PICARD: SIMULTANEOUS MEASUREMENTS OF THE SOLAR DIAMETER, DIFFERENTIAL ROTATION, SOLAR CONSTANT AND THEIR VARIATIONS

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ABSTRACT

PICARD, from the name of the French astronomer who first observed with consistency the Solar diameter changes during the Maunder minimum, is a CNES microsatellite mission due for flight by the end of 2002. It consists of two instruments measuring (i) the Solar diameter and differential rotation, and (ii) the total Solar irradiance. These quantities are fundamental for the understanding of the Solar-Terrestrial relations, e.g. the influence of the Sun on the Earth's climate, and of the internal structure of the Sun. The permanent – or near permanent – viewing of the Sun from an appropriate orbit, the 5 minutes sampling rate and the very low noise measurements, will allow g modes detection and precise diameter measurements besides accurately establishing the relationship between irradiance and diameter changes. Providing an absolute measure of the Solar diameter to 1 mas, PICARD is the first step towards instruments capable of accurate and perennial measurements, for the centuries to come, of the Solar-Terrestrial influence. The objectives of the mission, instrument capabilities, observing modes and performances will be described.

INTRODUCTION

Their has been considerable work linking the various global Solar parameters in order to answer – both theoretically and with observations – to the prominent and actual question of our capability to understand and to predict the Earth's climate changes (e.g. Sofia and Fox, 1994). However, yet further efforts are required to measure, study, and understand how our global environment is evolving.

The Sun is the fundamental source of the energy that establishes the Earth's radiation environment and controls its temperature and atmospheric composition. The amount of energy received at one AU by the Earth, the Solar constant, may vary due to two specific phenomena:

i. change in the earth's orbital eccentricity,

ii. the intrinsic Solar variability.

In the first case, periodical eccentricity, obliquity and precession changes are acknowledged to be the cause of the alternating glacial-interglacial periods of the last million years. This is refereed as the Milankovitch's theory. For the second case, it exists some correlations between surface temperature changes and Solar activity. However, the detailed mechanisms by which the Solar activity may be responsible of a climate change is still debated due to the specific role of the UV change associated with the Solar constant variations.

Since the Solar energy is one of the major driving inputs for terrestrial climate, it is important to know on what time scale the Solar irradiance and other fundamental Solar parameters – like the diameter – vary in order to better understand and assess the origin and mechanisms of the terrestrial climate changes.

The PICARD Mission will provide information on Solar global parameters. Its strategy is to measure diameter, differential rotation, total irradiance, spectral irradiance in selected wavelengths and oscillations, concurrently, to determine their relationships experimentally.

The expected stability of the experimental environment (near continuous measurements from a near-permanent non-eclipsing Sun-synchronous orbit) will allow PICARD to contribute to the direct study of the Sun's deep interior, by providing the first realistic opportunity to observe long period oscillations gravity modes, "g modes" (with a sensitivity to the μarcsec for coherent oscillations). These will make possible to probe the Solar interior and to reveal the underlying mechanisms of Solar variability to better understand its role in Solar-induced climate changes.

PICARD is now an approved CNES microsatellite program (100 kg Mission class, satellite and payload) to be launched by mid or end 2002, most probably as a passenger on the ASAP plateau of one of the Geostationay Transfer Orbit (GTO) launches of Ariane V.

SCIENTIFIC OBJECTIVES

PICARD (from the French Astronomer Jean Picard who first observed the diameter changes during the 17th century, at "Maunder Minimum" epoch) will carry simultaneous measurements of the Solar diameter, differential rotation, Solar irradiance and of their variabilities, and study their consequences for Earth's climate and the internal structure of the Sun.

Historical importance of the diameter measure

Louis XIV, King of France took the decision in 1666 to found the Académie Royale des Sciences and to built the Observatoire de Paris. As we shall see below, this has been a fortunate decision for the study of the Sun-Earth's Climate connection. Astronomy was a significant part of the program of the Académie, in particular the study of the Sun (sunspots, rotation...) and the Earth's orbit parameters (eccentricity, distance to Sun and obliquity). Among some other works concerning the Earth's radius determination, Jean Picard, member of the Académie, devoted a significant part of his activity to Sun observations. To determine the Earth's orbit eccentricity, he measured the Solar diameter, and also observed the sunspots and determined the Sun rotation velocity. After his death, in 1682, his program was carried on by his student Philippe de la Hire. Fortunately, the measurements extent from 1666 to 1719, covering the Maunder minimum and some time after. The data were re-examined by Ribes *et al.* (1987). The micrometer used for the measurements has a claimed accuracy of 0.5 arcsec following the statement of A. Auzout who built it. However, it is always difficult to estimate the absolute accuracy of the old instruments (Toulmonde, 1997). The processing of Picard and La Hire's data shows a much better precision. After removing the seasonal variation of the Solar diameter, the annual mean was obtained at 1 AU. These values averaged for the Maunder minimum period and after the Sun having recovered a significant activity, show a definitive difference of the order of 0.5

