PERFORMANCE AND EARLY RESULTS FROM THE GOLF INSTRUMENT FLOWN ON THE SOHO MISSION

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Abstract. GOLF in-flight commissioning and calibration was carried out during the first four months, most of which represented the cruise phase of SOHO towards its final L1 orbit. The initial performance of GOLF is shown to be within the design specification, for the entire instrument as well as for the separate sub-systems. Mal-functioning of the polarising mechanisms after 3 to 4 months operation has led to the adoption of an unplanned operating sequence in which the mechanisms are no longer used. This mode, which measures only the blue wing of the solar sodium lines, detracts little from the detection and frequency measurements of global oscillations, but does make more difficult the absolute velocity calibration, which is currently of the order of 20 %. Data continuity in the new mode is extremely high and the instrument is producing exceptionally noise-free p-mode spectra. The data set is particularly well suited to the study of effects due to the excitation mechanism of the modes, leading to temporal variations in their amplitudes. The g-modes have not yet been detected in this limited data-set. In the present mode of operation, there are no indications of any degradation which would limit the use of GOLF for up to 6 years or more.

Key words: sun, helioseismology

1. Introduction

GOLF is designed to measure the Global Oscillations of the integrated solar disk, by determining the line-of-sight velocity of the photosphere as a function of time. Although the instrument is sensitive to a wide range of frequencies 10^{-7} to 10^{-2} Hz, the priority objectives concentrate on the frequency range 10^{-5} to 10^{-3} Hz, where are found the lower frequency p-modes and the predicted g-modes. This is the range in which ground-based measurements are severely penalised by the disturbance of the earth's atmosphere and the lack of continuity in the observations. By taking full advantage of the unique platform offered by SOHO, GOLF has proved capable of enhancing the sensitivity and decreasing the observational noise, especially at lower frequencies.

For a full description of the GOLF instrument concept and design, the reader is referred to a detailed article published before launch (Gabriel et al. 1995). A pre-launch description of the SOHO platform and mission can also be found (Domingo, Fleck and Poland 1995). SOHO maintains its payload in a full-sun orbit around the Lagrange point L1, from where it remains pointed at the centre of the sun throughout its normal operating sequences. In this way, the environment has a long- term continuity and stability, in terms of temperature, illumination and pointing, at a level never previously obtained for solar observations.

The GOLF instrument is a development for the space environment of instruments operated for many years on the ground, in particular the BISON (Chaplin et al 1996) and IRIS (Grec et al 1991) networks. More closely related to IRIS, GOLF compares the frequency of the solar sodium D Fraunhöfer lines with that of an atomic standard sodium vapour cell carried in the instrument. The Doppler shift between these two gives the line-of-sight relative velocity and analysis of its time variation gives the global solar frequencies. Each sodium line is split into two Zeeman components by a strong permanent magnet on board, and these monitor the two wings of the broader solar absorption line. The actual configuration of GOLF differs somewhat from the IRIS concept; in the choice of the plane of polarisation used, in the use of both of the sodium D lines and in the system of polarising mechanisms adopted for switching between the two wings. In addition, GOLF carries small electrical coils, allowing the 5000 gauss permanent magnetic field to be modulated by a small field of about ± 100 gauss, to enable also the mean slope of the operating points on the two wings of the solar line to be determined. GOLF carries an additional rotatable quarter-wave plate. This has the dual objective of measuring the intrinsic global solar magnetic field and providing a redundant back-up in the case of failure of the other GOLF polarising mechanism.

Many subsystems of the GOLF instrument carry redundant duplication. These include most of the electronics, some sensitive mechanisms (such as door actuators), local heaters and the photomultiplier detectors. The selection of these is linked globally, so that GOLF provides a choice of either a Channel A or a Channel B.

The pre-launch plan foresaw a 40-second cycle of operations, in which at least one of the two rotating mechanisms and the magnetic field modulation were switched each 5 seconds. In this way, ratios could be derived giving data points every 40 seconds, relating to the line-of-sight velocity, the mean slope of the solar absorption line and the global magnetic field.

The SOHO mission was launched with outstanding precision on December 2 1995. GOLF was switched on some hours later and was subjected to some months of commissioning and calibration during the transfer to L1. In most respects GOLF has been shown to meet fully the scientific specification and is producing data of an outstanding quality, never before obtainable. The malfunctioning of the two rotating mechanisms on GOLF has led us to adopt after some months an in-flight sequence which does not use these mechanisms and which was not planned before launch. It is demonstrated that this alternative mode has only a small effect on the sensitivity or noise level of GOLF in detecting solar oscillations, or in measuring their frequencies. It does however considerably increase the task of providing the last 10 % to 20 % precision on the velocity amplitude of the measured oscillations. In this mode, adopted since April 1997, the secondary objective of measuring the global solar magnetic field cannot be accomplished. However, operating as it does with no mechanical movement, it can be claimed that the reliability for long undisturbed observing sequences is considerable enhanced.

2. Commissioning

2.1. Early Switch-on

GOLF was switched on for the first time on December 3 1995 at 01:53 UT. The primary purpose of this 8 minutes test was to check that the experiment aperture cover had remained close through the launch period and was protecting the GOLF entrance filter from contaminating deposits throughout the initial experiment and spacecraft outgasing period. This was also an opportunity to verify that the instrument automatic boot performed nominally and that substitution heaters, directly powered by the spacecraft, provided adequate dissipation when GOLF was not powered. The GOLF collectively controlled units (Power Supply Unit and Data Processing Unit) were respectively at 14.0 and 18.3 deg C, close to their eventual operating temperatures. Temperatures ranged satisfactorily between 20 deg C for the front end of the sensor unit to 13 deg C at the anti-solar end, the filter being at 7.9 deg C, its passive radiator at -8.7 deg C, the magnet at 16.3 deg C and detector cathodes at 14.5 deg C. These and all other parameters observable in the telemetry were within their predicted range. The first GOLF command was sent and verified.

