VIRGO: EXPERIMENT FOR HELIOSEISMOLOGY AND SOLAR IRRADIANCE MONITORING

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Abstract. The scientific objective of the VIRGO experiment (Variability of solar IRradiance and Gravity Oscillations) is to determine the characteristics of pressure and internal gravity oscillations by observing irradiance and radiance variations, to measure the solar total and spectral irradiance and to quantify their variability over periods of days to the duration of the mission. With these data helioseismological methods can be used to probe the solar interior. Certain characteristics of convection and its interaction with magnetic

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fields, related to, for example, activity, will be studied from the results of the irradiance monitoring and from the comparison of amplitudes and phases of the oscillations as manifest in brightness from VIRGO, in velocity from GOLF, and in both velocity and continuum intensity from SOI/MDI. The VIRGO experiment contains two different active-cavity radiometers for monitoring the solar 'constant', two three-channel sunphotometers (SPM) for the measurement of the spectral irradiance at 402, 500 and 862 nm, and a low-resolution imager (LOI) with 12 pixels, for the measurement of the radiance distribution over the solar disk at 500 nm. In this paper the scientific objectives of VIRGO are presented, the instruments and the data acquisition and control system are described in detail, and their measured performance is given.

Key words: Helioseismology – Total Solar Irradiance – Spectral Solar Irradiance – Low-Resolution Solar Radiance – SOHO Mission

1. Introduction

The VIRGO investigation (Variability of solar IRradiance and Gravity Oscillations) on SOHO (SOlar and Heliospheric Observatory) emerged from several former experiments that had already been flown or were in the manufacturing phase at the time of the proposal. SOHO offered the unique opportunity to continue the research on solar irradiance variability and to push forward helioseismology by the observation of brightness fluctuations under the ideal conditions at the Sun-Earth Lagrange point $L1$ where continuous exposure to the Sun is possible.

This research field is already well established at the participating institutes, not only for building the experiment, but also in many theoretical solar and astrophysical aspects.

The instruments used for these observations – active cavity radiometers and high-precision sunphotometers (filter-radiometers) – have flown on balloons and rockets (Fröhlich & van der Raay 1984, Brusa et al. 1983, Willson et al. 1986), on several US shuttle missions (Crommelynck & Domingo 1984), on the European Retrievable Carrier (EURECA) mission (Crommelynck et al. 1993) and on the Russian interplanetary mission to Mars and Phobos (Fröhlich et al. 1990). They have proven their ability to perform to the specifications set forth by the objectives of VIRGO (see Section 3). Thus, the design and manufacture of these instruments is based on long-standing experience. Only small modifications were applied to improve the performance or to correct for problems encountered in former experiments. One instrument, the Luminosity Oscillation Imager (LOI), is new in concept and design and was conceived mainly for the observation of dynamical solar oscillations. Together with a data acquisition and control system and a power supply, these instruments form the VIRGO experiment which is described in detail in this paper.

An investigation like VIRGO depends strongly on theoretical support, both in the design phase of the instrumentation and for the planning of the

evaluation of the observations. Some of these aspects as well as the plans for the VIRGO Data Centre will briefly be described.

2. The VIRGO Team

VIRGO is a co-operative effort of many individual scientists and engineers at several institutes all over Europe and in the USA. The team is led by Principal Investigator (PI) Claus Fröhlich, and consists of the following Co-Invesigators (CoI), listed in alphabetical order together with their responsibilities:

Bo Andersen (NSC, Experiment Scientist), Thierry Appourchaux (SSD, luminosity oscillation imager LOI), Gabrielle Berthomieu (OCA, theoretical support), Dominique Crommelynck (IRMB, radiometer DIARAD), Philippe Delache (OCA, theoretical support, died 13 October 1994), Werner Däppen (USC, theoretical support), Vicente Domingo (SSD, VIRGO operations and liaison with the SOHO Project), Alain Fichot (IRMB, radiometer DIARAD) Douglas Gough (IoA & DAMTP, theoretical support, liaison with the GOLF and SOI/MDI experiments on SOHO), Todd Hoeksema (CSSA, liaison with the SOI/MDI experiment on SOHO), Antonio Jiménez (IAC, EGSE and VIRGO Data Centre), Andrew Jones (NOAO, LOI instrument development and data interpretation), Judit Pap (JPL, data interpretation support), Janine Provost (OCA, theoretical support), Teodoro Roca Cortés (IAC, VIRGO Data Centre), José Romero (PMOD/WRC, radiometers PMO6-V), Thierry Toutain (OCA, theoretical support, liaison with the GOLF experiment on SOHO), Christoph Wehrli (PMOD/WRC, sunphotometers SPM) and Richard Willson (JPL, liaison with other solar irradiance monitoring experiments).

The following institutes provided hardware; their work has been coordinated by the VIRGO Instrument Manager Hansjörg Roth (PMOD/WRC), and the hardware was constructed at the institutes under the responsibility of the technical staff listed:

 - Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center (PMOD/WRC): responsible for the overall management of VIR-GO, the design and manufacturing of the active cavity radiometers PMO6-V, the sunphotometers (SPM), the data acquisition and control system (DAS), the power distribution unit in the the sensor package (SP) and the SP itself. Technical staff: Thomas Fröhlich (procurement, electronics, cleanliness), Adolf Geisseler (electronics), Silvio Koller (procurement, electronics), Hansjörg Roth (managment, electronics), Urs Schütz (radiometers, mechanics), Urs Wyss (mechanics);
 - Institut Royal Météorologique de Belgique (IRMB): responsible for the design and manufacture of the IRMB active cavity radiometer (DIA-RAD). Technical staff: André Chevalier (management, radiometer, elec-

tronics), Christian Conscience (optical characterization, cleanliness), Marc Lombaerts (software, electronics), Pierre Malcorps (mechanics);

- Space Science Department of ESA (SSD): responsible for the design and manufacture of the luminosity oscillation imager (LOI); technical staff: Thierry Beaufort (electronics), Didier Martin (electronics), Jos Fleur (mechanics), Samuel Lévêque (detector and optical tests, cleanliness), Udo Telljohann (management, electronics);
- Instituto de Astrofísica de Canarias (IAC): responsible for the design and manufacture of the power supply (PS) and for the VIRGO Data Centre (VDC) including the design and programming of the electrical ground support equipment (EGSE); technical staff: José Herreros (management, contracts), Maria Gómez (software).

The hardware institutes have been concerned not only with manufacturing and testing their instruments or sub-units, but have also participated with their personnel in many performance and environmental tests at experiment and system level.

3. Scientific Objectives

The VIRGO experiment will provide the following observational and derived data:

- continuous high-precision, high-stability and high-accuracy measurements of the solar total and spectral irradiance and spectral radiance variation;
- continuous measurements of the solar polar and equatorial diameter;
- frequencies, amplitudes and phases of oscillation modes in the frequency range of 1 μHz to 8 mHz;

The total irradiance is measured with active cavity radiometers (PM06-V and the Differential Irradiance Absolute Radiometer, DIARAD), the spectral irradiance by three-channel Sunphotometers (SPM) and the radiance with 12 resolution elements on the solar disk using the Luminosity Oscillations Imager (LOI).

These data will be utilized to achieve the main scientific objectives of VIRGO summarized in the following list :

- detect and classify low-degree g modes of solar oscillations;
- determine the sound speed, density stratification and rotation in the solar interior, specifically determine the physical and dynamical properties of the solar core;
- study the solar atmosphere through comparison of amplitudes and phases of the p modes with these from GOLF (Global Oscillations at Low Frequencies) and SOI/MDI (Solar Oscillation Investigation/Michelson Doppler Imager);

- search for the long periodicities or quasiperiodicities that have been found in other solar parameters;
- utilize the solar 'noise' signal to develop models for the global signature of stellar surface parameters;
- determine properties of the solar asphericity and its variation in time;
- study the relation between p-mode frequency changes and irradiance variations;
- study the influence of solar active regions and other large-scale structures on total and spectral irradiance;
- study the solar energy budget;
- provide accurate total and spectral irradiance data for input in terrestrial climate modelling.

Observations of the total solar irradiance will be a continuation of previous measurements from satellites, which have been performed by the radiometer HF of the Earth Radiation Budget experiment (ERB) on the NIMBUS-7 satellite from November 1978 until January 1993 (Hoyt et al. 1992), by ACRIM I on the Solar Maximum Mission satellite (SMM) from February 1980 until June 1989 (e.g. Willson & Hudson 1991), by ACRIM II on the Upper Atmosphere Research Satellite (UARS) since October 1991 (Willson 1992) and by SOVA (Solar Variability) on the European Retrievable Carrier (EURECA) from August 1992 until May 1993 (Crommelynck et al. 1993, Romero et al. 1994).

The spectral irradiance data will resemble the data from IPHIR (Interplanetary Helioseismology with irradiance observations) on the Soviet PHOBOS Mission (Fröhlich et al. 1990). As a secondary output the internal guider of the LOI component will produce time series of data proportional to the polar and equatorial solar diameters. All the data will have higher precision than any of those acquired formerly, both because of improvements to the instrumentation and because of the ideal location of the SOHO spacecraft which allows uninterrupted observation of the Sun. In addition, the spatial resolution of the LOI will allow us to deconvolve effects of different photospheric spatial variation on the solar irradiance, thereby enabling us to identify degrees and azimuthal orders of low-degree solar oscillations. The variations seen in these time series are a superposition of random and periodic phenomena that cause the whole variability of solar irradiance, both bolometric and at different wavelengths. This will be supplemented by even more detailed information from the flux budget product (128 × 128 pixel temporally averaged image of the solar disk), which will be studied in conjunction with the magnetograms provided by SOI/MDI on SOHO.

