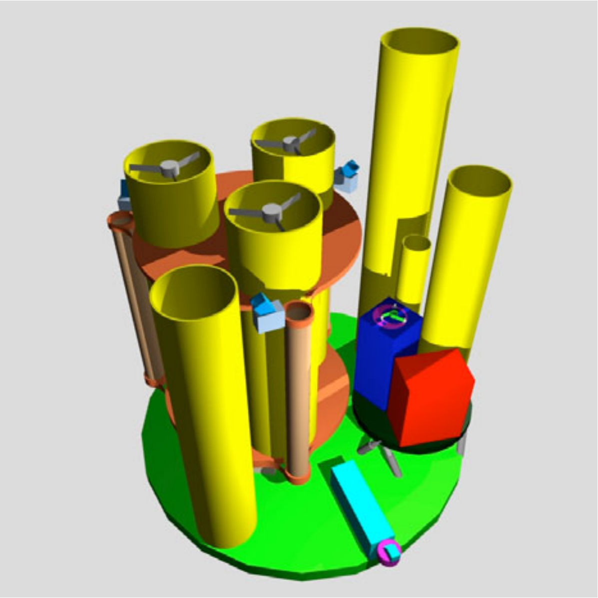
Mission Proposal in Response to the ESA Call for Mission Proposals for Two Flexi-Missions (F2 and F3)

SPI — The Solar Physics and Interferometry Mission

A New Generation Mission for High Resolution Solar Physics, Helioseismology, Variability and the Sun-Earth Connection



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Executive Summary

The scientific rationale of **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. The most interesting and novel observations will 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 never be able to 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 complete 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 Alpha 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 coronograph 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 launcher also. The many high technology, new features 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**.

For the first time a mission will address directly the key in understanding the Sun: the magnetic fields structuring. We will resolve it in much smaller features to analyze thoroughly the **Sun's magnetic activity** on multiple scale: time variability, evolution and fine-scale structure of the dynamic chromosphere, transition region and corona, origin, confinement, acceleration and release of energy, heating of the chromosphere and corona. SPI will complement the *in situ* observations of the Solar Probe and built upon SOLAR-B moderate spatial resolution.

The payload consists in 8 instruments, the SOLARNET three-telescopes cophased interferometer with 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 coronograph, NG-PICARD (Solar diameter absolute measure and oscillations), NG-DIARAD/VIRGO (Solar constant and intensity oscillations) and NG-SWAN (full sky Lyman Alpha).

The payload, platform and mission scenario were reviewed by major Space industries up to providing consolidated cost estimates (154 MEuro). The mission is international but without the need of NASA. The cost conscious approach allows to include in the cost the three telescopes interferometer as an ESA provided facility as well as the hexapod pointing platform for the helioseismology and coronograph assembly. A Rockot launcher is largely sufficient to reach a high 1000 km orbit 6:00–18:00 minimizing eclipses (a few minutes 50 days or so per year). The spacecraft is a low cost reusable platform of the Leostar or PROTEUS type, 3-axis stabilized and always Sun-pointing. This is possible because of the compactness of the interferometer. Telemetry by an X-band antenna at Kiruna (Sweden), on such a near Earth orbit, 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.

1. Introduction

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 a serie of approved US missions (SOLAR-B, STEREO, Solar Probe) and some Space weather applications may also be monitored in the future — if the program is approved end of next year — by NASA Solar Dynamics Observatory.

This proposal is therefore going one significant step further than the present ambitions of ESA *Solar Physics Planning Group* (SPPG). It takes our European competencies in 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. If our mission is approved in September 2000, there will be ample time for NASA to plan a complementary mission, or a contribution, and to attract instrumentalists and groups in Europe currently involved in the Solar Orbiter or NG SOHO (hopefully as soon as end of February to help with the assessment study phase).

The SPI Mission is a further development of the SIMURIS and SOLARNET concepts (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, first, indicated in the resolution the need for high spatial resolution. This was subsequently "denatured" somehow by adding (after the fact) additional mission scenarios, including polar orbits and closer approaches to the Sun (which were finally discarded for technical reasons). ESA, the SPPG, conducted only one pre-assessment study on the Solar Orbiter. The limited objectives of the resulting mission (not near the Sun, not at the pole and for limited periods of time and telemetry) resulted in two other proposals, SPI, dedicated to high resolution, helioseismology and Space weather and something called NG-SOHO, a melting pot of reusable European instruments that Americans would not care including in their proposal ("complementary"). An F mission is not a corner stone but this is not a reason to limit ambitions to providing a complement to an non-existing NASA pseudo-high resolution mission which do not provide anything more than an enhanced MDI that we can do better in Europe with the Cacciani Magneto-Optical Filter.

The SPI program could benefit from a partnership between ESA and NASA, although the mission and payload are possible without any support or involvement from NASA. US participations in instruments are possible up to the point that a collaborative framework could be agreed between ESA and NASA. For instance much alike SOHO where NASA supported the launch of this spacecraft. But, again, this is not necessary and should represent a scientific advantage.

In the present scenario, the SPI mission, our F-mission opportunity, will be managed and built by ESA alone and will carry, as the label of ESA and Europe competencies, a three telescopes cophased interferometer of the meter class (SOLARNET) feeding a high resolution imaging spectrometer: the double subtractive monochromator. 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 Coronograph, Solar Diameter Telescope ó limb oscillations, radiometers, Sun photometers and full sky Lyman Alpha imager.

The important technologies needed by the proposed interferometer concept include optical delay lines and a cophasing system together with its control software. These technologies have been breadboarded by the Service d'Aéronomie and by IRCOM in the framework of an ESA study called "Optical Aperture Synthesis Technologies", lead by MATRA. Both experiments have been successful and all components needed by an interferometer have been validated through an end to end test from object to image reconstruction (Midi-Pyrénées Observatory). These achievements fully secure the development of the SOLARNET interferometer as both detailed and system design issues are perfectly mastered. A working three telescopes imaging interferometer is currently in use and visible a Service d'Aéronomie (please follow the link http://must.aerov.jussieu.fr).

Because of ESA and industrial acquired competencies, of limited resources in local Institutes in Europe to manage such a large telescope assembly, of limited funding capabilities of National Agencies which support ESA and the PIs instruments and, moreover, of the need to give with this mission a clear message to the scientific community and to the public at large, we believe that, much alike Hipparcos, ISO or XMM, the central telescope assembly has to be done by ESA itself. With this imaging interferometry first realization in Space, ESA will reinforce its largely positive image in the mastering of leading technologies. Further, note that MATRA and ALCATEL have reviewed the mission scenario, platform and payload, and in particular the three-telescopes assembly, and that they guarantee the SOLARNET feasibility for a consolidated cost below 40 MEuro.

We propose an Earth orbiting platform 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, coronograph) these instrument will be mounted on an Hexapod pointing platform. Again, this is an expertise of ESA (the Hexapod platform for Sage III on the Space Station was provided by ESA to NASA as a barthering for the Payload Adapter place for instruments on the Space Station) and the required signal to guide the hexapod can directly come from the pointing telescope of PICARD (the guiding telescope of PICARD is driving the CNES microsatellite platform). 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.

2. 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 Alpha 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 instance, 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 much 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 will ideally complement *in situ* plasma studies by the Solar Probe 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.

2.1 The Big Questions

An excellent review of the "Big" questions in Solar Physics is given on the web site of the Marschall Space Flight Center (which we recommend: http://wwwssl.msfc.nasa.gov/ssl/pad/solar). In summary they are:

– the coronal heating process
– the nature of solar flares
– the origin of the sunspot cycle (the variability)
– the missing neutrinos

These questions 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?).

All these questions will be addressed by SPI which 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 in particular. For the rest, SPI will do extremely well with high resolution for the magnetic structuring, with helioseismology, oscillations, for solar interior (dynamo, g-modes, neutrinos) and with Lyman Alpha, diameter and solar constant measurements for variability and Space weather (we have 100 times the sensitivity with diameter measure rather than with the Solar constant).

2.2 High resolution paradigms

The supergranulation network, which dominates the chromospheric plasma dynamics, is apparent in the EUV emission pattern as seen by the SUMER instrument on SOHO is shown in Fig. 2.1. 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 uncanceled 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 (see the review of Axford and McKenzie, 1997) according to which the wind originates in the chromospheric network, and draws 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. Plasma outflow has indeed been detected by SUMER on SOHO and is illustrated in Fig. 2.1. 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 (March, 1991) 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 (Kohl et al., 1997; Antonucci et al., 1997; Wilhelm et al., 1998; Tu et al., 1998). 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 (Priest et al., 1999).

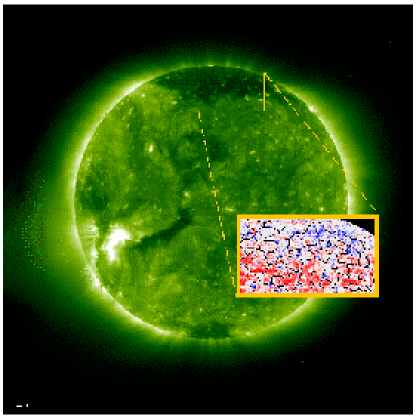


Fig. 2.1 – SUMER observations of the Solar-wind source regions and magnetic structure of the chromospheric network. The insert shows the measured Doppler-shifts of Neon ions, indicating blue-shifts, i.e. outflow, at the network cell boundaries and lane junctions below the polar coronal hole, and red-shifts (down-flow) in the network regions underlying the globally closed corona (adapted from Hassler et al., 1999).

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.

