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GONG instrument and science

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Abstract. The Global Oscillation Network Group (GONG) is an international project to study the solar interior using helioseismology. The major goal is to accurately measure those modes of solar acoustic oscillations that have global characteristics in order to diagnose solar structure and dynamics throughout most of the interior. Starting in October 1995, observations of solar oscillations have been obtained with a duty cycle averaging 90% using a network of six identical instruments sited around the world. These instruments produce full-disk images with a pixel size of about 8 arc seconds every 1/60 second. The Doppler shift of a photospheric spectrum line is encoded into three intensity images as the phase of a sinusoidal intensity variation. Calibration of instrumental effects is difficult, but is adequate for measurements of the acoustic oscillations. The instrumental noise level is less than solar sources at all temporal and spatial scales necessary to meet the main science goal. The statistical properties of individual modes of oscillation make it difficult to accurately measure characteristic frequencies, amplitudes, etc. without averaging over some domain. GONG is providing large quantities of unaveraged mode characteristics for the first time. The properties of the interior inferred using the unaveraged GONG data agree with previous determinations in general, but there are some interesting differences.

Key words: sun: helioseismology – sun: instrumentation – sun: interior

1. Introduction

The Global Oscillation Network Group (GONG) is an international project to study the solar interior using helioseismology. This technique is now more than 20 years old and has been frequently reviewed (e.g. Harvey 1995; Christensen-Dalsgaard 1996; Gough et al. 1996). The main goal of the GONG project is to provide accurate measurements of the frequencies of the acoustic (p) modes that are global in nature in order to determine the sun's interior structure and dynamics. The project involves more than 150 researchers, observers and technicians around the world. The GONG project has been described several times (e.g. Leibacher et al. 1995; Harvey et al. 1996; Kennedy 1996).

Helioseismology has two distinct branches – local and global. Both are based on observations of acoustic waves believed to be generated by convective processes near the solar surface. In principle, the structure of the sun supports of the order of 10^7 acoustic wave modes. It is observed that about 3% of these involve wave motions that remain coherent long enough to form global standing wave patterns. These patterns are characterized by three integers: l, spherical harmonic degree; m, azimuthal order; and n, radial order. Global modes have resonant frequencies and amplitudes that depend upon averages of internal properties over various cavities in latitude, and depth. The GONG project is specifically aimed at measuring frequencies of these global modes with high accuracy. These frequencies are then the basis for making inferences about the sun's internal structure and dynamics.

Local helioseismology is an exciting new branch that primarily uses running waves rather than trapped modes. It is based largely on high-degree oscillations that involve high-angular resolution observations. In its present form, the GONG instrument is not as well suited for local helioseismology as are other instruments and projects—especially the SOI/MDI project on board the SOHO spacecraft (Scherrer et al. 1995).

2. Instrument

Frequencies of individual modes of oscillation are usually measured from spectra. The spectra indicate the strength of an oscillating variable such as Doppler shift, as a function of l, m, and ν (temporal frequency). The spectra need a low noise level, adequate resolution in the independent variables, and freedom from spectral artifacts. It is the latter consideration that was the main motivation for the GONG project. Observations from single ground-based sites suffer diurnal interruptions that cause spurious spectral features. These extra features complicate an already crowded spectrum and degrade the quality of measurements that can be made. The solution to this problem provided by GONG is to use six sites around the world to obtain nearly continuous observations of the solar oscillation spectrum. Not only are spurious spectral features greatly reduced, but the signal-to-noise ratio of the spectrum is improved and various systematic effects associated with single sites are reduced. The major disadvantage is the need to merge data taken with different instruments.

The signal measured with the GONG instrument is the line-of-sight Doppler shift of a photospheric spectrum line. Other observables are sensitive to the p-mode oscillations, but none provide a stronger signal for the global p modes. The spectrum line chosen is 676.8 nm Ni I, a line that is exceptionally free from solar and telluric blending. To get the best possible resolution in l and m, the full solar disk is observed. The highest degree global modes have l values of about 200 and their observation requires that the disk be resolved into at least 200 elements along a diameter. Global p modes are not seen at frequencies above about 5 mHz and there is little solar power at frequencies above 8 mHz so observations taken once per minute provide adequate temporal sampling while avoiding significant temporal aliasing. The most challenging part of the GONG instrument is to produce the Doppler shift measurement with adequate sensitivity, dynamic range, stability, and freedom from atmospheric effects.