2.2. Activities with door closed

GOLF Channel A was powered ON definitively on December 10 1995 at 02:14 UT. At switch-on, the sensor mean temperature was close to 20 deg

C, the filter being at 16 deg C, and its passive radiator at -6.6 deg C. The Data Processing Unit was at 13.7 deg C and the Power Supply Unit at 15.9 deg C.

At first, the instrument was set to an almost nominal observation mode except for the resonance cell stem, which was unheated and the aperture cover that was kept closed. On December 11, the resonance cell stem heater was turned on, completing the successful functional testing of Channel A. Except for a short filter temperature scan, the GOLF Sensor dissipation remained constant up to December 16 to allow the temperatures to stabilise. The instrument was then set into a safe mode while awaiting the end of the first month outgasing. This period has been used to verify the detector background and to study the influence of cosmic rays and any electrical perturbations from the spacecraft or other instruments (see Section 5.2).

2.3. Channel A Commissioning

The GOLF entrance door was opened following the SOHO Mid Course Correction 2. The sub-systems full performance characterisation and optimisation were performed between January 9 and 24 1996. This was continued between February 6 and 13 just before the experiment was set into a safe mode for the duration of injection activities into the Halo Orbit. GOLF was then set into a science observation mode on February 19, with the polariser mechanism alone providing the polarisation switching necessary to obtain velocity measurements.

Channel A in-flight overall performance, being in very good agreement with the results obtained during ground testing, and these ground measurements having shown that Channels A and B sensitivity were very similar, it was decided to continue gathering science data with Channel A, rather than switch over for commissioning Channel B. This change of policy was in line with the general strategy adopted by most of the SOHO instruments, regarding the testing of redundant systems. It should be recalled that although switching from one channel to another can be done within a few hours, reaching the thermal stability to allow science quality observations takes a few days, in accordance with the predictions of the thermal model, and as verified in flight on February 16.

However, GOLF did take advantage of a period of disturbed pointing due to spacecraft testing on March 21 1996, in order to carry out a short functional test of Channel B. All functions were tested and showed very similar performances to those of Channel A. This gave confidence that Channel B is always available, should it ever prove necessary to switch over. After six hours the instrument was returned to the Channel A mode.

3. In-flight Calibration Activities

Calibration sequences have been carried out for the two most likely environmental disturbances on the instrument performance: temperature and spacecraft pointing. For temperature, the subsystems most sensitive are firstly the cell stem, which determines the sodium vapour pressure, and next the entrance filter.

3.1. Cell Temperature

Calibration measurements on the cell temperature were carried out between January 12 and 23. The stem temperature was progressively increased, while the bulb was maintained at a higher temperature by means of its heater at constant dissipation. The apparent velocity sensitivity reached a maximum at a stem temperature of 170 deg C. However, as predicted (Boumier and Damé 1993), the total PM count rate however continued to increase almost linearly with the stem temperature up to the maximum tested of 180.5 deg C. At this level, each PM count rate was nearly 8 10^6 per second and the bulb temperature reading was 195.5 deg C. It should be emphasised that there is an unknown but constant difference between these thermistor readings and the real cell or vapour temperatures due to contact conductivity effects. At the end of these tests, on January 23, cell heater currents were adjusted to values which have since remained unchanged. For these settings the stem temperature was close to 170 deg C and the bulb temperature reading was 188 deg C. The stem temperature increase per heating current commanding step was 0.012 degree (which is close to the temperature reading digitalisation step amplitude). A change in the heating of the bulb modifies the temperature of the stem by about 19 % of that obtained at the bulb. The counting rates were close to 5.5 10^6 per second for each detector, with a sensitivity of 126800 c/s per one degree change of stem temperature, in accordance with pre-launch calibration. This implies that a stem temperature change of a 0.01 deg C digitalisation step corresponds to a counting rate change equal to the statistical error in the counting rate over 1 second.

3.2. Filter Temperature

The filter band-pass is directly influenced by its temperature, as observed and studied before launch. In addition, since the filter area is directly imaged in the vapour cell, any variations across its surface can introduce disturbances in the symmetry and uniformity of the scattering system. As the two photomultipliers cannot view precisely the same scattering volume, this can be tested by comparing their outputs. The filter temperature was scanned very slowly and automatically on January 23 and 24, to be completed on February 6 and 7. The range scanned was from 17 to 20 deg C. The operating temperature of 17.5 deg C was chosen as a result of these scans and has been adopted since February 8 for subsequent observations. At this temperature, the velocity signals from the two PMs are similar and do not vary rapidly with temperature. The filter heater current is maintained constant and has only once been adjusted since, in order to compensate for some very slow temperature drift due to variation in the performance of the various thermal coatings. Monitoring of filter temperatures is maintained at the level of 0.01 deg C, and to this precision no variations are observed at frequencies relevant to the GOLF measurements.

3.3. Off-set Pointing

Measurements of the sensitivity of GOLF to spacecraft pointing errors was considered to be of great importance, since it had been judged too difficult to carry out meaningful tests on the ground before launch. Moreover, such measurements as had been quoted from tests on IRIS instruments reported a high sensitivity to off-set pointing, at levels that could have produced serious problems for the spacecraft platform mounting of GOLF.

GOLF Sensitivity to off-set pointing was measured for Yaw and Pitch excursions on February 21 and 22 respectively. Calibration for Roll had to be postponed to March 15, after SOHO Star Sensor software patching. During 16 continuous hours of each of these days the spacecraft was oscillated around one of its three reference axis, with a period of 800 seconds and a square-law amplitude of 30 arcsec in Pitch and Yaw and 90 arcsec in Roll. This is more than an order of magnitude larger than the worse case short term variations of SOHO observed pointing errors. Should the experiment have been sensitive to such movements, a peak would have appeared at 1.250 mHz in the Fourier spectrum of the detector signals. This frequency being in the area where the solar background "noise" reaches a minimum provides the best conditions to observe the created peak with the largest signal to noise ratio. For all three axes, no peak was detectable above the normal experiment noise- level. This confirmed the efficiency of the instrument optical system which has been designed specifically to minimise the sensitivity to spacecraft pointing off-sets.

