Preliminary velocity flows inside NOA AR 10720
derived by temporally evolving ring diagram analysis
of SOHO/MDI dopplergrams

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Abstract. Between 13th and 16th January 2005, NOA active region 10720 was the site of
several large flares, one of which induced a solar quake. The expanding wave front of the quake
was visible across the surface, causing both horizontal and vertical plasma displacements. Using
a new temporal scanning technique for ring diagram analysis of SOHO/MDI (Michelson Doppler
imager on board the Solar and Heliospheric Observatory) dopplergrams, we have calculated the
horizontal and vertical velocity flows within the active region and the surrounding areas to a
depth of 15Mm. We have been able to prove that it is possible to determine changes to a steadily
varying subsurface flow, over time scales of hours.

1. Introduction

Solar flares are associated with surface sunspot activity and reorganization of magnetic flux
within the lower atmosphere. Most flare eruptions are directed outwards, away from the sun and
into the heliosphere. However, flares can also direct all the stored kinetic and thermal energy
inwardly, causing a response within the photospheric layers. This kind of eruption can cause
white light emission and visible ripples to appear on the solar surface, and is known as a solar
quake. [1][2] have suggested rapid heating of the low photosphere as a possible mechanism for
this type of event.

NOA active region 10720 rotated onto the visible solar disc on January 11th 2005 and evolved
into a highly complex delta region. It produced many significant X and M class flares, and a
large earth directed CME. On January 15th 2005 an eruption caused one of the largest flare
induced quake events of cycle twenty three. The waveform of the quake was visible on the
surface, expanding away from the foot point of the flare [1][2]. Figure 1 is an SOHO/MDI
(Michelson Doppler imager on board the Solar and Heliospheric Observatory) continuum image
taken after the quake event, and shows the complex shape of the active region.

It is of interest to know how the subsurface plasma within the active region reacted to the
sudden impulsive shock of the quake event. Temporally averaged plasma flow patterns can be
achieved using the local helioseismic technique of ring diagram analysis. [3] realized that it was
possible to extend global helioseismology to localized patches of the solar surface. By using
the millions of oscillations generated within the convection zone, it was possible to disentangle
information about the material which each wave passed through. From this information, interior
plasma flows and structure can be determined in the horizontal and vertical directions.
Ring diagrams have also been very successful at determining subsurface global flows such as the meridional and zonal flows within the convection zone. These are likely to be controlled by the dynamo and could also be the anchor points of sunspot activity. This technique has been very successful in determining large scale subsurface weather patterns, which have been used as early forecast tools in space weather prediction. One major part of ring diagrams which has, until now, not been possible is analysis of temporal flows on time scales of hours or minutes. This has meant many short lived events such as flare, CME eruptions, and solar quakes have not been studied in terms of the subsurface structure and effects.

2. Method

The quake event occurred between 00:21 and 00:43 UT and was induced by a X1.2 flare which erupted above the active region. In order to study the effects which the quake had on the subsurface plasma flows, we have used the local helioseismic technique of ring diagram analysis. We have developed a method of analyzing the temporal variations of these flows, before, during and after the time of the quake.

We created an IDL code which is able to select all the relevant dopplergram images, based on the header information for each file, and a list of start and end dates and times to analyze. This method results in blocks of time which are independent of any other and so subsurface velocity flows can be easily calculated. The code can also be used to study events which occur over time scales of minutes, down to the cadence limit of the MDI instrument. We have designed the code to take an initial start date and time, the total length of time, the number of time blocks, and the length of each time block. It will then determine the relevant data files for each time range, again based on the file headers. The program will then perform ring diagram analysis on each block of time and for a pre-determined number of data cubes surrounding a specific region of interest. When complete, the code produces plots which display the horizontal and vertical components of the flow.

