The history of solar g-mode detection: contribution of Alan Gabriel

T. Appourchaux

Institut d'Astrophysique Spatiale, Orsay

The 3 ages of g-mode detection

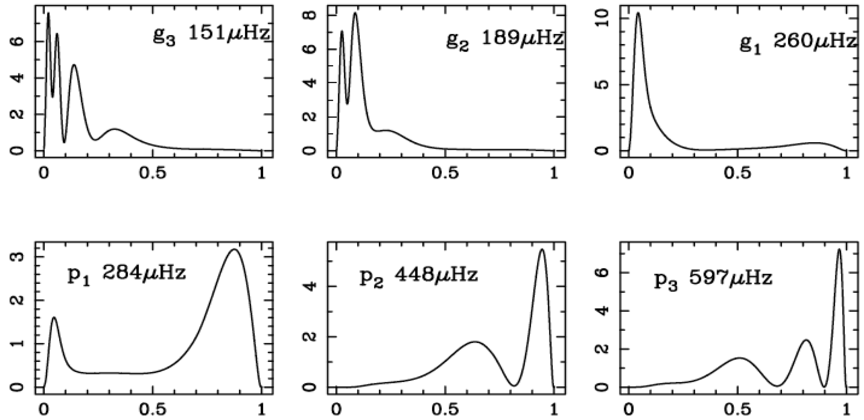
- 1962-1976: Foundation
- 1976-1995: Foundation and Empire
- 1995-2010: Second Foundation

g-mode characteristics

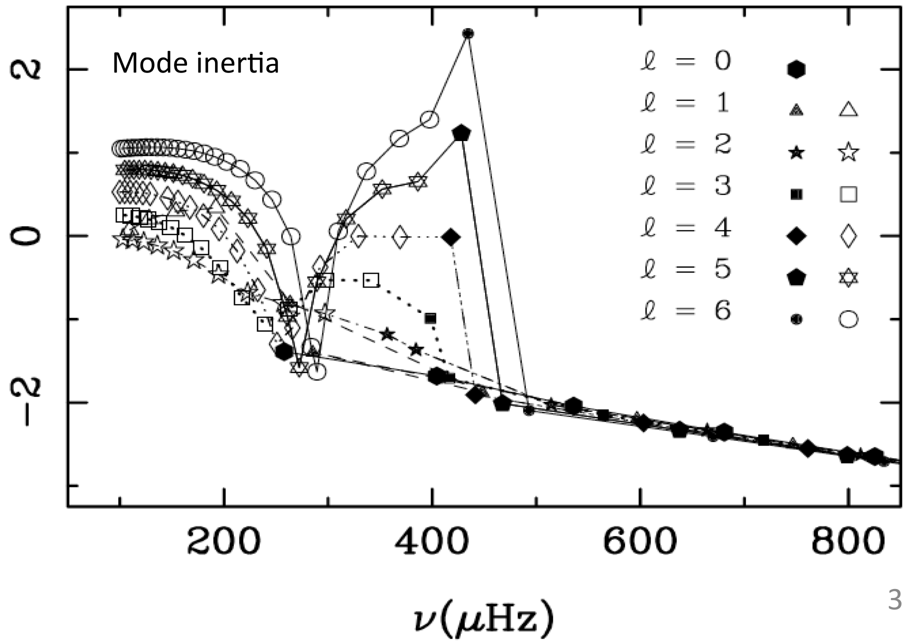
- Frequencies:
  - Below 500 μHz
  - Mixed modes
  - High n: asymptotic periods (Vandakurov, 1967)

$$P_{n,l} \sim \overline{P}_{n,l} = \frac{P_0}{L}\left(n + l/2 - \frac{1}{4} + \vartheta\right)$$

- Amplitudes: 10^{-4} to 1 $cm.s^{-1}$
- Lifetimes: 1-10 Myears !



Provost et al (2000)



The 160-min oscillation

Nature Vol. 259 January 15 1976 87

articles

Severny et al (1976)

Observations of solar pulsations

A. B. Severny, V. A. Kotov & T. T. Tsap

Crimean Astrophysical Observatory, p/o Nauchny, Crimea, 334413 USSR

We have modified our solar magnetograph to measure velocities at the solar surface, rather than magnetic fields. Using this apparatus, we have observed fluctuations of period 2 h 40 min, which are remarkably stable. The inter-

calibration signal $\delta_{\parallel}(O)$, with the aid of the plane-parallel glass plate of the velocity compensator (which is 'off' for calibrations, and 'on' for recording $\Delta\lambda_v$), and β is the ratio of the intensity at the central part of the solar image to that at the rim, $\beta = I_c/I_r \approx \frac{1}{3}$ in our case (intensities measured by photo-multipliers). The calibration is made for a standard shift $\Delta\lambda_c = \pm 0.031$ Å of the 5,123.7 Å line, which corresponds to velocity of $\pm 1,815$ m s^{-1}, so that $\delta_{\parallel}$ equals $\delta_{\parallel}(O)$ when $\Delta\lambda_v = 2.34 \times \Delta\lambda_c$—for a speed of 4,238 m s^{-1}.

Accuracy of experiment

The accuracy of the method is limited by turbulence in the spectrograph and electronic noise, and can be determined from the accuracy of magnetic field measurements[2]: where mean field strengths of 1 gauss were measured, corresponding to $\simeq 2.2$ m s^{-1}. By increasing the data accumulation time to 15 min, we can achieve $\simeq 1.0$ m s^{-1}, corresponding to a Doppler shift $\Delta\lambda_v \simeq 10^{-5}$ Å.

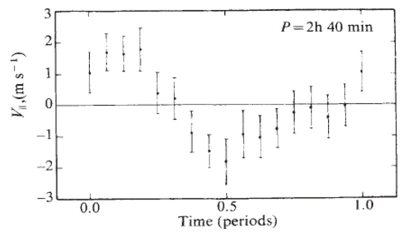


Fig. 3 Result of the superposed epoch analysis with 2 h 40 min period. Error bars represent r.m.s. deviations of individual measurements for each 10-min block of the data.

by Eddington[11] and Rosseland[12], where the best agreement with observations can be reached for almost homogeneous spheres at $\gamma = 5/3$. We agree with Rosseland's conclusion that 'a thorough discussion of the problem on a new basis seems to be called for.'

We thank Dr D. Gough for helpful discussion of the paper before publication.

Note added in proof: Preliminary results of observations for 16 d in 1975 show the same periodicity in the mean magnetic field of the Sun, with an amplitude of 0.01 gauss.

Received June 2; accepted October 23, 1975.

9 days of data

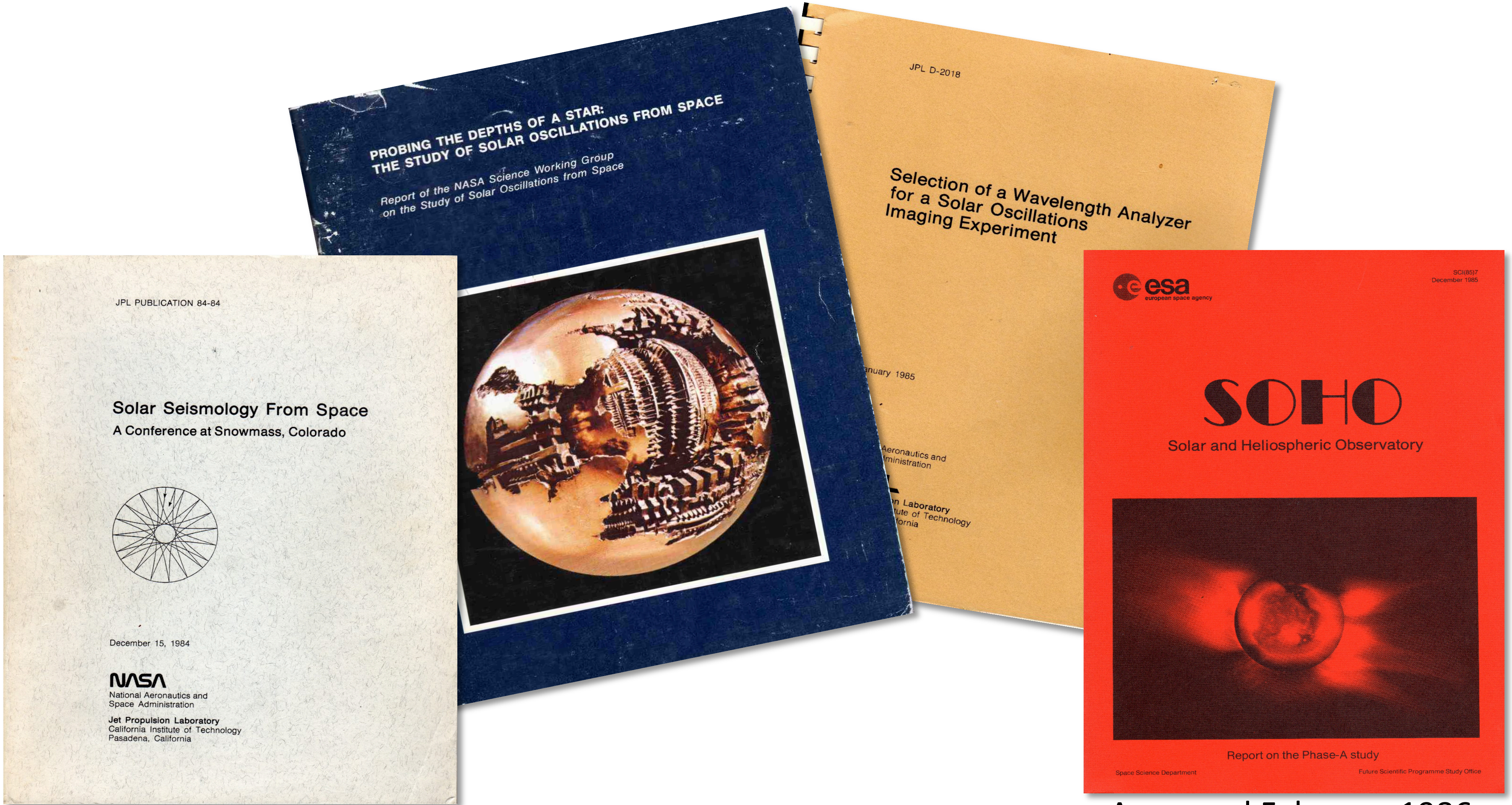
Number of detection papers citing (1976-1989)

