GOLF: A RESONANCE SPECTROMETER FOR THE OBSERVATION OF SOLAR OSCILLATIONS

I) NUMERICAL MODEL OF THE SODIUM CELL RESPONSE

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ABSTRACT

GOLF (Global Oscillations at Low Frequencies) is an instrument to study the line-of-sight velocity of the solar photosphere, to be flown on the SOHO satellite in 1995. It uses a sodium vapour cell in resonance scattering mode, in order to measure the absolute Doppler shift of the solar sodium absorption lines. We have developed a model of the resonance cell performance. We describe here the main characteristics of the model, and report the most important results concerning the performance of the cell and its dependance on temperature.

I INTRODUCTION

During the last three decades, Helioseismology has become a powerful tool for the investigation of the detailed structure of the Sun, as it offers the best chance to test models of the star, particularly to understand the neutrino problem. The use of resonance spectrometers in astrophysics was developed independently by Brookes et al (1978) and Fossat and Roddier (1971), in order to determine the velocity of the outer solar layers by the Doppler shift measurement of an absorption line. As far as ground based instruments are concerned, this is now a very well proven technique to study solar oscillations (Claverie et al, 1979 and 1981; Grec et al, 1980 and 1983; Pallé et al, 1986 a and b; Fossat et al, 1987). However, the detection of the gravity modes (g modes), which contain information on the deep layers of the Sun, is still controversal (Gu et al, 1988; van der Raay 1990; Pallé 1991) due to the poor signal to noise ratio in that spectral range (periods from 45 minutes to infinity). The surface amplitude of the gravity modes is very small, perhaps no more than 1 mm/s, and may be hidden by the noise coming mainly from the terrestrial atmosphere and from discontinuities in the data stream. An excellent opportunity to study long-term solar variations is provided by the SOHO (SOlar and Heliospheric Observatory) spacecraft, to be launched in 1995, as in its location at the L1 Lagrangian point, it offers at least two years of continuous observations. Eventually, 3 instruments were selected to observe solar oscillations from SOHO, each being optimized for different modes of oscillations, i.e. for the study of different layers of the Sun by observation of surface phenomena. One of them, optimized for the very deep layers, is the resonance spectrometer GOLF (Global Oscillations at Low Frequencies) which is an improved space version of the ground based instruments, as we will see in the next paragraph.

At the beginning of the GOLF development (Damé et al, 1987; Damé 1988), it was decided to model the response of the instrument, and particularly the performance of the resonance cell. The goal of this work was to provide, for the instrument design team, the importance of the various instrument parameters, and to determine the specifications required to reach the scientific objectives. In this paper, we present the basic assumptions and the formalism of the model, and we concentrate

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on results constraining the temperature control, as it shows very well how complex the optimization of the instrumental configuration may be.

II DESCRIPTION OF GOLF

II.1) Scientific objectives

The primary objective of GOLF is to understand the physical structure of the interior of the Sun. This includes the variation as a function of radius of the density, the helium abundance and the rotation rate. These quantities couple through a derived solar model to the temperature structure, the nuclear reaction rate, the neutrino production rate and the structure of the convection zone. Thus, the measurements planned will help to answer a number of outstanding questions and problems regarding the interpretation of existing data. The measurement consists of a determination of the line-of-sight velocity of the photosphere, this velocity being spatially integrated over the entire solar disk, in order to select low degree modes of oscillation, i.e. the modes which penetrate very deep in the Sun. The frequency range covered by GOLF will extend from the solar cut-off frequency at around $6\ 10^{-3}$ Hz down to frequencies of the order of 10^{-7} Hz, an order of magnitude lower than the solar rotation rate. For frequencies higher than about 10^{-4} Hz, the instrument will be photon noise limited, which permits in principle a sensitivity of 1 mm/s for 20 days of continuous observations. The limit on the measurement will be however imposed by the "solar noise" level which increases exponentially as the frequency decreases (Harvey 1985; Jiménez et al, 1988). At 10^{-4} Hz, the "solar noise" level is already between 2 and 3 orders of magnitude larger than the GOLF photon noise level, and thus, for lower frequencies, the specifications on the instrument stabilities are relaxed so that the required sensitivity level remains about 2 orders of magnitude below the "solar noise". This margin is in the hope to gain in sensitivity by understanding and correcting for part of the "solar noise", particularly for the contribution of the active regions (Damé et al, 1990; Gabriel et al, 1991; Ulrich et al, 1991).

An important secondary objective of GOLF is to measure the variations of the global average of the line-of-sight magnetic field. The precision of the measurement of the mean field is expected to be about 1 mgauss, representing a considerable advance on what is currently available.

II.2) Design principle

The optical resonance technique is used to determine the Doppler wavelength shift of the solar Na D Fraunhofer lines, by comparison with an absolute standard given by a sodium vapour cell in the GOLF instrument. The two lines at 5896 Å and 5890 Å are both used, but it is easier to understand the principle if one considers, at first, only one line. The solar absorption line of half-width approximately 500 mÅ traverses a sodium vapour cell which has an intrinsic absorption line width of about 25 mÅ (see section III). Thus, a 25 mÅ slice of the solar line is absorbed and re-emitted in all directions. Part of the signal re-emitted is recorded by a photomultiplier at 90 degrees to the optic axis. By placing the cell in a longitudinal magnetic field of 4750 gauss, the absorption line is Zeeman split into two components displaced from the natural wavelength by plus and minus 100 mÅ approximately. These components, called σ, are circularly polarized in opposite directions. If the incoming solar flux is polarized circularly, using a plane polariser followed by a quarter-wave plate, it is possible to select only one component at a given time. By changing the direction of the polarisation of the incoming flux, one samples alternately in one wing and then in the other, at plus or minus 100 mÅ from the instrument rest sodium wavelength, with a cycling time for GOLF of 40 seconds. Clearly, a shift between the solar and the GOLF profiles, produced for example by a non-zero value of the line-of-sight relative velocity, will generate a difference between the intensities recorded for the two directions of polarisation, as illustrated on Figure 1. The D1 and D2 lines behave in a similar way, but with small differences in the atomic physics introducing small quantitative variations. GOLF will measure the sum of the contributions of the two lines, being unable to distinguish the two components. With I_B and I_R the intensities recorded in the blue and red wings, the velocity may be basically expressed as follows:

