GOLF-NG spectrometer, a space prototype for studying the deep solar dynamics

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Abstract

The GOLF-NG (Global Oscillations at Low Frequency New Generation) instrument is an instrument devoted to the space search of solar gravity and acoustic modes, and may be chromospheric modes. This instrument, successor of GOLF/SoHO will contribute to improve our knowledge of the dynamics of the solar radiative zone. It is a 15 points resonant scattering spectrometer, working on the D1 sodium line. The ground prototype is under construction to validate the hard points and will join the Teide Observatory, at Tenerife in 2006 to analyse how to separate the effects of magnetic turbulence on the line from the solar oscillations. We are prepared to put a space version of this instrument including a capability of identification of the modes, in orbit during the next decade. We hope to insert this search in the ILWS program. This instrument represents in combining observations with SDO and PICARD, a key to improve our knowledge of the solar core, in determining its rotation and magnetic field, through precise mode splitting measurements. The magnetic field of the radiative zone is fundamental for progressing on the solar activity sources, a clue for the long-term solar-earth relationship.

1. Historical context

Helioseismic measurements have been continuously improved since more than 25 years. After observations on one site, networks (BiSON, IRIS and GONG) and nowadays space instruments (GOLF, MDI, VIRGO aboard SoHO) have revealed important characteristics of the deep plasma. Traditionally, the American teams have concentrated their efforts on Doppler imagers while European teams have dedicated their efforts to global oscillations not only for the Sun but also for other stars.

The present proposal of a new instrument in the ILWS program corresponds to this second category. SoHO satellite has been successful to demonstrate the power of the Doppler velocity technique to get very precise information down to the solar core. Different absorption lines have been studied to extract the Doppler velocity. We extend with GOLF-NG our expertise on the sodium line obtained with IRIS ground network and GOLF instrument aboard the SoHO satellite in order to reach extremely tiny signals (down to 0.1mm/s) as are the gravity mode velocities at the solar surface. We need to decrease by at least a factor 10 the effect of the solar granulation which appears as the first source of noise at frequencies below 1mHz where stand the gravity modes. We also limit by an other factor 10 the instrumental noise to detect better modes around 1 mHz and above 4.5 mHz . We hope to improve our knowledge of the upper atmosphere and of the chromospheric region.

2. Scientific status and scientific goals

SoHO has been rich in discoveries. One major advance is certainly to be able to understand and observe the different actors which produce the solar activity. We are convinced nowadays that it is not only a surface effect. We are more and more conscious that the solar interior plays a crucial role, so we need to introduce magnetic field in the structural stellar equations. For doing this tremendous improvement, we must accumulate observations. By chance, SoHO has opened this avenue with the Doppler resonant spectrometer, which stays a very promising technique for the near future.

In the first period of SoHO observations, most of the highlights have been concentrated on the convection zone and on the transition with the radiative zone, called “the tachocline” without which the solar dynamo cannot be understood (Dikpati et al., 2001). Today, we cannot imagine understanding long trend magnetic evolution without a good insight of the internal dynamics of the whole sun, including the deeper layers probed by global oscillations (Bertello et al. 2000, Garcia et al. 2001, 2004). The dynamics of the radiative zone is more difficult to reach than the dynamics of the convective zone because the acoustic modes are principally sensitive to the outer layers, but the instruments GOLF and MDI have extracted the low frequency acoustic modes which are not influenced by surface effects. This advance leads today to an unprecedented accuracy on the sound speed profile in the solar core (Turck-Chièze et al. 2001a, Couvidat et al. 2003a) and on the rotation profile in the radiative zone, down to 0.2 $R_\odot$ (Couvidat et al. 2003b). Such progress gives already important constraints for modelling. It is due to the very low instrumental noise of GOLF added to long and continuous observations. The rigid rotation between 0.4 to 0.7 $R_\odot$ has probably a magnetic origin. The presence of magnetic field in the radiative zone blocks the diffusion of the shear tachocline layer in the radiative zone (Rüdiger & Kitchatinov, 1997, Gough &McIntyre 1998, MacGregor & Charbonneau 1999. Consequently it may play some role in the solar cycle (s). In parallel, observations for practically two solar cycles of the global oscillation show the effect of the surface solar time variabilities on the modes (Jimenez-Reyes et al., 2003, 2004a,b).