- Crimea: 5
- Birmingham: 3
- Stanford: 3
- Nice: 2
- UoAZ: 2

Total number of papers citing (1976-1989): 97

Space missions in the thinking

Mid 1980's



Approved February 1986

g-mode detection in 1983

15 december 1983

NATURE VOL. 306 15 DECEMBER 1983 ARTICLES 651

Detection of solar gravity mode oscillations

Philippe Delache* & Philip H. Scherrer

Center for Space Science and Astrophysics, Stanford University, Stanford, California 94305, USA

An analysis of solar velocity data obtained at the Stanford Solar Observatory shows the existence of solar global oscillations in the range 45–105 μHz (160–370 min). These oscillations are interpreted as internal gravity modes of degree l = 1 and l = 2. A good estimate of the order of the modes has also been made.

OBSERVATIONS of the global solar velocity field have been recorded[1] at the Stanford Solar Observatory since 1976. Similar recordings from the Crimean Astrophysical Observatory are available[2] starting from 1974 and a spectral analysis of the combined data showing the prominent 160.01-min peak has been published recently[3]. A careful examination of the combined Stanford–Crimea spectrum has convinced us that there may be a few other peaks in the low frequency portion of the spectrum which are significantly above the noise level. For that reason, we decided to re-analyse the original Stanford data.

Data set and analysis

The previous report described the observing and data reduction procedures in detail[3]. The observations, which are differential measures of the line-of-sight velocity of the solar surface, are made by comparing the average Doppler shift from the centre of the solar disk with the Doppler shift from a concentric annulus. As it seemed that interesting features were present in the low frequency part of the spectrum, we extended the computation down to $\nu = 0$. Because only the low frequency part of the spectrum is examined here, the data were averaged into 5-min intervals and normalized within each day as in the previous analysis. First the Fourier transform of the 4 yr of Stanford data (1977–80) was computed using a standard fast Fourier transform (FFT) code. It was found that the largest power is in the range 45–105 μHz (about 160–370 min). The resulting power spectrum shows several sets of lines with separations

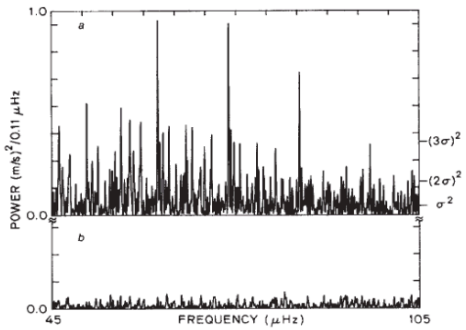


Fig. 1 The power spectrum of velocity observations from the Stanford Solar Observatory in 1979. The spectrum in the range 45–105 μHz (360–160 min) is shown. *a*, The original spectrum; *b*, the spectrum to the same scale after 14 peaks were identified and the associated sinusoidal waves subtracted from the data. The scale shown has been corrected for the average normalizing factor.

corresponding to day side bands (that is, 11.57 μHz) which obviously come from the nightly gaps in the data. Comparing the 4-yr spectrum with individual yearly spectra, we discovered that the strongest lines were more prominent in 1979 than in the other years. This may be due to the relatively clear skies

* Permanent address: Observatoire de Nice, Laboratoire Associé au CNRS 128, BP 252, 06007 Nice Cedex, France.

0028–0836/83/500651—03$01.00

Number of detection papers citing (1983-2013)

- Particle: 6 (see next)
- SOHO: 4 (see next)
- ACRIM: 1
- UoAZ: 2

Total number of papers citing (1983-2013): 96

Answering the SOHO AO[1]

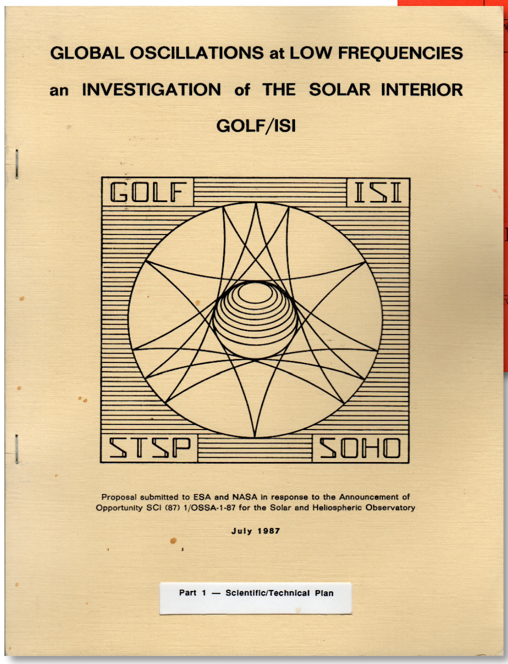
Submitted in July 1987

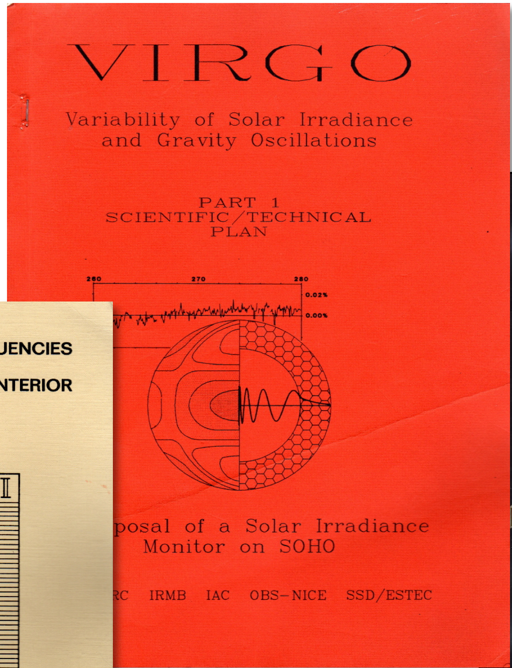
Selected in March 1988

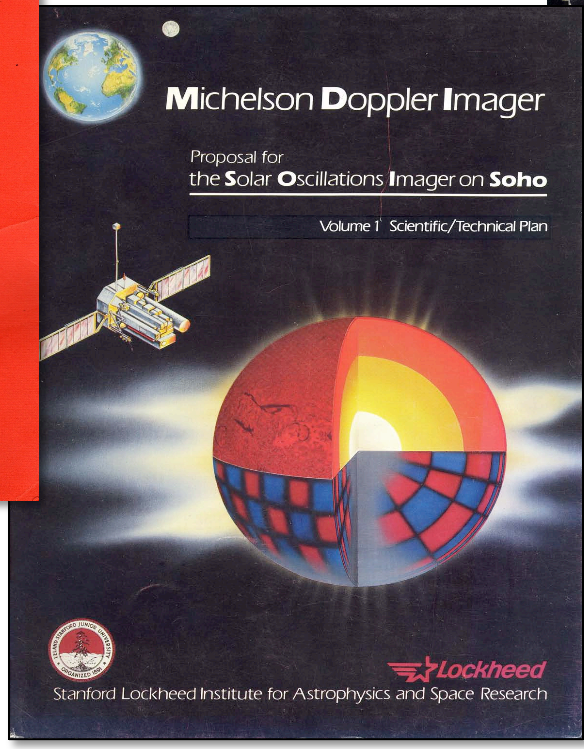
1) AO: Announcement of Opportunity

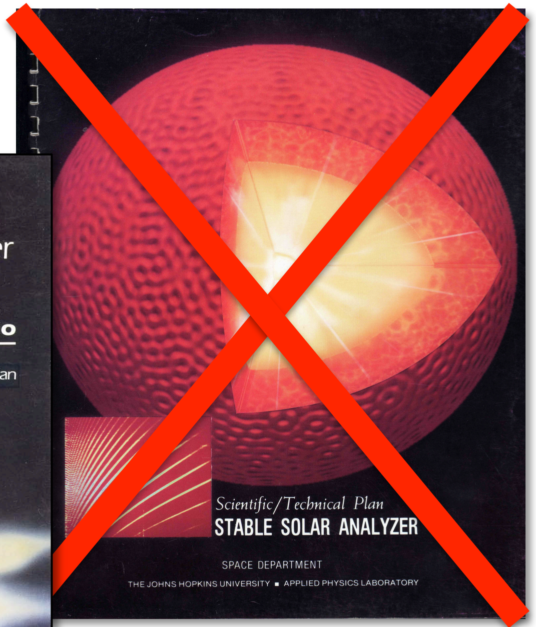
Answering the SOHO AO[1]