Of the many possible ways of measuring Doppler shifts, the method used by GONG is called phase-shift interferometry by the optics community and Fourier tachometry by some in the solar community. The idea is simple. The phase of one component of the Fourier transform of a portion of the solar spectrum around one spectrum line is measured and interpreted as a Doppler shift using a Michelson interferometer. This may be done simultaneously on all parts of a resolved image of the sun using a suitable optical system and detector. The potential advantages of the method are linearity, freedom from many detector defects, and relatively standard optical technology. The disadvantages are a weak signal, sensitivity to wavelength drifts of filters, and stringent requirements on the performance of the interferometer.

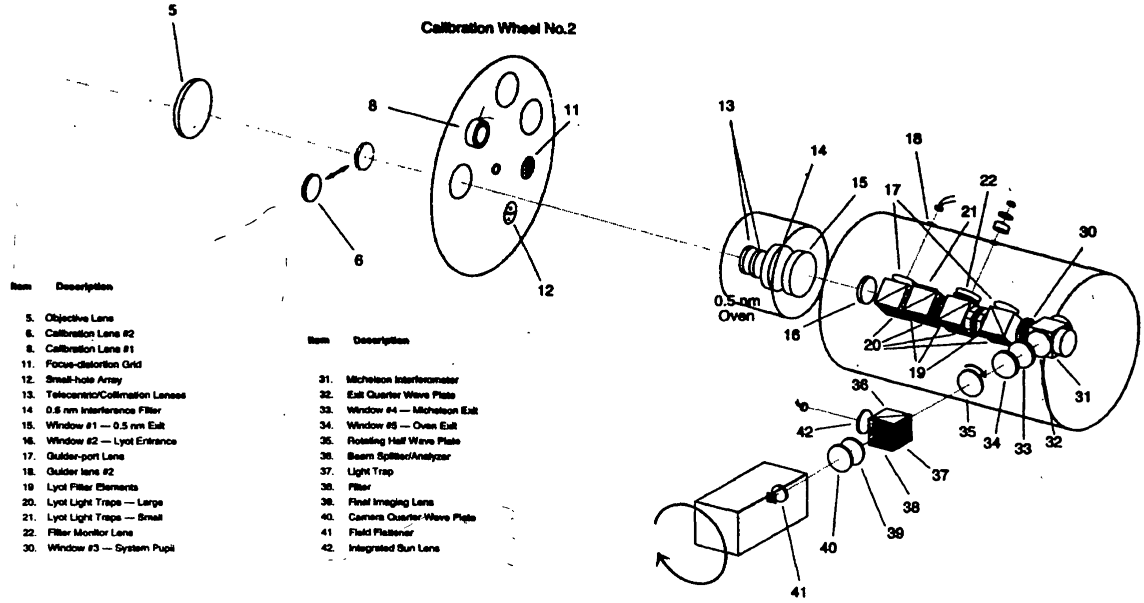

Figure 1. Schematic diagram of the GONG instrument.

Implementation of this technique uses a small telescope and optical system that focuses a full-disk image of the sun onto a CCD television camera that produces 60 digitized frames per second. The optical system is laid out on a horizontal table inside a refurbished shipping container. Sunlight is fed into an objective lens by an exterior turret that contains an entrance window (which also reflects most of the unwanted solar spectrum), and a pair of mirrors. The major remaining elements are 0.5 nm band pass interference prefilter (item 14 in Figure 1), a 0.1 nm band pass Lyot filter (19), a Michelson interferometer (31), and a rotating polarization analyzer (35).

The interference prefilter and Lyot filter produce a 0.1 nm transmission band centred on the 676.8 nm solar line. The interference filter uses ion-assisted deposition technology to insure long-term stability. It is mounted inside a temperature-controlled cell. The Loyt filter is designed to have a wide angular field and to be temperature compensated. It is also mounted in a temperature-controlled cell. The Michelson interferometer uses a polarizing beam splitter with mirrors in its two arms that are respectively supported by solid glass and copper spacers. This design allows the field of view to be widened as well as simultaneously temperature compensated following the principles given by Title and Ramsey (1980). Some details about the interferometer are given by Harvey et al. (1995).

