SOLAR PHYSICS AND INTERFEROMETRY MISSION (SPI)

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ABSTRACT

This paper presents the scientific objectives of the Solar Physics and Interferometry Mission (SPI), describes succinctly the model payload and summarizes mission's issues. Novel instrumentation (interferometry) and clever mission design (small platform on low orbit with high telemetry and dedicated smaller platform on hexapod for permanently Sun-centered instruments) allow both spectral imaging and Helioseismology at very high spatial and temporal resolutions. Although not retained by ESA, this mission could become reality through NASA MIDEX and/or CNES PROTEUS opportunities as soon as 2007–2008.

INTRODUCTION

The scientific rationale of proposing a Solar Mission like **SPI** (the Solar Physic and Interferometry Mission) is to provide, at high spatial and temporal resolution, observations of the Solar atmosphere and new insights of the Solar interior. Novel observations would be made by a cophased interferometer of 1 meter baseline coupled to a UV double monochromator to join high spatial, temporal and spectral resolutions. By using **interferometry in the UV with a spectro-imaging mode** SPI will allow remote sensing of the Solar surface and atmosphere with an unprecedented spatial resolution of 20 km on the Sun that Solar Probes or Orbiters, despite their closer distance to the Sun, will not achieve. But SPI novelty is also its nearly **permanent Sun viewing orbit** which, alike SOHO, allows resolved and global **Helioseismology**. This is the second breakthrough of SPI, its unique package of 3 helioseismology instruments for diameter oscillations (highest g-modes sensitivity), intensity, global and resolved observations, and high resolution full Sun velocity oscillations (with the Magneto Optical Filter). The third breakthrough is the thorough set of diagnostics to study the Solar variability and Space weather aspects. A new set of Solar constant global and spectrally resolved irradiance monitors are implemented coupled with an enhanced full sky Lyman α imaging and a unique diameter, Solar differential rotation, and full Sun Lyman α imager. To this third set, the MOF brings the magnetograph information. This will directly address the nature of UV variability and its climate consequences. EUV and X-ray imagers and spectrometers and an UV/visible coronagraph complete the payload. SPI will achieve its impressive aims with a relatively small and simple spacecraft on a common reusable small platform on a low orbit, novelty being in state of-the-art, new instruments allowing the use of such a small platform and, consequently, a small and affordable launcher. The several new technologies of SPI will lead to new insights into how the Sun works from the interior to the corona and to the Earth. With orders of magnitude in spatial resolution but also in sensitivity (diameter oscillations, g-modes) SPI has the potential to resolve major open questions in Solar physics and to bring in important **discoveries**. SPI will complement the *in-situ* observations of the Solar Probe type missions and built upon SOLAR-B moderate spatial resolution.

The payload consists in 8 instruments, the SOLARNET three-telescopes cophased interferometer with UVIS, its UV Imaging Spectrometer (with lines from chromosphere to corona), an X-ray/EUV full-Sun imager, a high-resolution EUV imaging spectrometer (10 kK–2 MK), a high-resolution visible telescope, magnetograph and velocity oscillations (MOF), a EUV and visible-light coronagraph, NG-PICARD (Solar diameter absolute measure and oscillations), NG-DIARAD/VIRGO (Solar constant and intensity oscillations) and NG-SWAN (full sky Lyman α).

Thanks to the compactness of the interferometer, SPI can benefit from a low cost reusable platform of the LEOSTAR or PROTEUS type, 3-axis stabilized and always Sun-pointing. A Rockot launcher is largely sufficient with such small platforms to reach a high 1000 km orbit 6:00–18:00 minimizing eclipses (a few minutes 50 days or so per year). In consequence of such a near Earth orbit, telemetry, by a now-simple X-band antenna, allows impressive telemetry average downlinks superior to 3 Mbits/s. The expected volume and format of the data coming from the various instruments will be orders of magnitude higher than SOHO and previous Solar Physics spacecrafts but small compared to current Earth Observation Missions. We therefore anticipate no particular difficulties to handle, process and archive data in an operation facility in Europe.

SCIENTIFIC RATIONALE

SOHO has been a very successful mission addressing all aspects of Solar and heliospheric physics and, consequently, pointing out the areas in need for a better and deeper understanding of the Sun. It was truly a worthy mission but progress can now be achieved in the areas where SOHO and other missions stopped: high resolution of the surface and atmosphere and global and local optimized helioseismology. The in-situ plasma objectives, heliosphere, field and particles are already covered by several approved US and European missions (SOLAR-B, STEREO, Solar Probe, Solar Orbiter) and some Space weather applications may also be monitored in the future by a program like the NASA Solar Dynamics Observatory.

The SPI Mission Proposal is therefore going one significant step further than the current Solar Physics ambitions. It builds upon EUV/XUV imaging and spectroscopy, uses the revolution in high resolution made possible by interferometry, and adds a novel helioseismology package with and enhanced resolved velocity experiment (the MOF, Magneto Optical Filter) and the determination of the Solar limb figure with NG-PICARD; this latter could provide for the first time the detection of g-modes, the sensitivity of limb oscillations being 4 to 5 times the one on the disk.

The SPI Mission is a further development of the SIMURIS Mission (Damé et al., 1998) which was presented to the community at the Tenerife ESA Conference "A Crossroads for European Solar and Heliospheric Physics" in March 1998 and very well supported by the participants who plebiscited the need for high spatial resolution. In the SPI mission, this need is fulfilled by novel instrumentation, a three telescopes cophased interferometer of the meter class (SOLARNET) feeding a high resolution imaging spectrometer (a double subtractive monochromator), rather than by orbitography, not to compromise, by reduced telemetry, the spatial and temporal resolutions, evolution of structures and configurations. Seven other major experiments complete the payload: high resolution EUV spectrograph, global and localized helioseismology and magnetograph experiment, high resolution EUV/XUV imagers, New Generation Coronagraph, Solar Diameter Telescope and limb oscillations, radiometers, Sun photometers and full sky Lyman α imager.

The important technologies needed by the proposed interferometer concept include optical delay lines and a monitoring and cophasing system together with its control software. These technologies have noticeably been breadboarded by Service d'Aéronomie (cf. Damé et al., 2002, Damé et al., 1999a) and by IRCOM in the framework of an ESA study called "Optical Aperture Synthesis Technologies", lead by MATRA. Both experiments have been extremely successful and all components needed by an interferometer have been validated through an end-to-end test from object to image reconstruction. These achievements fully secure the development of the SOLARNET interferometer as both details and system design issues are perfectly mastered. A working three telescopes Solar imaging interferometer is currently in use and visible at the "Grand Sidérostat de Foucault" at Meudon Observatory (see Damé et al., 2002, or follow the link http://must.aerov.jussieu.fr for up-to-date results).

