PRESENT STATUS OF THE TAIWAN OSCILLATION NETWORK

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Abstract. The Taiwan Oscillation Network (TON) is a ground-based network measuring solar intensity oscillations for the study of the internal structure of the Sun. So far, four telescopes have been installed at Teide Observatory (Tenerife), Huairou Solar Observing Station (near Beijing), Big Bear Solar Observatory (California), and Tashkent (Uzbekistan). The TON telescopes take K-line full-disk solar images of diameter 1000 pixels at a rate of one image per minute. The TON high-resolution data is specially suitable to study local helioseismology. Here, we present recent results of three topics on local helioseismology from TON data: (1) Inference of Subsurface Magnetic Field From Absorption Coefficients of p-modes in Active Regions, (2) Subsurface Structure of Emerging Flux Regions From Helioseismology, and (3) Flow Around Sunspots From Measurements of Frequency Shift.

1. Project of Taiwan Oscillation Network

The Taiwan Oscillation Network[1] (TON) is a ground-based network measuring solar K-line intensity oscillations for the study of the internal structure of the Sun. The TON project has been funded by the National Research Council of ROC since the summer of 1991. The headquarters of the TON is located at Physics Department of Tsing Hua University, Hsinchu, Taiwan, where the telescope systems are designed, built, and tested. So far, four telescopes have been operated. The first telescope was installed at the

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Teide Observatory, Canary Islands, in August of 1993. The second and third telescopes were installed at the Huairou Solar Observing Station near Beijing and the Big Bear Solar Observatory, California in 1994. The first three telescopes have been taking data simultaneously since October of 1994. The fourth telescope was installed in Tashkent, Uzbekistan in July of 1996, and started taking data since then. The site selection and arrangement of the fifth telescope in South America is underway.

The TON is designed to obtain informations on high-degree solar p-mode oscillations, along with intermediate-degree modes. That is complementary to other ground-based networks, such as BISON, IRIS, and GONG. A discussion of the TON project and its instrument is given by Chou et al. (1995). Here we give a brief description. The TON telescope system uses a 3.5-inch Maksutov-type telescope. The annual average diameter of the Sun is set 1000 pixels. A K-line filter, centered at 3934, of FWHM = 10 and a prefilter of FWHM = 100 are placed near the focal plane. The measured amplitude of intensity oscillation is of about 2.5%. A 16-bit 1242 by 1152 CCD is used to take images, but only 1080 by 1080 pixels are read out. The CCD is water-cooled, and the CCD chip is operated at a temperature of of about 223– 233 °K. The exposure time is set to 800 ms. The photon noise, about 0.2%, is greater than the thermal noise of the CCD and its circuit. The size of each image is 2.33MB. The image data are recorded by two 8-mm Exabyte tape drives.

The TON full-disk images have a spatial sampling window of 1.8 arcseconds per pixel, and they can provide information of modes up to $l \approx 1000$. The TON high-resolution data are specially suitable to study local helioseismology. In this paper, we present results of three topics on local helioseismology from TON data. For a more detailed description of these three topics, see the proceedings for posters of this conference.

2. Inference of Subsurface Magnetic Field From Absorption Coefficients of p-modes in Active Regions

Local analyses of helioseismic data have shown that a sunspot would modify the amplitude and phase of p-mode waves (Braun et al. 1987; Braun et al. 1992; Braun 1995) as the waves are passing through the sunspot. The interaction between the waves and the magnetic field provides a tool to probe the properties of sunspots, such as magnetic field, density, and temperature, below the surface. In this study we will use a phenomenological model proposed by Chou et al. (1996) and measured absorption coefficients to infer the subsurface magnetic structure of sunspots. In this model, the interaction of p-mode waves with a magnetic region is described by introducing a complex sound speed