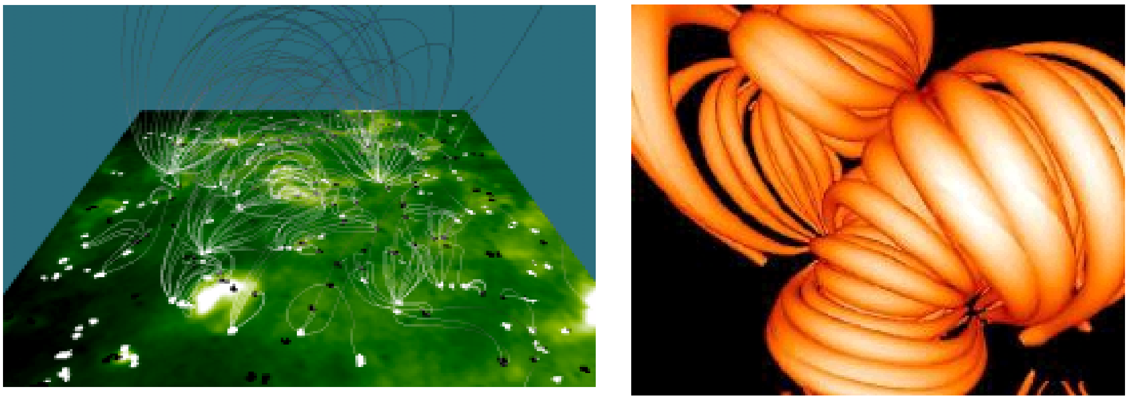


Fig. 2.2 – Modeling magnetic fields extension in the chromosphere and corona is now possible and will gain from higher resolution and atmospheric height sampling.

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 much better than 1 arcsec. These images (see, for example, Strong et al., 1994; Shrijver et al., 1999) 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 brightness structures lie well below the best current spatial resolution. This points to the need for still higher spatial resolution. The active Sun has still not been 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.

2.3 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., 1999). This amplification factor was roughly predicted by theory (Appourchaux and Toutain, 1997). 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 and further more with NG-PICARD on SPI we can seriously envisage detecting them in 16 months 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 properly in the strict 30 pages limit of this proposal. Please refer to our web site for details (http://must.aerov.jussieu.fr/spi).

2.4 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 larger than 200 (assuming 0.4" over 11 years). To substitute diameter to constant is the ratio is known (goal of the CNES microsatellite PICARD) would allow monitor with a much better precision the influence of the Sun on the Earth climate. More with NG-PICARD and NG-SWAN descriptions in the payload part.

3. Scientific Payload

3.1 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 coronograph) 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 coronograph since it best works centered on the Sun) and the small NG-SWAN instrument which benefits from its own periscope.

The SPI Mission provides unique possibilities to do optical remote sensing observations of the Sun with unprecedented spatial resolution at scales below 25 km in images obtained in various wavelength bands. With the recent SOHO revelations of fine structures existing in the 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 is suggested which are combined in two packages involving several teams of scientists. Emphasis is put here on the scientific requirements and on a demonstration of feasible designs. 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.

The instrument set is completed by an EUV-white-light coronograph, 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 out to 2.6 R_s. 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).

3.2 SOLARNET and UVIS

The SOLARNET interferometer and its double monochromator are described in details in the paper "High Resolution Solar Physics by Interferometry", 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 (ESA SP-**417**, 109-131, 1998). It is much more complete and detailed that whatever we could present in 2 pages and, therefore, we do include first the rationale of using a 1 meter interferometer rather than a single dish, a view of the interferometer and of the focal plane instrument (the UltraViolet Imaging System: a subtractive cascading double monochromator in FUV and UV). Accessible lines, line ratios for density and temperature diagnostics are also in the

paper, as well as image reconstruction indications. Because this paper, and a second one on the laboratory work (ESA SP-**417**, 345-348, 1998), are important in understanding the readiness of the proposed instrumentation they can directly be downloaded from the web in pdf format:
http://must.aerov.jussieu.fr/fichiers_pdf/proc_Tenerife98.pdf
http://must.aerov.jussieu.fr/fichiers_pdf/proc_Tenerife98_demo.pdf

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:

- 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. Fig. 3.1), 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 (tools of 10 cm or so).
- Adaptive optics. Interferometry requires to control 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.*

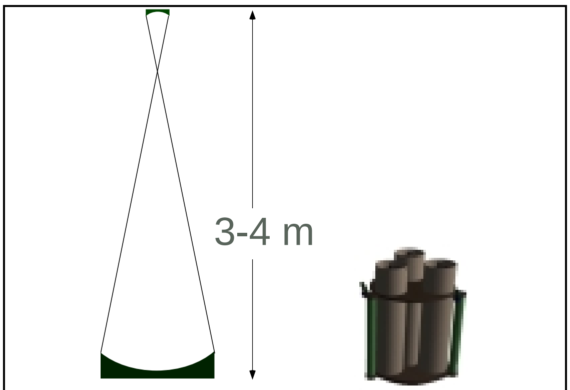


Figure 3.1. The evident size, mass, alignment control... advantages of an interferometer of 1 m over a monolithic telescope of the same diameter.

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.

Taking into account the sustained R & D program, first with ESA, and now for 3 years with CNES (3 telescopes imaging breadboard with fine pointing, phase control and image reconstruction on the Sun and Planets), we believe that an imaging interferometer is not at all premature as the major instrument of the next ESA Flexi missions F2/F3. We proved that the major assumption of the overall concept, the cophasing of the array, is feasible and, moreover, that performances to expect are very high. SOLARNET breadboard is WORKING IN LABORATORY finding fringes, stabilizing them and reconstructing images from the interferograms (please visit our web site: http://must.aerov.jussieu.fr).

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.

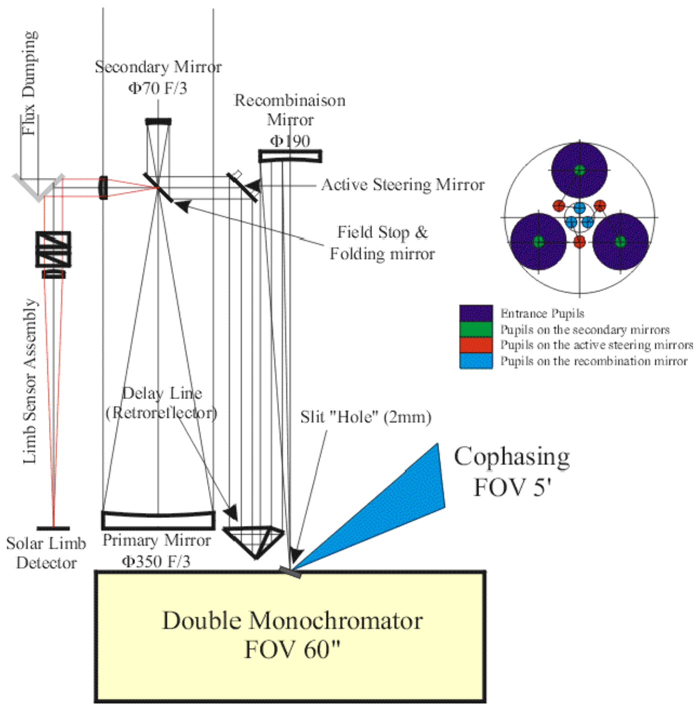


Fig. 3.2 – Design of SOLARNET (one of the 3 telescopes shown). Note the special use of relays at 30° to fit the recombination on a "small" 190 mm mirror, yet preserving a proper pupil orientation. Fine pointing is achieved on the solar limb taken off from the field stop inside the Gregory. The cophasing (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.

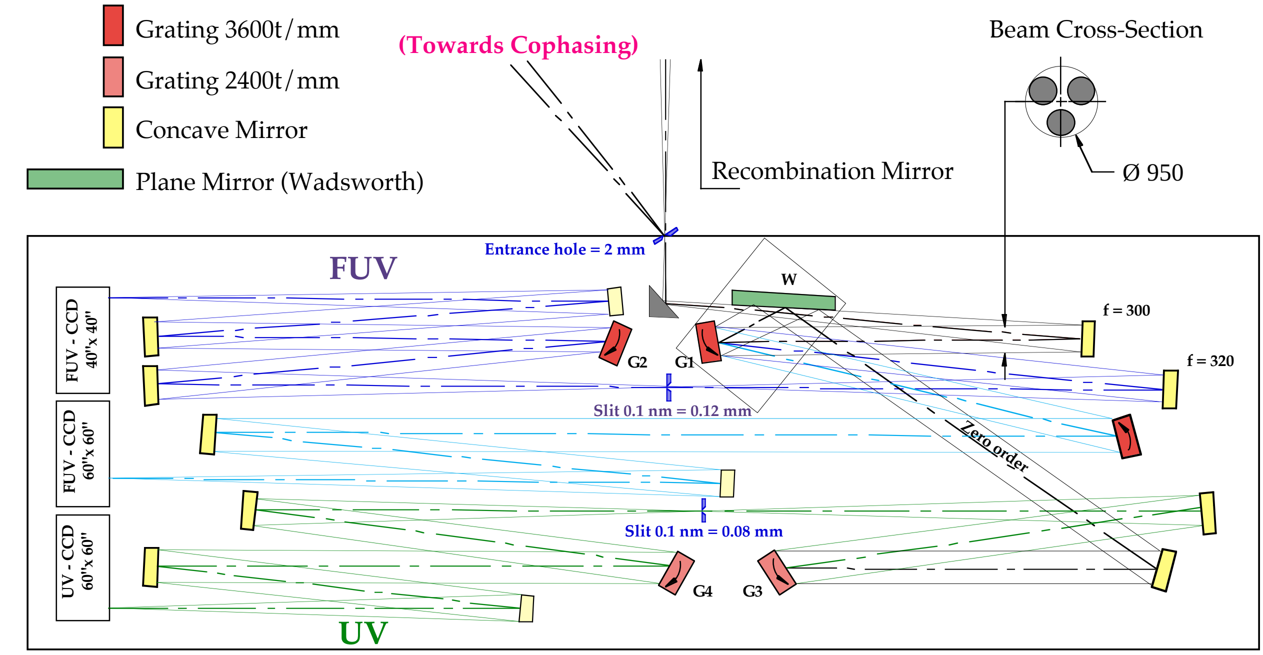


Fig. 3.3 – Configuration of the Subtractive Double Monochromator (SDM) of SOLARNET. Note, in particular, the sets of double gratings (G1,G2) and (G3,G4). They rotate synchronously to compensate for the spectral dispersion. The second SDM is fed by a flat mirror (W) linked to the first grating (G1) which has the particularity to send the zero order always in the same direction (Wadworth's mount).