SCIENTIFIC OBJECTIVES

The global understanding of the Solar machine and its influence on Earth is at the center of the three major thematics addressed by SPI. They are complementary: the internal structure of the Sun explaining the surface activity, magnetic structuring explaining in turn the variations and influence of the Sun on Earth. The major goals of the SPI mission are:

- to reveal and understand the detailed structure and evolution of the Solar atmosphere. SPI high-resolution imaging and spectroscopy will trace the Sun's magnetic field structure and evolution from the photosphere to the corona. SPI will reveal the links between the layers of the Sun's atmosphere. It will track the complete evolution of magnetic processes from the smallest scales to the largest, address magnetic emergence and reconnection, the development and regression of active regions, the development and nature of transient events in the atmosphere, the onset and fine structure of flares from the smallest (nanoflares) to the largest (white light chromospheric flares), and the propagation of magnetic activity through the different regimes of the Solar atmosphere.
- to reveal the internal structure of the Sun, the transfer from the radiative to the convection zone, the links between internal flows and the magnetic cycle. Magnetic activity and its variations are the consequences of the internal regimes of convection. g-modes and long-period p-modes are the only one capable to penetrate deeply enough to constrain the Solar internal parameters. These modes are best observed at the limb where their amplitude is 4 to 5 times greater than for full-disc measurements. Moreover, second generation observation of local oscillations guarantees the correct understanding of the transition from inside to outside the Sun, from sub to surface flows and manifestations.
- to measure and understand the profound influence of the Sun on the Earth and the consequences for our life through the predictions of long-term (10–200 years) climatic changes. SPI carries the new generation of Solar diameter, Solar constant, stratospheric UV and IR flux inputs and Lyman α monitors. They are necessary to measure and follow in great details the Solar inputs received on Earth and their variations with an unprecedented absolute precision (for in stance, the Solar diameter measurement will have a noise level of 1 milli-arcsec which, in turns, means a milli-degree in global cooling or warming).

The high-resolution imaging of the Solar atmosphere will be better than in past missions by more than an order of magnitude. These capabilities in concert will enable us to analyze thoroughly the time-variability, evolution and fine-scale structure of the dynamic chromosphere, transition region and corona, to study fully the Sun's magnetic activity on multiple scales, to investigate energetic particle acceleration, confinement and release, and to reveal plasma and radiation processes underlying the heating of the chromosphere and corona.

The relevant minimum observable scale in the Solar atmosphere may be of the order of 10–30 km since smaller scales will probably be smeared out by plasma micro-instabilities (such as drift waves). This scale range is comparable to the photon mean free path in the chromosphere. Slightly larger scales can be expected in the corona (though gradient across coronal loops may also be a few km). Altogether this situation is rather fortunate because we have access to higher resolutions in the far UV than in the visible and X-rays (multilayer telescopes are limited to resolutions of 1 arcsec or so). In the UV, the emission lines are generally thin, i.e. not affected by the optically thick transfer conditions (which prevail in the visible and near UV lines accessible from ground) and we can expect to see structures with scales 10 to 30 km. In the visible, thick transfer in the atmosphere blurs the signature of structures and nothing smaller than 70–100 km should be observed. This means that with a single instrument of meter class diameter we have the appropriate, scientifically justified, spatial resolution for both the far UV (20 km in the C III line 117.5 nm) and the near UV (60 km in the Ca II K line λ396.3 nm). SPI would ideally complement *in-situ* plasma studies of Solar Probe's type missions and preliminary observations of SOLAR-B in the arcsec resolution range.

A breakthrough in high spatial resolution observations (20 km is 40 times more spatial resolution than any previous Solar instrument in Space) should allow to understand in finer physical details processes like magnetic heating in coronal loops (temperature profiles, time dependence, spatial local ionization of heating processes) but, also, by access to visible wavelengths, the coupling between turbulent convective eddies and magnetic fields in the photosphere. Another scientific objective is the plasma heating processes and thermal inputs of flares and microflares and their fine magnetic field structures. Heating, flares and microflares but also internal structure (g-modes) are "big" questions that indeed, after years of limited observations, now deserve a dedicated and efficient program: SPI.

THE "BIG" QUESTIONS

"Big" questions in Solar Physics, as summarized, for example, by the Marschall Space Flight Center (http://wwwssl.msfc.nasa.gov/ssl/pad/solar):

- the coronal heating process,
- the nature of Solar flares,
- the origin of the sunspot cycle (the variability),
- the missing neutrinos,

will directly be addressed by SPI, since both the coronal heating process (or processes) and the nature of Solar flares are linked with the magnetic filed which is the key in understanding these dissipation mechanisms SINCE THEY NECESSARILY INVOLVE SMALL SCALES. The missing neutrinos is linked with helioseismology in a problem that is more an understanding of the Sun core that only g-modes, internal gravity modes will allow to reveal. And g-modes are best observed at the limb as shown by MDI (Kuhn et al., 1997). The origin of the Solar cycle is the variability problem and the important issue for life on Earth of the consequences of Solar variations (constant, UV, diameter) on the Earth climate or on shorter time scales, space weather issues.

The Sun is a fantastic physical laboratory, orders of magnitude from the plasma, temperature and magnetic concentration available on Earth, and the Rosetta stone of Stellar Physics since never a single star will be observable in so much details (imagine stellar limb oscillations?).

SPI will provide new views, diagnostics and answers. Those not addressed (CME's, *in-situ* plasma) will be addressed in parallel by the US missions STEREO and the Solar Probe's type missions in particular. For the rest, SPI will do extremely well with high resolution for the magnetic structuring, with Helioseismology for Solar interior (dynamo, g-modes, neutrinos), and with Lyman α, diameter and Solar constant measurements for variability and Space weather.

HIGH RESOLUTION PARADIGMS

The supergranulation network, which dominates the chromospheric plasma dynamics, is apparent in the EUV emission pattern as seen, for example, by the SUMER instrument on SOHO (cf. Hassler et al., 1999). Magnetograms from SOHO have revealed the ubiquitous appearance of small magnetic bipoles at the Solar surface. After emergence, the polarities separate and are carried to the network boundaries by the supergranular flow, where they merge with the pre-existing network flux. This leads to flux cancellation, submergence and reconnection events. The magnetograms also show that the magnetic field exists in the network in two components side-by-side, i.e. in uncancelled unipolar fields or in a carpet of closed loops and flux tubes. The small loops will of course emerge or contract downwards and collide, and thus constitute a permanent source of energy, which can be tapped by the particles through magnetic field dissipation. Recent numerical simulations suggest that many of the bipolar structures can only be resolved at a resolution of 20 km or less.

As a consequence of these observations, theoretical ideas about the origin of the Solar wind have been put forward according to which the wind would originate in the chromospheric network, and draw its energy from high-frequency waves generated by magnetic reconnections of the dynamic and complex fields prevailing there. Above mid-chromospheric altitudes the field expands rapidly, fills the overlying corona and guides the Solar wind mass flux, emanating from the open chromosphere, where the plasma is created by photo ionization. SPI with its unprecedented spatial resolution will for the first time reveal the fine structure of the network and provide definitive answers to the question of where and how the Solar wind originates allow, images and 2D spectro-imaging to reliably disentangle spatial and temporal structures observe the source signatures of the plasma (reconnection, dissipation).

For example, small-scale magnetic activity is expected to continually produce waves, energetic particles, and rapidly-moving plasma. The dissipation of the waves could involve cyclotron damping. This process is observed to operate in the distant Solar wind and known to heat the plasma. SPI will make the first detailed observations of such key plasma processes originating in the transition region and heating the extended outer corona afterwards.