Submitted in July 1987









1) AO: Announcement of Opportunity

Selected in March 1988

The 160-min oscillation: an artefact

Elsworth et al (1989)

THE ASTROPHYSICAL JOURNAL, 338:557–562, 1989 March 1

THE 160 MINUTE SOLAR OSCILLATION: AN ARTIFACT?

Y. P. ELSWORTH,[1] S. M. JEFFERIES,[2] C. P. MCLEOD,[1] R. NEW,[1] P. L. PALLÉ,[3]
H. B. VAN DER RAAY,[1] C. RÉGULO,[3] AND T. ROCA CORTÉS[3]
Received 1987 December 16; accepted 1988 August 11

ABSTRACT

Analysis of data obtained at Izana over the years 1980–1985 are analyzed to show that the period of the 160 minute signal is indeed 160.00 minutes. It is further demonstrated that this signal may be simulated by a slightly distorted diurnal sine wave such as that occasioned by differential atmospheric extinction.

Subject headings: Sun: oscillations

I. INTRODUCTION

The birth of helioseismology was heralded by the simultaneous publication in *Nature* (Brookes, Isaak, and van der Raay 1976; Severny, Kotov, and Tsap 1976) of papers from the Birmingham University and Crimean Astrophysical Observatory groups announcing the discovery of a 160 minute solar oscillation of amplitude ~ 2 ms^{-1}. However the earlier work of Leighton, Noyes, and Simon (1962), Ulrich (1970), and Leibacher and Stein (1971) should not be overlooked. It was realized that the authenticity of this signal was in some doubt, as 160 minutes is exactly one-ninth of a day. Later analysis of data obtained over the period 1974–1976 (Brookes *et al.* 1978) indicated that the experimental evidence for the existence of a stable, phase-coherent 160 minute solar oscillation was far from conclusive. Although the signal was still detected the amplitude appeared variable and generally lower than first reported.

The reaffirmation of the 160 minute signal was obtained from an analysis of the combined data of Stanford and Crimea over a long period of time. Using a superposed epoch technique, it was found that the phase of the signal was not constant from year to year but indicated a steady drift, thus implying that the correct period was not 160 minutes but 160.01 minutes (Scherrer *et al.* 1980). This slight difference, if substantiated, would establish the authenticity of the solar origin of the signal. In addition it was found that the phases of the 160 minute signals from all three sets of observations

solar surface is determined.

$$V_m = V_{\rm orb} + V_{\rm spin} + V_{\rm grs} + V(t)\,, \qquad (1)$$

where $V_{\rm orb}$ is the line-of-sight component of velocity resulting from the orbital motion of the Earth about the Sun; $V_{\rm spin}$ is that due to the rotation of the Earth about its axis; $V_{\rm grs}$ is the gravitational redshift resulting from the differing gravitational potentials at the surfaces of the Sun and Earth due to their different masses, and $V(t)$ represents a time-dependent velocity signal due to solar oscillation (Brookes, Isaak, and van der Raay 1978). The magnitudes and dominant periods of these terms are indicated in Table 1.

The term $V_{\rm spin}$ may be expressed as

$$V_{\rm spin} = V_s \cos\delta \sin\left[\frac{2\pi}{24}(t - t')\right], \qquad (2)$$

where t' is the time of local noon, expressed in hours, V_s is the Earth's peripheral velocity at the point of observation and δ is the apparent solar declination. It should be noted that during any one year t' varies by ~ 31 minutes, thus causing phase modulation of the $V_{\rm spin}$ term.

Observations of the line-of-sight velocity of the Sun during a particular day therefore consist of a dominant sine wave of amplitude V_s and period 24 hr, offset by $V_{\rm orb} + V_{\rm grs}$, with a much smaller amplitude signal $V(t)$ superposed. An example of data recorded at Izana on 1985 May 16 is illustrated in Figure 1. Any distortion of the line of sight velocity signal will gener-

g-mode detection in 1995

13 July 1995

Propagation of solar oscillations through the interplanetary medium

David J. Thomson, Carol G. Maclennan & Louis J. Lanzerotti

AT&T Bell Laboratories, Murray Hill, New Jersey 07974, USA

Time-series analysis of the fluxes of interplanetary charged particles measured by the Ulysses and Voyager spacecraft reveals many periodic components. From 1 to 140 μHz, the spectral components are consistent with those estimated (but not confirmed) for gravity-mode oscillations of the Sun: from 1,000 to 4,000 μHz, the spectral lines closely match the frequencies of known solar pressure modes. These concordances imply that the solar wind and the interplanetary magnetic field transmit solar oscillations and thus might be used to probe the interior structure of the Sun.

THE Sun oscillates, in much the same way as a drum or a ringing bell, with various modes of oscillation. The pressure or *p* modes are acoustic standing waves, which have been thoroughly mapped using optical techniques. The gravity or *g* modes, on the other hand, result from gravitational restoration of density gradients within the Sun. The *g* modes should be sensitive indicators of the structure deep within the Sun, particularly in the core, about which we have little direct information. The detection of *g*-mode oscillations has been reported[1], but not been confirmed (P. H. Scherrer, personal communication). Between the lack of observations and the modes' sensitivity to density gradients, the possible frequencies of *g* modes[2] are much less certain than those of *p* modes.

Although *g*-mode oscillation frequencies are not currently included as constraints in models of the solar interior[3], they may play an important role in mixing the hydrogen fuel and helium fusion products at the centre of the Sun, and thus may be relevant to the problem of the missing solar neutrinos[2-4]. Models of the solar interior predict more neutrinos than are observed[4,5]. This long-standing discrepancy strikes at the heart of our understanding of stellar structure and basic nuclear physics.

We have analysed the time series of fluxes of low-energy interplanetary charged particles, whose ultimate origin is the Sun. Based on time-series analysis of data from the Voyager II spacecraft (during 1985) and from the Ulysses spacecraft (1992–94), we find evidence that solar oscillations can be observed in the variations of the particle flux. We were surprised to find evidence for periodic components other than solar rotation in these data. Traditionally, time variations in the particle fluxes have been ascribed solely to sources such as the injection and propagation of particles from solar disturbances (for example, flares), the release of particles from planetary magnetospheres, the acceleration of particles at interplanetary shock waves and fluctuations in the magnetic field intensity and direction in interplanetary space. All of these effects[6,7] imply a continuous spectrum, not discrete features.

The Sun's control over the interplanetary environment, through its magnetic field and the solar wind, makes the Sun a likely source of the observed periodicities. The prime candidates in our observed frequency range of 1–140 μHz are *g* modes that are transmitted into the interplanetary medium. We found that the observed oscillation in the particle flux had the characteristic stability and nearly equally spaced periods expected for *g* modes[8]. We also looked for, and found, evidence for solar *p*-mode oscillations in the 1,000–5,000 μHz range.

What physical mechanism could explain this apparent modulation of the solar wind by solar oscillations? We suggest that supergranulation motions, which have been assumed to be random motions on the solar surface, are not completely random, but partially the effect of many *g* modes. It has been predicted[9] that magnetic flux 'frozen' in the supergranulation is responsible for the observed transverse magnetic fields in the polar regions of the Sun[10]. Periodic components in the interplanetary magnetic field would cause periodic modulation of the charged-particle flux.

Solar modes

Viewed from a sidereal reference frame, the surface motion of a *p*- or *g*-mode oscillation is given approximately[8] by

$$a_{nl} P_l^m (\cos\theta) \cos(m\phi - 2\pi f t) \qquad (1)$$

where f is the frequency of oscillation, a_{nl} is the amplitude depending on the spherical harmonic degree l and radial order n, and P_l^m is the associated Legendre function of order m. The solar longitude is given by ϕ, and θ is the colatitude. The frequencies of the *p* modes have been mapped thoroughly using optical Doppler methods[11,12] for frequencies in the range 1,000–5,000 μHz (periods 4–20 minutes). The ratio of circulating energy to energy dissipated per cycle (Q) is about 10,000, so the amplitude of the *p* modes stays fairly constant over several days[13]. Our understanding of the convection zone of the Sun results largely from models that reproduce the observed *p* modes[14].

