GLOBAL OSCILLATIONS AT LOW FREQUENCY FROM THE SOHO MISSION (GOLF)

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Abstract. The GOLF experiment on the SOHO mission aims to study the internal structure of the sun by measuring the spectrum of global oscillations in the frequency range 10^{-7} to 10^{-2} Hz. Both p and g mode oscillations will be investigated, with the emphasis on the low order long period waves which penetrate the solar core. The instrument employs an extension to space of the proven ground-based technique for measuring the mean line-of-sight velocity of the viewed solar surface. By avoiding the atmospheric disturbances experienced from the ground, and choosing a non-eclipsing orbit, GOLF aims to improve the instrumental sensitivity limit by an order of magnitude to 1 mm s^{-1} over 20 days for frequencies higher than 2.10^{-4} Hz. A sodium vapour resonance cell is used in a longitudinal magnetic field to sample the two wings of the solar absorption line. The addition of a small modulating field component enables the slope of the wings to be measured. This provides not only an internal calibration of the instrument sensitivity, but also offers a further possibility to recognise, and correct for, the solar background signal produced by the effects of solar magnetically active regions. The use of an additional rotating polariser enables measurement of the mean solar line-of-sight magnetic field, as a secondary objective.

Key words: sun –helioseismology

1. Introduction

Helioseismology uses the temporal and spatial properties of solar oscillations to study the solar interior. The quality of analysis as measured by the precision of the deductions and the ability to probe all parts of the sun's interior is dependent on the acquisition of observations of the widest possible range of solar oscillation modes. The SOHO satellite includes three helioseismology instruments which aim to cover in a complementary manner a wide range of oscillation measurements. GOLF is one of these helioseismology instruments and emphasizes the lower frequencies utilising global oscillations of the line-of-sight velocity vector of the solar photosphere as measured by the full-disk integrated light. The frequency range will extend from beyond the solar atmospheric cut-off frequency at around 6.10^{-3} Hz down to frequencies of the order 10^{-7} Hz, depending on the long-term stability achievable from SOHO. At the higher frequencies, sensitivity will be limited by photon counting statistics to the equivalent of a velocity amplitude of 1 mm s^{-1} for an observing time of 20 days. At the lower frequencies the limit will be imposed by the satellite stability and the level of non- coherent solar signals (solar "noise"). It is hoped to gain in sensitivity at lower frequencies by understanding and correcting for the source of some of this solar noise. The low frequency modes, especially the g-modes, can contribute uniquely valuable information on the structure of the deep solar interior.

The technical principle employed by GOLF is to measure the Doppler wavelength shift of the solar Na D Fraunhöfer lines by comparison with an absolute standard given by a sodium vapour cell within the GOLF instrument. The absorption cell line is symmetrically split into its Zeeman components by means of a longitudinal magnetic field, and thus monitors two points on either wing of the solar absorption line. The ratio of the two wing intensities is sensitive to small Doppler shifts in the solar line wavelength and can be measured with great precision.

This technique is similar in principle to that carried out in ground-based measurements of solar oscillations, as for example in the IRIS network (Grec et al. 1991). Moreover, due to the position of SOHO at the L1 Lagrangian point, GOLF will be free of many of the specific influences limiting the ground-based experiments; day-night eclipsing, differential atmospheric extinction, missing periods, data merging, etc. Thus we expect significant improvements in the sensitivity limit and in the spectral cleanliness with a resulting extension of the useful range of measurement to lower frequencies. An additional device, specific to GOLF, will provide the slope of the wings of the observed solar line, giving a means to compensate for the effects of magnetic active regions.

The idea of extending to space the principle of the ground-based IRIS instrument was first proposed as an ESA mission DISCO by Roger Bonnet in 1980. However DISCO was not retained in the subsequent competitive selection procedure. The present instrument GOLF was proposed by a consortium led by Luc Damé, in response to the Announcement of Opportunity for instruments aboard SOHO in 1987.

The requirement of a high sensitivity at low frequency places particular demands on the stability of the instrumentation both for GOLF and the SOHO satellite. However, there is nothing gained in insisting on an instrumental noise level at low frequency that is far smaller than the solar noise, since it is the latter that will ultimately limit the measurement sensitivity for the solar oscillations.

2. Scientific Objectives

Helioseismology can contribute to several aspects of solar physics. Primary objectives include the derivation of the interior structure from resonant frequency values, the excitation and damping of oscillation modes from coherence times and resonant line shapes, and the state of the sun's internal rotation from rotational splittings. For each of these objectives the quality of the derivation is greatly enhanced by the inclusion of the low frequency, global modes of oscillation that are emphasized with the GOLF experiment. However, the detailed analysis techniques which can utilize the information from the low frequency, global modes are beyond the scope of this mainly instrumental paper. The volume edited by Cox, Livingston and Matthews (1991) contains several useful and comprehensive reviews. In particular, the basic theory of the oscillations is given by Christensen-Dalsgaard and Berthomieu (1991) and the techniques of deriving properties of the solar interior from inverse theory are well described by Gough and Thompson (1991). A complete description of the theory of the solar interior with a discussion of the related problems of solar neutrino fluxes has been given by Turck-Chieze et al. (1993). Neutrino flux measurements and helioseismology have appeared as complementary probes of the solar internal structure. The present detection of about 2700 acoustic modes have led to determine precisely the sound speed and the density inside the Sun down to 0.3 solar radii. The comparison with predicted values deduced from a classical solar structure model shows a discrepancy of the order 2% or less. However, in the nuclear core of the Sun, the uncertainties on such quantities are still rather large. It is here that the very precise and long-duration measurements from GOLF can improve the knowledge of the Sun, as well as giving some constraints on the effects of variations during the solar cycle.

At present only higher harmonics of the pressure or p-modes have been definitely identified in the solar oscillation spectrum, whether the observation is spatially integrated (Claverie et al. 1979, Grec et al. 1980) or spatially resolved (Duvall and Harvey 1983). The mode amplitudes favour the observations of periods around 5 minutes, these resulting in some of the best data reported to date (Anguera Gubau et al. 1992, Elsworth et al. 1980). Spatially integrated data favours the low degree modes, which are limited to l = 0, 1, 2 and 3. For higher degrees, the spatial integration leads to a cancellation of phase and a rapid loss of visibility, although less rapidly for velocity measurement than for luminosity measurement, on account of the directivity of the velocity vector. The radial orders that contribute to the 5 minute region then range from n = 13 at 2 mHz to n = 34 at 5 mHz. Accurate measurement of the frequency of the modes can be interpreted in terms of the model of the solar interior. One can either compare the observed frequencies with those calculated from different solar models, or use inversion techniques on the mode frequencies to determine, for example, the speed of sound throughout the solar interior directly (Gough and Thompson, 1991). In either event, the sensitivity depends on the region of the solar interior which participates most in the modes observed. The p-modes do not propagate to the solar centre with the exception of $l = 0$, and favour the regions at larger radius. The $l = 0$, 1, 2 and 3 modes which are selected by the integrated observing technique do penetrate the deepest and therefore have the best chance to interpret the radiative core.

In addition to the accurate frequencies, important conclusions can be drawn from other parameters of the modes. Fine structure splittings will arise due to the rotation of the solar material with respect to the observer. In principle one could expect to deduce the rotation as a function of depth and latitude from a sufficiently complete set of mode observations. The possible presence of very strong magnetic fields of primordial origin deep within the sun may also produce fine structure in the frequencies.

The observed mode amplitudes and line-widths can be used to learn about the dynamics of the solar interior that drives the modes; an aspect that is currently very poorly understood. Present observations show that the coherence life-time of an individual mode is a strong function of frequency at low l, ranging from a day at 5 mHz to over a month at 1.5 mHz (Libbrecht, 1988)

Frequencies below 2 mHz are very difficult to observe from the ground due to a combination of decreasing amplitude and increasing terrestrial and solar noise. The lowest frequency p-mode with $l = 0$ and $n = 1$ has a period of the order of 60 minutes, and has never been identified. An important objective of GOLF is to measure for the first time the p- modes below 1 mHz and to study the entire predicted range of p-modes with a resolution better than 3.10^{-7} Hz and a sensitivity around 1 mm s^{-1} in 20 days.

The gravity or g-modes make use of buoyancy rather than pressure for the restoring force. Here also a range of modes with different order and degree are predicted, but their propagation characteristics and thus their diagnostic properties are somewhat different. The g-modes can propagate freely in the deep solar interior, but are reflected at the base of the convection zone at around $r = 0.72R_{\odot}$, since the convection zone is unstable with respect to buoyancy disturbances. Because of this different radial distribution, the g-modes, which are also subject to the rotational fine-structure splitting, are a much more sensitive indicator of the core conditions than are the p-modes. The frequency range for low degree g-modes extends downwards from the fundamental, which is expected in the region of 0.4 mHz. Calculations show that the *periods* of high order g-modes are approximately uniformly spaced, analogous to the uniform *frequency* spacing of the p-modes. Observations show no confirmed identification of g-modes, following initial unsuccessful efforts at detection (Pallé 1991), so that we have no indication of their spectrum, their intensity distribution or their coherence life-times, although the latter are predicted to be very long.

