IN-FLIGHT PERFORMANCE OF THE VIRGO LUMINOSITY OSCILLATIONS IMAGER ABOARD SOHO

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Abstract. The Luminosity Oscillations Imager (LOI) is a part of the VIRGO instrument aboard the Solar and Heliospheric Observatory (SOHO). The scientific objective of the LOI experiment is to identify and characterize pressure and internal gravity oscillations of the sun by observing the radiance variations. The LOI is a low-resolution imager with 12 pixels, for the measurement of the radiance distribution over the solar disk at 500 nm. The low resolution capability of the instrument allows the identification of individual azimuthal orders for l=0 to 7, without suffering the mixing that affects integrated solar disk instruments. The performance, calibrations and instrumental effects of the LOI are described together with the procedures for extracting the solar p modes.

Key words: Helioseismology – SOHO Mission

1. Introduction

The European Space Agency (ESA) embarked in 1985 on a collaborative mission with the National Aeronautics and Space Administration (NASA), the so-called Solar and Heliospheric Observatory (SOHO). On board this spacecraft are 3 helioseismology instruments: MDI/SOI (Michelson Doppler Imager/Solar Oscillation Instrument), GOLF (Global Oscillations at Low Frequency) in velocity and VIRGO (Variability of solar Irradiance and Gravity Oscillations). Each observes the Sun, in velocity and intensity on a detector with 1000 × 1000 pixels, as a star in velocity, and at three different wavelengths in brightness, respectively.

VIRGO aims specifically at detecting the gravity modes of the Sun. These modes are extremely important, as they propagate mainly in the core and the radiative zone. They would considerably improve our knowledge of the deep interior of the Sun, which is presently known only by inverting the frequencies of the pressure modes, which have a smaller resolving power than the gravity modes in the core. The VIRGO experiment (Fröhlich *et al.* , 1996) consists of several instruments. One of these, the Luminosity Oscillations Imager (LOI) was designed and built by the Space Science Department of ESA. Its scientific objective is to detect the p and g modes of the Sun and to study the radiance variability due to solar active regions and other phenomena.

Here we discuss the performance and operation of the LOI and present some first results as an illustration. First we describe how the instrument cover was opened; it is a story of perseverance that has to be told once and for all. Next we briefly describe the instrument and show how it performs and how the data are analyzed for extracting reliable p-mode parameters.

2. The opening of the cover

On December 2, 1995, the SOHO satellite was launched by an Atlas-Centaur rocket from Cape Canaveral. A few days later, VIRGO was powered on, and the LOI remained in calibration mode until December 24, 1995 when its cover was opened for 5 minutes for a 'first light' experiment. Then the cover was closed to continue the outgassing of the instrument. On January 17, 1996, we tried to open the cover in order to start the regular operation of the LOI. Unfortunately, the cover remained closed, even after several attempts. During this operation the LOI could see the Sun for about 1-2 sec which was sufficient to lock the guider onto the Sun. The cover is operated by a 90-degree motor which is switched to the open position by a nominal current pulse length of 710 msec. The only explanation we had was that the cover was bouncing back to the closed position and/or that the length of the impulse sent to the motor was too short to keep it in the open position.

At this stage, the inability to open the cover concerned the whole SOHO community and a team was set up to resolve the problem. A model of the cover was developed in collaboration with the Mechanics Section of the Mechanical Systems Department of ESTEC. The first idea to open the cover by reducing even more the length of the pulse sent to the motor was confirmed. The pulse length to be used was determined empirically from the extensive modeling of the cover movement together with actual measurements on the spare in Davos. The major question was how to perform the same operation on an experiment without computer and thus without the necessary flexibility. The only way was to send a command for opening the cover, and then to switch-off VIRGO with a delay according to the pulse length wanted. To achieve this, MATRA/MARCONI (main contractor of SOHO), SAAB (on board computer) and the SOHO project devised a patch that would allow the accurate timing of the switch-off of VIRGO. One week before the real execution with the spacecraft, a rehearsal was performed at the SAAB premises using the VIRGO flight spare and a prototype of the SOHO onboard computer. The timing of the switch-off worked very well and allowed a variation in the pulse length from 70–700 ms with a precision of a few ms.

On March 27, 1996, the two most likely pulse lengths were sent to the spacecraft and the second one with 480 msec length worked. Clearly, this was a relief to all of us that had been working for more than 10 years on this project. The opening of the LOI cover was a concerted effort by many people as listed in the acknowledgments. The success was mainly due to the highly motivated co-operation between the different parties in order to allow LOI to play its important role for the unambiguous identification of low degree solar oscillations.

