HELIOSEISMOLOGY : FROM GROUND OR SPACE
A WORLDWIDE COOPERATION

THE STATE OF THE ART IN HELIOSEISMIC GROUND-BASED EXPERIMENTS

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Abstract. The new results obtained from the observation of solar oscillations over the past decade, have a direct impact on our knowledge of the Sun's interior. As a consequence, a great interest in helioseismology has arisen and is reflected in the development of new observational projects as well as new analyse and inversion techniques. In this review we will describe the present ground-based observational programmes, which, unlike the space ones, are mostly designed to produce high quality data over very long time spans (up to solar cycle time scales). The characteristics of the various observational programmes, single-site and network, will be described together with their performances, the main results obtained up to now, and some other logistical aspects.

1. Introduction

At present, helioseismology observations are carried out from both space and ground-based observatories, and by both means it is possible to overcome the main difficulty for progress in helioseismology: the non-continuity of observations. By establishing ground-based networks at appropriate locations on the Earth (like *BiSON, GONG, IRIS*, etc.) and spacecraft in adequate orbits (like *SOHO*), it is possible to continuously observe the Sun for long periods of time (months, years). It is not now the right time for establishing a competition between these two types of observing modes; each one has clear advantages and disadvantages. On the contrary, it is hoped that real progress in helioseismology will take place only from the extensive and precise analysis, as well as comparison, of both types of data. Since this particular review is devoted to ground-based observational projects, let us point out two distinct aspects of this kind of observation: the *control* and the

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lifetime. The possibility of repairing, modifying or even re-designing ground-based experiments leads to the possibility of having them operational over very long periods of time (many solar cycles). This is, at present, not possible with space experiments. In addition, the former offer the possibility of performing simultaneous observations which could allow for detection of annoying systematic errors. In summary, as pointed out recently (Harvey 1995), the combination of already existing space and ground data will accelerate the transformation of helioseismology from an *Art* into a *Science.*

In the following sections we will describe two groups of ground-based experiments: those having more than one *identical* operational instrument at different places (networks) and those having a single one (single site). For each of these groups we will compare the different characteristics and performances.

2. Helioseismology networks

Performing solar seismology observations from two or more sites simultaneously with similar instruments, fulfills various objectives: it not only provides with an uninterrupted series of observations but also serves to detect systematic errors and, most importantly, to prove the solar origin of any detected signal. Of course, since this last objective is very well accomplished today in the case of the solar origin of the 5 minute oscillation, the former ones become more important. Historically, it was in 1978 when the Birmingham-Tenerife group performed simultaneous solar oscillation observations from two different observatories (Claverie *et al.* 1979). Although the two sites were 2500 km distant, they were separated by only 1 hour in longitude. However, the detected signal (see Figure 1) definitively proved the solar origin of the 5 minute signal and also served to anticipate the network strategy.

After that big success, the Nice University group performed observations at the South Pole in the winter of 1979–80 to make use of the Sun's continuous presence during southern summer, in order to obtain continuous observations. As a result, they obtained 5 full days of continuous data (Grec, Fossat & Pomerantz 1980) used to obtain the best power spectrum of solar p-modes at that time. Moreover the strategy of the Birmingham-Tenerife group proceeded according to the network concept. As a result, in the summer of 1981 they ran two identical instruments at Haleakala (Hawaii) and Tenerife obtaining a superb $\sim$ 60% duty cycle over three months. The clean power spectrum of solar p-modes obtained from these observations, was used as a reference until very recently. The most important of these historical facts is that in 1981 the "network" became well proven and feasible, allowing other groups all around the world to develop the different projects they had in

