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DESIGN RATIONALE OF THE SOLAR ULTRAVIOLET NETWORK (SUN)

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ABSTRACT

This contribution briefly explains the aims and current design options of the SUN interferometer: a 4 telescopes linear array of 2-meter baseline in a so-called "compact" configuration. Special attention is given to the focal plane instrumentation: a subtractive double monochromator. This intends to concretely indicate how an interferometer can also be used as a scientific instrument, i.e. providing properly selected spectral resolution in addition to spatial resolution.

1 — INTRODUCTION

SUN (*Solar Ultraviolet Network*) is a short wavelengths — ultraviolet and visible — space interferometer dedicated to high resolution solar physics, altogether with astrophysics objectives during night cycles (binary stars, planets, comets, asteroids). It has been proposed in November 1989 in answer to the Call for Proposals of ESA for the next medium size mission, for flight on the Space Station as part of the SIMURIS mission (a *Solar Interferometric Mission for Ultrahigh Resolution Imaging and Spectroscopy)*. The SIMURIS mission was accepted in February 1990 for an ESA Assessment Study in the context of the Space Station, and which was carried from June 1990 to May 1991 (Coradini et al., 1991). A second study phase should start in 1992.

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The goal of SUN/SIMURIS is to appreciably deepen our understanding of the highly complex processes of electrodynamics, plasma physics, magnetohydrodynamics and radiation hydrodynamics as they operate in many astrophysical objects. They can be observed in detail for the nearest ones (the Sun, solar system objects and nearby galactic objects); studying astrophysical processes in this local environment provides physical insights needed to interpret phenomena occurring throughout the universe. Thus, SUN/SIMURIS links physics and astronomy. It delivers process-scale resolution with appropriate diagnostics while it addresses astrophysical parameter regimes far outside the ranges available in terrestrial laboratories.

The main solar objectives are:

- *plasma processes:* current sheets, reconnection, double layers, Alfvenic wave heating, plasmoid formation, electrodynamic coupling;
- *magnetohydrodynamic configurations:* coronal loops, prominences, chromospheric spicules, sunspots, photospheric flux tubes;
- *radiation hydrodynamics:* granulation, acoustic heating, shock formation and dissipation;
- *fine scale activity:* evolution of magnetic patterns, flux emergence and disappearance;
- *eruptive phenomena and instabilities:* flares, micro-flares, "disparition brusque" of prominences, surges, coronal bullets, ephemeral active regions.

In addition SUN will fruitfully address:

- *solar system science*: solid surfaces of planets, moons and small bodies, atmospheres, magnetospheres and their interaction with solar radiation and wind;
- *galactic physics*: activity, surface structures and flares of nearby stars, binary separations, galactic distance scale.

2 — SUN DESIGN RATIONALE

Interferometric imaging by aperture synthesis asks for numerous apertures or for rotation of the array to optimize the spatial frequencies — u,v plane — coverage. SUN is designed to *image* complex <u>and</u> extended objects. As such images with high dynamic are required and rotation of the array to fill the u,v plane is essential. When recognized the need for rotation, the amplitude of the rotation — whether it be 30° or 180° — becomes a second order concern, and favors the least complex configuration choice: a linear array.

The maximum baseline length is achieved with a minimum of elements when a non-redundant configuration (no duplicate spatial frequencies) is adopted. However, one further constraint when considering true imaging is to use a "compact" configuration. By "compact" is meant that the spatial frequency coverage of the array is comparable to a single dish telescope in one fundamental aspect: complete coverage of spatial frequencies, i.e. there are no zeroes in the resulting modulation transfer function (MTF) of the array.

