LOCAL HELIOSEISMOLOGY: ANALYSIS OF LOCALIZED TIME-DISTANCE DIAGRAMS FROM QUIET AND ACTIVE REGIONS

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ABSTRACT We have used a time-distance correlation analysis to reduce localized sub-rasters of full disk line-of-sight velocity observations. We describe here our implementation of this emerging technique, based on the simple but powerful concept of pairs of virtual sources and virtual receivers separated by a prescribed distance. We present time-distance correlation maps computed for two quiet regions, and one active region, on two consecutive days of observation and compare the time delays measured from the different localized sub-rasters. At the present level of accuracy, no significant differences have been found between time delays measured from the different sub-rasters.

INTRODUCTION

Following the ground-breaking work of Duvall et. al. (1993), we have started an independent effort to develop analysis tools based on measuring the local propagation delay of the acoustic waves generated by the solar oscillations. An update of the status of this emerging technique is given by Duvall (1994). We present here our initial attempt to investigate the signature of the interaction of these acoustic waves with the perturbation associated with an active regions from a propagation time delay approach using time-distance diagrams.

Observations

Results presented here are based on time series of full-disk, 1024 by 1024, Dopplergrams, taken at a one minute sampling rate, at the 60-Ft. Solar Tower of the Mt. Wilson Observatory. Our time-distance analysis was carried out on two consecutive days covering respectively 8.7 and 10 hours of observations taken on July the 12th and 13th, 1988.

Three regions were analyzed: region A, a quiet region, localized at disk center, and spanning 34 degree on the solar sphere; region B, an active region, centered around a spot group, and spanning 45 degree; and region C: a control quiet region, localized at the same distance from disk center as region B is, and also spanning 45 degree.

DATA ANALYSIS

Conceptually, independently of the nature of the excitation mechanism, one would expect a correlation of the acoustic signal observed between two points at
the solar surface for a delay corresponding to the time the acoustic wave takes to travel from one point (source) to another (receiver).

Since at the difference of geo-seismology, we cannot isolate actual excitation sources, we select a pair of virtual source and receiver. In the work presented here, we have used a single point as our virtual source, and all the annuli centered on the virtual source as virtual receivers. Thus, in an isotropic media, the coherent signal present over the annulus should be correlated with the signal at the virtual source, for a delay that corresponds to the travel time required for the wave to travel back to the surface at a distance equal to the annulus radius.

Method

The analysis method starts, for convenience, with extracting a time-series of sub-rasters, on an equispaced grid in longitude, and in the cosine of the co-latitude, defined in heliospheric coordinates. This extraction follows a preset differential rotation law. Then, the time-series of sub-rasters is detrended by subtracting a 20 min running mean. Each detrended sub-raster is then spatially filter, using a “notch filter” in the $k_h$ space (i.e., we keep only the signal corresponding to a restricted range of horizontal wave-numbers, $k_h^2 = k_x^2 + k_y^2$, or equivalent spherical harmonic degree, $\ell$).

For each detrended and spatially filtered sub-raster, we then compute the average of the residual velocity signal over a set of annuli (defined on the sphere), contained within the sub-raster and centered around a selected location. Finally, we cross-correlate the time-series of annulus averaged residual velocities (receiver signals) with the time-series of the residual velocities corresponding to the center of the set of annuli (source signal):

$$Q(\Delta, \tau) = \int v(t - \tau, \Delta)v(t, 0) \, dt$$

where $\Delta$ is the radius annulus, and $\tau$ the time delay.

This procedure is then repeated by moving the location of the virtual source by few pixels, and the correlation maps, $Q(\Delta, \tau)$, are averaged for a set of nine nearby virtual sources to increase the signal-to-noise ratio (SNR).

TIME-DISTANCE CORRELATION MAPS

Figures 1a and 1b show the resulting correlation maps (i.e., $Q$-maps) for regions A, and for a spatial filtering corresponding to $174 < \ell < 334$ and $259 < \ell < 419$ respectively. Ridges of high cross-correlation corresponding to time propagation delays associated with one to up to four bounces are visible. Since the signals being cross-correlated are periodic, “side-ridges” some five minute apart are present as well. The extent of the ridges where high correlation is present is limited to distances corresponding to the distances waves with horizontal wavelengths included in the spatial filtering will travel.

To further increase the SNR, and combine in one map the different spatially filtered $Q$-maps, composite $Q$-maps were computed by including from each spatially filtered $Q$-map only the portions of that map where a time-distance ridge is clearly visible. Examples of the resulting composite $Q$-map for region A is presented in Fig. 2a.

The location of the observed time-distance ridge was then measured from the composite $Q$-maps, for all 4 ridges, for each region and each day. The four
ridges were collapsed onto one curve by dividing distance and time-delay by the number of bounces. Figure 2b illustrates the resulting curve for region A.

Fig. 1. Correlation maps, $Q(\Delta, \tau)$, for region A and for spatial filters corresponding to $174 < \ell < 334$ and $259 < \ell < 419$ respectively. These maps correspond to the average over 9 virtual sources all located near the center of the sub-rasters.

Fig. 2. a) Composite $Q$-maps, for region A, computed by including from each spatially filtered $Q$-map only the portions of that map where the time-distance ridge is clearly visible. b) Measured time propagation delays as a function of distance for region A, collapsed by dividing by the number of bounces.

Finally, we have compared propagation delays measured for the quiet and active regions. Figures 3a and 3b show observed differences of propagation delays between active and quiet regions, as well as the control case, where the differences resulting from comparing the two quiet regions is presented.
Fig. 3. Observed time propagation delay differences between quiet and active regions (left) and between quiet at disk center and quiet away from disk center regions (right).

CONCLUSIONS

While the computation of time-distance diagrams is still in its infancy, we seem to be able to measure the propagation delay to better than 20 sec, for delays of the order of 25 to 65 min.

At this point, we cannot claim to see any significant differences in the propagation delays between quiet and active regions when comparing out results with the systematic differences observed in our control cases (i.e., quiet region A versus quiet region C). We can nevertheless place an upper limit on the sound speed perturbation in the active region. If the observed waves spend at least a quarter of their time in the perturbed region, the sound speed perturbation must be smaller than \( \approx 3\% \) to be consistent with our null result.

A marginal difference in propagation delays between active and quiet regions can be observed at small distances (\( \delta \tau \approx 20 \) sec for \( \Delta \leq 3^\circ \)). If real, this would correspond to a \( \approx 1\% \) perturbation of the sound speed, for modes sampling the outer 2% of the solar interior and traveling over 1.5\(^\circ\) to 3\(^\circ\).

To improve the diagnostic potential of time-distance diagrams we still have to learn how to compute \( Q \)-maps with better SNR and with less systematic effects. Henceforth, we expect a) to improve our spatial filtering as to eliminate the edge effects present in the current reduction procedure; b) to increase the \( Q \)-maps SNR by averaging over more virtual sources; and c) to investigate different source–receiver topologies that might prove to give a better SNR.

REFERENCES

Duvall, T. L., Jr., 1994, these proceedings.