Table 3.1 – 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 — 200 130 — 300	40 x 40 60 x 60	2048 x 2048	CCD	0.025 — 0.04 0.04 — 0.1	0.002 ~ 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 3.2 – 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)

3.3 EUV spectrometer

Observations of the EUV spectral range are critical for the determination of plasma diagnostics in the Solar atmosphere across the broad temperature range from tens of thousands to several million Kelvin. Analysis of the emission lines from trace elements in the Sun's atmosphere can provide information on plasma density, temperature, element/ion abundances, flow speeds and the structure and evolution of atmospheric phenomena. Current spacecraft instrumentation provides EUV spatial and spectral resolution elements of order 1-2 arcsec and 0.05 Å, respectively.

The basic design parameters of the EUV spectrometer are given in the subsequent table. The heritage of this instrument comes from the SOHO/CDS and Solar-B/EIS projects. We envisage a semi-synoptic operation - i.e. a basic set of operation modes which are run in a predefined sequence or over long periods. Day-to-day planning will be minimised. The instrument requires a spacecraft pointing stability of the order of 1 arcsec/15min, with absolute pointing to better than 2 arcmin.

The instrument is sized to achieve a spatial resolving element of 1 arcsec. With regard to spectral resolution, our basic aim is to return a sufficient number of spectral lines to allow thorough spectroscopic studies, without telemetry limitations thanks to the high downlink orbit. We anticipate using a CCD-based detector system with 13.5 micron pixels in an array of 4k x 4k. Thus, we would expect to return a spectral range of 40 Å at 0.01 Å /pixel. The same array will give a spatial extent (vertical distance on the detector = slit length) of 0.5" x 4096 = 2048" = 34 arcmin.

Table 3.3 – Parameters for a potential EUV spectrometer

Telescope	Ritchey-Chretien type; 250 mm diameter
Spatial resolution element	0.5 arcsec
Spectral resolution element	0.01 Å/pixel (5 km/s)
Raster Mechanism	Through motion of the secondary
Detector	Back thinned EUV CCD; 13.5 micron pixels; 4096 x 4096 array.
Initial Wavelength Selection	580-620 Å (e.g. 1st and 2nd = Fe XII 291, Si X 293, He I 584, Si IX 296, O III 599, He II 304, Mg X 610).
Slit Length/Width	34 arcmin length; adjustable width
Field of View/Pointing	Raster over 34 arcmin; pointing to anywhere on the Sun
Telemetry	400 kbit/s
Mass	35 kg
Power	30 W
Size	Instrument = 180 cm x Ø32 cm
Thermal	Operating temperature 20°C with passively cooled (-40°C, radiator to space) CCD.

The instrument structure could be made of carbon fiber, with silicon carbide optical components as implemented in PICARD currently. Multi-layers will be considered if the final wavelength selection requires it. The Ritchey-Chretien telescope design was chosen here to minimize the size of the instrument. Assuming a spectrograph magnification of 1.5 and given the resolving elements, band width and field of view stated above, the telescope has an effective focal length of 5 m. We assume a telescope magnification of about 3, giving a physical focal length of 1.4 m. Including the spectrometer will make the total instrument envelope approximately 180 cm x Ø32 cm. The associated electronics box is 30 cm x 20 cm x 20 cm.

3.4 EUV imager and X-ray imager

The EUV and X-ray telescope should combine some of the virtues of the SOHO, NIXT and Yohkoh, and the TRACE imaging instruments. The images in various selected EUV and X-ray emission lines, corresponding to temperatures between 40000 K in the lower transition region of the Sun and a few million Kelvin in the corona, will allow studies of the two-dimensional morphology of magnetic structures on the disk and off the limb. A bundle of telescopes with small appropriately coated primary mirrors, suitably arranged in accord with their different sizes, could be envisaged but the TRACE design with segmented coatings on the primary and secondary, although more bulky, is far better (stable detector plane) and retained for SPI. The telescope will deliver high resolution full-Sun images routinely, whereas the others will at high-resolution concentrate with limited fields of view on selectable target areas on the Solar disk.

At a wavelength of 30 nm, a mirror of only 3 cm diameter would theoretically give an angular resolution of 0.2 arcsec at the diffraction limit. Thus even with comparatively tiny mirrors one could easily achieve a fine spatial resolution at perihelion, the equivalent of which to be obtained in Earth's orbit requires a sub-arcsec-resolution telescope. The ideal mirror sizes for the EUV and X-ray imagers still need to be determined. Multilayer coatings and dimensions of the mirrors and spectroscopic capabilities and spectral resolution of the instruments will depend on the lines selected. Within a broad pass band, a narrow wavelength window can for example be selected for spectroscopy by a pair of identically-coated movable flat mirrors like in a double-crystal monochromator, yielding a tunable imager without image motion in the focal plane (Golub et al., 1997). The scientifically optimal selection is left open and should be made in connection with future detailed designs. The detectors employed may be coated microchannel plates currently in use, providing photon detection and signal amplification, combined with a multilayer cross-delay-line anode or a CCD (with glass-fibre optics for image adaptation) accomplishing electronic readout. Detector technology in this field (in particular for soft X-rays) is advancing rapidly and low-mass detectors dedicated to the specific bandpasses will be available soon.

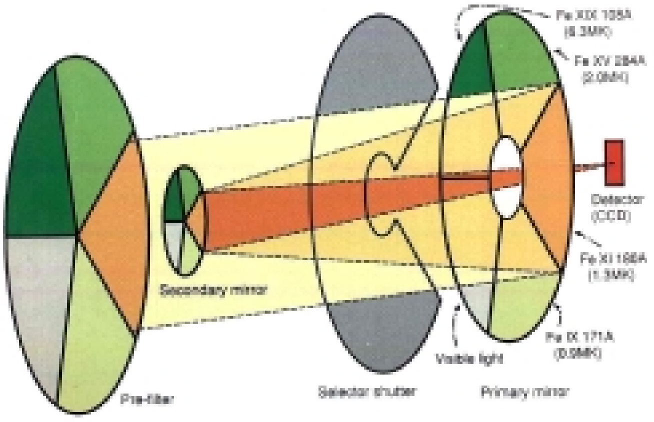


Fig 3.4 – Conceptual schematic design of the EUV X-ray imaging telescope using segmented deposited coatings on mirrors and a shutter for selection (along TRACE design).

3.5 NG-PICARD

Since the Solar energy is one of the major driving inputs for terrestrial climate and since it exists some correlations between surface temperature changes and Solar activity, it appears 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.

Why the diameter?
From 1666 to 1719, Jean Picard and his student Philippe de la Hire measured the Solar diameter, observed the sunspots and determined the Sun rotation velocity. Fortunately, these measurements covered the Maunder minimum and some time after. The data were re-examined by Ribes et al. (1987) who, after removing the seasonal variation of the Solar diameter, obtained the annual means at 1 AU. These values, averaged for the Maunder minimum period and after while the Sun recovered a significant activity, show a definitive difference of the order of 0.5 to 1 arcsec, 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). This shows that the Solar constant experienced a 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. To assess this suggestion, climate models were run by Sadourny (1994) that show the Maunder minimum as the possible cause of the Little Ice Age. However, volcanic eruptions (major ones) also play a certain role, but their effects do not extent more than a few years.

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 (1996), 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. Therefore, 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.

Lyman Alpha monitoring
Lyman Alpha irradiance has been monitored since 1977 and more recently by 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.

NG-PICARD instrument

NG-PICARD is a simple telescope of useful diameter 110 mm. It forms a complete image of the Sun on a large, back thinned, CCD of 2048 x 2048 useful pixels. The pixel, 13.5 µm, corresponds to 1.05 arcsec (at 1 AU) and the effective spatial resolution is also 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 1) accessible through the use of 2 cascading filterwheels, each with 5 positions.

Table 3.4 – Operational observing and calibration modes of NG-PICARD.

UV nominal mode	230 nm
Visible	538 nm
Active regions	160 nm
Prominences and ionosphere	Lyman Alpha
CCD Flat Field	"Diffusion"
Scaling factor	"Star field"

Operational modes

The main observing wavelength is 230 nm (5 to 9 nm bandwidth). It corresponds to a mostly 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, NG-PICARD observes 538 nm which is the center wavelength of 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 avoiding in the diameter computation the pixels at the limb affected by faculae, active regions, prominences, sunspots or pores, NG-PICARD has a reduced sensitivity in the ratio of a few diameters over 3000 or so but this does not add noise to the diameter measure.

The diffusion plates are simply used to monitor the CCD response and sensitivity (Flat Field). The CCD itself is a 2048x2048 pixels back thinned.

Finally, specific to NG-PICARD — and providing the ABSOLUTE diameter reference at the mas (milli arc second) level — is the "Star field" 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 a filter set 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 flux will easily be evacuated.