$$V = V_0 \frac{I_B - I_R}{I_B + I_R}$$

The velocity sensitivity V_0 is not a true constant, but varies with changes in the solar line shape and with the actual line-of-sight velocity observed. V_0 would remain constant only for a constant, linear and symmetrical solar line profile. We know from ground based observations that the value of V_0 is close to 4000 m/s, but classical resonance spectrometers have no means to evaluate the real time variation of V_0. To address this point, it was decided to impose a square-wave modulation on the magnetic field of GOLF, in order to change slightly the position of the sampling points in the solar lines. This is achieved by the commutation of a current in coils placed around the poles of the magnet, allowing a measurement of the slopes in the solar profile wings every 20 seconds. This technique, similar to the one originally used by Isaak and Jones (1988) on another kind of spectrometer, was tested with a GOLF-type instrument on the real Sun. In spite of terrestrial atmospheric limitations, a significant reduction of the noise has been obtained thanks to the magnetic modulation, in a part of the spectral range where gravity modes are expected (Boumier 1991; Boumier et al, 1991). Another interest in the determination of the slopes in the solar profiles is their observed correlation with the solar magnetic field, which suggests that it might be a good quantitative indicator of the active regions velocity noise (Damé et al, 1990).

The sodium lines being magnetically active, their intrinsic solar circular polarisation is a measure of the solar longitudinal magnetic field. By adding another quarter-wave plate at the front of GOLF, it is possible to measure the separation of the two solar sigma components, and therefore to deduce the mean value of the solar field.

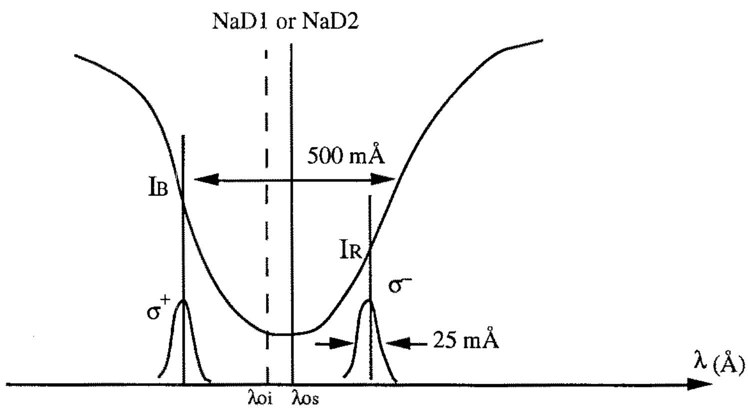
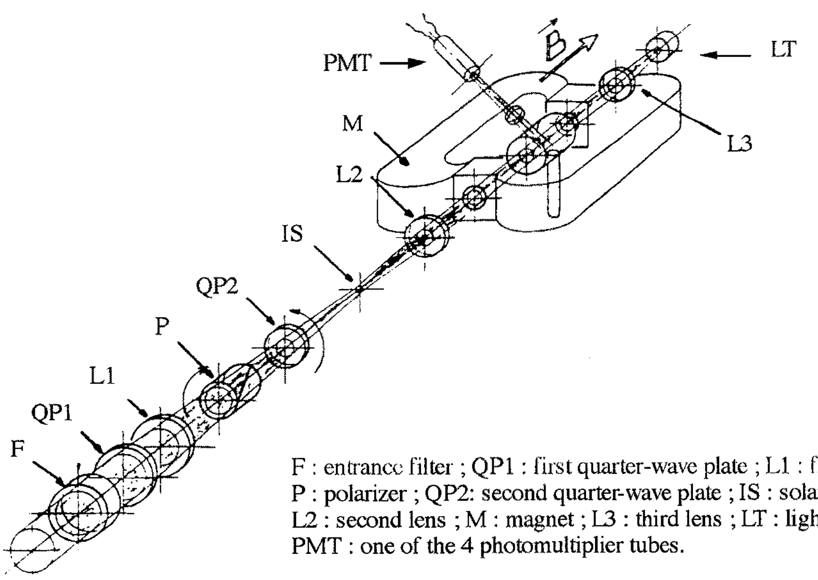


Figure 1: measurement of a Doppler shift by a classical (2 points) resonance spectrometer
λ_{oi} = sodium natural wavelength: D1: 5896 Å, D2: 5890 Å (instrument referential)
λ_{os} = solar sodium line

II.3) Overview of the instrumental configuration

Figure 2 shows an isometric view of the GOLF instrument. Briefly, a first module (F) filters the solar light to keep roughly 20 Å centered on the sodium lines. A two-lense system (L1 and L2) produces a 1° aperture beam in the sodium cell, with an entrance pupil image at the center of the cell. This optical arrangement minimizes the sensitivity of the measured signal to the position on the solar disk, and consequently the pointing of the instrument. The cell is a glass body with a stem in which is stored a droplet of sodium, and with a cylindrical head aligned with the optic axis. By heating the cell, the sodium vaporizes in the head where resonance can occur. Special attention is required to maintain the head somewhat hotter than the stem (nominaly 20° for GOLF), in order to keep the head glass clear from deposits of sodium. Two relay optics collect the re-emitted signal, at 90 degrees to the optic axis, each carrying the light to two photomultipliers (PMT). Only one of the two PMTs is operational (in photon counting mode), the other assuring a cold redundancy. To reach the 1 mm/s sensitivity on 20 days observation, the nominal total counting rate is 1.2 10^7 c/s. The cell is placed between the poles of a permanent magnet, giving a longitudinal field in the vapour of 4750 Gauss. The amplitude for the magnetic modulation is ± 100 Gauss.

The polarization system is composed of a plane polarizer (P) followed by a quarter-wave plate (QP2) and preceded by a second one (QP1). The velocity measurement is possible thanks to the change of the relative position between P and QP2, the magnetic field measurement being linked to the relative position between P and QP1. The changes in these positions (90 degrees) are assured by two mechanisms which rotate the polarizer and the plate QP2. It was decided to change one element every 5 seconds (mechanism or magnetic modulation), giving a total cycle time of 40 seconds per measurement.