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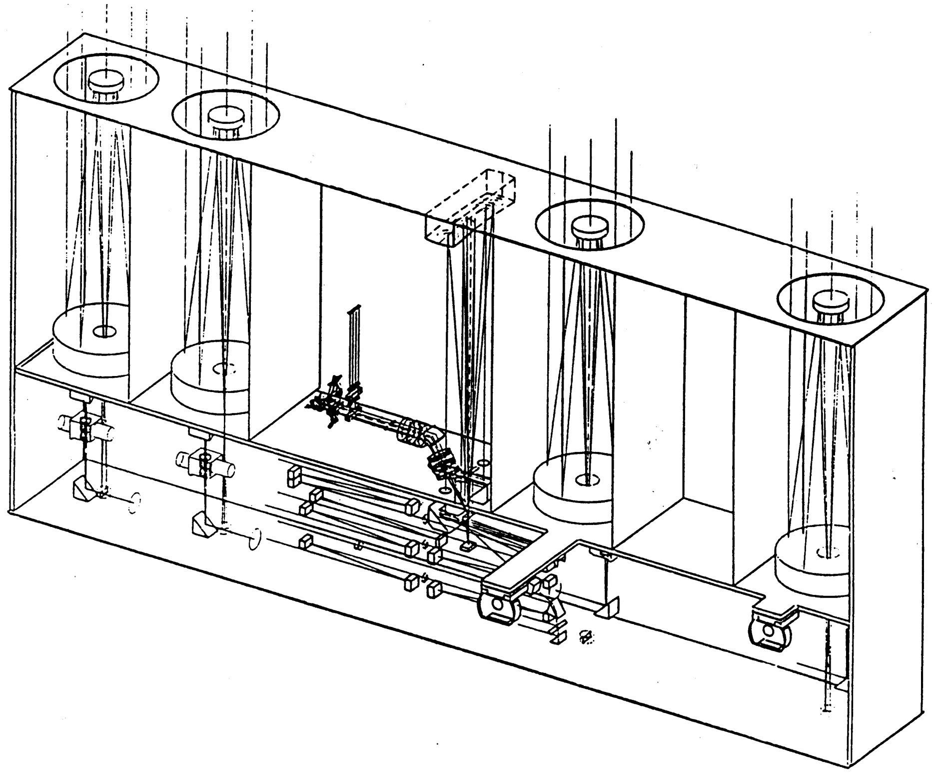

Fig. 1 — General optical layout of the SUN interferometer. Note the use of the space in between the central telescopes of the non-redundant configuration for the recombination mirror (top) which focalizes the beams on the entrance slit of the triple stage subtractive double monochromator (center and bottom). In the middle (on the left) lies the cophasing system which uses a Ø5' solar disk field reflected from the entrance slit of the double monochromator.

This exceptional coverage would however be of little use if phase and pointing errors were left uncontrolled. In the SUN design one further conceptual choice for the interferometric approach is therefore to "cophase" the array. By "cophase" we mean real-time control of the phase differences between the telescopes, i.e. constant monitoring of the equality of the optical path lengths travelled by the different beams. This, again, has a sound justification. Only cophased arrays can integrate light, i.e. benefit from long exposure duration. This directly results in a gain of $\sqrt{\text{time}}$ in signal to noise, and in an increase in the accessible complexity and dynamic range with which images can be reconstructed, since the phase is permanently better than $\lambda/8$ in the UV. Image reconstruction simulations (Damé and Cornwell, these proceedings) demonstrate that such cophased arrays can properly observe complex and extended objects, and reconstruct images with dynamical range $\geq$ 1000. This capability requires specific cophasing control — reference interferometers — which use a synchronous detection technique to track the "white light fringe", i.e. a broad spectral band interferogram. This technique was demonstrated to work in laboratory (recent results are presented in Damé, these proceedings, and Damé, 1991).

One further particularity of SUN is that it uses a reference object for both the cophasing and the pointing of the telescopes. This allows excellent low-flux performance necessary for faint UV lines, and also for

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Stellar and Galactic programs since the light from the object can be integrated for minutes while the array is cophased independently on the reference source (a small solar field in the visible, a planetary disk, a nearby star, *etc.*). This is implemented in the design by the use of a specific device: a diasporameter, i.e. a pair of wedges (not necessarily achromatic) which allows to introduce an angle in between the line-of-sight and the desired reference object. Further, the diasporameter as a whole can be rotated to perform aperture synthesis by rotation. The design of the SUN cophasing system has been presented in Damé et al. (1991a) and results of laboratory experiments implementing the proposed cophasing technique (the synchronous detection on the "white light fringe") are reported in Damé (these proceedings), Damé, 1991, Damé et al. (1991b) and Damé et al. (1990).