The scientific content of the gathered time series of irradiance can be studied in different ways. One way is to use it to observe and characterize solar oscillations. For the p modes the method has proven its value (e.g. Toutain & Fröhlich 1992), and VIRGO will contribute by improving the

reliability of the data to help resolve still controversial issues such as, for example, the temporal amplitude variation which is crucial for understanding in detail the excitation and damping mechanisms. But more important is the determination of the structure of the energy generating core. Of greatest interest, perhaps, is its relevance to the solar neutrino problem, for that has implications in other branches of physics. We do not even know for sure whether the neutrino problem is an issue in stellar-structure theory or is an issue in nuclear or particle physics (see e.g. Anselmann *et al.* 1994). If it is the former, our task must surely be to investigate the wider implications in astrophysics. If it is the latter, it behoves us to determine the structure of the core - its radial stratification and its horizontal and temporal variations - as accurately as possible, in order to provide the most reliable information about the neutrino source to couple with the next generation of neutrino observations. To this end we need not only to model the variation of temperature, pressure and density, but also to try to model the related variation of chemical composition, both helium (hydrogen) abundance and the heavy-element abundances, using the direct seismic inferences. Together, the instruments on VIRGO will be able to provide extremely accurate frequencies of low-degree modes which are an essential complement to the intermediate- and high-degree data from SOI/MDI required to render it possible to carry out inversions for both the spherical and aspherical components of the stratification in the region where the thermonuclear reactions are taking place (Gough & Kosovichev 1993).

The unambiguous detection and identification of solar gravity modes would be a real breakthrough for improving quite substantially our knowledge of the structure of the solar core. All attempts up to now have somehow failed because the amplitudes of the modes seem to be so small that the g-mode signals are buried in the noise (Fröhlich & Delache 1984). Although most of this noise is of solar origin, some observational and methodological improvements can be expected. Oscillation periods of several hours are difficult to observe from the ground and from satellites in low-Earth orbits; moreover, this range could not be explored by IPHIR owing to the noise introduced by the influence of the variability of the spacecraft pointing. This period range, however, looks promising for the search of g modes, because the modes are not as crowded in frequency as they are at lower frequencies, and the separation of the different l and m is easier. Nevertheless, the amplitudes may still be smaller than the solar noise. Probably, the only possibility to overcome this problem is similar to the heterodyne detection of a signal at a known frequency buried in noise. Another possibility may be to utilize the difference in centre-to-limb variation of the g-mode signal and the solar noise. The crucial point in the detectability of solar g modes is the surface amplitude of the modes. This again depends on the mode amplitudes below the convection zone and the amount of attenuation of the modes through

the evanescent convection zone. Numerical modelling indicates that convective overshoot into the interior may excite the waves (Andersen 1994) to amplitudes that should be detetcable at the surface. This result, however, may be uncertain due to the inadequate treatment of radiative damping in the interior.

We do not know the values of the frequencies of the individual modes, but we do have information from theory about the frequency pattern for different solar models, and the splitting as a functional of rotation (e.g. Berthomieu et al. 1978, Provost & Berthomieu 1986) and asphericity. As several trials of this method have shown – although with less reliable data and at lower frequencies –this a priori information alone may not be sufficient (e.g. Fröhlich & Delache 1984). As a further ingredient the predicted relative visibility of different modes observed as intensity fluctuations and as Doppler shifts can be used. The relation between the different apparent amplitudes varies with frequency and depends also on the degree of the g mode (Berthomieu & Provost 1990), and thus the detection and unique identification of these modes may be possible only by combining data from VIRGO, GOLF and SOI/MDI, which are all on SOHO observing the Sun simultaneously. A reliable calculation of the visibilities is not available, however, because it must certainly be influenced by convection, which cannot reliably be modelled. It is important to realize that even if g modes cannot be detected the accurate measurement of low-degree p modes of low order, which VIRGO is well suited to accomplish, will augment quite substantially our diagnostic capabilities for investigating the structure of the solar core.

Solar irradiance variability can be used to investigate many physical phenomena related to convection, the effects of magnetic fields, solar activity, etc. (e.g. Fröhlich 1994). We may be interested in the phenomena causing the variation, e.g. sunspots, or in the underlying physical causes for the existence of sunspots, e.g. dynamo theory, rotation and convection. The causes of irradiance changes are crucially important for the understanding of solar and stellar evolution. Irrespective of the cause, knowledge of the possible medium- and long-term variations of the solar irradiance are equally important for the understanding of terrestrial climatic change. While the solar energy in the entire spectrum and particularly at UV wavelengths has been monitored from space for more than one and a half decades, no simultaneous space observations of the solar total and spectral irradiance have been made systematically. Besides its climatic implications, knowledge of the amount of the solar energy flux and its variability at visible and red wavelengths is also important for solar physics. Comparison of visible and infrared solar radiation with surface manifestations of solar activity will give us a better understanding of the physical processes taking place in the photosphere. Parallel studies of the changes in the total flux and in various spectral bands

will provide the first information on the spectral redistribution of the total flux variability.

These aperiodic or quasiperiodic phenomena are best studied in the time domain, where the variations may be compared directly with the signatures of solar surface intensity structures (e.g. Willson & Hudson 1988) or by multivariate spectral analysis (e.g. Fröhlich & Pap 1989). Although irradiance variations and solar oscillations are, for simplicity, currently treated independently, it is highly likely that these domains overlap physically. The influence of the changing magnetic fields during the solar cycle on the frequency of p modes and solar luminosity is one example (Kuhn & Libbrecht 1991, Bachmann & Brown 1993). Moreover, the long-period solar oscillations may be coupled to the seemingly aperiodic or quasiperiodic variations in irradiance (which has been suggested, for example, by Wolff 1984), either directly or by influencing surface intensity configurations. Although the solar background signal has the effect of a noise signal on the oscillation measurements, this 'noise' contains valuable information about the causative physical phenomena such as granulation, mesogranulation, supergranulation and active regions, which influence the oscillation frequencies. It will be necessary to take the modifications to the oscillation frequencies into account in order to establish what they would have been had the activity not been present. Those putative unmodifed frequencies are required for the structure inversions.

4. Instrumentation

The apparatus comprises a power supply, spacecraft interface, sequencer-based controller, data acquisition system and three different types of sensors:

- two types of absolute radiometers (one DIARAD and two PM06-V) for the measurement of total irradiance and its variations with high accuracy and precision;

- two 3-channel sunphotometers (SPM): the continuously exposed SPM is for the measurement of solar oscillations with high precision, the backup SPM for the measurement of the spectral irradiance with high accuracy and for corrections to the degradation of the continuously exposed instument;

- one luminosity oscillation imager (LOI) for the measurement of the radiance in 12 pixels over the solar disk and the determination of the solar diameter.

The instruments are packaged in a sensor package (SP) which contains also the controller, the analogue-to-digital acquisition system and the spacecraft interface. The power supply (PS) is located in a separate box. Fig.1 shows an overall view of VIRGO and Fig.2 the four types of instruments. In
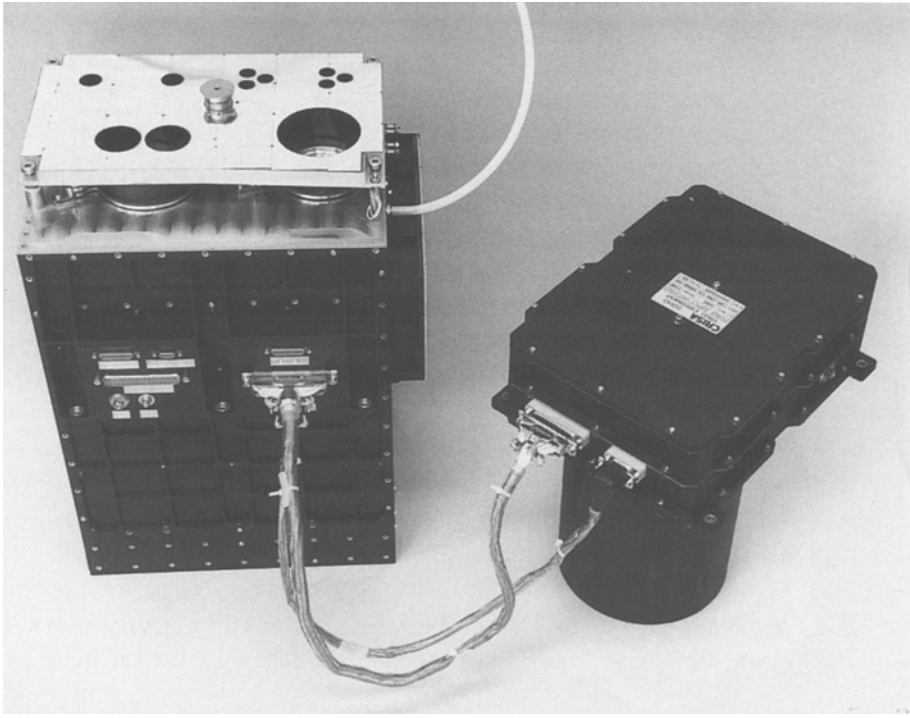
Fig. 1.   VIRGO sensor package (left-hand side, outside dimensions 392×293×230 mm, weight 13.0 kg) and power supply (right-hand side, outside dimensions 250×204× 90 mm, weight 1.5 kg). The SP will be mounted at the feet which end at half-way between the top and the bottom; this is also the reason why the PS is put on a stand for the picture, the height of which corresponds to its mounting level. The instrument apertures (clockwise from left upper corner of SP) are for 2 PMO6-V radiometer, 2 SPM, LOI and DIARAD.

the following the instruments and sub-units are described in detail together with their measured performance.

