The GOLF-NG prototype and the Solar European Perspective for Cosmic Vision 2015-2025

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Abstract. The progress on the dynamics of the radiative zone by global Doppler velocity measurements aboard SoHO (GOLF+ MDI) and with ground networks (BiSON and GONG) opens a new perspective for solar and stellar physics. It is why we prepare a new generation of solar resonant spectrometer. The objectives of the GOLF-NG instrument and its present status are described. We have demonstrated this year that most of the technical challenges have been successfully faced and the next steps are mentioned. We then recall the scientific questions that might be solved with the next generation of instruments in construction in different european laboratories to reach a complete 3D vision of our star from the core to the corona. Two formation flying missions DynaMICCS and HIRISE have been proposed to ESA in the framework of the 2015-2025 Cosmic Vision perspective to contribute to solve these questions. A strategy of measurements must be found for the next decade.

1. Introduction
The SoHO satellite [1] was the first milestone of the programme ESA Horizon 2000. Launched in December 1995 it appears today like a real success. Effectively, this mission cannot be only considered as a unique opportunity to understand how the Sun is working. SoHO has also largely enriched this transition period between a classical view of stars and a more dynamical and complex view that we begin to build. This success is partly due to the fact that helioseismology has revealed the properties of million of modes not yet reachable for any other type of stars, this important fact allows a new, strong and large scientific return with some problems solved and totally new emerging questions. COROT and KEPLER will deliver a smaller number of modes but the stellar evolution community will benefit from the diversity of the observed stars and from the experience accumulated along the 12 years of GOLF/SoHO observation. So it is
clear that seismology will continue during the next two decades to be determinant in astronomy
and that our view of the Sun will largely evolve. The successors of MDI will be SDO in United
States (launch in 2009) and Solar Orbiter in Europe (launch in 2014). But these missions have
not been designed to probe the solar deep interior.

After more than a solar cycle of continuous observation with the SoHO satellite, it is time
to critically review the results obtained by the european GOLF instrument to enlighten the
advantages and the limitations of such an helioseismic instrument in order to deduce the
directions of improvement. In the first section, we recall the characteristics of this instrument
and its results. The second section recalls the objectives of the GOLF-NG successor, the present
status will be described together with the next steps. The last section will be devoted to the
questions that we need to solve for a complete view of the Sun in the broader context of the
ESA Cosmic Vision perspective.

2. Probing the solar core with the GOLF instrument

It is a french spanish collaboration who has built the GOLF/SoHO instrument and has analyzed
its observations. The name of this instrument, Global Oscillation at Low Frequency, was given
because it has been designed to measure low degree low frequency modes, that means the modes
which penetrate deeply in the radiative zone down to the core. This instrument measures the
variability of the Doppler velocity by the resonant spectrometer technique on the three sodium
D1, D2a and D2b lines [2] . This method has been invented by [3] and used previously in IRIS
and BiSON ground networks. The GOLF instrument filters the solar wavelengths corresponding
to the mentioned lines. The corresponding photons, left or right polarised, are absorbed by the
atoms of a hot sodium cell and reemitted in a narrow band shifted thanks to the presence
of a permanent magnet which produces a Zeeman effect. The Doppler velocity is theoretically
deduced from the comparison of the left and right circularly polarized photons. Its time variation
is measured every 10 s. The Fourier transform of the two first weeks of the velocity signal is shown
on Figure 1. Despite the malfunctioning of the quarter wave plate motor, this measurement has
been done on one wing (left or right depending on the period of observation) along the 12 years
of the SoHO mission [4] thanks to the presence of a small modulation of the magnetic field.

Figure 1 shows the superiority of GOLF compared to the VIRGO observation. On the first
two years of observations, one has noticed up to a factor 10 to 30 gain in the Fourier transform
at low frequency in the range of the gravity modes located between 10 to 400 \( \mu \)Hz. This is
due to two factors. First the GOLF velocity is extracted in the solar atmosphere at an height
of 300 to 500 km and this region is less turbulent than the photosphere. Secondly, the GOLF
instrument has been specifically designed to detect very low amplitude signal at low frequency
(down to 1 mm/s which was supposing to be the amplitude of the first gravity modes). This
performance is obtained by using two photomultipliers which count typically 1.2 \( \times \)10^7 photons/s
associated to a very stable electronics. Consequently the noise instrument was slightly below
the statistical noise already choosen as low as possible in relative value.