Finally, image reconstruction algorithms are up to now extension of the radio-astronomy software and are using two-dimensional monochromatic data. In addition, scientific requirements — either solar, solar system, or stellar — sought after a spectral resolution of 1 to 0.1 Å. This has oriented the SUN design to develop a specific focal plane instrumentation approach, described hereafter.

3 — FOCAL PLANE INSTRUMENTATION: THE SUBTRACTIVE DOUBLE MONOCHROMATOR

The image reconstruction simulations performed (Damé and Cornwell, these proceedings) work for filtergram type data, i.e. for non-dispersed narrow bands data. Adding spectral dispersion would produce extra complexity: overlapping fringes pattern — and their noise — over the 2D field at the different free wavelength bands allowed in the output. Interferometric imaging of complex and extended objects therefore requires the radio approach of limiting observations to narrow-band filtergrams. [Note that in ground optical interferometry the problem has not arisen yet since a slit usually selects a very narrow field, corresponding to the natural aperture angle of a single speckle size: turbulence driven choice. In that case, it is a 1D field which gets to the spectrograph which subsequently and classically disperses it.] In the optical domain, various techniques are available: interference filters, Fabry Perot, and birefringent filters. However these are not suited for UV applications since bandwidths in demand are as narrow as 0.1 Å for scientific reasons (e.g. to isolate spectral lines against the background or for rough velocity measurements), and only a dispersive approach with gratings can be envisaged.

How to obtain such narrow bandwidths with grating spectrometers maintaining full two-dimensional imaging (no dispersion) and also tunability over a wide wavelength range? The answer is the use of a double monochromator (DM) in which the dispersions of the two gratings are subtractive. This concept is illustrated in Fig. 2. The intermediate slit (S_2) allows selection of the width of the bandpass independently from the aperture. A further advantage of such a double monochromator is that it is suited for low-flux observing of UV lines because the intermediate slit eliminates stray-light from the first spectrograph stage. Also, from aberrations point of view, the magnification introduced in the DM allows to keep the one of the telescopes small which is essential for the interferometric recombination (cf. Damé et al., 1990b).

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Further, tolerances on the position, orientation and surface precision of each optics in the optical train (telescope, recombination and UV-DM) have been calculated (Snijders and Braam, 1991), and the quality is maintained over the entire field of view, 6 x 6 arcsec^2, i.e. the diffraction spot is smaller than the diffraction spot of the telescope array. Most critical is the positioning of the active secondary and entrance mirror of the SDM .

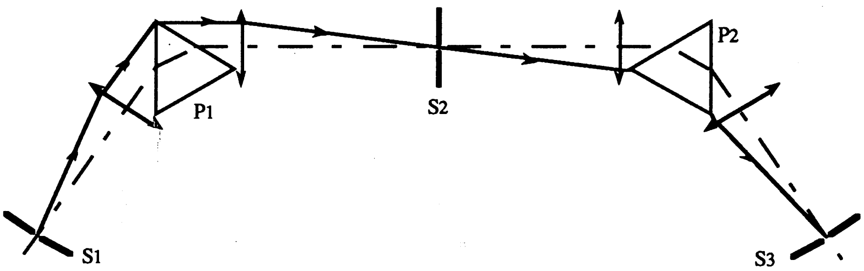

Fig. 2 — Illustration of the double monochromator principle with lenses and prisms rather than with the mirrors and gratings actually used. The second prism is compensating the dispersion introduced by the first one. This is a so-called subtractive mounting, providing dispersion-free filtergrams of the field transmitted by the entrance slit S_1. The spectral bandwidth is selected by the intermediate slit S_2.

