PERFORMANCE AND FIRST RESULTS FROM THE GOLF INSTRUMENT ON SOHO

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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, over the frequency range 10^{-7} to 10^{-2} Hz.

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), together with a description of the SOHO platform and mission (Domingo *et al.*, 1995). The special L1 orbit of SOHO, with continuous sun-

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centre pointing, is ideally suited for the long-term stability requirements of GOLF.

GOLF is a development for the space environment of instruments operated for many years on the ground, in particular the BISON (Chaplin *et al.*, 1994) 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.

The pre-launch plan foresaw a 40 sec cycle of operations, in which at least one of the two rotating mechanisms and the magnetic field modulation were switched each 5 sec. In this way, ratios could be derived giving data points every 40 sec, 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.

2. Commissioning and Calibration

GOLF was switched on for a period of 8 minutes on December 3 1995. This served to verify that the protective door was closed and enabled a check on the instrument temperatures, which were all nominal. GOLF Channel A was powered on on December 10 and put into an operating configuration, ecept for the cell, which was unheated and the door, which was kept closed. On December 11, the cell stem heater was turned on and the temperature allowed to stabilise. The functional testing of Channel A was then completed, as well as a temperature scan of the entrance filter. At this time, the detector background and cosmic ray counts were also established.

In January 1996, the door was opened, and the full operations commenced. During January, February and part of March, while the spacecraft was still on its way to the final L1 orbit, a range of tests were carried out of the sub-systems performance. This served to fully qualify the functioning and calibration of Channel A. It was decided to follow the policy adopted by the other SOHO instruments and not to fully commission the redundant Channel B, until it might be needed. However a brief 6 hour operation of Channel B served to show that it is fully functional, and can be used if required.

2.1. CELL TEMPERATURE

Critical calibrations were carried out on the two systems most sensitive to temperature variations. The cell temperature was scanned slowly, and the changes in the overall detector count rates were monitored, as well as the amplitude of the variations associaated with the 5 minute solar oscillations. As a result of these tests, the cell temperatures were set at optimum values of 170 deg C for the bulb and 188 deg C for the stem. It should be emphasised that there is an unknown but constant difference between these thermister readings and the real cell or vapour temperatures due to contact conductivity effects. At the temertures adopted, the counting rates were close to 5.5 10^6 per sec for each detector, with a sensitivity of 221000 c/s per one deg C change of stem temperature, in accordance with pre-launch calibration.

2.2. 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

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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.

2.3. OFF-SET POINTING SENSITIVITY

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 sec 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.

This good performance was confirmed when large static off-set pointings were performed later for some hours for a specific South Pole Joint Observation Program. This showed no detectable signal perturbation for several arcminutes of pointing off-set. Depending on the off-set direction and duration, disturbance of the experiment thermal equilibrium could become an eventual source of detected signal. 360 deg spacecraft roll manoeuvres, carried out on March 19 and 20, established also that measured solar surface velocities were undisturbed by up to 90 deg rotation angles, in both positive and negative directions, a small measured velocity amplitude off-set being detected for larger angles.

3. 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 (the 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 sec total, with at least one component switched each 5 sec. 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 sec, or even more frequently if desired.

This nominal sequence was successfully operated from the switch-on until early February 1996. At this point, the intermittent mal-functioning of the QW mechanism led to a decision to stop it in its optimum position. The operation continued in an approved back-up mode, in which the full data set is recovered by use of the POL mechanism alone, losing only the possibility to extract a secondary GOLF objective, the global magnetic field data.

The POL mechanism developed the same mal-funtion towards the end of March 1996. Early in April a decision was taken to stop the POL mechanism in its optimum position. This left the possibility of measuring the solar velocities using only the blue wing of the solar line, a mode of operation unforseen before launch. The limitations of this mode, which uses no mechanical motions were found to be less serious than anticipated, and will be 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.

4. Technical Performance

With the exception of the operating sequence changes, already described, all of the GOLF sub-systems are functioning within their designed specification. The overall GOLF performance is thus at the level of sensitivity forseen and the analysis potential of the data remains limited only by the intrinsic solar problems of separating global modes from non-coherent solar velocity signals.

The measured stray diffused light in the cell has remained unaltered from the pre-launch value, as verified during switch-on, and again in March 1996 and September 1996, during brief cold cell periods. No change in overall counting rate has been observed which might be attributable to a deterioration in the cell performance or in the window transparency.