The magnetohydrodynamic waves generated in the photosphere by convective motions of the granules and supergranules are primarily of low frequency. In the small-scale magnetic structures of the strongly inhomogeneous network fields higher-frequency waves could be excited up to the kilo-Hertz range. Such waves would certainly transfer very effectively wave energy, e.g. into the transverse kinetic degrees of freedom of the protons, and particularly the heavy ions, thereby heating them to very high coronal temperatures, a process for which the UVCS instrument and the SUMER experiment on SOHO have recently found evidence in the strong Doppler-broadenings of emission lines (cf. Wilhelm et al., 1997, for example). Due to its investigation potential in the UV, transition zone heating sites of the corona, and the high sensitivity and spatial resolution of its instrumentation, SPI will for the first time be able to see very dim emissions, concentrated for high contrast in emissivity, for instance in plasma confined in small loops (threads of 10-20 km?), or loop profiles, diagnostics of direct use to determine the heating mechanisms of the Solar corona (Priest et al., 2000).

The major part of the magnetic flux permeating the Solar photosphere outside sunspots is concentrated in small (scales of 20 km or so) flux tubes of kilo-gauss field strength. The structure and dynamics of these fundamental elements of the near-surface magnetic field has profound implications for a number of basic questions, e.g.:

- How do magnetic foot-point motion, wave excitation, flux cancellation and reconnection contribute to the flux of mechanical energy into the corona?
- In which way do the emergence, evolution and removal of magnetic flux elements determine the magnetic flux budget of the Sun? Is there a local dynamo operating on the scale of granulation?
- What is the origin of the facular contribution to the variability of the Solar constant?
- What is the physics of the interaction between convection and magnetism?

Answers to the questions require the study of magnetic flux elements on their intrinsic spatial scale. The high-resolution of the imagers, spectro-imagers and magnetograph is intended to monitor the emergence, dynamics, twist, shearing, mutual interactions and possible coalescence and subduction below the surface in order to follow the evolution and scrutinize the life cycles of magnetic flux elements. Coupled with the resolved oscillations of the MOF, the rotation below the surface can be addressed and, accordingly, the relation between convection and magnetism.

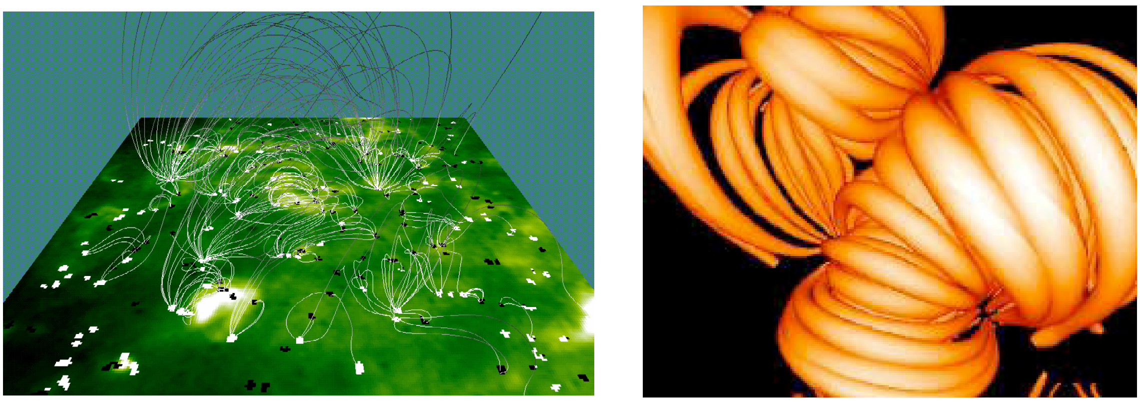

Fig. 1. Modeling magnetic fields extension in the chromosphere and corona is current and will gain from higher resolution and atmospheric height sampling (magnetic canopy from MDI/SOHO and loops modeling from TRACE).

A key scientific objective of SPI is to study the new emergence and the cancellation of photospheric magnetic flux (the latter is the disappearance of opposite polarity regions in close contact), and to investigate the consequences of such processes for the overlying global coronal magnetic loops and for the chromospheric and transition region magnetic network. Flux cancellations are known to be associated with or at the origin of various active phenomena, such as filament formation and eruption, evolution of small points of emission bright in radio or

X-rays, or the occurrence of flares. Magnetograms combined with UV, FUV, EUV and soft X-ray images as well as FUV and EUV spectra are the key data necessary to understand the bearing that small scale magnetic activity has on the transition zone and corona.

The Yohkoh, SOHO and TRACE extreme ultraviolet and soft X-ray telescopes have provided a rich harvest of coronal images, yet only at a spatial resolution not better than 1 arcsec. These images (see, for example, Schrijver et al., 1997) illustrate the existence of fine-scale structures in the corona, such as polar plumes and thin post-flare loops, and reveal continuous dynamics occurring on all resolved scales in particular the finest. There is also strong evidence that the actual bright structures lie well below the best current spatial resolution. From high resolution spectra of the Si IV line, Brekke (1999) could only explain the complex profiles observed (multipeaks) assuming that several much smaller, sub-arcsec structures (threads less than 0.1 arcsec), were contributing to the emission profile. This points to the need for still higher spatial resolution. The active Sun has yet to be imaged with sufficient resolution, a task to be performed by SPI. The early triggering phase of Solar flares and small activity regions and the evolution of point-like events or bright X-ray spots will be monitored, with simultaneous observations in relevant wavelengths and foot-point (photospheric and chromospheric) magnetic field measurements being carried out. The wide coverage of coronal temperatures by the visible-light, UV, FUV, EUV, and X-ray telescopes on SPI will enable complete images to be obtained in fast cadence. From these the density and temperature distributions can reliably be derived, such that the traits of coronal heating processes in current sheets, shock fronts, or acceleration in small explosive events and rapid plasma jets might become clearly visible and be resolved in time and space.

SOLAR INTERIOR

The two major objectives of SPI in helioseismology are: first, to detect the gravity modes (g modes) of the Sun; second, to build upon MSI/SOHO with an improve resolved velocity imager at higher resolution (1 arcsec) and with improved magnetic field.

g-modes are of prime importance to understand 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 et al., 1998). Given a velocity amplitude of 1 mm/s at 200 μHz, the displacement of the Solar surface would be 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 NG-PICARD on SPI — to observe a 10 μarcsec high frequency p mode (5 min.) Solar limb oscillation signal (Kuhn et al., 1997).

With NG-PICARD we detect intensity fluctuations at the Solar limb that 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 (cf. Damé et al., 1999b). This amplification factor was roughly predicted by theory (Appourchaux and Toutain, 1997). If we assume 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 and further more with NG-PICARD on SPI we can seriously envisage detecting them in less than 2 years with the amplification factor above.

Although resolved oscillations in velocity and resolved oscillations in intensity and global are of prime interest, we cannot address them completely enough in this paper. Please refer to our web site for more details (http://must.aerov.jussieu.fr/spi).