to 1 arcsecond, corresponding to a larger Sun diameter during the Maunder minimum. As expected, few sunspots were observed. However, Picard's data also showed a slow down of the Sun rotation velocity at equator and more sunspots in the south Sun hemisphere than in the north.

Diameter and Earth's climate

The Solar constant measurements performed in space by the radiometers since 1978 were modeled using the sunspots number and faculae. This allowed to reconstruct the Solar constant variation till 1610 (Lean, 1997). Fig. 1 shows the Solar constant and its significant decrease during the Maunder minimum. The temperature in the northern hemisphere has been also reconstructed for the same period. The cooling of this period is known as the Little Ice Age. The similarity of the temperature and Solar constant variations strongly suggests the Maunder minimum as the cause of the Little Ice Age.

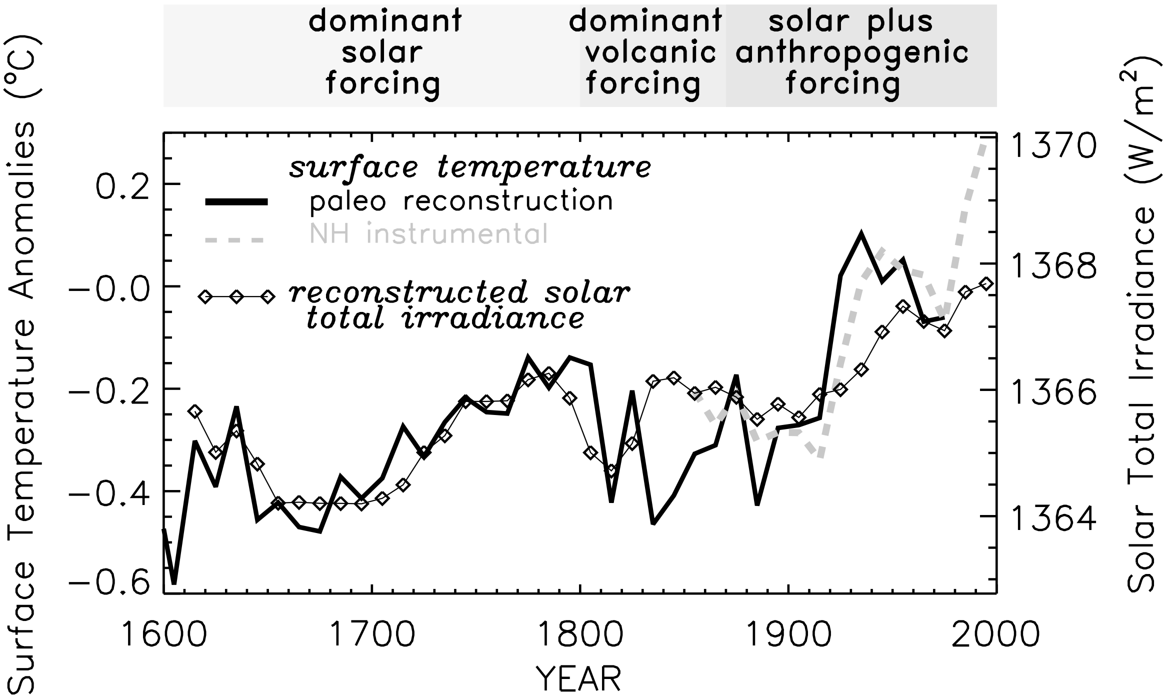

Figure 1: Reconstructed Solar total irradiance from 1610 to 1995 (from Lean, 1997). Notice the excellent agreement up to 1920–1975 and the possible anthropogenic contribution afterwards. Volcanic forcing (cooling) can be seen on short periods after the major eruptions: 1815 (Tambora), 1831 (Babuyan), 1835 (Cosiguina) and 1883 (Krakatoa).

