side maps image. However, it is still quite uncertain whether such anomalies are due to the near-surface perturbation in solar magnetic regions (Fan et al. 1995; Lindsey & Braun 2005) or caused by faster sound speed structures in the interior of those active regions (e.g., Kosovichev et al. 2000; Zhao & Kosovichev 2006).

Time-distance helioseismology is another local helioseismological tool that is capable of mapping the solar far-side active regions. It was demonstrated that time-distance helioseismology could map the central areas of the far-side Sun in a similar way as Lindsey & Braun (2000b) had done (Duvall et al. 2000; Duvall & Kosovichev 2001); however, no studies have been carried out to extend the mapping area into the whole far side. In this Letter, utilizing the time-distance helioseismology technique, I explore both the previously used four-skip scheme and a new five-skip scheme and image two whole far-side maps using four-skip and five-skip acoustic signals separately. Combining both maps gives us solar far-side images with better signal-to-noise ratio and more reliable maps of active regions on the far side. This provides another solar far-side imaging tool in addition to the existing holography technique, hence allowing the possibility to cross-check the active regions seen in both techniques, and enhances the accuracy of monitoring solar far-side active regions.

2. DATA AND TECHNIQUE

The medium-l program of SOHO MDI provides nearly continuous observations of solar oscillation modes with l from 0 to ~300. The medium-l data are acquired with 1 minute cadence and a spatial sampling of 10” (0.6 heliographic degrees per pixel) after some averaging on board the spacecraft and ground pipeline processing (Kosovichev et al. 1997). The oscillation modes that this program observes and the continuity of such observations make the medium-l data ideal to be used in solar far-side imaging.

The acoustic wave signals that originate from and then return to the solar front side after traveling to the back side and experiencing four and five bounces are to be used in the time-distance far-side analysis. It is natural and often useful to first examine whether such acoustic signals are detectable by the time-distance technique. A 1024 minute MDI medium-l data set with a spatial size of 120” x 120” is used for such an examination after the region is tracked with Carrington rotation rate and is remapped using Postel’s projection with the solar disk center as its remapping center. The l-v power spectrum diagram of this data set is shown in Figure 1a. The time-distance diagram computed using all oscillation modes (Fig. 1b) clearly shows acoustic bounces of up to seven times on the front side; at the locations of the expected signals traveling back to the front side after four and five bounces, there are some not-very-clear but existing signals. Since the acoustic signals that are needed for the far-side analysis should have a fairly long single-skip travel distance, thus corresponding to low-l modes, it is helpful to filter out all other acoustic modes and keep only those signals that are corresponding to the required travel distances. Such a filtering should help to improve the signal-to-noise ratio of time-distance signals at the desired distances. However, such a filtering is
The white boxes in Figure 1 come back from the far side after four or five skips are used. It is understandable that theoretical travel time is a bit off from the ray group travel time after four and five bounces. Considering distance shorter and longer than $96.9^\circ$, respectively. The white boxes in (c) delimit the acoustic travel distances and times used for far-side imaging.

In order to keep good signal-to-noise ratio as well as reasonable computational burden, not all acoustic signals that come back from the far side after four or five skips are used. The white boxes in Figure 1c indicate the distances that are utilized for far-side imaging. Namely, as sketched in Figure 2, for the four-skip scheme, the time-distance annulus radii are $133.8^\circ$–$170.0^\circ$ from the target point for the double-double skip combination that is used to map the far-side central area, and $66.9^\circ$–$85.0^\circ$ for the single-skip and $200.7^\circ$–$255.0^\circ$ for the triple-skip in the single-triple combination that is used to map the areas that are close to the far-side limb and polar regions; such a combination covers a total of $190^\circ$ in longitude (at the equator, $5^\circ$ past the limb to the front side near both limbs). For the five-skip scheme, the annulus radii are $111.6^\circ$–$174.0^\circ$ from the target point for the double skip and $167.4^\circ$–$261.0^\circ$ for the triple skip; this scheme covers a total of $160^\circ$ in longitude, less than the whole far side. Unlike in Braun & Lindsey (2001), where far-side polar areas were also included in the imaging, in order to reduce unnecessary computations only those areas lower than the latitude of $48^\circ$, where nearly all active regions are located, are included in the time-distance far-side imaging computations reported here.

The computation procedure is as follows. A 2048 minute long MDI medium-$l$ data set is tracked with a Carrington rotation rate and remapped to Postel’s coordinates centered on the solar disk as observed at the midpoint of the data set, with a spatial sampling of 0.6° pixel$^{-1}$, covering a span of 120° along the equator as well as the central meridian. This data set is then filtered in the Fourier domain to keep only the oscillation modes that have travel distances in agreement with the distances listed above. Corresponding pixels in the annuli on both sides of the target point are selected, and the cross-covariances with both positive and negative travel time lags are computed. Such computations for all distances shown in the white boxes of Figure 1c are repeated. Then both time lags are combined, and all cross-covariances obtained from different distances after appropriate shifts in time that are obtained from theoretical estimates are also combined. The final cross-covariance is fitted with a Gabor wavelet function (Kosovichev & Duvall 1996), and an acoustic phase travel time is obtained. This procedure
is repeated for the double-double and single-triple combinations in the four-skip scheme, and for the double-triple combination for total distances both shorter and longer than 360° in the five-skip scheme, separately. The far-side image is a display of the measured acoustic travel times after a Gaussian smoothing with FWHM of 2.0°.