The *g* modes have frequencies less than about 400 μHz (periods >40 minutes). They are expected[15] to have extremely high values of Q, so their amplitudes should stay relatively constant for thousands of years.

Data preparation and analysis

Table 1 lists the different sets of interplanetary data[16,17] that we analysed, giving the particle species, channels and time-intervals. We selected the data sets by several criteria: data continuity, location of the spacecraft within or outside the heliospheric current sheet, and the presence or absence of distinct solar-particle events. For the most part, data were available as hourly averages, resulting in a minimum observable period of 2 hours, or a Nyquist frequency, $1/2\Delta t$, of 139 μHz. (Because averaging is not a good filter, some frequencies close to the band edge may be aliases.) Many of the processes involved in accelerating the solar wind are multiplicative[18], so, for most of the analyses, logarithms of the hourly flux values were used.

The more lengthy data sets all have short gaps due to tracking omissions, instrument calibrations, telemetry noise and so on. We used a two-pass procedure (formally an EM algorithm[19]) that has been proven analytically to be statistically consistent in missing-data problems. This spectrum estimation method corres-

United States Patent [19]
Lindberg et al.

[11] **Patent Number: 5,442,696**
[45] **Date of Patent: Aug. 15, 1995**

[54] **METHOD AND APPARATUS FOR DETECTING CONTROL SIGNALS**

[75] Inventors: **Craig R. Lindberg; David J. Thomson,** both of Murray Hill, N.J.

[73] Assignee: **AT&T Corp.,** Murray Hill, N.J.

[21] Appl. No.: **816,332**

[22] Filed: **Dec. 31, 1991**

[51] **Int. Cl.**[6] **H04M 3/00**
[52] **U.S. Cl.** **379/386;** 379/283; 340/825.73
[58] **Field of Search** 379/386, 282, 283; 370/110.3; 340/825.39, 825.73, 825.74, 825.76

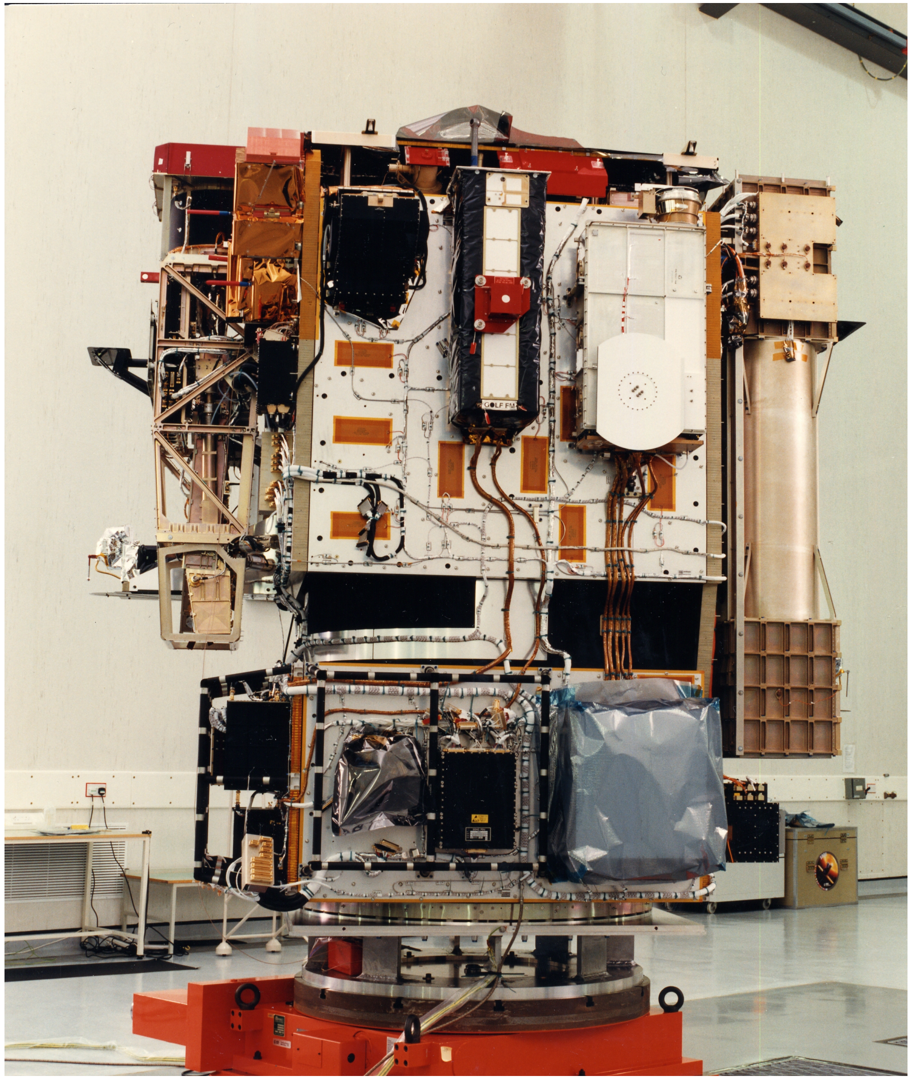
[57] **ABSTRACT**

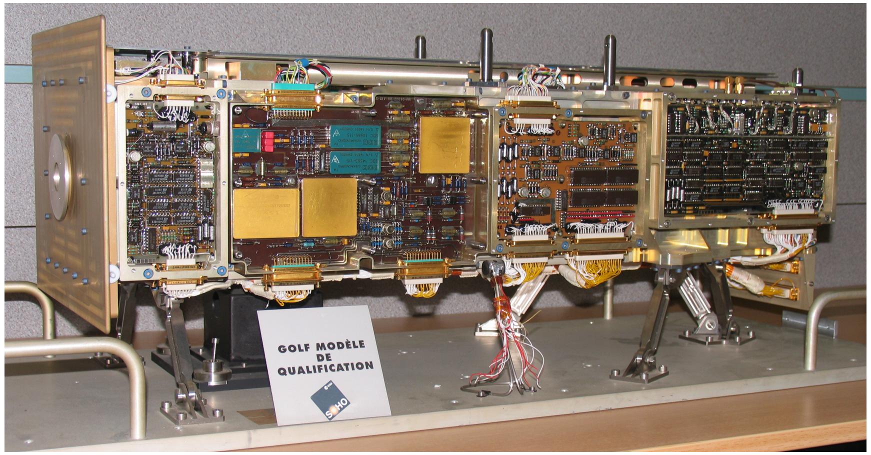
The present invention provides a method and apparatus for detecting control signal information for an element of a communication system. The control signal information is included in one or more segments of a signal communicated over a communication system channel. The invention provides for the application of a plurality of tapers to a segment of a communicated signal; the transformation of a tapered segment; the determination of a similarity score based on a transform of a tapered segment and a model of a control signal; the identification of control signal information based on a similarity score; and the creation of an indicator signal representative of the identified control signal information to the communication system element. The control signal information may comprise a dual-tone multi-frequency signal. The tapers may comprise a discrete prolate spheroidal sequence. A similarity score may be determined based on a ratio of energy distributions. The numerator of the ratio may comprise an energy distribution based on a control signal model, and the denominator of the ratio may comprise an energy distribution based on a difference between a transformed tapered segment and the control signal model.

Infirmed by:

- Riley and Sonett (1996)
- Hoogeveen and Riley (1998)
- Denison and Walden (1999)
- HH exercise with Thomson (2000)