VARIABILITY AND SPACE WEATHER

The irradiance of the Sun (i.e. its brightness as measured above the Earth's atmosphere) is known to vary by 0.1% over the Solar cycle. There is also some evidence for a longer term, secular variation. In spite of its small magnitude, the irradiance variation is a potential cause for climate change (in fact most probably its UV content which varies by nearly 10%). Radiometer on SPI mission will help to guarantee the continuity of the measurements of the Solar constant. Basic questions need to be answered before we can reach an understanding of the causes of this variability:

- How does the Solar luminosity (i.e. the radiation escaping in all directions) vary?
- Does it change at all or is a brightening at the equator compensated by a darkening over the poles?
- Why is the irradiance variability of the Sun a factor of three smaller than that of Sun-like stars?

However, radiometers have an absolute precision limited to ± 0.15% which is about the change level observed during a cycle. For continuity, one could think of using the same instrument, but the case of ACRIM I & II (0.125% readjustment) shows the limit of this approach. On the other side, the diameter is an absolute geometrical measure — reproducible with a precision as high as 2 mas i.e. a dynamics on the amplitude of 20 or so (assuming 0.04" over 11 years). To substitute diameter to constant if the ratio is known (ambitious goal of the CNES microsatellite PICARD, cf. Damé, 2000, Damé et al., 1999b & 2000b) could allow to monitor with a much better precision the influence of the Sun on the Earth climate. NG-PICARD will address this issue.

SCIENTIFIC PAYLOAD

Measurement requirements

Heritage of instruments from Yohkoh, SOHO, SPDE/TRC, TRACE, PICARD, *etc.* was used as a baseline for designing SPI payload. Instruments are state-of-the-art, and they can be, since mass, power and telemetry are almost not limited, granted by the low orbit and the mini-satellite class of the platform. The major instrument, the interferometer, makes a clever use of mass and is naturally compact and integrated in design. Even though, a large effort is made on on-board data compression/storage. Also, the use of a separated small pointing platform (the Hexapod Pointing Platform, HPT) for the Sun centered instruments (Helioseismology and coronagraph) simplifies the design of these instruments still bringing in only a very small mass (the platform and the six actuators whose extension is very small to accommodate the few degrees of required pointing range). The payload consists therefore in the interferometer and its spectro-imager (the UVIS subtractive double monochromator), the EUV and X-ray imagers and spectrometer telescopes, the Hexapod platform with the oscillation instruments (and the coronagraph since it best works centered on the Sun) and the small NG-SWAN instrument that benefits from its own periscope.

The SPI Mission provides unique possibilities to do optical remote sensing observations of the Sun with unprecedented spatial resolution down to scales of 20 km in images obtained in various wavelength bands. With the recent SOHO revelations of fine structures existing in the transition zone and corona it is obvious that coronal imaging is crucial to put the filamentary structures observed in the Solar wind and inner heliosphere in their proper Solar context.

An integrated ensemble of optical instruments, both for imaging and spectroscopy, are suggested. All the imagers, beside the very high resolution of the interferometer, aim at high spatial (0.5 arcsec) and temporal (0.1 s) resolution, to reveal the context of the small-scale dynamical processes in the atmosphere and to study the rapid changes in morphology associated with transition region and coronal magnetic activity. An invaluable advantage of the SPI near-Earth orbit is that the relative motion between the Solar targets can be limited by very high temporal resolution, ensuring that the images will not be blurred during the exposure time.

Table 1. SPI Instrumentation Summary.

Name	Measurement	Specifications	Mass kg	Size* cm x cm x cm	Power Watt	Telemetry kb/s
SOLARNET and the Ultraviolet Imaging System (UVIS)	Very high resolution disk and limb imaging and spectroscopy	UV and FUV spectroheliograms CIII, 117.5 nm to MgII lines, 280 nm	100 40	Ø110 x 140 20 x 30 x 70	60 60	20 1 200
EUV Imager and Spectrometer	Imaging and diagnostics of TR and corona	EUV emission lines	40	Ø32 x 180 (Telescope Ø25)	30	400
X-ray / EUV Imager	Coronal imaging	He and Fe Ion lines	30	Ø28 x 140 (Telescope Ø20)	30	400
Ultraviolet and Visible Light Coronagraph °	Imaging and diagnostics of the corona	Coated mirror coronagraph CCD detector	25	Ø20 x 80 (Telescope Ø12)	15	100
Oscillations, Visible-light Imager and Magnetograph °	High-resolution disk imaging and polarimetry	Na D1 Na D2	38	Ø30 x 120 (Telescope Ø25)	30	400
New Generation PICARD °	Diameter oscillations and measurement, and full Sun imaging	230 nm cont. Lyα 160 nm cont. 538 nm	25	25 x 30 x 70 (Telescope Ø12)	30	400
New Generation DIARAD/VIRGO °	Radiometers for Solar constant and Intensity Oscillations	UV, visible and IR light	25	20 x 30 x 40	25	1
New Generation SWAN	H Lyman α Solar activity	Sky Lyα imaging with Hydrogen cell (5° x 5° FOV)	7	18 x 17 x 36	12	10
TOTAL			**330**‡	**Ø170 x 180**	**292**†	**2931**

* Breadth x width x length.
° These 4 small instruments are always pointing to the Sun center. They are altogether on a Hexapod platform of the ESA/Sage III type (Ø50 cm x 50 cm). Offset pointing is limited to a few degrees.
‡ To this total one should add 40 kg of electronics.
† This does not include the thermal control that will add 40 to 50 W to this total.

The instrument set is completed by an EUV-white-light coronagraph, which has the capability to measure coronal plasma outflow velocity through Doppler-dimming of the HI 121.6 nm and He II 30.4 nm lines, and the H and He atom density and electron density, and to provide UV and visible-light global images of the corona. Critical issues like heat ingress into the telescopes, aperture locations, mechanical structures of the instruments, have been evaluated and proven solution implemented, for example in the CNES PICARD microsatellite program (SiC mirrors, Carbon-Carbon structure, internal shutters are used to limit the Solar thermal load problem, cf. Damé et al., 2000b & c).

The instruments characteristics are summarized in Table 1. In the following we concentrate the discussion on the justification and principal characteristics of the major instrument: the high-resolution spectro-imaging interferometer.

SOLARNET and UVIS

The SOLARNET interferometer and its double monochromator are described in some details in a recent paper: "High Resolution Solar Physics by Interferometry", by Damé et al. (1998). Information on the three telescopes 1 meter interferometer and its focal plane instrument (the UltraViolet Imaging System: a subtractive cascading double monochromator in FUV and UV) is also available on our web site: http://must.aerov.jussieu.fr. Accessible lines, line ratios for density and temperature diagnostics are also given in the paper (and on the site), as well as image reconstruction indications. Another paper (Damé et al., 2002) reports on the feasibility demonstration of Solar Interferometry (complete three telescopes breadboard installed at Meudon Observatory) and technologies readiness of the proposed instrumentation. But, despite these progress in design and demonstration, there is still a common belief that high resolution could be addressed by classical means like a large telescope or an appropriate orbit. This is not true.