3. Description of the LOI

The design of the LOI instrument is extensively described in Appourchaux *et al.* , 1995a. Briefly, it consists of a Ritchey-Chrétien telescope (f=1300 mm) imaging the Sun through a 5 nm bandpass interference filter at 500 nm. The image is projected on a photodiode array detector built to our specifications (Appourchaux *et al.* , 1992). The detector has 12 scientific pixels and 4 guiding pixels (Fig.1). The shape of the scientific pixels are trimmed to detect low degree modes for $l < 7$ (Appourchaux & Andersen, 1990). The guiding pixels are 4 quadrants of an annulus with an equivalent inner and outer radius of 0.95 and 1.05 solar radius, respectively. The error signals for the guiding servo are the differences between two opposite pixels. The error signals are fed back to two piezoelectric actuators that move the secondary mirror around its vertex. The actuators provide both the coarse and fine pointing; the total range is $\pm 7.5'$ with a 0.2" resolution; the 3db bandwidth of the servo control loop is at 10 Hz. The current of each scientific pixel is amplified and digitised using Voltage-to-Frequency Converters (VFCs). The current of each guiding pixel is amplified and digitised by the common data acquisition system. The 12 scientific pixels are read simultaneously while the 4 guiding pixels are read sequentially. The sampling time of the instrument is 60 s. The integration time of the scientific pixels is the same as the sampling time. The integration time of the guiding pixels is about 3 s distributed over the 1 minute period.

The LOI data products are of two kinds: the level 1 and the level 2 data. The level-1 data are those that have been converted from raw counts (level 0 data) 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 variations. The signals are also reduced to 1 AU distance and to zero radial velocity. The level-2 data are the level-1 data corrected for degradation. The data products at either level are the following:

- 12 radiances of the LOI scientific pixels every minute
- 4 radiances of the LOI guiding pixels every minute
- 2 diameters (N/S and E/W) every minute

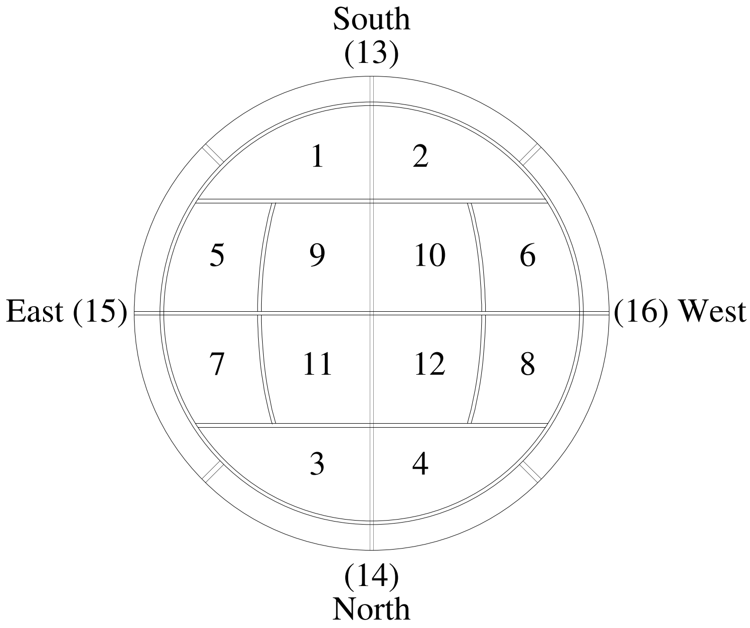

Fig. 1. Configuration of the in-flight detector of the LOI with the correct orientation.

– 4 VIRGO sunphotometers (SPM) flux corrections every day.

The first year's level-2 data will be made available to the scientific community one year after completion; for more detail on the data dissemination, see Fröhlich *et al.* , 1996. From the level-2 LOI data products the following derived data are used for the scientific evaluation:

– Time series of an l, m mode for p-mode analysis ($l < 9$)

– p-mode characteristics such as frequencies, splittings, amplitudes and linewidths

– Same as the above but for the g modes if they are found.

The level 0 and level 1 data will be made available to the scientific community only on request by a specific proposal to the VIRGO PI. The proposal will be discussed and eventually approved by the VIRGO team.

4. Instrument performances

4.1 Operations

The LOI was switched on December 6, 1995 and began, on this date, calibration measurements with the cover closed. These measurements entailed applying reference voltages to the amplifiers of the 16 pixels. The calibration measurements continued until the opening of the cover on March 27, 1996. A few minutes after the opening of the cover, the guiding servo loop was activated and the LOI was in its nominal observational mode where all 16 pixels are acquired every minute. On April 17, 1996, the calibration voltages were switched off, allowing a better determination of the offset voltages.

In addition to the normal operations of the LOI, the instrument took part in various useful joint payload operations: J3 and the roll operations. J3 occurred from April 3 to 5, 1996. During J3, the spacecraft scanned the solar rotation axis by ± 5 arcmin (North-South) and the solar equator (East-West) by ± 20 arcmin. During the North South scan the LOI active guiding was activated in the range -10 to 0 arcmin, and switched off outside this range. Similarly during the East-West scan the guiding was activated in the range ± 5 arcmin. The roll maneuver was performed on May 20, 1996. During the roll operations the spacecraft was rotated by 90° around the line of sight for about 20 hours.

Other regular spacecraft operations, such as the momentum management perturb the normal operations of the LOI; but due to the large guiding range, they can be handled without any additional specific operation of the LOI. Nevertheless, the data quality during such short periods is somewhat degraded.