GOLF aboard SoHO

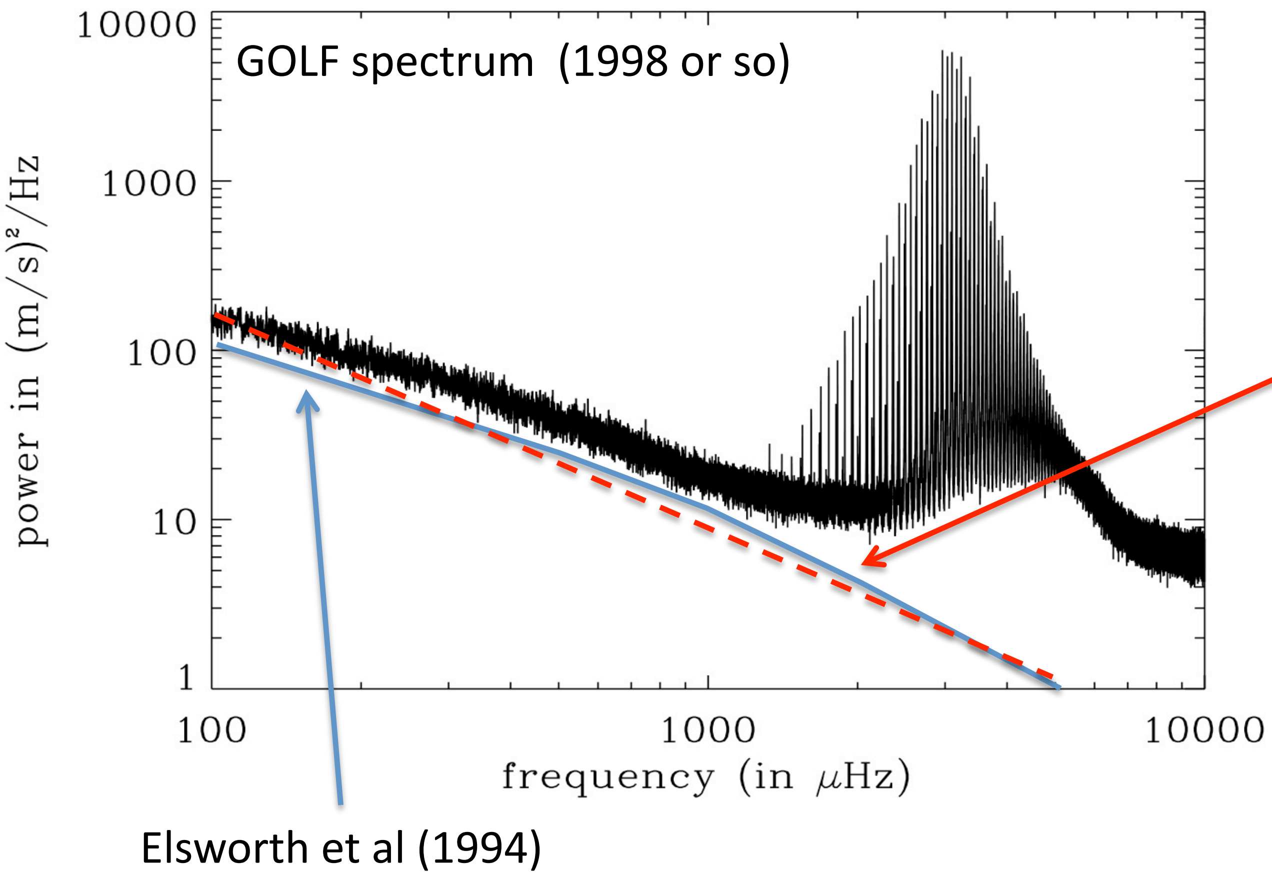




...and then SoHO was launched

2 December 1995

Back to the future before GOLF



Appourchaux (1983)

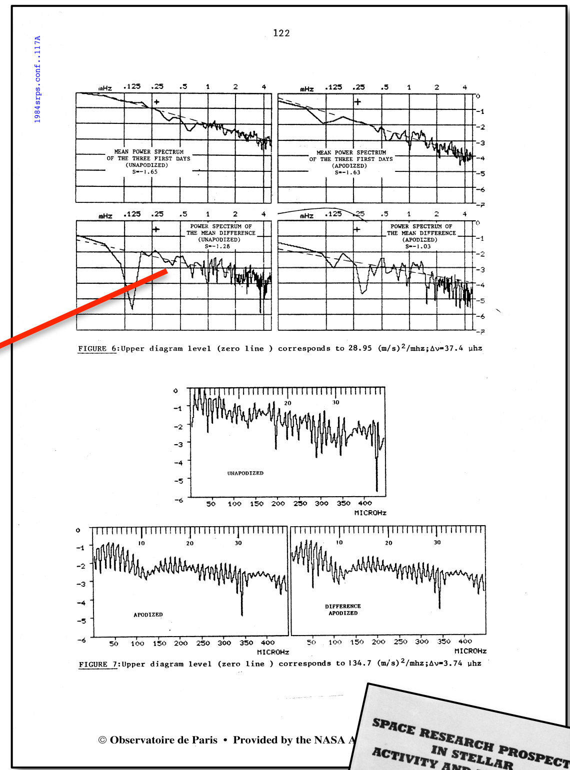
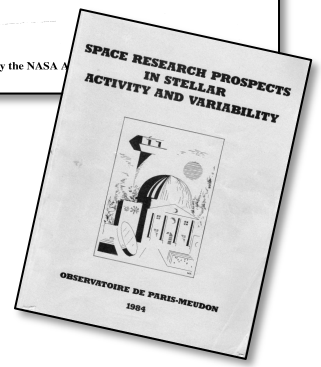

122

FIGURE 6: Upper diagram level (zero line) corresponds to 28.95 $(m/s)^2$/mhz; $\Delta\nu$=37.4 μhz

FIGURE 7: Upper diagram level (zero line) corresponds to 134.7 $(m/s)^2$/mhz; $\Delta\nu$=3.74 μhz