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 carbon-carbon structure. 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, a ± 0.1°C temperature regulation).

Pointing

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 is fine guiding the piezoelectrics which activate the primary mirror of the telescope. Fine guiding is used so that the image of the Sun on the CCD does not move by more than 0.1 arcsec, i.e. 1 tenth of a pixel (about 1 tenth of the Airy disk as well). The 4-quadrant detector will also provide (by access to the low frequency part of the control signal) accurate guiding to the microsatellite itself. In that case the coarse guiding of the stellar sensor is overruled by our sensor when the Sun acquisition is effective in the nominal ± 0.5° field of view. The 4-quadrant detector, the piezo electrics and the control loop will be provided by the Space Science Department of ESTEC.

Table 3.5 – Characteristics of SPI NG-PICARD.

Measurements	Solar diameter(s) and differential rotation by imaging
Number of channels	6 (230, 538, 160 nm, Ly α, "Flat Field" & "Star Field")
Telescope focal length— Solar image	2650 mm — Ø25 mm
Telescope primary mirror	Ø120 mm (used:110mm)
Telescope secondary mirror	Ø34 mm (used: 25 mm)
Back thinnedCCD detector	2048x2048 square pixels of 13.5µm (frame transfer)
Guider acquisition range	1.2°
Guider nominal pointing range	± 30"
Guider servo bandwidths	0–7 (Hexapod) & 7–50 Hz (fine guiding on the primary)
Quad-cell image displacement sensitivity	$< 10^{-2}$"
Piezo displacement range	± 6 µm (± 1 arcmin)

3.6 Oscillations Visible-light Imager and Magnetograph (OVIM)

The purpose of the Oscillations Visible-light Imager and Magnetograph (OVIM) is to give the photospheric context for the coronal imagers, to observe the morphology and strength of the magnetic elements and flux tubes at the photospheric level with a resolution that is consistent with the resolution of the other imaging telescopes, and to provide images, Dopplergrams and magnetograms of the Sun for helioseismology. OVIM will take data at high cadence (30s time resolution) all the time and with high resolution. The instrument will be capable of automatically detecting targets of opportunity (e.g., onsets of flares or other events of interest) to complement the other instruments observations.

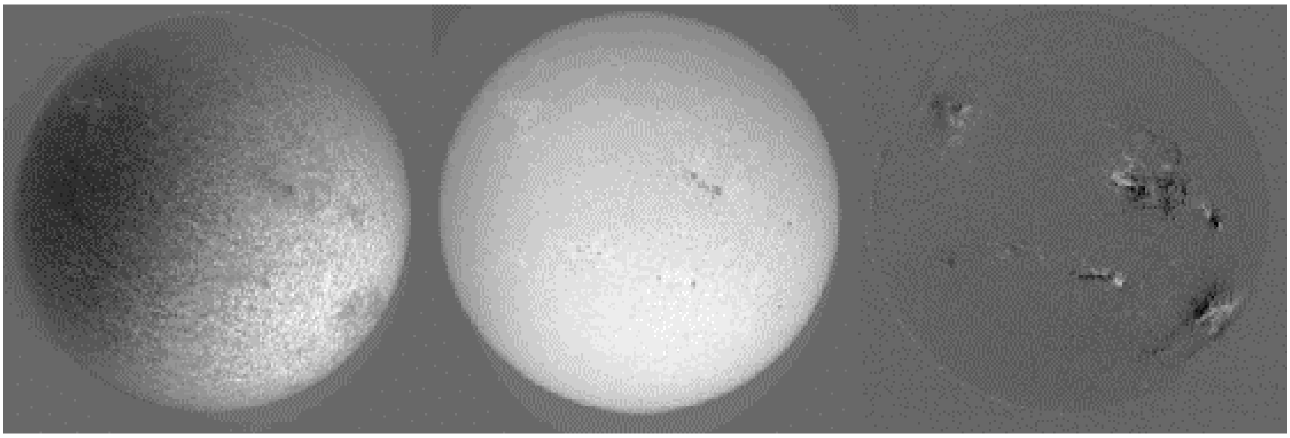


Fig. 3.5 – Global images of the Sun taken with the MOF instrument. From left to right: Sodium Doppler-magnetic image, intensity image and magnetic-field-polarity image. In the Doppler image the magnetic contamination is visible, which originated from the different line profiles obtained in the active region in comparison with the quiet regions (courtesy, A. Cacciani, 1999).

A Magneto-Optical Filter (MOF) is used as the baseline. The MOF is a narrow double-band filter transmitting the Red and/or the Blue side of a given photospheric/chromospheric line with intrinsic wavelength stability. In addition to the high stability, its second most important characteristic is that the two bands have orthogonal polarizations, so that they can be selected at will. There is only a limited number of usable spectral lines. Even if, in principle, any Zeeman sensitive line can be adopted, in practice only the Sodium and Potassium resonance lines have been used so far, and only Sodium in Space (GOLF/SOHO global velocity observations with a resonance spectrometer using a sodium cell). Na is formed in the low chromosphere, an advantage for the amplitude of the oscillations. The MOF is capable of acquiring simultaneously intensity, Doppler, and magnetic field maps at video rates. Two modulators, one in front and one behind the MOF, produce the wanted Doppler and magnetic information in the video signal. The signal is sent in parallel to three image processors, which can, using three different programs, produce simultaneously the Doppler, magnetic and line-intensity images. Using a suitable detector and integration time, the noise level of the global Doppler signal integrated over the whole Solar disk, is 1 cm/s in less then 30s.

The MOF does not require mechanisms for operation, has a mass (the cell assembly) as low as 2 kg, and dimensions as small as 15 x 15 x 25 cm. The wavelength stability is assured by intrinsic wavelength reference, given by the Na vapor. Temperature drifts cannot change the wavelength reference, but only the vapor optical depth, leading to second order effects only. A temperature variation of 1 K simulates a velocity signal of 10 cm/s, therefore the MOF is mostly insensitive to temperature. The MOF life time depends on the glass cell that contains the metal, Na in this case. For space applications this problem could have been critical. The MOF lifetime however is not a concern even if it has not been tested in Space, since the cell will use the same glass as GOLF/SOHO which is also a resonance spectrometer with a Sodium cell in Gelleniet Philips special glass now flown for several years without a significant degradation.

The filtergraph is fed by a Ø25 cm diameter Ritchey-Chretien telescope providing a full Sun high-resolution image. The telescope is equipped with a broad-band interference filter at the entrance to limit the incoming light flux to the sodium line (filter similar to GOLF SOHO which also used a Sodium resonance cell). The optics of the reflector will be made from SiC to limit degradation of the mirrors and for its high conductivity (large flux evacuation). For stability the structure is expected to be a Carbon-Carbon structure (tube or plates).

Table 3.6 - Parameters for the Visible Imager / Magnetograph

Telescope	Ritchey-Chretien; 250 mm diameter
Spatial resolution element (per pixel)	1 arcsec
Detector	Back thinned CCD; 13.5 micron pixels; 2048 x 2048 array.
Operational Wavelength	Na D1 / D2 589.0 and 589.3 nm
Telemetry	400 kbit/s
Mass	38 kg
Power	30 W
Size	Instrument = Ø30 cm x 120 cm
Thermal	Operating temperature 20°C with passively cooled (-40°C, radiator to space) CCD.

3.7 NG-DIARAD/VIRGO – Solar Irradiance Experiment

An experiment to extend the knowledge of our variable Sun. No Solar physics mission can really fly without a radiometer. Long-term studies of Solar variation are essential for an understanding of our star and we would want the next generation missions to extend the current data-sets into the next Solar cycle. The idea of the Next Generation SOHO radiometer is to extend the SOHO-VIRGO concept into both the infrared and the ultraviolet, especially for more detailed studies of the Solar irradiance variability and its redistribution within the spectrum. One of the crucial unsolved questions of Solar variability is whether activity is acting ëonlyí through its related magnetic fields or whether some other activity related effects influence the Solar brightness (or even luminosity) as e.g. temperature changes of the photosphere. For this a wider spectral range is important. Obviously, helioseismology is also an important objective, and the envisaged observations can possibly be used to complement the SOHO measurements and to continue the time series, especially for the search for g-modes. The instrument is, in fact, a package which contains (i) two types of radiometers (one will be a new PMO type, the other a new generation DIARAD) with their backups, (ii) four filterradiometers (two with the three (402, 500, 862 nm) channels as with VIRGO (one operational and one as a backup for tracking the degradation), and two with four channels, three in the UV (230-350 nm) and one in the IR (1600 nm) and (iii) a luminosity oscillation imager (LOI) with enhanced spatial resolution.

Table 3.7 – NG-DIARAD/VIRGO Solar Irradiance Experiment

Field of View	Full Sun as a star and with moderate resolution
Wavelength Range	Total and IR to UV in selected 8 nm bands
System	Set of radiometers and filter-radiometers
Pointing	Center of the Sun
Instrument size	0.3 m x 0.3 m x 0.4 m & 0.09 m x 0.25 m x 0.09 m
Mass	22 kg (sensors, electronics & cable)
Telemetry	< 1 kb/s
Power	24 W

3.8 Ultraviolet and visible-light coronagraph

High-resolution eclipse pictures and the corona images obtained by SOHO of the Solar corona have revealed that the corona is highly structured in the form of plumes and rays on the scale of 2° - 3°, about equivalent to the angular scale of supergranules, and that the coronal density distribution is very inhomogeneous. The main objective of the coronograph and full-Sun imager is to image and diagnose the structures of the dynamic corona in EUV and white light on the relevant scales. Full-corona context images are necessary for the simultaneous analysis with the visible, UV and EUV imager of features observed on the disk, from the photosphere to the corona such as sunspots, filaments, loops and active regions.