The GOLF instrument has been successful in solving the different questions for which it has
been designed. There are three domains where it has given very positive answers:

- the description of the solar core and the prediction of the emitted neutrinos thanks to the
detection of previously unknown low degree low frequency acoustic modes. In reaching
radial modes below 1.8 mHz down to 0.5 mHz and also non radial degree 1 and 2 [5,6,7]
in the same range, we have been able to determine very precisely the sound speed down to
6% of the solar radius [8]. The importance of detecting these modes is due to the fact that
they are not polluted by the variability of the external layers along the solar cycle. This
point was important to properly constrain the microphysics of the solar core and to predict
without ambiguity the solar neutrino fluxes [10] (see also Turck-Chièze, Nghiem & Mathis,
this volume).
Figure 1. Comparaison of the power spectrum of the two instruments aboard SoHO which look to the Sun globally. GOLF uses the Doppler velocity technique and VIRGO observes the variability of the luminosity in different wavelengths. It is clearly visible after 20 days of observations that the Fourier transform of the signal favours largely the first technique at low frequency where acoustic modes are not perturbed by the solar cycle and where the gravity modes are waited (below 0.4 mHz). From [9]

- a better understanding of the solar variability with the solar cycle. The GOLF instrument has detected for the first time practically all the low degree acoustic modes (orders from 7 up to 40) and has followed the varying ones along a complete solar cycle [11,7,12]. This important fact allows us to study the Sun like a star for which only these modes are available. The understanding of the properties of these modes and their evolution along the Hale 11 year solar cycle [13] allows us to put some constraint on the local and varying subsurface magnetic field [14].
- and the capability to detect gravity modes. The GOLF instrument has been specifically designed to detect some gravity modes. Nevertheless the publication of [15] just after the SoHO launch on their probably very low surface amplitude coupled to the malfunctioning of the polarizer motors have put some doubts about the capability of GOLF to detect any signal. Nevertheless, intensive studies have been dedicated to this field since the first years and a search strategy (among others) has been defined: first to look for multiplets (it improves the capability of detection of very low signal) in the region above 150 µHz where the velocities are the greatest and then to examine the low frequency region if the first research was successful. In both cases, signals have been detected with more than 90 then 98% [16,17,18] and even at low frequency at more than 99.7% [19] (see also García et al., in this volume).

Consequently, we may be confident that GOLF has detected some solar gravity mode signatures. Nevertheless the information on the central rotation stays poor [20]. It is nevertheless interesting to note that the two analyses are only compatible if the core of the Sun turns quickly and if
the axis of the core rotation is oblique in comparison with the rotation axis of the rest of the radiative zone. Of course due to the very low amplitude of the signals, this conclusion needs to be confirmed by improved observations. Presently, the analysis of the other instruments has shown the superiority of the GOLF instrument for the gravity mode detection but one component of the GOLF gravity mode candidate seems to appear continuously in the VIRGO data.

All the GOLF objectives have been reached, unfortunately the knowledge of g-modes is not yet sufficient to properly describe the dynamics of the solar core and its consequences on the deep magnetic field. So it is necessary to try to go further. The french PICARD mission will try to exploit the potential increase of the gravity mode sensitivity at the solar limb. A factor 4 or 5 enhancement has been measured with MDI in the range of acoustic modes but it is not evident that such effect would be sufficient to detect gravity modes with a photometric instrument so, it is natural to push in parallel the velocity measurements to their limits. It is why we are presently developing a new instrument that derives from our expertise of the SoHO results.

3. The GOLF-NG prototype

The GOLF-NG (Global Oscillation at Low Frequency New Generation) instrument measures, like GOLF, the global Doppler velocity variations. It is developed in CEA/Spain in collaboration with IAC/Spain. It results from the 30-year expertise on resonant scattering spectrometers used on the ground (IRIS and BISON networks) and in space (GOLF/SoHO).

The characteristics of this instrument are described in [21]. The objectives are to lower the detection threshold by a factor 5 to 10 to detect a range of gravity modes. The improvements are the following:

- measure the velocity at eight positions in the solar atmosphere between the photosphere and the chromosphere to reduce the effect of the solar granulation in the range of g-modes (see figure 2). Effectively the observed patterns of the solar noise differ and consequently we hope to improve the signal over noise in the gravity mode range of frequencies,
- increase the number of photons detected to lower the relative instrumental noise. For this purpose we multiply by 2 the number of detectors per height in the atmosphere: 4 detectors instead 2, and use of a detector with a high quantum efficiency (60-75 % instead 5%). Altogether we get 32 outputs from the cell, in fact 31 due to the presence of the cell stem, a necessity to get a cold thermal point,
- the gravity mode spectrum is very dense so the identification of the observed pattern components will be easier in putting some masks at the entrance of the instrument. Detection and identification of degrees up to 5 for gravity modes is an objective for the coming decade and might allow a precise determination of the rotation profile in the whole solar core,
- Some configuration of the polarizers could be used to give access to the measurement of the mean magnetic field and its time evolution, like in the nominal operation of GOLF (only used during the first month).