Why an Interferometer?

If the need for high spatial and spectral resolutions is commonly agreed, the question left is: why an interferometer and not a single-dish large telescope? The first answer is that the required measurement needs exceed conventional instrumentation possibilities. A 1 m telescope diffraction-limited in the far UV is, in practice, exceedingly difficult to construct. And, even assuming that such a perfect 1 m telescope could be built for the far UV, it would be more costly and difficult to control and assemble than an interferometer.

In fact, the Michelson interferometric approach represents significant advantages over diffraction-limited large telescope imaging and the "natural" choice for high resolution is the interferometer for several reasons:

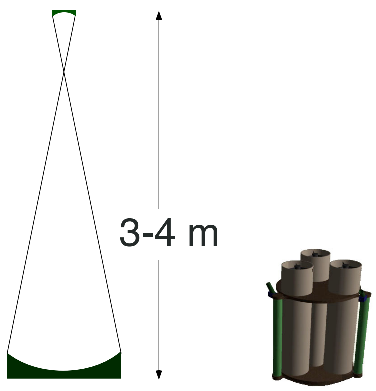

Fig. 2. The evident size, mass, alignment control and optical advantages of an interferometer of 1 m over a monolithic telescope of the same diameter.

- size, mass and cost: between an interferometer of 1 m baseline and height 1.3 m and a classical monolithic telescope of nearly 4 m height (cf. Figure 2), the mass, difficulties and launch cost will explode.
- Figure and ripples. Telescopes larger than Ø400 mm cannot be polished to the specification of $\lambda/8$ (wave, peak-to-valley) at Lyman α (121.6 nm) while small ones can. The Hubble Space Telescope, a 2.4 m mirror, even with a perfect figure, would still be a factor 10 away (0.1 arcsec rather than 0.01 arcsec) from its diffraction limit in the far UV (Damé and Vakili, 1984) due to the residual ripples left on its surface by the polishing process (size of the grinding tools).
- Adaptive optics. Interferometry requires controlling the residual optical path delays between telescopes but this, consequently, guarantees a perfect output wavefront suitable for diffraction-limited imaging. Adaptive optics is not an alternative to obtain the correct figure precision of large mirrors or to control the resulting errors, because of the extended field-of-view, the time response required and the severe in orbit thermal cycling. Note that aligning a segmented mirror requires 6 degrees of freedom and a control of the distance between the primary and secondary mirrors. Further, this very complex control loop — which is not required with an interferometer made of small telescopes since, beside fine pointing needs, only one degree of freedom is required: the phase control — does not work properly on *Solar extended objects*.
- Active pointing. Only small telescopes are necessary and their small secondary mirrors can act directly as active pointing mirrors, without requiring intermediate optics for this purpose.
- Small telescopes means small beams, easier recombination, lower coast of optics (and better quality), simpler focal instrumentation, *etc.*

Altogether, the modest baseline required to obtain major scientific results and the simplified control of an imaging interferometer (which doesn't need an absolute metrology like complex astrometric missions) result in very reasonable cost and mass which open Solar interferometry programs to the medium size satellites programs.

It is also worth recalling that a near-Sun mission may not easily provide high-resolution imaging. With a thermal load of 1 Solar constant there is already a problem even when using SiC mirrors and Carbon-Carbon structures like in PICARD (Damé et al., 2000c), since gradients in the SiC do induce deformations of the mirrors (even if cooled). With several Solar constants we have not found any optical solution to pretend accessing higher resolution than a few arcsec, loosing the near-Sun benefice.

Interferometers are functional instruments

With the sustained R & D program, first with ESA, and now for 5 years with CNES (3 telescopes imaging breadboard with fine pointing, phase control and image reconstruction on the Sun and Planets), we proved that the major assumption of the overall concept, the cophasing of the array, is feasible and, moreover, that imaging performances to expect are very high. SOLARNET breadboard was working in laboratory and is now observing the Sun, finding fringes, stabilizing them and reconstructing images from the interferograms (cf. Derrien, 2000, Damé et al., 2002, and our web site, http://must.aerov.jussieu.fr, for recent results).

SOLARNET will not only provide breakthrough science with a spatial resolution in the UV 40 times better than anything flown — 0.02" spatial resolution on a 40" FOV — but also at an incredibly low cost because of the compactness of the interferometric concept allowing the use of a standard, industrial, mini-satellite platform. New Physics will come from new technologies readily available, and a Mission with a 1 meter equivalent telescope can be made around interferometry NOW, much earlier — and much easier — that most people would have thought of.

Table 2. Characteristics (spatial and spectral) of UVIS (SOLARNET focal plan instrumentation).

Wavelength range (nm)	Field-of-view (arcsec)	Detectors		Spatial resolution (arcsec)	Spectral resolution (nm)
		pixels	Type		
FUV: 117 — 200	40 x 40	2048 x 2048	CCD	0.025 — 0.04	0.002
130 — 300	60 x 60			0.04 — 0.1	~ 20
UV: 280 — 400	60 x 60	2048 x 2048	CCD	0.06 — 0.08	0.01 (0.001*)

* This could be achieved with an extra filtering (Fabry-Perot)

Table 3. SOLARNET and UVIS resources summary.

Mass	100 kg (including 20% margin)	40 kg (including 20% margin)
Telemetry	20 kbits/s average (control)	1200 kbits/s average
Envelope	Ø110 x 150 cm^3 (3 x Ø35 cm telescopes)	20 x 30 x 70 cm^3
Primary pointing accuracy	0.5°	—
Primary pointing stability	0.03°/s	—
Secondary (active) pointing stability	≤ 12 milliarcsec	—
Internal phase control	$\leq\lambda/8$ (at Lyman α, 120 nm)	—
Field-of-view	1.2° (Sun viewing)	1 arcmin
Power	60 watts (peak: 75 watts)	60 watts (peak: 75 watts)

Instruments for global and resolved oscillations

The high altitude (1000 km) polar orbit of SPI, allows a near-continuous observation cycle, suitable for global and resolved oscillations. With eclipses limited to a maximum of 13 minutes per orbit during less than 2 months over a year, the duty cycle is excellent and side lobes, usually detrimental to long period oscillations, very limited. In two years or so of observations, SPI should reach a precision of 0.1mm/s (the current pessimistic estimation of the g-modes amplitude, Damé et al., 2001), this assuming an enhancement factor of 5 for limb observations compared to velocity ones, following Appourchaux and Toutain, (1997). Although, in the nominal payload presented, global measurements are limited to intensity and diameter, it is worth considering also New Generation SOHO/GOLF type global velocity measurements since, with several measurement points in the line profile, a significant noise reduction could be obtained. The fourth instrument is the resolved oscillations one, of the MDI type, which was extremely successful on SOHO, or its contender, the Magneto Optical Filter, since of even superior imaging throughput (Cacciani et al., 1997). This Earth orbit allows to use the full potential available through X-band antennas (2x120Mbps with a station visibility – like Kiruna – of 8 minutes or so) providing an important telemetry equivalent to a permanent downlink of 3 Mbps, largely sufficient, with limited compression, for all these demanding imaging instruments.