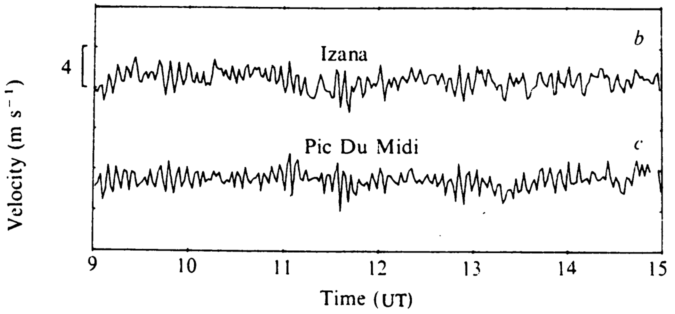

Figure 1. Comparison of the solar velocity residuals, showing the signature of the 5 minute oscillations, obtained simultaneously at the Observatorio del Teide (Izaña, Tenerife) and Observatoire de Pic du Midi (France) on 6 August 1978 (Claverie *et al.* 1979).

mind. At present, the operational helioseismology projects, in alphabetical order, are the following.

2.1. BISON

The BiSON (**B**irmingham **S**olar **O**scillations **N**etwork), was the first to become fully operational and has been conceived as "a global network of resonant-scattering spectrometers observing the low-ℓ solar p-modes" (Chaplin *et al.* 1996a). The zero resolution (Sun as a star) basic instrument consists of a spectrometer using the resonant scattering technique with potassium cells (KI 769.9 nm) to obtain very precise and stable measurements of the radial velocity of the Sun, from which the signals from solar oscillations of degree $\ell \leq 4$ are obtained. The project was fully funded by the PPARC (Particle Physics and Astronomy Research Council) to construct, deploy and operate a six-site network and became fully operational in 1993 once the last node was installed (Narrabri, Australia) late in 1992 (see Table 1 and Figure 2 for the node location). The whole network deployment took more than 10 years, after the first two sites were established in 1981. This is why the network consists of 3 different generations of instruments, the first one being the "Mark-I" at the Observatorio del Teide built in 1974. In spite of this apparent weakness, the quality of the actual data is the best among the low-degree helioseismic data sets.

From the scientific point of view, the contribution of this particular data set to helioseismology is really important in the sense that many of the basic results previously obtained by other groups using one-site instrument were confirmed and, in many cases, extended (*i.e.* the solar cycle changes in the p-mode spectrum, the spacings of the p-modes and their relation with solar models, the background solar velocity spectrum, etc.). The BiSON

Project has set up a WWW page (http://bison.ph.bham.ac.uk) where much more information can be found not only about the project but also on the scientific results and publications.

2.2. GONG

The GONG (**G**lobal **O**scillations **N**etwork **G**roup) is a "community based project to conduct a detailed study of the solar internal structure and dynamics, using Helioseismology" (Leibacher 1995). This project was developed in 1985 at the National Solar Observatory and funded by the NSF (National Science Foundation) to take observations over at least three years. The Network completed deployment in October 1995 and the first year's data has been obtained recently. The Network consists of 6 nodes which, from a 5 year site survey, have proven to be able to produce a duty cycle as large as 93% over a full year. The basic instrument, a modified Michelson interferometer, produces radial velocity, intensity and modulation images of the whole Sun on a 256 x 243 pixel^2 CCD camera at the Ni 676.8 nm spectral line. With the given geometry, GONG instruments will cover a wide range of mode degree (ℓ up to 250), although the sensitivity to lowest degree modes ($\ell < 3$) is still unclear. Due to the imaging capabilities of the instruments, the network is producing a huge amount of data ($\sim$ 1 Gbyte per day) which needs to the reduced, calibrated, combined and analysed. To undertake this enormous task, GONG has not only supplied the required computational and software tools but also, and more importantly, invited scientists world wide to contribute significantly in the project's success. In this spirit, the project has also tried, whenever possible, to involve the local people and institutions that host the GONG nodes, thus converting GONG into a really community-based research project.

The extensive analysis of the first operational month has been published recently (GONG team 1996), showing not only the exceptional data quality but also new results on the Sun's internal structure (latitudinal dependence of the temperature distribution, the fast rotation just below its surface, detection of poleward flows at the surface, etc.). A complete description of the project and related issues, can be also found at the WWW (http://www.gong.noao.edu).