4.2 In-flight performance

4.2.1 Dark current noise

During the 4 months that the cover was closed, we had ample time to characterize the noise of the electrical chain. This was derived using the so-called calibration mode described above. Fig.2 shows the power spectrum of an equivalent $l=0, m=0$ mode together with a typical real solar spectrum. A similar spectrum was measured on ground (Fröhlich *et al.* , 1996) for a single pixel, confirming an adequate performance of the instrument in space. The noise in the p mode range is about 0.1 ppm$^2/\mu$Hz which is about a factor 4 lower than what was observed from the ground by Appourchaux *et al.* , 1995b. This higher noise is obviously due to the Earth's atmosphere.

4.2.2 Guiding calibrations and performance

The J3 operations permitted calibration of the guiding when the servo loop was activated. This was useful to make sure that the piezoelectric actuators were performing as expected. It helped also to measure an offset towards the

South pole already observed by all the SOHO instruments. This offset was due to the spacecraft and amounted to 3 arcmin for the LOI. A repointing occurred on April 17, 1996 that put the solar image close to the LOI optical axis. Fig. 3 shows the calibration of the guiding, i.e. the high voltage applied to the actuators as a function of the offset angle. The sensitivity is about 1.6 arcsec/volt. The performance is the same as measured on ground. Fig. 4 shows the guiding stability of the instrument which is better than 0.01 arcsec at 1 σ. It is interesting to note that higher noise in the E-W direction remained when the spacecraft was rotated by 90° which indicates that the noise is from the pointing system of the spacecraft and not a solar feature.

4.2.3 Pixel sensitivity calibrations

The J3 operations were also used to perform a flat field calibration. The idea is derived from Kuhn *et al.* , 1991: a flat field of a multi-element detector (such as a CCD or a photodiode array) can be derived by moving an image with a known intensity distribution on the detector. We tried to use a very similar technique for flat fielding the LOI pixels.

As an example, Fig. 5 shows how the intensity varied on the pixels as a function of the offset angle. The measured profile is then compared with a theoretical profile, taking into account the limb darkening at 500 nm (Neckel & Labs, 1994) and the LOI pixel shapes. Since the active guiding was off (a fixed voltage was applied to the actuators) the position of the Sun was derived by maximizing the correlation between the measured and theoretical profiles (Fig. 6).

Unfortunately, the technique did not work because the intensity distribution must be convoluted with the point spread function (PSF) of the telescope. The PSF of the instrument varies a lot, especially when the image is not centered on axis; the variation of the PSF in the field can lead to variations in the intensity falling on the pixels of a few percent. The effect of a varying PSF was also measured when the active guiding was on. For example on Fig.7, the pixel intensity varies with the offset angle. These variations are calibrated for each pixel and used for producing the level-1 data.

4.2.4 Solar diameters

The guiding pixels of the LOI are also used to derive an equivalent solar diameter. We used the limb darkening function at 500 nm to derive the ratio of the guiding pixels to the central pixels. This ratio is almost a linear function of the size of the solar image, but it is insensitive to the decrease in flux which is due to the degradation. The diameters derived, for North-South and East West, are then converted to 1 AU using the orbit data of SOHO. Fig. 8 shows the solar diameters for June 1996. At the time, the Sun's apparent diameter was still decreasing. The opposite trend is still visible in Fig. 8 showing that the calibration has a systematic error of about 5%.