The coronograph proposed is an innovative **Hydrogen-Helium-Coronograph** instrument for the imaging of the most abundant elements in the corona: hydrogen and helium. Helium is the second largest contributor to the density of coronal plasma, making it potentially important for the dynamics of Solar wind acceleration. Particle flux measurements at 1 AU show variable helium abundance over the range 1% to 30% (in CME) of hydrogen, with typical values of 5% (quite constant) in high-speed flows and of 2% (highly variable) in the slow Solar wind. In fast streams, Helium flows faster than hydrogen by the Alfven velocity. The overall low abundance of helium is most easily attributed to its high First Ionization Potential, suggesting fractionation in the chromosphere, but the abundance variability is an open question.

The primary scientific objective of this instrument is the determination of the H and He abundances in the corona and of their flow speeds in the Solar wind. The science goals include the measurement of the electron density in the extended corona between 1.1 and 2.6 Solar radii. UVCS has measured high acceleration of the hydrogen atoms and oxygen ions in the polar regions close to the Sun. The coronograph will be able to measure also the helium outflow velocity and abundance in polar coronal holes. It will allow the first determination of the absolute abundance (i.e., relative to hydrogen) of helium in Solar corona. The coronal imager encompasses an extreme ultraviolet (EUV) channel for the observation of the Ly α emission of H I 121.6 nm and He II 30.4 nm, and a broad-band visible-light channel. The H I and He II Ly α (images are separated with narrow-band transmission filters. UVCS/SOHO has obtained the first HI Ly α coronal images only by scanning the corona. The UV coronagraph proposed here will image simultaneously the entire UV corona in HI Ly α and (extending the UVCS capability) for the first time obtain images of the full corona in He II Ly α.

The coronagraph is an externally occulted telescope designed for narrow-band imaging of the EUV corona in the He II 30.4 nm line (with a metallic (Al) polyamide filter) and the H I 121.6 nm line (with an interference filter), and for broad-band polarization imaging of the visible K-corona (polarimeter channel from 450 – 600 nm). The telescope optical configuration is a two-reflection Gregorian, giving real images of the occulter and the edge of the telescopes primary mirror (blocked with stops). The two EUV Ly α lines are separated with EUV transmission filters. The visible-light channel includes an achromatic polarimeter, based on electro-optically modulated liquid crystals, with no moving parts. The reflecting coronograph is externally occulted, which ensures better stray-light rejection at shorter wavelength. The mirrors with coatings optimised for 30.4 nm (e.g., Mo/Si multilayer coating) still have good reflectivity at 121.6 nm and in the visible. Two detectors (ultraviolet and visible) are foreseen: a ICCD with an EUV photo-cathode (121.6 nm, 30.4 nm) and a CCD for the visible band.

A wide-angle white-light instrument with a FOV from 1.5 to 6 R_s, equivalent to the LASCO-C2 on SOHO, could complement the payload and see extended coronal structures and evolving CMEs. It would cover the cusp regions of helmet streamers, where the slow Solar wind is released and begins accelerate. The most successful LASCO-C3 instrument (FOV from 3 to 32 R_s at 1 AU) could serve as a design baseline. The required mass could be small, < 5 kg (assuming a common electronic systems with the other coronograph).

3.9 NG-SWAN - Full sky Lyman Alpha

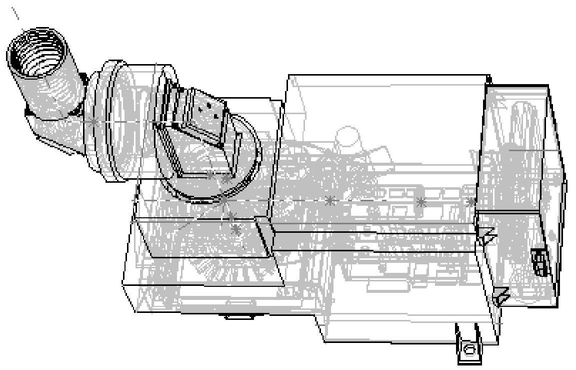


Fig. 3.6 – NG–SWAN configuration (note the periscope in entrance).

Table 3.8 – Instrumental characteristics of SPI NG–SWAN

Mass	7 kg
Volume	18 x 17 x 36 cm^3
Average Power	12 W
Temperature Op.	-30˚ to +30˚
Temperature Survival	-40˚ to +50˚
Nominal Telemetry Rate	10 kbps (Science and Housekeeping)

Summary of Scientific Goals

- Observe Solar activity changes on all sides of the Sun, with application to Space weather forecasting.
- Determine the global time-average properties of the Solar wind mass flux.
- Monitor cometary H emissions, and assess comet water production rates versus Solar distance.
- Monitor the time variations of the H Lyman Alpha radiation pressure over Solar gravitation (line center flux).

Instrumental Configuration

- A two-mirror periscope system allowing for a coverage of 2π steradian.
- Hydrogen Cell (with large optical thickness to remove geocoronal emission).
- Cs-I photocathode image intensifier (110-220 nm), high voltage supply, fiber optics coupled CCD camera.
- Optical Baffle.
- Commanding and Data Analysis Electronics. Interface and Power Electronics.

Rationale

Investigators on Orbiting Geophysical Observatory 5 found that interplanetary space contained Lyman Alpha radiation at 121.6 nm due to Solar photons that were scattered from H atoms flowing from deep space (upwind). They found a cavity near the sun, elongated in the downwind direction, that was depleted in slow neutral H atoms capable of scattering the Solar Lyman Alpha line (Bertaux and Blamont, 1971; Thomas and Krassa, 1971). Two main processes empty the cavity of slow neutral hydrogen: H – H^+ charge exchange with Solar wind protons, the dominant loss process, and Solar EUV photoionization. Because the Lyman Alpha emission is bright, it provides an excellent way to perform remote sensing of the neutral atoms in the heliosphere. Patterns in the Lyman Alpha radiation are controlled by variations in the Solar wind mass flux and in the Solar Lyman Alpha flux (Bertaux et al., 1997). SWAN has confirmed the previous detection of a «groove» in the neutral hydrogen distribution near the upwind ecliptic plane which was made by reanalyzing the data from Prognoz 5 and 6 (1976 and 1977) satellites (Bertaux et al., 1996). This groove is caused by enhanced charge exchange at low Solar latitudes due to the slow, dense Solar wind near the current sheet. As in the case of Prognoz, it was seen by SWAN at Solar minimum, but was not present in Galileo data taken at Solar maximum (Pryor et al., 1992, Ajello et al., 1994, Pryor et al., 1996). Recent SWAN data show dramatic changes of the interplanetary background with the Solar cycle (Bertaux et al., 1999).

Lyman Alpha studies may prove useful in space weather predictions. Solar activity changes, the presence and evolution of active regions on the Solar disk, impact the spatial distribution and intensity of the Solar Lyman Alpha photon flux. Those changes are reflected by the neutral hydrogen atoms in the interplanetary medium. The big asset of this technique is that half of the sky is lit by Lyman Alpha photons which are issued from the far side of the Sun from the observer. This means that the study of the full Lyman Alpha pattern in the sky gives information on Solar activity on both the near and far sides of the Sun. This has been recently demonstrated by the SWAN team by comparing images of the Solar disk and Solar Lyman Alpha flux distributions obtained from SWAN data. The following address (http://sohowww.nascom.nasa.gov/gallery/ESAPR/199924/) gives the text of the ESA press release related to this topic. This opens the possibility of improved predictions of when a large active region is about to come into view from Earth and how active regions vary during the period when they are not on the near side.

SWAN has made use of its absorption cell to carefully map the heliospheric H velocity field. One of the interesting conclusions of that work was determination of the Solar Lyman Alpha line-center radiation pressure acting on the trajectories of the H atoms. SWAN was able to check the UV calibration of the UARS SOLSTICE Lyman Alpha instrument in this fashion. Accurate knowledge of the Solar Lyman Alpha line-center flux is important in many areas of terrestrial and planetary photochemistry.

An additional highlight of the SWAN experiment has been its measurements of the H Lyman Alpha emissions from a number of comets. This H is produced from the photolysis of water subliming from the comet. Lyman Alpha measurements of comets can be used to monitor the H_2O production rate of comets that approach the sun.

Observation Plan

At the altitude of about 1000 km, which is presently considered for the SPI mission, the expected geocoronal signal, due to neutral H atoms in the Earth atmosphere, will be equal to a few thousand Rayleigh. However, it is possible to remove most of this emission by using a hydrogen cell with a large optical thickness (τ= 500). The cell will absorb Lyman Alpha photons scattered in the geocorona but not those scattered in the interplanetary medium because they have a larger Doppler shift. A new technology is presently developed at Service d'Aéronomie to build hydrogen cells with a long lifetime.

The instrument must be placed on the spacecraft so that its view of the hemisphere centered on the Sun is unobstructed. The instantaneous field of the view of the instrument is 5° x 5°. An observation of a portion of the sky is achieved by exposing in one direction for a given time then moving the periscope mirrors to select a new line of sight and exposing again. The duration of the observation is then defined by the individual exposure time, which depends on the desired signal to noise ratio, and by the area of the sky which is observed.

To follow the Solar Lyman Alpha flux distribution it is necessary to make a full hemispheric observation every other day. The study of the Solar wind mass flux evolution requires at least a weekly full hemispheric photometric observation. The study of the radiation pressure variations requires a full hemispheric observation with the hydrogen cell. Comet observations follow the same scanning principle as the full hemispheric observations. The scanning steps of the periscope motors and the integration can be varied to ensure the best signal to noise ratio.