2.1. Frequencies of Global Oscillations

We give here only a brief introduction to those aspects of oscillation theory which are of particular relevance to the use of low frequency oscillations. This will serve to point out the particular importance of the observation of solar g-modes for the analysis of the structure of the solar core.

The solar oscillations obey the standard equations of motion consisting of the momentum, continuity and energy conservation, along with Poisson's equation which defines the time dependent gravitational potential. These are supplemented by boundary conditions defining the physically realizable solutions and the combination of equations of motion and boundary conditions yield an eigenvalue problem for the frequency of oscillation. By using some simplifying approximations, Gough (1985) has shown that the oscillation amplitude obeys a second order differential wave equation with a variable wave number k, which depends on a generalized atmospheric cut-off frequency, a local acoustic frequency or Lamb frequency and gravity wave or a buoyancy frequency. The atmospheric cut-off frequency is relevant only in the surface layers. Propagating waves are possible only where the wave frequency is greater than both the Lamb and buoyancy frequency (p-modes) or less than both the Lamb and buoyancy frequency (g-modes). An approximate condition for frequency resonance is that the integral of the wave number over the solar interior yields $\pi(n+\alpha)$ where α is a surface wave shift. The p-modes are most sensitive to the Lamb frequency which is proportional to the *value* of the sound speed while the g-modes are most sensitive to the buoyancy frequency which is proportional to the difference between the actual and adiabatic density *gradients.*

In addition and perhaps most important to the use of the g-modes is the fact that their eigenfunctions are concentrated toward the solar centre in contrast to the eigenfunctions for the p-modes which are concentrated toward the solar surface. The sensitivity of the mode frequencies to solar structure depends on the amplitude of the mode as a function of position through the sun's interior. For this reason, g-mode analysis contributes more sensitively to the derivation of the solar core structure.

2.2. Shape and Structure in the Mode Profiles

A number of factors determine the shape and width of the observed p-modes. These include the limited coherence time of the oscillations and variations in amplitude and phase with time, due to the physical process of excitation of the modes. In some respects, these properties can be regarded as limitations in the Fourier transform technique, commonly used to interpret the observations. Such techniques are only strictly applicable to oscillations which are invariant with time. For the real situation, Fourier techniques may be limited in their capacity to separate the various effects of amplitude and frequency variations with time, excitation or damping time-scales, or other reasons for lack of coherence. Other techniques of harmonic analysis are being developed (Baudin et al. 1993, 1994) with the aim of better understanding the physical reasons for departure from coherence.

A different and time-invariant reason for fine structure in certain resonances lies in the splittings due to solar rotation. Such splittings have been well-observed for intermediate and high-l p-modes and found to correspond approximately to the solar rotation period (Duvall and Harvey 1983). A real prize awaits the analysis at high precision of these splittings together with those from low-l, including a range of different radial dependencies. In this case, it should be possible to derive the rotation rate as a function of radial distance down to $0.2R_\odot$. The inversion involved is ill-conditioned and therefore demands high-precision low- noise data. Such results as have been so-far reported are close to the limit of significance for detecting non-rigid core rotation (Jimenez et al. 1994).

2.3. Solar Cycle Variations

All of the above parameters are susceptible to systematic variation with the 11 year solar cycle. Frequencies of very low l-value p-modes (between 2 and 5 mHz) have been found to vary with time, on scales of the solar activity cycle (Pallé 1995, Woodard and Noyes 1985, Gelly et al. 1988). This correlates very well with several solar activity indices, such as sunspot number, magnetic field measurements and indices, UV and 10.7 cm radio flux (Pallé et al. 1989, 1990a, Elsworth et al. 1990, Régulo et al. 1994). The experimental data converge to a value for the frequency shift of 0.45 ± 0.04 Hz, with a maximum at solar activity maximum. However there are differences of opinion on whether this shift depends on the l-value of the mode (Régulo et al. 1994). As far as high l-value p-modes are concerned, a similar effect has been measured by Woodard et al. (1991) and Bachmann and Brown (1993), although the frequency shifts seem to be slightly less than the above mentioned value, suggesting a possible variation with l-value. There is also a hot debate on whether the correlation with l-value holds at shorter time scales, of the order of a few solar rotations. Experimental data available do not show conclusive evidence. Finally, there seems to be an anticorrelation of these frequency shifts with the measured total neutrino flux and with the solar radius (Delache et al. 1993). On the other hand, the amplitudes of these modes are also reported to change with the solar activity cycle. Their energies (amplitude squared) are found to be 30% higher at solar minimum when compared to solar activity maximum (Pallé et al. 1890a, 1990b, Anguera Gubau et al. 1992). This change is obviously related to the efficiency of the poorly understood excitation mechanism of the modes.

If the SOHO mission is successful and is eventually extended to 6 years duration, it will be possible with GOLF to study and attempt to interpret these effects.

3. The Instrument Concept

The optical resonance technique is used to isolate a narrow region of the solar sodium resonance line. In fact the two lines, D1 and D2 at 5896 Å and 5890 Å are both used, but the principle is best understood if one considers only one line. The solar absorption line of half- width approximately 500 mÅ traverses a sodium vapour cell which has an intrinsic (thermal) absorption line width of the order 25 mÅ. Thus a 25 mÅ slice of the solar line is absorbed and re-emitted in all directions. Part of the signal re-emitted at 90 degrees is recorded by suitably positioned detectors. By placing the cell in a longitudinal magnetic field of 5000 gauss, the absorption line is Zeeman split into two components displaced from the original by plus and minus $\sim$ 108 mÅ. If the incoming solar flux in now analysed circularly using a linear polariser followed by a quarter-wave plate, it is possible to select first one, then the other absorption component, respectively right and left circularly polarised, and thus measure the amplitude of a point on each of the two wings of the solar profile at plus and minus 108 mÅ from the instrument rest sodium wavelength. For zero line-of-sight velocity, the ratio of these two signals will be close to unity, as shown in Fig. 1. (Here we ignore small constant effects, such as the gravitational red-shift, integrated limb-shift and residual line asymmetry.) Clearly, a Doppler shift between the solar and SOHO sodium wavelengths is manifested by a difference between the two signals for the two directions of polarisation, as seen in Fig. 1(b).

Effectively we are measuring two points on the solar line profile, symmetrically placed around the SOHO rest wavelength. If the intensities I_r and I_l on the right and left wings of the line are measured sequentially, then the instantaneous line-of sight velocity is given by

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

where s is the background stray light arriving at the detectors, other than by resonance diffusion. v_a is the calibration factor, normally of the order of 5 km s^{-1}. The satellite at the L1 point follows closely the orbit of the earth around the sun. The ellipticity of this orbit leads to an annual variation in the line-of sight velocity of the order ± 0.55 km.s^{-1}. This leads to a departure from unity for the average value of I_r/I_l, which takes values of between 1.05

Fig. 1. Showing the relationship between the solar photospheric line profile and the Na vapour cell scattering signals. a) static field with zero velocity vector, b) with Doppler shifted solar line, and c) slope measurements with a modulated magnetic field.

and 1.6, after taking account of the constant solar gravitational red shift. Since v_a depends on the slopes of the solar line at the two points of measure, it will vary with the width and asymmetry of the line, as well as with the time of year.

If the cell magnetic field is now increased by a small factor, we can measure two more points, further separated in wavelength, as seen in Fig. 1(c). This will not directly increase the reliability of the centroid shift measurement, but it will give an instantaneous measure of the slope of the line wings, which is an indication of the width and shape of the solar line and a determination of the factor This additional measurement, originally suggested by Isaak and Jones (1988), is a unique feature of the GOLF design, giving an instantaneous calibration of the velocity sensitivity. This will be important when the presence of solar active regions produces changes in the observed global line profile.

This method of velocity calibration has been tested at Observatorio del Teide, Tenerife, using a 4-point resonance spectrometer, in operation during 1989 and 1990, which reproduces the relevant features of the GOLF design. Analysis of the results carried out by Boumier et al. (1994b) show that, using this technique to measure the factor v_a, results in reducing the solar noise level in the region of the spectrum where the gravity modes occur.

The sodium lines being magnetically sensitive, their intrinsic solar circular polarisation is a measure of the solar longitudinal magnetic field. It is possible to add to the GOLF instrument a capability to measure the mean value of this field by adding another quarter-wave plate at the front, and measuring the relative amplitude of the two directions of incident circular polarisation.

With regard to all of the above measurements, the second sodium resonance line D2 will behave in exactly the same way, but with small differences in the atomic physics and Zeeman patterns introducing small quantitative variations. The GOLF instrument cannot distinguish the two components and operates with the sum of the scattering signals from both lines.