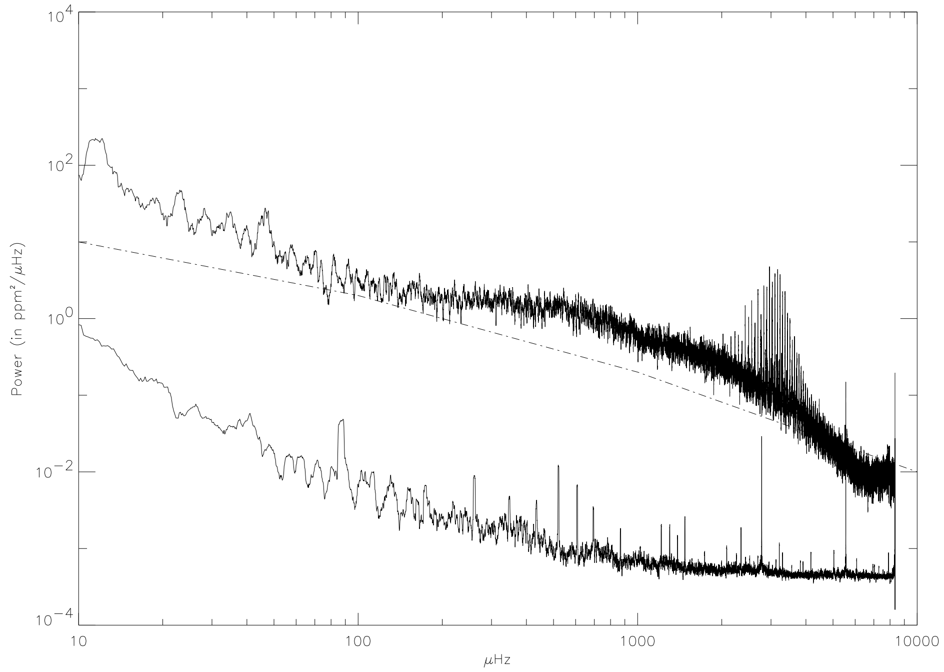

Fig. 2. (Top) Full power spectrum for an l=0 m=0 showing the 5-min oscillation modes. The spectrum becomes flatter around 1 mHz and then rises again; this is mostly due to the granulation noises and a Sun at its minimum of activity. (Dashed) This is the noise as simulated by Andersen *et al.* , 1994. (Bottom) This is the equivalent l=0 m=0 noise obtained during the calibration mode of the LOI (with the cover closed). The spectrum shows the noise due only to the electronic chain. The noise level in the p-mode range is about two order of magnitude less than the one of the granulation noise. Several spikes are present which are due to changing calibration modes (at regular intervals) of another VIRGO instrument. A large spike at 3 minutes is also present (at 5555 μHz and its 'harmonics' at 2778 μHz). This is due to the basic acquisition block rate of VIRGO, which is 3 minutes.

The seasonal variation of the Sun apparent diameter will be used to correct for this systematic error. The noise on the diameters is about 0.1 arcsec and 0.2 arcsec peak-to-peak for the North-South and East-West directions, respectively.

4.2.5 Solar image distortion

Although most of the performance characteristics are excellent, the LOI is still very sensitive to slight distortion in the shape of the solar image. The distortion affects both the size of the image and its circular shape.

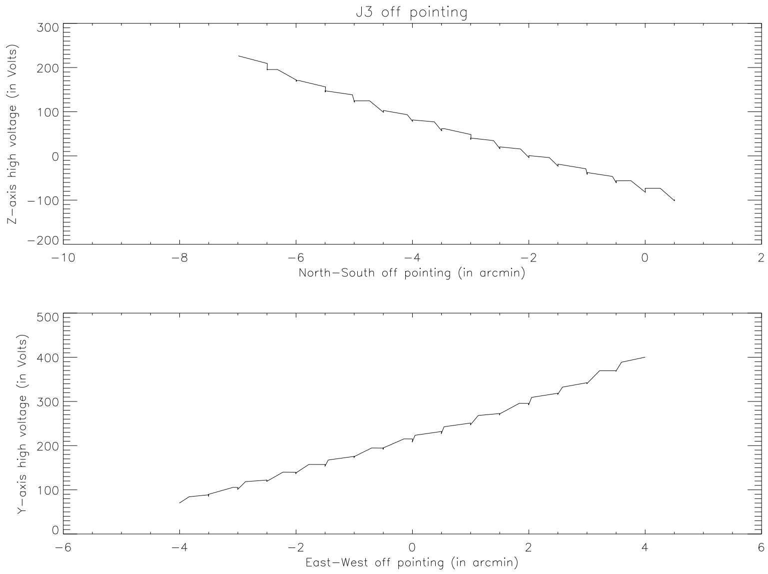

Fig. 3. High voltage as a function of the offset in arcmin for the East-West axis (bottom), and the North-South axis (top). The variations observed in voltage for a given offset angle are due to the creep in the piezoelectric material of the actuators.

In addition, this distortion has a 1-day periodicity creating, mainly in the $m = \pm l$ spectra, harmonics below 200 μHz, making the detection of the g modes more difficult. It has been empirically found that the temperature of the DC-DC converter of the high voltage can be used for compensating the distortion. Using the guiding pixels, we can derive that the magnitude of the distortion of the solar image is about 0.4 arcsec and 1.3 arcsec for a temperature change of 1 °C on the DC-DC for the North-South and East-West diameters, respectively. The magnitude of the correction is about 900 ppm/°C, 1550 ppm/°C and <400 ppm/°C, for the pixels 1–4, 5–8 and 9–12 respectively. The most affected pixels are, of course, the ones closest to the limb. The linear correction given above can reduce the amplitude of these harmonics by about a factor 3. This attenuation is not sufficient to facilitate the detection of the g modes in this range. A non-linear correction has yet to be derived that would provide better attenuation of the harmonics and would cope with larger temperature variations, as can be seen in Fig. 8 at the end of the day.

At the time of writing, the reason for the distortion is not yet understood. However since it has been observed that the distortion redistributes the flux among the pixels (i.e. the distortion disappears when summing up all the 16 pixels), there is great confidence that the effect will be explained. We used the linear corrections mentioned above for producing the level-1 data.