Table 3.9 – 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	Very high resolution disk and limb imaging and spectroscopy	UV and FUV spectroheliograms between CIII 117.5 nm and the 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 Coronograph °	Imaging and diagnostics of the corona	Coated mirror coronograph CCD detector	25	Ø20 x 80 (Telescope Ø12)	15	100
Oscillations, Visible-light Imager and Magnetograph °	High-res. 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. Ly α 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 Visible and IR light	25	20 x 30 x 40	25	1
SPI NG–SWAN	H Lyman α Solar activity	Sky Ly α 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) provided by ESA. 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.

4. Spacecraft design concepts

The instruments require a three-axis stabilized platform. The ones without internal pointing have to point to the Sun with a high pointing stability (1 arcsec/15 seconds) during science data acquisition (other instruments achieve their high-pointing stability by independent internal mechanisms, such as active piezoelectric mirrors but gain from starting with good pointing since their required dynamic range is reduced accordingly). The absolute pointing accuracy requirement satisfying the needs of all instruments is also better than 15 arcsec. This may seems a though constraint but it is not since the error signal come for the instruments: for the satellite, from the pointing system on the Solar limb of SOLARNET guiding telescopes and for the Hexapod small platform (which permanently centers the pointing of the 4 instruments on the Sun center, it is also made in absolute by the error signal from the pointing telescope of NG-PICARD. Since the major source of error comes from the star tracker usually, the accuracy and stability will be much better, only limited by electronic noise and the inertia wheels noise, for the spacecraft, and actuators noise and precision for the Hexapod platform. The commanding of the platforms is not performed by the spacecraft but by the absolute pointing telescope system of SOLARNET and NG-PICARD (guiding telescopes). The instruments have to be protected from Sun illumination (except for the telescope apertures) and the instrument thermal system has to ensure low temperatures, e.g. an operating temperature at -40 degrees Celsius for the CCD detectors. Due to the high data rate during scientific operation, the spacecraft must provide sufficient storage memory to ensure up to 6 orbits with the high data rate experiments (108 Gbits, cf. Table 5.1). The communication system has to be sized to ensure the downlinking of these data to Earth.

Mechanisms, Solar sensors and motors are part of the experiments to the exception of the Hexapod Pointing Platform (HPT) to be provided by ESA (experience of Sage III on the Space Station for which the small 60 cm pointing platform is made by Alenia under ESA responsibility — but with a much larger excursion range than the few degrees required on SPI: ± 40°).

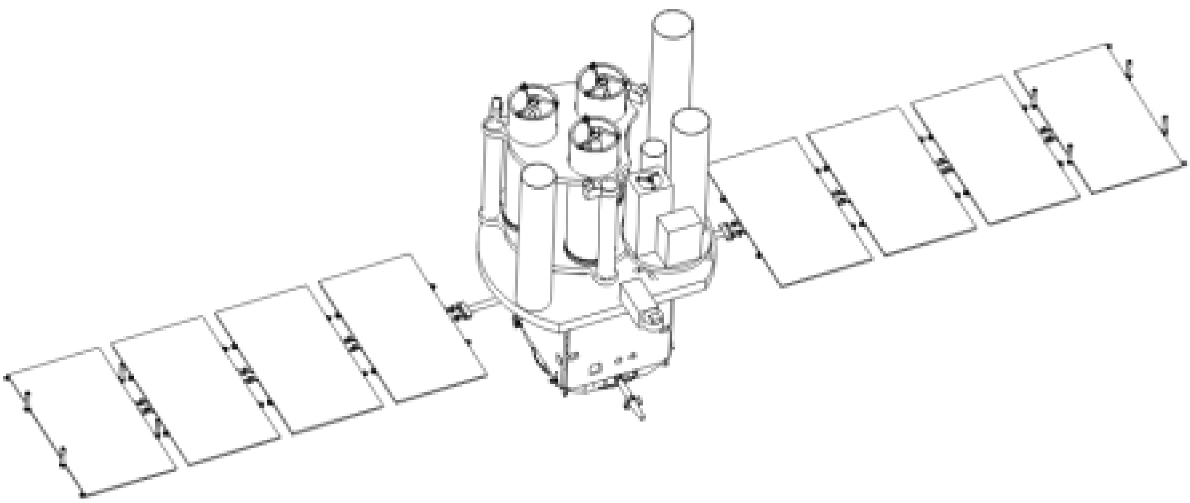


Fig. 4.1 – The SPI Mission accommodated on the ALCATEL PROTEUS platform. The payload size if Ø1.7m x 1.8 m. Note the small platform of Ø60 cm, beside the three-telescopes SOLARNET interferometer, mounted on 6 linear actuators (the Hexapod) and accommodating the Helioseismology package and the coronograph (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. (This .eps drawing will print nicely on a postscript printer).

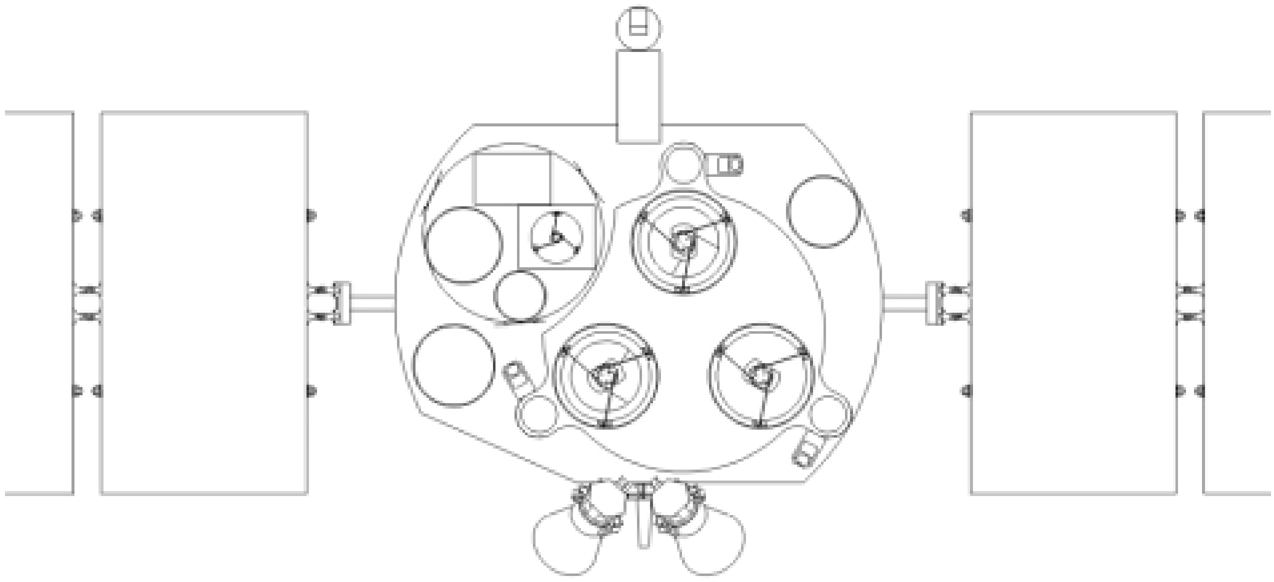


Fig. 4.2 – Preliminary scientific instrument accommodation on the PROTEUS platform of ALCATEL, top view. (This .eps drawing will print nicely on a postscript printer).

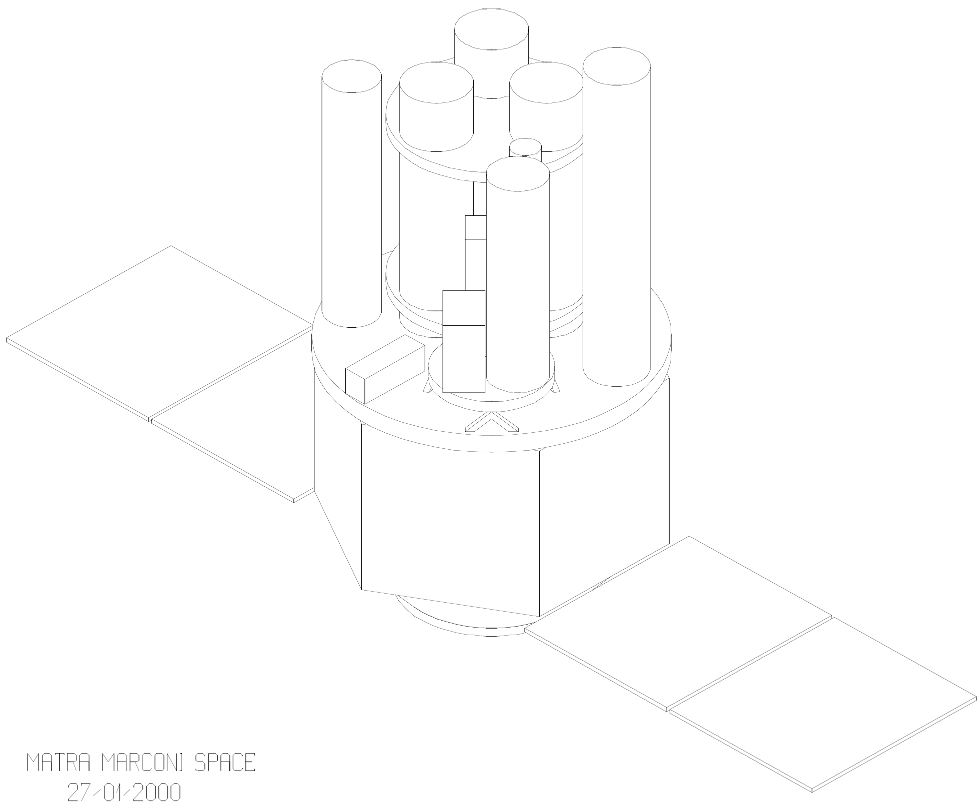


Fig. 4.3 - Preliminary scientific instrument accommodation of the SPI payload on the LEOSTAR Platform of MATRA MARCONI SPACE. Note that the hexagonal platform is the size of the payload, Ø170 cm.