2.3. HDHN

The third network currently operational is so recent that no official acronym yet exists. We have named it HDHN (**H**igh **D**egree **H**elioseismology **N**etwork). It has been concieved as a "three stations network capable of studying high degree *p*-modes on a nearly continuous basis for several month a year" (Rhodes *et al.* 1995). The background of this joint international

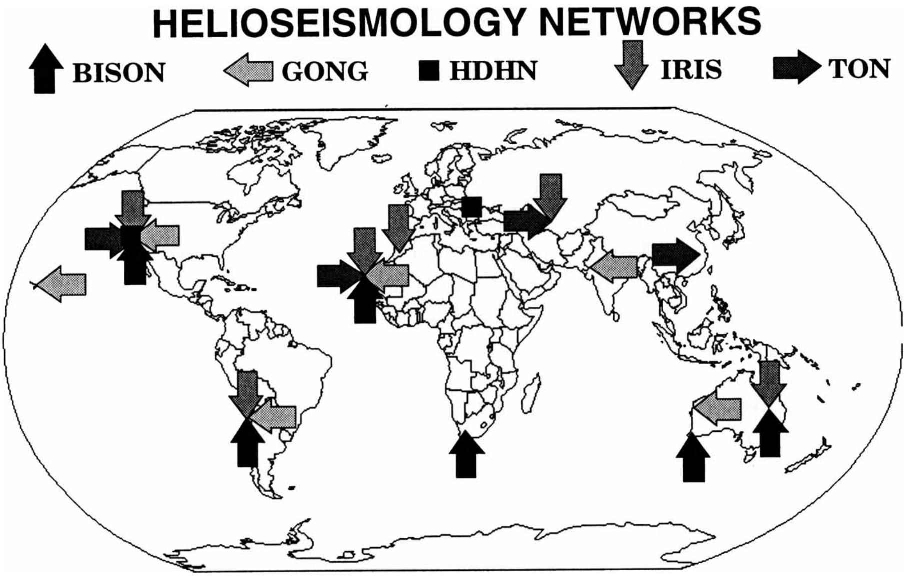

Figure 2. Geographical location of the currently operational Helioseismology Network nodes.

research project was the helioseismic programme operated, since 1984, at Mount Wilson 60-Foot Solar Tower. The second node, located at the Crimean Astrophysical Observatory, came into operation in June 1996, thus converting this programme into a network (Rhodes 1996). Plans for a third node (possibly at the Solar Observatory of the V. G. Fesenkov Astrophysical Institute, Kazakhstan) already exists although negotiations have not yet been concluded. Even with the first two sites, it is expected to obtain up to 22 hours per day solar coverage 5 month per year. The basic instrument of the network is a sodium magneto-optical filter (MOF), originally developed by A. Cacciani (Cacciani *et al.* 1978), which will produce radial velocity maps of the whole Sun. The nominal detector, a 1024 x 1024 pixel^2 CCD camera, will allow angular mode degrees up to $\ell \sim 1000$ to be reached; the currently installed ones (490 x 490), covers only up to $\ell = 600$. One of the main interests of this network is to provide the Dopplergrams for coordinate space and ground-based studies of the high-degree oscillations during the flight of the SOI experiment on board *SOHO*. Of course, the capability of extending the observations over much longer time scales, results in a great interest in the investigation of temporal variability in the internal and atmospheric solar structure. The financial support for this project is provided by NASA and the NSF.

TABLE 1. Location of the ground-based network nodes.

BiSON
Mount Wilson Observatory, California (USA)
Las Campanas Observatory (Chile)
Observatorio del Teide, Tenerife (Spain)
South African Astronomical Observatory, Sutherland (South Africa)
Carnarvon, Western Australia (Australia)
Paul Wild Observatory, Narrabri, NSW (Australia)
GONG
Big Bear Solar Observatory, California (USA)
High Altitude Observatory, Mauna Loa, Hawaii (USA)
Learmonth Solar Observatory, Western Australia (Australia)
Udaipur Solar Observatory (India)
Observatorio del Teide, Tenerife (Spain)
Cerro Tololo Interamerican Observatory (Chile)
HDHN
Mount Wilson Observatory, California (USA)
Crimean Astrophysical Observatory, Nauchny (Crimea)
IRIS
IPS Solar Observatory, Narrabri, NSW (Australia)
Kumbel, Tashkent (Uzbekistan)
Oukaimeden (Morroco)
Observatorio del Teide, Tenerife (Spain)
European Southern Observatory, La Silla (Chile)
John Wilcox Solar Observatory, Stanford, California (USA)
TON
Huariou Solar Observing Station, Beijing (P. R. China)
Tashkent Astrophysical Institute, Tashkent (Uzbekistan)
Observatorio del Teide, Tenerife (Spain)
Big Bear Solar Observatory, California (USA)