It should be noted that GOLF aims to measure the integrated disk velocity vector to a precision of a millimetre per second. The rotation of the sun produces at the limb a velocity vector of times this value. It is therefore implicit in the design of GOLF that the uniformity of response of the instrument to all points on the solar disk enables the exact cancellation of the velocities from the two halves, to a precision of one part in 10^6. The optical system chosen for GOLF is a non-focusing system in which the entrance pupil is imaged onto the critical element. Although such a system in principle averages all points on the sun, it is important in order to reach the above precision that this average is strictly maintained and that no disturbing influences exist with periodic variations falling in the GOLF frequency band.

4. Instrument Overview

4.1. Optical Layout

The instrument configuration is shown schematically in Fig. 2. Light from the sun passes through a filter which isolates a band of 17 Å centred on the Na D lines. It is then brought to a focus by the lens L1. The lens L2 serves to produce a near parallel beam to traverse the vapour cell, while at the same time imaging the entrance pupil of the system at the centre of the cell. This optical arrangement serves to minimise the influence of transverse variations in instrument sensitivity, by minimising their correlation with points on the solar image. After traversing the cell, the beam is effectively absorbed in a light trap. Light scattered from the vapour in the cell at 90 degrees is collected by two photomultiplier tubes in a symmetrically opposed configuration, operating in photon counting mode. The cell is placed between the poles of a permanent magnet, giving a 5000 gauss longitudinal magnetic field through the sodium vapour. An additional longitudinal field of ± 94 gauss is applied by means of the small coils, which can be seen in Fig. 2.

The incident light is circularly polarised by a combination of the linear polariser P1 and the quarter-wave plate QP2. A change of relative orientation of P1 and QP2 by 90 degrees results in a change in the sense of the circularly polarised light transmitted. This change provides the measure-

Fig. 2. Schematic representation of the GOLF instrument configuration.

ment of the intensity ratio of equation 1, which is the direct indicator of the solar velocity vector.

The addition of the second quarter-wave plate QP1 facilitates the measurement of the longitudinal component of the average solar magnetic field. Switching the relative orientation of QP1 and P1 by 90 degrees yields an intensity ratio which is sensitive to the intrinsic circular polarisation of the solar sodium lines, which is in turn determined by the average solar magnetic field. The addition of this facility offers the possibility of measuring these mean fields to a precision of the order 1 mGauss, representing a considerable advance on what is currently available. The mean disk magnetic field is a parameter difficult to obtain from resolved magnetograms. This parameter contains the lowest order multipole components of the solar magnetic field, and is thus important in understanding the interplanetary fields and the evolution of the solar cycle. The presence of the two rotating mechanisms on the GOLF instrument has a second important advantage of permitting recovery of the prime oscillations objective in the event of a failure in either of the two mechanisms.

4.2. The Physical Configuration

GOLF consists of three units: the Sensor Unit, the electronic Data Processing Unit (DPU) and the Power Supply Unit. These are mounted separately on two different sides of the payload module and linked together by the GOLF main harness, which also connects to the spacecraft interface.

The configuration of the GOLF Sensor Unit is shown in Fig. 3. The structure is that of a hollow beam. For cleanliness considerations, optical and detection components are located inside. On the outside are attached: local drive electronics, interconnecting harnesses and surface thermal control

Fig. 3. Physical layout of the GOLF Sensor Unit

items such as a Second Surface Mirror facing the sun, Multi Layer Insulation covering external surfaces and passive radiator panels.

The Sensor Unit structure is separated longitudinally into four different elements. Where applicable these sub-units give accommodation to the necessary local electronics and thermal control hardware, in order to constitute autonomous sections. This facilitates the development and integration of the sub-units by different institute teams of the GOLF Consortium and allows local sub-system testing prior to overall experiment assembly.

The Front Section includes the solar shielding screen, and the entrance optics accommodation structure, where are packaged the entrance door, the filter with its thermally controlled housing, the first lens group and the fixed Quarter-Wave Plate. A passive radiator and local electronics are located on the outside of this structural element. The Intermediate Section structure provides the necessary interfaces for the two other mechanisms, used for rotation of the Polariser and the second Quarter-Wave Plate. Outside are attached their associated electronics, the non-operational substitution heaters and the S/C powered thermistors, to ensure respectively a constant power dissipation and a temperature measurement of the sensor when the instrument is not powered. The Mid Section structure provides the mechanical fixations for the second lens group, the sodium cell housing and its thermal control, the permanent magnet, the light trap, the magnetic modulation coils and associated electronics, magnetic shielding and relay optics for the photomultiplier tubes. The Analogue to Digital Converter for the housekeeping electronics is also attached to this section. The Rear Section structure houses the photomultiplier tubes together with associated detection circuits.

The Sensor Unit is mounted on six isostatic struts. A large passive radiator is common to the Intermediate, Mid and Rear Sections. Two separate boxes house the Data Processing Unit (DPU) and the Power Supply Unit (PSU). These are located on a lower panel of the spacecraft.

4.3. The Operating Cycle

The two rotating optical elements plus the modulation of the magnetic field must be switched periodically, at a frequency safely above the cut-off frequency of $6mHz$. The three switched devices must be operated on a staggered cycle, so that eight separate measurements are made. The three resulting ratios can then be analysed to give; a) the velocity calibration from the magnetic field modulation, b) the velocity measurement from the relative position of P1 and QP2, and c) the solar magnetic field from the relative position of QP1 and P1. One element is actuated every 5 seconds, giving a total cycle time of 40 seconds per measurement, as shown in Fig. 4.

After an initial turn on, calibration and verification activity in orbit, the objective is to carry out a single-mode fully automatic observation sequence

Fig. 4. The timing sequence for switching the polarisers and modulating the magnetic field.

in as continuous manner as permitted by the constraints of the instrument and satellite systems.

Analysis of the data stream in terms of the various oscillation modes demands as long a duration of continuous data as possible. This is particularly true for the low frequency long- duration modes, for which such extended operations offer the advantages of reliable mode life- time measurements and improved signal-to-noise ratios. Thus, the formal requirement is for a two-year observation sequence, consistent with the planned life-time of the SOHO mission. However, every effort will be made to benefit from an extended period, should the SOHO mission succeed in functioning for six or more years. Such an extension would permit the study of variations due to the solar cycle.

4.4. Division of Responsibilities

GOLF has been developed by a consortium of five institutes, supported by an international group of scientific CoInvestigators. The instrument development institutes are:

Institut d'Astrophysique Spatiale (IAS) at Orsay, with responsibility for the PI role (A. H. Gabriel), the Project Management (J. Charra), the overall programme of integration and testing and the integration and test of the Middle (Cell) Section of the Sensor Unit. The IAS also has specific responsibility for the optical architecture, thermal control and modelling, development of the cell and management of the operations phase.

The Service d'Astrophysique of CE Saclay (SAp) is responsible for development, integration and testing of the Rear section of the Sensor Unit, (including the detection sub-system and electronics), electronics for the magnetic modulation and thermal control, the Data Processing Unit, including the on-board software. SAp also provides the electronic ground support equipment and the software for command and telemetry reception. SAp has responsibility for the overall electronic architecture.

The Instituto de Astrofísica de Canarias at Tenerife (IAC) is responsible for the Front and Intermediate sections of the Sensor Unit, including the development of the mechanisms used for the door and polariser components. The IAC also provides the power supply units and the operations support ground equipment.

The Observatoire de l'Université Bordeaux 1 has responsibility for the design and testing of the permanent magnet and magnetic modulation, together with its associated magnetic shielding system.

The University of Nice has responsibility for the Project Scientist role (G. Grec), the development and operation of the data evaluation software and the preparation of data products.

5. Performance Requirements

In order to specify the instrument design parameters, it is necessary to define first the requirements for sensitivity as a function of frequency of the oscillation spectrum. This has been determined as equivalent to a velocity of 1 mm s^{-1} for a mode having a lifetime of 20 days. For the instrument described, this sensitivity is equivalent to the limit imposed by the photomultiplier photon noise. At the high frequency end of the spectrum, the overall sensitivity limit should indeed correspond to this figure. However, as the frequency decreases, the solar noise spectrum increases, and will ultimately impose a higher limit on the detectable oscillations. In addition, the problem of ensuring a low value for systematic instrumental noise becomes increasingly difficult at the lower frequencies.

The observed background solar velocity spectrum has been measured from the ground over a period of eight years by Pallé et al. (1995) and is reproduced in Fig. 5. This low resolution spectrum shows a continuous slope, with super-posed peaks due to the first and subsequent harmonics of the day/night period and the p-mode 5-minute oscillations. The main slope is principally due to the solar noise caused by the effects of granulation, super- granulation and active regions (Harvey, 1985), although there will be some component due to terrestrial atmospheric disturbance and the instrument itself. The contribution at low frequencies due to active regions is the component that we hope to evaluate and correct for in the GOLF data analysis. If this should prove possible, it will effectively reduce the solar noise contribution below that of the curve of Fig. 5. It is not excluded to measure oscillation amplitudes significantly below the level of the remaining solar noise. This will depend on the precise nature of the two signals; for example, if the first consists of sharp lines and the other of a very smooth continuum.