F : entrance filter ; QP1 : first quarter-wave plate ; L1 : first lens ;
P : polarizer ; QP2: second quarter-wave plate ; IS : solar image ;
L2 : second lens ; M : magnet ; L3 : third lens ; LT : light trap ;
PMT : one of the 4 photomultiplier tubes.

Figure 2: isometric view of the GOLF instrument configuration

III MODEL OF THE RESONANCE CELL PERFORMANCE

To evaluate the photon flux on each photomultiplier and to assess its sensitivity to different parameters of the instrument, we model the physical processes of the radiative transfer in the sodium vapour.

III.1) Zeeman transitions and absorption profiles

The response of the cell depends on the sodium vapour properties (temperature, pressure) which determine the monochromatic absorption profiles, i.e. the probability for a photon to be absorbed by the medium. These profiles correspond to the transitions $3^2S_{1/2}$-$3^2P_{1/2}$ for D1 (5896 Å) and $3^2S_{1/2}$-$3^2P_{3/2}$ for D2 (5890Å) shown in Figure 3.

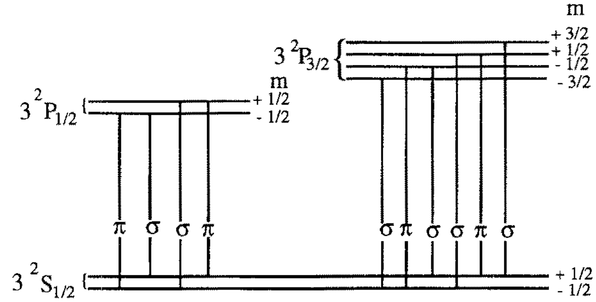


Figure 3: Zeeman diagram for sodium D lines

Since the magnetic field in the vapour is parallel to the incoming radiation (see section II.2), only the σ components can be excited, the π excitation being forbidden. Moreover only one component for D1 and two components for D2 are selected by the sense of the incoming polarization, in order to work in only one wing of the solar lines at one given time. The Lande factor (g) relative to these components is 4/3 for D1, 3/3 and 5/3 for D2. Each σ component is composed of 4 hyperfine transitions, and for the high magnetic field used (4750 Gauss), an asymptotic range is reached. This means that the Zeeman shift from the natural wavelength and the probability of the transitions follow very simple laws (Boumier 1991). Each of these hyperfine transitions has a quasi Doppler absorption profile, implying a gaussian shape with only two parameters, a width $\Delta\lambda_D$ and a maximum value k_0. The width is the same for all the profiles, being simply given by the vapour (cell head) temperature T (Mitchell and Zemansky, 1934):

$$\Delta\lambda_D = \frac{2\sqrt{2.10^3\,R\ln 2}}{c}\,\lambda_0\sqrt{\frac{T}{M}}$$

M: molecular weight (= 23), R = 8.3143 J/K/mol, c = 3 10^8 m/s.

λ_0 is relative to the center of the profile.

On the other hand, the value of k_0 (which is linked to the probability of the transitions) is constant within a σ component, and can be expressed in simple ratios of the three components: 1.5 and 0.5, respectively for the g=3/3 and g=5/3 D2 groups, relatively to D1. For a gaussian, the integral over the profile is:

$$J = \int_{\substack{\text{hyperfine}\\ \text{profile}}} k_\lambda \, d\lambda = \sqrt{\frac{\pi}{4 \ln 2}} \, k_0 \, \Delta\lambda_D \tag{1}$$

Moreover, it was shown by Mitchell and Zemansky (1934) that the integral over an absorption line is determined by the density of atoms in the vapour:

$$I = \int_{D1 \text{ or } D2} k_\nu \, d\nu = \frac{\lambda_0^2}{8\pi} \frac{g_2}{g_1} \frac{N(1 - \frac{g_1}{g_2} \frac{N'}{N})}{\tau} \tag{2}$$

ν: frequency (= c/λ)

g_2 , g_1: statistical weights of the excited and normal levels (D1: $g_2/g_1=1$; D2: $g_2/g_1=2$)

N', N: densities of atoms in the excited and normal levels

τ: lifetime of the excited level (1.6 10^{-8} s)

For our purpose, the only process responsible for the formation of excited atoms is the absorption of the light itself. The ratio N'/N is exceedingly small, of the order of 10^{-4} or less (Mitchell and Zemansky, 1934), and equation (2) may be simplified. In the case of the D1 line, equations (1) and (2) lead to:

$$k_0 = \frac{N \sqrt{\ln 2} \, \lambda_0^4}{16 \, \pi^{3/2} \, \tau \, \Delta\lambda_D \, c}$$

The only free parameters in this formula are the density and the temperature in the head of the cell, through the term $\Delta\lambda_D$. Knowing the temperatures we apply to both parts of the cell, we can deduce the density N (and therefore k_0) using the following:

law of effusion : $P/P_q = \sqrt{T/T_q} = N_q/N$

(equilibrium for which the flow of gas from the head of the cell to the stem is equal to that from the stem to the head).

law of ideal gases : $N_q = \alpha P_q / T_q$

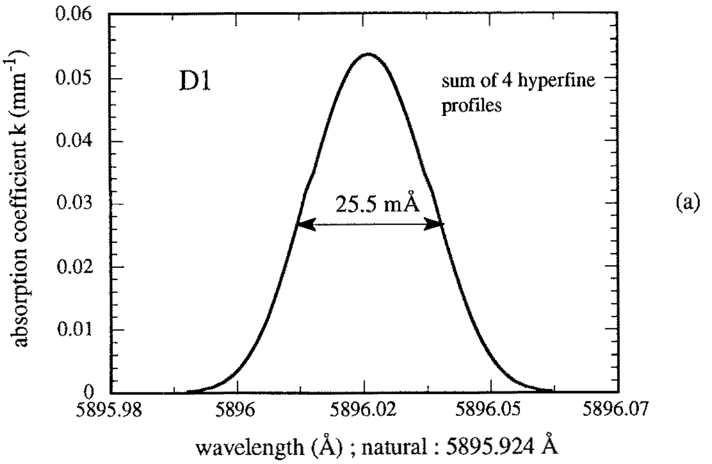
vapour pressure relation : $\log_{10} P_q = \frac{-0.05223 \, a}{T_q} + b$

$\alpha = 0.966 \; 10^{19}$

a = 103300; b = 7.553 for sodium

The index q refers to density, pressure and temperature of the stem of the cell, their units being : cm^{-3}, mmHg and °K.