$$c^2 = \frac{c_0^2}{1 - i\sigma(\vec{x})}, \tag{1}$$

where c_0 is the sound speed in non-magnetic regions. The dimensionless

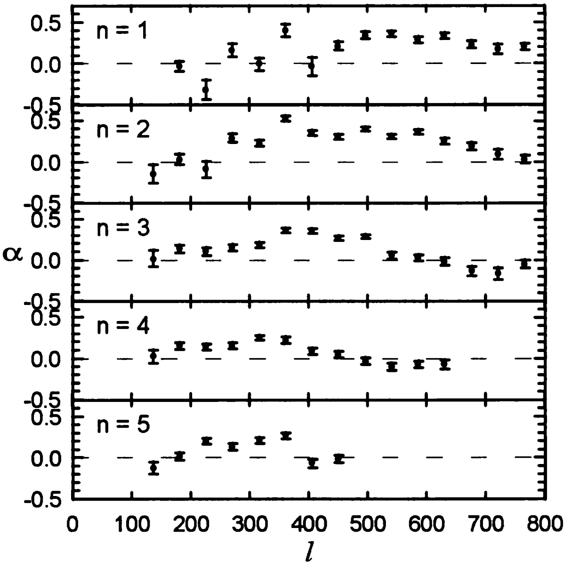

Figure 1. Absorption coefficient α of NOAA 7887 measured from TON data.

parameter σ is called the interaction parameter. σ relates to the distribution of the magnetic field that requires the theory of interaction mechanism. In general, σ is a complex. If σ is small compared with unit, to the lowest order, the real part of σ corresponds to the dissipation of waves, and the imaginary part describes the change of the phase velocity due to the change of physical conditions in magnetic regions. In this paper, we assume that σ is small, and use only measured absorption coefficients to invert the real part of σ. Our result shows that σ is small, and this assumption is a good approximation.

To make the problem tractable, we make the following assumptions about the magnetic region. (1) The distribution of σ is axisymmetric. (2) σ is constant in the horizontal direction within the spot, and zero outside the spot. (3) The spot radius is constant in depth. Then, the absorption coefficient α_{nl} is approximately related to σ by

$$\alpha_{nl} \approx \int K_{nl}(z)\sigma(z)dz, \tag{2}$$

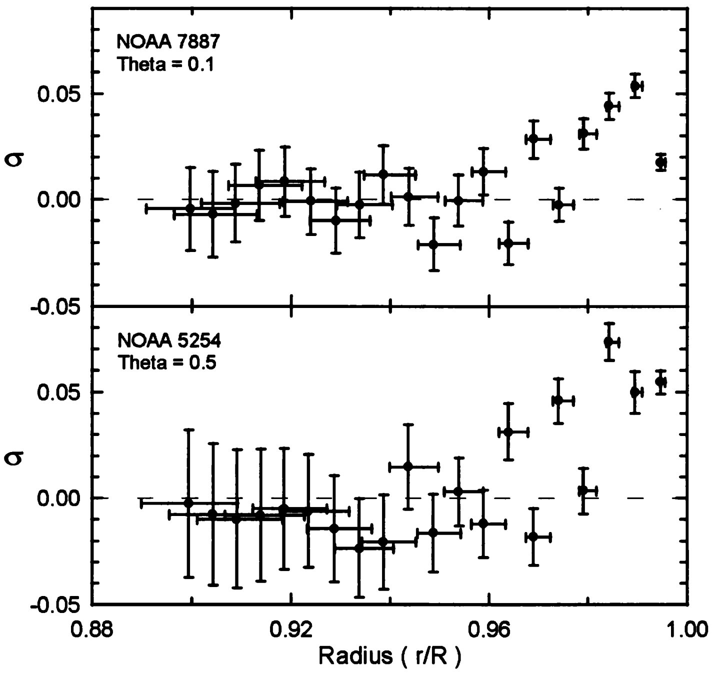

Figure 2. σ of NOAA 7887 (upper) and 5254 (lower).

where the kernel K_{nl}, given in Chou et al. (1996), is a functional of the wavefunction, which can be computed from the standard solar model. α_{nl} can be measured by decomposing the p-mode oscillations around a sunspot into the modes propagating toward and away from the sunspot (Braun et al. 1987; Chen et al. 1996). We use the Optimal Averaging Kernel method (Christensen-Dalsgaard et al. 1990; Pijpers and Thompson 1992) to invert the measured α_{nl} to obtain the distribution of σ below the surface.