The detection system has been functioning nominally. The dark current is very close to pre-launch levels. Large pulses are observed, attributable to cosmic ray particles, but at a frequency which is negligible in comparison to the scientific count-rate. The system is equiped with a facility to record a pulse-height analysis from time to time, without interrupting the scientific data stream. These show that the pre-launch measurements and prediction of the decay of gain with time were unduly pessimistic. In reality this decay rate has been found to decrease with operating time. This can be extrapolated to predict many years of useful life from Channel A of GOLF, without needing to consider a switch to Channel B.

The thermal behaviour of the instrument confirms well the thermal model and the pre-launch tests. 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 1.6 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 estimated annual modulation of about 1 deg C amplitude.

The data retrieval from GOLF has proved to be quite exceptional. The data reception provided by the NASA and DSN systems has been averaging better than 99 %, on the basis of CD roms, delivered some 3 weeks after the observations, a mean figure that conceals the fact that on some poor days the figure falls to 90 %. However, with the GOLF data buffer and retransmission after 10 hours and 16 hours, the total recovery rate is more than 99.99 %. With the sensor unit operating continuously between April 11 and early September 1996, this provides by far the most complete 5 months sequence of helioseismic data ever recorded.

5. Scientific Data

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

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

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 $4kms^{-1}$, 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 may become important to calibrate or to otherwise compensate for the variation of α_b, due to aging or instrumental drifts.

Several different techniques are being explored at present, in order to correct for these effects; both the first order variations in α_b and the higher order variations in v_a. Although these corrections are unimportant for p-mode analysis, and may not be important for the search for g modes, they will become necessary for later analysis, involving detailed comparison with other measurements, such as intensity oscillations from VIRGO, or spatially resolved measurements from MDI.

Using the early two-wing measurements from GOLF, a comparison has been made between its sensitivity and that of a good ground based solar oscillation instrument. 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. Fig. 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.

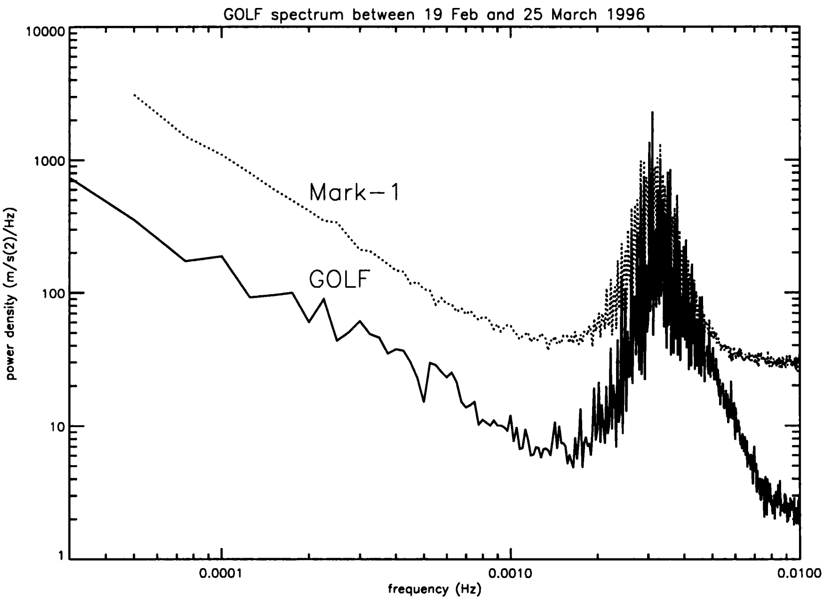

Figure 1. Low-resolution spectrum from GOLF compared with that from the ground-based instrument Mark 1, showing the lower background level obtained from space.

Examination of Fig. 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. Whereas this might be the case for the space measurements from GOLF, it is clear that for the Mark-I there must be an additional contribution, since its level is almost an order of magnitude higher. It seems reasonable to assume that this additional signal is due to noise from the earth's atmosphere. The much lower photon noise level of GOLF at the high-frequency end is in accordance with its design specification and the high PM counting rates adopted.