Fig. 5. The observed background solar velocity spectrum (Pallé et al. 1995) The dashed line indicates the target sensitivity for GOLF.

This cannot be predicted until we observe the solar noise spectrum at the level of GOLF sensitivity.

Our aim for the performance of GOLF is therefore to obtain an instrument sensitivity curve which is constant at the photon limit at higher frequencies, but is allowed at lower frequencies to rise while remaining comfortably below the estimated solar noise curve. We place this level of comfort at a factor 10^3 below the solar noise, in order to profit from any success we obtain in discriminating against the solar noise. This sensitivity target is shown as the dashed line on Fig. 5. If this target can be maintained, then the sensitivity in the region of the principal g-mode spectrum will remain at the level of the photon noise. At the very low frequency end, it is difficult to guarantee the GOLF instrumental noise performance, since this will be due to many factors affecting long term stability of the instrument and the satellite. It is also impossible to measure such quantities in an inevitably noisy laboratory environment.

The design requirement is now to be able to measure a real solar oscillation spectrum of the order of the dashed line level. Clearly the problem is of a different nature depending on whether the oscillation spectrum consists of sharp lines or a quasi-continuum. The same two possibilities exist also for the nature of the residual instrumental noise. The definition of the engineering parameter requirements (stability of temperature, precision of positioning, etc) thus becomes very complex. In evaluating this problem, we are reassured by the fact that the ground-based oscillation instruments function effectively within their specification, with a level of engineering sophistication significantly lower than that usual for space instruments.

The essential requirement on the instrument performance is that a discreet spectrum of solar oscillations, having spectral line-widths equivalent to 20 days and amplitudes of the order 1 mm s^{-1} can be measured, in the presence of instrumental and photon noise, down to frequencies of the order 10^{-4} Hz. This can be readily converted into system technical performance levels. It must be recognised that the difficulty is to avoid that instrumental and operational procedures introduce into the data spurious effects, which contaminate or confuse the measured spectrum. Such effects can have the nature of discreet frequencies, of broad resonances, or even a continuous white noise.

The environment of GOLF, situated on the SOHO satellite at the point L1, with a fixed solar orientation, is exceptionally stable. The design of the spacecraft is also optimised in this sense, with a strict limit on the thermal variations permitted at the instrument mounting points. To test the complete assembled GOLF instrument in a comparably stable environment for the period of integration of 20 days, has been judged as non-feasible in the laboratory. On the other hand, the residual perturbations anticipated in orbit can be clearly identified as of two types: thermal variations, and variations in instrument pointing due to spacecraft pointing excursions. The technique adopted is to specify the performance of each GOLF sub-system (eg entrance filter, cell, etc.) in order to avoid predictable system level sensitivities to these two parameters, which might exceed the required figures. For thermal disturbances, this is straightforward, and can later be verified in sub-system level testing. For pointing disturbances, the situation is much more complex.

Information on the predicted or achievable offset pointing sensitivity of GOLF is very difficult to obtain. The effect arises for a number of reasons, but the principal one is due to the specific nature of the solar source. As indicated above, we have to rely on the uniformity and symmetry of the instrument to ensure the cancellation to one part in 10^6 of the blue and red shifts arising from the rotation of the sun. The optical concept is designed to ensure that this remains valid when the instrument is offset by small angles. Although this concept is true to zero and first-order, second and third order effects, such as non-uniform transparency or polarisibility of optical components, may induce an apparent solar velocity signal which is related to the degree of offset. Some data exists for the ground-based instruments of IRIS which use a similar principle to GOLF. However, this is not considered as sufficiently reliable to use, as the optical system is different. In addition, the degree of rigour in the design and construction of GOLF is expected to ensure a far lower sensitivity. The difficulties evoked above for providing a laboratory simulation of the environmental stability of GOLF are multiplied many times if it is necessary to include a good simulated solar source. Even if 20 days of stable conditions could be found at a good mountain site, the presence of atmospheric disturbances, for which GOLF is not designed, would invalidate the procedure.

The best efforts to estimate the offset pointing sensitivity of GOLF indicate that it may not be a problem. The effect will be measured by a programmed calibration sequence of offset satellite pointing to be carried out early in transfer orbit. Should it be found to need correction, steps have been taken to ensure that the GOLF analysis team will receive the necessary detailed and frequent information on the spacecraft pointing.

5.1. The Effect of Active Regions

Magnetic active regions have long been known to produce local changes in the profile of the photospheric absorption lines. In the case of the sodium line, these profiles are the subject of a programme of measurement directed towards a better understanding of the analysis of the GOLF data. A study of these profile changes is currently in progress using the Mt Wilson Observatory. A further study has been carried out at Observatorio del Teide, Tenerife using a 4-point magnetic modulation in a GOLF-type instrument (Boumier et al. 1994b). A theoretical model of these effects has been produced by Marmolino et al. (1995) and is being further refined.

The changes in profile can be represented schematically as shown in Fig. 6. The line becomes broader, less deep at the centre, and more asymmetric. These changes are also confirmed by 5-point measurements being carried out at the Observatory of Bordeaux (Robillot et al. 1993). The effect is confined to certain significant areas in the active regions, sometimes referred to as "downdraft" regions. Clearly the presence of one or more such regions on the sun will contribute to a deformation of the integrated solar profile of the same character, but of smaller extent. Such deformations, and their time variations represent an important component in the solar noise spectrum at low frequencies. The object in studying this effect in detail is to see whether it is possible to: a) recognize these contaminations to the data, and b) learn how to extract them in order to remove some of the induced "solar noise", and thereby increase the effective sensitivity to oscillations.

Fig. 6. Schematic representation of the effect of active region “downdraft” on the solar Na D line profile.

The existence of active region contamination to the observed profile will have a number of effects, as follows:

It will change the velocity sensitivity, or calibration factor, due to a change in the solar line width and depth. The presence of the 4-point GOLF measurement which can correct continuously for changes in slope of the line wings should help correct for this effect.

The line is shifted, due to a combination of a real local line shift, plus the effect of asymmetry, plus a solar rotation effect if the region is not at central meridian. To correct here, we need to know: a) the precise local change expected, b) information to recognize the existence of the contamination in the observed profile, and c) the position on the disk of the source. Point a) we hope to obtain from the present Mt Wilson studies; point b) could be resolved by using the slopes evaluated from the 4-point measurements, as suggested by Damé et al (1990); and point c) we can obtain with the co-operation of the MDI instrument on board of SOHO.

There is also the possibility of a false velocity signal if a region which is not at sun centre has a change in its average intensity; that is to say in the mean signal from all four points measured on the line profile. We can readily calculate that if 2% of the surface near one limb has a 2% change in its mean intensity, then this will produce a false mean velocity signal of the order 80 cm s^{-1}. For a typical sunspot having 0.01% of the surface and a 90% reduction in intensity, this gives a false velocity measurement of 18 cm s^{-1}.

In evaluating all these effects it is important to remember that it is not the false velocity signals themselves that pose a problem; it is only their time variation when this falls within a frequency band of interest. The passage of active regions across the disk will obviously give a modulation at the frequency (and harmonics) of the solar rotation. This may not be too serious and should be easily recognized. In fact, recent work by Ulrich et al. (1993) shows a very good correlation between the measurements of the IRIS velocity signal of 13 day period and a model based upon observations from Mt Wilson of the effects of magnetic active regions on the sodium line profiles. However, if the physical processes in the "downdraft" regions induce significant modulations at periods of around an hour, this could provide a much more serious noise contribution. It is one of the objectives of the Mt Wilson programme to investigate this aspect, which is also an aim of a collaborative programme with the MDI/SOI instrument on SOHO.

6. Resonance Cell Sub-System

The Middle Section of the GOLF Sensor Unit, the cell sub-system, consists of the cell itself, with its heaters in a controlled thermal environment, between the poles of a powerful permanent magnet, complete with its magnetic modulation coils and shielding. The configuration is shown in Fig. 7.