4.1. ABSOLUTE RADIOMETERS

Absolute radiometers are based on the measurement of a heat flux by using an electrically calibrated heat flux transducer. The radiation is absorbed in a cavity which ensures a high absorptivity over the spectral range of interest for solar radiometry. During practical operation of the instrument, an electronic circuit maintains the heat flux constant by accordingly controlling the power fed to the cavity heater. This is called the active mode of operation; hence also the name: 'active cavity radiometer'. The irradiance can be calculated from the shaded and irradiated electrical powers P_s and P_i according to: $S = C \times (P_s - P_i)$, with C being the reciprocal of the aperture area times a correction factor for the deviations from ideal behaviour. The correction
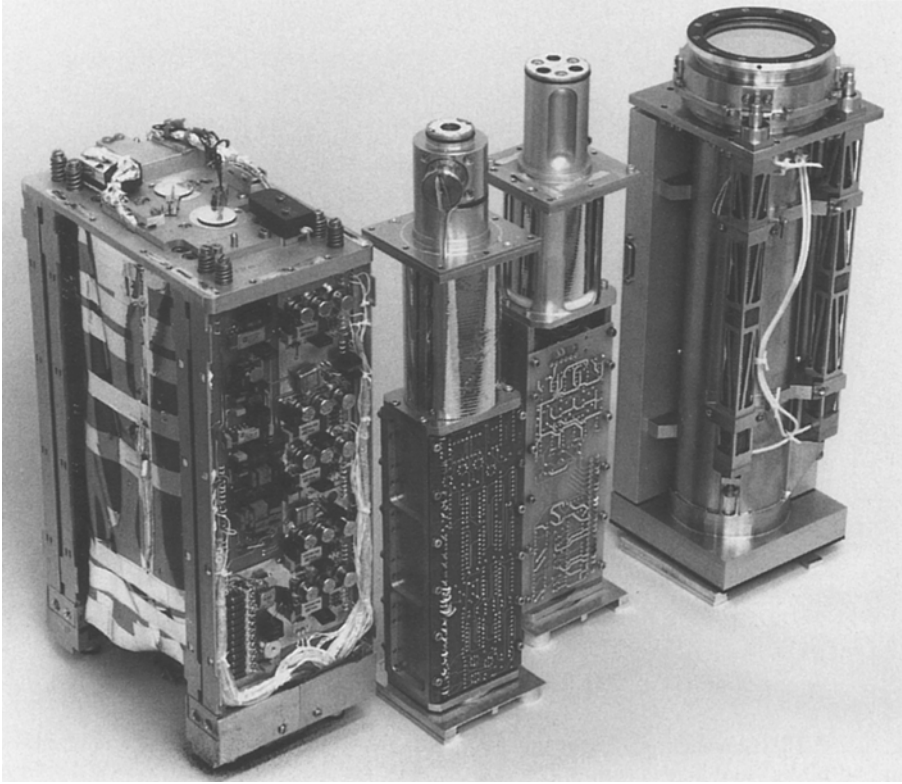
Fig. 2.   The four types of instrument in the VIRGO SP (from left): DIARAD, PMO6-V, SPM and LOI.

factor accounts for different effects such as the reflectivity and efficiency of the cavity, the losses due to diffraction at the apertures, straylight in the view-limiting muffler, heating of leads and the non-equivalence of electrical and radiative heating. The procedure to determine these factors is called characterization of the radiometer, and it provides both the correction factors and their uncertainty, the sum of the latter determining the absolute accuracy of the radiometer.

Although the designs of both radiometers are based on the same principle, the physical realization is different. Indeed, it is this difference that is the main reason for having both. In Fig.3 and 4 the detector arrangements and control and analogue electronics of the DIARAD (based on a design as described by Crommelynck & Domingo 1984) and PMO6-V (based on a design as described by Brusa & Fröhlich 1986) radiometers are shown. Major differences between them are the arrangements of the compensating cavities and the forms and coatings of those cavities. The main advantage
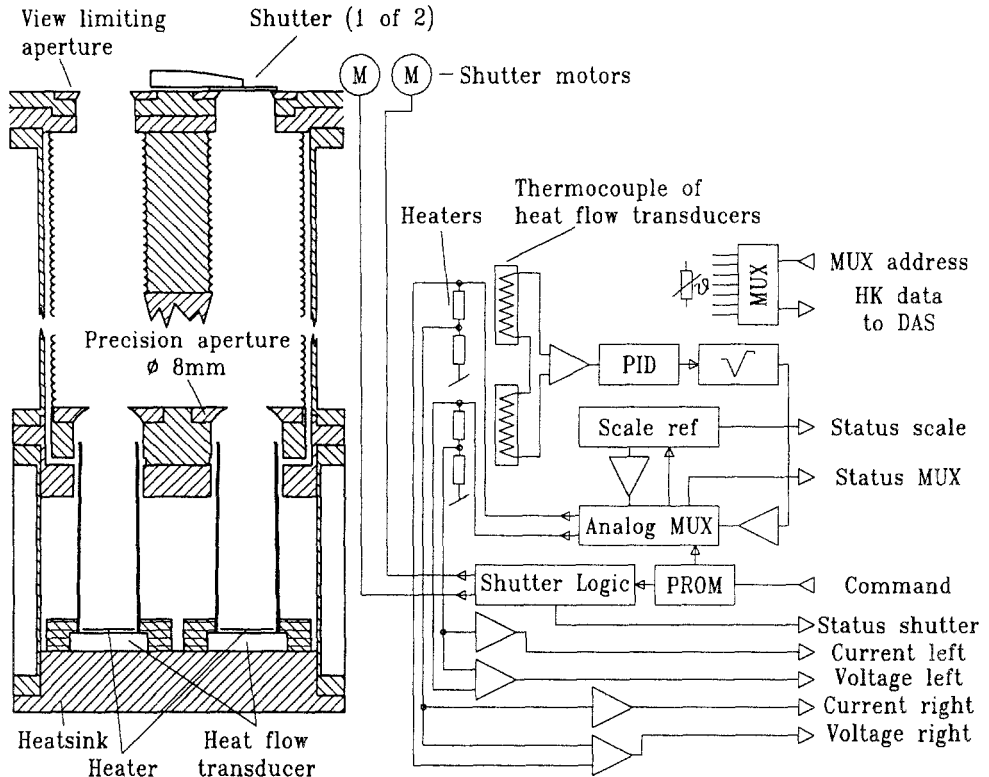
Fig. 3.   Blockdiagram of the DIARAD absolute radiometer with the arrangement of the sensor and the control and analogue electronics.

