THE LUMINOSITY OSCILLATIONS IMAGER ON BOARD VIRGO: DESIGN AND PERFORMANCES

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ABSTRACT

The Luminosity Oscillations Imager is a part of the VIRGO instrument to be flown aboard the Solar and Heliospheric Observatory (SOHO) in Oct-Nov 1995. The main scientific objectives of the instrument are to detect solar g and p modes in intensity. The instrument is very simple. It consists of a telescope making an image of the sun onto a silicon detector. This detector resolves the solar disk into 12 spatial elements allowing the detection of degree lower than 7. The guiding is provided by 2 piezoelectric actuators that will keep the Sun centred on the detector to better than 0.1". The detailed design of the instrument is presented, together with its performance obtained with a ground-based version of the instrument. Preliminary scientific results have been obtained showing that the instrument performs extremely well (Appourchaux et al, 1995, A&A294, L13; and these proceedings)

Keywords: solar oscillations - p modes - g modes - instrumentation - space

1. Introduction

Helioseismology is a powerful tool to infer the internal structure of the Sun. In the past few years, a great deal of information on the internal structure and dynamics of the Sun have been gathered by various instrumentation (Harvey, 1988 and references therein). Thanks to the p modes, we have been able, so far, to probe down to $0.2R_\odot$ the solar internal rotation (Tomczyk et al, 1994).

Unfortunately, the structure and dynamics of the solar core is not yet determined because the g modes have not been yet detected. This will be the main challenge of helioseismology in the very near future. In 1995, the Global Oscillations Network (GONG) will come into operations. At the same time two others networks will be operating: BISON (Birmingham Solar Network) and IRIS (International Research on the Interior of the Sun); the all three together might detect the elusive g modes if they can reduce the atmospheric noise.

The upcoming satellite of the European Space Agency: the Solar and Heliospheric Observatory (SOHO) will not be limited by this type of noise. Aboard the spacecraft, three helioseismic instruments will join their force for detecting the g modes (Domingo and Poland, 1989; and these proceedings). One of these is the VIRGO instrument (Variability of Solar Irradiance and Gravity Oscillations). A sub-unit of VIRGO is specially dedicated to the detection of g modes: the Luminosity Oscillation Imager (LOI). In this article, we present the detailed design of the instrument, and its performances obtained with a ground-based version of the instrument. We will conclude by looking at the (bright) future of the LOI.

2. Design of the instrument

2.1 General concept

The design of the LOI instrument was an original idea of Andersen et al (1988) (Figure 1). It consists of a telescope imaging the Sun through a narrow passband filter. The image is projected onto a photodiode array detector. The detector is made out of 12 scientific pixels and of 4 guiding pixels. The shape of the scientific pixels is trimmed to detect modes for $l < 7$. The great advantage of this configuration is that we can isolate and identify individual l, m modes for up to $l = 6$ (Appourchaux and Andersen, 1990); this will help to detect and identify the g modes. The error signals given by the guiding pixels are used to keep the Sun centred on the detector using piezoelectric actuators. The current of each scientific pixel is amplified and digitised using Voltage-to-Frequency Converters (VFCs). 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 about 99% of the sampling time. Thanks to a sun that never sets on SOHO, the temperature variations of the spacecraft will be minimal. That is why the instrument is not thermally stabilised. It is better to have open loops than closed loops. These latter might mask the signal of the g modes.

The instrument without its high voltage power supply fits into a box of $9 \times 9 \times 30$ cm^3. Its weight and power consumption are 2.5 kg and 2.5 Watt, respectively. The integration and testing of the instrument was performed in ESTEC. The operations of the instrument are almost limited to the switch-on and observe modes.

2.2 Telescope

The telescope is a Ritchey-Chrétien with a 1300-mm focal length. The effective diameter of the telescope is 50 mm, with a central obstruction of 26-mm diameter. The concave primary has a focal length of 289.63 mm and an aspherisation of -1.02. The convex secondary has a focal length of 70.30 mm and an aspherisation of -2.7. The intermirror distance is 235 mm. Both mirrors are made out of Zerodur. To minimise the effect of temperature variation the mirrors are mounted in an Invar tube. The primary mirror is registered on 3 small Invar pads of 2-mm diameter; they are built in the Invar tube. At the back of the primary mirror, opposite of the pads, 3 2-mm diameter pins apply each a 10-N force; this insures that the mirror is kept in place for accelerations up to 30 g. The secondary mirror is mounted with 3 similar pads, but instead of a known force, the ring supporting the pads is just lightly clamped and its holding screws are glued. The secondary mirror is mounted in a gimbal allowing to keep the Sun centred on the detector. The design is such that the Modulation Transfer Function (MTF) of the telescope is not degraded even for a 10' offset of the Sun. The mirrors of the telescopes were made by SESO,