4. Operating Sequence

The nominal pre-planned operating sequence of GOLF is fully described in the earlier instrument publication (Gabriel et al 1995). In this, switching the orientation of the two mechanisms (quarter-wave plate (QW) and the polariser (POL)) as well as switching the direction of the magnetic field modulation are carried out in a sequence of 40 seconds total, with at least one component switched each 5 seconds. By regrouping the data, it is possible to construct signals characteristic of solar velocity, solar magnetic field and slope of the solar line wings each 40 seconds, or even more frequently if desired.

This nominal sequence was put in operation from the start of science data collection on January 18 1996. However, it soon became evident that there were occasional glitches in the performance of the QW mechanism. At first not too frequently, these lost only a small number (1 to 5) 40-second sequences per day. Later on, these became more frequent, and more difficult to control. It was decided on February 11 to stop the QW mechanism in its optimum position. With the POL mechanism alone it was then possible to continue the full solar velocity studies, losing only the possibility to extract global magnetic field data.

Towards the end of March 1996, the POL mechanism developed progressively the same symptoms. Early in April, the POL mechanism was also halted in its optimum position. This left the possibility of measuring the solar velocities using only the blue wing of the solar line. The limitations of this mode, which uses no mechanical motions were found to be less serious than anticipated, and will be more fully discussed later. The advantage of freeing the observation of all further risk from mechanical failures persuaded us to leave GOLF in this mode for a substantial period of time and not to risk compromising a long coherent data set by using the flight instrument to attempt to diagnose the fault.

We therefore have today three modes of accumulated GOLF data:

> Mode A, the full 40-second pre-planned sequences from January 18 to February 11. This is the only set usable for global magnetic field studies.
>
> Mode B, the modified sequence using only the Polariser mechanism, from February 19 to April 1. This enables in principle the full analysis of velocities, using both wings.
>
> Mode C, from April 11 1996 up to the present. This is the most stable and reliable data with a maximum of continuity.

It should be noted that the period covered by the Mode A and Mode B data includes the later part of the spacecraft and instrument commissioning. Conditions of temperature and pointing are not always stable and this Commissioning Phase data must be treated with caution. However, the data from Mode B is nevertheless uniquely valuable in enabling GOLF to evaluate the limitations and difficulties that might exist in interpreting the subsequent Mode C data. This point will be treated later. Mode C provided six months of data from April 11 to September 11, with 100 % coverage and continuity. This is unique in the history of helioseismological observations. Starting September 11th there was a three-day interruption, for reasons that will be explained later, followed by a resumption in the continuity up to the present.

5. Sub-system Performance

Many aspects of sub-system performance have already been treated in Section 3 dealing with in-flight calibration. In the present section we consider the remaining elements.

5.1. The Vapour Cell

The stray light level in the detection system was measured on December 10 1995, shortly after switching on the instrument. This measurement was made with the cell bulb heated to 166 deg C, but with the stem cold. In effect, conduction within the cell brought the stem temperature up to 48 deg C, in accordance with prediction. The measured detection level of 270000 c/s on each detector, in excellent agreement with pre-flight tests, is largely due to diffusion of light within the walls of the cell. When the experiment was switched off briefly during tests on March 21 1996 and during the interruption of September 11 1996, this measurement was repeated. No significant change in the stray light level was detectable.

5.2. The Detection Sub-system

With the instrument door closed, the detector dark-current could be measured during the early switch-on sequence. For instrument temperatures identical to ground-test conditions of 22.4 deg C, the dark-current counting levels were very close to pre-flight levels of 190 c/s and 130 c/s for detectors 1 and 2. An important difference in flight was the presence of occasional larger spikes on the counting rate, which can be attributed to luminescence in the photomultiplier systems due to high-energy cosmic particles. These occurred a few tens of times per hour with peak rates up to 500 c/s. Randomly distributed in time and amplitude, they contribute a mean rate which is only about one tenth of the one sigma statistical uncertainty in the science data counting rates.

From the start of observations in January 1996, the detector 2 counting rate exceeded detector 1 by about 4.1 %. In April 1996, this had increased to 4.3 %, remaining stable up to mid- July.

Each photomultiplier is equipped with two counting channels. The first, or "science" channel has its threshold set at 40 mV and is used to provide the primary science data. The second, or "spectral" channel is normally set with a threshold much higher at 450 mV and serves to emphasise any perturbations on the high voltage or the detector itself. This second channel can also be used occasionally to perform threshold variation scans, giving a pulse-height distribution for the photomultiplier output. These pulse-height distributions, or "spectra" can be used to monitor the changes in gain in the photomultipliers; changes which can be corrected for by increasing the high voltage.

During the first year of operation, three spectra of the two detectors have been performed, which give a measurement of the rate of change of gain. As a result, a first readjustment of the high voltage was made in mid-March 1996. Measurements of the evolution of gain with time, confirm the prediction that the rate of loss of gain decreases with time. Thus, the pre-launch figure of 0.2 % loss per day can be seen to be decreasing and is down to 0.05 % to 0.08 % per day after 10 months operation in flight. These reducing rates of gain decrease can be extrapolated to predict many years of useful life from Channel A of GOLF, without needing to consider a switch to Channel B. A close monitoring of the count-rates from the two active photomultipliers shows on several occasions small jumps in their ratio. These are of the order of 0.05 %. Their origin is not yet understood, but they have no detectable effect on the scientific data obtained.