© Observatoire de Paris • Provided by the NASA A

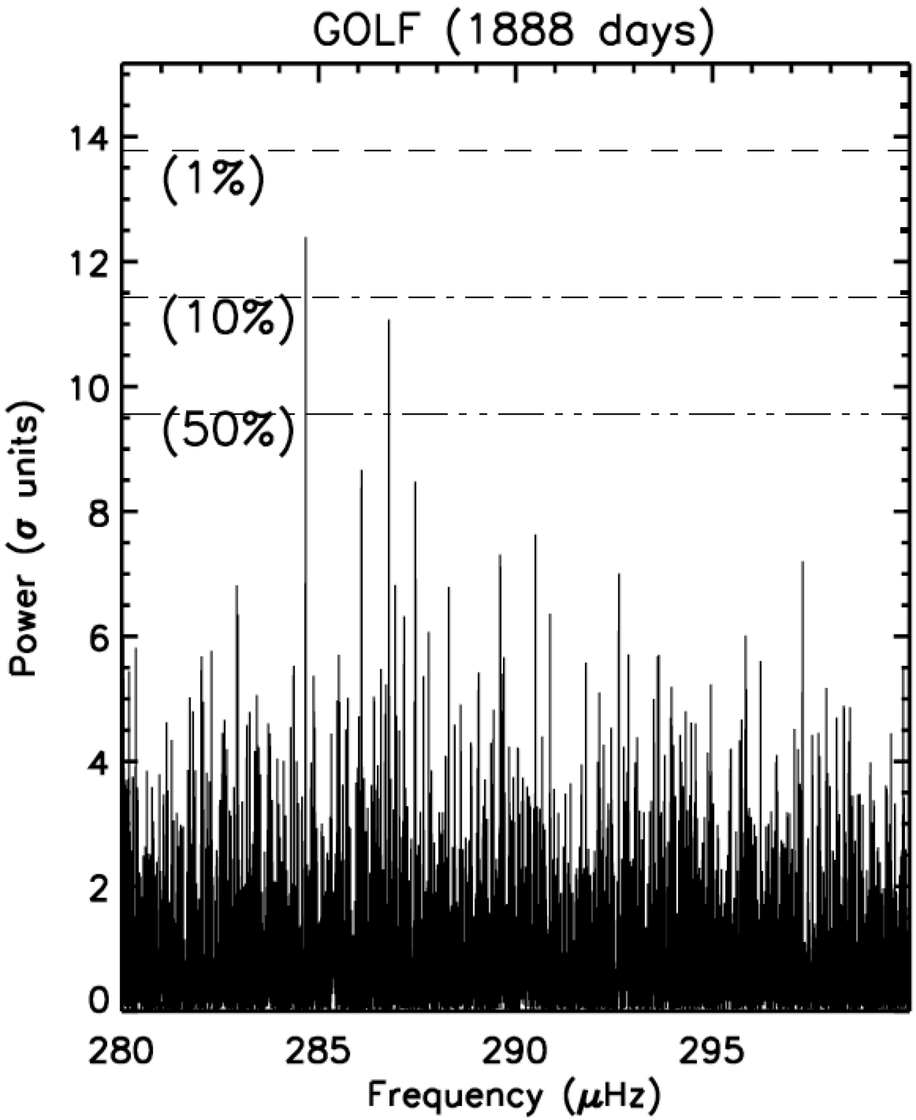


GOLF and the g-mode search: the secular view

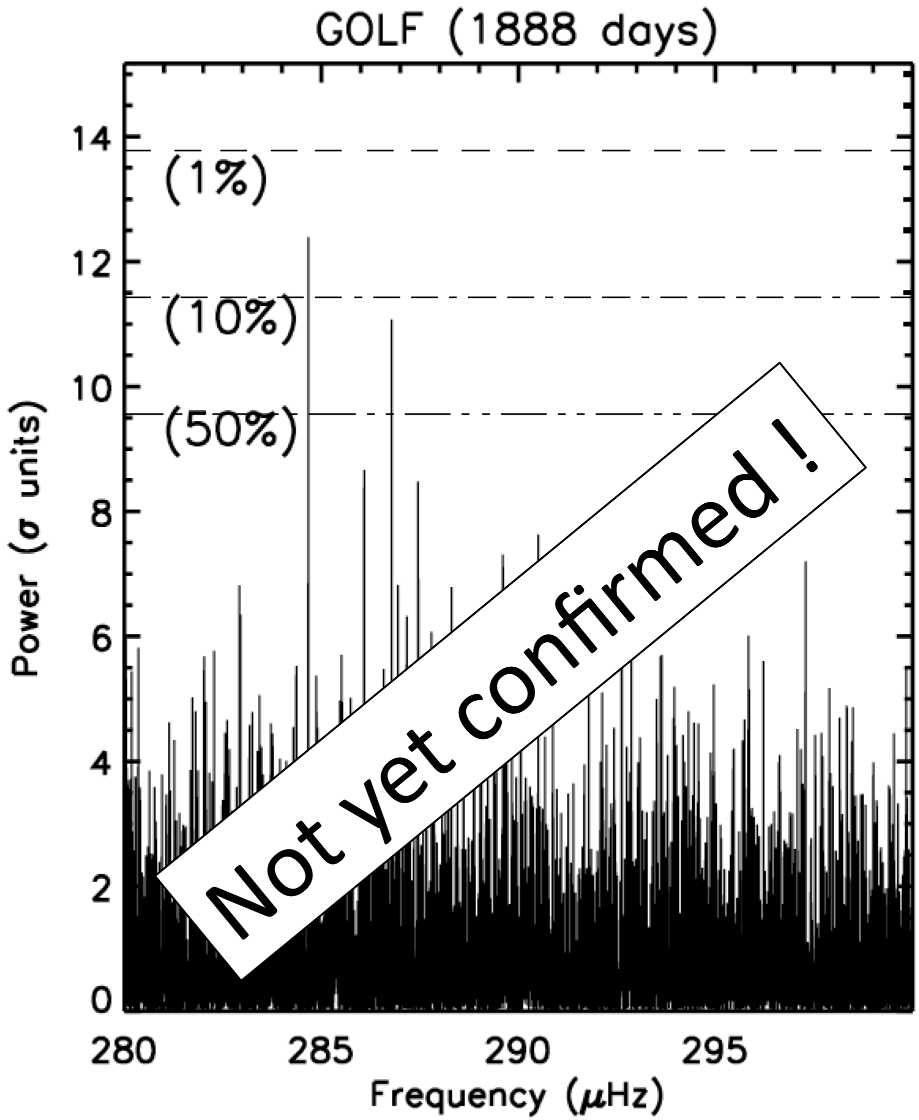
- Detection techniques of Gabriel et al (2002):
  - Single spectrum or averaged spectra
  - Oversampling (zero padding)
  - Understanding of noise and signal statistics
  - Use of H0 and H1 hypotheses

GOLF and the g-mode search:

- Detec (2002):
  - Sing
  - Ove
  - Unc atistics
  - Use



GOLF and the g-mode search:



- Detec (2002):
  - Sing
  - Ove
  - Unc atistics
  - Use

GOLF and the g-mode search: the faithful view

- Detection techniques of Turck-Chièze et al (2004):
  - Frequencies above 150 μHz
  - Look for frequencies within ±10 μHz of theoretical ones
  - Look for multiplets (from rotationally split frequencies) assuming some rotation
  - Use a frequentist approach
  - Follow temporal evolution of the candidates

GOLF and the g-mode search: the faithful view

- Detection t… (2004):
  - Frequenc…
  - Look for f… oretical ones
  - Look for r… frequencies) assuming…
  - Use a fre…
  - Follow te… es

TABLE 2

The g-Mode Patterns with More Than 90% Confidence Level of Not Being Noise Compared with the Theoretical Central Value for 1290 Days of GOLF Observations

Order	Seismic Model (μHz)	Periodogram (μHz)	Multitaper (μHz)
	$l = 1$		
$n = -3$	153.25	...	...
$n = -2$	191.55	196.94/198.01	...
$n = -1$	262.73	...	262.15
	$l = 2$		
$n = -6$	151.26	144.63/145.62/146.60	...
$n = -5$	170.46	...	...
$n = -4$	194.06	...	193.86/195.25
$n = -3$	222.02	218.95/220.10/220.70	218.95/220.10/221.28
$n = -2$	256.09	251.37/252.5	251.14/252.48
$n = -1$	296.38	...	...
	$l = 3$		
$n = -9$	148.33	146.79/149.99	...
$n = -8$	161.72	...	...
$n = -7$	177.46	...	171.56/172.26/173.56
$n = -6$	195.93	...	193.86/195.25
$n = -5$	217.07	218.95/220.11/220.73	218.96/220.72
$n = -4$	238.35	...	...
$n = -3$	261.31	251.37/252.5	262.15
$n = -2$	296.50	...	...
$n = -1$	340.07	...	337.56/338.01/338.94

GOLF and the g-mode search: the faithful view

- Detection t … (2004):
  - Frequenc …
  - Look for f … oretical ones
  - Look for r … frequencies) assuming …
  - Use a fre …
  - Follow te … es

TABLE 2

The *g*-Mode Patterns with More Than 90% Confidence Level of Not Being Noise Compared with the Theoretical Central Value for 1290 Days of GOLF Observations

Order	Seismic Model (μHz)	Periodogram (μHz)	Multitaper (μHz)
		$l = 1$	
$n = -3$	153.25	...	...
$n = -2$	191.55	196.94/198.01	...
$n = -1$	262.73	...	[illegible].15
		$l = 2$	
$n = -6$	151.26	144[illegible]	...
$n = -5$	170.46	[illegible]	...
$n = -4$	194.06	[illegible]	193.86/195.25
$n = -3$	222.02	[illegible]220.70	218.95/220.10/221.28
$n = -2$	256.09	[illegible]/252.5	251.14/252.48
$n = -1$	29[illegible]	...	...
		[illegible] 3	
$n = -9$	[illegible]	146.79/149.99	...
$n = -8$	[illegible]	...	...
$n = -7$	[illegible].46	...	171.56/172.26/173.56
$n = -6$	195.93	...	193.86/195.25
$n = -5$	217.07	218.95/220.11/220.73	218.96/220.72
$n = -4$	238.35	...	...
$n = -3$	261.31	251.37/252.5	262.15
$n = -2$	296.50	...	...
$n = -1$	340.07	...	337.56/338.01/338.94

Not yet confirmed !

The Phoebus group

Learning how to blow the whistle

Hare...and hounds

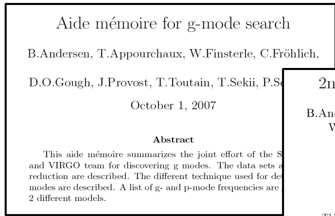
Group named after Gaston III, Count of Foix who wrote *The Book of Hunt* (1388)

The Phoebus workshop

- 1st @ ESTEC: 3-7 November 1997
- 2nd @ ESTEC: 26-30 October 1998
- 3rd @ ESTEC: 25-29 October 1999
- 4th @ ESTEC: 7-11 May 2001
- 5th @ ESTEC: 17-21 Juin 2002
- 6th @ ISSI: 31 Oct-4 Nov 2005
- 6.5 @ Fréjus: 27-31 March 2006
- 7th @ ISSI: 23-27 April 2007

VIRGO / MDI / BiSON (1st–5th)

+ GOLF (6th–7th)



Aide mémoire for g-mode search

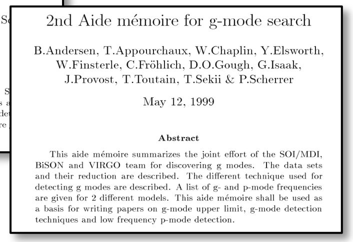
B.Andersen, T.Appourchaux, W.Finsterle, C.Fröhlich,

D.O.Gough, J.Provost, T.Toutain, T.Sekii, P.S

October 1, 2007

Abstract

This aide mémoire summarizes the joint effort of the S
and VIRGO team for discovering g modes. The data sets a
reduction are described. The different technique used for de
modes are described. A list of g- and p-mode frequencies are
2 different models.



2nd Aide mémoire for g-mode search

B.Andersen, T.Appourchaux, W.Chaplin, Y.Elsworth, W.Finsterle, C.Fröhlich, D.O.Gough, G.Isaak, J.Provost, T.Toutain, T.Sekii & P.Scherrer

May 12, 1999

Abstract

This aide mémoire summarizes the joint effort of the SOI/MDI, BiSON and VIRGO team for discovering g modes. The data sets and their reduction are described. The different technique used for detecting g modes are described. A list of g- and p-mode frequencies are given for 2 different models. This aide mémoire shall be used as a basis for writing papers on g-mode upper limit, g-mode detection techniques and low frequency p-mode detection.

The Phoebus years

g-mode detection in 2007...