of the DIARAD is that both cavities see the same thermal environment (with compensation of thermal gradients in the muffler system) and that the compensating cavity can also be used for radiation measurements. In a PMO6 type radiometer the back-cavity cannot be exposed to the Sun. From the experience with the ACRIM and SOVA radiometers it is known that radiometers continuously exposed to the Sun degrade relatively to sensors that are exposed only occasionally; in this way a drift of about 30 ppm per year was measured for the continuously used ACRIM sensor (Willson & Hudson 1991), and a similar degradation has been determined from the SOVA2 experiment during the EURECA mission (Romero et al. 1994). This means that one needs at least one spare sensor for each radiometer; DIARAD is using the compensating cavity and for PM06-V a second instrument is included, which evidently also increases the redundancy of the radiometric measurement. Moreover, the different geometries and coatings of the cavities (diffuse for DIARAD and specular for PM06-V) will most probably lead to different degrees of degradation. The corrected data from both instruments can then be used to check for the reliability of the individual corrections.
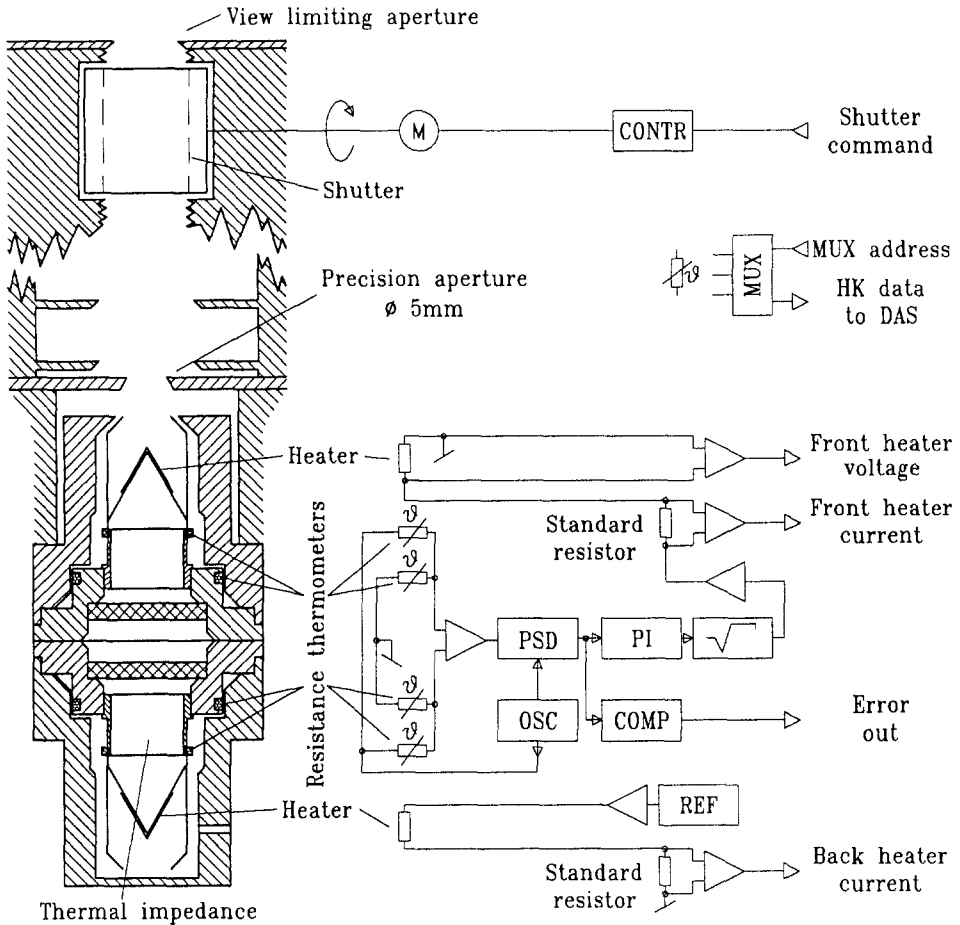
Fig. 4.   Blockdiagram of the PMO6-V absolute radiometer with the arrangement of the sensor and the control and analogue electronics.

With these measures, the unambiguous detection of even small long-term trends of the solar total irradiance will be possible. The backup sensors will be exposed only very rarely, probably once every 1–2 months at the beginning of the mission. After one year, the intervals between the measurements will be increased in accordance with the expected decline of the degradation rate.

4.2. ASSESSMENT OF THE RADIOMETRIC ACCURACY

Two different ways of assessing the absolute accuracy of the solar irradiance measurements are possible:

— The radiometers used in VIRGO are fully characterized and their measurements are individual realizations of the SI unit Wm^{-2}. As stated above, the absolute accuracy is estimated from the sum of the uncer-

tainties of the experimentally determined correction factors and of the uncertainty of the area of the precision aperture. For the DIARAD and PMO6-V type instruments this amounts to ±0.15% (Crommelynck 1988) and ±0.17% (Brusa & Fröhlich 1986) respectively. For measurements in space (vacuum) the uncertainty is reduced, as the correction factor for, e.g. the non-equivalence between electrical and radiative heating is much smaller. The disadvantage of this approach is that incompletely understood or even unknown effects in the radiometer will yield an unknown bias, because either an unreliable correction factor or even none at all is applied. The existence of such an effect is suggested by the fact that, e.g. the PMO6 radiometers are nearly 0.3% below the cryogenic radiometer, that difference lying outside the estimated uncertainty of PMO6-type instruments.

— Radiometers operated at cryogenic temperatures (<4 K) have been developed in recent years (Martin *et al.* 1985) and are realizations of the SI unit Wm^{-2} with a much lower uncertainty (<0.01%). The uncertainty is so small because at such low temperatures all the thermal effects, and therefore the correction factors, are orders of magnitudes smaller than at room temperature. They cannot be used directly for measurements of the Sun from the ground because they have to be operated in vacuum. But comparisons with room-temperature radiometers can be performed by measuring the power of the same laser beam alternatively with both radiometers. Because the transmission of the window used for the cryogenic radiometer can be determined very accurately at the laser wavelength the comparison has an estimated uncertainty of <0.02% (Romero *et al.* 1991). A redetermination with a different setup and a different radiometer in 1994 yielded a result within 0.01% of the value determined in 1990, which may indicate that the estimated uncertainty of the transfer is actually rather conservative (Romero *et al.* 1995). The result of such comparisons has to be transferred from power to irradiance measurements. This transfer involves the area of the precision aperture and the value of the diffraction correction of the VIRGO radiometer. The corresponding uncertainties amount for DIARAD and PMO6-type instruments to 0.03% for the area and 0.01% for the diffraction correction (Brusa & Fröhlich 1986). Using the Sun as a source, any room-temperature radiometer can now be compared with the one which has been compared with the cryogenic radiometer. The standard deviation of the mean ratio determined from such comparison amounts to <0.02%, which is a rather conservative estimate for comparison of instruments of the same type (identical view-limiting geometries and response times). For the transfer to space the air-to-vacuum ratio has to be known, and its uncertainty (for PMO6 types typically 0.02%) adds to the uncertainty of the traceability. Thus the total uncertainty

(sum of the uncertainties of the cryogenic radiometer, the aperture area of the radiometer used in the comparison and the root-mean-square of the remaining uncertainties) of the realization of the SI unit Wm^{-2} in space amounts to $<0.07\%$, which is lower than that of the direct method and is probably more reliable.

For the PMO6-V radiometers, both approaches can be tested during the SOHO mission because the radiometers are fully characterized and can be directly compared to PMO6-11 which is directly traceable to a cryogenic radiometer.

The noise of PMO6-V characterized by the standard deviation (determined in the VIRGO SP) of the difference between the electrical power at the end of a reference and measuring phases with closed shutter (no irradiance) is, for a single measurement (every 2 minutes), of the order of 30 ppm. The corresponding power spectrum is more or less flat, as expected for a thermal detector, and amounts to <0.4 $ppm^2\mu Hz^{-1}$. DIARAD has similar characteristics. It has to be noted that actively operated radiometers are not well suited for the measurements of solar p modes because the sampling rate is too low (every 2 minutes for PMO6-V and 3 minutes for DIARAD) and, more importantly, the measurement duty cycle is very low (17% and 11% respectively), which increases the spectral noise by folding back noise and signal from above the Nyquist frequency (see also Section 4.5). At low frequencies, however, the noise level of the radiometers is probably low enough (as it does not increase with decreasing frequency) and the medium-term stability is good enough to make a significant contribution to the search of g modes.

4.3. SUNPHOTOMETERS

The SPM has three independent channels at 402, 500 and 862 nm (Fig. 5), each consisting of a Si-diode interference-filter combination (Wehrli and Fröhlich 1991). The three S1337 detectors from Hamamatsu, Japan, and the interference filters (from Dr. Hugo Anders, Naburg, Germany) are mounted in a common body which is heated with constant power and remains always a few degrees above the temperature of the heat sink. This reduces degradation of the optical elements due to condensation of gaseous contaminants. The actual detector temperature is monitored by two thermometers and used to correct the sensitivity during evaluation of the data.

Similar SPM, used in earlier experiments, showed rather strong degradation of the sensitivity. In the case of the continuously exposed SPM of the SOVA2 experiment on EURECA (total exposure time of about 180 days), this degradation amounted to 17%, 49% and a factor of 95% for the 862, 500 and 335 nm channels respectively (Wehrli *et al.* 1995). These values are similar to those found during the IPHIR experiment. Because EURECA was retrieved, the SOVA2 SPM could be analysed after the flight. A sig-
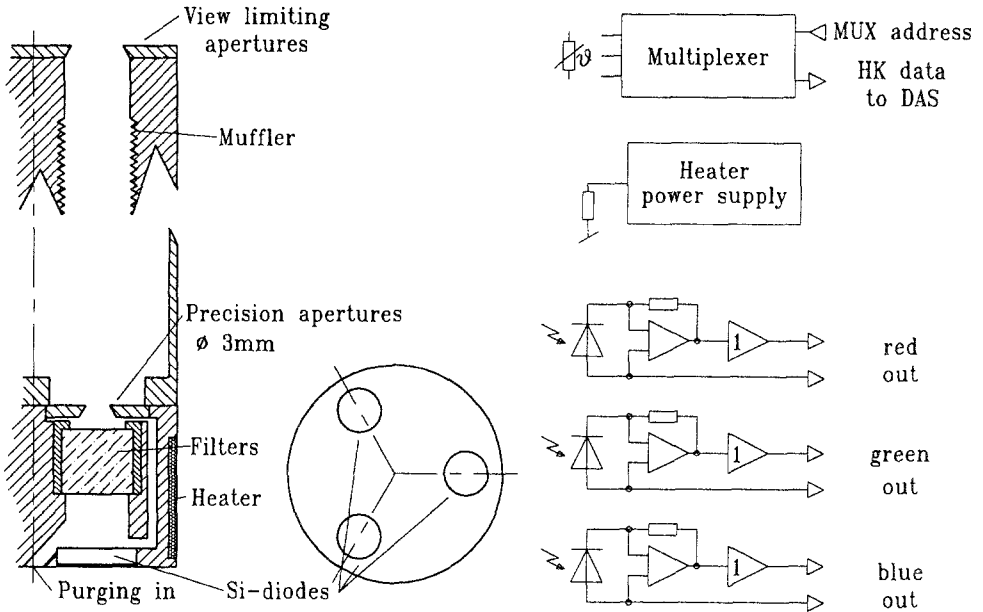
Fig. 5.   Block diagram of the sunphotometer with the arrangement of the detector/filter combination and the control and analogue electronics.

nificant amount of the degradation could be attributed to a brownish stain deposited on the entrance window, which is most probably due to molecular contamination photopolymerized by the strong solar UV radiation. Another part is believed to be caused by the optical cement used in the filter construction and, for the 335 nm filter, by the degradation of a blocking filter glass UG11. The following measures have been taken for the VIRGO SPM to prevent degradation as far as possible:

— the shortest wavelength is 402 nm permitting the use of a different blocking glass instead of the rather unstable UG11;

— to protect the filter against energetic particle flux and UV radiation below 380 nm, a 3 mm thick radiation resistant BK7-G18 glass is used as front element;

— a SOHO/ESA approved optical cement is used in the filters;

— a compartment within the instrument containing the filters and detectors is physically separated from the rest of the SPM and the SP with their electronic circuitry; before launch this compartment is continuously purged with 5.5-grade nitrogen.