To assess this suggestion, climate models were run. A simulation (Sadourny, 1994) has provided the results of Table 1. This shows the Maunder minimum as the possible cause of the Little Ice Age. However, volcanic eruptions also play a certain role, but their effects do not extent to more than a few years.

Location	Authors	Reconstructed temperature ($°C$)	Simulated
British Isles	Lamb, 1977	0.5 to 1	1.4
Netherlands	Van der Dool *et al.*, 1978	1	1.5
Paris	Legrand *et al.*, 1990	0.8	1.5
South Norway	Matthews, 1976	1.6	1.6
Switzerland	Pfister, 1978	0.2 to 2	1.6

Table 1: Climate models simulation of the reconstructed temperature (Sadourny, 1994).

As during the Maunder minimum where, as suggested by Picard's data, the Sun radius experienced a significant change, the modern data of Sun diameter measurements and sunspots number, set together by

Laclare *et al.*, 1996 (cf. Fig. 2), reveal a relation between the Sun radius and Solar constant variations corresponding to an increase of the Sun radius for a decrease of the Solar constant. However, the Sun's diameter as measured on the ground may be suspected of atmospheric effects. Many papers have discussed these sources of errors. Another concern is the controversial evaluation of the Solar constant–diameter relation derived from the Mount Wilson data (see, e.g., Ulrich and Bertello, 1995). One should notice that in this last case the diameter is "photometric", evaluated at 25% of the Sun center flux, that the authors recognize a large trend in their measurements and, more questionable, that the line used for the measurement is 525 nm, a well known magnetic line. That the sunspots number (a measure of activity) is directly related to the photometric diameter measured in a line used as a magnetic tracer is not surprising us. Mount Wilson data are not measuring a "quiet Sun diameter" but, rather, another activity indicator. Anyhow, in order to establish experimentally without ambiguity, the Sun constant and diameter relationship, we propose to operate from space by measuring simultaneously both quantities from the same platform and in non-magnetic lines or continua. The importance of the measurements for climatology is straightforward taking into account the Little Ice Age and the Maunder minimum events.

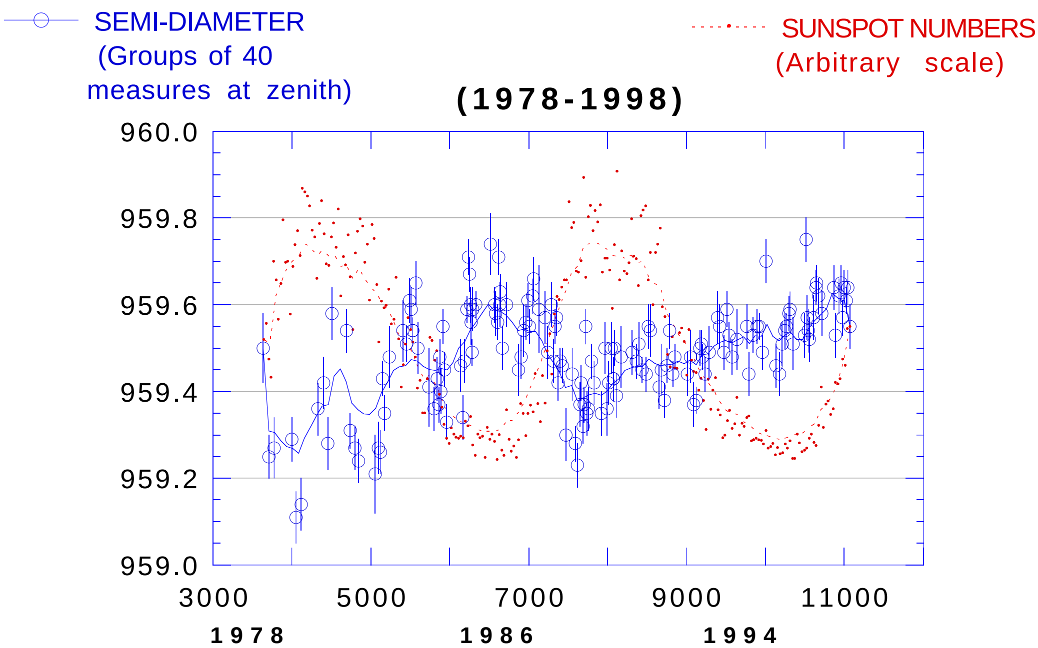

Figure 2: Opposing phase observed between the Sunspots number and the semi-diameter measured at the CERGA Astrolabe over the last 20 years (courtesy of Delmas and Laclare).