So new questions encourage new investigations (Turck-Chièze et al. 2005b) and a real insight of the radiative dynamics down to the core needs the non ambiguous detection of gravity modes. GOLF/SoHO has already improved the capability of detection by a factor 40, with a limit of detection of these modes of 2±1 mm/s (Gabriel et al. 2002, Turck-Chièze et al., 2004a). Gravity-mode candidates, identified with more than 98% confidence level after 8 years of visibility of not being pure noise (Turck-Chieze et al. 2004a,b) could be compatible with an increase of the rotation in the core and with a different rotation axis in this region than in the rest of the Sun. A relic of the solar system of the formation period is not excluded and suggests the presence of a strong magnetic field located in the central region which may be observed through hyperfine structure. It is on this scientific basis that GOLFNG has been designed, to contribute to answer to the following questions:

- What is the rotation profile in the solar core?
- Is there a differential rotation near the limit of the nuclear core? (see Eff-Darwich 2004)
- Can we estimate the order of magnitude of the magnetic field in the radiative zone?
- Is there some variability of the rotation or of the magnetic field in the radiative zone, along the solar cycle or on a larger period of time?
- Could we put in evidence other solar periodicities than the 22 year cycle?
- Can we put more constraints on the atmosphere up to 600 km/s and on the chromosphere.

These questions are fundamental questions, they are connected to the determination of the transport of energy inside the Sun (or stars), which is presently insufficiently known. The present solar models must be improved to reproduce all the present seismic and neutrino observations, and encourage physics beyond the standard framework of stellar evolution (Turck-Chièze et al. 2004c, 2005a). For that, we need to understand the angular momentum transport in the radiative region where energy is emitted (Mathis and Zahn 2004) and we need to understand its variability.

These objectives are reachable if we improve the best techniques used in SoHO and get simultaneous observations as for GOLF and MDI, a useful help for the detection of very low signals.

GOLF-NG hopes to detect without ambiguity gravity modes thanks to long observations (several years), it will follow the annual variability of low-order low-degree acoustic modes in detecting them quickly, will put constraints on the high atmosphere and chromosphere by the evolution of the sodium line which extends on 500-600 km above the photosphere. A more detailed review of the present results and scientific motivation can be found, for example, in COSPAR proceedings of the Solar-Earth relationship session (Turck-Chièze, 2004d) and in the roadmap for Europe dedicated to the future of the discipline (Turck-Chièze, 2005b).

3. The instrumental concept

A good insight on the dynamics of the radiative zone supposes a precise determination of the frequencies of the modes at low frequencies. A mode frequency accuracy of some nHz below 1mHz allows to extract properly the rotational splittings, with an accuracy of several %. This is very important for establishing any differential rotation profile in the radiative zone. It supposes also a correct extraction of very low velocities (of the order or below 1mm/s). To reach this second objective, one needs a very low instrumental noise and a reduction of the solar granulation or chromospheric noise.

The principle of GOLF-NG instrument is to measure the Doppler shift of the D1 sodium Fraunhöfer solar line by a comparison with an absolute standard given by the sodium vapour cell, the heart of the experiment. The absorption line provided by the vapour cell is splitted in its Zeeman components by means of a static longitudinal magnetic field whose intensity varies along the longitudinal axis. By changing the circular polarization of the incoming flux, it is possible to select 8 points on either the right or left wings of the line included in both cases the center of the line (see figure 1).