5.3. The Thermal Sub-system

The GOLF sensor unit is strongly decoupled from the spacecraft both for radiation and conduction. It receives heat from the sun and radiates heat to deep space. The entrance filter system has its own thermal balance being also somewhat decoupled from the sensor unit and with its own dedicated radiator to space. Heaters control separately the cell stem and bulb and the filter unit. Closed-loop stabilisation of temperature has been excluded in order to avoid thermal oscillations influencing the science data. GOLF relies on the high stability of the SOHO environment and the decoupled sensor thermal system in order to avoid the influence of thermal oscillations in the prime frequency range of study. If either the cell or filter temperatures drift outside their acceptable ranges, the input power from their heaters can be varied manually to bring them back.

Spacecraft and GOLF sensor temperatures drift slowly throughout the observations. This is due in part to variations in the spacecraft/sun distance and in part to drift in the properties of the thermal coatings. It is difficult to separate these two effects without more than one year's observations. In general, the overall sensor drift is seen directly on the cell temperatures. However, the filter sub-system is more directly influenced by the solar flux and can show larger variations. Since the last thermal adjustment control on January 23 1996, a very slow positive drift has been observed and should reach about 1.2 deg C over the first year. This is due to the ageing of the thermal finishes on the GOLF sensor and on the spacecraft. Seasonal variation of solar flux adds to this drift an annual modulation of about 1 deg C amplitude. Thus in early January 1997, when both effects add, the mean sensor temperature is 2.2 deg C higher than one year earlier when SOHO was still cruising towards the L1 point.

5.4. The Data System

More than 95 % of GOLF data is available in Near Real Time or in playback modes, and thus within a few hours of the observations. This provides a very efficient monitoring of the instrument behaviour, as well as an evaluation of the scientific performance. Final data collection efficiency follows the delivery of the CD-roms, typically some 4 weeks later. Over the first 11 months of the mission, this brought the total collection rate up to 99.04 %, a mean value, that conceals the fact that on some poor days the figure falls to 90 %.

As described in the earlier instrument paper, the GOLF instrument includes its own data buffer, which re-transmits the GOLF data after delays of both 10 hours and 16 hours. These re-transmissions have complemented the data collection by 0.95 % and 0.01 % respectively, bringing the total rate to 99.998 %. This loss of only 6 blocks out of 352995 over the first 11 months represents a unique record of continuity and one of the major strengths of the GOLF project.

On September 11 1996, the instrument was found to be switched into an unexpected mode, with the cell stem heaters off. This has been attributed to a rare occurrence producing a two-bit error, which the automatic recovery response is not able to correct in all circumstances. Although the normal operations were restored by command intervention within a few hours, the resultant thermal excursion produced a disturbance in the science data quality lasting 2 to 3 days.

6. Scientific Observations

6.1. Sensitivity and Calibration

The most obvious and immediate method of analysing the data consists in first combining the signals from the two active PMs, and then, according to the sequence adopted, in choosing the appropriate algorithm to combine different intensities in order to derive a function which depends on line-of-sight velocity. For the pre-planned sequences of Mode A or B (see Section 4) we showed in the earlier paper (Gabriel et al 1995) that the velocity is given by

$$v = v_a \frac{I_b - I_r}{I_b + I_r + 2s}, \tag{1}$$

where s is the signal due to stray solar light reaching the detectors without resonant scattering. v_a is the calibration factor, which can be taken approximately as $4 kms^{-1}$, but is ultimately calibrated by using either the known slow variation in SOHO/sun distance, or the calculated shift due to the magnetic modulation of the instrument magnetic field. The function in Equation (1) is insensitive to first order to changes in the overall sensitivity of GOLF to the solar intensity. Such changes can arise from changes in the solar intensity or solar distance, or through changes in the instrument, such as the temperature of the cell stem.

For the sequence Mode C, using only the blue wing, the equation becomes

$$v = \alpha_b I_b. \tag{2}$$

The quantity α_b must also be calibrated and again the magnetic modulation provides one method of approach. However it is obvious that, without the denominator, equation (2) is also sensitive to first order changes in solar intensity or instrument sensitivity. With the exception of the intensity variations due to solar oscillations themselves, most of the variations are slow compared to the 5 minute oscillations. Such variations will not contaminate the spectrum of p-modes, but they will lead to uncertainty and variation in the velocity calibration to be applied to the p-modes. However, for low frequency oscillations, as when searching for g-modes, it becomes important to calibrate or to otherwise compensate for the variation of α_b, due to aging or instrumental drifts.

Three different techniques have been used separately in order to correct for these effects; both the first order variations in α_b and the higher order variations in v_a. These can be summarised as :

a The use of filtering functions, in order to reject frequencies below those corresponding to periods of the order of 1 day. This corrects for a wide range of causes of calibration variations. It is then necessary to apply an assumed known velocity scale.

b Use of the differences in signal due to the magnetic modulation. In principle this corrects for the slope of the solar line wing and includes implicitly a correction for slow intensity variations. However, this small difference between two large quantities has the effect of amplifying the photon noise. It cannot be used directly for individual 40 s data points, but must itself be averaged over a reasonable time period of hours, before being applied. In this way it introduces some of the filter cut-off problems associated with the first method.

c The third method consists in trying to model correctly all of the factors influencing the variation in α_b, including orbital motions, solar line profile and measured instrumental temperature changes.

All three methods have given some success and it remains to be seen which will offer long-term advantages.

Whilst the Operating Modes A or B offer in principle the best protection against velocity calibration uncertainties, it must be remembered that these are available only for a short period and that this period is still somewhat disturbed by the final spacecraft commissioning manoeuvres. The precision currently obtained in Mode C for the velocity calibration is of the order 20 % or better.

