HMI time-distance pipeline: an overview and data products

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Abstract. The Helioseismic and Magnetic Imager onboard Solar Dynamics Observatory provides uninterrupted high-resolution observations of solar oscillations over the entire disk. This gives a unique opportunity for mapping subsurface flows and wave-speed structures and investigating their role in the Sun’s dynamics and magnetic activity on various scales by methods of local helioseismology. A data analysis pipeline for the time-distance helioseismology analysis has been developed and implemented at the SDO Joint Science Operation Center (JSOC) at Stanford. It provides near-real time processing of the helioseismology data. We provide an overview of this pipeline, including the data flow procedures, measurement and inversion codes, and our data products.

1. Introduction
The Helioseismic and Magnetic Imager onboard Solar Dynamics Observatory (SDO/HMI, [1]) observes the solar full-disk intensity, Doppler velocity, and vector magnetic field of the photosphere with high spatial resolution and high temporal cadence. Similar to the Michelson Doppler Imager (MDI, [2]), an instrument onboard a previous space mission Solar and Heliospheric Observatory (SOHO), the HMI Dopplergrams are primarily used for helioseismology analysis to investigate the interior structure and dynamics of the Sun. Helioseismology data analysis pipelines are planned for near real-time analyses of the HMI observations in order to provide the analysis results to the helioseismology and solar physics communities. The time-distance analysis pipeline is one of the pipelines for local helioseismology studies. It is designed for routine derivations of nearly full-disk subsurface wave-speed perturbations and horizontal flow fields every 8 hours, as well as synoptic flow maps for every Carrington rotation. It can also be used to analyze specific target areas and time periods.

2. Acoustic travel time measurement
SDO/HMI continuously observes the full-disk Sun, providing Doppler velocity, continuum intensity, line-depth, line-width, and magnetic field maps with a 45-sec cadence, and also vector magnetic field measurements with a cadence of 12 minutes. Each full-disk image has
4096 × 4096 pixels with a spatial resolution of 0.504 arcsec pixel$^{-1}$ (i.e., approximately, 0.03 heliographic degree pixel$^{-1}$ at the solar disk center). The Doppler observations are primarily used for helioseismology studies.

As illustrated in Figure 1, the primary input for the pipeline is Dopplergrams, although in principle, the HMI intensitygrams and line-depth data can also be analyzed in the same manner. Users of the pipeline can select specific areas for analysis, preferably within 60° from the solar disk center. In practice, the users provide the Carrington longitude and latitude of the center of the selected area, and the middle time of the selected time period, then the pipeline code selects an area of roughly 30° × 30° centered at the given coordinate, and for a time interval of 8 hours with the given time as the middle point. The data for this selected area and the time period are then tracked to remove the solar rotation, and remapped to Postel’s projected coordinates (Postel’s projection is also known as azimuthal equidistant projection) relative to the given area center. Normally, the tracked area is 512 × 512 pixels with a spatial sampling of 0.06° pixel$^{-1}$; and the temporal sampling is kept concordant with the observational cadence.

Each tracked and remapped Dopplergram datacube is filtered in the 3D Fourier domain. Solar convection and $f$-mode oscillation signals are removed first, and then phase-speed filtering is applied following the procedures prescribed by [3]. For the travel-time measurements, for each central point, we select 11 annuli with various radii and widths chosen from our past experiences with MDI analyses. All the phase-speed filtering parameters, including the central phase-speed, the filter width, and the corresponding inner and outer annulus radii, are shown in Table 1. The filter is a Gaussian function of phase speed. After the filtering, the data are transformed back to the space-time domain for cross-covariance computations for fittings to get acoustic travel times.

3. Subsurface wave-speed perturbation and flow field inversions
As illustrated in Figure 1, the acoustic travel times are derived by two different fitting methods: the Gabor wavelet function and the GB algorithm. Then, to infer the subsurface wave-speed perturbations and flow velocities, the Gabor wavelet fitted acoustic travel times are inverted using the ray-path approximation sensitivity kernels, and the GB algorithm fitted times are inverted using the Born approximation sensitivity kernels. Born approximation kernels are calculated based upon the GB definition of acoustic travel times. In this analysis pipeline, we
Table 1. Phase-speed filtering parameters used for the selected travel distances (annulus ranges).