Lyman Alpha monitoring. Lyman alpha irradiance has been monitored since 1977, first from the AE-E satellite between 1977-81, then from the Solar Mesosphere Explorer (SME) between 1982 and 1989, and most recently from UARS since 1991. The EOS/SOLSTICE experiment will be launched in late 2002 and it will also monitor Lyman alpha irradiance. Since these irradiance monitoring experiments observe the Sun as a star, there is no information about the physical causes of the observed irradiance changes. To identify the causes of changes in Lyman alpha, one needs to compare the full disk irradiance data with images. PICARD will provide high resolution and continuous Lyman alpha images which will well complement the EOS/SOLSTICE measurements. These images will make it possible to better account for the observed Lyman alpha changes and also for a better reconstruction of a long-term Lyman alpha data set. Since Lyman-alpha irradiance is important for the ozone changes and the formation of the ionospheric D-region in the Earth's atmosphere, better understanding of the variations in Lyman alpha will also be important for atmospheric science and aeronomy.

Oscillations

Another objective of PICARD is to detect the Solar gravity modes (g modes) of the Sun. These modes are of prime importance for understanding the structure and dynamics of the Solar core which cannot be studied by using Solar pressure modes (p modes) alone. So far the g modes have not been discovered by any set of instruments onboard the SOHO spacecraft. The 1-σ upper limit of g-mode amplitude at around 200 μHz is typically 1 mm/s or 0.1 ppm (Fröhlich and the Phoebus Group, 1998; The Phoebus group is described by Appourchaux, 1998). Similar limits in the same frequency range have been reported by the GOLF team (Gabriel *et al.*, 1998). Given a velocity amplitude of 1 mm/s at 200 μHz, the displacement of the Solar surface would be of about 1.6 m p-p which is equivalent to a variation of Solar radius of about 2 μarcsec. This level could be marginally detected by PICARD although this is not the method we are using for detecting the g modes with our instrument. Nevertheless, it is worth noticing that MDI/SOHO was able to – without an optimized, stable and distortion free telescope as SODISM/PICARD – to observe a 10 μarcsec high frequency p mode (5 min.) Solar limb oscillation signal (Kuhn *et al.*, 1997).

With PICARD we want to detect intensity fluctuations at the Solar limb that will perturb the equivalent Solar radius signal. Appourchaux and Toutain (1997) reported to have detected p modes using the limb data of the LOI instrument. In some case the amplification with respect to full-disk integrated data is about 4, i.e. it means that a p mode with an amplitude of 1 ppm in full disk is observed with an amplitude of 4 ppm at the limb (Fig. 3). The amplification factor was roughly predicted by theory (Appourchaux and Toutain, 1998). If we hope that the same amplification factor holds for the g modes, we may detect them faster with the limb data of PICARD than with the SOHO data. A pessimistic derivation gave 20 years for the detection of the first few g modes with SOHO (Fröhlich *et al.*, 1998). With PICARD we can seriously envisage detecting them in 16 months with the amplification factor above.