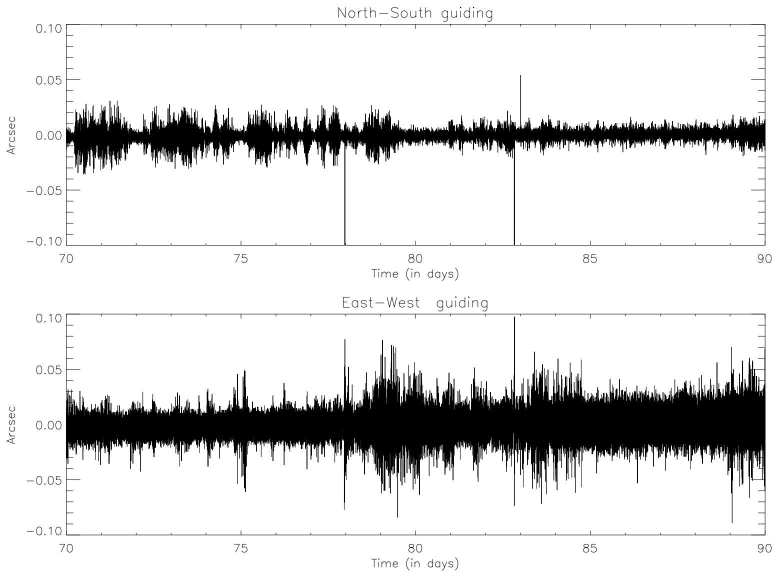

Fig. 4. Guiding stability for the East-West and North-South direction as a function of time. The East-West guiding pixels are noisier than those of North-South; this could be due to a combination of instrumental and spacecraft pointing noise. It is probably not of solar origin.

5. Scientific data analysis

5.1 Level 0 to level 1 processing

After the unpacketizing the data, the level-0 data are built from the 3 delayed transmissions of the VIRGO data; this is done at the VIRGO data center (VDC). The data are then converted from counts to engineering values using the calibration performed on ground. The offset calibrations were refined in flight after the calibration mode switch off. The 16 pixels are then converted to flux measured at 1 AU using the SOHO-Sun distance derived from the orbital data. The correction takes into account the real shape of the pixels, the limb darkening at 500 nm, and the in-flight size of the solar image at 1 AU. The precision of the correction better than 0.1 % is for all the scientific pixels. The pixels are also converted to zero velocity using the orbital data. These level-1 conversions are done at the VDC.

In addition, for comparing the LOI integrated flux with the SPM, 4 conversion factors are derived. These factors take into account the pixel shapes, the limb darkening and the non sensitive tracks on the detector. Since the variations are slow, these factors are generated once for a whole day. This is also done at the VDC.

The 16 pixels are corrected for the variations in intensity using the attitude data of the spacecraft. Finally, the distortion effect is corrected, using

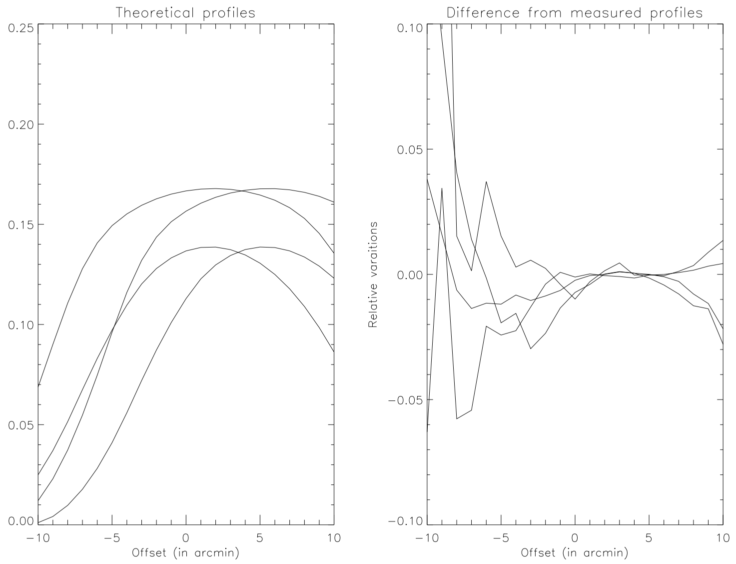

Fig. 5. (Left) Theoretical East-West pixel intensity as a function of the offset angle during the North-South scan. The lack of symmetry between the 4 profiles is due to the offset of the Sun during the J3 operations; the active guiding was off and a fixed voltage was applied to each actuator. (Right) Relative difference between the measured profile and the theoretical ones for these pixels.

the temperature of the DC-DC, by applying the same coefficient for all pixels having the same shape. These latter corrections are yet to be implemented at the VDC.

5.2 Comparison with the green channel of the SPM

Using the 4 SPM conversion factors, we compared the LOI integrated flux with the SPM. Fig. 9 shows the result of the comparison. The LOI flux decreases much faster than that of the SPM. The degradation affects all the pixels in the same manner . The stronger degradation is probably due either to the fact that the LOI entrance filter has a much larger viewing angle for the solar wind than the SPM, or to the higher temperature of the LOI filter (about 5090°), and possibly also to the fact that the filter were produced by different manufacturers. After correction for degradation, the LOI integrated flux compared quite well with the SPM. Especially the decrease in flux due to the emergence and the passage of a sunspot is very well correlated.