One SPM is operated almost continuously, the dark current being checked only from time to time by shading the instrument with its cover. The other SPM is provided as a backup in case of failure of the first, in order not to lose the helioseismic capability. Normally the second SPM is used to check for the
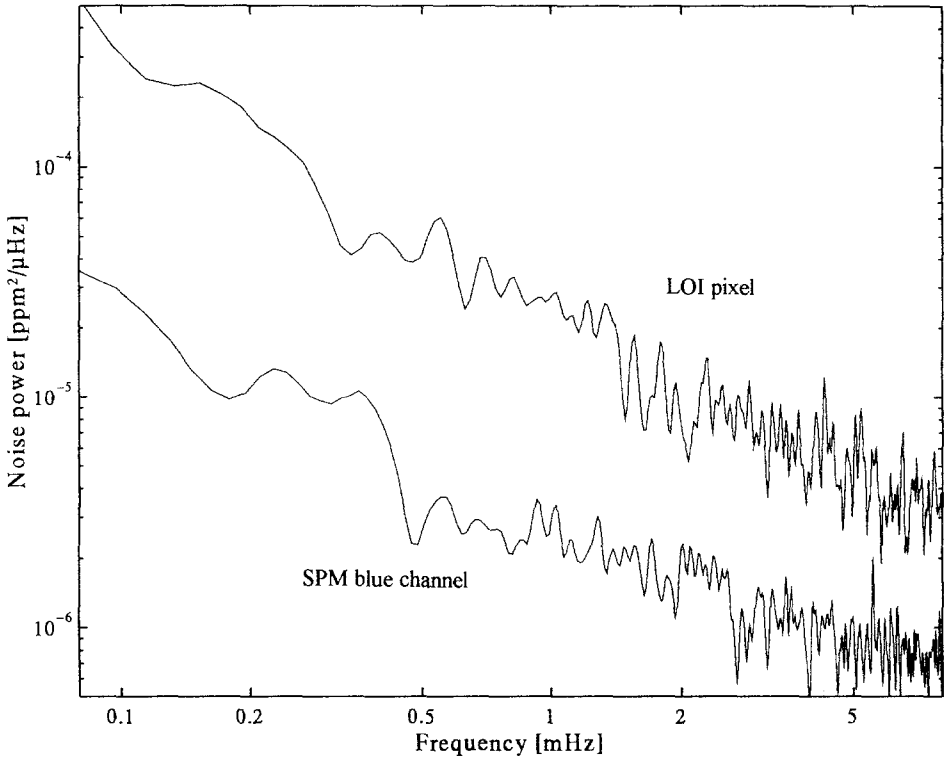
Fig. 6. Power spectral density of the dark-current noise of the SPM blue channel (lower curve) and a LOI pixel (upper curve) calculated from time series of 68 and 45 h respectively. In the 5-minute range the noise of the SPM is about 5×10^5 times smaller than the noise between the p-mode lines of IPHIR (≈ 0.5 ppm$^2\mu$Hz^{-1}) and of the LOI pixel 1.2×10^6 times smaller than the noise expected for a 12th of the solar disk (12 times the noise power of the full disk).

small but still possible degradation of the continuously exposed SPM, and to determine the spectral irradiance and its variablility at these wavelengths with high accuracy. The detectors are used in unbiased mode in order to minimize $1/f$ noise. Low-noise electrometer amplifiers with ultra-low bias current are used to convert the detector current to voltage. The three analogue signals of the continuously operated SPM are measured simultaneously by three dedicated channels of the common data acquisition system. The backup SPM is read (normally zero points) through a multiplexed channel which is shared with the PMO6-V backup radiometer.

Four SPM were calibrated by two NIST traceable FEL standard irradiance lamps. There extraterrestrial signal are about 10% below the full range of the data acquisition. Temperature coefficients were determined by relating the response of five instruments at 7 different temperatures to a reference instrument at constant temperature. The average values for channels

red/green/blue are -270, -1040 and -710 ppm/K respectively with a scatter or uncertainty of a few per cent. The power density spectrum of the dark current of the SPM in the VIRGO SP is shown in Fig.6. In the 5-minute range the noise power of the VIRGO SPM is about 500 000 times smaller than the noise power between the p-mode lines of IPHIR (≈ 0.5 ppm$^2\mu$Hz^{-1} at 3 mHz, from Toutain & Fröhlich 1992); this corresponds to a signal-to-noise ratio for the highest p modes of about 3000:1. This leaves enough margin for the instrumental noise even if part of the IPHIR background noise was not solar but operational (which is possible due to the pointing corrections needed). At lower frequencies the noise is much lower than what ACRIM-SMM (≈ 8 ppm$^2\mu$Hz^{-1} at 80 μHz, Fröhlich 1993) or simulated solar-noise data (≈ 4 ppm$^2\mu$Hz^{-1} at 80 μHz, Andersen *et al.* 1994) indicate. Thus, instrument noise will most probably not be the limiting factor for the study of the detailed line structure of the p modes and the detection of solar g modes.

4.4. LUMINOSITY OSCILLATION IMAGER

The LOI instrument is a solar photometer with very high stability. Its layout is shown in Fig. 7. It resolves the solar disk into 12 spatial elements. The precision for each pixel is about 1 ppm for an integration time of 10 s. The 12.5 mm diameter image is provided by a 50 mm diameter, 1300 mm focal-length Ritchey-Chrétien telescope purchased from SESO, Aix-en-Provence, France. The spectral bandpass is defined by a 5 nm bandwidth interference filter centred at 500 nm, which is placed in front of the telescope. It was manufactured by Andover Corp., Salem, New Hampshire, USA, using materials similar to those used for the 500 nm filter of the SPM. The position of the secondary mirror of the telescope is controlled by two orthogonally placed piezoelectric stacks allowing the solar image to be stabilized on a customized Si-diode array. The detector, with 16 separate elements, is a deep diffused silicon photodiode made to our specifications by AME, Horten, Norway.

Twelve of those elements are shaped specifically to allow detection of radiance variations on spatial scales corresponding to spherical harmonics up to degree 7 (Appourchaux & Andersen 1990). As in the SPM, the detector is used in an unbiased mode in order to minimize $1/f$ noise. As shown in Fig.6 the instrumental noise amplitude is well below the expected solar noise. The analogue-to-digital conversion is performed in parallel for all channels by 12 dedicated voltage-to-frequency converters (VFC) within the LOI. The output of each VFC is counted in separate 24-bit counters and the results transmitted to the common data acquisition system.

The other 4 elements of the detector constitute an outer circular boundary of the detector, and are used for guiding. The outputs of these four elements are amplified, and error signals are generated to drive the piezoelectric stacks. The bandwidth of the control loop is about 10 Hz and the
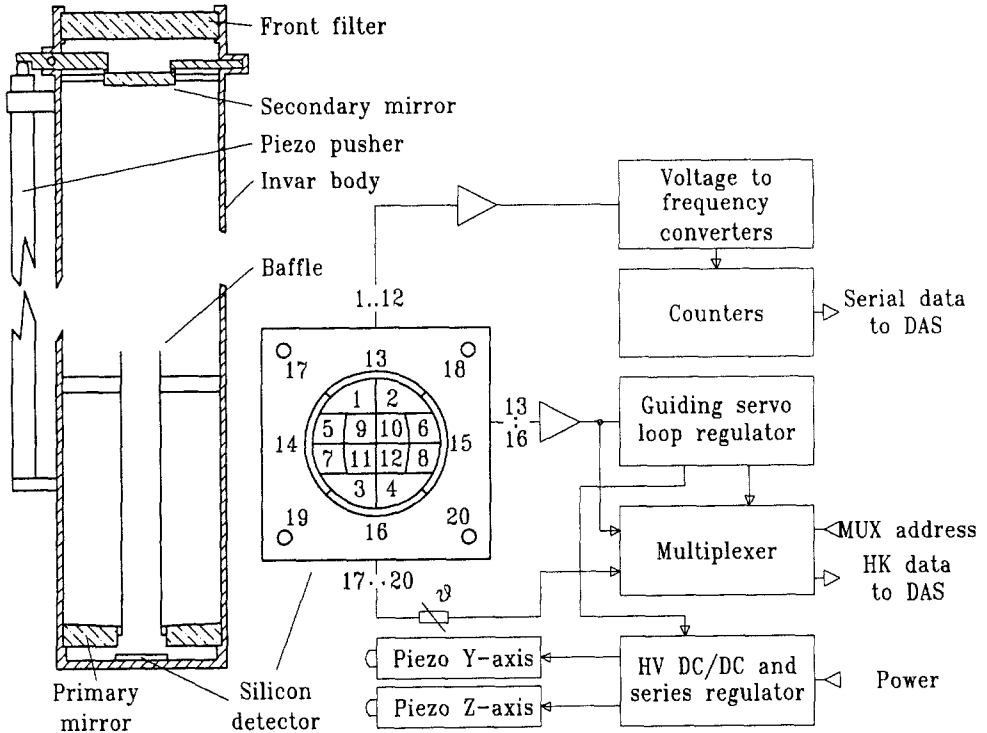
Fig. 7. Blockdiagram of the Luminosity Oscillation Imager (LOI) with the telescope and
the arrangement of the detector. For the detector the two latitudinal lines cut the rotation
axis at half the radius of the solar image and the two meridian lines cut the equator also
at half the solar radius.