The cell itself is a T-shaped glass structure, with a cylindrical head aligned with the optic axis and a stem in which is held a droplet of sodium. The head is terminated at each end with a flat window, through which passes the primary beam of solar illumination. By heating the cell, the sodium vaporizes in the head where the resonance occurs. The cell, together with its windows, is made from a special glass Philips Gehleniet, chosen for its resistance to the hot sodium vapour. Unfortunately, this glass does not have a good optical homogeneity. It is supplied in the form of solid blocks and each part has to be machined. Since the principal origin of stray light reaching the photomultiplier tubes is the scattering produced as the main beam traverses the cell windows, particular attention is given to their optical quality and they are produced and polished separately, from the same glass. Since this glass is optically quite inhomogeneous, windows for the flight cells were carefully selected. The two tubes are first welded together and the windows are then optically joined to the ends of the head tube. The windows are then laser welded to the tube. The cell is coated with black enamel, in order to further reduce stray reflections, leaving clear the two side regions, from which the scattered resonance radiation is observed. The cell is then optically tested, evacuated, baked out and filled with one gram of pure sodium.

The cell is maintained at a highly stable temperature between 180 deg C and 195 deg C, by separate heaters around the stem and the head and a carefully designed thermally insulating support system. The density of vapour in the cell head is determined mainly by the temperature of the liquid/gas interface in the stem. However, in order to ensure that no vapour condenses on the windows, the cell head is maintained at a significantly higher temperature. The heater electrical connections act as a thermal conduction path,

Fig. 7. The sodium vapour cell, showing its mounting system.

maintaining a head to stem thermal gradient, even in case of electric power failure.

An important criterion for selection of the cells for flight was a high value for the resonance ratio R_r, this being the ratio of the signal resonance scattered by the vapour to the light scattered by the cell walls and its housing,

$$R_r = \frac{I_r + I_l}{2s}, \tag{2}$$

the value of the non-resonant stray light s changing significantly from one cell to another.

The GOLF magnet configuration is a "8-shape", previously developed by Bordeaux Observatory for both the MR5 (Bordeaux) and IRIS instruments, as shown in Fig. 8. The magnetic field in the cell region has a "saddle-shaped" distribution. The field deformation for GOLF is greater than for the earlier configurations, due to the hole through the pole-pieces and to the recesses required in order to position the modulation coils within the 23 mm gap between the pole-pieces. Along the side of a cylinder of 6 mm of diameter, the angle of deviation from field parallelism is within 2 or 3 degrees at the entrance or exit window of the cell.

For the flight model, the mean permanent magnetic field along the axis of the resonant cell is 5070 gauss at 20 degC, in the full flight configuration. The samarium-cobalt magnetic blocks are temperature dependent. The permanent field decreases about 7 gauss for each deg C. The expected temperature stability is about 0.05 degC. On the other hand, ageing tests carried out over

Fig. 8. Configuration of the GOLF permanent magnet, showing also the spatial distribution of field-strength in the scattering region.

two years in the presence of the modulation cycle, indicated a drop of less than 4 gauss per year, which is well within the GOLF requirements.

The required modulation is carried out by two flat conical coils mounted on the pole pieces. The two coils are connected in series and a regulated current ± 0.100 amps gives ± 94 gauss magnetic modulation. The field modulation stability is linearly dependent on the current stability itself, which is of the order 10^{-4}.

A double magnetic shielding was installed within the GOLF Middle section, constructed from mumetal and soft iron. Tests with the shielding showed that it produced a 170 gauss reduction of the field inside polar pieces. Outside of the shielding, the residual field is less than 10^{-5} gauss, measured at a distance of 1 meter. This satisfies the requirements for non-interference with the GOLF detectors, as well as for the other instruments and the spacecraft systems.

The scattering properties of the sodium vapour in the cell have been modelled. This has been used to derive the optimum operating temperature for the cell, its required stability and the anticipated flux on each photomultiplier (Boumier 1991, Boumier and Damé 1993). The limiting amplitude of the stem temperature variation leading to an apparent velocity signal of 1 mm s^{-1} has been estimated to be of the order of 0.05 degC, which can be readily maintained.

Tests performed at sub-system level agree very well with the predictions of the model, especially concerning the efficiency of the cell (fraction of the incoming light which is collected by the photomultiplier tubes), (Boumier et al. 1994a). The measured resonance profiles are shown in Fig. 9. Due to the

Fig. 9. Measured profiles of the scattered sodium lines.

inhomogeneity of the magnetic field in the resonating volume, these profiles reveal an asymmetry, more or less pronounced for each component. The fraction of the light scattered through transitions of the wrong polarisation is of the order of only 1 percent.

7. Entrance Filter

The entrance filter is a narrow band-pass filter, centred on the pair of Sodium D lines. Its function is to exclude from the instrument most of the light of other wavelengths, whilst admitting the two sodium D lines without perturbing their profiles. The need is therefore for a flat-topped rectangular pass band which includes the two sodium lines.

Several requirements concerning this filter are classical for an entrance filter. These include sufficient out of band blocking, a high plateau transmittance (typically 70%) and narrow half- width. However, there are two further specific requirements which are critical for GOLF. As the filter is close to the entrance pupil, its surface is imaged inside the cell resonant volume, so that its performance must be uniform across its surface. Furthermore, if the plateau part of the profile is not flat, any wavelength shift of the filter profile, due to changes in temperature, induces variations in the transmission ratio at different wavelengths, and thus in the measured solar velocity. Thus fluctuations in the temperature translate into apparent solar oscillations. It is this last requirement that imposes the most difficult constraint on the fabrication and test.

To reach the required specification limit for instrumental variations appearing on the measured velocity v of $\Delta v/v < 10^{-5}$, two properties of the filter performance must be considered. These are the plateau profile flatness, and the displacement of the band-pass as a function of temperature. The measured values of these two parameters determine the degree of filter temperature regulation required.

In order to achieve a 17 Å wide band-pass filter it is necessary to use a prefilter, which blocks the radiations far from the transmitted wavelength, and a band-pass filter, which defines the band pass. In addition, a front silica window is necessary to protect the filter against the effects of particle radiation. The blocking prefilter reflects towards the sun an important part of the unwanted incoming flux, but also absorbs a part of it. For this reason, and to minimize possible thermal drifts due to ageing, this component is thermally isolated from the band-pass filter, and is coupled directly to the instrument structure. The band-pass filter is located after the prefilter, and receives a very low thermal flux. It has a special thermal regulation, being placed in a housing thermally decoupled from the instrument structure, and with its own radiator. The heaters are controlled by an open loop current regulation system to maintain the temperature for which the band-pass filter spectral centring is optimum.

Irradiation tests with high-energy particles were performed by ESTEC and lead to the conclusion that, with the silica entrance window, no irradiation problem is to be expected The filters were tested under vacuum, in their temperature regulated housing, with a tuneable laser beam, presenting the same optical geometry as the sun. For each elementary measurement, the flux transmitted by the filter was compared to the flux obtained on the same detector when without the filter. An auxiliary normalization detector was used to correct for the laser intensity drift. The laser wavelength was measured by means of an absolute spectrograph ("lambdascope"). Homogeneity across the surface, angular response, temperature dependence and spectral profiles were measured. In particular, the plateau profile was measured with a $\pm 0.5\%$ accuracy for the transmittance, and ± 0.001 Å accuracy on the wavelength. It is concluded that the filter control capability of 0.01 deg C will suffice to maintain the GOLF overall stability requirements.

8. Detection Sub-System

Scattered light from the cell is recorded by two photomultiplier tubes, which receive the photons re-emitted in the two laterally opposed directions.

The collection system is a four-lens convergent device, matching the resonant beam geometry to an optical fibre, which carries the light to the detector tubes. This serves to image the centre region of the cell onto a physical aperture, so that the scattering volume used is strictly limited and stray light from the windows is not seen by the detectors.

This use of the optical fibres avoids mapping of the scattering area onto the photocathodes, homogenizes the response and, by avoiding local high intensities, serves to prolong the useful photocathode life. A redundant channel is provided, composed of two other photomultipliers located adjacent to the previous ones. This is a component of the overall cold redundancy, if any problem appears on the main electronic channel of GOLF. Alternatively, it can be used as a means of doubling the lifetime of the detector system. The corresponding counting electronic boxes are located on the two sides of the sensor detection rear section.

The detection chain has been designed to meet a number of performance requirements. The nominal total counting rate of 6.10^6 counts.s^{-1} (to within 20%), determines the photon statistics contribution to the GOLF overall sensitivity. The counts are integrated for 4 s every 5 s, with the requirement for a stability over the counting cycle of 80 s of 10^{-6} for periodic disturbances, or 10^{-5} for white noise. The dark current signal is smaller than 400 counts.s^{-1} for a nominal power supply voltage at 20 deg C and the photocathode is selected for a high quantum efficiency at the sodium line wavelengths.