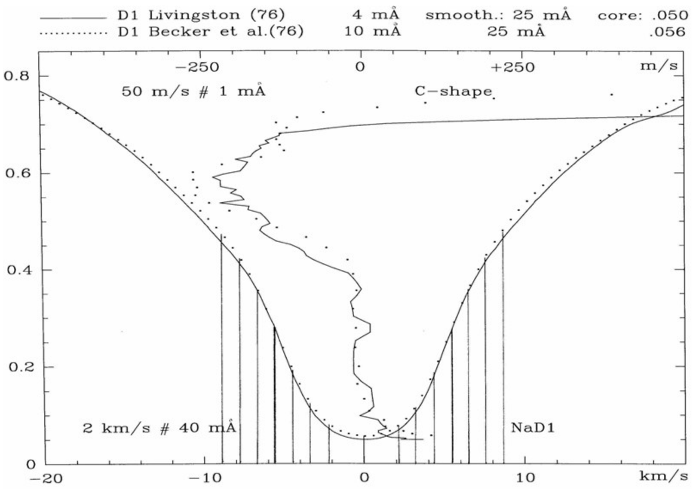

Figure 1: D1 sodium line as measured by Livingston or Becker in 1976. Superimposed is observed C-shape behaviour which is due to the solar granulation in the upper part of the line and which is a chromospheric signature at the bottom of the line, the varying behaviour of this line corresponds to about 250 m/s (upper abscissa). This line extends up to 500-600 km above the photosphere. The 15 channels of GOLF-NG are drawn on the line, it allows an excursion of ± 10 km/s (lower abscissa).

The concept of a 15 points resonant spectrometer has been presented for the first time in Turck-Chièze et al., (2001b). It is an extension of the GOLF spectrometer (Gabriel et al. 1995) and of the 5 points spectrometer developed at Bordeaux for looking to the flow dynamics. Solar oscillations will be extracted from the bottom of the line to 50% of the continuum. Due to these 15 sampling points, the line is carefully determined and its magnetic effect deformation or palpitations will be followed in time. Espagnet et al. (1995) have shown that chromospheric dynamics dominates at an altitude of 500 km, while photospheric dynamics and granulation is the main contributor at lower altitude. Playing with these different sources of noise is one important progress of the present instrument in comparison with the present observations to disentangle the solar mode signals from solar noise. Doing so, it should be easier to extract the faint residual Doppler velocity signals induced by gravity modes. We have demonstrated with the 4 points GOLF instrument, exploring about 2 km/s that we can gain on signal/noise in playing with the signal at different heights or sides of the line (Garcia et al. 2004). On GOLF-NG, about ± 10 km/s will be covered (see figure 1), and we hope to gain at least a factor 10 to explore velocity signal as low as 0.1 mm/s as recommended by theoretical estimates of these modes.

The small periodic signals are in fact lost in an equivalent velocity noise of about 1m/s and can be found through its coherence with time (in contrast with the non coherent noise) in a long duration observation, using the frequency analysis of the signal. The original measurement is a stochastic velocity signal of about 1 km/s including the displacement of the satellite around the Sun and the gravitational contribution. Figure 2 shows the power spectrum of the GOLF instrument. The two improvements that we consider here are the lower solar noise and the lower instrumental noise.

The concept of this instrument should help to understand the sources of the solar noise which are also good indicators of the atmosphere. The high frequency part of the spectrum will be devoted to the search of chromospheric modes. Moreover a simultaneous measurement of the continuum will help to disentangle intensity from velocity measurements. The expected instrumental sensitivity is of the order of 10^{-7} to reach large range gravity mode detection, it is an order of magnitude better than in the GOLF instrument. To reach this goal, some key-issues must be checked through laboratory tests, it is the main reason to build a prototype and test different detectors.