Garcia et al (2007)

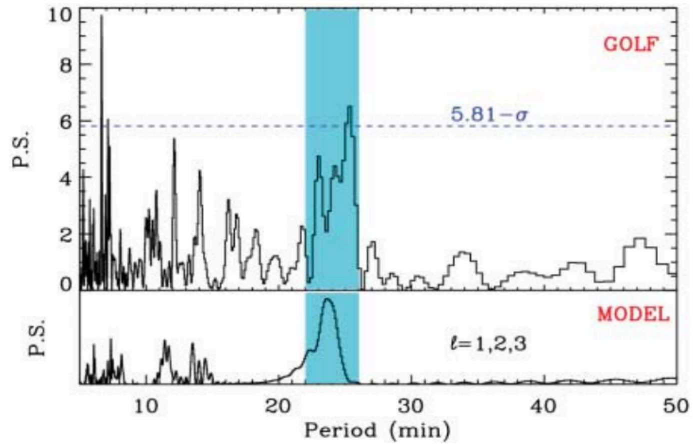
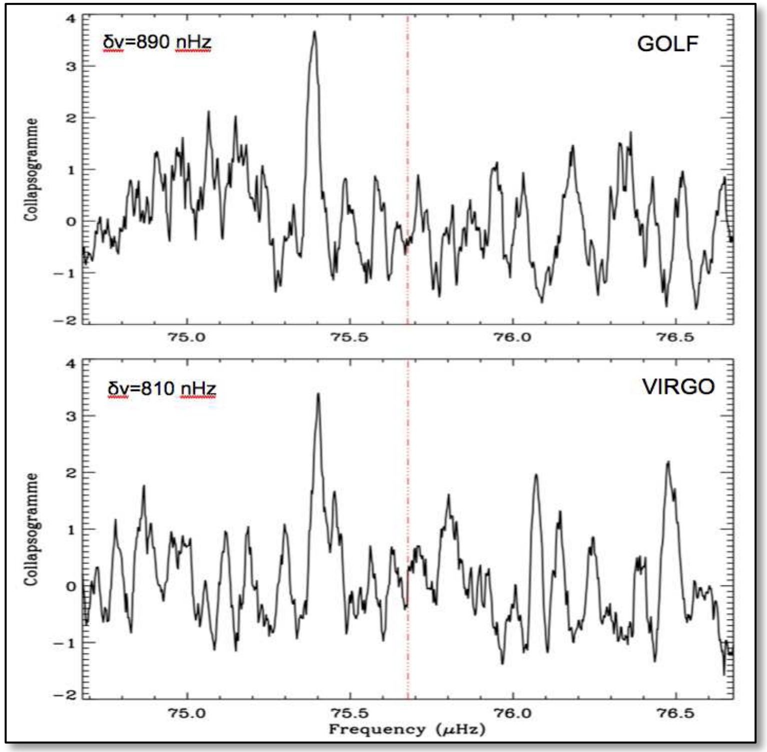


Fig. 3. Power spectrum of the PSD, normalized to the standard deviation, for the real GOLF data (top) and a numerical simulation (bottom) of $\ell = 1$, 2, and 3 gravity modes computed using the seismic model, for a core rotating at 433 nHz and without noise. The shaded region corresponds to the zone where the ΔP_1 peak is expected. This pattern changes slightly (with maxima at $\sim 7.3\sigma$ or 6σ) when shorter frequency ranges in the PSD are used (fig. S2). The horizontal dashed line at 5.81σ corresponds to 99.7% confidence level for individual peaks (equivalent to 3σ level of a normal distribution). A full interpretation of the other highest peaks at low period is given in (*22*).

1592 15 JUNE 2007 VOL 316 **SCIENCE** www.sciencemag.org

Garcia et al (2010)



$$P_{n,l} \sim \overline{P}_{n,l} = \frac{P_0}{L}\left(n + l/2 - \frac{1}{4} + \vartheta\right)$$

g-mode detection in 2007…

Garcia et al (2007)

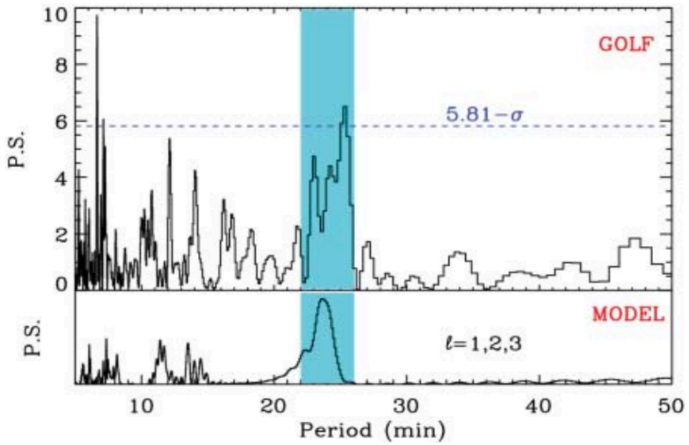
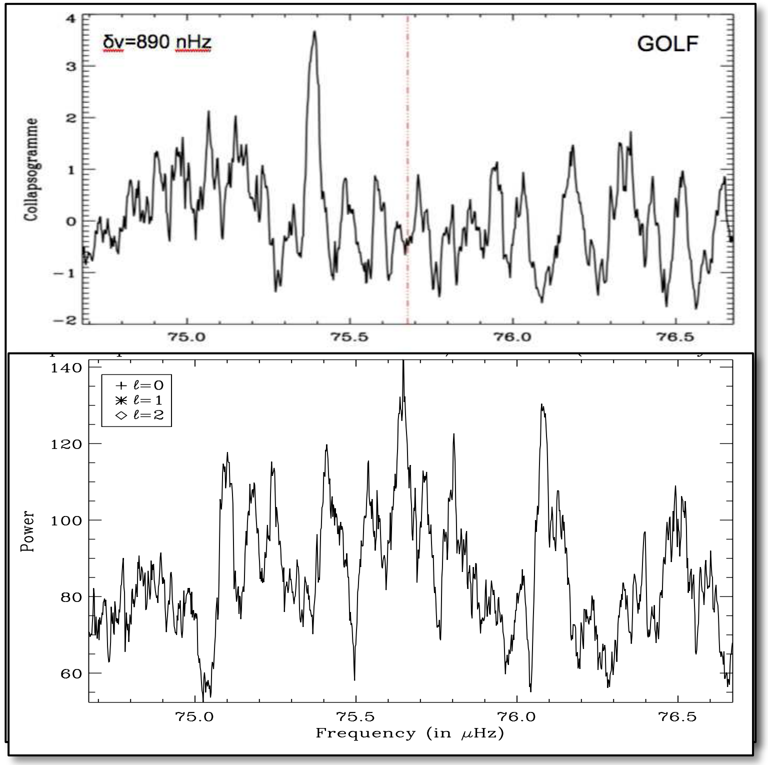


Fig. 3. Power spectrum of the PSD, normalized to the standard deviation, for the real GOLF data (top) and a numerical simulation (bottom) of $\ell = 1$, 2, and 3 gravity modes computed using the seismic model, for a core rotating at 433 nHz and without noise. The shaded region corresponds to the zone where the ΔP_1 peak is expected. This pattern changes slightly (with maxima at ~7.3σ or 6σ) when shorter frequency ranges in the PSD are used (fig. S2). The horizontal dashed line at 5.81σ corresponds to 99.7% confidence level for individual peaks (equivalent to 3σ level of a normal distribution). A full interpretation of the other highest peaks at low period is given in (*22*).

1592 15 JUNE 2007 VOL 316 **SCIENCE** www.sciencemag.org

Garcia et al (2010)



$$P_{n,l} \sim \overline{P}_{n,l} = \frac{P_0}{L}\left(n + l/2 - \frac{1}{4} + \vartheta\right)$$

17 years of LOI data

Phoebus and the g modes

THE ASTROPHYSICAL JOURNAL, 538:401–414, 2000 July 20

2000

OBSERVATIONAL UPPER LIMITS TO LOW-DEGREE SOLAR g-MODES

T. APPOURCHAUX,[1] C. FRÖHLICH,[2] B. ANDERSEN,[3] G. BERTHOMIEU,[4] W. J. CHAPLIN,[1,5] Y. ELSWORTH,[5] W. FINSTERLE,[2] D. O. GOUGH,[6,7] J. T. HOEKSEMA,[8] G. R. ISAAK,[5] A. G. KOSOVICHEV,[8] J. PROVOST,[4] P. H. SCHERRER,[8] T. SEKII,[6] AND T. TOUTAIN[4]

Received 1999 December 1; accepted 2000 February 29

ABSTRACT

Observations made by the Michelson Doppler Imager (MDI) and Variability of solar IRradiance and Gravity Oscillations (VIRGO) on the *Solar and Heliospheric Observatory* (*SOHO*) and by the ground-based Birmingham Solar Oscillations Network (BiSON) and Global Oscillations Network Group (GONG) have been used in a concerted effort to search for solar gravity oscillations. All spectra are dominated by solar noise in the frequency region from 100 to 1000 μHz, where g-modes are expected to be found. Several methods have been used in an effort to extract any g-mode signal present. These include (1) the correlation of data—both full-disk and imaged (with different spatial-mask properties)—collected over different time intervals from the same instrument, (2) the correlation of near-contemporaneous data from different instruments, and (3) the extraction—through the application of complex filtering techniques—of the coherent part of data collected at different heights in the solar atmosphere. The detection limit is set by the loss of coherence caused by the temporal evolution and the motion (e.g., rotation) of superficial structures. Although we cannot identify any g-mode signature, we have nevertheless set a firm upper limit to the amplitudes of the modes: at 200 μHz, they are below 10 mm s^{-1} in velocity, and below 0.5 parts per million in intensity. The velocity limit corresponds very approximately to a peak-to-peak vertical displacement of $\delta R/R_{\odot} = 2.3 \times 10^{-8}$ at the solar surface. These levels which are much lower than prior claims, are consistent with theoretical predictions.