3 to 4 oscillations' instruments are therefore expected for the payload. Important is to keep them Solar centered when the high-resolution experiments are pointed, by the satellite platform, to the Solar region or phenomenon under investigation. This is achieved by placing these instruments (which are always Sun centered) on a small, self pointed platform, based on the Hexapod principle (6 linear actuators to orient the platform on a few degrees up to 40°). First designed and proposed for the MUST Solar interferometer (Damé, 1996, 1994) at the time an ambitious External Viewing Platform was envisaged on the Space Station discussions, it has been realized by ESA for the US experiment SAGE III as a bartering for Space Station use of external US facilities, and could be a valuable contribution of ESTEC or ESA to the mission proposed.

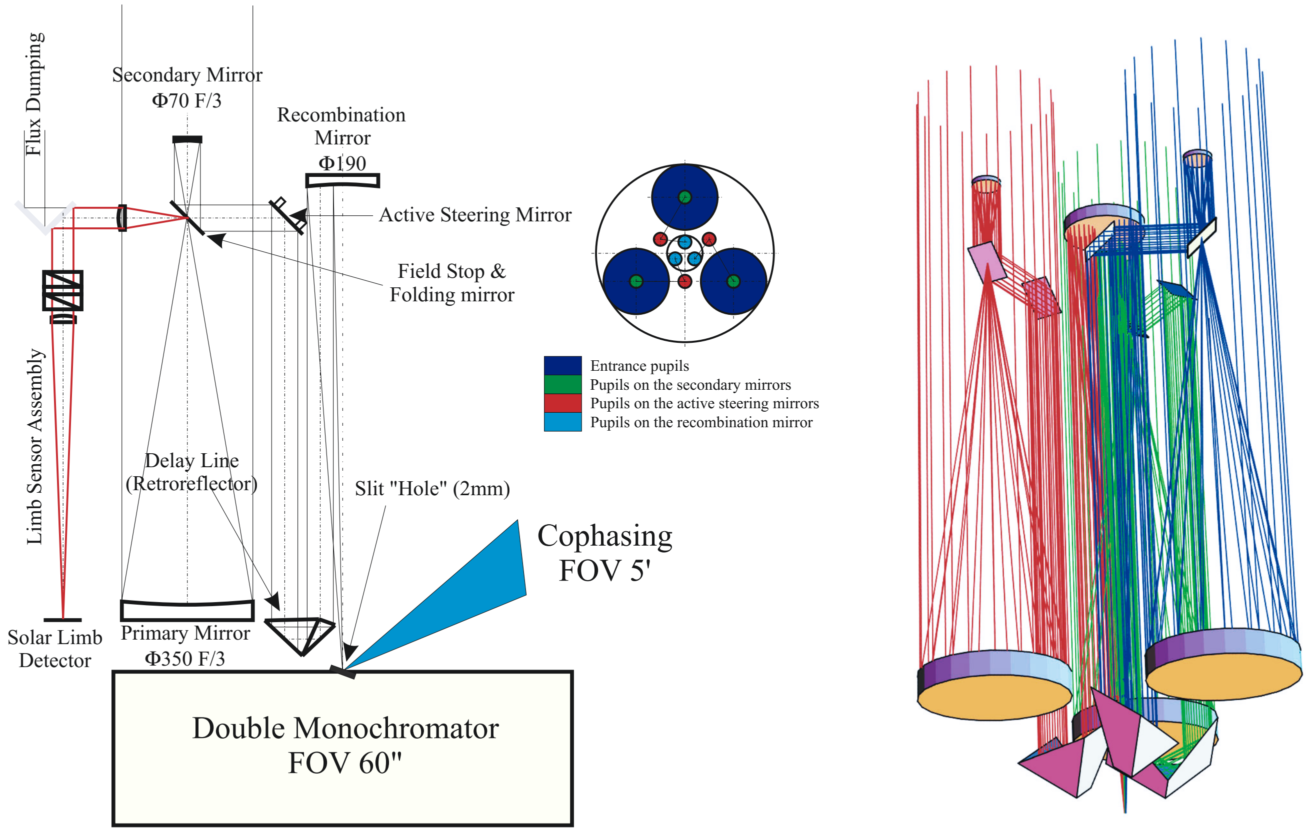

Fig. 3. Design of SOLARNET (one of the 3 telescopes shown). Note the special use of relays at 30° to fit the recombination on a "small" 190 mm mirror, yet preserving a proper pupil orientation. Fine pointing is achieved on the Solar limb taken off from the field stop inside the Gregory. The cophasing (by the delay lines) is monitored from a reference field feeding 3 reference interferometers directly from the entrance slit (2 mm hole) of the scientific instrument. Nothing is lost: 42 arcmin to pointing — 5 arcmin for cophasing — 1 arcmin for the scientific instrument.

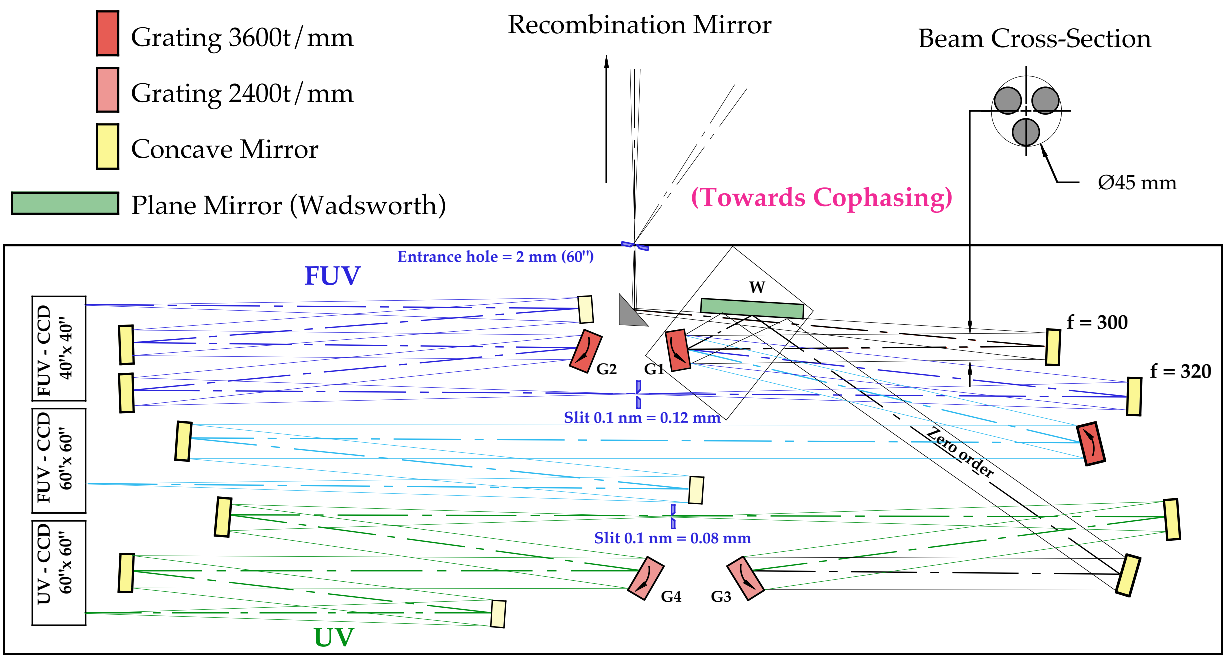

Fig. 4. Configuration of the Subtractive Double Monochromator (SDM) of SOLARNET. Note, in particular, the sets of double gratings (G1,G2) and (G3,G4). They rotate synchronously to compensate for the spectral dispersion. The second SDM is fed by a flat mirror (W), linked to the first grating (G1), which has the particularity to send the zero order always in the same direction (Wadworth's mount).