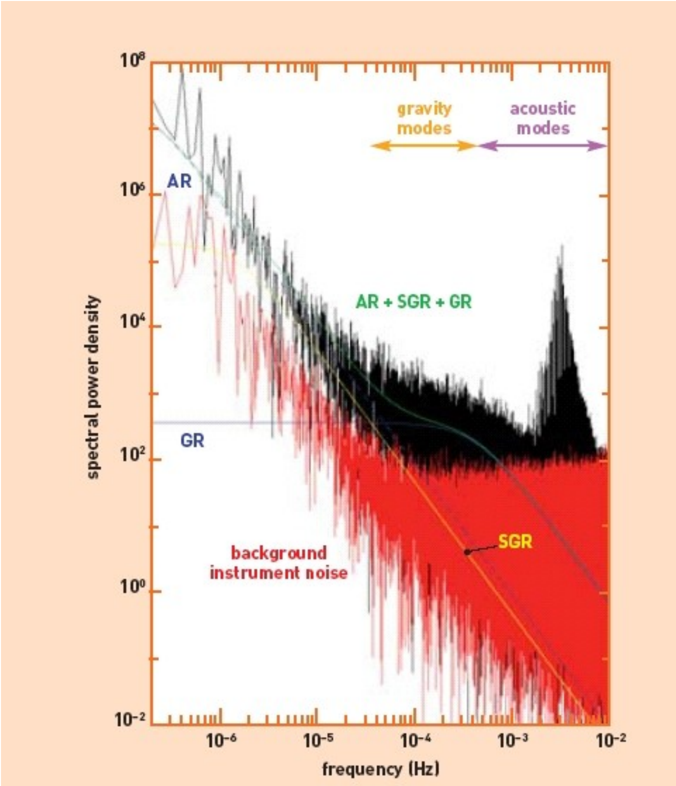

Figure 2: Solar power spectrum density obtained by the GOLF instrument after two years of observations (Turck-Chièze et al. 2004a). The solar granulation noise dominates the region of gravity modes below 0.5 mHz. The instrumental noise, dominated by statistical noise (in red or grey), was small at the beginning of the mission. GOLF-NG will reduce both noises by a factor 10.

4. The instrument description

The principle of the instrument is summarized on Figure 3 and described here:

- The solar light passes through a wide 500 Å band pass filter which provides an UV and infrared protection and arrives on a first lens L1.
- A first magnet selector chooses between sun or white light for laboratory tests.
- A multimode optical fibre of 40 cm guarantees the homogeneity of the sunlight and removes any incident polarisation.
- The optical system (L2 +L3) produces a rather parallel beam along the cell
- The second magnet selector allows the selection of the narrow filters: filter 5896 Å for the scientific case, filter 5891 Å centered on the continuum for checking the scattering beam in the cell (optional filter during flight, it may follow the time evolution of the cell without changing the cell temperature)
- The narrow filter at 5896 Å isolates a 5 Å band centred on the Na D1 line, It contains a large range of the continuum + the NaD1 line.
- The splitter cube separated the beam in two parts. One, (dominated in fact by the continuum) is directly sent to the detector box. This added information allows us to disentangle the intensity variation of the line from the velocity variation and to measure every 5s the ratio signal/continuum.

- The other one solar is circularly polarised right or left by *a crystal liquid polarizer* + the quarter-wave plate before traversing the sodium vapour cell. Doing so, one selects the σ+ or σ- Zeeman components. Thereby, at the level, we select blue (left) or red (right) wings.

- The cell is placed inside a static varying permanent magnet. Its field topology guarantees a practically linear variation of the magnetic field between 0 to 12 kG. The resonant light scattered from the vapour cell maintained at a temperature around 200°C is finally extracted by 8 outputs along the cell. The 8 points correspond to values: 0, 2, 3, 4, 5, 6, 7, 8 kG. The sodium cell is equivalent to a very narrow band pass filter of 30 m Å (the intrinsic absorption line).

So the line is carefully determined from the bottom up to 50% of the continuum.

- Four optical fibres bring the light flux to the detectors for each of these points. That means a total of 32-1 (for mechanical reason near the stem) outputs.
- The mean required counting rates of the detectors are 10^8 photons/s with a dynamics of 10 according to the sampling position along the line, that means 2.5 10^7 photons/s/detector as four outputs are placed around the cell for each extraction position.