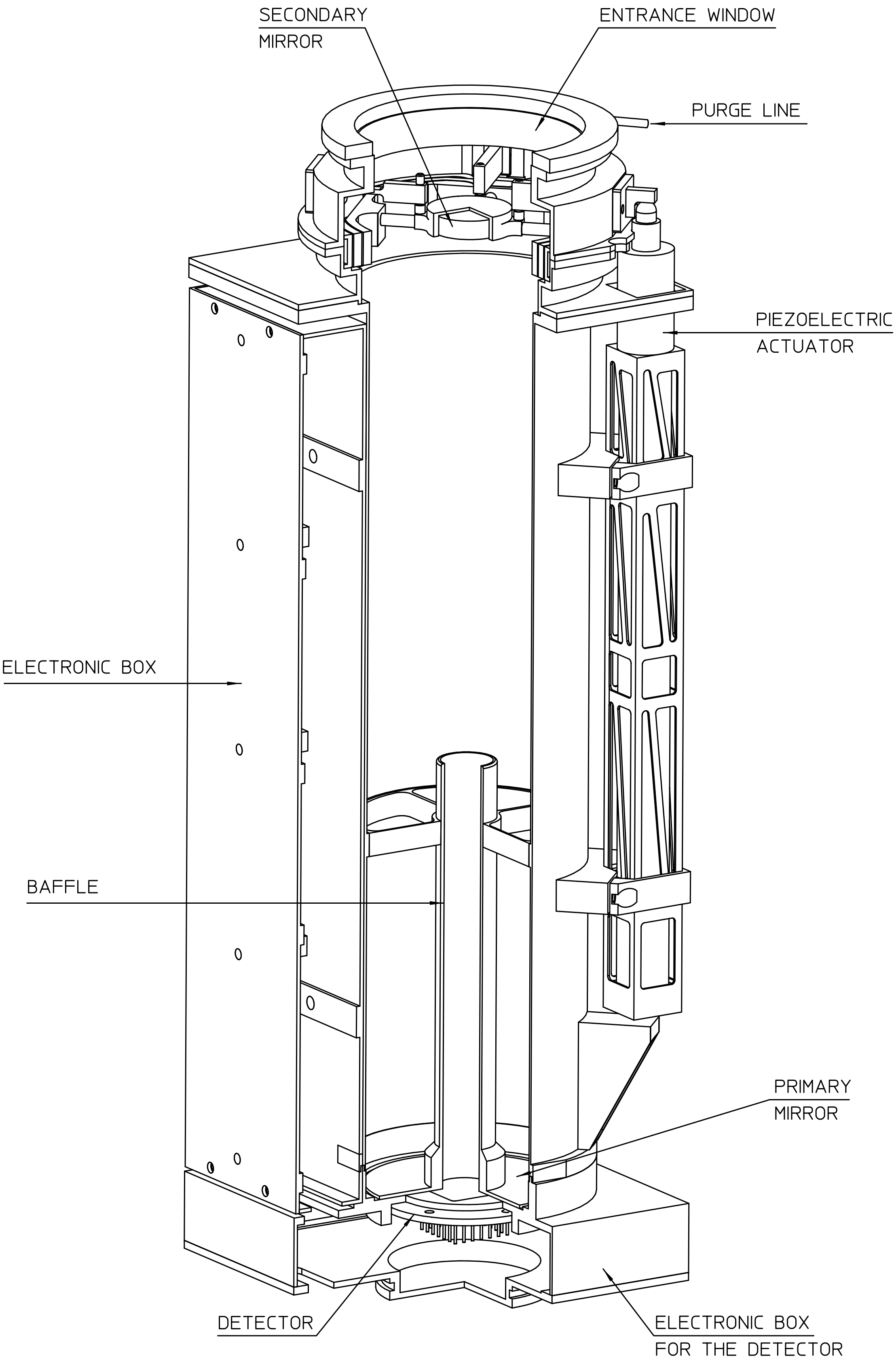

Figure 1: Cut-out of the Luminosity Oscillations Imager.