These criteria have resulted in the following configuration. The photomultiplier tube, a Hamamatsu R4444, has been specifically developed with a ruggedized structure. It is used in a photon counting mode to minimize the effects of gain drift, with a multialkali (Na-K-Sb-Cs) photocathode of diameter 8 mm. It has a wide spectral response, with an efficiency of about 6% at the sodium wavelength, a maximum operating voltage of 1200 V, and a current amplification of 3.10^6. The high voltage supply and a preamplifier are mounted immediately behind and integral with the phototube. The configuration is shown in Fig. 10. The assembly is potted in a soft resin in order to avoid electrical arcing. The high voltage supply is adjustable by telecommand in 1024 steps of 0.25 V. The design of the high voltage has been optimized to give a stability of 10^{-4} over 1 hour at constant counting rate. The anode mean pulse amplitude per photoelectron, is about 11–12 mV and is preamplified by a factor 10. In the counting electronics box, this signal is amplified by a further factor 5 and sent in parallel to two detection channels. The first is the signal channel which integrates over 4 s every 5 s with a threshold of 30 mV, adjustable by telecommand. The second, called the spectrum channel, is similar, but with a variable threshold which can be incremented by 10 mV every experiment cycle of 80 s, in order to produce a pulse amplitude distribution. This is used to follow the gain deterioration and to re-adjust the high voltage when necessary. Alternatively, the second channel threshold can be set at a selected fixed value by telecommand in order to monitor the presence of any high amplitude pulses, which could be due to high-energy particles.

In order to respect the stability requirements of GOLF, a high precision is required for the generation of both the 5 s sequence interval and of the 4 s counting duration. The SOHO spacecraft carries an Ultra Stable Oscillator (USO). Nevertheless, the drift of such an oscillator will not be negligible for the SOHO mission duration, so that it cannot be used to generate an accurate on On Board Time (OBT), without periodic re-trimming. This trimming is specified by commands and performed on board the spacecraft in order to always keep the OBT within 20 ms of TAI (Temps Atomique International). GOLF Local On Board Time (LOBT) being driven by the same corrected clock keeps the same accuracy and is used to generate the 5 s intervals. The spacecraft High Frequency clock at 131072 Hz, derived from the USO, is sufficiently stable (4.10^{-8} per day) to permit a hardware generation of the 4 s intervals throughout the mission, with the advantage of having a monotonic evolution undisturbed by the periodic On Board Time trimming activity.

8.1. General Performance

Selection of flight phototubes has been carried out for the best quantum efficiency, low dark current and a good pulse height distribution. The high voltage has been chosen to set the mean position of the distribution maximum at 250 mV and phototubes have been selected with the smallest ratio valley/peak (0.5–0.6). This selection serves in effect to exclude tubes in which the first dynode plays a role of photocathode and limits the effect of the threshold fluctuation.

In order to verify the stability of the whole detection chain, at a level of some 10^{-5} or 10^{-6} over 80 s, it is necessary to perform long duration tests. These have been carried out in a stabilized environment (avoiding rapid thermal periodic variation), illuminating with a small lamp supplied by a well-stabilized current supply and a filter selecting photons in the range of sodium lines. To comply with the flight conditions, we have imposed constant counting rates of 6.10^{6} on the two phototubes or a counting rate modulated every 5s. Taking data continuously during 3 weeks and after Fourier transform of the velocity signal, it is possible to demonstrate conformity with the GOLF requirements for a distribution of white noise of mean amplitude 1 mm s^{-1}.

It has also been possible to verify the absence of hysteresis on the counting rate between two successive integrations of 5 s and the evolution of gain with time over a period of two years. Stability of about 0.2% per day is achieved after one week of operation. The consequent loss of counting rate can be compensated by an increase in the high voltage It has also been possible to verify the performance of the phototube up to a counting rate of 10^7 s^{-1} and show that such levels can be used. These very high currents lead to a quicker ageing of the photocathode.

8.2. Linearity of Detection Chain

A number of effects must be corrected in order to obtain maximum linearity in the detection system. The most important is due to the effect of dead time at these high counting rates. This non-linear characteristic of the detection chain has been measured in different ways. We identify two sources of dead time. The phototube itself has an anode pulse width of 10 ns and the discriminator has a fixed dead time of 11.2 ± 0.1 ns, leading to a total dead time of 15 ns. This has been verified by varying the incident source intensity in a known manner and analysing statistically the response. The observed values for the mean count rate N_c and its rms deviation σ_c are related to the dead time τ by:

$$\frac{\sigma_c}{\sqrt{N_c}} = 1 - N_c\tau \tag{3}$$

This method is extremely sensitive to the stability of the total detection chain and of the incident light source and converges towards a dead time precision of 0.5 ns after 3 or 4 days, corresponding to the time required for stabilisation. With a counting rate of 6.10^6 s^{-1}, the counting loss is 9%, so that it is necessary to correct for this effect before calculation of the velocity. This is especially true when the two sampled wings of the solar line are especially unequal, around April (see table 1).

TABLE I

Magnitude of required velocity correction, as a function of time of year. Diaphony is the only periodic effect.

Error	Velocity in cm.s^{-1}		
	Dec	Apr	Sept
dead time	−500	−850	−60
H.T.variation	−3.4	−4.7	−0.5
diaphony	±0.3	±0.6	±0.05

A second source of counting rate reduction comes from a linear decrease in the high voltage arriving at the photomultiplier tube with the count rate. This correction on the counting rate is small and the modification to the velocity is summarised in table 1.

The third reason for counting rate errors is due to a small diaphony between the two electronic counting channels: "signal" and "spectrum". The sequential increase of the spectrum discriminator threshold during a spectral scan slightly modifies the threshold of the counting channel by AC coupling. This effect has been measured for each electronic box and a variation up to 10^{-5} on the counting rate has been identified which produces small peaks in the signal frequency spectrum at frequencies connected to the periodicity of the measurement. As the spectrum channel threshold is unchanged during the operation for the entire sequence of 80 s, this effect mainly influences the sum $I_r + I_l$ (see equation 1) and is summarized in table 1. One may appreciate that this is a small effect and can be corrected, since the diaphony has been measured for each electronic module. This problem can be reduced by limiting the survey of the count-rate spectrum to occasional use.

9. Mechanisms

Three components within the GOLF instrument involve mechanical actuation. As already indicated in Section 4, two components of the principal optical chain, the polariser and the second quarter-wave plate, must be capable of rotation about the optical axis by 90 deg, in order to carry out the primary operations cycle. In addition the instrument is provided with an entrance door, capable of being opened and closed many times during the mission.

9.1. Entrance Door

The purpose of the entrance door is to protect the filter optics against pollution (dust and/or chemical deposits) and the secondary effects when these are polymerised by the action of solar UV radiation. The requirements are that the door when closed should obscure all line-of-sight access from the exterior to the interior of the GOLF assembly. It is not intended that the door should provide a leak-proof seal. This was not considered necessary and would have imposed much additional complexity, together with increased risk of potential failure. The required door function is accomplished by positioning a shutter element across the optical axis of the instrument in front of the filter. The system has two bistable positions (open/close) driven by a stepper motor. Being a potential single-point failure, the system has complete internal redundancy, both mechanical and electrical.

The design of the mechanism was constrained by the following three requirements: no single point failure, ability to test both operational modes (main and redundant) during ground tests without the need for disassembly and capability to switch from one mode to the other by use of specific commands to modify the status of the mechanism. The concept adopted responds to these requirements. The first implies two actuators of electromechanical type (due to the second requirement) and the third has been solved with a specific mechanical design that allows the mechanism to reach the same rest positions for both operational modes. In the main mode the shutter is actuated by the main stepper motor. In case of failure, the shutter together with the main motor are driven by the redundant motor via a gear and pinion transmission. The sub-system is composed of an electromechanical assembly, located within the front section structure, an electronic box located on one side of the same structure and a harness that interconnects the two.

9.2. Polariser Sub-System

As described in Section 4, this subsystem allows the instrument to measure sequentially on each wing of the selected solar line, thereby providing the possibility to determine its wavelength shift relative to the sodium line produced in the cell. It contains two separate rotatable polarizing elements (a quarter wave-plate and a linear polariser) and an extra quarter wave plate which is fixed and placed in front of the other two. The overall system converts the incoming light into circularly polarized light, either left or right handed, depending on the relative position of the two movable polarizing elements. Note that the movement of either of these elements achieves the required effect. However both are movable to ensure redundancy in case of failure. The presence of the two mechanisms, together with the third polarising element in front, enables the secondary scientific objective to be achieved of the measurement of the mean solar magnetic field. The requirements on the relative angular positioning is ± 6 arcmin in order to achieve the required velocity sensitivity limit. This is translated into a requirement of ± 3 arcmin on the absolute setting and reproducibility of each mechanism. This requirement imposes severe constraints on the components of the mechanisms. The solution adopted is direct drive and angular positioning measurement of the rotating shaft, i.e. no gearing is used.

The rotation of these elements is achieved with the use of a hollow shaft stepper motor controlled in the so-called "microstepping" control mode. Since the two elements have to be positioned relative to the front fixed one and, moreover, to be able to continue operating in case of failure of one of the mechanisms, a knowledge of the absolute position of the motors is needed. This is achieved by the use of an absolute encoder which consists of two resolvers, the first (coarse) one gives the positioning information in an absolute value for all the circumference, but with a low resolution. The second one (fine) is more accurate but its information is repeated each 90 degrees. The result of this combination is an absolute position information with a resolution of 15 bits over the entire circumference. The two mechanisms sub-systems which move the polarizing elements are identical.