2.4. IRIS

The IRIS (International **R**esearch of the **I**nterior of the **S**un) network is an "International Cooperative Project to deploy and operate a 6-site network, to perform continuous full disk measurements to give access to the solar modes of very low degree, along, at least, one complete solar cycle" (Fossat 1995). The project was conceived by the Nice University group in the mid eighties; their experience with the South Pole observations led the project to be funded by the INSU (Intitute National des Sciences de l'Univers), which allowed the development and construction of better instrumentation. Deployment started in 1989 and ended in summer 1994 with 6 nodes fully operational. The basic instrument is similar in concept to BiSON: by using the resonant scattering technique the radial velocity of the Sun is precisely measured, thus allowing a good determination of the low-degree solar oscillation modes. Unlike BiSON, IRIS uses the D1 sodium spectral line instead of potassium; some other technical differences also exist. Due to the limited resources of the project, in terms of money, spares and manpower and also to the goal of running over more than one solar cycle, the strategy has been to involve, at all levels, local institutions hosting the nodes. In the IRIS framework, collaboration between the different institutions has been exploited to the full, thereby resulting in a great benefit not only to the project but also to local groups. Furthermore, IRIS is an open scientific community in which any one interested in the research can access the data and the existing project facilities. Like GONG, IRIS has a clear structure and policy in order to give adequate credit to all participants according to the importance of their contributions. More extensive information about the project, scientific achievements and future plans can be found at the WWW address: http://boulega.unice.fr.

2.5. TON

The TON (**T**aiwan **O**scillations **N**etwork) is a "ground-based network to measure solar K-line intensity oscillations to study the internal structure of the sun" (Chou *et al.* 1995). Unlike the other experiments, the oscillations are measured only as spectral intensity variations of the whole Sun and with a very high spatial resolution (1080 x 1080 pixel^2), allowing mode degrees up to $\ell \sim 1000$ to be reached. The whole network will consist of 6 nodes, 4 of which are already operational (see Figure 2). It is surprising how fast the construction, deployment and operation has proceeded, when compared with the other projects: TON has spent only 3 years in reaching its present state. The project, although funded by the National Research Council of the ROC, has very limited manpower resources compared with the enormous tasks that the data require: at present TON is producing ~ 6 Gbyte per day and once completed will go up to 9 Gbyte. Because of the high resolution and quality of these data, they have become very useful for sunspot and local helioseismology (Chen *et al.* 1996) and ring diagram analysis (González *et al.* 1995).

3. Discussion

Now the main characteristics of the five existing networks have been presented, it would be convenient to summarise, compare them and comment on some aspects. In Table 3 some of the networks' characteristics are presented. First of all, one can appreciate that two of the networks are still not fully deployed as planned. Furthermore, the BiSON group is pushing for a large number of nodes (eight). The reasons given are twofold. First, after many years of experience, they concluded that with 6 nodes a duty cycle of not more than 80% over a full year could be achieved. Secondly, increasing the number of modes implies more overlap between different stations' data, which can be used for many scientific/instrumental purposes, such as checking the local clock timing, proving the validity of the data calibration, studying the solar background noise by cross-correlation techniques, etc. The reduced number of solar spectral lines used to measure the solar oscillations as well as the observed magnitudes (spectral intensity and Doppler velocity), is also surprising. Concerning the observing strategies that the different networks follow, we can separate these in three groups. The first aims at the full involvement of the local people-institution performing the observations, into the project. In this case, the degree of interest and care taken over the observations is very high and is reflected in the degree of automatisation required in the instruments and also in the high operational duty cycle. This is the case for IRIS and TON. For the second group, a complementary strategy is used. By working really hard, it is possible to get a rather simple instrumentation with a high degree of automatisation and even remote control. Local people and institutions become irrelevant as far as operation is concerned, and only minor services are required from them. This is the way in which the BiSON project proceeds with a very high level of performance from 1993 onwards. The third group is a mixture of the other two and is probably the ideal one: instrumentation highly automated and local people deeply involved in the project. This is the case for GONG. Of course in the first and last options, the network and local data gathered (as well as the derived products) are shared among the community involved, which results in a clear scientific benefit.