Figure 4 shows the absorption profiles calculated for temperatures equal to 150°C (stem) and 170°C (head), which are typical values for ground based instruments.



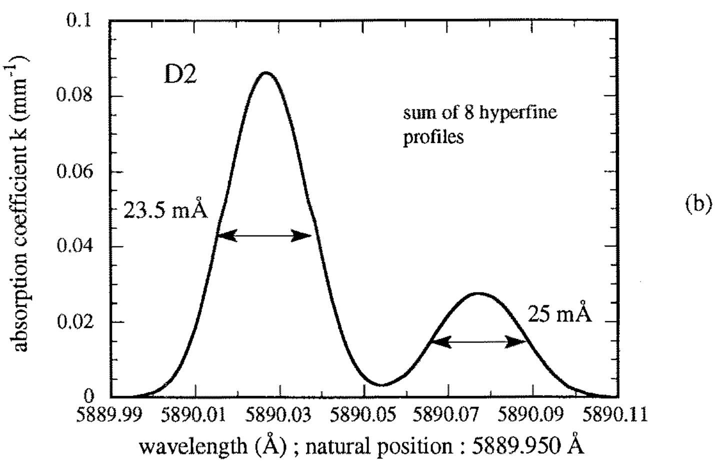


Figure 4: calculated absorption profiles for one polarization of the sigma components of the D lines, (a) D1, (b) D2.
Temperatures: 150°C for the stem, 170°C for the head of the cell.
The remaining components are symmetric relatively to the natural wavelengths.

III.2) Assumptions of the model

• The geometry of the cell is illustrated in Figure 5. The optical design leads to an incoming light beam being made up of cylinders, each corresponding to a point on the Sun. All the cylinders converge to the pupil image at the center of the cell, their axis depending on the observed position on the solar disk. The divergence being rather small (1°), we consider in our model a single cylinder, parallel to the optic axis and carrying the whole of the solar flux. We are very confident of the value of this assumption for the present application of the model, but it should be reconsidered in the case of more complex studies requiring a more realistic optical geometry, as for example the pointing sensitivity of the instrument or an active region effect on the signal.

• Next, we consider only the primary resonance, i.e. the collected photons resulting from only one absorption - re-emission process. We know from Mitchell and Zemansky (1934) that secondary emission is globally negligeable for vapour pressures below 10^{-4} mmHg, which is the case here, as we will see. Wavelengths close to the maximum absorption will suffer some secondary resonance, resulting in a change in the collected photons of a few percent in the central part of the profiles, which does not affect the global performances of the cell.

• We consider that an absorption leads to re-emission at the same wavelength, i.e. the Doppler redistribution effect is neglected. We consider also that the absorption - re-emission process is isotropic (we know from Lory-Chanin, 1965, that the anisotropy is less than a few percent).

• Finally, we consider that the magnetic field is perfectly homogeneous in the vapour. Measurement of the spatial distribution of the field carried out by our colleagues J.M. Robillot and R. Bocchia (private communication), could allow us to compute the field inhomogeneities if necessary.

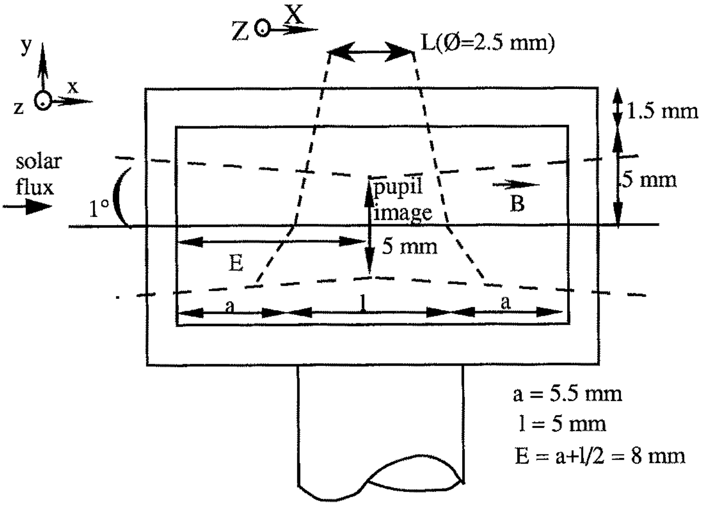


Figure 5: optical geometry of the cell. L: lens which collects the resonantly scattered light. The intersection of the dashed lines (entrance beam and field of view of the lens L) defines the volume where the primary resonance is seen. This volume will be further referred to as the useful volume.

III.3) Formalism of the model

For a given wavelength, the primary intensity absorbed by an elementary volume dV may be expressed as follows:

$$d^3I_\lambda = I_{0\lambda}\, dy\, dz\, \exp(- k_\lambda\, (x + E))\, k_\lambda\, dx$$

$I_{0\lambda}$: incoming intensity per surface unit at the entrance window of the cell

k_λ: monochromatic absorption coefficient

E: distance cell entrance window to y axis (ie to the cell center)

The coordinates x, y, z are defined Figure 5, the origin being at the center of the pupil image (cell center)

The absorption does not depend on y or z since the solar beam is taken parallel to the x axis, but the collected re-emission does depend on it, and the intensity collected by an elementary surface dXdZ of the output lens (L) may be writen as follows:

$$d^5I_\lambda = (I_{0\lambda}\exp(-k_\lambda(x+E))\,k_\lambda\,dxdydz)\,\left(\frac{\exp(-k_\lambda d_a)\cos\theta}{4\,\pi\,d_b^2}\,dX\,dZ\right)$$

where the parameters relative to the absorption on the way out and to the solid angle of the element dXdZ are defined in Figure 6:

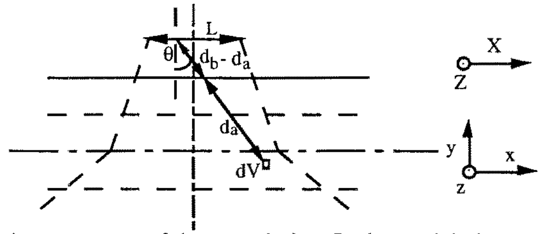


Figure 6: geometric parameters of the re-emission. In the model, the entrance beam is assumed to be a single cylinder (parallel dashed lines).