When working in the nominal mode both mechanisms will perform the same movements: 90 degree rotations in 0.9 s, followed by a delay of 0.1 s to verify that it has attained the required position, followed by a rest period of 19 s. These movements will be shifted by 10 s for the second mechanism to allow for the defined sequence of measurements. There is also an emergency mode that is activated when failure of one of the mechanisms occurs. In this case, when the relative positioning is re-established, the remaining mechanism will have to operate at twice its nominal frequency.

To command the mechanisms, two electronic drive units have been constructed. Their main function is to perform an absolute position control loop, with the specified resolution and accuracy, and to determine and transmit to the DPU the position achieved.

G0LF mechanisms belong to the category of equipment of new design, which requires their performance to be demonstrated by qualification. Three prototypes (SM, EM and QM) and two flight models (FM and FS) were built, which allowed the achievement of qualification of the design at an early stage of the project. Following a specific test plan, functional, vibration and thermal vacuum tests were performed at unit level and an EMC test was carried out at instrument level. The results of these tests were satisfactory and demonstrated that the performances of the mechanisms were within the specified requirements.

9.3. Polariser Elements

The plane-polariser uses a design based on the multi-Brewster principal. It is in the form of a cube, made up from two right-angled prisms assembled in the plane of their common hypotenuse. In this common plane is deposited a multi-layer reflection coating. The non- transmitted polarised component is reflected on the successive layers at the Brewster angle. It is then totally reflected on the mirror coating on the corresponding lateral face of the cube, reflected once more by the multi-layer coatings, after which it is rejected towards the sun. The ratio for the direct transmission of the two components is around 5000.

The quarter wave plates are composed of two thick (of the order one millimetre) elementary quartz plates, optically bounded together, their neutral lines being crossed. The difference between the plates thicknesses is adjusted after optical bonding, to obtain a resulting phase retardation of one quarter wave for the Na D lines. The phase retardation is $1/4 \pm 1/300$. The measured ratio between wanted and unwanted circular polarizations is typically 5000.

Fig. 10. Showing the system of redundancy for the GOLF instrument.

10. Redundancy and Back-up Modes

10.1. Redundancy

As usual for space instruments, GOLF is protected against many forms of failure in orbit by the provision of duplicate sub-systems, which can be switched into operation when the main sub- system fails. A general overview of GOLF redundancy is summarized in Fig. 10. As can be seen, GOLF can be considered as two instruments in one. In the GOLF documentation these are referred to as the MAIN and REDUNDANT channels.

One can select either one channel or the other, corresponding to one side or the other of Fig. 10. The remaining channel is not then powered or functional until needed; a system referred to as "cold redundancy". It is not possible in general to "criss-cross" between the two channels, except for one subsystem, the entrance door mechanism. This unit being independent and fully internally redundant mechanically and electronically, one has at first to select both the electronics and the motor to be connected, independently of which instrument channel is chosen to be powered.

This exception apart, the selection of one of the redundant channels will determine which of the following duplicated systems is powered up: Power Supply Unit, Data Processing Unit, Filter heater and associated electronics, Resonance Cell heaters and associated electronics, Magnetic Modulation current source and a set of two of the four Detectors with related electronics, as well as a complete set of Thermometric measurement hardware. In addition to the above mentioned case of the entrance door, one should note that certain sub-systems cannot be duplicated and must therefore be switched into whichever channel is functioning. This includes the magnetic modulation coil, which has a relay automatically connecting it to the correct channel. On the other hand, the Polariser and Quarter-Wave Plate mechanisms are not powered automatically, so that their relays must be actuated into the correct position.

As indicated previously, GOLF has only one nominal observation mode in which all subsystems of one channel are powered, the Magnetic Modulation is active and both the Polariser and the Quarter-Wave Plate are alternately rotated. When GOLF is switched from one channel to the other, different hardware is used, different adjustments may have to be selected to obtain the same observing conditions, and different transfer/calibration functions must be selected to convert telemetry data into calibrated physical values. It should also be noted that switching from one channel to another cannot be accomplished rapidly, especially when the cell is warm. It is necessary to first let its stem cool down below 100 degC to avoid sodium vapour deposition on cell windows then switch the channel OFF, actuate mechanisms relays, power up the other channel and finally re-start the cell heating procedure, bulb first, then the stem. The overall duration of this sequence can be a little less than one hour but nevertheless high quality observations depend on a good thermal equilibrium and will be delayed for a further day.

10.2. Back-up Modes

A back-up mode is a mode compensating for a channel subsystem failure without degrading the prime scientific output. Changing from the GOLF main to redundant channel, or vice versa is one such case. Another is to modify the mechanisms actuation duty cycle in order to have only one mechanism, polariser or quarter-wave plate, actuated instead of both alternately. The active one is rotated at twice the frequency as in nominal mode but, since the dissipated power remains the same, no thermal perturbation is generated. GOLF primary science output is fully maintained. However, the secondary objective, solar global magnetic field monitoring, would be lost in this case. This mode can also be selected if one of the mechanisms position repeatability becomes a limitation to the reliability of the science data, or for other optical reasons. If instead of just stopping the mechanism, it is powered OFF, the same result can be obtained, but in this case with a decrease in dissipation and thus a decrease of Sensor mean temperature by a few degrees.

10.3. Contingency Modes

Besides the possibility to switch to the other redundant channel, which may not be desirable or possible for other reasons, contingency modes respond to the need to compensate for some system or subsystem non-nominal behaviour, the new mode inducing a more or less severe degradation of the experiment scientific performance. The occurrence of a second failure of the experiment would likely be a situation that forces the selection of a contingency mode.

Without going into too many details a few examples give an idea of the GOLF instrument control flexibility. Some subsystems can be switched OFF to overcome a short circuit problem or over-heating of the Sensor. Non-operation heaters can also be powered up to increase the Sensor temperature by steps of about 5 degC. An excess of small-amplitude pulses detected by the photomultipliers can be corrected by increasing the detection threshold level. On the other hand, high amplitude pulses (due for example to energetic particles) can be distinguished from normal pulses by setting the spectral channel thresholds to a large value. An excessive counting rate can be decreased by decreasing the cell stem temperature. Finally, as already indicated, a new on-board software load can be uplinked, but with the drawback that this new load is lost each time the instrument is switched off.

11. Data Processing Unit

Two parallel electronic systems in cold redundancy are housed in the Data Processing Unit, which is based upon a CMOS microprocessor 80C86. Both have a PROM containing the On- Board Software. If necessary, new software can be up-linked during the mission, to be implemented in place of that held in the PROM. The software has the following functions:

copying the programme from PROM to RAM,

executing the RAM programme and switching the PROM power supply OFF,

initialising the experiment,

receiving, controlling and executing commands,

reporting telecommand quality in telemetry,

synchronizing gates and reading PMT counters,

storing selected scientific data for 8 hr and 16 hr, and re-inserting them in the telemetry, in order to overcome as far as possible discontinuities in data reception, (the value of the nominal 8 hr storage duration can in fact be selected by command between 80 s and 16 hr, by steps of 80 s),

reading housekeeping data,

formatting and sending to the S/C the Scientific telemetry blocks,

formatting and sending the Housekeeping telemetry blocks,

managing the Magnetic Modulation,

performing Hamming control of code areas,

re-initiating some processes if the microprocessor is watch-dog reset,

writing up-linked new software in RAM and initiating it if required by command,

commanding the mechanisms,

managing filter and cell thermal control systems,

re-synchronising the cycle after the first Daily Pulse reception.

If commanded to do so, it can also monitor maximum count values and interrupt high voltage power on the detector(s) if a selectable count rate is reached for a selectable duration. It can similarly protect the resonance cell by monitoring the bulb temperature and stem-to-bulb gradient and interrupting the stem heater if these exceed selectable maximum values.

Almost all of these activities are concentrated during the one second deadtime out of each 5 s prime counting period, in order to avoid any disturbance of the detector counting performance. It is worth noting that the DPU being mounted more than 3 m from the Sensor Unit, critical data, such as count rates, mechanism positions and temperature measurements are digitized at the Sensor Unit prior to their transmission to the DPU.

12. Power Supply Unit

The GOLF Power Supply Unit (PSU) provides galvanic isolation and converts the spacecraft input voltage range 26 to 28.3 V (27 V nominal) into five regulated output voltages, +28 V, +15.2, -15 V and ±5.4 V, which are current-limited and over voltage protected. The PSU consists of two DC/DC Converter modules which operate in cold redundancy, so that either the main or the redundant unit is powered up at a time. The spacecraft power bus is connected to the Buck converter via a so-called soft starter and input filter. This provides a regulated and current-limited voltage to the push-pull converter, which supplies the five voltage outputs obtained from five voltage regulators.