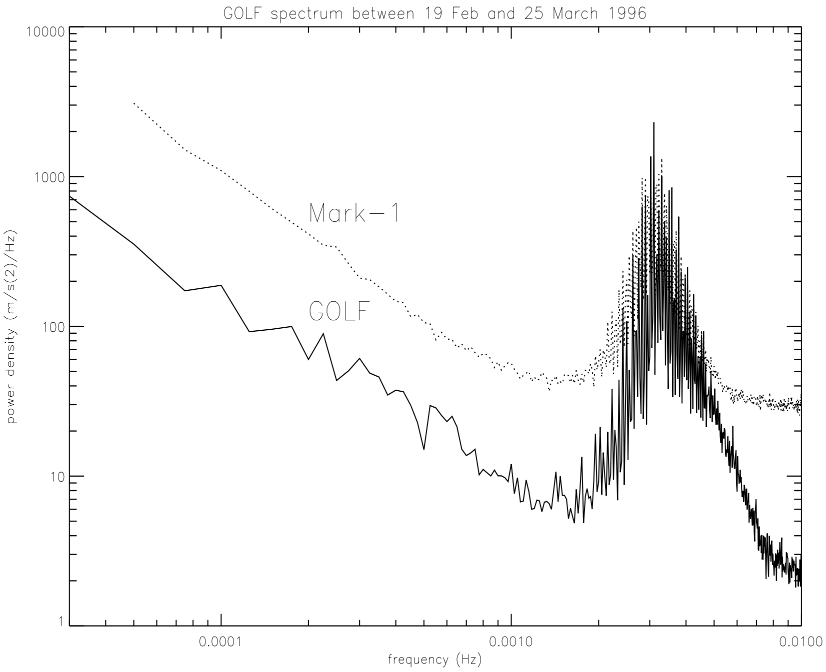

Fig. 1. Low-resolution spectrum from GOLF compared with that from a good ground-based instrument Mark 1, showing the lower background level obtained from space.

6.2. Background and Noise Level

An attempt has been made to evaluate the early performance of GOLF, by comparing a Fourier spectrum over a wide frequency range with that obtained from one of the best ground-based solar oscillation instruments. The comparison was made with the Mark I instrument at Tenerife (Brookes, Isaak and van der Raay 1978). This is a potassium vapour instrument and a component of the BISON network.

In order to improve the validity of the comparison, the spectra were computed using 11 hour periods or “days” for each. Figure 1 shows the average of 280 days of Mark-I, compared with 70 “days” of GOLF spectra obtained in Mode B. Frequency resolution is limited in this plot by the 11 hour periods used for the Fourier transforms. This approach has been used in order to demonstrate the level of the “continuous” spectrum, rather than the p-modes, which are not here well resolved.

Examination of Figure 1 shows several interesting features. The photon noise flat background instrumental spectrum can be seen in both cases at the high-frequency end. At the low-frequency end the general $(\text{frequency})^{-1}$ variation of the background signal is well demonstrated. This signal has normally been thought of as due to the random velocity fields of solar convection. Differences between the two signals can be attributed to a combination of effects: the lower instrument (photon) noise from GOLF, the absence of terrestrial atmosphere disturbances, and the different height in the solar atmosphere sampled by the sodium and potassium lines. Detailed studies now in hand aim to separate these contributions. The much lower photon noise level of GOLF is in accordance with its design specification and the high PM counting rates adopted.

6.3. Validation of Blue-wing Only Measurements

Following the adoption of Mode C for the routine operation of GOLF it is relevant to pose the question of what, if any, is the effect of Mode C on the signal to noise ratio for the g-modes. Although we can put reasonable limits on the loss, it is difficult to determine a precise figure. This is due to uncertainties in the absolute velocity calibration for the Mode C, as indicated in Section 6.1 above. The usual technique is to compare the blue wing only signal with the blue plus red wings, for the same epoch, during which GOLF was operating in Mode B. These two different types of data pose different problems for the calibration. Furthermore, the absolute sensitivity to the oscillation amplitudes is not the same for the two wings, a difference that may vary between p-modes and g-modes. The problem of comparison reduces to one of normalisation between the two sets. One approach is to normalise so that the p- mode power is the same. This is the technique adopted for the comparison shown in Figure 2. Here we see that the increase in background noise level in the blue-wing only case is something between 1.4 and 2 in the g-mode region. This would be a valid figure for the loss of signal to noise for the g-modes, if we assume that their relative sensitivity on the two wings is the same as for the p-modes. Taking account of uncertainties in these assumptions, we cannot say more than that the factor loss of detectability for g-modes, due to the Mode C operation is between 1.4 and 2 in units of power.

This small factor justifies the decision to continue operations in Mode C rather than endeavour to re-activate the mechanisms. Effort is instead being invested in improving the resultant difficulties in obtaining a high precision in the oscillations amplitude calibration (see Section 6.1).

6.4. p-mode measurements

The low background level in the region of the g-modes is clearly evident in Figure 1, in spite of the low spectral resolution of this plot. Figure 3 shows a section of the p-mode spectrum obtained by Fourier analysis of a 6-month period of GOLF data. Here again one can see the exceptionally clean background, allowing the identification of some very low amplitude modes. A first identification of GOLF p-modes has been made, using a variety of techniques, but for the most part by the fitting of Lorenzian profiles by