This instrument measures the Doppler shift of the D1 sodium Fraunhofer solar line by a comparison with an absolute standard given by the sodium vapour cell, the heart of the instrument. A small portion of the line is measured by the resonant photons which escape from the vapour cell. It is split into its Zeeman components by means of a longitudinal magnetic field, the strength of which varies linearly along its axis to explore different heights of the atmosphere. One selects 8 points on the right wing of the line or 8 points on the left wing, including one fixed point at the center of the line (supposing no shift of the line) by changing the circular polarization of the incoming flux thanks to a liquid crystal polariser to avoid a motor for the polarization change. The instrument must measure a sufficient high flux to reduce the instrumental noise.
or (and) to allow consecutive measurements of portions of the Sun. A second liquid crystal polariser could be installed to get a spectrum of the mean magnetic field.

![Figure 2](image)

**Figure 2.** a) Solar resonant spectrometer GOLFNG principle: alternative measurement of 8 points along the blue wing and of 8 points along the red wing. b) View of the new cell equipped with the heaters and prepared with its 31 outputs (8*4-1). c) The same cell inside an insert piece which ensures the high temperature of the cell and the low temperature of the magnet.

During the last 3 years, the different sub systems have been realized and a lot of time has been devoted to solve the technical problems that we need to face to measure 8 points along the line [22], such an instrument is extremely complex to perform. It supposes: (1) a permanent magnet of small size varying linearly between 0-12 kG, (2) good thermal conditions along the cell heated around 170 °C inside a magnet at 25 °C, (3) a long cell filled with pure sodium without opacity of the glass, (4) a good thermal equilibrium of the cell despite the 31 outputs (8mm*60 mm) with a temperature homogeneity within 1 °C, (5) no important loss of counting rate between the cell and the detector, (6) a high performance of the final detectors to be sensitive only to the statistical noise.

Most of the hard points have been solved and the complete instrument has been used during laboratory tests in space conditions, that means in vacuum. Different tests have been performed with a led at the sodium wavelength. Then some measurement has been done during several minutes with the Sun. In March 2007, the feasibility of the instrument has been demonstrated and we have observed the 31 resonances with a relatively good efficiency and a low level of
parasite light for the two polarities. The resulting reduction of the solar granulation noise might be checked rather soon in Tenerife.

Three hard points stay important to solve before having a scientific useful instrument:
- a cell with a high resistance to the sodium attack (in GOLF we were using a galeniet glass),
- a specific detector which counts up to \(2.5 \times 10^7\) photons/s per channel at mid height of the line continuously with a specific noise slightly smaller than the statistical one. It is not the case today in using some photodiode arrays of Hamamatsu delivered with an integrated electronic at 6 °. We will probably use a CCD detector at low temperature with a specific electronic.
- some masks at the entrance of the instrument in order to take advantage of the amplification of the signal at the limb or to identify without ambiguity the observed pattern.

4. The Solar ESA Perspective for Cosmic Vision 2015-2025
The success of SoHO invites the european community to pursue its investigation of the Sun as a whole because the Sun is the only star which can deliver a complete information on all the processes in action and also because SoHO has revealed strong interaction between Sun and Earth which needs a continuous and permanent observation of our star. SDO and Solar Orbiter will partly answer to this objective but some questions will not receive any definitive answer. It is why we have proposed a new perspective for a 3D picture of the Sun from the core to the corona, first during the Cosmic Vision meeting at ESA [23] secondly through the DynaMICCS formation flying mission as an answer to the call for mission at the horizon 2015-2025 [24]. The new questions which will not be solved by the already engaged missions are:

- What is the dynamical influence of the central internal rotation and magnetic field on the external activity?
- Which processes are at the origin of the solid body rotation in part of the radiative zone? What is the respective role of the agents responsible for the redistribution of the angular momentum: rotation, gravity waves, magnetic field? What are the consequences of a rapidly rotating core? Is there another dynamo in the core?
- What is the topology, strength and influence of a fossil field? How the progressive internal waves modify the overall internal dynamics? Could we determine the nature of the nonlinear interactions between the convective dynamo and the fossil field if it exists?
- How can we check the presence of large scale flows, their amplitude and their mixing properties in the radiative zone? Could we put some constraints on the presence of magnetohydrodynamical instabilities in the radiative zone and their coupling with the convection zone.