Finally, we should comment on the data duty cycles already obtained by the networks. GONG had the expectation, after many years of site survey data, of obtaining a 93% duty cycle over a full year with the selected nodes. At present, and after the first 8 month of six-site operation (November 95 to June 96), the achieved mean value is 90%, the best and the worst monthly values being 94 and 82%, respectively. It looks, then, as if the claim by the BiSON group of a maximum of 80% over a full year with six sites can no longer be supported. The BiSON network has reached monthly peak values up to 94% and the values for a complete year are 68 and 78% for 1993 and 1994, respectively. On the other hand, the IRIS network has not yet reached comparable figures. The best duty cycle for a full year's data is ~30%; the highest values for a two-month series between 1989 and 1994 are ~ 60%. This situation can radically change in the near future: thanks to the collaborative IRIS spirit, it is planned to use other similar data to be merged and combined with the IRIS ones in order to increase the observational duty cycle. In particular, integrated data provided by the MOF instrument (Cacciani *et al.* 1988), GONG and others is planned to be used.

TABLE 2. Main characteristics of the ground-based helioseismology networks: present and expected number of nodes, date of completion, observed physical magnitude (Doppler velocity, intensity and modulation), wavelength used, mode angular degree range and sampling time of the basic measurement.

	Present Nodes	Total Nodes	Fully Oper.	Obser. Param.	λ (nm)	$\Delta\ell$	Δt (s)
BiSON	6	8?	1993	V_D	KI 769.9	$\ell \leq 4$	40
GONG	6	6	1995	$V_D IM$	Ni 676.8	$\ell \leq 250$	60
HDHN	2	3	-	V_D	Na D1,D2	$\ell \leq 600^\dagger$	60
IRIS	6	$6^\ddagger$	1994	V_D	NaD1 589.6	$\ell \leq 4$	15
TON	4	6	-	I	CaK 393.4	$\ell \leq 1000$	60

($\dagger$): will go up to $\ell \sim 1000$. ($\ddagger$): uses data from other instruments.

4. Single-site experiments

Having seen the previous projects one can ask if still there is a role to play for the single-site helioseismology experiments. Apparently, they cannot compete in data quality, as they are limited to data duty cycles below 30% over a full year. There is, however, a positive answer: these experiments have an extremely important role in the future of helioseismology. In a recent review (Duval 1995) some of the important issues that small ground-based experiments can face have been pointed out: long-term (solar cycle) and high temporal frequency studies (for which high duty cycles are not so important), testing new techniques and developing new instrumentation, to compare their results with other experiments or with network's results in order to understand systematic errors, etc. Let us briefly describe each one of the operational experiments.

4.1. CRAO-WSO

This acronym stands for the **Cr**imea **A**strophysical **O**bservatory and the **W**ilcox **S**olar **O**bservatory, whose observational programmes have run in parallel since ~1977, (Kotov, Haneychuk & Tsap 1995; Scherrer, Hoeksema & Kotov 1993). Both instruments are modified magnetographs to measure the differential Doppler velocity of the central part of the solar disc, and thus have sensitivity to mode degrees $2 \leq \ell \leq 6$. Although observations at both places have not been continuous on a daily basis, they have significant coverage for most of the years. Their main interest has been focused on studying and proving the solar origin of the 160-minute oscillation: how it appears in both data sets separately and in the combined data; the frequency, phase and power stability over the last twenty years, etc. As everyone is aware today, the results claimed (Kotov *et al.* 1995) are not generally accepted and many opposite claims exist too. The Stanford data have also been used in the past (Henning *et al.* 1986) for p-mode studies to cover the lack between low and intermediate-degree mode determinations and for low-degree gravity modes detection (Delache & Scherrer 1983).