We have used several standard techniques to create ring diagrams from dopplergram data produced by the SOHO/MDI instrument. Firstly the dopplergrams were remapped onto great circles using Postel’s projection, and subsections cut out surrounding regions of interest [4][5]. These patches of the surface were spaced evenly around the centre of mass of the active region. This was calculated from an initial continuum image, using contour lines of constant intensity.

For this analysis, the size of each patch was 16° x 16° or 128 x 128 pixels and the patch centers were separated by 7.5°. Individual patch centers were tracked at a rate equal to the doppler differential rotation rate given by [6], where the coefficients have been adjusted to match the
rotation rate of the active region. The form of the rotation equation used here is within the quoted errors and is given by equation 1.

\[
\omega_r(\vartheta_0) = 473.92 - 89.83(\sin^2(\vartheta_0)) - 59.22(\sin^4(\vartheta_0)) \text{ nHz}
\]  

Data cubes were assembled by stacking together many images from the same patch site, and missing images were replaced by zeros to keep the cadence the same throughout the analysis. Each data cube was detended in time to remove the large scale effects of solar rotation and apodized with a cosine bell function, to remove Gibbs ringing, that can occur later in the analysis. A three dimensional Fourier transform was applied to the data, two in space and one in time. The resulting power spectrum which, when cut at constant frequency, shows rings nested inside each other, one ring for each radial mode n.

The ring diagrams were unwrapped and filtered to remove high order variations in the theta direction \[7\][8]. Each ring diagram was fit with a model of the form

\[
P = \left( \frac{A}{(\omega - \omega_0 + U_x k_x + U_y k_y)^2 + \Gamma^2} + \frac{b_0}{k^3} \right)
\]

where the flow parameters \(U_x\) and \(U_y\) and central frequency \(\omega\) of each oscillation mode were inverted using a 1D RLS (Regularised Least Squares) inversion procedure, similar to that used in the GONG pipeline. We have produced velocity flows to a depth of 15Mm below the photosphere for several patches of the surface.

3. Discussion

We have previously presented preliminary velocity flows and disturbances caused by the quake event. We did this for 2 patches of the surface, one centered on the active region and one centered 7.5° south west of the first. The ring diagram procedure used for the preliminary results was similar to that previously described, but the tracking rate was not uniform. This caused very high velocities to be imprinted into the subsurface flows, masking out the true velocities. Figure 2 shows the original results for a patch co-rotating with the active region, where the velocities are wildly larger than should be expected.

![Figure 2](image)

**Figure 2.** These plots show the horizontal and vertical velocity components of subsurface flows for a patch rotating with the active region. The large velocities are due to the non uniform tracking originally used for this research. The plots represent blocks of time, before, during and after the quake respectively.

We now only track at a uniform rate for each latitude. We recalculated the flows for several patches of the surface. Here we display only the velocity profile of the main patch rotating with the active region.
Figure 3. The plots here show the same patch of the surface, tracked at a uniform rate. Again blocks of time before, during and after the quake have been investigated. The near surface layers under the active region show a reaction to the quake, and a slow relaxation to a previous steady flow.

As can be seen in Figure 3 there is a steady plasma flow field before the quake event, which changes direction with depth and is typical of large active regions. During the quake event, large disturbances in the near surface layers can be seen, which indicate an inward radial path for some of the energy of the quake event. The subsurface plasma appears to relax back towards the bulk flow of the active region and surrounding area. Further investigation is needed to determine how the quake is coupled to the subsurface flows seen with ring diagram analysis.

4. Conclusions
NOA active region 10720 was one of the largest and most complex magnetic structures to appear on the solar disk during solar cycle twenty three. It produced many large flares and a disruptive CME during its transit across the surface. The acoustically active flare of January 15th 2005 caused a solar quake event between 00:21 UT and 00:43 UT which caused visible ripples on the solar surface. We have shown that it is possible to detect temporally varying flows using a new method of ring diagram analysis. We need to extend this work to examine the sub-photospheric reaction to the quake and its links with the flare eruption.

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