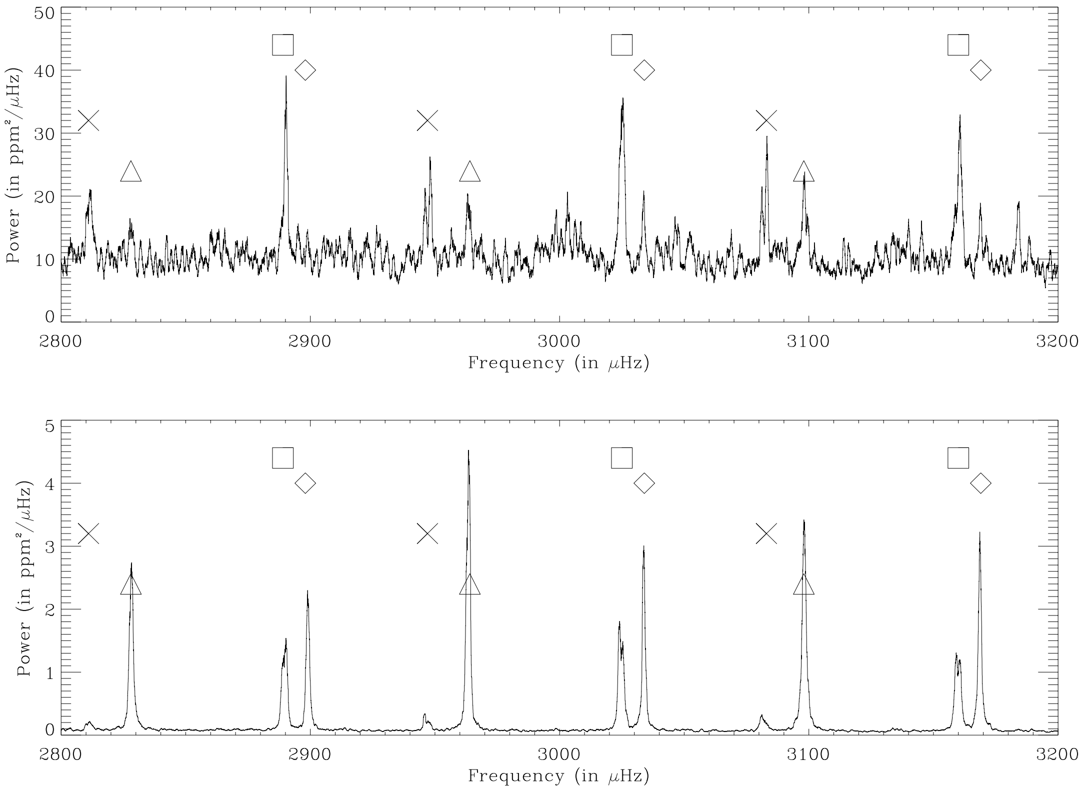

Figure 3: Power spectra of 733 days of LOI data for the East-West guiding pixels (top) and for the full-disk signal (bottom). The location of the p modes is indicated: $\diamond$ l=0, $\triangle$ l=1, $\Box$ l=2, $\times$ l=3. The large amplification of the l=2 and l=3 modes was predicted by theory, so was the lack of amplification for l=1 (Toutain and Gouttebroze, 1993). The weak amplification of the radial mode compared to theory remains to be solved.

PICARD INSTRUMENTS

To carry the proposed measurements PICARD has 2 instruments: SODISM, the "Solar Diameter Imager and Surface Mapper", for the measure of the diameter and differential rotation (this is, therefore, a whole Sun imager) and VIRGO (Variability Irradiance Gravity Oscillation) or SOVA (Solar Variability), for the measure of the total absolute Solar irradiance (correlation with SODISM measurements). A complimentary package of 4 UV photometers at 230 nm is also envisaged.

SODISM/PICARD

SODISM is a simple telescope of useful diameter ∅10 cm (cf. Fig 4). It forms a complete image of the Sun (∅25.9 mm) on a large, back thinned, CCD of 2048 x 2048 useful pixels. The pixel corresponds to 1 arcsec (at 1 AU) and the effective spatial resolution is about an arcsec (at the limb). SODISM observes in 4 wavelengths bands the whole Sun (230 nm, 538 nm, 160 nm and Lyman alpha) and 2 calibration channels (cf. Table 2) accessible through the use of 2 cascading filterwheels, each with 4 positions.

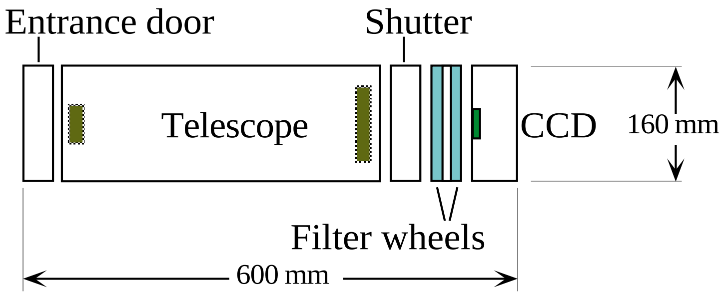

Figure 4: Concept of the SODISM/PICARD telescope assembly.

UV nominal mode	230 nm
Visible	538 nm
Active regions	160 nm
Prominences and ionosphere	Lyman alpha
CCD Flat Field	"Diffusion"
Focusing Calibration	"Window"

Table 2: The 6 observing/calibration modes of SODISM/PICARD.

Observing/calibration modes. The main observing wavelength is 230 nm (8 nm bandwidth). It corresponds to a *flat* UV continuum formed in the high photosphere. It is the best possible choice of wavelength since it is sensitive to UV variations (about half of the MgII index variability for instance), it corresponds to the ozone bands (and by chemical interaction in the stratosphere, the UV may affect the stratospheric dynamics and, consequently, the clouds coverage – which may be one of the paths of the Sun influence on the Earth's climate) and the limb darkening in this continuum is limited.