4.2. HLH

The **H**igh-**ℓ** **H**eliosismometer is an NSO project whose primary goal is the "long term observations of high degree frequencies and to study local helioseismology" (Bachmann *et al.* 1995). The instrument is a modification of the device used for the South Pole campaigns and is located at the Kitt Peak Observatory, measuring the brightness signal at the Ca-K line with a high spatial resolution (ℓ up to 1200). The operational plan, started in March 1993, is to run in a systematic way four days every four weeks; some additional and different plans are also foreseen (Hill 1996). These observations could be very useful in the framework of the new research fields arising in helioseismology, such as time-distance analysis, the ring diagrams, etc.

4.3. LOI-T

The **L**uminosity **O**scillations **I**mager installed at the Observatorio del **T**eide is the Qualification Model of the instrument flying in the VIRGO package on board *SOHO*. Its primary goal is to perform "measurements of the low degree p-modes and to test the performances and develop new techniques applied to the space model." It has been running continuously on a daily basis since 1994, measuring the brightness signal at 550 nm. Its special pixel design allows it to measure modes of degrees up to $\ell = 7$ and scientific exploitation of the data is now taking place: the rotational splittings and mean frequencies have been determined and inversions performed (Rabello-

Soares *et al.* 1996). Also, the solar radius signal provided by the instrument has been analysed (Rabello-Soares 1996). Overall, the great success of this instrument raises expectations of a good scientific output from its space counterpart, free from the earth's atmosphere and without the day-night interruption.

4.4. LOWL

The **Low-ℓ** is an HAO project whose primary goal is to "measure frequency splittings of low-degree modes in order to infer rotation rate and other properties of the solar core" (Tomczyk *et al.* 1995). By using the MOF technique at the potassium line with a moderate spatial resolution (25 arcsec), it produces full-Sun Doppler velocity maps. Installed at Mauna Loa Solar Observatory in Hawaii at the beginning of 1994, it has been continuously running since then on a daily basis. The first two years of data have already been analysed for p-mode frequency determinations, rotational splitting and the corresponding inversions (Schou, Tomczyk & Thompson 1996). The good point of this instrument is precisely the combination of the advantages of an imaging instrument (allowing separation of m-components), with the extreme stability provided by the resonant scattering technique. In addition, it provides a homogeneous set of p-mode frequencies ranging from ℓ=1 up to 80, which is ideal for performing inversions of the deeper layers of the Sun. In principle, because of the spatial resolution, it should be able to cover the whole range from $\ell = 0$ up to $\ell = 100$, but some work should still be done on the instrumental and on the data analysis areas. Recently, the project has been funded to construct and deploy a second instrument, which will be operating possibly by the end of next summer, the LOWL thus becoming the sixth helioseismology network.

4.5. MKI

The MKI instrument corresponds to the first resonant scattering spectrometer made by the University of Birmingham group, back in 1974. It was installed in 1977 at the Observatorio del Teide where it ran, mainly over summer seasons, until 1984. At that point it was upgraded and since then it has been operated continuously, by the IAC group, on a daily basis. The extremely high temporal stability of this instrument, which unlike the rest of the BiSON network ones works in photon counting mode, makes it ideal for long-term study of solar oscillation behaviour. The scientific exploitation of the data provided by MKI has been very successful: it is at present the single ground-based instrument that produces the greatest quantity of scientific papers (Harvey 1995). Among the many issues studied with this data set, we should mention the detailed study of the p-mode spectrum (Anguera *et al.* 1992), its changes related with the solar activity cycle (Régulo *et al.* 1994), the study of the background solar velocity spectrum (Pallé *et al.* 1994), the gravity mode search, etc.