MISSION REQUIREMENTS AND SPACECRAFT DESIGN

This section summarizes two preliminary analysis carried out by MATRA MARCONI SPACE (MMS) and ALCATEL for the SPI mission. The baseline solution is based on:

- the reuse of a small platform, PROTEUS or LEOSTAR. Due to their innovative concepts and high modularity, the avionics can be successfully reused for the SPI mission. Baseplate is adjustable in the PROTEUS approach while the current LEOSTAR structure (in development), with its hexagonal shape, fits perfectly the size and shape of the payload.
- An adapted geometry of the Solar array, with simple, fixed, Solar panels pointed to the Sun.

The satellite mass and geometry are compatible with the Rockot launcher capabilities for the selected orbit (1000 km altitude, SSO 6h–18h).

Note that the satellite configuration analysis is of course preliminary. Limited analysis of the payload assembly has been performed. Probably some additional structures (struts, supports) will be added in order to maintain the instruments at launch. However, because there are large margins for the satellite volume in the Rockot fairing, it will be easy to adapt and reinforce slightly the current proposed design. This could probably be made without mass a significant mass increase since, along the ALCATEL design, the baseplate and three telescopes structure of the interferometer could be optimized (cf. Figures 5 & 6).

The Earth orbiting platform is proposed in a polar, Sun synchronous orbit, precessing with the day/night terminator (6:00–18:00), providing a nearly uninterrupted view of the Sun and maximizing the telemetry capabilities (which is extremely important for such high resolution continuous observations). This, alone, allows very significant advances over SOHO where the telemetry capability was strongly limited. The platform is a typical LEO mini-satellite one (PROTEUS, LEOSTAR), 3-axis stabilized and Sun-pointed, with a stability of 1 arcsec/a few seconds (15 as a goal) and an absolute pointing of a few arcsec (accuracy similar to the COROT Scientific Mission of CNES on PROTEUS were a reference is given also by the instrument itself). To interface a standard LEO bus with the scientific payload a dedicated payload equipment bay will be implemented. Also, to ease the life of Sun centered instruments (helioseismology, coronagraph) these instrument will be mounted on an Hexapod pointing platform (e.g. of the Sage III type on the Space Station as provided by ESA to NASA) and the required signal to guide the Hexapod can directly come from one of the pointed telescopes. We anticipate a mission lifetime of 2 years in the first instance, but with hardware and consumables sized for a 6 years mission, consistent with a mission observing the rising phase of the Solar cycle, and an extended mission observing the Solar maximum and initial decline.

SCIENCE OPERATIONS AND ARCHIVING

The science operations are expected to be performed in a European Mission Center (operation facility and full data archive), foreseen as part of a large European Institute. This would give European Solar science clear visibility (preference being given to a full mission data center rather than separate PI data centers). The data volume will be several orders of magnitude greater than SOHO, but for current technology and trends, this will not pose serious problems for ground stations or archives in view of the present low cost of X-band equipment driven down by the rapid development of communications and Earth sciences satellites. Note that the operations by themselves are eased by the permanent pointing of the satellite. Alike SOHO, some targets of opportunity are envisaged that would find place in the weekly organized science observing plan. Data are not available real time since up to 6 orbits could be stored onboard the satellite (visibility of a Kiruna X-band antenna, for example).

The mission exploitation will not be restricted to the instrument PI teams, but the data should be made public and accessible to a larger scientific community, a procedure which has been shown by the Yohkoh and SOHO communities to be largely successful and would ensure that the best possible use of the data would be made. The expected number of direct users would be about 400, a number corresponding to the community being presently active in Solar physics, helioseismology, variability and Space weather.

CONCLUSION

Despite its quality, merits and readiness, SPI was not retained by ESA in its recent selection process. But needs for a high-resolution mission with high telemetry throughput, large spectral coverage and continuity of observations, have never been so strong in the Solar community. SPI realization possibilities are yet under investigation, both in Europe and the US, and this could materialize in a collaborative NASA MIDEX / CNES PROTEUS mission as soon as the next mission cycle, in 2007–2008 (decision expected early in 2002).

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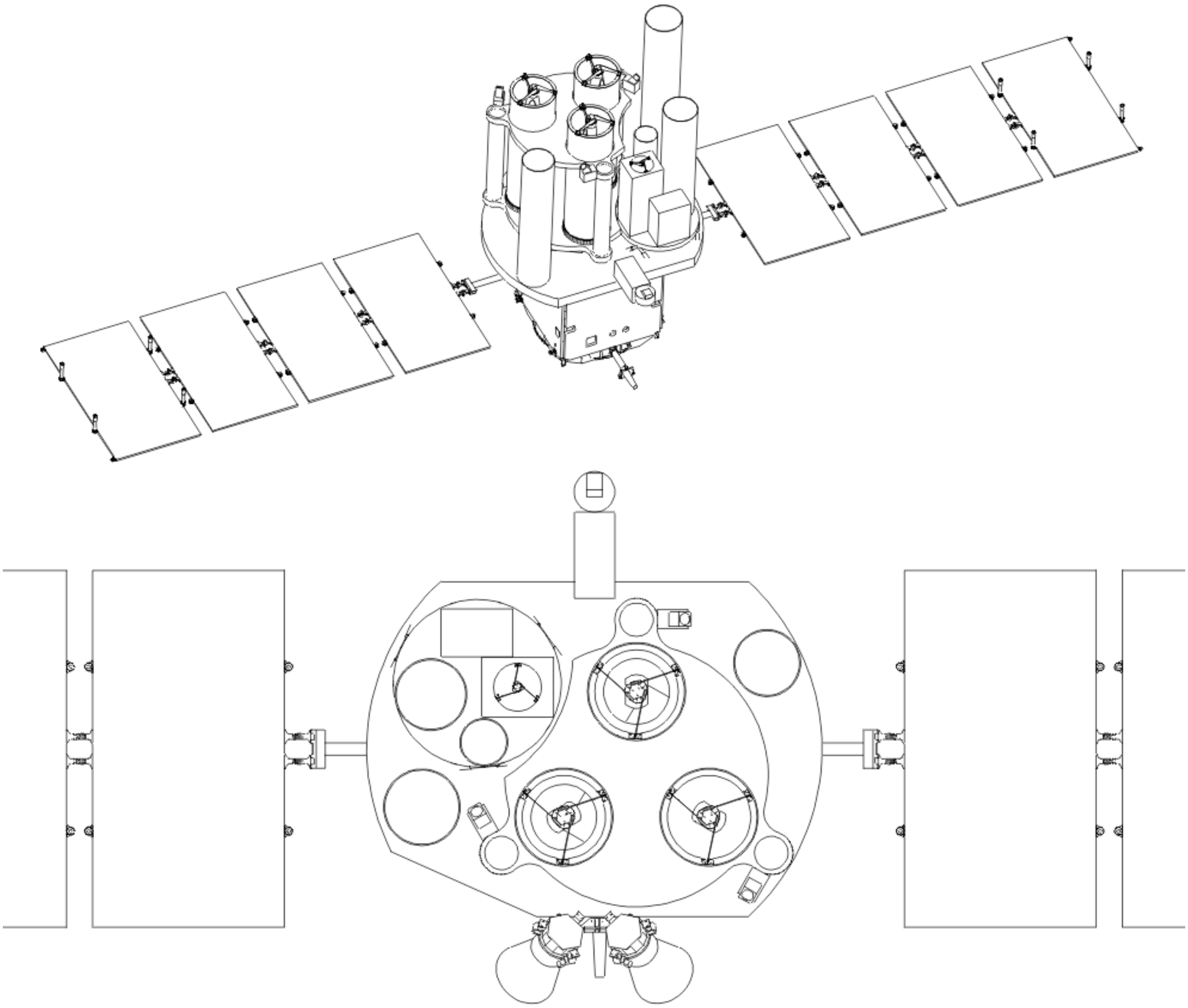