UV to near IR multi-wavelengths observations

The need to cover the full spectrum from the UV to the near IR with a single instrument, with the additional requirement to achieve simultaneous observations in UV, visible and near IR passbands, for multi-temperature multi-heights diagnostics, has further pushed us to implement a Wadsworth mounting of the first dispersive element (cf. Fig. 3). This optical set up, often used is small spectrometers, has the advantage that the output beam has a fixed direction (the prism always working at minimum deviation), i.e. the exit slit is fixed. In our case it allows the zero order reflected by the first grating of the UV double monochromator (cf. Fig. 4, elements 34 and 44) to enter a second double monochromator for the visible. The input beam is fixed while the UV double monochromator scans the UV. By this approach, several channels are observable simultaneously with a completely free choice of the lines in each of them: they are fully independent.

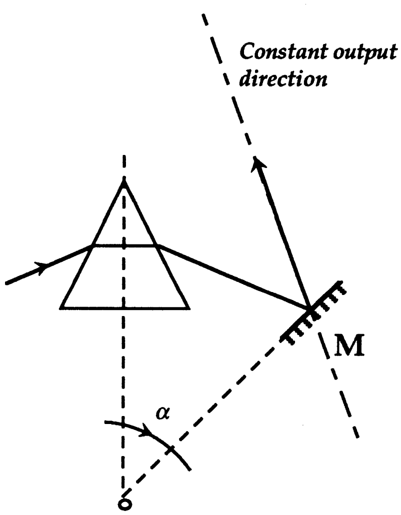

Fig. 3 — Illustration (with a prism) of the Wadsworth mounting of a dispersive element in order to obtain the same output direction independently from the spectral bandwidth (α angle) observed.

Even though it might appear of some complexity, this is the only way by which interferometric imaging of complex and extended objects can presently be achieved

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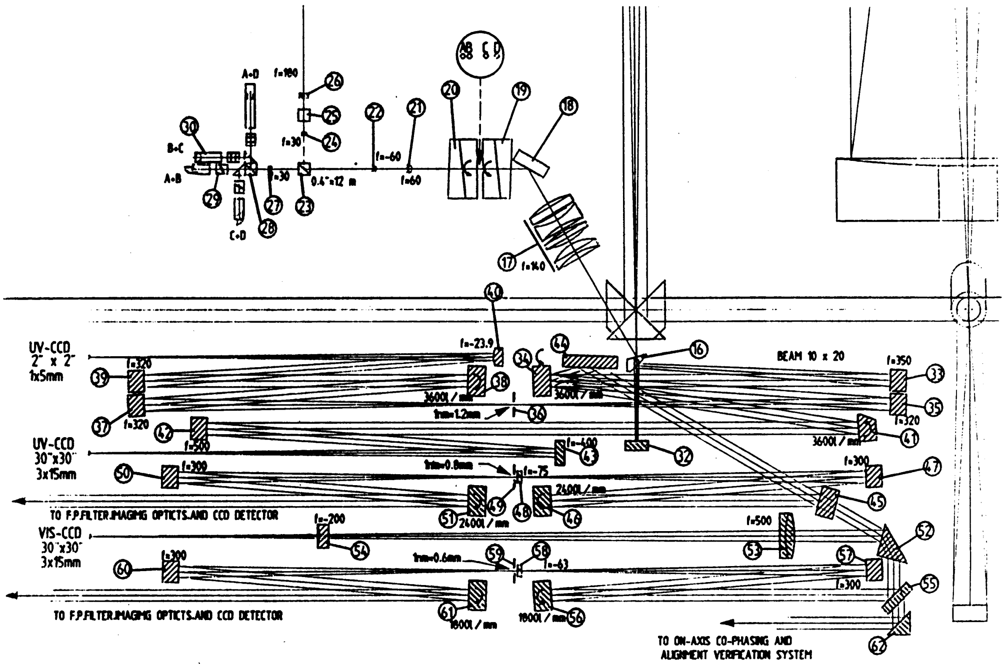

Fig. 4 — The subtractive double monochromator of SUN. It has three levels. The entrance slit is in (16) and (32), (16) and (33) are relay optics. From the UV channel (gratings 34 and 38), the near UV-visible channel (gratings 46 and 51) is fed by a Wadsworth mounted mirror (44) which is linked to the grating (34). The third double monochromator channel (gratings 56 and 61) is fed by a dichroic (45).

with spectral resolution of 0.1 to 1 Å and in different lines simultaneously. Other means do not allow the adequate spectral resolution required for the solar studies.