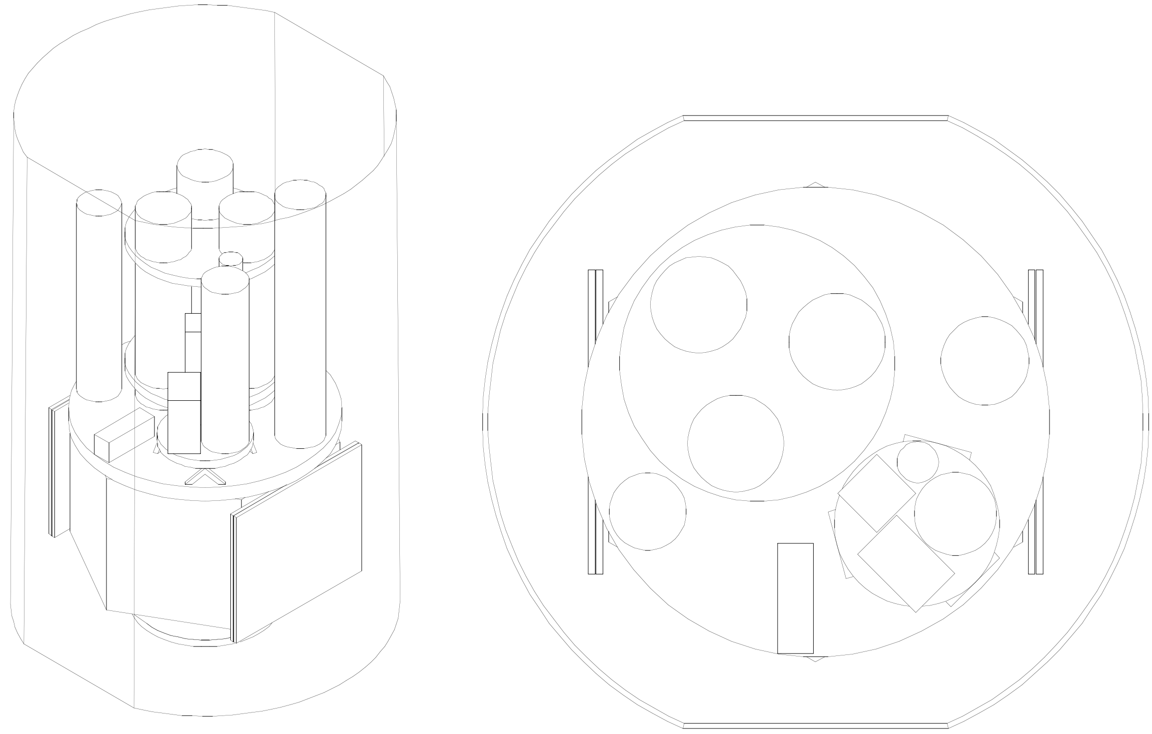


Fig. 4.4 – Possible accommodation of SPI in the nominal volume of the Rockot launcher.

5. Mission requirements

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

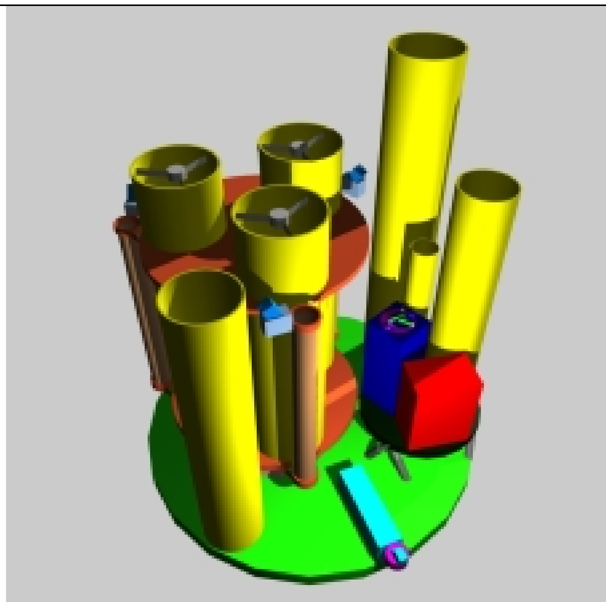
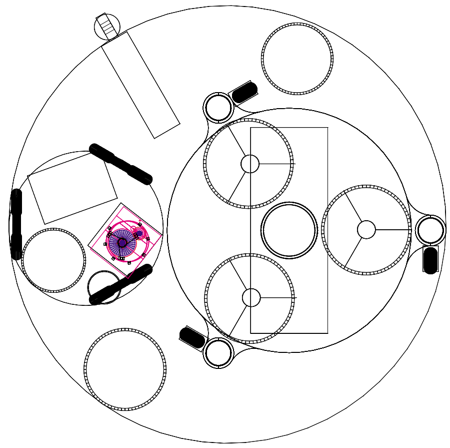
- the reuse of a Leostar platform: due to their innovative concepts and high modularity, the avionics can be successfully reused for the SPI mission. In addition the current Leostar structure (in development) with its hexagonal shape fits perfectly with the size and shape of the payload;
- an adapted geometry of the Solar array, with simple fixed Solar panels pointed to the Sun.

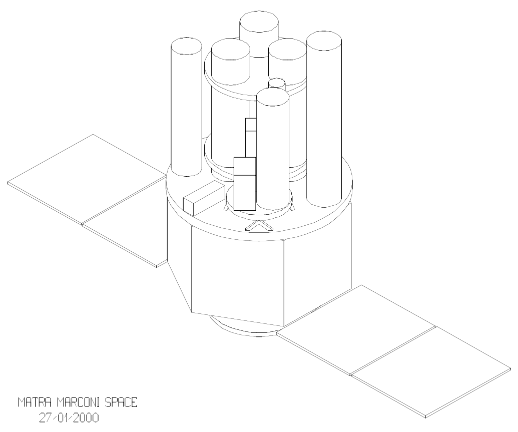
The satellite mass and geometry are compatible with the Rockot launcher capabilities for the selected orbit (1000 km altitude, SSO 6h–18h).

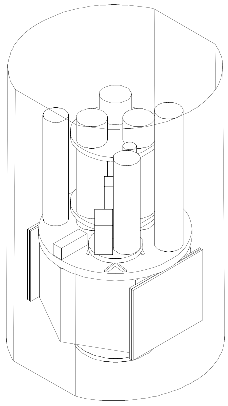
Note: the satellite configuration analysis is of course preliminary. Limited analysis of the payload assembly has been performed. Probably some additional structures (struts, supports) will be added in order to maintain the instruments at launch. However, because there are large margins for the satellite 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 increase since, along the ALCATEL design, the base plate and three telescopes structure of the interferometer (under responsibility of ESA) can be easily optimized.

Table 5.1 – Mission analysis summary

	Baseline solution	Comments
MISSION	Solar Physics and Interferometry (complementary to the Solar Probe insitu plasma investigations) High resolution imaging and spectroscopy, helioseismology	Main instrument = one interferometer (to be paid and developed by ESA in the 154 MEuros of the mission) Several auxiliary instruments (imagers, spectrometer, magnetograph, radiometers)
	Orbit SSO 6h-18h (without eclipse if possible) **1000 km selected** (eclipse during a period of about 60 days, centered on solstice, with a maximum duration of 800 s)	Orbit SSO 6h-18h without eclipse ⇒ altitude > 1400km Leostar and PROTEUS avionics reuse ⇒ altitude < 1500km (due to magnetic control) But Rad-hard design necessary if 1400 km altitude selected (about 30 krad), and marginal capacity of Rockot So, 1000 km selected, because compatible with current Leostar and PROTEUS design (10 to 15 krad, magnetic control) and Rockot mass capacity
	Lifetime 2 years min, target 6 years	Propellant < 20 kg estimated for 6 years
	Launch in 2008-2009	
	Imaging duration: continuous	
	Pointing requirement: a few milliarcsec for some instruments	Constraining requirement: the platform classical pointing performance (based on gyros and stellar sensors) is about 0.05°. After partial calibration of biases (created for example by thermoelastic distorsions), this can be reduced to about 0.02° which is mainly due to the star sensor noise. To improve the pointing performance to the required level, it is necessary to use measurements coming from experiments (using Solar secondary telescopes as guiders). **So the experiments pointing measurements must be included in the AOCS control loop**. This modification, though not particular complex, requires an adaptation of standard Leostar AOCS software but is already developed for PROTEUS (COROT satellite)
	Stability during imaging: Mini: 1 arcsec / a few seconds Target:1 arcsec / a few minutes (SOHO: 1 arcsec/15minutes)	Constraining requirement. **A S/C inertial attitude is then mandatory** (the geocentric attitude involves a rotation of 1 mrad/s, 200 times greater than the required stability). This inertial attitude limits the data downlink capacity due to limited ground station visibility duration. **AOCS required**: Leostar AOCS with high performance gyros Compact S/C with rigid Solar array preferred (so, a Solar array with long wings like PROTEUS is less adequate): Leostar XO structure + rigid Solar array