In this study, we invert α_{nl} of two active regions. α_{nl} of NOAA 5254 are measured by Braun (1995) from 67.7-hour data taken at the South Pole. α_{nl} of NOAA 7887, shown in Figure 1, are measured by us from five-day data taken by TON. σ inverted from NOAA 7887 and 5254 is shown in Figure 2. With the above assumptions, the curve of σ vs. depth will be scaled up and down by changing the spot radius. In this study, we use the radius of penumbra as the spot radius, which is 16.4 Mm for NOAA 7887 and 18 Mm for NOAA 5254. Figure 2 shows that distributions of σ for two regions are similar. It drops from about 0.05 near the surface to zero at a depth of about 0.04 solar radius (28 Mm), which is consistent with the result of Chou et al. (1996). Our method can also apply to invert measured phase shifts.

3. Subsurface Structure of Emerging Flux Regions From Helioseismology

The helioseismic data have shown that magnetic regions absorb energy of p-mode waves. The motivation of this study is as follows. Since the different p-modes sample different regions in the solar interior, the magnetic field before emergence would not interact with higher-l p-modes whose cavities are shallow. The comparison of p-mode absorption coefficients before and after emergence can be used to infer the depth of the magnetic field before emergence.

We have studied two emerging flux regions (EFRs), NOAA 7754 and 7874 with TON data taken at Big Bear. These two EFRs are selected based on the following criterions. (1) The EFR is isolated; namely, the surrounding region, used to compute the absorption coefficient α, is flux-free judging from Kitt Peak magnetograms. (2) At the location of interest, it is flux-free on the day before the flux appears on the surface. For NOAA 7754, the magnetic flux appears on July 12, 1994, and we measured α with data of July 11 and July 12, respectively. For NOAA 7874, the magnetic flux appears on June 2, 1995, and we measured α with data of June 1 and June 2, respectively. The measured α are shown in Figure 3. Apparently, α after emergence is greater than before emergence for most modes. An important feature of Figure 3 is that the absorption is detectable before the flux appears on the surface for some modes; for example, in $n = 2$ of NOAA 7754, and $n = 1$ of NOAA 7874. Although the error bars are not small in our measurements, from our experiences on the quiet Sun analyses, we believe that here we detect the absorption of p-modes before the flux appears on the surface. For higher n, α is slightly negative in all our quiet Sun analyses. Thus it is difficult to conclude from Figure 3 that there exists absorption prior to emergence for the modes with $n > 2$.

In principle, the difference of α measured before and after emergence could provide information about the depth of the top of flux at the time α is measured prior to emergence. We expect that for the case prior to emergence, for a fixed n, α decreases with l and becomes zero when the mode cavity is too shallow to interact with the flux. Because of the low S/N, the present results would not allow us to identify the l value for a fixed n where α drops to zero. But, we can estimate the depth of the top of the flux prior to emergence from the difference of α measured before and after emergence, which is shown in Figure 4. For n=1, the difference of absorption coefficients peaks around $l = 600$ for NOAA 7754 and $l = 500$ for NOAA 7874. If the peak approximately corresponds to the mode which does not interact with the flux, the top of flux is located at a depth of about 4000 km for NOAA 7754 and 4700 km for NOAA 7874. The low S/N of α is due to the limitations: (1) the time series used to compute α has to be short (512 minutes in this study) such that the measured α represents the information of the EFR at a certain depth; and (2) the absorption is weak for EFRs.

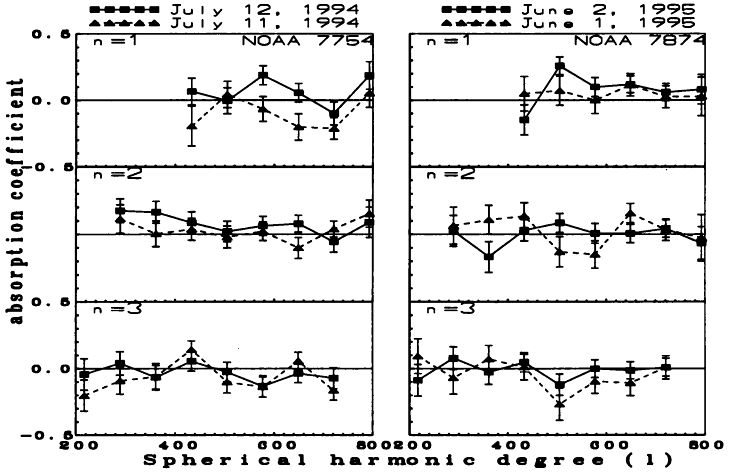

Figure 3. Absorption coefficients before and after emergence vs. l for different n.