In addition, SODISM/PICARD observes 538 nm which is the center wavelength on the 100 nm bandpass used by Francis Laclare CERGA's group for the Solar diameter measurement with the Astrolabe (and, in the near future, with the new DORAYSOL instrument). The 160 nm and Lyman alpha filters are used for identification and elimination of the active regions and prominences. This is essential to prevent activity manifestations to affect the "quiet" radius determination. By eliminating from the diameter computation the pixels at the limb affected by faculae, active regions, prominences, sunspots or pores, SODISM/PICARD only reduces its sensitivity in the ratio of a few diameters over 3000. This doesn't add noise from these Solar sources to the diameter measure.

The diffusion plates are simply used to monitor the CCD response and sensitivity (Flat Field function).

The CCD itself is a complete state -of-the-art system (EEV 42-80 2048x4096 pixels back thinned and with frame transfer) hopefully developed in parallel of our program for the COROT asteroseismology PROTEUS satellite program of CNES (to be launched in the same time frame than PICARD).

Finally, and specific to PICARD – and providing the ABSOLUTE diameter reference at the mas (milli arc second) level – is the "Window plates" channel. It provides access to stellar fields in which (with a limit magnitude of 9) stars' triplets of the HIPPARCOS reference catalog are imaged, allowing to identify and to follow any structural change in the focus or CCD dimensions which could affect the diameter measure directly.

Optical concept. SODISM has a sound optical concept allowing to achieve a distortion free and dimensionally stable image of the Solar limb. It has a symmetry of revolution (no complex optics – filters at normal incidence – nothing else than the two mirrors and 2 filters in the optical path) and a single telescope-detector-guiding telescope support structure for common referencing and stability. The telescopes mirrors (and, as well, those of the guiding telescope) are made of SiC without coatings (reflectivity of 40 % in the UV and yet 20 % in the visible). Advantage is indeed that the photometry will not change by aging and degradation of coatings since there will be no coatings. Further, the primary and secondary mirrors will help to remove 96 % of the visible Solar flux, preserving the filters from degradation and, due to the high conductivity of SiC, this observed flux will easily be removed.

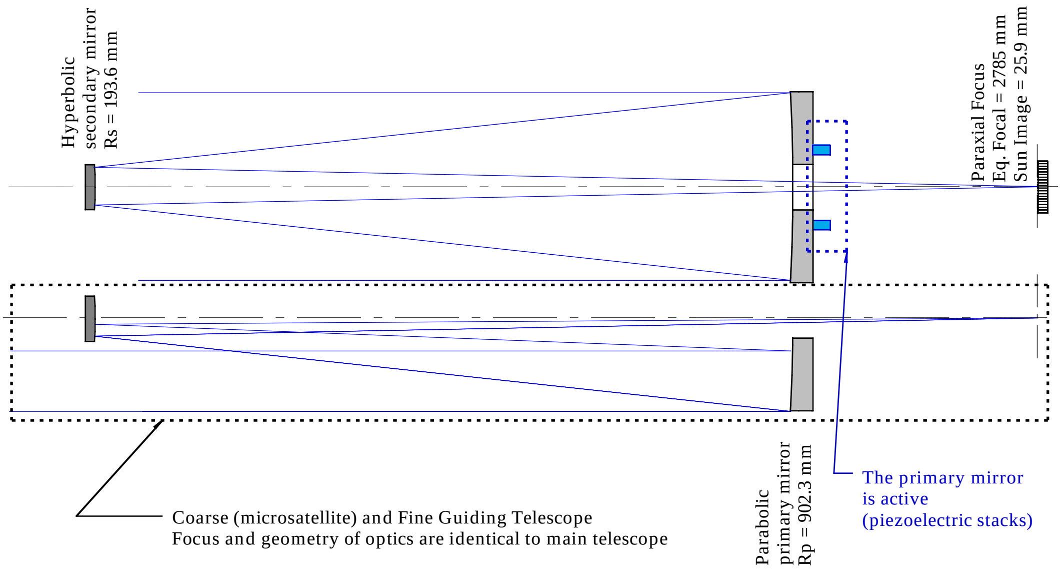

Figure 5: Optical concept of the SODISM telescope and guiding assembly.