5.3 p-mode analysis

After the production of the level-1 data, the 12 scientific pixels are ready to be used for extracting the p modes. Each pixel is detrended using a triangular smoothing with a full width of 1 day, and then the residuals are

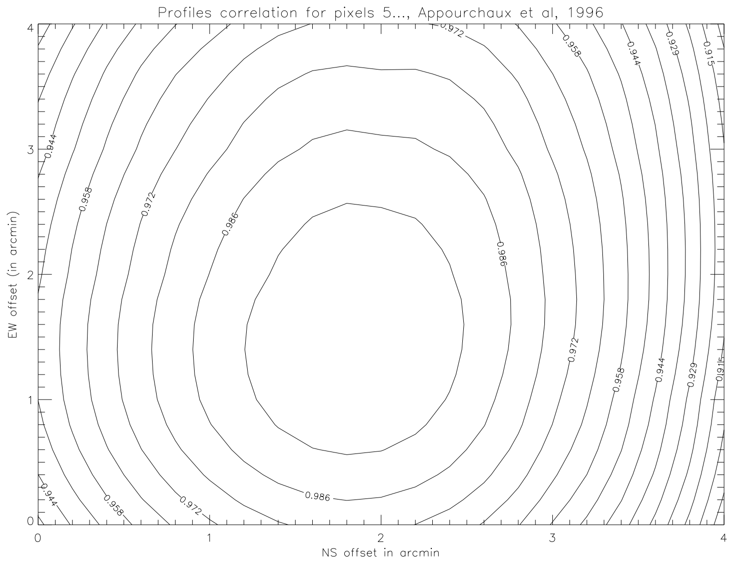

Fig. 6. Correlation map between the measured profiles and theoretical profiles for the East-West pixels as a function of the North-South and East-West offset angles. The scan was North-South which explains why the minimum is better defined in this direction. The maximum is very close to 1. Its location gives the offset of the solar image with respect to the center of detector during the J3. Similar correlation maps have been obtained for the other pixels and the other East-West scan.

converted to relative values. For extracting a given degree, the 12 pixels are combined using so-called optimal filters. The optimal filters were derived by Appourchaux & Andersen, 1990. Since these filters are complex they allow each m to be separated in a l,n multiplet. These filters were successfully used by Appourchaux *et al.* , 1995b,c and Rabello-Soares *et al.* , 1996. The optimal filters were computed weekly using the real size of the solar image (calibrated in flight) and the orientation of the Sun (only the B angle as P is maintained zero by the spacecraft orientation).

The spectra obtained have been used to derive the p-mode parameters. A given (m,ν) diagram is fitted using the maximum likelihood method as described by Appourchaux *et al.* , 1995b. As outlined in that paper, the different $2l{+}1$ spectra of a given (l,n) multiplet are correlated with each another due to the imperfect isolation of the modes, i.e. this gives rise to crosstalk between the modes (see also Rabello-Soares, 1996). In principle, the full correlation matrix should be used to fit not the power spectra, but the amplitude or Fourier spectra (Schou, 1992). Nevertheless, an additional complication has prevented us from implementing the fitting of the Fourier spectra: the crosstalk of higher degree modes into the lower degree modes is much more important. For example, in the $l=1$ we can detect $l=6$ and *vice*

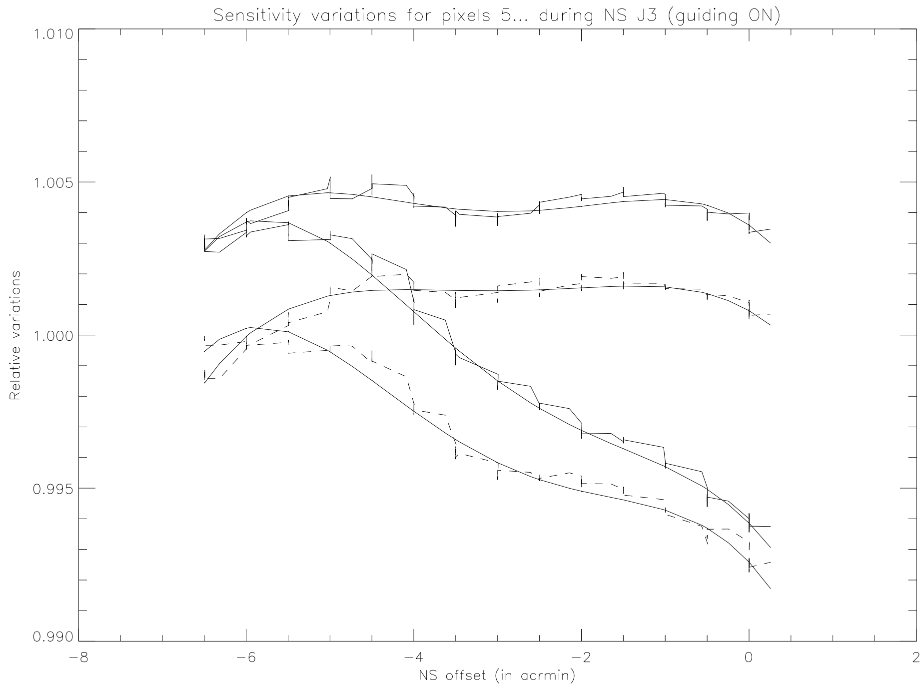

Fig. 7. Variation of the intensity of the 4 East-West pixels as a function of the offset angle when the guiding is active. The smooth lines are fifth order polynomial fits.