Aix-en-Provence, France. The Invar body was made by Brandt, Amsterdam, The Netherlands.

2.3 Filter

The spectral selection is performed by a 5-nm passband interference filter at 500 nm, used as an entrance window. It closes the Invar tube and isolate the mirrors and detector from the outside. The thermal design of the filter insures that its temperature is hotter that the VIRGO structure by 10 K (Appourchaux and Cislaghi, 1992); it will reduce the risk of condensing contaminants coming from the spacecraft. The filter is made of 3 different substrates, all are 3-mm thick and from Schott. The first one is a BK7G18 glass, cerium doped and radiation resistant; it is used to reduce the radiation dose and proton flux received by the other substrates and coatings. The second substrate is a GG475 coloured filter which absorbs about 20% of the incoming solar radiation, it is also used to reduce the amount of blue light received by the coating. The coatings making the spectral selection are deposited on the GG475. The last substrate is a BG18 heat absorbing glass, it is used as back-up in case the coatings reflecting the infrared get degraded. Finally an Inconel coating is deposited at the back of the BG18 glass for getting a 7% transmission; this low transmission insures that the detector is used in a linear regime. Irradiation tests of the filter confirmed its ability to resist the 6-year SOHO radiation dose (Appourchaux et al, 1993; Appourchaux, 1993). In addition, the filter after a 1-year dose of UV irradiation showed no significant sign of degradation either in its absorptance (Marco et al, 1994) or spectral characteristics. The filters were made by Andover, Salem, New Hampshire.

2.4 Detector

The detector is a silicon photodiode array (Figure 2). It is made out of 12 scientific pixels and of 4 guiding pixels. The photodiodes are deep diffused p-n junction with an epitaxial substrate (low resistivity). In addition 4 temperature diodes are built in the detector for having the temperature across the substrate. For improving the definition of the sensitive area of the scientific pixels, a layer of aluminium is deposited outside the pixels and over the temperature diodes. In addition, each pixel and each temperature diode is surrounded by a n^+ deep diffused guard ring; this will minimise the crosstalk between the pixels. It will also insure that the signal of the pixels do no get contaminated by a pixel for which the bonding wire breaks; in this case the electrons flow to the ground and not the other pixels. Each guiding pixel is made of two independent pixels that are connected to the same output (Figure 2). In case one of these pixels would not be functional, we would still have guiding information and the image of the sun would have a slight offset. The detector is directly mounted into a Kovar plate which is bolted on the Invar structure behind the primary mirror. The ground lead of the detector is connected to the Kovar plate, and this plate is isolated from the Invar using an Ertapeek washer. The tests showed that the temperature dependence of the quantum efficiency of the photodiode is less than 100 ppm/K @ 500 nm (Appourchaux et al, 1992). There are major concerns that the measured dependence might change with time. At the time of the SOHO flight, the dependence will probably need to be re-evaluated and compared to the laboratory measurements. The measured crosstalk between pixels is smaller than 0.01%. The detectors and their cases were made by AME, Horten, Norway.

Figure 2: LOI detector optimised for the detection of low degree modes. The parameter a is about half the solar radius (a=3.055 mm). The guiding pixels are 4 quadrants of an annulus with an inner and outer radius of about 0.95 and 1.05 solar radius, respectively. The four black spots at the corners are the temperature diodes. These diodes are below an aluminium layer shown here in grey.

2.5 Guiding system

The guiding system is the critical part of the LOI. The SOHO spacecraft is stable within a few arcsec over 15 minutes, in principle this stability is good enough for detecting p modes. Nevertheless, the noise at low frequency will be considerably reduced with a guiding system which is crucial for detecting g modes; in addition it is now proven that a functioning guiding system simplifies enormously the data reduction (Appourchaux et al, 1995).

The guiding system provides both the coarse and the fine guiding. This system is based on the following principle: 2 piezoelectric actuators rotate 2 lever arms that push on a gimbal in which the secondary mirror is mounted. The rotation of this mirror is done around its vertex. Two spring arms opposite of the two lever arms provide a restoring force (about 20 Newton) and act as a locking mechanism (Figure 3).