Subject headings: methods: data analysis — Sun: general — Sun: interior — Sun: oscillations

Astron Astrophys Rev (2010) 18:197–277
DOI 10.1007/s00159-009-0027-z

REVIEW ARTICLE

2010

The quest for the solar g modes

T. Appourchaux · K. Belkacem · A.-M. Broomhall · W. J. Chaplin · D. O. Gough · G. Houdek · J. Provost · F. Baudin · P. Boumier · Y. Elsworth · R. A. García · B. N. Andersen · W. Finsterle · C. Fröhlich · A. Gabriel · G. Grec · A. Jiménez · A. Kosovichev · T. Sekii · T. Toutain · S. Turck-Chièze

Received: 6 July 2009 / Published online: 12 January 2010

Abstract Solar gravity modes (or g modes)—oscillations of the solar interior on which buoyancy acts as the restoring force—have the potential to provide unprecedented inference on the structure and dynamics of the solar core, inference that is not possible with the well-observed acoustic modes (or p modes). The relative high amplitude of the g-mode eigenfunctions in the core and the evanesence of the modes in the

T. Appourchaux (✉) · F. Baudin · P. Boumier · A. Gabriel
Institut d'Astrophysique Spatiale, UMR8617, Bâtiment 121, 91405 Orsay Cedex, France
e-mail: Thierry.Appourchaux@ias.u-psud.fr

Use of collapsogramme

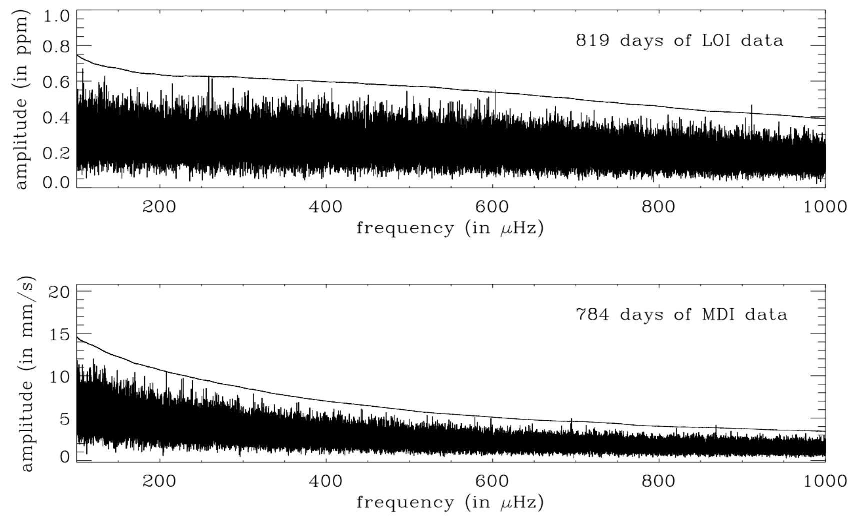
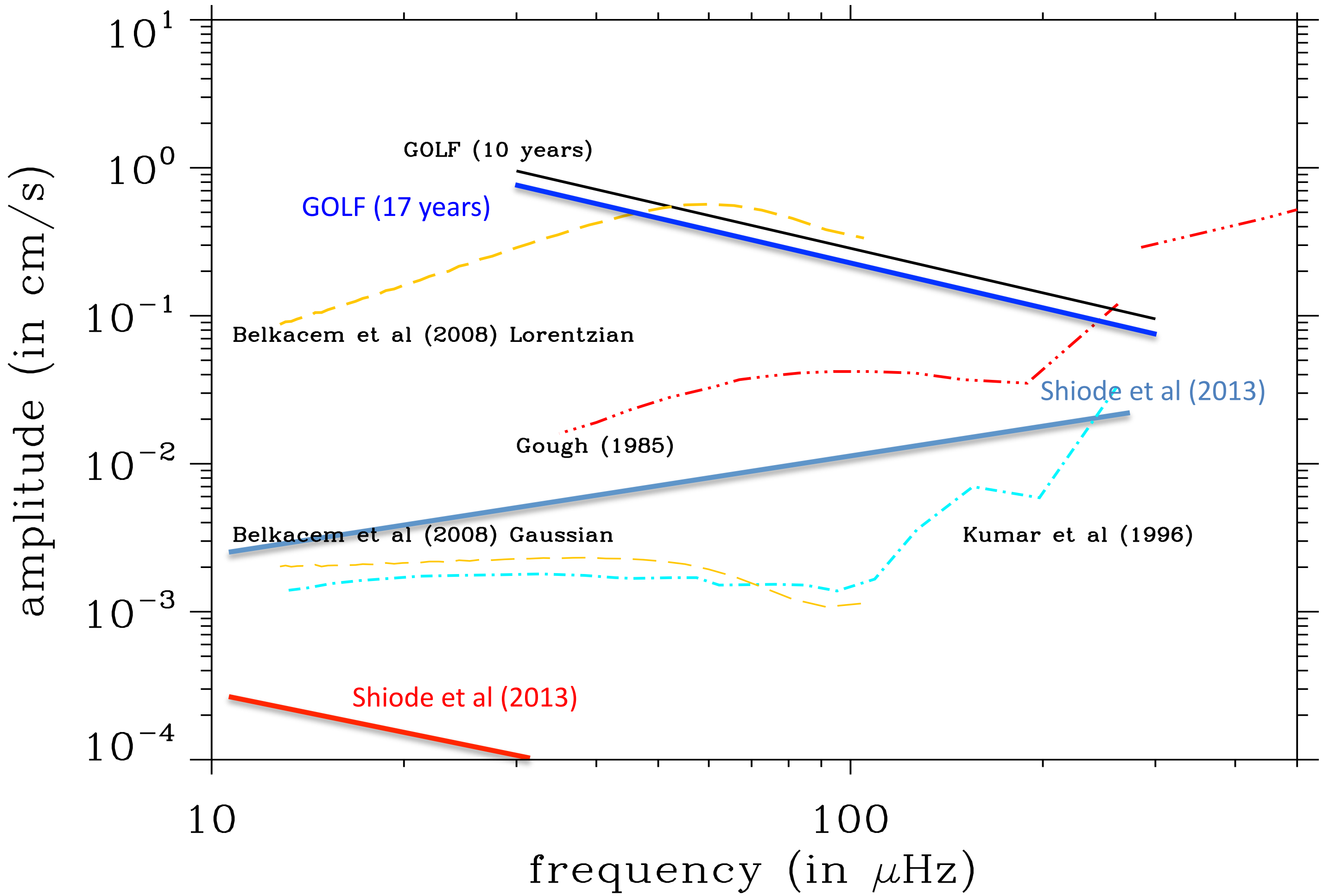


FIG. 4.—$l = 1$ collapsogram for the LOI (*top*), MDI (*bottom*) resolved data, corrected for the spatial filter functions. The continuous line gives the 0.1 probability limit that a peak is due to noise in a 70 μHz bandwidth. The shift differs slightly between spectra since each was chosen to be an integer number of frequency bins (the observation times being different for each instrument). Note that while the magnitude of the shift is known to be valid for p-modes, it is not expected to be so for g-modes. The detection limit (in amplitude) is $(5.3\bar{s})^{1/2}$ both for LOI and MDI. This is to be compared with the $(10.8\bar{s})^{1/2}$ levels returned for the full-disk spectra.

...there is currently no undisputed detection of solar g modes.

g-mode amplitudes: a zoo !



Conclusion

It is superficially unfortunate that we discovered no g modes. On the brighter side, on which I always prefer to be, it shows that we have before us a greater challenge which will yield [ ] greater satisfaction when we overcome it.[. . .]. We are all now much more prepared to continue the search.

Douglas Gough, December 1997

2013-?: Third Foundation ?

Merci Alan !

- For allowing me to return to my home country
  - Remember that chat in Warsaw in 2000?
- For allowing us to pursue the g-mode quest
  - It took time to have GOLF part of Phoebus !
- For allowing me to realize which field of Science was really mine: helioseismology !
  - Finally we will be doing the Filtergraph of PHI