Fig. 4 shows the design of the subtractive double monochromator (SDM) of SUN. It has been studied and optimized since 1989 in collaboration with TPD (Visser et al., 1989, 1991, Snijders and Braam, 1991). The entrance slit (16), is reflecting the light to the cophasing system, while accepting a 30 x 30" field inside the monochromator. The gratings (34) and (38) respectively introduce and suppress the dispersion, in the subtractive approach which we adopted. The flat mirror (44) is linked to the grating (34) — Wadsworth mounting — for relay of the zero order beam to the second stage (near UV/visible) of the SDM. Note that an extra grating (47) forwards part of the first order to image a large field output of 30" x 30" on another intensified CCD detector.

In order to carry out the scientific program SDM/SUN has 3 major channels (UV, near UV/vis, and vis/near IR) with large band, tunable, double monochromators. And to achieve this large spectral coverage we introduce a pupil anamorphosis (we don't rearrange the pupil but we stretch it: cf. Fig. 5) on the low resolution axis. This results in a reduction of the beams opening and, then, of the weight of the gratings. As a consequence, the rotation angle can be increased because mechanisms with the required precision are available. This is not a free extra complexity but a science requirements consequence. It also results in a reduced number of useful pixels since the image is reduced by the anamorphosis factor (the

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high resolution is only required in the baseline direction). A 5:1 anamorphosis factor was used for the design. It could be as high as 10 (the ratio of the telescope diameter to the baseline). The flux concentration achieved is also an advantage for the photometry.

The second stage of the SDM works like the first with the two gratings (46) and (51). There is no Wadsworth mounting this time but a dichroic (45) which separate the near UV/visible from the visible/near infrared stage of the SDM — gratings (56) and (61). Note that in between the two stages, a specific channel with large field in between 480 — 500 nm is dedicated to "white light" for granulation survey. The output beam of the near UV/visible beam (280 — 480 nm) is shown collimated for possible use with a subsequent Fabry-Perot, but it could as well be used directly focalized on a CID detector. The spectral resolution can also be tuned from 0.1 to 100 Å.

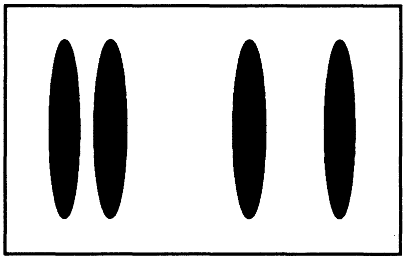

Fig. 5 — Anamorphic pupil configuration with a 5 to 1 size reduction in one dimension (low resolution axis)

The third two-gratings stage (500 — 800 nm) of the SDM is indicated with a collimated beam in the output, directed suitable and pre-filtered to enter a Fabry Perot stage. Since the pre-filtering achievable with the SDM can easily be at the level of 2-3 Å, and since Fabry Perot with a high finesse (> 50) are available (e.g. by Queensgate), bandpasses as narrow as 50 mÅ can be achieved for direct magnetic field measurements. One extra dichroic element (55) allows to select part of the light for a direct on-axis verification system of the cophasing and coalignment which is intended for verification on bright sources when available. It could use synchronous detection or follow dispersed fringes on 4 CDDs. This last system, not shown, has been designed too. Also, since this last wavelength range (800 — 1100 nm) is presenting a large interest for planetary studies, it is planned to be equipped with a beam splitter and a detector for observations (a CID). In the following we complete the description of the focal plane instrumentation of SUN by presenting the characteristics of the detectors to be used in the different science channels.

4 — DETECTORS

The detectors for SUN are particularly challenging due to the requirements for: high total count rate, high pixel count rate, and far UV sensitivity. For active regions, the count rates are exceptionally high, and at the very high spatial resolutions of the instrumentation, even for 'quiet sun' observations, individual pixels could also experience such rates. On the other hand, for coronal and planetary observation, the same detectors will be required to work efficiently at very low count rates and with very low system noise.