For the fine guiding, the error signals, provided by the guiding pixels, are fed back to the high voltage power supply that drives the actuators. The guiding regulator is an integrator. The cut-off frequency of the complete guiding system is 10Hz @ 3dB. The precision reached from the ground is about 0.2"-0.4", limited by the atmosphere. The expected in-flight guiding precision will about 0.1".

For coarse guiding, the total range needed is ±7'. This is for allowing for the long term drift of the spacecraft (±5'), the temperature setting of the actuators (±1') and alignment errors (±1'). This corresponds to physical extension of the actuators of 80μm; this includes. the reduction effect due to the fact that a variable force is applied onto the actuators (72%) by the spring arms and gimbal.

A finite element analysis of the whole guiding assembly (gimbal+arms+actuators) was performed. The main goals of this analysis was to verify the effectiveness of the locking mechanism when the guiding was subjected to the vibrations of the launch. It also helped to verify that the first and second resonance frequencies of the guiding system were high enough for not being excited by the servo loop. Vibration tests at qualification levels confirmed the analysis (i.e. it survived and stayed aligned within 1'!). The predicted resonance frequencies of the system (250 Hz and 380 Hz), were found during the bench tests.

The critical components of the guiding system are the actuators. They are made of about 200 piezoelectric discs. On each of these discs, a high voltage is applied (range: 0-600 Volt). For increasing the redundancy, each actuator is made out of 12 separate stacks, each in series with a resistor. If we would not have this feature, a single failure of a disc (a short circuit) would destroy the high voltage power supply. The length of the 200-disc stack is about 230 mm. To avoid to break the stack during launch vibrations, the middle of the stack is strapped to the case over 10 mm; this design is qualified for the launch of SOHO. The actuators were built by Queensgate Instruments Ltd, Bracknell, England.

2.6 Electronics

The 12 scientific pixel currents are converted into voltages by 12 low-noise operational amplifiers (AD-OP97) in a zero bias configuration. This latter will minimise the $1/\nu$ noise. The analog-to-digital conversion is performed by synchronous Voltage-to-Frequency converters (VFC) (AD652). The VFCs are co-located on an aluminium-oxide substrate (hybrid technology) for improved thermal stability. The VFC outputs are accumulated into 24-bit counter ASICs (Application Specific Integrated Circuit). The integration time is 99% of the sampling time of 60s. The ASICs are read by the VIRGO DAS (Data Acquisition System) (Fröhlich et al, 1995, these proceedings). The resolution of the data chain is better than 0.1 part-per-million (ppm). The accuracy is better than 3 ppm which was limited by the voltage standard used for calibration. The main source of drift is the temperature coefficient of the VFC which is about 1.5 ppm/K.

The guiding pixels are amplified in the same way as the scientific pixels. The North- South and East-West guiding errors are obtained using differential amplifiers. The error signals are fed into servo regulators driving high voltage output stages (bipolar discrete technology). The high voltage amplifiers have a fixed gain. They are built with high voltage DC/DC converters with a fixed output voltage (600 Volt) and series regulator circuits. The negative lead of the actuators is kept at a constant voltage of +150 Volt. The positive lead is variable between 0 and 600 Volt. If needed the servo loop can be switched off and a fixed voltage can be applied to the actuators. The fixed voltages are selectable by telecommands. The whole electronic system was built in ESTEC.

3. Discussion and conclusion

The scientific and technical performances of the instrument were checked using the qualification version of the instrument. This latter was installed in Tenerife on May 2nd, 1994. Since then it has been operating nominally without any malfunctions. The scientific results are discussed in Appourchaux et al (1995) and in these proceedings. So far only the atmosphere prevent us to reach a better signal-to-noise ratio in the power spectra, and a more precise guiding. In addition, the guiding effect as reported by Appourchaux et Andersen (1990) are much bigger than effectively measured with the ground-based instrument; the overestimation is about a factor 4. Apart from this, the behaviour of the instrument follows the theoretical prediction. Others articles using the LOI data report in these proceedings on measuring the solar radius fluctuations (Rabello-Soares et al, 1995) and the solar noise background in intensity (Jiménez et al, 1995).

One of the authors (TA) has great confidence that the LOI will detect the g modes. Using the capability of the instrument to isolate the $2l+1$ modes of a given l will allow to reduce considerably the crowding of the g modes in the power spectrum. The future of the LOI can only get brighter if the space instrument resists the various hurdles of the launch, cover opening...and operations.