guiding system can compensate for large misalignment of up to ±8 arcmin
with a stability of the order of 0.1 arcsec. The signals of these four elements
are transmitted in the housekeeping data and will be used to monitor the
solar equatorial and polar diameters to better than 0.1 arcsec.

For the choice of the detector configuration several considerations were
taken into account. It is reasonable to assume that global g modes with
degree higher than about 7-10 will be attenuated so much in the convection
zone as not to be observable. This gives the upper limit for the l values we
seek to observe. In order to acquire a knowledge of the internal structure of
the Sun as complete as possible, we must isolate and measure as many low-
degree modes as we can. The total number of modes observable for a given
number of detector elements is approximately constant, it is the distribution
between different values of m, l that is variable. For p and g modes and for
all $|m| < l$, our aim is to have a high sensitivity for degrees lower than 7. The
configuration that has been selected was designed to optimize our ability to
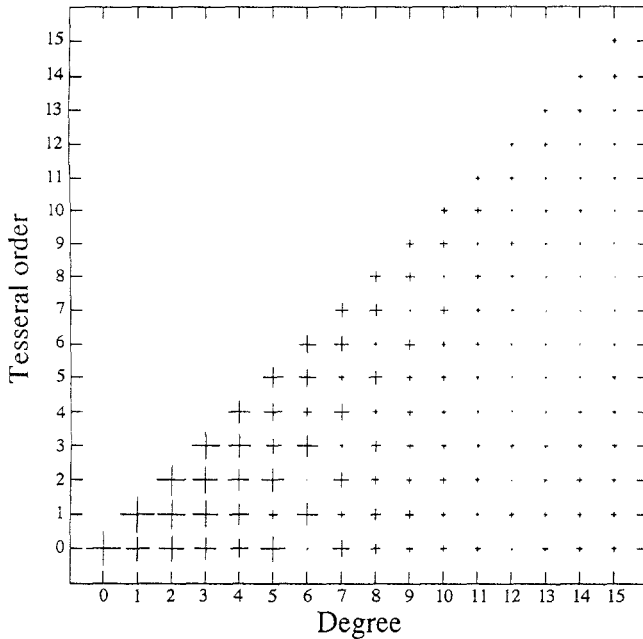distinguish between different values of l and m, and is shown in Fig.8.

Fig. 8. The p-mode sensitivity as a function of l and m for the LOI detector arrangement.

The performance of the LOI was recently checked using the Qualification Model of the instrument. It was installed in Tenerife in May 1994 and five months of data have been used for analysing solar p modes. The data analysis and the results are described in Appourchaux et al (1995). The results demonstrate the ability to identify the different l and m of the modes which allows a clean determination of the p mode splitting which is rather difficult due to the mixing of the various m components from power spectra of instruments observing the Sun as a star. The LOI feature to separate the $2l + 1$ components of a given l, n mode will be used to search for g modes. In this way the crowding of the g modes will be much less disturbing.

4.5. DATA ACQUISITION AND INSTRUMENT CONTROL

The overall concept of the data acquisition and control system (DAS) is shown in Fig.9. It comprises the OBDH (Onboard Data Handling System) interface for telemetry, telecommands and timing signals. The controller is based on a hardware sequencer with 2Mbit memory (electrically ereasable PROM-type) for 25h autonomy of data storage.

The scientific objectives of VIRGO rely on long and uninterrupted time series. These time series are analysed by calculating power spectra, the noise in which depends strongly on the way the sampling is carried out. Ideally, one should integrate the signal during the whole sampling interval, otherwise
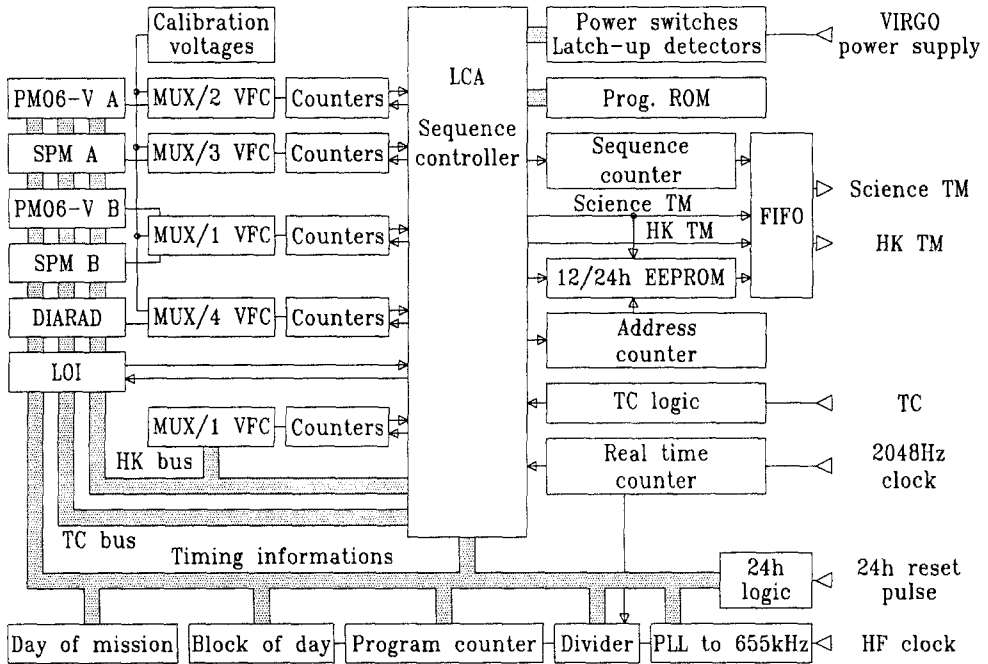
Fig. 9.   Block diagram of the data acquisition and control system (DAS).

high-frequency noise leaks into the power spectrum. As the integration time relative to the sampling interval decreases, the power of the folded-in high-frequency noise increases. It has to be noted that this noise is an inherent part of the time series, and cannot be reduced by any *a posteriori* filtering of the time series. Simulation experiments have shown that in the case of solar observations with a sampling corresponding to a Nyquist frequency around 10 mHz, integration during at least 90% of the sampling interval is needed to reduce the folded-in noise to tolerable levels. Technically, this is best achieved with voltage-to-frequency converters (VFC) which allow for true integration over a given time interval. The data acquisition is performed by 11 parallel VFC with a full-scale frequency of about 320 kHz. The basic sampling period is 10 s, allowing for a theoretical resolution of 0.3 ppm for one reading. Within the 10 s period the signals are integrated during 9.4 s, the rest of the period being used for the calibration of the VFC with reference signals (during 400 ms with a fs-resolution of 16 bit) and the reading and resetting of the counters (twice 100 ms). This timing allows for a continuous electrical calibration and a high duty cycle of the reading (94%). The electrical calibrations are performed in turn at three points, namely zero, half full scale and full scale, allowing for a first-order correction of the nonlinearity ($\approx 5 - 10$ ppm) of the VFC during the evaluation of the data.

With this system it is necessary to have as many parallel channels as signals to be measured simultaneously. There are 10 VFC for the science data and 1 VFC for the housekeeping (HK) channel. The accuracy of the electrical calibration has been checked thoroughly, and it has proven to be <30 ppm of full scale.

Another important aspect of time series analysis is the fact that accurate knowledge of the timing is necessary. The rate of the SOHO on-board clock is adjusted in such a way that over the whole mission the spacecraft time is identical with International Atomic Time (TAI). Because VIRGO cannot read the numerical spacecraft time directly, the internal timing is based on the adjusted spacecraft clock (2048 Hz) and the 24h reset pulse. The latter is used to start the measurements at the beginning of the mission and as a daily check of the timing. For the oscillation data the SPM and LOI integrate over one minute, which is centred around the full minute. The measurement timing of SOI/MDI is identical. That of GOLF is similar, and is renormalized to the same timing on the ground. This allows for direct comparison of all the helioseismic data from SOHO.