The ratio $d^5I_\lambda/I_{0\lambda}$ integrated over the output lens and over the volume seen by this lens (useful volume) is called $T_{ce\lambda}$ the monochromatic efficiency of the cell. It is calculated from the cell temperatures (head and stem) which give the profiles of the absorption coefficient k_λ. Knowing the spectral dependance of $I_{0\lambda}$ and the transmissions of the other sub-systems, it is then possible to estimate the counting rates of the instrument (white light) as well as their sensitivity to either instrumental or signal fluctuations. This model was synthesized in a Fortran program on a Vax computer (Boumier 1991).

III.4) Results

III.4.1) Monochromatic response of the cell

In the nominal geometric and magnetic conditions of GOLF, we concentrated on the influence of the cell temperatures, which was expected to be critical. In the following, we assume a constant nominal gradient head-stem of 20°C, and we mostly refer to the stem temperature since it determines the vapour pressure and has a large influence on the signal.

Figures 7 and 8 show the absorption (k_λ) and the efficiency ($T_{ce\lambda}$) profiles obtained for temperatures of the stem varying from 140°C to 180°C (steps of 10°C). The $T_{ce\lambda}$ curves exhibit a saturation effect of the same nature as the self reversal phenomenon in a hot arc (Mitchell and Zemansky 1934). The efficiency of the cell has a maximum value which corresponds to an optimal optical thickness in the vapour. More precisely, it corresponds to the best equilibrium between the light absorbed then re-emitted in the volume seen by the lens L (volume referred to as the useful volume, defined in Figure 5), and the absorption of the light in the other parts of the cell (absorption before the useful volume and on the way to the lens L). There also exists an optimal value of the absorption coefficient (k_{opt}) from which the efficiency $T_{ce\lambda}$ decreases with k_λ, due to the too high opacity. It is very easy to show that in the case of one monochromatic ray, the value of k_{opt} corresponds to an optical depth (τ) of unity considering the total path of the ray in the vapour. In our geometry, we are not too far from this simple case, since the model gives a value close to unity (τ=1.015) for a ray travelling on a mean trajectory from the entrance to the output windows via the center of the cell. Note that the maximum efficiency of the cell, independent of the wavelength, is about 0.076%.

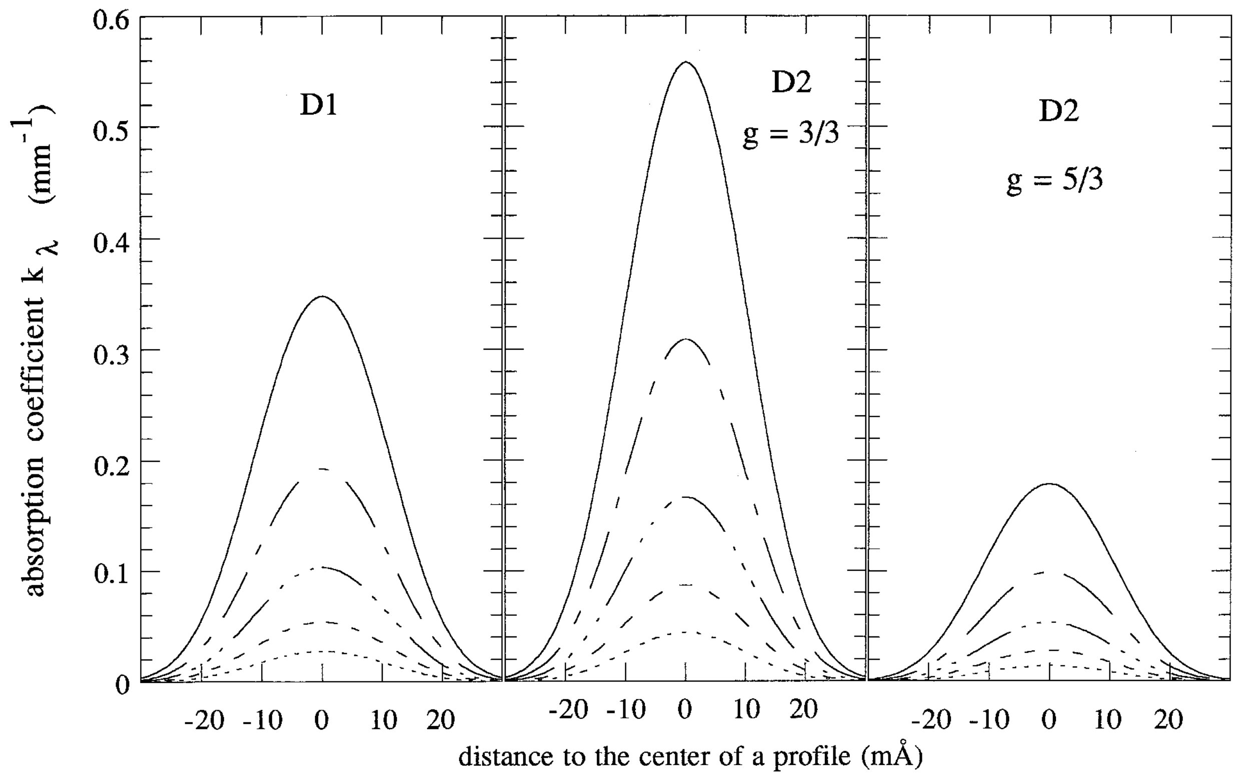


Figure 7 : absorption profiles in the GOLF cell for different stem temperatures:

----- : 140°C, _ _ _ : 150°C, ___ _ _ _ ___ : 160°C, ___ _ ___ : 170°C, ______ : 180°C

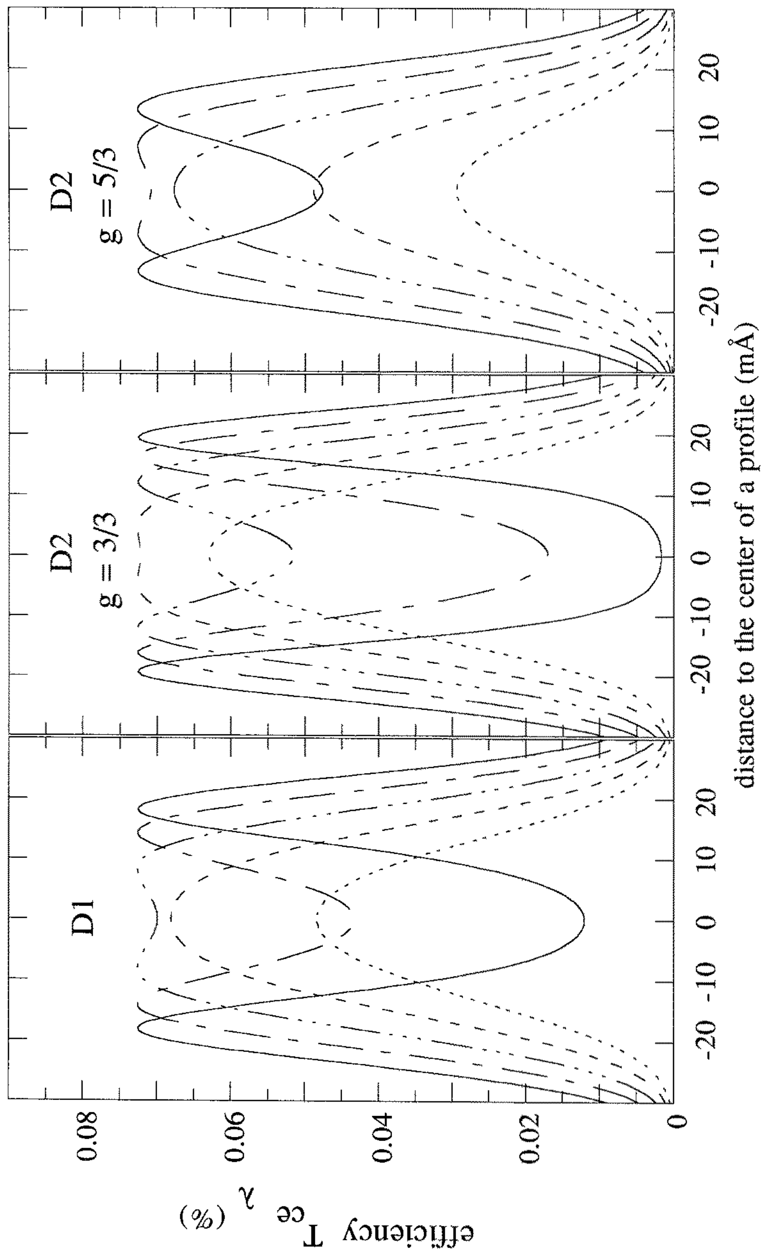


Figure 8 : monochromatic efficiency of the GOLF cell for different stem temperatures :

----- : 140°C, _ _ _ : 150°C, _____ : 160°C, _ _ _ _ _ : 170°C, _____ : 180°C

III.4.2) White light response of the cell

To get the signal measured by GOLF, we have to sum up the monochromatic intensity over the wavelength range where the process is efficient. Theoretically, the absorption profiles are infinite, and we have tested numerically that an integration over 65 mÅ for each component is enough to reach the desired precision, this interval contributing about 99.75% of the total flux.

a) Measured intensities

Due to the saturation effect in the vapour, an optimal temperature exists for which the counting rate of the detected photons is a maximum. This temperature corresponds to the best integrated product $T_{ce\lambda}$ $I_{0\lambda}$ and depends also on the spectral distribution of the solar input intensity. First, this distribution varies during the year, as the radial orbital velocity of the satellite varies, and second, it varies with the instrument cycle, following the measurements in the blue or in the red wings of the solar lines. In the model, we have used two gaussian forms whose parameters were given by Petitdidier (1969), to estimate the input solar flux. The values of the width at mid-depth are 450 mÅ for D1 and 650 mÅ for D2, the center of the lines being respectively at 5.4% and 6.3% of the continuum. The values obtained are summarized in Table 1 for 3 times of the year, in terms of the temperature of the stem and the resultant maximum counting rates. The stem temperature is close to 167.5°C (sodium pressure close to 2 10^{-5} mmHg), with a yearly excursion of about 0.2° and a maximum asymmetry in April (when the analysis windows are the most asymmetric) also of 0.2°. Note that the uncertainty on these values estimated from the uncertainties on the relative position of the analysis wavelengths and the line profiles is about 10% (flux) and 0.3°. The precision on the absolute values displayed in the table is only significant in relative terms. Figure 9 shows the thermal evolution of the counting rates for the worst time of the year, April.

		December	April	September
blue wings	T (°C)	167.47	167.39	167.55
	F (10^6 c/s)	14.3	16.0	12.8
red wings	T (°C)	167.67	167.71	167.58
	F (10^6 c/s)	11.0	9.75	12.4

Table 1: maximum flux collected by a GOLF relay optic, and stem temperatures, for 3 times in the year.

The model shows that for a temperature of about 167.55°C, the mean counting rate when we consider both wings is nearly constant over the year, being 1.25 10^7 c/s, which is fully compatible with the counting rate required to give the desired photon noise limit (1.2 10^7 c/s). From Figure 8 we can see that the monochromatic response profiles of the cell are saturated when the white light collected is maximum. This reflects simply that when the core of a profile begins to saturate, the loss of efficiency is compensated by the gain in the wings over a large range of temperature. Note that the global efficiency of the cell corresponding to these profiles is 0.042% (when calculated over 65 mÅ for each component), and that the width of the profiles is bewteen 35 mÅ and 45 mÅ at half maximum. Note also that the flux contribution of D2 is only 15% more than that of D1, the sampling points being deeper in D2 (relative to the solar continuum).