The interferometer produces a transmission function that is a sine squared function of wavelength. The phase of the function depends on the angle of a rotating analyzer. The analyzer is rotated synchronously with the exposure of the camera to the solar image so that exactly three images are collected for one complete cycle. These three images have intensity variations that depend on the relative position of the transmission function of the interferometer and the Doppler shift of the solar spectrum line. The three intensity samples are averaged separately for one minute and then fit with a sinusoid that describes amplitude, mean intensity and phase. The phase is converted to a Doppler shift.

3. Operation and performance

There are six instruments in operation. They are located at existing observatories in India, Spain, Chile, Australia, and the United States. At each site a small computer system operates the instrument semi-automatically. Data are recorded on 8mm digital tape. Copies are retained on site and are also mailed to Tucson where the data are processed. Each instrument in interrogated from Tucson to assess its status. Local hosts and personnel have been absolutely vital to maintaining a high network duty cycle that currently exceeds 90%.

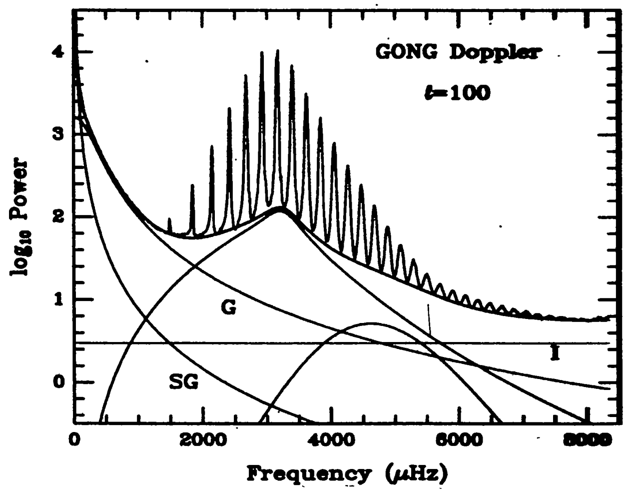

Figure 2. The power spectrum of solar oscillations derived from full-disk observations made with the GONG network for 36 days. A fit of this *m*-averaged spectrum at *l* of 100 is done in terms of a model consisting of supergranulation (SG), granulation (G), instrumental noise (I) , and two-power-law functions underneath the p modes and a broad, so-called chomospheric mode. Note that the instrumental noise level is below the solar back-ground.

The instrument was specified to have a noise level below 10 m/s per pixel per minute. The limiting factors are the camera and atmospheric seeing effects and a pleasant surprise is the good performance of the instrument at l=0 where these effects are the strongest. Of course, the real test is how well the solar oscillations stand out above the instrumental background. An indication of this is shown in Figure 2. Additional examples of performance may be seen in Harvey et al. (1996).

The spectra produced by the network are of high quality. The diurnal sidelobes have been reduced by a factor 1000 compared to spectra from a single site. The low noise level has revealed some artifacts in the spectra that can be reduced further. In particular there is a small amount of spatial aliasing that contaminates high degrees. There is also a substantial amount of cross talk between individual spherical harmonics. The latter problem will be reduced when the data is reprocessed, but some of it is the inevitable result of observing from the ground. Several other improvements for the reprocessing are planned. In particular, better merging of data from different sites.

4. Calibration and merging

The calibration of the GONG instrument is complicated. An overview is given by Toussaint et al. (1995). The basic idea is to exchange an image of the sun for an image of an entrance pupil. This is done with two additional lenses that can be moved into the optical path. Under these conditions, and because of a small stop located on an image of the sun, every point in final focal plane uses light from the same part of the sun which has identical average Doppler shift, intensity, etc. Thus, any deviations from constant values are due to the instrument. These deviations are measured and removed from solar images. Unfortunately, the interferometer produces a small amount of modulation even in the absence of a solar spectrum line. This modulation has to be measured and eliminated from the observed solar data. Much of the complexity of the calibration is cause by this spurious modulation. The spurious component of the modulation is determined by doing two independent calibrations using different parts of the solar disk. Since the Doppler shifts of the two regions are different, this allows the purely instrumental part to be separated.