Every three minutes – the basic time interval of the VIRGO sequencer – the following data are produced and transmitted to the spacecraft and ground station: 3 Science (SC) packets of 512 bytes of realtime, 12.8 and 25.6 hour delayed science data and 1 HK-packet of 192 bytes of houskeeping data. The HK packet is not repeated, but all scientifically relevant HK data are also contained in the SC-packet. Thus the data organization of VIRGO can allow for drop-outs in the transmission to ground, and guarantees continuous data.

4.6. ELECTRICAL DESIGN

In order to comply with the radiation environment at $L1$, radiation-hardened parts have been used in all sections of the DAS electronics in which a loss of information would disable the continuity of the timing, and in the interfaces to the instruments and sub-units in order to avoid back currents in case of a latch-up in the instrument. The remaining parts are protected by detectors which switch off the corresponding circuit immediately after a latch-up occurs, and will switch them on again either automatically for circuits that are important for maintaining the continuity of the measurements or by telecommand for the others.

4.7. POWER SUPPLY

The VIRGO Power Supply (PS) provides galvanic isolation and converts the spacecraft 27 V into five regulated output voltages, ±7.4 V, 5 V and ±9.6 V, which are current limited and over-voltage protected. The PS consists of two redundant DC/DC converter modules which operate in cold redundancy: that is, only one is powered at a time. The input converter

provides a regulated and current-limited voltage to the push-pull converter which supplies the five switch-voltage regulators. The outputs of the two redundant converter modules are connected in parallel; thus the five voltages are single-point failure free. The PS is packaged in a box 250 × 204 × 90 mm weighing 2.5 kg (Fig.1). It is designed for a maximum output power of 9.3 W and has an efficiency of 69%.

4.8. MECHANICAL DESIGN AND MECHANISM

The stringent cleanliness requirements demand a mechanical design of the instruments and SP that allows for continuous purging of the critical parts before launch, and defines well the paths through which the instrument is evacuated. The main purging line entering the SP is divided into three separate lines to the LOI and the two SPM; the exhausts of the three instruments are through hoses of small diameter to the interior of the SP and then to the outside. This guarantees that during evacuation after launch the flow is from the very clean to the less clean areas, and then finally the outside. Moreover, the SP has one tight cover for each instrument which remains closed during the ground operations and in flight until the degassing is completed.

The covers are pressed to o-ring seals around the instruments' apertures in the top plate of the SP by the radiation shield (see also Fig.1). The shield is locked in this position and can be released by either of two redundant mechanisms. This latter action is not reversible, and is actuated in flight only once after the completion of the degassing phase. Redundancy is present to make sure that the locking mechanisms really do succeed in releasing the shield, although sufficient safety margins for each mechanism have separately been verified. The six covers are operated by 90-degree actuators, and can be opened and closed individually after release of the shield. Thus, covers can be closed during the non-measuring period of the backup PMO6-V and SPM, and used to check periodically the dark current of the SPM and LOI. Moreover, the cover of the PMO6-V could also be used as an operational shutter to replace the internal shutter in case of failure.

4.9. ELECTRICAL GROUND SUPPORT EQUIPMENT

The Electrical Ground Support Equipment (EGSE) is to support the electrical verification and operation of VIRGO during the development and verification phase at instrument and system level. The EGSE is interfaced either to the Spacecraft Interface Simulator for stand-alone operation or to the Common Check-out System during system tests. Moreover, the EGSE is used at the Experiment Operations Facility (EOF) during the first phase of the mission: that is, during start-up of the experiment and commissioning. Because of the rather simple tasks to be performed by the EGSE, a 386-type PC running under MS-DOS has been chosen. The software is written in Modula-2 and has been developed according to the ESA Software

Engineering Standards. The EGSE software package comprises four main programmes:

- VIRGO EGSE Operation Software (VEOS) which allows direct commanding and receiving of telemetry data and displays all the data on different selectable screens;
- VIRGO EGSE Package Reader (VEPAR) which allows one to inspect the telemetry block-by-block in hexadecimal format;
- VIRGO EGSE Block Reader (VEBOR) displays the telemetry blocks in the same way as VEOS but off-line;
- VIRGO EGSE Constant Definition (VECOD) provides management of the data base containing all the conversion and calibration factors specific to each model and used by the other programmes.

5. Operations and Data Evaluation

The basic operation of VIRGO is very simple: take measurements continuously by running the instrument without any interruption. From time to time, backup operations will be commanded during normal operations. The frequency of this backup operation will depend on the observed degradation. During the start-up phase of the experiment some time will be devoted to a thorough test of all operational modes and telecommands in order to make sure that everything works properly. Moreover, during the cruise phase to $L1$ some tests for the pointing sensitivity of the SPM and the internal pointing capabilities of the LOI will be performed. It is planned to start the scientific measurements during the cruise phase; thus VIRGO will have already some 5 months of data when SOHO enters the official operational phase in the halo orbit around $L1$. The VIRGO data are managed and processed at the VIRGO Data Centre (VDC) which is located at the IAC in Tenerife.

During normal operations the only task to be performed by the Experiment Operations Facility (EOF) and VDC is to check for aberrant values in the SC or HK data, signalling when corrective action needs to be taken. The raw data that arrive from the EOF are known as level-0 data. Level-1 data are those that have been converted to physical units; they include the calibrations and contain all the corrections known *a priori* for instrument-related effects, such as the influence of temperature variation. The signals are also reduced to 1 AU distance and to zero radial velocity. The processing is based on the algorithms developed and tested by the CoI responsible for the instrument concerned (Instrument CoIs: Th. Appourchaux for LOI, D. Crommelynck for DIARAD, J. Romero for PMO6-V and Ch. Wehrli for SPM). The ideal case would be that the algorithms be delivered by each ICoI well before operations start, and can be retained in unmodified form throughout the mission. This will probably not actually be the case, however, and updated procedures will probably be needed. Whenever a new

algorithm has to be implemented, new versions of the level-1 data will be produced. The algorithms are to be the responsibilities of the corresponding ICoIs, the implementation and management of which will be carried out at the VDC. Access to level-0 data has to be guaranteed to the ICoIs for the improvement and testing of their algorithms.

Level-1 data are still raw in the sense that they do not contain corrections for, e.g. degradation, which can be calculated only from *a posteriori* analysis. Such corrections will be included in the level-2 data set. For the total solar irradiance an average of the measurements with the 2 operational and the 2 backup radiometers will be given. The arguments and methods to arrive at this average are also developed by the ICoI. They will have to be reviewed and agreed within the VIRGO team, and can be decided only after a few months of operation. Thus, only one VIRGO total solar irradiance value will be made available and be used for the final scientific evaluation of the total solar irradiance. For the SPM and LOI the situation is more difficult because degradation will probably be larger than for the radiometers. Only after some time, maybe even after some calibration by comparison with, e.g. balloon or rocket experiments, can final level-2 data be produced. They will contain:

- 1 solar irradiance value every 2 minutes;
- 3 spectral values every minute;
- 12 radiances of the LOI pixels every minute, normalized to the SPM green channel;
- 2 diameters (N/S and E/W) every 10 minutes.

The VDC will develop a data bank and archiving system to allow easy access to data through networks by those with permission, as defined in Section 6. A further task of the VDC is to provide the EOF and other identified SOHO remote PIs (with no permanent delegation at EOF) with the daily data-base of VIRGO for mission planning, and similarly to receive, store and make available to the VIRGO team the daily databases of other SOHO experiments. This data base has to be available to the EOF within 24 hours.

The VIRGO team will use data reduction methods based on the methods developed for the IPHIR/PHOBOS and SOVA/EURECA missions. Currently the team is developing methods for the LOI data reduction based on the data being acquired from the ground-based observations at Tenerife. In addition to the traditional power spectral analyses, other methods have been studied, e.g. wavelet methods. Some of these methods show promise for more specific usage like the study of mode lifetimes, excitation and damping. Methods for the detection of g modes will be developed based on previous work (e.g. Fröhlich 1990). In addition, methods for noise reduction are also being investigated. The theoretically orientated members of the team have

access to sophisticated inversion codes that will be used to deduce parameters of the solar interior.

6. Data Policy

All VIRGO CoIs and AS have access to all levels of data and to the SOHO data base after they are on the VIRGO archive at the VDC. It is likely that only the ICoIs will really use level-0 data. For the scientific evaluation of the data each potential user of data submits a written proposal to the PI of what he/she would like to do and how it will be done. These proposals will be discussed and 'approved' by the VIRGO team. This is to make sure that the data are used correctly by those team members not directly involved in instrumentation, to avoid duplication by coordination, and to manage in the broadest sense the attribution of science projects amongst the team scientists and CoIs. On the other hand, it shall also foster co-operation between 'observers' and theorists. Whenever a substantial change of the content or direction of the proposed research arises, the PI should be notified, and he will decide whether the case shall be discussed by the VIRGO team or simply disseminated as information amongst the team.

If a scientist who is not a member of the VIRGO team would like to participate as a Guest Investigator (GI) before the data are public, he/she may also submit a written proposal to the PI. Such a proposal, however, has to be in cooperation with a member of the VIRGO team and the proposal will be reviewed and approved or rejected by the VIRGO team. We shall seek to attract well qualified graduate and postgraduate students to the team early in the mission phase.