One practical solution to the problem is to use an intensified CCD (ICCD). The CCD would have a multi-port readout (giving a full-frame readout time of 1 msec) and would be coupled to a 25 mm diameter

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microchannel plate (MCP) intensifier. By suitable design of the tube, and by incorporating specialized processing circuitry, it would be possible to run such a system in dual-mode, providing the capabilities to either accumulate counts on the CCD (analogue mode), or to run in photon-counting mode. While the analogue mode would cope with the high count rates, it would have a spatial resolution in the 40-50 micron range, in contrast, the photon counting mode would provide essentially a zero noise detector with a resolution limited only by the pore spacing of the microchannel plate.

Table 1 — Spectral and spatial characteristics of the SUN focal instrumentation

Wavelength range (nm)	Field-of-view (arcsec)	Detectors		Spatial resolution (arcsec)	Spectral resolution (Å)	Notes
		pixels	Type			
UV: 117 — 200	6 x 6	1024 x 1024	ICCD (CsI)	0.012	0.1	a
UV: 130 — 280	30 x 30	1024 x 1024	ICCD (CsI)	0.06	~ 200	b,c
UV: 280 — 480	7 x 7	512 x 512	CID	0.028	0.1	a
Visible: 480 — 500	25 x 25	1024 x 1024	CID	0.05	~ 200	d
Visible: 500 — 800	13 x 13	512 x 512	CID	0.05	50 milliÅ	e
Near IR: 800 — 1100	20 x 20	512 x 512	CID	0.08	~ 10	f

Notes:
a) the spectral resolution is adjustable from 0.1 Å to 100 Å;
b) in this channel, which favors access to a large FOV, the diffraction limited resolution (0.013 arcsec) is not achieved;
c) the spectral bandwidth is about 200 Å but a filter wheel could be implemented to reduce it as required;
d) the full bandwidth isolated by the dichroic is used (granulation channel: "white light");
e) an added Fabry Perot (finesse 50) in the collimated output beam of the SDM allows to achieve this very high spectral resolution; the pre-filtering is achieved by the SDM;
f) the spectral selection can be achieved directly by interference filters.

Such a device, by suitable selection of photocathode (e.g. CsI), could provide a range of detectors to match the SUN requirements. However, there must be some concerns about the photometric stability (and lifetime) of the microchannel plates when run continuously at very high count rates. Consequently, Table 1 identifies CID devices for the longer wavelength channels. These will have the necessary UV sensitivity down to 200 nm (particularly interesting for the 280-480 nm channel), and will not be prone to the gain fatigue effects anticipated for the MCP intensifiers. The down side is that cooling will be required to ensure sufficiently low noise levels. In principle CCD could be used for the other channels. This would have the benefit of reducing noise levels, but would increase the chance of radiation damage.

An effort has already been made to minimise the number of detectors types required by the instrument (to reduce development and qualification costs), but clearly there are still important trade-offs to be made between the scientific requirements (resolution, field-of-view) and the available technology, telemetry, or cost. This trade-off study will be a necessary step in the further definition of the subtractive double monochromator, and more generally of the payload.

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Note that because of the anamorphosis in entrance of the SDM only 1/5th of the detector pixels are normally necessary in one direction, and rectangular arrays would probably be more appropriate. The high resolution content of the fringes is only visible in one direction (along the baseline). In the other direction, 10 pixels could be binned (Ø20 cm resolution compared to 2 m baseline).

5 — CONCLUSION

The optical and mechanical design of the SUN interferometer has been completed during the first phase of the Scientific and Technical Study of the SIMURIS mission. Of particular concern were the proper capacity of an interferometer to address the scientific issues of spectral resolution and image reconstruction of complex and extended images. The concept of the subtractive double monochromator (SDM) which we proposed and studied fulfill the scientific requirements and has the additional advantage of a large internal beam magnification which lower the tolerances on the recombination before it.

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