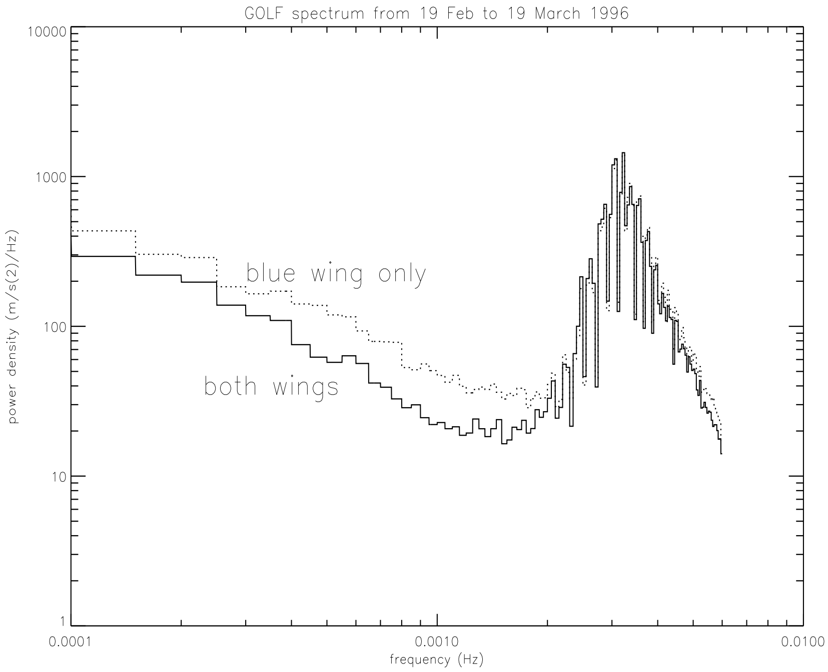

Fig. 2. Low-resolution spectrum from blue wing only (dotted), compared with that from blue and red wings (full line).The curves are normalised for the same energy in the 2 to 4 mHz range.

maximum likelihood technique to a Fourier spectrum. This is the subject of separate more detailed presentations (Grec et al 1997, Lazrek et al 1997a, Lazrek et al 1997b).

At the time of writing, p-mode identification and frequency measurements have been made for 100 modes in the range 1.1 to 4.6 mHz, covering $n = 7$ to 33 and $l = 0$ to 4. At this point, with only 10 months of data, the frequency precision is not in general significantly better than existing ground-based measurements. The precision quoted is not yet the ultimate, even for the existing data set, since decisions need to be taken concerning which of the present methods of determination should be given the most weight. However, the lower noise levels of the GOLF data have enabled us to identify several new modes at low frequencies. It is clear that with a longer data set from GOLF, significant improvements will be made on both the range and the precision of the measured p-mode frequencies.

In considering the implication of these data for the analysis of the internal structure of the sun, some preliminary inversions have been carried out to determine the sound speed as a function of radial distance. For this work it is necessary to start with some other existing data for the higher degree modes,

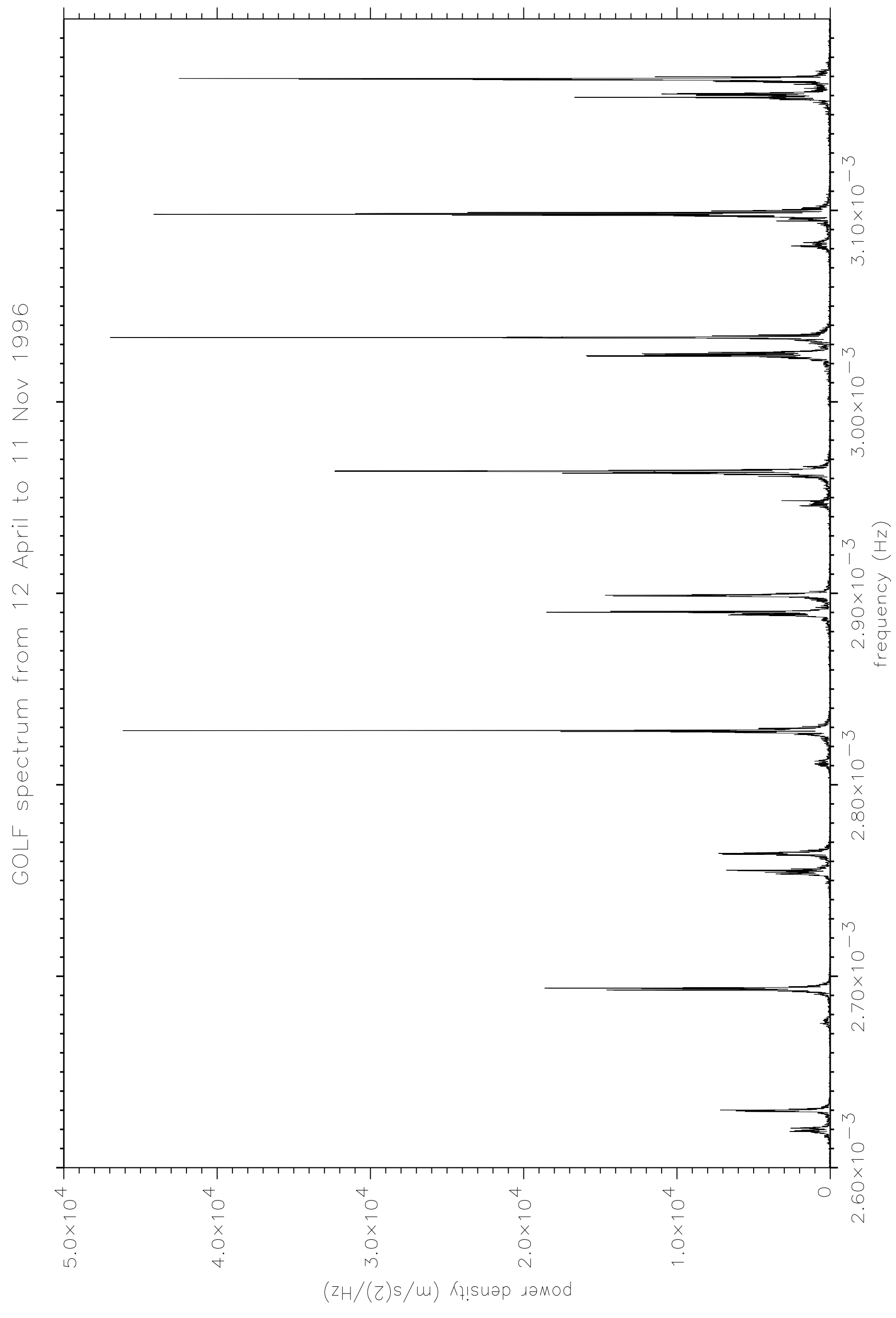

Fig. 3. Section of the p-mode spectrum obtained from 9 months of data. Note the extremely low background level.