versa; in $l = 4$ we get $l = 7$ (Fig. 10) and *vice versa*; in $l = 5$ we get $l = 8$ and *vice versa*. This additional crosstalk was easier to implement in the fitting of the power spectra. The full crosstalk between the $2l+1$ modes of a multiplet and the amplitude of the aliasing higher degree modes has been computed using the optimal filters, but this time we kept the crosstalk amplitude fixed as in Rabello-Soares, 1996; this was not the case in Appourchaux *et al.* , 1995b. For the spectrum showing aliasing degrees, an estimate of the higher (or lower) degree frequency was fitted. For internal consistency, we checked that the frequencies derived were the same as for the nominal degree. We also kept the frequency of the aliasing degree fixed using known frequencies (from BBSO for instance). This did not affect the frequencies but helped to converge faster. In this way the bias due to cross talk on the frequency estimates was minimized.

As far as the rotational splitting is concerned, we believe that the estimates are biased for ($l \leq 3$) because we do not fit the amplitude. In addition, the inaccuracy in the knowledge of the crosstalk will lead to a bias on the splitting, the sign of which depends on the under– or over–estimation of the crosstalk amplitude. This effect is more important for low degree modes ($l \leq 3$). Fortunately, fitting the amplitude spectra is easier to implement

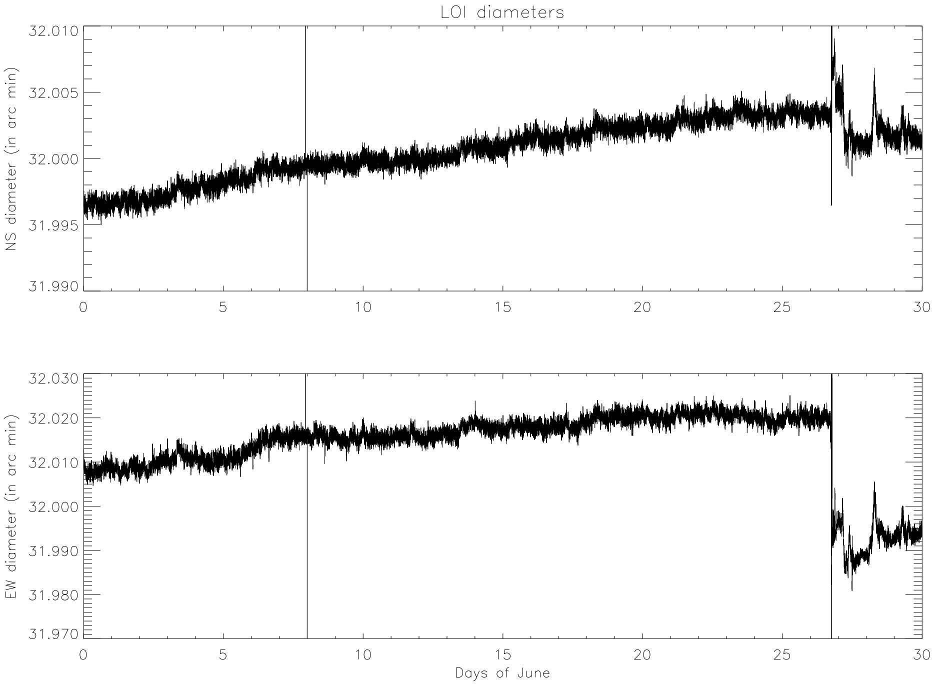

Fig. 8. The 1 AU diameters for the North-South (top) and East-West (bottom) as a function of time for the month of June. The slight trend remaining is due the imperfect correction for a decreasing apparent solar diameter. The typical precision over one day is less than 1 marsec.

for these degrees because the higher degree aliases are either very weak or non-existent. In any case, the sources of systematic errors in the estimate of the low degree splitting have to be carefully assessed before drawing any conclusion on e.g. the internal rotation of the Sun. From this point of view, longer time series will improve the situation.

6. Conclusion

In retrospect, only a few changes would have improved the instrument's performance. For example, we could have had more pixels; it would have reduce the leakage from the higher (or lower) degree. We could have read the guiding pixels using also individual VFCs, it would have reduced the high frequency noise by a factor of about 3.