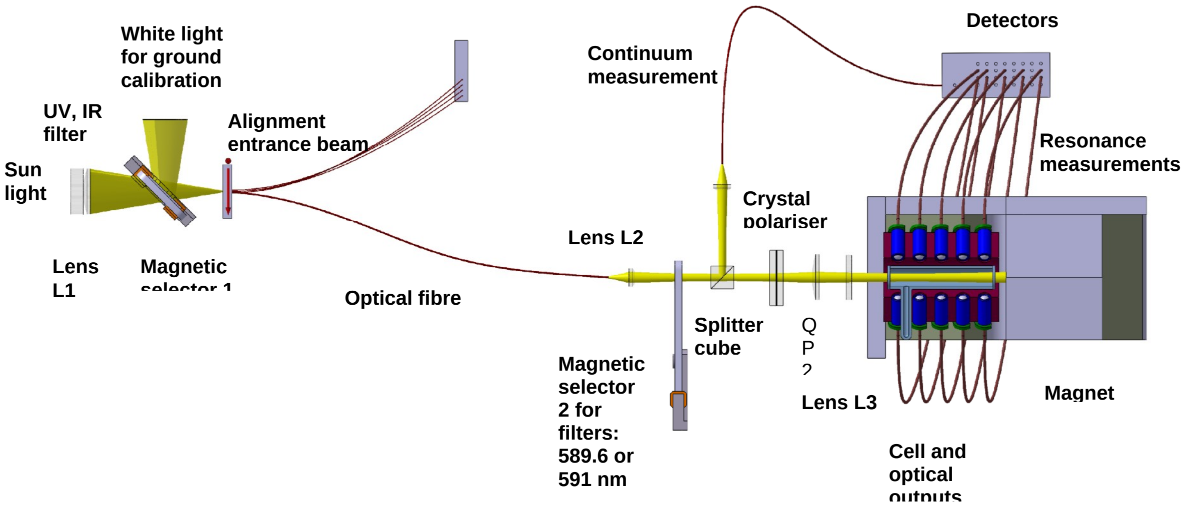

Figure 3: Principle of the resonant spectrometer prototype GOLF-NG.

4. The present status

The needed performances of GOLF-NG are difficult to reach. It is why we are building a prototype to study all the hard points. This instrument will demonstrate the capability to get the expected improvements. Therefore, this solution guarantees a gain of time for the space phase A. It guarantees also a low cost as different solutions will be studied in advance. This prototype is under construction in our laboratories. It is an international French-Spanish collaboration (PI: S. Turck-Chièze, Project Manager: PH Carton, Instrument Project manager: JM Robillot, Scientific Performances Manager: R. A. Garcia, Spanish supervisor and Site Manager: P. Palle). This prototype is financially supported by CEA and CNES for the French part and IAC and Space Spanish Agency for the Spanish part. The preparation of this prototype takes benefit of the Europe expertise on networks and space instruments aboard SoHO. This collaboration will extend hopefully to other countries (Turck-Chièze et al. 2005b).

The built prototype has improved performances in comparison with the instruments presently in the ground networks. It will join the Tenerife site in 2006 where sodium line studies could be pursued. Nevertheless the signal/noise ratio performances at low frequencies need space to be established, One may note that the excursion along the line, during one day on earth is of the same order than the excursion of the 8 points: about 0.5 km/s instead only 1 or 2 km/s for the space conditions along the orbit in the case of GOLF every 6 months.

The prototype should solve the following problems (see figure 4 showing subsystems):

(1) get a magnet (not too heavy) which guarantees a linear variation of the magnetic field on a small volume to be able to determine equidistant points along the cell. The magnet has been built by TE2M industry (like the GOLF magnet). It is a NdFeB magnet with polar elements in Fe-Co with 50% of Co and a saturated induction of 24.5 kG. The measured magnetic field along the cell is nominal.
(2) get a well thermally equipped cell containing sodium. Its length is 6 cm. This element must be thermally stable in order to get a good and regular resonant factor. To study this important instrumental piece, a mechanical and thermal simulation has been done, then two subsystems studies have been performed: an optical study including all the different optical elements: filters, lens, and polarizer, and a thermal study including vacuum in the magnet to respect space conditions (magnet at 20-25°C and cell at 200°C with a stem at 175°C), thermal heaters and temperature sensors at 0.01°C. The phase studies are practically finished, they have demonstrated mechanical and thermal solutions to get the expected performances, we are now checking these performances in laboratory.
(3) limit the number of motors in the design for a long use of the space instrument. This point has encouraged two innovative studies:

- a magnetic selector which allows to have a secure position and another one, it is useful for the choice of the filters, it may be used for entrance polarisation if one needs.
- a liquid crystal polarizer to avoid weight excess and mechanical problems. One changes the circular polarisation of the solar light every 5 s. For this important improvement of the GOLF-NG, we use a development done by the Spanish group of IAC for the project IMAX aboard the balloon SUNRISE, the performances of the polarizer seem well adapted for our instrument.

- get suited performant detectors. The performances we need are extremely difficult to reach: very high counting rates during several years, + very low detector and electronic noises, small volume and uniformed performance from one output to the other because we compare neighbour channels. The GOLF instrument was using Hamamatsu photon counting photomultipliers but these detectors have too low quantum efficiency and a rather high dead time, moreover, the performances decrease with time due to the photocathode ageing. As we would like to count 4 times more by detector, and have 31 detectors instead 2, we are studying some other solutions. We have analysed the performances of a matrix of 32 photodiodes S6494-64, provided by Hamamatsu, at relatively low temperature (6°C). The difficulty is to guarantee that the intrinsic noises (electronic + detector) are fractions of the statistical noise, and that the detection will keep good performances for one solar cycle. Another study is under consideration, using EEV CCD at very low temperature.

