GONG'94: Helio- and Astero-Seismology
ASP Conference Series, Vol. 76, 1995
R.K. Ulrich, E.J. Rhodes, Jr. and W. Däppen (eds.)

GONG CALIBRATION PROCEDURE

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ABSTRACT The Global Oscillation Network Group (GONG) project has developed a procedure to calibrate solar Doppler oscillation measurements. After correcting for instrumental effects, we estimate a systematic velocity error of less than 10 meters/sec.

INTRODUCTION

The GONG project has developed a procedure to calibrate solar Doppler oscillation measurements. The solar image is measured with an array of about 250 × 250 pixels covering the full disk. At each pixel, an observation consists of three interleaved intensity-modulated measurements integrated for one minute. From these measurements, we calculate a vector, whose phase ideally represents a Doppler shift and whose magnitude is related to the line strength. Imperfections, primarily associated with the Michelson interferometer, add a spurious instrumental vector to the solar signal vector and alter the solar vector across the field of the instrument. The vectorial nature of this spurious modulation results in leakage between the signal amplitude and the phase, which must be removed before a measured phase can be reduced to a solar velocity.

The basic strategy for determining the spurious modulation is to feed light with known characteristics into the instrument and compare the output with what is expected. In calibration mode, two lenses are added to the normal optical system to form an image of the entrance pupil where the solar image is normally formed. These optics also form an image of the sun near the mirrors of the interferometer. The effect is to produce light at the final focal plane that would, in the absence of instrumental effects, have uniform phase across the camera image. There is an aperture at the interferometer that isolates a circular piece of the solar image. For calibration purposes, the telescope is pointed alternately to the east and west limbs, which are then compared. If the difference in average velocity and relative amplitude between the two observations are known, the spurious contribution can be determined. In practice, these parameters are not known and the phase difference and relative amplitude between the two limb measurements must be themselves determined from observations. Typically, the solar modulation amplitude is 4-5% with a spurious contribution of about 0.2%.

MEASUREMENT OF SOLAR INTENSITY IMAGES

The GONG instrument uses the Fourier tachometer principle of sweeping a squared-cosine transmission function across a limited region of the solar spectrum centered on the Ni I line at 676.8 nm. The Michelson interferometer produces a channel transmission function which is then effectively swept in wavelength by a rotating half-wave plate following it. In this way, the instrument isolates one Fourier component of the input spectrum, and velocity fields on the sun's surface can be obtained from the phase (ϕ) of this Fourier component.

The presence of an isolated solar absorption line in the narrow spectrum of sunlight admitted into the interferometer reduces the intensity for some phases of the varying transmission function. Consequently, each pixel at the focus of the instrument will be exposed to a time-varying signal of the form

$$I(t) = I_0 [1 + M \cos(4\omega t - \phi)] \tag{1}$$

where I_0 is the average intensity, M is the modulation amplitude and ω is the half-wave plate angular frequency (5 Hz)(Harvey 1988). The signal is integrated for 120° of a modulation cycle to produce three signals I_1, I_2 and I_3. From these, we calculate a vector at each pixel, whose phase ideally represents a Doppler shift and whose magnitude is related to the line strength:

$$\phi = \tan^{-1}[\sqrt{3}\frac{I_2 - I_3}{I_2 + I_3 - 2I_1}] \tag{2.1}$$

$$M = \sqrt{\frac{2}{3}}\frac{1}{I_0}[\sum_{i=1}^{3}[I_i - I_0]^2]^{\frac{1}{2}} \tag{2.2}$$

$$I_0 = (I_1 + I_2 + I_3)/3 \tag{2.3}$$

The bottom row of Fig. 1 shows the phase velocity, modulation amplitude and average intensity (left, middle, and right, respectively) of an image before calibration. Imperfections of the Michelson interferometer add a spurious instrumental vector to the solar signal vector and reflections in the air arm produce the obvious ring pattern in the uncalibrated images.

MEASUREMENT AND COMPUTATION OF SPURIOUS MODULATION

In calibration mode, the optics produce light at the final focal plane that would, in the absence of instrumental effects, have uniform phase across the camera image. The instrument pupil isolates a circular piece of the solar image. Two separate Doppler images are obtained in this way, one near the east limb and one near the west limb. In the absence of spurious modulation, the two images should be nearly identical except for a phase shift resulting from solar rotation.

These parameters can be represented in a vector diagram, where phase is indicated by a vector's direction, and amplitude by its length. If the phase separation (the mean velocity difference) and the relative amplitude of the two observations are known, then the true origin of the coordinate system can be located and the spurious vector component can be deduced. Let E_x, E_y represent the east limb measurement, in rectangular coordinates. Similarly, let

W_x, W_y represent the west limb measurement. The spurious modulation vector, in rectangular coordinates, can then be expressed as

$$S_x = \frac{1}{2}[(E_x + W_x) - \frac{(E_x - W_x)\sin\alpha}{\sin\Phi} - (E_y - W_y)(\frac{\cos\alpha - 1}{\sin\Phi} + \frac{1}{\tan\frac{\Phi}{2}})] \quad (3.1)$$

$$S_y = \frac{1}{2}[(E_y + W_y) - \frac{(E_y - W_y)\sin\alpha}{\sin\Phi} + (E_x - W_x)(\frac{\cos\alpha - 1}{\sin\Phi} + \frac{1}{\tan\frac{\Phi}{2}})] \quad (3.2)$$

where

$$\alpha = \sin^{-1}[\frac{(m^2 - 1)\sin\Phi}{1 + m^2 - 2m\cos\Phi}] \quad (3.3)$$

and m is the relative amplitude of the east and west limb signals. The parameter α is called the "balance angle" and allows the relative amplitude of east and west vectors to be changed while holding the difference in average velocity between the two measurements, Φ, constant.