| annulus No. | annulus range (heliographic degree) | phase speed (µHz/ℓ) | FWHM (µHz/ℓ) |
|-------------|------------------------------------|---------------------|--------------|
| 1           | 0.54 – 0.78                        | 3.40                | 1.0          |
| 2           | 0.78 – 1.02                        | 4.00                | 1.0          |
| 3           | 1.08 – 1.32                        | 4.90                | 1.25         |
| 4           | 1.44 – 1.80                        | 6.592               | 2.149        |
| 5           | 1.92 – 2.40                        | 8.342               | 1.351        |
| 6           | 2.40 – 2.88                        | 9.288               | 1.183        |
| 7           | 3.12 – 3.84                        | 10.822              | 1.895        |
| 8           | 4.08 – 4.80                        | 12.792              | 2.046        |
| 9           | 5.04 – 6.00                        | 14.852              | 2.075        |
| 10          | 6.24 – 7.68                        | 17.002              | 2.223        |
| 11          | 7.68 – 9.12                        | 19.133              | 2.039        |

employ the MCD inversion method [4] with a horizontal regularization [3].

For both the wave-speed and flow field inversions, and for both the ray-path and Born approximation kernels based inversions, we select a total of 11 inversion depths as follows: 0 – 1, 1 – 3, 3 – 5, 5 – 7, 7 – 10, 10 – 13, 13 – 17, 17 – 21, 21 – 26, 26 – 30, and 30 – 35 Mm. There are a total of 11 depth intervals. The inversion results provide the wave-speed perturbations and flow velocities averaged in these layers. Due to the lack of acoustic wave coverage in the deep interior, the reliability of inversion results decreases with the depth. Thus, only inversion results shallower than 20 Mm are given in the pipeline output.

In recent years, several studies have been carried out to validate the time-distance measurements and inversions. To validate the derived subsurface flow fields, [5] and [6] have analyzed realistic solar convection simulations and found satisfactory inversion results for shallow depths covered by the simulations. Validations of the wave-speed perturbation inversions based on numerical simulations with preset structures have also been performed, and a publication is under preparation. Meanwhile, numerical simulations for magnetic sunspot structures with flows are also under development. Validations of the time-distance helioseismology techniques will be carried out as well using these simulations.

4. Data products

The time-distance data analysis pipeline is used for routine production of nearly real-time full-disk (actually, nearly full-disk covering 120° × 120° area on the solar disk) wave-speed perturbation and flow field maps every 8 hours. These maps are then used to construct the corresponding synoptic maps for each Carrington rotation. The pipeline can also be used for specific target areas, such as active regions. For the routine production of the full-disk wave-speed and flow maps, for each day of HMI observations, we select three 8-hour periods of 00:00 – 07:59UT, 08:00 – 15:59UT, and 16:00 – 23:59UT. For each analysis period, we select 25 regions, with the central locations at 0°, ±24°, and ±48° in both longitude and latitude, where the longitude is relative to the central meridian at the middle time of the selected period.

Figure 2 shows a sample of selected areas on the solar disk. The total number of areas is 25, 5 rows and 5 columns. Because of the Postel’s projection, the boundaries of these areas are often not parallel to the latitude or longitude lines. It is also evident that many areas overlap, and some areas overlap two times and some overlap four times. The travel times and inversion results are averaged in these overlapped areas. For each full-disk map and each synoptic map,
Figure 2. Schematic plot showing how areas are selected for a routine calculations of the full-disk wave-speed and flow maps. Not all of the 25 selected areas are showed in this plot.

the east-west velocity \( (v_x) \), the north-south velocity \( (v_y) \), and wave-speed perturbation \( (c_s) \) in each depth layer are derived with a horizontal spatial sampling of 0.12° pixel\(^{-1}\). For each of 25 areas, the inversion results are first obtained in the Postel’s projected coordinates, and then converted into the longitude – latitude coordinates.

As already mentioned, the pipeline can also be run for specific target areas and specific time intervals. Users are required to provide the Carrington coordinate of the center of the target area, and the middle time of the time interval.

5. Summary
We have developed a time-distance data analysis pipeline for SDO/HMI Doppler observations. This pipeline performs acoustic travel time measurements based on two different fitting methods, and conducts inversions based on two different inversion kernels calculated in the ray-path and Born approximations. The pipeline gives nearly real-time routine products of full-disk wave-speed perturbations and flow field maps in the range of depth 0 – 20 Mm every 8 hours, and provides the corresponding synoptic wave-speed perturbation and flow field maps for each Carrington rotation. In addition to these routine production, the pipeline can also be used for analysis of specific target areas for specific time intervals.

References
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