Up to now the LOI has been performing extremely well. There are also great expectations from the measurement of the diameters. Nevertheless, a lot of work remains to be done to understand the cause of the distortion of the solar image, especially if we want to detect the g modes. The data

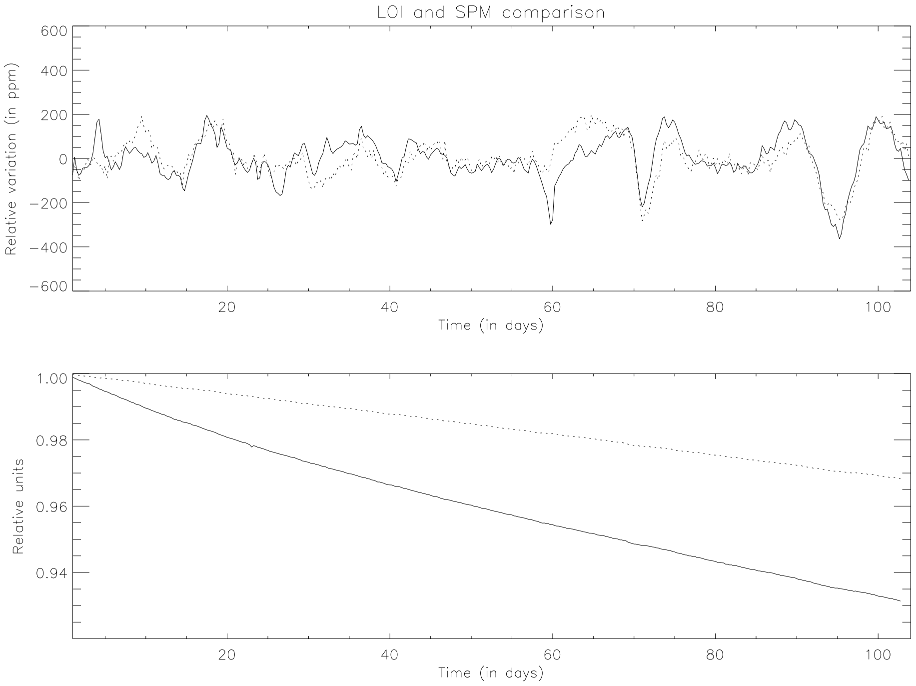

Fig. 9. Comparison of the LOI (solid) and SPM (dotted) green channel, both viewing the sun as a star. The time series starts on May 1, 1996. (Top) Relative variations. The agreement is quite good but there are still unexplained differences which need more detailed analysis. Both signals show very nicely the emergence and passage of an active region on day 70 and 90 respectively. (Bottom) Absolute variations normalized to the first datum.

allow to measure the p modes for $l \leq 7$ with a very high precision which is presented in the first scientific result paper by Fröhlich *et al.* , 1997.

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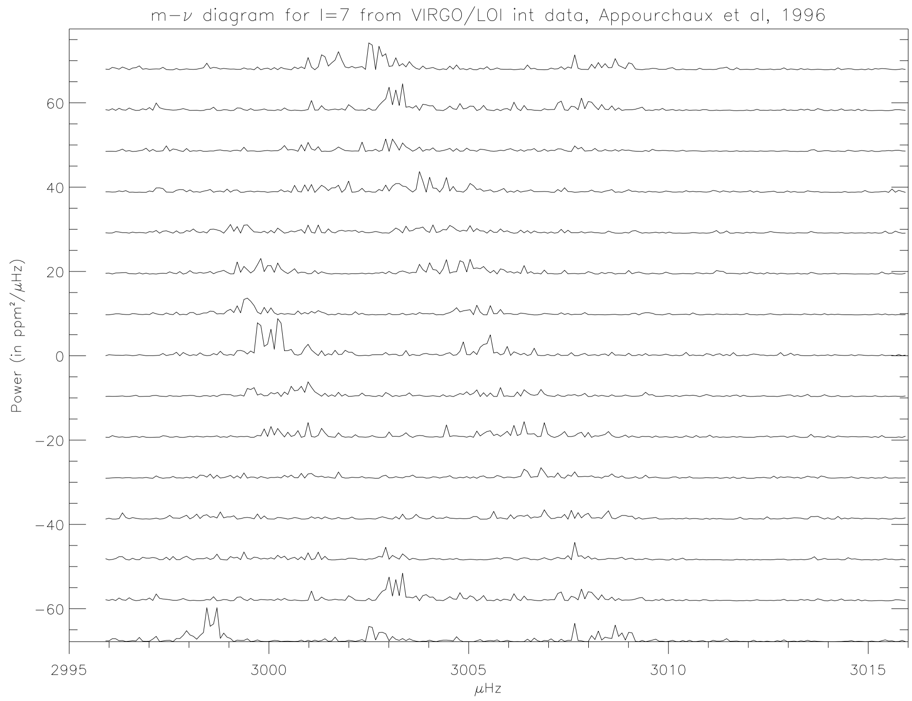

Fig. 10. m, ν diagram for an the $l = 7$, $n = 18$ mode; $m = -7$ is at the top. It shows an example of the effect of the leakage of the l=4, n=19 into the l=7. We see clearly the splitting of the l=7 mode and the also the effect of the crosstalk between the m modes. The splitting of the $l = 4$ is not visible as such because the leakage is more complex: in the $l = 7, m = -7$, the $l = 4, m = +4$ shows up; and in the $l = 7, m = +7$ the $l = 4, m = -4$ is transmitted.

Last but not least, we are thankful to H.J. Roth for his faithful dedication to the VIRGO instrument and all tests performed on the spare.

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