Mechanical/thermal stability. To provide an ABSOLUTE measure of the diameter of 1 mas over the two years time period of the mission is the goal of SODISM/PICARD. The design selected achieves mechanical and thermal stability because of the choice of a single monolithic structure linking the SiC mirrors of the telescope to the detector. As well the guiding telescope is in the same structure, its mirrors (same optical properties than the main telescopes) and 4-quadrant detector being linked to the structure carbon-carbon. This new type of structure (developed by Alcatel Space, ex-Aerospatiale, under ESA contracts in particular, cf. Bailly *et al.*, 1997) allows to reduce the thermal regulation to ± 0.5°C for an absolute tolerance of the diameter to 1 mas (1 thousand of a pixel). The isotropic property of carbon-carbon and a detailed knowledge of the experiment (interferometric calibration), will help to further gain, by modelisation, a factor 100 to 1000 on the diameter variations (useful for the Solar limb oscillations). This means that 10 to 1 μarcsec could be inferred, allowing a direct monitoring of limb oscillations. Note that, beside focusing, the only other systematic error which affects the diameter directly is the size of the detector (silicium has an expansion coefficient of 3 10^{-6} and requires, to keep errors below the mas, 0.2°C temperature regulation).

Pointing strategy. Image guiding and stabilization is provided by an off-axis telescope with the same optical properties than the main telescope and implemented in the same carbon-carbon cylinder structure. The 4-quadrant detector assembly – also bundled with the carbon-carbon base sandwich structure at the level of the CCD detector – is fine guiding piezoelectrics which activate the primary mirror support. If imaging properties are the same, the field of view is twice (∅56 mm, i.e. $\sim$ 1.1°) in order to allow acquisition and pointing (low frequency) of the Sun by the 4-quadrant detector (the microsatellite has a stellar sensor for coarse guiding that can be overruled by our pointing signal). Fine guiding of the telescope is used so that the image of the Sun on the CCD does not move by more than a fraction of pixel. This reduces the jitter to mas although, formally, at first order, the inflection point position for limb determination is not affected by jitter. Note that the custom Si 4-quadrant detector will be similar in some respects to the one used by the VIRGO/LOI on SOHO and will provide the accurate guiding to the microsatellite ($\pm 0.5 arcmin$) and fine guiding to SODISM (a few mas expected).

Radiometer

To measure the Solar constant, PICARD will either use the spare of the VIRGO/SOHO radiometer or a SOVA 1 type radiometer. The VIRGO spare is available and has demonstrated for over two years its capabilities and the intrinsic advantages of using two different radiometers – PMO6 and DIARAD – for the measurements. VIRGO is the baseline option of PICARD although mass and power consumptions, limited on the microsatellite, may prevent using it. Currently, up to released margins on SODISM and the platform, we may have to use a SOVA 1 type of radiometer instead of the VIRGO spare.

The SOVA 1 type radiometer (as DIARAD) is a differential absolute Solar radiometer developed at the RMIB, Royal Meteorological Institute of Belgium (Crommelynck and Domingo, 1984). Its radiometric core is formed by two blackened cavities constructed side by side on a common heat sink. In between each cavity and the heat sink a heat flux transducer is mounted. The difference between the two transducers' outputs gives a differential heat measurement, in which the common part of the thermal surrounding radiation seen by the two cavities is eliminated. By the symmetrical construction and good insulation thermal asymmetry is minimized.

Both cavity channels are equipped with a shutter in front of them, by which the sunlight can be kept away from (closed shutter) or allowed into (open shutter) the cavity. In the open shutter phase, Solar radiative power flows into the cavity through a precision aperture and is absorbed near the bottom of the cavity. Besides Solar radiative power, electrical resistive power can be dissipated in the cavity. During the design of the cavities, careful attention has been paid to obtain maximally corresponding spatial locations and distributions for the Solar and the electrical power.

Equilibrium between the two cavity heat fluxes is maintained by regulating, using a servo system, the electrical power in one of the two cavities. In the default measurement sequence a constant electrical power is fed into one cavity, the "reference" cavity, while its shutter remains closed. The electrical power in the other cavity, the "measurement" cavity, is regulated continuously, while its shutter sequentially opens and closes (both open and close phases take 90 seconds). When the instrument is pointed to the sun, the equilibrium electrical power in the measurement cavity drops proportional to the absorbed Solar power when going from the closed to the open phase.

Accurate electrical power measurements are obtained by separate measurement of the voltage over and the current through both cavity heating resistors. The electrical measurement chains are calibrated continuously using six reference voltages, derived from a single, temperature stabilized, reference voltage. The resistance values of the heating resistors, which were chosen maximally stable with temperature, are used as quality indicators of the electrical measurements.