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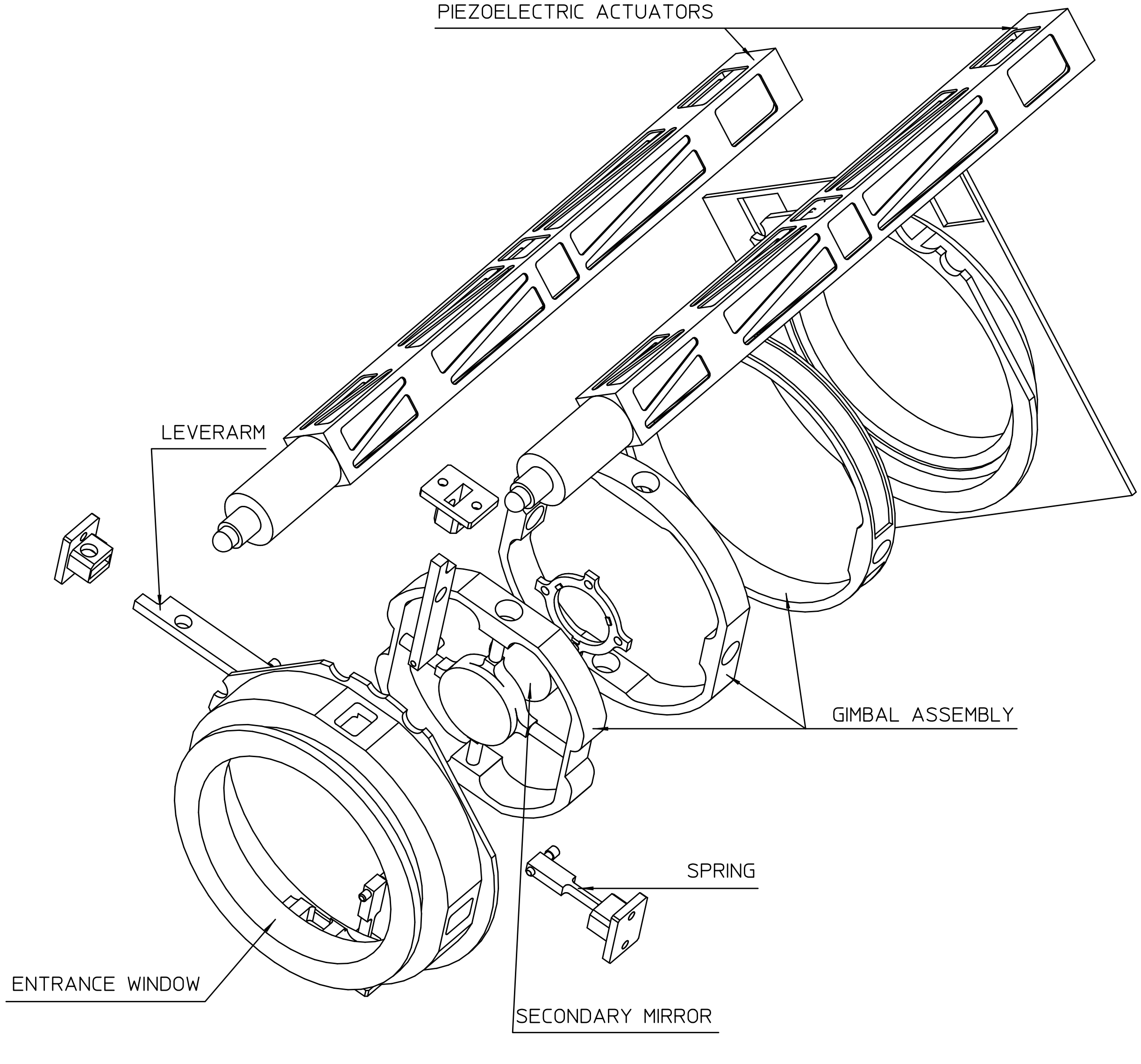

Figure 3: Artistic blow-up of the guiding system. The assembly of the 3 rings making the gimbal is very critical. Friction between the rings modify the normal behaviour of the guider. The piezoelectric actuators are longitudinally kept in place by back screws, not shown here. For each axis, the fine adjustment is made with a screw located on the lever arm. The 20-N force is adjusted with a screw located on the spring arm.