13. Integrated Instrument Tests

13.1. GOLF Model Philosophy

The GOLF instrument consists of distinct hardware components, accommodated on different parts of SOHO Payload Module: the Sensor Unit, the Power Supply Unit, the Data Processing Unit and the interconnecting harnesses. To comply with the SOHO development schedule, as well as with some special difficulties of GOLF, five separate models for GOLF have been prepared.

> The Structural Model (SM) is composed of each of the different units, being representative of physical parameters (mass, centre-of-mass, moment-of-inertia, dimensions, connector locations), mechanical interface parameters, strength and stiffness. Vibration tests were performed both at unit level and after assembly on the SOHO spacecraft SM.
>
> The GOLF Engineering Model (EM) is representative of the shape, dimensions, mounting interfaces, connector type and location. All hardware is electrically, functionally and EMC representative, for one channel only, without redundancy. Electrical/functional tests and EMC tests were performed prior to delivery as well as after integration with SOHO Payload Module.
>
> The GOLF Qualification Model (QM) is not deliverable to ESA. This model was the first to be optically and thermally representative of the instrument. It is dedicated to optical component integration, adjustment and control procedure validation, optical system overall qualification, mechanical and thermal model validation, overall calibration and associated hardware, software and procedures validation.
>
> The Flight Model (FM) and Flight Spare Model (FSM) are compliant with all agreed interfaces and have undergone a full programme of acceptance testing and verification. Either can be flown on the spacecraft. The Cleanliness Plan applies fully to both models. The FSM has been delivered and is presently mounted on the SOHO spacecraft.

13.2. Tests

Starting in the spring of 1993, many tests were performed successively on the Qualification Model (QM), the Flight Model (FM), and the Flight Spare Model (FSM), using the technical facilities at the Institut d'Astrophysique Spatiale at Orsay. Two alternative light sources have been used, a Xenon discharge lamp to simulate the solar continuum, or a tuneable dye laser to study the spectral properties of the instrument. Moreover, preliminary tests have been carried out using a Fabry-Perot in reflection between the Xenon lamp and the sensor, in order to simulate solar absorption lines.

The following is a list of the most important tests performed.

a) *Photometric test.* A direct exposure to the sun, with realistic environmental conditions, being considered impossible, two methods were used to check if the nominal counting rate ($6.\ 10^6$ counts.s^{-1} per PM tube) would be obtained in flight with the nominal entrance pupil. For the first, a calibrated detector was placed in the focal plane of a lens, intercepting the total Xenon light flux which would otherwise enter the instrument. The response of this detector was compared to the instrument counting rate (when illuminated by the same flux, assumed to be spectrally flat over the GOLF band-pass). The flight counting rate was then calculated using the known solar flux in the Na D lines, above the earth's atmosphere.

In the second method, a system composed of a GOLF filter, a lens, an attenuator and a photodiode was first placed in the beam entering the instrument, in the same conditions as for the above method. This system was then illuminated by a real solar beam (behind a heliostat at the Observatorio del Teide, Tenerife). The flight counting rate was then calculated, using the known flux ratio between the solar flux behind the GOLF filter and the solar flux in the Na D lines.

These two approaches gave consistent results, indicating that the expected mean counting rate in flight is $(5.2 \pm 0.2).10^6$ counts.s^{-1} for each PM tube.

b) *Standard white light tests.* A series of tests was carried out, illuminating the instrument with a simulated solar beam of 32 arcmin divergence, the source being the Xenon white light discharge.

c) *Laser light tests.* The absolute spectral positions of the GOLF Zeeman lines and their variations with the magnetic modulation additional field were measured, using a tuneable dye laser. For this purpose, the GOLF polarization system was de-tuned, giving a linear polarization at the resonance cell entrance, in order to transmit both Zeeman components. A typical curve obtained in these conditions can be seen in Fig. 9. A verification was performed at system level of previous subsystem-level measurements concerning the polarizer and quarter wave plate angular positions. For this purpose, the GOLF polarization system was tuned to determine a circular polarization at the resonance cell entrance, in order to use one of the Zeeman components. The laser was tuned to the wavelength corresponding to the other Zeeman shift. A scan of the quarter-wave plate around the nominal angle displayed an accurate position of the minimum of the resonant flux detected by the instrument, corresponding to the quarter-wave best angular position. The results were very slightly different from the subsystem "nominal" values, probably due to the hot cell entrance window residual birefringence.

d) *Cell thermal behaviour.* A verification of former subsystem level measurements, concerning the resonant flux variations with the cell temperature was performed. A major conclusion of the tests is that the cell stem has to be heated significantly more than predicted (by 20 to 30 C) to reach the point of maximum collected flux. This is attributed to the difference between the temperature given by the thermal sensor and the temperature of the sodium liquid-vapour interface itself: after a stabilization phase of several days, the liquid sodium is concentrated at the extremity of the stem (coldest point) while the heater coil and thermal sensors are positioned around the cylindrical part of the stem. Although a little lower than the optimal resonance, it was decided to operate at a maximum value of 195 degC for both parts of the cell, in order to maintain the materials at a safe temperature. The precise value of the stem operating temperature will be determined during flight calibrations, in order to function where the temperature derivative of the velocity is zero (some degrees lower than the optimal resonance as suggested by Boumier 1991). In this condition the instrument is the least sensitive to parasitic temperature fluctuations in the cell.

14. Instrument Commanding

The GOLF Instrument status can be modified by the use of two different types of commands:

a) About 50 so-called "Spacecraft Commands" are under the SOHO Spacecraft Flight Operation Team (FOT) control. They are forwarded to spacecraft subsystems and not directly to GOLF. They select instrument and non-operational substitution heaters ON/OFF status and GOLF main or redundant electronics. One of them also transmits to the instrument the SOHO On-Board Time (OBT). Some of them result in sending pulses to GOLF to actuate experiment mechanisms relays or to S/C LCL (Latching Current Limiters) in order to switch ON or OFF power lines.

b) Seventy two "Instrument Commands" are under GOLF Operation Team control. These 16 bits serial words are directly routed by the spacecraft to the GOLF on-board processor which executes or manages the corresponding specific functions, selecting door position, filter or resonance cell heater modes and dissipated power, magnetic modulation modes, polarisation mechanisms modes and positions, detectors modes and parameters, as well as on-board software tests modes, data dump and uploading.

Each Instrument Command is formatted as a specific "Block Command". The simplest ones use only three 16 bits words, a header (identifying GOLF, the type of command and the number of words of the block) the command identifier (sometimes referred as a mnemonic) and a check sum. These are used for ON/OFF or opening/closing type commands. Almost all others associate one "parameter" word to the command identifier, allowing the selection of a value for a given voltage, current, position, etc., this in a range extending from 256 to 65536 steps, depending on the commands. The OBT is an exception and needs three 16 bits parameters words. Finally, by making use of a different header type of command identifier, Block Commands can also be used to uplink a complete new on-board software load, to replace the one stored in the instrument PROMs. Due to ground operations constraints the uplinked data has to be packaged into blocks no larger than 0.5 Kbytes corresponding approximately to 10 seconds of commanding time.

Some GOLF commands are considered as "Critical", which means that if sent improperly, irreversible hardware damage could result. This is the case, for example, for mechanisms relays, which should not be actuated when the instrument is powered ON.

15. Operations, Data Analysis and Science Co-ordination

Operations will be carried out initially from the SOHO Experiment Operations Facility (EOF) at Goddard Space Flight Center, USA. The GOLF Electrical Ground Support Equipment (EGSE) will be used for preparation of commands, for the reception of the telemetered data and for the quick-look evaluation of instrument performance and data quality. After the initial switch-on and functional verification, some important in-flight calibration sequences will be carried out during the cruise phase of SOHO, during transit to the final orbit. Following arrival at the Lagrange L1 Point, and the commencement of routine scientific measurements, the operations activity will be moved back to Orsay, where it will be housed in the SOHO Multi-Experiment Data and Operations Centre (MEDOC).

The initial treatment of the prime data will be carried out either at Nice or Orsay under the responsibility of the GOLF Project Scientist. This will lead to a number of levels of data products, which will be archived at MEDOC, for distribution to the GOLF users.

A letter of invitation has been sent out to the community, seeking proposals for involvement in the GOLF data analysis. It is proposed, following review of the responses, to set up teams within the GOLF consortium, having responsibilities for different areas of interpretation and analysis of the data. This invitation is open to the wider community, who are encouraged to participate. In the event of an over-subscription or a large duplication, it may prove necessary to give a priority to members of the GOLF team, with a later access being provided for outside scientists. In any case, all of the GOLF data will pass eventually into the public domain, following a schedule agreed with the SOHO Science Working Team. In general, this provides for release one year following the completion of certain specified data sets.

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