The model confirms that the head temperature has a very small effect on the signal, compared to the stem. The effect of the gradient between the two parts is not significant either, leading to a change in the temperature for the maximum counting at a rate of 0.03 (deg/deg).

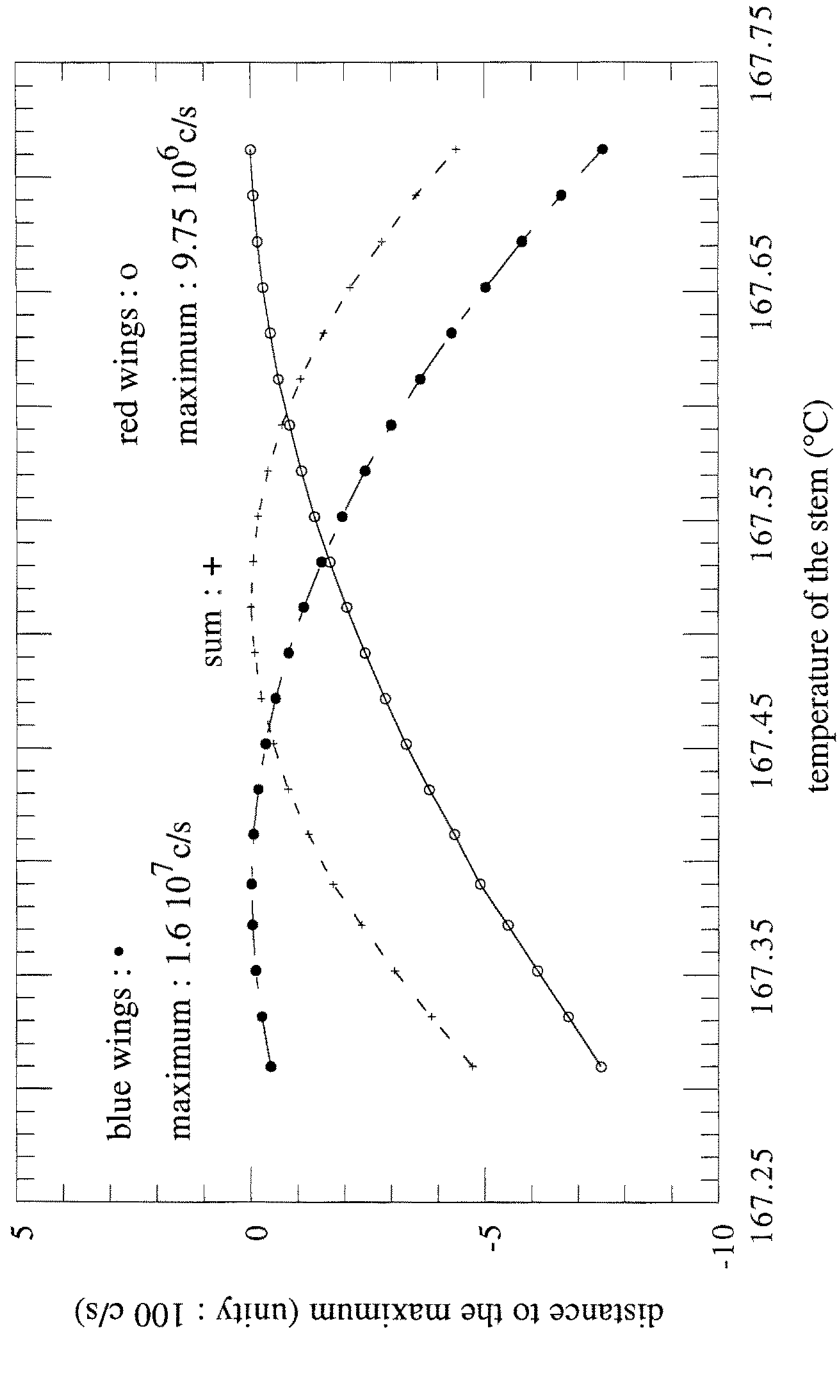


Figure 9 : thermal evolution of the GOLF counting rates for April, around the maximum.

b) Deduced velocities

The objective of GOLF is to determine solar velocities from the measured intensities, and thus it is essential to analyse the instrumental sensitivity in terms of velocity and not only in terms of flux. A basic relation gives the velocity:

$$V = V_0 \frac{I_B - I_R}{I_B + I_R}$$

where V_0 is the coefficient introduced in paragraph II, I_B and I_R being the intensities detected in the blue and red solar wings. Rigorously, the measured intensities contain a background contribution coming mainly from dark counts of the photomultipliers and from scattering in the walls of the cell. We should also write $I_{Br} + b_B$ and $I_{Rr} + b_R$ rather than I_B and I_R, in which the index r stands for resonated light, b_R and b_B being the background contributions in the two configurations. The mean values of b_B and b_R are generaly equal and the relation becomes:

$$V = V_0 \frac{I_{Br} - I_{Rr}}{I_{Br} + I_{Rr} + 2b}$$

Formaly, the minimal thermal dependance may be investigated writing:

$$\left(\frac{dV}{dT} = 0\right) \Leftrightarrow \left(\left(\frac{1}{(I_{Br} + b)} \frac{dI_{Br}}{dT} - \frac{1}{(I_{Rr} + b)} \frac{dI_{Rr}}{dT}\right) = 0 \right) \Leftrightarrow \left(\frac{dLog(I_{Br} + b)}{dT} = \frac{dLog(I_{Rr} + b)}{dT} \right)$$

We supposed here that the background counting is not temperature dependent, which is realistic to first order, especially when we deal with the stem which is the most influential on the signal. A quick look at the above equation suggests that the root corresponds to a behavior with the temperature similar for both intensities. We saw that the temperature maximizing the counting rates is somewhat different for each wing, and also around this temperature the intensities vary in opposite ways with the temperature (cf. Figure 9). This means that optimizing the counting rates does not correspond to optimizing the temperature independence of the velocity measurement. Figure 10 shows the results we obtained with our model for April, and for several levels of background countings. We plotted only the ratio deduced from the intensities, the velocity being obtained after a multiplication by V_0.