4.6. POI

The **P**-mode **O**scillation **I**mager is an instrument devoted to "p-mode measurements at intermediate degree and high temporal frequencies" (Ronan & LaBonte 1994). The instrument measures the Ca-K line brightness signal with a spatial resolution that allows mode degree up to $\ell \sim 300$ to be reached. It was installed in 1991 at the Mees Solar Observatory in Hawaii and the possibility of a second site at Fort Yukon (Alaska) is envisaged (LaBonte, Ronan & Kupke 1995).

TABLE 3. Characteristics of the single-site helioseismology projects

	Operated since	Obser. Param.	λ (nm)	$\Delta\ell$	Δt(s)	Institution
CrAO	1974	V_D	FeI 512.4	$2 \leq \ell \leq 4$	300	CrAO
HLH	1993	I	CaII 393.4	$\ell \sim 1200$	60	NS-NOAO
LOI-T	1994	I	500 ± 5	$2 \leq \ell \leq 5$	~ 53	SSD-IAC
LOWL	1994	V_D	KI 769.9	$\ell \leq 80$	15	HAO-NCAR
MKI	1976	V_D	KI 769.9	$\ell \leq 4$	2	IAC
WSO	1977	V_D	FeI 512.4	$2 \leq \ell \leq 5$	15	U. Stanford
POI	1991	I	CaII 393.4	$\ell \leq 300$	30	U. Hawaii

5. Conclusions

From the above description of all operational ground-based helioseismology projects, the perspectives seem really exceptional. Although the various projects provide a good coverage of mode-degree sensitivities (some of them overlapping), the variety of spectral lines used, techniques and physical parameters measured, is rather poorer (see Tables 2 and 3). This drawback has already been pointed out (Harvey 1995) and can be overcome by simultaneous comparison of data from different instruments in order to minimise or even to identify the possible sources of systematic errors. In addition, data provided by currently operational space instruments, which are similar in type to those obtained at ground-based observatories, will really help in this task. It seems that at present the sources of discrepancy between results obtained by different experiments are more in the realm of data analysis techniques than in the instrumental part, although this is not conclusive. As a good example, we could mention the measurement of the frequency splittings of p-modes: different data sets produce different rotation profiles derived from inversions. In particular, the basic splitting measurement, that corresponding to the $\ell = 1$ p-modes, is very contradictory, as can be seen in Figure 3.From this figure it would seem that the state of the art of helioseismology is very crude, in that there is no agreement in one of the most basic measurements. We do not think that this is so; these measurements are extremely delicate and the physics of the solar oscillations is not yet well understood. This is the basic reason for running many experiments simultaneously: to get rid of systematics and also to establish the obtained results beyond doubt.

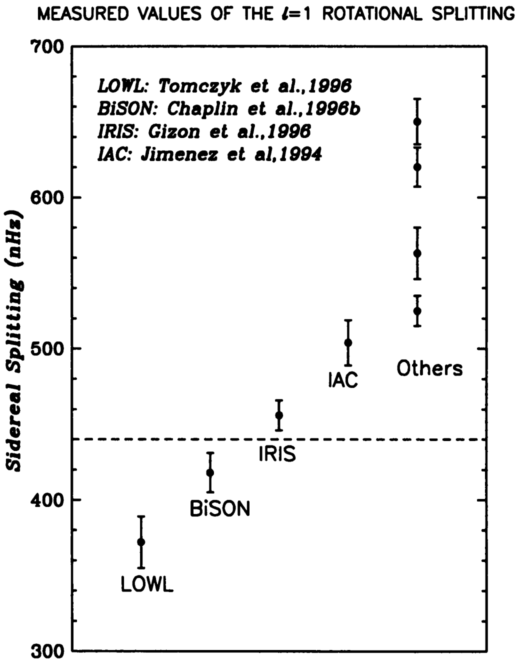

Figure 3. Some of the most recent observational determinations of the $\ell = 1$ rotational splitting. Under the label *Others*, values not yet published are included. The dashed line corresponds to the Sun's equatorial surface rotation.

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