The availability of data to the VIRGO team together with the delays is summarized in the following list:

- summary data of SOHO including VIRGO: 1 day;
- level-0 data: a few hours after receipt;
- level-1 data: 10 days;
- level-2 data: 1 and 3 months for radiometers and SPM/LOI respectively (at the beginning at least the whole time series may be updated once per month);
- level-2 Data to SOHO Archive: same as VIRGO availability of level-2.

As an ESA rule the data have to be released to the public after one year. Open access to level-2 data is fixed according to the following scheme: first one-year set of data one year after completion; at intervals of 3 months follow six-month blocks, until data become near real time. Then, every sixth month, six months of data will be released with a one-month delay. These data will be available either from VDC or the SOHO archive. Level-0 and level-1 data will be made available to the public only on request by a specific

proposal to the VIRGO PI, which will be discussed and eventually approved
by the VIRGO team.

7. Conclusions

The VIRGO investigation will yield for the first time a concerted approach
to the assessment of solar variability by studying simultaneously irradiance
changes, frequency variations of solar oscillations and photospheric effects
related to those variations.

Either selfstanding or in collaboration with the other helioseismological
investigations on SOHO, VIRGO will be the first realistic attempt to detect
unambigously solar g modes. If this is achieved the investigation will pro-
vide a valuable contribution to the understanding of stellar structure and
evolution. Even if the g modes have amplitudes too low to be detected, the
information about low-frequency solar p modes and irradiance and radiance
variability will more than justify the mission.

8. *In Memoriam* Philippe Delache

During the preparation of this paper we have been shocked by the unex-
pected and untimely death of Philippe Delache. He was not merely another
CoI interested in the science of VIRGO: indeed, it was his initiative to add
the helioseismology to the scientific objectives of the potential ESA space
mission DISCO (Dual Irradiance and Solar Constant Observations) during
its assessment study in 1981. The objective of DISCO was to measure total
and spectral irradiance of the Sun from the far UV to the near IR. Because
of the continuity needed for the solar oscillation studies, a halo orbit around
$L1$ was proposed. The helioseismological payload comprised sunphotometers
similar to those of VIRGO and a high resolution spectrometer for velocity
measurements similar to GOLF. When in December 1982 DISCO was not
selected as a mission, the helioseismology instruments, the total solar irra-
diance and the *in situ* solar-wind measurements were taken over by a new
solar mission just starting an assessment study. The Solar High-resolution
Observatory (SOHO) for the study of the corona then became the Solar and
Heliospheric Observatory. Owing to the much better pointing characteristics
of SOHO, it was possible to augment the original DISCO helioseismological
payload with a high-resolution instrument. Thus, it is as a consequence of
Philippe's early initiative that a powerful and sophisticated helioseismolog-
ical payload on the ESA Cornerstone SOHO is now becoming a reality. To
honour this and his continuous contributions to the field of helioseismology
and solar variability we dedicate VIRGO to the memory of Philippe Delache.

Acknowledgements

References

Andersen, B.N.: 1994, *Solar Phys.* **152**, 241.

Andersen, B.N., Leifsen, T. and Toutain, T.: 1994, *Solar Phys.* **152**, 247.

Anselmann, P., Hampel, W., Heusser, G., Kiko, J., Kirsten, T., Laubenstein, M., Pernicka, E., Pezzoni, S., Rönn, U., Sann, M., Schlosser, C., Wink, R., Wójcik, M., von Ammon, R., Ebert, K., Fritsch, T., Hellriegel, K., Henrich, E., Stieglitz, L., Weyrich, F., Balata, M., Ferrari, N., Lalla, H., Bellotti, E., Cattadori, C., Cremonesi, O., Fiorini, E., Zanotti, L., Altmann, M., von Feilitzsch, F., Mössbauer, R., Schanda, U., Berthomieu, G., Schatzman, E., Carmi, I., Dostrovsky, I., Bacci, C., Belli, P., Bernabei, R., d'Angelo, S., Paoluzi, L., Bevilacqua, A., Charbit, S., Cribier, M., Gosset, L., Rich, J., Spiro, M., Stolarczyk, T., Tao, C., Vignaud, D., Hahn, R. L., Hartmann, F. X., Rowley, J. K., Stoenner, R. W. and Weneser,J. : 1994, *Phys. Letters B* **327**, 377.

Appourchaux, T. and Andersen, B.N.: 1990, *Solar Phys.* **128**, 91.

Appourchaux, T., Toutain, T., Telljohan, U., Jiménez, A. and Andersen, B.N.: 1995, *Astr. Astrophys.* **294**, L13.

Bachmann, K.T. and Brown, T.M.: 1993, *ApJLett* **411**, L45.

Berthomieu, G., Gonczi, G., Graff, Ph., Provost, J. and Rocca, A.: 1978, *Astr. Astrophys.* **70**, 579.

Berthomieu, G. and Provost, J.: 1990, *Astr. Astrophys.* **227**, 563.

Brusa, R.W., Fröhlich, C. and Wehrli, Ch.: 1983, 'Solar Radiometry from High-Altitude Balloons' in E.Kopp, ed(s)., *Sixth ESA Symposium on European rocket & balloon Programmes*, ESA SP-183, Noordwijk, 429.

Brusa, R.W. and Fröhlich, C.: 1986, *Appl. Optics* **25**, 4173.

Crommelynck, D.: 1988, 'Factors limiting the Accuracy of Absolute Radiometry' in N.Fox, ed(s)., *New Developments and Applications in Optical Radiometry*, Inst.Phys.Conf.Ser.92, London, 19.

Crommelynck, D. and Domingo, V.: 1984, *Science* **225**, 180.

Crommelynck, D., Domingo, V., Fichot, A., Fröhlich, C., Penelle, B., Romero, J. and Wehrli, Ch.: 1993, *Metrologia* **30**, 375.

Fröhlich, C.: 1990, 'Search for g-Modes in the IPHIR Data' in Y.Osaki, H.Sibahashi, ed(s)., *Progress of Seismology of the Sun and Stars*, Lecture Notes in Physics 367, Springer, Berlin, 221.

Fröhlich, C.: 1993, *Geophysical Monograph 75, IUGG* **15**, 123.

Fröhlich, C.: 1994, 'Irradiance Observations of the Sun' in J.M. Pap, C. Fröhlich, H.S. Hudson & S.K. Solanki, ed(s)., *The Sun as a Variable Star: Solar and Stellar Irradiance Variations*, Cambridge University Press, Cambridge, 217.

Fröhlich, C. and Delache, Ph.: 1984, 'Solar gravity modes from ACRIM/SMM irradiance data' in R.K. Ulrich, J. Harvey, E.J. Rhodes and J. Toomre, ed(s)., *Solar Seismology from Space*, JPL Publ.84-84, Pasadena, 183.

Fröhlich, C. and Pap, J.: 1989, *Astr. Astrophys.* **220**, 272.

Fröhlich, C. and van der Raay, R.: 1984, 'Global solar oscillations in irradiance and velocity: a comparison' in T.D. Guyenne & J.J. Hunt, ed(s)., *Hydrodynamics of the Sun*, ESA-SP 220, 17.

Fröhlich, C., Toutain, T., Bonnet, R.M., Bruns, A.V., Delaboudinière, J.P., Domingo, V., Kotov, V.A., Kollath, Z., Rashkovsky, D.N., Vial, J.C. and Wehrli, Ch.: 1990, 'Recent Helioseismological Results from Space: Solar p-mode Oscillations from IPHIR on the PHOBOS Mission' in G. Berthomieu and M. Cribier, ed(s)., *Inside the Sun*, Kluwer, Dordrecht, 279.

Gough, D.O. and Kosovichev, A.G.: 1993, *MNRAS* **264**, 522.

Hoyt, D.V., Kyle, H.L., Hickey, J.R. and Maschhoff, R.H.: 1992, *J. Geoph. Res.* **97.**, 51.

Kuhn, J.R. and Libbrecht, K.G.: 1991, *ApJ.* **381**, L35–L37

Martin, J.E., Fox, N.P. and Key P.J.: 1985, *Metrologia* **21**, 147.

Provost, J. and Berthomieu, G.: 1986, *Astr. Astrophys* **165**, 218.

Romero, J., Fox, N. and Fröhlich, C.: 1991, *Metrologia* **28**, 125.

Romero, J., Fox, N. and Fröhlich, C.: 1995, *Metrologia* , in press

Romero, J., Wehrli, C. and Fröhlich, C.: 1994, *Solar Phys.* **152**, 23.

Toutain, Th. and Fröhlich, C.: 1992, *Astr. Astrophys.* **257**, 287.

Wehrli, Ch. and Fröhlich, C.: 1991, *Metrologia* **28**, 285.

Wehrli, Ch., Fröhlich, C. and Romero, J.: 1995, *Metrologia* , in press

Willson, R.C.: 1992, *EOS Transactions, AGU* **73** (14), 242.

Willson, R.C., Hudson, H.S., Fröhlich, C. and Brusa, R.W.: 1986, *Science* **234**, 1114.

Willson, R.C. and Hudson, H.S.: 1988, *Nature* **332**, 332.

Willson, R.C. and Hudson, H.S.: 1991, *Nature* **351**, 42.

Wolff, C.: 1984, *Solar Phys.* **93**, 1.