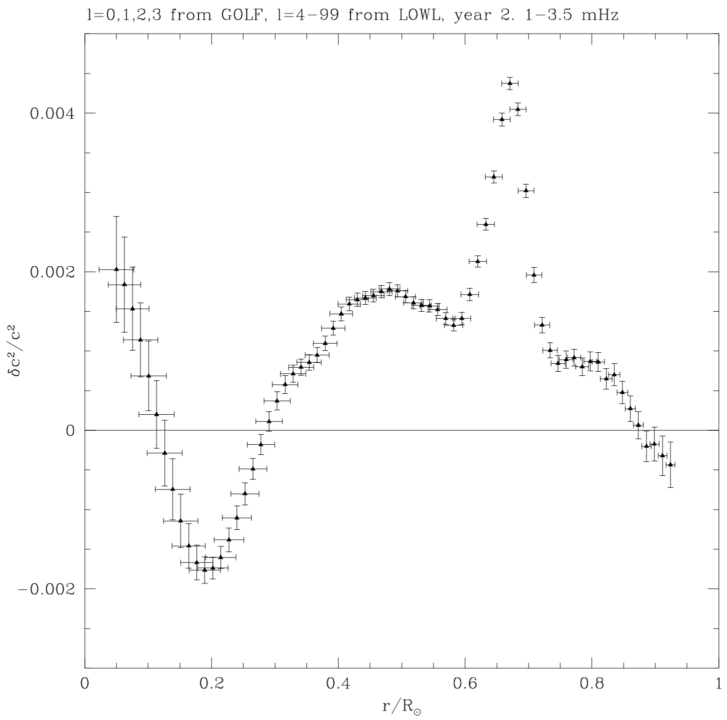

Fig. 4. Difference in the square of the sound speed in the sun and in the Model S of Christensen-Dalsgaard (1996), in the sense (sun - model), obtained from 4 months of GOLF data, combined with LOWL.

not available from GOLF. The data used is from the LOWL instrument (Tomczyk et al 1996) and is for the period February 1995 to February 1996, not fully coincident with the GOLF data. However, the two sets are in remarkable agreement, and the precision obtained can be seen in the plot of sound speed in Figure 4 (Turck-Chièze et al 1997a). A more complete discussion on the investigation of the core structure is reported in Turck-Chièze et al (1997b).

6.5. Excitation Effects

A time-frequency analysis has been carried out on many of the observed p-modes from GOLF (Baudin et al 1997). This uses the same techniques developed for analysis of the space observations in solar intensity oscillations from PHOBOS (Baudin et al 1994, 1996). An example of the time variation observed for an $l = 0$ mode (without fine structure or rotational splitting) is shown in Figure 5. In the present case of the low-noise GOLF data, it is much easier to demonstrate that noise, from either solar velocity fields or photon

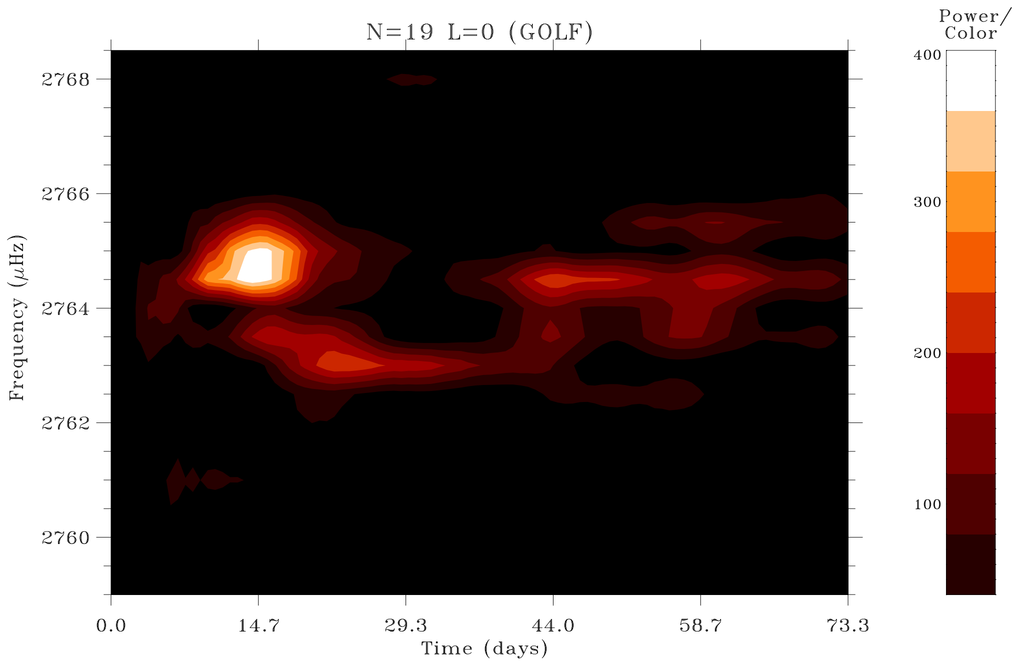

Fig. 5. Time/frequency analysis of a single GOLF $l = 0$ mode, showing variations in amplitude and apparent changes in frequency.

statistics does not contribute significantly to the observed effects. We can deduce from the observed variations that there is an important fluctuation in both the amplitude of the mode and in its observed frequency, on time scales as short as a few days. This limit is imposed by the need for a trade-off between time and frequency resolution in the analysis and the importance of avoiding beating between adjacent modes. It is this time variation that produces the characteristic spiky line profile when analysed by Fourier techniques. A number of studies have aimed at interpreting these variations as due to the stochastic nature of the excitation process for the modes (Chang 1995, Chang and Gough 1995). García et al (1997), developing the theory of Woodard (1984) and Duvall (1990), have modelled the excitation of a damped oscillator by stochastic impacts, and are able to reproduce Fourier profiles with similar appearance to those of Figure 5. According to García et al, the observed frequency shifts can be explained by excitation effects, without requiring shifts in the frequency of the solar oscillator, although this remains an open question. What is clear is that the time frequency analysis, as well as the complex profile of the Fourier spectrum, contain important information on the basic excitation mechanism of the modes.