PAYLOAD	**Payload size** ∅ 1.7 m x H 1.8 m (drawings refer to payload implementation provided by the scientific team)	 
	Payload mass: < 430 kg	• Instruments mass: 330 kg • Electronics: 40 kg • Support structures (circular plate ∅ 1.7 m, hexapod, struts …): 60 kg (estimated) • Platform mass: 400 kg (including 20 kg hydrazine) • Satellite mass: 830 kg (basic mass without margins)
	Payload power: < 350 W	Continuous imaging, except in eclipses
	Payload data rate: 2.5 to 3 Mbps (after compression)	The possibility of compression have not yet been thoroughly investigated in particular for the SOLARNET/UVIS imaging spectrometer
DATA STORAGE & DOWNLINK	**Data storage** 160 Gbits Beginning of Life 140 Gbits End of Life (Leostar Type)	• Maximum delay between two visibilities of Kiruna about 10 hours (6 consecutive orbits), due to the inertial attitude of the spacecraft pointed towards the Sun: the transmission antenna is not perfectly Earth pointed. This tilt angle follows the Earth seasonal inclination (+/-23.5°) • Storage required for continuous imaging at 3 Mbps during this delay: 36000 s x 3 Mbps = 108 Gbits • Compatible with the selected Leostar memory

	Data downlink X band, 2x120 Mbps (Leostar type)	Duration required to downlink 108 Gbits: 108 Gbits/ 240 Mbps = 450 s which is marginally feasible in one pass over the ground stations.(available visibility duration about 8 mn = 480 s). But a second consecutive pass over the ground station can be used if necessary without any difficulty (no time delivery constraint) Note: if required, the visibilities durations and then the transmission capabilities can be largely enhanced by the use of a pointing mechanism for the X band antenna (as proposed for some observation satellites)
POWER SUBSYSTEM	Solar array: about 800 W Fixed Solar array pointed to the Sun (subsystem derived from Leostar)	• Platform power: 250 W (including 50 W provision for thermal control to maintain high stability of the structures) • Total satellite power about 600 W • Solar array: about 4 m^2 of GaAs cells, in 2 wings of 2 panels
	Battery: NiCd 40 Ah	
COMMAND/CONTROL	On Board Central computer 2 S band omnidirectional antennas for TM/TC (2 to 4 kbps) Autonomous Normal and Safe modes	Omnidirectional antennas required for control at any time (for safety reasons) of the S/C whatever its attitude
AOCS	PROTEUS or Leostar type (with adaptation to take into account high accuracy pointing measurements done by some experiments) 3 axis stabilization	Autonomous magnetic control for Acquisition and Safe Hold mode (no gyros, no thrusters), with high autonomy: the satellite can stay in safe mode (with the Solar array pointed to the sun) several weeks Normal mode based on Stellar sensor, gyroscopes and GPS for “coarse” pointing to the sun, and then use in the AOCS control loop of the high accuracy pointing measurements performed by some experiments. 4 reaction wheels 0.2 Nm 3 magnetotorquers + magnetometer Star sensor Propulsion required = 20 kg hydrazine
Performances	Stability 1 arcsec/ a few seconds (goal: 1 arcsec/15 seconds)	Achieved with high performance star sensor and gyroscopes, and with particular attention at the thermoelastic stability of the structures)
Mechanical Architecture	Platform: aluminum structure (honeycomb panels) Hexagonal shape (Leostar type) or squared shape (PROTEUS type)	

		 **Rockot fairing**
MASS	Launch mass: 880 kg (without margin)	Satellite mass: 830 kg (basic mass without margins) Dispenser mass: 50 kg
LAUNCHER	Rockot	Compatible with Rockot capability @ 1000 km (about 980 kg), but with relatively low margins (100 kg = about 10%)
GROUND STATIONS	S band: one main station (used for spacecraft control and command)	One ground station of the ESA (or CNES) 2 GHz network, probably Kiruna (Svalbard would be a valuable alternative)
	X band: one main station (used for the scientific data download)	Transmission duration degraded due to the inertial attitude of the S/C (no geocentric attitude) However, due to the onboard storage capacity, one ground station like Kiruna is sufficient.

6. Science Operations and Archiving

The science operations are expected to be performed by ESA. A European Mission Center (operation facility and full data archive) is foreseen at the level of a large European Institute (IPSL, IAS, Lindau, IRMB, RAL, *etc.*). 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 the Kiruna X-band antenna).

Furthermore, the SPI Mission must give European Solar science clear visibility, a political reason that demands for the operations center to be located in an ESA member state. We therefore highly recommend that use is made of the existing facilities and technologies in Europe. Preference is given to a full mission data center rather than separate PI data centers.

The mission exploitation must 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. Other agencies, if contributing to the mission, could also be involved. 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.

7. Technological Development Requirements

No critical technological developments are required, neither for the platform (reusable Leostar or PROTEUS design) nor the orbit or launcher which, thanks to the reasonable size and mass of the interferometer and other instruments are of the mini-satellite class. The major technical advances are contained in the realization by ESA of the three telescopes cophased and pointed system — an endeavor made possible by the success of the ESA TRP OAST study —, and in the new instruments development, what is indeed expected since breakthrough instrumentation is a prerequisite to outstanding scientific outcome.

8. Management and Funding

The instruments, including the UV Imaging Spectrometer (behind the interferometer), will be funded, supplied and run by PIs and CoIs institutes from the ESA member states. US instruments could be considered if it is the will of ESA. For the spacecraft, ESA funding will include the interferometer, the payload equipment bay, the Hexapod pointing platform and the satellite platform itself. Since the interferometer allows to limit the size and mass of the equivalent meter size telescope to the point that a small platform (mini-satellite type) and a small launcher can be used (and allowing oscillations / non-eclipsing orbit), in practice this means:

	Cost (Meuro)	Remark
Launch in SSO 6:00-18:00 1000 km	14	Rockot including launch services
2 years operations	20	ESA ESOC operations
ESA management, technical cost and overheads	20	
Platform (Leostar or PROTEUS type)	42	including satellite development, system engineering and AIT
Payload Equipment Bay	8	Adaptation of the payload on the reusable PROTEUS or Leostar mini-satellite platforms
Small Hexapod Pointer	5	ESA responsibility (facility)
Interferometer	40	ESA responsibility (facility)
Science operations and archiving	4	
Public outreach	1	
TOTAL	**154**	

As you can appreciate this fits, with a large margin, in the framework of ESA Flexi Missions F2/F3. This is achieved with truly outstanding science (no compromise on what is high resolution), and the implication (return on investment) of ESTEC and industry in a major interferometry realization. This latter is a technology flag and develops competencies for future interferometry larger missions. Note that these costs are not arbitrary: both MATRA and ALCATEL which made the mission analysis and provided a consolidated cost (approved by the Director of Earth Observations for MATRA). Both industrials have a long experience of instrumentation and satellites (the Leostar platform is currently under realization for the Rocsat II Taiwan satellite, and several PROTEUS platforms are under fabrication for CNES). As well MATRA evaluated the cost of the interferometer (MATRA was in charge of ESA OAST interferometry study) and guarantee the cap cost of 40 MEuro. We have made a thorough cost evaluation truly based on INDUSTRIAL EVALUATIONS. We therefore estimate, jointly with the industrials, that the costs announced are realistic costs, carefully prepared.

The payload provision and funding would rest with the PI and Co-I institutes being supported by their national funding agencies. There is no doubt that sufficient scientific interest, special capabilities and hardware experience has been built up in Europe. From past missions many successful collaborative arrangements exist, which could be strengthened and new ones established.

9. Communication and Outreach

Imaging of our star, the Sun, in various wavelengths and the Space weather activities have shown a great media and public interest with YOHKOH, SOHO, TRACE, Solar eclipses... Thanks to the high bandwidth telemetry, the SPI mission, with the breakthrough of imaging interferometry, allows for unprecedented movies of the Sun variability and activity. As well the MOF will build on the success of the MDI/SOHO which was largely advertised. It will considerably expand on that interest, providing unique material for outreach purposes.

10. International Partners

The SPI program could benefit from a partnership between ESA and NASA, although the mission and payload are possible without support or involvement from NASA. US participations in instruments are envisaged favorably up to the point that a collaborative framework could be agreed between ESA and NASA. For instance much alike SOHO where NASA supported the launch of this spacecraft. Another possible collaboration is on the UVIS Double Monochromator which half of it (UV part) could be built in India at the Bangalore Institute of Astrophysics. The overall responsibility and FUV part would be in Europe.

11. Collaborative arrangements

In the present scenario, the SPI mission, our F-mission opportunity, will be managed and built by ESA alone and will carry, as the label of ESA and Europe competencies, a three telescopes cophased interferometer of the meter class (SOLARNET) feeding a high resolution imaging spectrometer: the double subtractive monochromator. 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 Coronograph, Solar Diameter Telescope — limb oscillations, radiometers, Sun photometers and full sky Lyman Alpha imager).

The important technologies needed by the proposed interferometer concept include optical delay lines and a cophasing system together with its control software. These technologies have been breadboarded by the Service d'Aéronomie and by IRCOM in the framework of an ESA study called "Optical Aperture Synthesis Technologies". Both experiments have been successful and all components needed by an interferometer have been validated through an end to end test from object to image reconstruction (Midi-Pyrénées Observatory). These achievements fully secure the development of the SOLARNET interferometer as both detailed and system design issues are perfectly mastered.

Annex A – Mission and Spacecraft 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) <u>Solar instrumentation - Imagers and spectrometers</u>: – SOLARNET Ø1 m interferometer with its UV spectro-imager system (UVIS) – EUV Imager and Spectrometer – X-Ray/EUV Imager <u>Oscillations and Solar Variability Package (on Sage III type Hexapod)</u>: – 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 Coronograph 1.1–2.6 Solar radius <u>Space weather</u>: – 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 ·**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)

Annex B – References

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