Image vectors are also corrected for interferometer field effects, the dominant source being path difference variation with angle. This is achieved by correcting a calibration image (east or west limb measurement) for spurious modulation. The phase of the resultant image is the phase variation and the modulation is the modulation efficiency of the interferometer.

In practice, the phase angle Φ and the balance angle α are not known to sufficient precision. Pointing errors result in an uncertainty in the phase angle Φ; whereas pointing errors and the distribution of solar active regions combine to cause significant variations in the modulation amplitudes of the two observations which translates into an uncertainty in the value of the balance angle, α. Therefore, these two parameters, Φ and α, must be determined in a self-consistent way from each east-west pair of calibration images. The criterion for determining the correct values of these parameters is the symmetry of the final, corrected solar modulation image. Since a properly calibrated modulation image is a map of the equivalent width of the solar absorption line being used, the modulation image should be, on average, symmetric about the center of the sun; isopleths of equal modulation strength should be concentric with the limb of the sun. The effect of an incorrect value for Φ is to distort the contours (either flattening or elongating along the sun's north-south line) into ellipses. The effect of an error in the balance angle, α, is to cause the centers of the circular contours to shift along an east-west line on the sun. In other words, the correct values of Φ and α are those that minimize crosstalk between velocity and modulation.

In practice, the root-mean-square (rms) deviation of the modulation from the mean value within a narrow annular ring on the sun's image is a sensitive indicator of symmetry. The rms goes through a distinct minimum over the range of possible Φ, α pairs. The optimum values of these two parameters are found by minimizing the rms deviation of the modulation in an annulus which is 90-98% of the sun's radius, using a downhill simplex method.

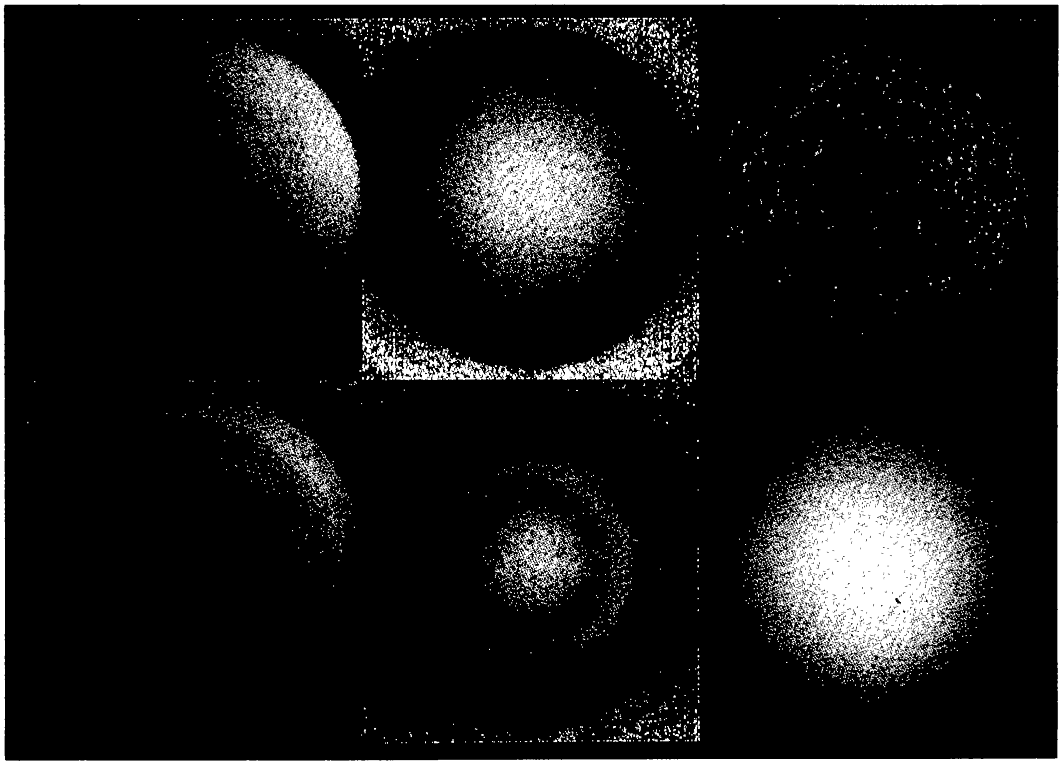

Fig. 1. The top row shows calibrated velocity and modulation images (left and middle, respectively). The top, right image shows the calibrated velocity image after detrending using observer motion calculated from ephemeris data and a simple model for solar rotation and limb shift. The bottom row shows the corresponding uncalibrated phase velocity and modulation amplitude, as well as the average intensity.

CONCLUSION

As shown in Fig. 1, no spurious effects are detectable after calibration. Pending simultaneous results from two independent instruments, we estimate a residual systematic velocity error of less than 10 meters/sec.

ACKNOWLEDGEMENTS

The National Optical Astronomy Observatories are operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the National Science Foundation.

REFERENCES

Harvey, J. 1988, in Proc. Symp. Seismology of the Sun and Sun-like Stars, Tenerife, Spain, 26-30 September 1988, ESA SP-286, p. 203.