4. Flow Around Sunspots From Measurements of Frequency Shift

We use five-day helioseismic data from TON to study the flow around a sunspot group, NOAA 7887, whose penumbra size is 16.4 Mm.

As in the analyses discussed in Section 2, the p-mode oscillations in an annular region centered at the sunspot are decomposed into modes propagating toward the sunspot and modes propagating away from the sunspot. The range of the annular region is $2° - 10°$. The frequencies of incoming modes and outgoing modes are determined by fitting the power spectra with a Gaussian profile (Libbrecht and Kaufman 1988). We find that for most modes the frequency of the outgoing mode is greater than that of the incoming mode. This indicates that the plasma is flowing outward from the sunspot. The frequency difference $\Delta\nu = \nu_{out} - \nu_{in}$ is shown in Figure 5. A region of quiet Sun in the same data set is studied to act as a control measurement. The corresponding $\Delta\nu$, also shown in Figure 5, is of about zero. We also measure $\Delta\nu$ with an annular region $(6° - 21°)$ farther away from the sunspot. For most modes, $\Delta\nu$ is still positive but

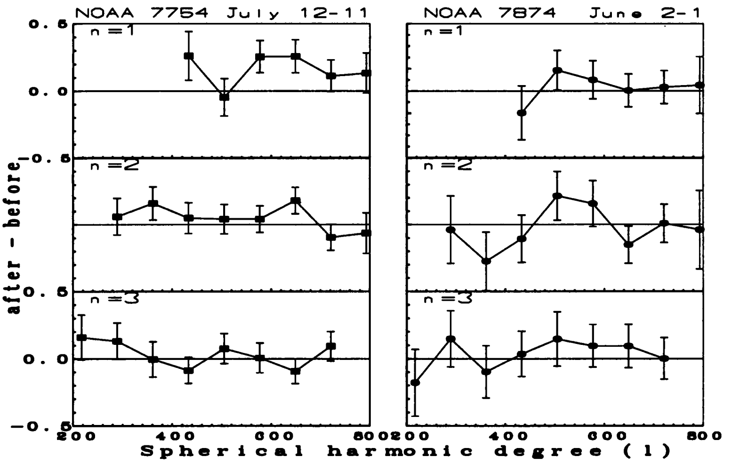

Figure 4. α(after emergence) - α(before emergence)

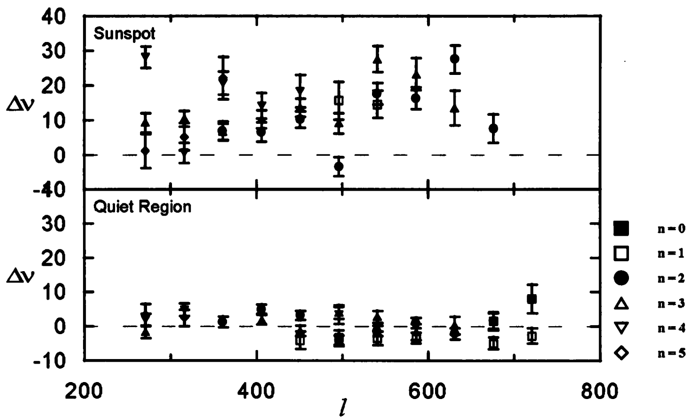

Figure 5. $\Delta\nu$ ($\nu_{out} - \nu_{in}$) vs. l for sunspot (upper) and quiet Sun (lower).

smaller than that of the annulus of $2° - 10°$. This is consistent with the picture that the outward flow is significant only near the sunspot. If we use $\Delta\nu \sim 2v\nu/c \sim vk/\pi$, where k is the wavenumber, to estimate the flow velocity, we obtain $v \sim 50 - 100 m/s$.

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