Figure 10 shows that the lower the background counting (i.e. the better the signal to noise ratio), the lower is the temperature of the stem for which the velocity signal is the least sensitive to thermal fluctuations (horizontal slope, dashed line). When the noise tends to infinity, the temperature tends to the point where the difference I_{Br}-I_{Rr} has a zero derivative, which we found to be of the order of only 0.5° lower than the temperature maximizing the sum of the intensities. On the other hand, when the noise tends to zero, the temperature has no well-defined limit, the velocity curve becoming very flat. The Figure 10 shows also that the better the signal to noise ratio, the flatter is the curve around the optimal point, which is of course a satisfactory result.

Throughout the year, the zero slope point of these curves moves a little (some tenths of a degree) and the more symmetrical the two measurement points in the solar lines, the flatter are the curves. The constraints on the temperature stability of GOLF must also be determined from the April curves, knowing approximatly the signal to noise ratio of the instrument. This ratio, defined by I_{Br}+I_{Rr} /2b and referred to as the resonance ratio, is expected to be at least 50, which means a background counting lower than 2 10^5 c/s. This would lead to a working value of 155°C maximum on the stem, and would also imply a loss of 15% in the flux, which would not increase too greatly the photon noise.

As far as temperature requirements are concerned, we have to consider two kinds of fluctuations depending on their frequencies. First, in the case of white noise, the effect of the spectral density of

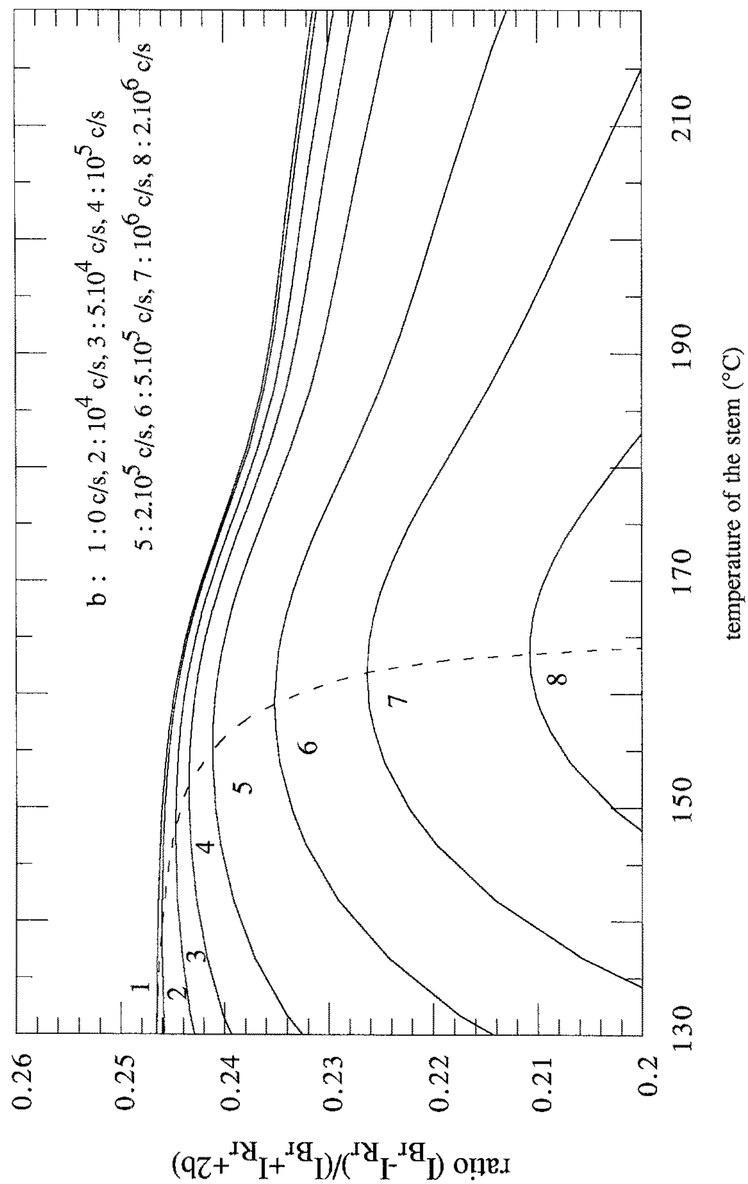


Figure 10: evolution of the measured ratio for various background countings (April)

the temperature fluctuations must be lower than the effect of photon noise, or in velocity terms: 1.66 $(m/s)^2/Hz$. Second, in the extreme case of a pure sinusoidal variation, the induced sinusoidal apparent velocity must have an amplitude lower than 1 mm/s, at least in the g-mode spectral range (expected periods from one to several hours). Following these criteria, and using a value of 4000 m/s for the coefficient V_0, we calculated that the standard error of a one hour integration series must be kept under 1°C, and that the amplitude of a sinusoidal variation must be kept under 0.05°C.

IV CONCLUSIONS

The model we developed for the transfer of the photons in the GOLF sodium cell allowed us to quantify the influence of instrumental parameters on the velocity measurement. We can also constrain the nominal temperature working point and the required stability as a function of the operational conditions (orbital velocity changes). The stability we deduced is a priori feasible, but experimental tests have to be performed, especially to ensure that the low frequency thermal noise is low enough. This implies a series of measurements carried out continuously over at least several days, and under very stable vacuum conditions. In any case, the definitive optimal stem temperature depends on other detailed instrumental conditions, and will be optimized finally in flight when testing the velocity measurement, before commencing the definitive two years observation period.

Some resonance tests were realised recently at the Institut d'Astrophysique Spatiale, in Orsay, with the help of a dye stabilized laser; the experimental results and their comparison with the model predictions will be reported in a future paper.

It should be noted also that apart from direct applications for GOLF, the model may be useful to the interpretation of other ground based solar data obtained with a resonance spectrometer (Boumier 1991).

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