For the later GOLF data, based upon only the blue wing measurements, we have attempted to evaluate more precisely the real loss in sensitivity due to the loss of the red wing data. The technique adopted is to use the early two-wing data and to analyse it using the two techniques; two wings, or the blue wing only. This comparison is demonstrated in Fig. 2, where the two methods have been normalised for the same power in the p-mode region. Here we see that the increase in background noise level in the blue-wing only case is something between 1.4 and 2 mHz in the g-mode region. This

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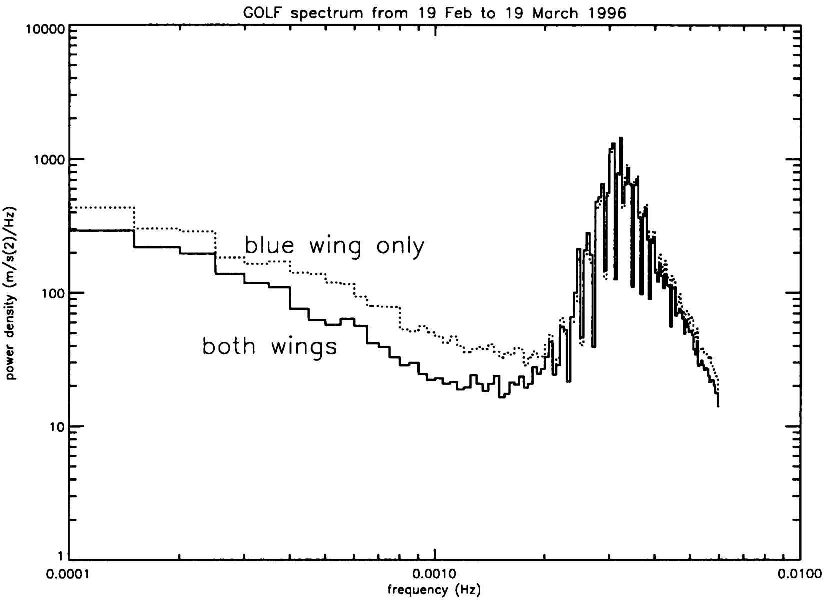

Figure 2. Low-resolution spectrum from blue wing only (dotted), compared with that from blue and red wings (full line).The curves are normalised for the same energy in the 2 to 4 mHz range.

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 appears to be 2 or lower 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 reasonable precision in the oscillations amplitude calibration.

The lower background level of the GOLF spectrum is more clearly seen in a high-resolution spectrum of the p-mode region. Fig. 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 maximum likelihood technique to a Fourier spectrum. This is the subject of separate more detailed presentations (Grec *et al.*, 1997, Lazrek *et al.*, 1997).

At this time, around 100 p modes have been identified and their frequencies measured. This number will be increased and the precision of

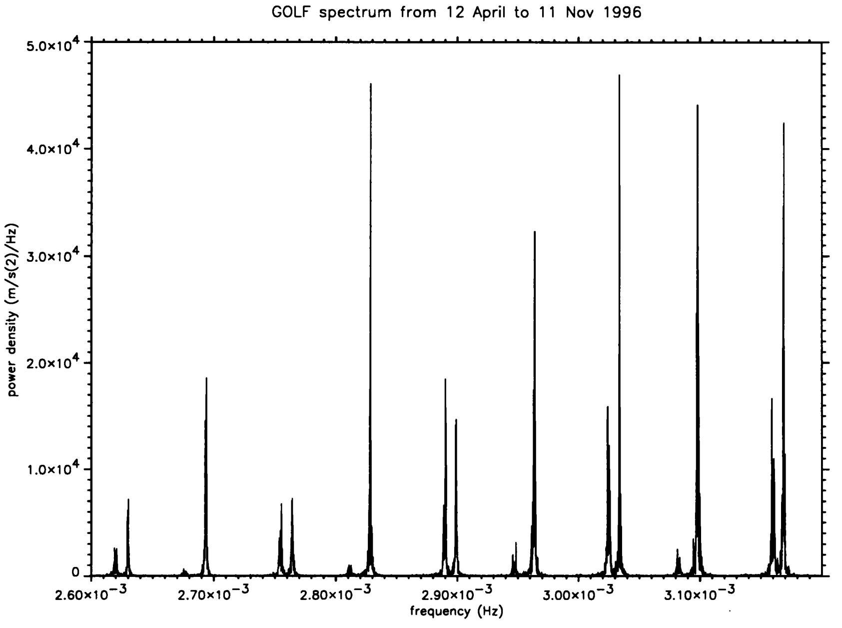

Figure 3. Section of the *p*-mode spectrum obtained from 9 months of data. Note the extremely low background level.

measurement improved with more sophisticated analysis techniques. In addition, significant improvements are expected from the analysis of a longer GOLF data set. A preliminary inversion of these *p*-mode frequencies has been carried out, using the LOWL data for the higher l modes (Tomczyk *et al.*, 1996). The precision obtained can be seen in the plot of sound speed in Fig. 4 (see also Turck-Chièze *et al.*, 1997).