This calibration procedure is adequate for the frequency range that contains the modes. However, the orientation of the solar image relative to the optical system changes during the day. This introduces slow changes that are not completely compensated by the calibration. The result is systematic errors in Doppler shift measurements of rotation and slowy changing features. Another factor is the absolute sensitivity of an instrument to Doppler shift. This is set principally by the Michelson interferometer path difference. All of the interferometers were manufactured to be nearly identical, so this is not an issue. However, secondary factor, such as prefilter profiles, cause the sensitivity of each instrument to Doppler shift to be slightly different. At present this difference is calibrated empirically and not entirely satisfactorily.

Merging data from different instruments is challenging. The major difficulty has been rotational alignment of the images. This requires accuracy at the 0.01 degree level. It is done in two steps. First, the camera is rotated during data collection to try to keep the solar equator parallel to pixel columns at each site. The residual errors of about 0.1 degree are later determined by cross correlation of images from different sites using the entire network and a minimization of parameters that represent the errors at each site.

5. Science highlights

The GONG project is producing a huge amount of data. It will take a long time for the helioseismology community to fully extract knowledge about the sun from this data. The first scientific results from the GONG project were published in a special issue of Science on 31 May 1996. More results were presented at a meeting of the American Astronomical Society in June 1996 (see BAAS, 28 (2)) and at the recent IAU Symposium 181 in October 1996. It is possible here only to mention a few highlights and point out a unique aspect of the GONG results.

While some local helioseismology has already been done using GONG data, the main results to date concern inferences about internal structure and rotation. From preliminary GONG data, Gough et al. (1996) found that the variation of sound speed with depth just below the convection zone and just above the energy-generating core is smoother than predicted by models. This suggests that the models are not correctly accounting for gravitational settling or that there are macroscopic motions that are mixing these layers. These investigators also confirmed that there are significant aspherical components in sound speed near the surface. There is an intriguing hint of deeper aspherical perturbations, but confirmation of this will require more data.

Analysis of rotational splitting data by Thompson et al. (1996) confirms previous results that the differential rotation observed at the surface persists throughout the convection zone. At the bottom of the convection zone there is a relatively sharp transition to nearly uniform rotation at a rate similar to that seen at the surface near 30 degrees latitude. Another shear layer near the surface, in the sense that the surface rotates slower than the interior, seems to be a robust feature of inferences based on GONG data. The rotation of the core is still uncertain but extremely fast rotation seems to be excluded. Local analysis applied to GONG data confirms a curious spiral flow pattern as a function of depth seen in earlier data.

Observations of the surface flows and magnetic fields are also possible with GONG data. Hathaway et al. (1996) measured differential and meridional flows using GONG data. The latter has been elusive and controversial. The analysis shows poleward flow peaking at about 40 degrees latitude and 18 m/s which is consistent with some previous measurements. Another elusive flow is the so-called torsional oscillation which is a narrow band of latitudes wherein the rotation rate is about 3 m/s slower than the surroundings. Previously it was necessary to average over long time periods to reveal this flow. In GONG data it is readily detected in one month. This sensitivity should help in understanding its cause.

A unique aspect of GONG data and analysis is that for the first time, an effort is being made to provide large numbers of individual mode frequencies. Previously, averaging over various ranges of m or ν was performed prior to fitting the spectra to reduce uncertainty. Figure 3 shows why averaging dramatically improves the ability to fit spectral features. As discussed by Anderson, Duvall, & Jefferies (1990), a spectrum of a single spherical harmonic of observed oscillations has a probability distribution function at a single frequency that follows χ^2 with two degrees of freedom. Averaging more spectra together increases the degrees of freedom by two for each added spectrum. The curves of these distributions in

Figure 3 show that a single spectrum is very noisy with many more small than large excursion from the expected value. Even a small amount of averaging makes the distribution closer to the Gaussian distribution that is so familiar. In other words, there is a rapid improvement in noise by averaging. Despite the obvious advantage of averaging, it is highly desirable to avoid it since differences between modes convey the principal observational messages of helioseismology. Whether averaging can be avoided in extracting the maximum amount of science from GONG remains to be seen. At this point of the GONG project, it is worth emphasizing that systematic effects have not yet all been discovered and that science results are accordingly preliminary.