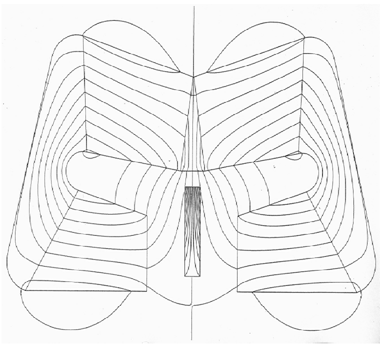
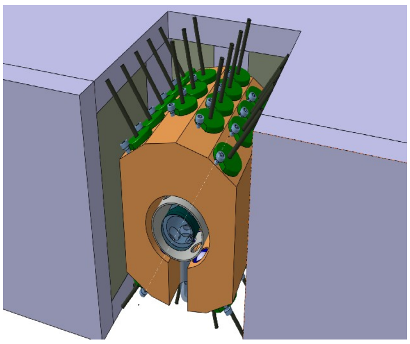


Figure 4: Some subsystems of the GOLF-NG instrument already mounted in the laboratory: the magnetic lines of the magnet and the location of the cell (left) the magnet and the cell inside with the 31 outputs (middle), the cell design equipped with thermal heaters (right).

6. The space strategy

GOLF-NG represents the third generation of instrument which measures a Doppler velocity variability on the sodium line. It is dedicated to the detection of very low signal in space mainly thanks to the reduction of the solar noise. The sodium line allows this progress because it is a broad line with a not too abrupt profile, it can support Zeeman splitting at different heights measured through a quasi linear permanent varying magnet. In the present design, GOLF-NG will measure only low degree modes (typically ℓ = 0, 1, 2, maybe 3 or 4), this is not sufficient to identify the modes and describe the complete radiative zone dynamics. For the space version, other improvements will be added, several masks at the entrance to allow degree detection up to ℓ = 5 and the identification of the modes. One does not exclude also to measure global magnetic field as it has been the case in the GOLF design.

It will be extremely judicious to launch this instrument during observations done by other space instruments to maximize the scientific return. Such instrument couples to HMI will take advantage of the large range of accessible degrees of HMI and of the solar noise reduction of GOLF-NG. Altogether, we will measure deviations from equal splittings and put constraints on internal magnetic field for degrees from 0 to 5. The orbit of HMI and its design has not led to real progress in the radiative region of the Sun, if it observes alone. The present instrument will be also a precious companion of PICARD which will benefit of the enhancement of the signal at the limb without any action to reduce the solar noise. Continuity with SoHO effort is also important so the best strategy will be to launch such instrument as soon as possible, on a microsatellite or as part of a payload at the L1 Lagrange point for a long-term observation.

GOLF-NG needs continuous observation on a sun-synchronous orbit, the PICARD orbit is appropriate and the SoHO orbit is perfect. The following characteristics of the space instrument are under reexamination:

- dimension : 0.8 *0.3 * 0.3 m3
- mass between 30-50 kg (magnet 15 kg)
- power 60 W (this point must be verified)
- telemetry 30kbits/s
- same pointing accuracy than PICARD or HMI.

This instrument has been proposed as part of the SOLARIS project payload in the F2/F3 call of ESA in 1998. The selection of SOLAR ORBITER has not offered yet to Europe the opportunity to pursue helioseismic investigation of the deep interior. It is very important to pursue helioseismic measurements in Europe during the next solar cycle because gravity modes are key in the understanding of the magnetism of the whole Sun and there is a strong need to improve our observation in the region containing more than 98% of the solar mass (see the roadmap for ESA described in Turck-Chièze et al. 2005).

7. Acknowledgement

This project is inspired by European efforts of the last twenty years. We would like to thank our scientist colleagues and engineers who have contributed to BiSON, IRIS and GOLF, We would like also to thank space agencies of our different countries, together with CEA for financial and dedicated contracts.

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