6. Excitation Effects

A time-frequency analysis has been carried out on many of the observed p modes from GOLF (Baudin *et al.*, 1996, 1997). This uses the same techniques developed for analysis of the space observations in solar intensity oscillations from PHOBOS (Baudin *et al.*, 1994). An example of the time variation observed for an $l = 0$ mode (without fine structure or rotational splitting) is shown in Fig. 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 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

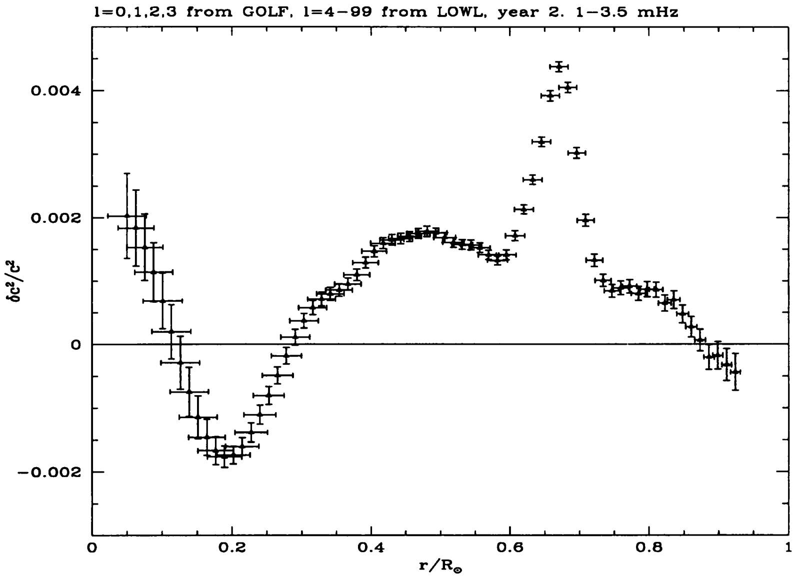

Figure 4. Difference in sound speed as derived from observations (GOLF and LOWL), compared with the model of Basu *et al.*

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 Woodward (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 Fig. 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

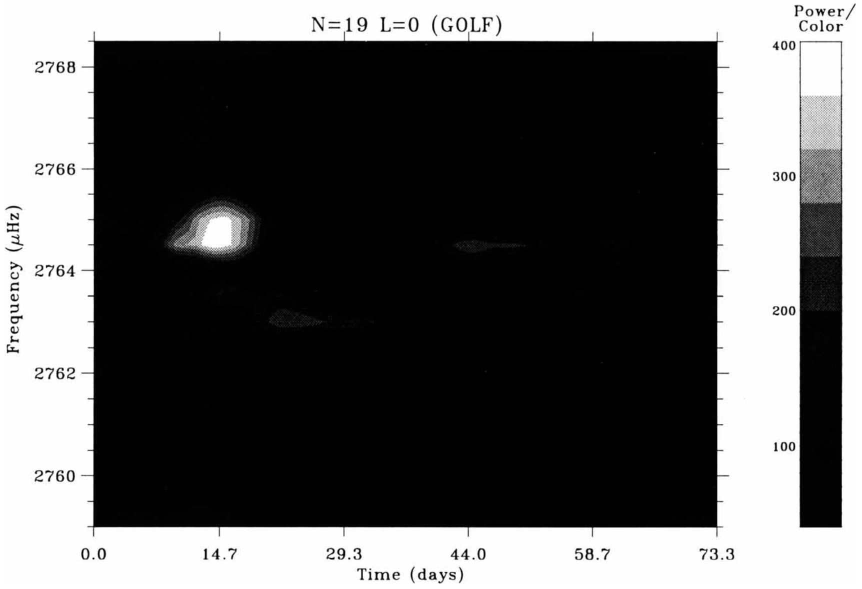

Figure 5. Time/frequency analysis of a single GOLF $l = 0$ mode, showing variations in amplitude and apparent changes in frequency.

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.

7. The search for g modes

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.

8. 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.

Acknowledgements

The GOLF programme is based upon a consortium of institutes involving a large number of scientists and engineers, as enumerated in the earlier instrument publication. The analysis work described here is also a team activity, involving many workers outside of the instrument teams.

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 Experiment Operations Facility 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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