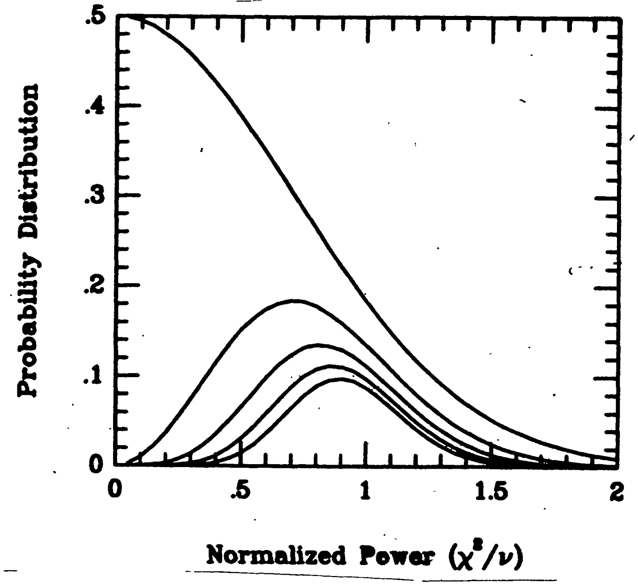

Figure 3. Distributions of observed measurements relative to expected values for various amounts of averaging of solar oscillation spectra. Abscissa is the value of a measurement relative to that expected. Ordinate is the relative probability of making a particular measurement. The top curve is for a single spectrum. Successively lower curves are the distribution for two through five spectra averaged together. Notice that a single spectrum is expected to show a wide range of values quite different from the expected value.

Another interesting aspect of the GONG project is the nice way that investigators from all over the world are working together to analyze the data. This is being done using the capabilities of the World Wide Web to create a virtual workshop where researchers can discuss and compare results before going to publication. This development has been very productive.

6. Prospects

Since the GONG project was initially proposed, it was discovered that the frequencies of p modes change as the level of solar activity waxes and wanes. Techniques for doing local helioseismology have also been invented. For these reasons, a proposal to continue operating the GONG for a complete 11-year solar cycle is being prepared. The proposal includes a continuation of the present observations, but using a camera that will have improved resolution and lower noise. This will enable high resolution imaging of internal structure and dynamics, improvement of inferences about he time-averaged internal properties, and an unprecedented study of solar variability.

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References

Anderson E.R., Duvall T.L. Jr., Jefferies S.M., 1990, ApJ, 364, 699.

Christensen-Dalsgaard J., 1996, BASI, 24, 103.

Gough D.O., Leibacher J.W., Scherrer P.H. Toomre J., 1996, Science, 272, 1281.

Gough D.O. and 25 coauthors, 1996, Science, 272, 1296.

Harvey J., 1995, Physics Today, 48 (10), 32.

Harvey J., and GONG Instrument Team, 1995, GONG'94: Helio- and Astero-Seismology, ed. R. Ulrich, E. Rhodes, W. Dappen, ASP Conf. Ser. 76, 432.

Harvey J.W. and 16 coauthors, 1996, Science, 272, 1284.

Hathaway D.H. and 9 coauthors, 1996, Science, 272, 1306.

Kennedy J.R., 1996, Sky & Telescope, 92 (4), 20.

Leibacher J. and the GONG Project Team, 1995, in GONG'94: Helio- and Astero-Seismology, ed. R. Ulrich, E. Rhodes, W. Dappen, ASP Conf. Ser. 76, 381.

Scherrer P.H. and 24 coauthors, 1995, Solar Phys., 162, 129.

Thompson M.J. and 25 coauthors, 1996, Science, 272, 1300.

Title A.M., Ramsey H.E., 1980, Appl. Opt., 19, 2046.

Toussaint R., Harvey J., Hubbard R., 1995, in GONG'94: Helio- and Astero-Seismology, ed. R. Ulrich, E. Rhodes, W. Dappen, ASP Conf. Ser. 76, 532.