Fig. 5. The SPI Mission accommodated on the ALCATEL PROTEUS platform. The payload size if Ø1.7m x 1.8 m. Note the small platform of Ø60 cm, beside the three-telescopes SOLARNET interferometer, mounted on 6 linear actuators (the Hexapod) and accommodating the Helioseismology package and the coronagraph (instruments needing to be pointed to Sun center permanently). The two larger tubes are the EUV imager and spectrometer and the small instrument in front, slightly pointing outside the platform base, is the NG-SWAN instrument.

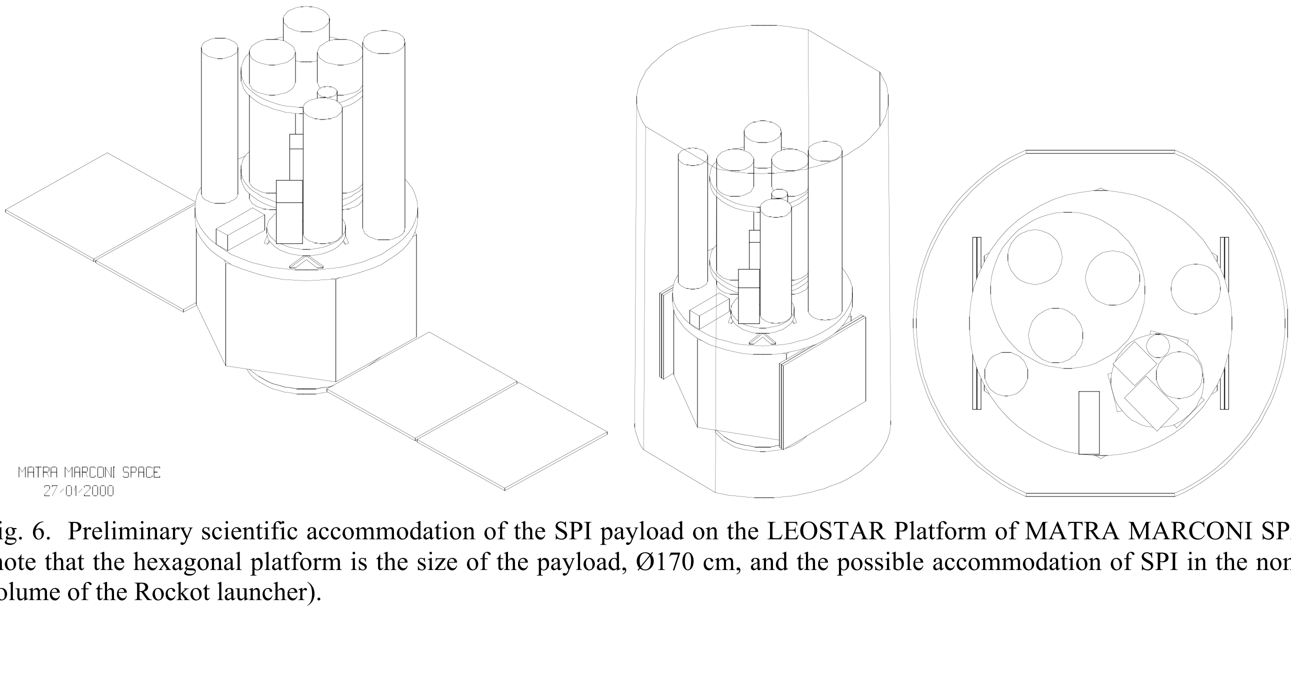

Fig. 6. Preliminary scientific accommodation of the SPI payload on the LEOSTAR Platform of MATRA MARCONI SPACE (note that the hexagonal platform is the size of the payload, Ø170 cm, and the possible accommodation of SPI in the nominal volume of the Rockot launcher).

Table 4. The SPI Mission in summary

Scientific Objectives	Solar imaging, spectro-imaging, helioseismology and Solar activity: • Spectroscopy and imaging at very high spatial and temporal resolution • Helioseismology, resolved and global oscillations, g-modes (diameter oscillations) • Solar variability, influence of the Sun on the climate, space weather (Lyman α imaging)
Payload	8 instruments and adaptation totaling **430 kg** and consuming **350 W** power (with thermal control included) Solar instrumentation - Imagers and spectrometers: – SOLARNET Ø1 m interferometer with its UV spectro-imager system (UVIS) – EUV Imager and Spectrometer – X-Ray/EUV Imager Oscillations and Solar Variability Package (on Sage III type Hexapod): – OVIM-MOF (resolved velocity oscillations and magnetographs) – NG-PICARD (limb oscillations, g-modes, and absolute diameter measure) – NG-DIARAD/VIRGO (Solar constant, global and resolved intensity oscillations – Ultraviolet and visible light coronagraph 1.1–2.6 Solar radius Space weather: – NG-SWAN full sky Lyman α imager
Launcher	• Dedicated launch with **Rockot**; launch mass **880 kg** (including 50 kg of dispenser mass) • Nominal launch from Plesetsk (62.7°) well situated (high latitude) for an injection on a polar orbit • **10 months non-eclipsing 6:00-18:00 polar orbit 1000 km height**
Spacecraft	• Design lifetime = 2 y, consumables sized for 6 y (extended mission) • Total satellite mass = **830 kg** • Main S/C bus (with payload): 300 cm x Ø170 cm • 3-axis stabilized • Pointing stability better than 1 arcsec/15 seconds and 5 arcsec/15 min • Deployable Solar arrays (no rotation) of 800 W (4m^2) • 2 S-band antennae for TC • X-band LGAs, omni coverage, for TM • 1 ground antenna at Kiruna (or Svalbard) compatible with permanent **3 Mbps** telemetry

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