The basic measurement of the Solar radiative flux is the drop in the measurement cavity electrical power divided by the precision aperture area. To this basic quantity corrections have to be applied for the optical characteristics of the cavity (e.g. diffraction around the precision aperture borders, absorption coefficient of the cavity, ...) and for the thermal emission of the shutters. The optical characteristics are part of the parameters determined during the pre-flight characterization phase. The thermal emission of the shutters is measured in space during deep space pointing. The optical aging of the instrument is verified in space by periodic comparison between measurements from the both cavities. For this purpose, the exposure to the sun of the right side cavity is systematically kept lower than the one of the left side cavity.

Table 3 summarizes the space flights of the RMIB radiometers. From these radiometers, SOLCON II and SOVA 1 have the same characteristics, summarized in Table 4.

Spacecraft	Date (number of days)	Mission	Instrument
STS-9	28/11/1983 (10)	Spacelab 1 (NASA/ESA)	SOLCON I
STS-45	24/03/1992 (9)	ATLAS 1 (NASA)	SOLCON II
STS-46/57	31/07/1992 - 21/06/1993	EURECA (ESA)	SOVA 1/SOVA
STS-56	07/04/1993 (9)	ATLAS 2 (NASA)	SOLCON II
STS-66	03/11/1994 (10)	ATLAS 3 (NASA)	SOLCON II
Atlas-IIAS	02/12/1995 (continues)	SOHO (ESA/NASA)	DIARAD/VIRGO
STS-85	07/08/1997 (13)	Hitchhiker/TAS-01 (NASA)	SOVA 1
STS-95	29/10/1998 (10)	Hitchhiker/IEH-03 (NASA)	SOLCON II

Table 3: Space flights of the RMIB radiometers. SOVA 1 and SOLCON II are exact copies of each other.

Measured quantity	Total irradiance (Wm^{-2})
Number of channels	2
Number of reference voltages	6
Cavity type	Cylindric, diffuse black
Diameter precision aperture	1 cm
Slope angle	2.5°
Pointing device	4 quadrant
Solar sampling period	3 minutes
Duty cycle	50 %
Instrument noise	< 0.1 Wm^{-2}

Table 4: Characteristics of the SOVA 1 type radiometer (default measurement mode).

MISSION SCENARIO

Several scenarios are still under consideration for the PICARD flight mid to late 2002 (the launch date is important since the diameter/constant relationship will definitively be better determined during the near linear part of the cycle, rising or falling – our case – than at minimum or maximum when the constant is mostly "constant"...). The favored orbits are those providing only brief or non-eclipsing Sun-synchronous viewing in order to achieve both the thermal stability for the absolute long term diameter measurement and the near continuous sampling for the long periods g modes oscillations. The most promising and realistic possibility is the Geostationary Transfer Orbit (GTO) of an Ariane V launch in which up to 8 microsatellites are placed on a ring (the ASAP plateau) at the base of the major satellite(s). Such an orbit (of 10:30 to 11:00 hours) with brief, varying and sliding eclipses of 20 minutes or less, allows an excellent thermal environment and sampling for the oscillations measurements. It is, however, subject to intense radiations which may limit the life time of the platform to less than the expected two years of the mission if nothing is made to reduce the radiation level. The microsatellite platform is currently under study by CNES and a definite answer on this possibility should be known by April or May 1999.

Table 5 summarizes the mass, power and telemetry characteristics of the PICARD mission. Note that PICARD Mission Center will be operated by the RMIB and that, most probably, antennas (S band) in Toulouse, Bruxelles, Kourou or Kiruna will be used for telemetry needs (about 1.3–1.4 GBytes per day).

Characteristics	μ-sat	SODISM	SOVA
Mass (kg)	32*	16	6
Size (cm^3)	60x38x25	60x18x25	35x19x25
Power (W) [on secondary]	26	19	7
Average Telemetry (kbits/s)	17	16	1

Table 5: Major characteristics of PICARD model payload (*including 10 kg of electronics).

ACKNOWLEDGMENTS

The PICARD Mission on a microsatellite is the result of an iterative process with CNES instances in which support and understanding of several have to be acknowledged and, in particular, the very constructive participation of Bernard Tatry, Jean-Yves Prado and Nicole Papineau. We are grateful to Judit Pap and Jean-Pierre Rozelot for several instructive discussions. And, finally, we would like to emphasize the prominent role played for each of us interested in these fundamental measurements by the pioneering work of Elizabeth Ribes.

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