These manifestations of stochastic excitation impose important constraints on the precision obtainable in the frequency measurements of the modes. It is generally accepted that with a long enough time-series, a mean profile of a modified Lorenzian form can be accurately applied. However, it is not clear how rapidly we can converge to this limit, or whether real frequency shifts due, for example to solar cycle effects will intervene before we reach a high precision. With the present data set of some 10 months, there is clearly a limitation in precision imposed by the stochastic excitation.

This difficulty is particularly troublesome when measuring the difference between two close resonances, as is the case in determining rotational splitting. Reported rotational splittings in the literature cover a very large range of values, much wider than the precision quoted in fitting the Lorenzian profiles. Values are now beginning to emerge from the GOLF data, but it is obvious that with less than one year of data, it is too soon to make an important contribution to the debate concerning solar internal rotation rates.

Both the Fourier techniques and to some extent the time-frequency analysis are based on the assumption of a continuous or smoothly varying oscillation amplitude. If the solar response is really the result of repeated impulse excitation of a damped resonator, then it is possible to derive analysis techniques, more closely adapted to the solar situation. This is the basis of a method termed "homomorphic deconvolution" (HD), which had been developed originally by geophysicists for application to terrestrial seismology. In the HD analysis, the solar response is assumed to be the convolution of an excitation function (consisting of a delta function, randomly distributed in amplitude and in time) and a damped sine wave solar response function. The HD method serves to isolate the damped sine wave component, enabling its Fourier transform, which is a smooth Lorentzian, to be derived, unencumbered by the familiar complex structure due to the stochastic excitation. These techniques have been developed for solar seismology, and applied initially to IPHIR data (Baudin, Gabriel and Gibert 1993, Baudin et al 1997). Now they are being applied to GOLF data (Baudin et al 1997b, Lazrek et al 1997). For the determination of frequency, HD gives much cleaner profiles with more confident Lorenzian fits. For the measurement of rotational splitting, the apparent advantage is sometimes dramatic, yielding two clean separated lines, where otherwise it was difficult to recognise the doublet structure. Work is continuing in order to investigate whether the adoption of this technique in all cases can be justified. At present it is one of a number of techniques being used for the analysis of GOLF data.

6.6. Search for g-modes

All of the p-modes frequencies are influenced predominantly by the outer layers of the sun. Inversion of p-mode frequencies to obtain the core properties is therefore an ill-conditioned problem. In practice, this means that a much higher degree of precision is required in the p-mode frequencies, in order to extract a reasonable precision in the core parameters. GOLF, with its low-noise data, is capable of this high precision, provided a long enough data set can be accumulated. We therefore anticipate important advances in this area, but this will need many more months of data. On the other hand, g-modes are all concentrated towards the core. This means that knowledge of g-modes, even with rather approximate frequency values would give quite precise core parameters. However g-modes have not so far been identified.

The discovery of g-mode oscillations from GOLF could never be confidently anticipated, since there are no reliable predictions of their expected amplitudes. However, it was always clear that their detection would provide an inestimable advantage for the interpretation of conditions in the solar core. The search for g-modes is therefore an important priority for GOLF, whose low-noise long-term stability offers the best chance for their detection. The solar spectrum in the expected g-mode range is dominated by the more random velocity fields produced by the various scales of convection. The approximate form of this continuous spectrum has been predicted by Harvey (1985). When we examine the Fourier transform of GOLF data in this region, we see the background shape predicted by Harvey, with a number of superposed peaks, well above the background level. Although, this is somewhat what one might expect from g-modes, this interpretation has not yet withstood critical tests concerning long-term invariance of the features. Since such tests depend strongly on the length of the available data base, it is with more months of data that we can expect to arbitrate with more confidence. At the time of writing, with some 10 months of data, it can be stated that no definitive identification of solar g-modes has been made. However, as the time passes, it is possible to decrease progressively the upper limit in amplitude for the existence of solar g-mode oscillations. For the moment, this is around 1 cm. s^{-1} in velocity.

7. Conclusions

The GOLF instrument has been successfully launched and is operating for the most part very well. The exception concerns the rotating polariser mechanisms. After persistent malfunctioning, these have been stopped in optimum rotation orientations and an unforeseen mode of instrument operation has been adopted. This mode, which now involves no moving mechanisms, allows the full determination of frequencies to be performed, with little or no loss of precision. It does however pose difficulties for the absolute velocity calibration, which is currently of the order of 20 % or better. In all other respects, GOLF is maintaining its full design specification and is showing no degradation which would impede its continued operation for up to 6 years or more.

The p-mode oscillations from GOLF have a considerably improved signal to noise ratio, which has already allowed the identification of a some of new resonances. The precision today for the determination of p-mode frequencies must be regarded as preliminary. Significant advances are anticipated, both from improved analysis techniques on the existing data base as well as of course a substantial prolongation of this base. Continuity of the data set is so far quite exceptional, offering ideal opportunities for the study of excitation processes and solar-cycle effects. The search for g-mode oscillations is continuing, but they have not so far been identified. All indications at this point are that GOLF is capable of continuing operations into the next solar maximum.

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The exceptional performance of the GOLF instrument is in large part due to the unique facilities offered by the SOHO platform, in terms of long-term stability of temperature and pointing and an extremely reliable and accurate clock. The continuous and dedicated attention of the ground system, including the Flight Operations Team at GSFC and the Deep Space Network have enabled an exceptional continuity in the data reception, essential for this project. Our thanks are due to these vital contributions from ESA, NASA and Matra Marconi.

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