These questions show the need to understand the solar magnetism in its different forms. The mission called DynaMICCS for Dynamics and Magnetism from the Core to the Corona of the Sun would like to reveal the different sources of the solar cyclic variability. It is built to reveal any source of variability, including the potential ones coming from the deep interior and must be the successor of SDO and Solar Orbiter to maintain a permanent observation of our star. To reach this objective, crucial regions of the Sun must be scrutinized simultaneously: (1) the previously unexplored dynamics of the inner core thanks to gravity modes, (2) the time evolution of the radiative/convective zone interface layer thanks to a large number of acoustic modes, (3) the emergence of the flows from the photosphere to the chromosphere layers thanks to the study of different lines and different heights in the atmosphere. (4) the evolution of the low corona never explored continuously thanks to a permanent eclipse, (5) the total and spectral irradiance and (6) in-situ measurements of plasma/energetic particles/magnetic fields of the solar wind.

A formation flying mission can deliver simultaneously all these global quantities no other known mission has already provided. This information is important for understanding Space Weather and Space Climate and for advancing stellar and fundamental physics (neutrino
magnetic moment and mass, atomic physics, gravitational moments ...). To fully achieve these objectives, the DynaMICCS mission must provide uninterrupted observations of the Sun for about a decade. This mission uses an original concept studied by Thalès-Alenia Space in the framework of the CNES call for formation flying missions. It consists in obtaining an external occultation of the solar light by putting a discal occulter supporting the main spacecraft located in front of the second spacecraft.

![Diagram of DynaMICCS mission](image)

**Figure 3.** The formation flying DynaMICCS mission formed by 2 Proteus platforms: the occulter spacecraft equipped with 3 helioseismic instruments + 3 irradiance other instruments, and the second one equipped with coronograph, imagers and solar wind instruments.

The two spacecrafts reuse a LEO platform of the mini sat class, e.g. PROTEUS type which defines a distance of 150 m between the two satellites. The first one carries the helioseismic and irradiance instruments and the formation flying technologies (see figure 3). The latter spacecraft of the same type carries a visible and infrared coronagraph for a unique observation of the solar corona down to less than 1.1 solar radius and instrumentation for the study of the solar wind. This mission must guarantee long (one 11-year solar cycle) and continuous observations (duty cycles higher than 94 %) of signals that can be very weak (the gravity mode detection supposes the measurement of velocity smaller than 1 mm/s). This assumes no interruption in observation and very stable thermal conditions. The preferred orbit therefore is the L1 orbit, which fits these requirements very well and is also an attractive environment for the spacecrafts due to its low radiation and low perturbation (solar pressure) environment. This mission is summarized in [24]. From this study has emerged just before the deadline of the ESA call, another proposal called HIRISE for High Resolution Imager and Solar Explorer which puts also the accent on the ultrahigh spatial, spectral and temporal resolution of the solar atmosphere in using an Herschel platform for the occulter spacecraft, it allows more weight capabilities and an increased data flow sent from the Lagrangian L1 point. The consequent increased distance of 300 m between
the two spacecrafts improves also the study of the low corona [25]. We are sure that the main objectives of DynaMICCS and HIRISE can coexist on the same mission if we invite partners to contribute to this very impressive mission.

So we have finally presented to ESA in October 2007 the formation flying solar perspective with the reuse of european platforms mission at relatively low cost, putting together all the instruments necessary for the 3D vision of the Sun with global and local information covering most of the questions of the whole european solar community and announcing China like a strong partner for coronography studies. The complementarity of DynaMICCS and HIRISE leads to the most promising and exciting mission that we ever think for the solar exploration. It will definitively establish the complete 3D vision of the Sun and its real impact on the earth environment. Such a mission could not been selected for the first class M mission due to the launch of Solar Orbiter in 2014 just before the beginning of the Cosmic Vision period but we hope that such mission, supported by a very large european, american, indian and chinese collaboration will be realized as soon as possible.

In the meantime, we need to find a way to continue to progress on the dynamics of the deep core during the coming decade. So we propose to develop a scientific ground instrument with the space characteristics in weight, size and power and to observe in Tenerife and Dome C to reach a long continuous observation of at least 1 month at the same sight to be able to qualify the performances and improve them. The best periods for these observations will be the years 2009-2011 where PICARD and SDO will be operational.

Acknowledgments
The scientific GOLF team acknowledges the engineers who have realized this instrument, C. Renaud who provides the raw data to the consortium and JM Robillot for its stimulation to build a multi-channel instrument like GOLF-NG. The DynaMICCS/HIRISE proposals have been prepared by scientists from at least 30 institutes coming mainly from Europe but also from India, United States and China with the support of the industrial THALES ALENIA SPACE.

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