3. RESULTS

NOAA AR 0484, AR 0486, and AR 0488 are selected to test this time-distance far-side imaging technique. Figure 3 shows the MDI synoptic magnetic field chart when these active regions were on the near side of the Sun before they rotated into the far side. AR 0488 was still growing when the magnetic field data to make this synoptic map were taken.

Selected far-side images of these three active regions, obtained from separate four- and five-skip measurement schemes, and a combination of both measurements, are shown in the top three rows of Figure 4. In each image, the near-side magnetic field map is combined with the far-side acoustic travel time map, and the combined map is displayed based on Carrington longitudes. Standard deviations, $\sigma$, are 4.1 and 4.5 s for four-skip and five-skip far-side maps, respectively, and after combination of both measurement schemes, $\sigma$ falls to 3.3 s. In these maps, the three interested active regions are mostly visible in all four-skip, five-skip, and combined results, except when the regions fall into the uncovered areas of five-skip measurement.

The bottom row of Figure 4 presents the same map as the third row but highlighting active regions by Gaussian smoothing the unsigned near-side magnetic field, and displaying the far-side travel time map with a threshold of $-3.5$ to $-2.0\sigma$, i.e., $-11.5$ to $-6.5$ s. It is clear that the images combining four- and five-skip results are quite clean of spurious signals, although unidentified features still exist. It is also noteworthy that the far-side images clearly show these active regions when part of the regions were on the far side and part on the near side, like AR 0486 and AR 0488 in the fourth row and third column of Figure 4.

Both four- and five-skip far-side acoustic travel times are displayed after a mean travel time background is removed. It turns out that the background mean travel time depends on its angular distance from the antipode of the solar disk center. Figure 5 presents the variation of background mean travel times at different locations for both measurement schemes after the mean value of the background is removed. Basically, the mean acoustic travel times vary with a magnitude of $\sim 4$ s for four-skip measurement and a magnitude of $\sim 9$ s for five-skip measurement. The measured mean acoustic travel times are shorter for the four-skip scheme but longer for the five-skip scheme when the targeted areas are near the limb and near the antipode of the solar disk center. These variations are unlikely physical, yet it is unclear why there are such variations in the measurement. The rms of travel times can be used to assess the quality of far-side images. Also shown in Figure 5 is travel time rms variation with distance to the far-side center. It shows that the double-double scheme has the lowest rms near the far-side center, while the single-triple scheme has the lowest rms near the far-side limb. For the five-skip measurement, it has the lowest rms when at and roughly 30° from the far-side center, and the rms increases substantially close to the limb.

It is interesting to make a statistical study investigating how accurate the far-side active region imaging is. Since sometimes active regions change fast, grow, or decay unexpectedly, it is
When analyzing low- and medium-mode oscillations by use of helioseismic holography technique, it gives results that are in reasonable agreement with the holography results (which can be seen at the SOHO MDI Web site) by visual comparison, yet detailed comparisons are not done. It is intriguing to calibrate the measured far-side acoustic travel times into magnetic field strength, and some efforts have been taken using holograph results (González Hernández et al. 2007). However, there are some apparent difficulties to carry out the calibration, because the far-side images of active regions are often relatively noisy, and sizes and shapes of those regions change from image to image. In addition, the magnetic field strengths of the far-side active regions are also unknown, although the full sphere magnetic field made by use of flux dispersal model (Schrijver & DeRosa 2003) may help in this. Eventually, a numerical simulation of solar oscillations in the whole Sun is needed to determine a satisfactory calibration.

It is notable that the five-skip measurement scheme has a large fraction of overlapping areas as the four-skip measurement in the annulus of one side and has one more skip on the other side (see Fig. 2), but results from both measurement schemes have quite uncorrelated noises (see Fig. 4). It is unlikely that the noise differences of two schemes are caused while waves travel merely one more skip, $\frac{1}{4}$ of the total distance; however, it may imply noises come from data or the filtering of geometrically distorted data.

The holography far-side images show strong acoustic travel time variation from the far-side center to limb, with an order of 70 s or so in their four-skip measurement scheme (P. Scherrer 2007, private communication), and this is believed (C. Lindsey 2007, private communication) to be connected with the “ghost signature” described by Lindsey & Braun (2004). Although such a travel time variation trend also exists in time-distance far-side images, the variation magnitude is merely 4 s in the four-skip scheme, substantially smaller than the holography trend. The variation in the five-skip scheme measurement is about twice that in the four-skip scheme. What causes such travel time variations in our measurement, although small, is worth further investigation.

With the availability of both time-distance and helioseismic holography far-side images, it is more robust to monitor activities on the far side of the Sun, and we can forecast the appearance of large active regions rotating into our view from the far side with more confidence. Furthermore, the success in far-side imaging provides us some experiences and confidence in analyzing low- and medium-mode oscillations by use of local helioseismology techniques, and this will greatly help us in analyzing solar deeper interiors and polar areas by use of these techniques.

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By combining four-skip and five-skip measurement schemes, I have successfully made time-distance far-side images of the Sun with a fast computation speed. The combination significantly enhances the signal-to-noise ratio of far-side acoustic travel times over either four- or five-skip measurement, thus significantly enhances the signal-to-noise ratio of far-side acoustic travel times, and we can forecast the appearance of large active regions rotating into our view from the far side with more confidence. Furthermore, the success in far-side imaging provides us some experiences and confidence in analyzing low- and medium-mode oscillations by use of local helioseismology techniques, and this will greatly help us in analyzing solar deeper interiors and polar areas by use of these techniques.

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