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SOLAR PHYSICS AT ULTRAHIGH RESOLUTION FROM THE SPACE STATION WITH THE SOLAR ULTRAVIOLET NETWORK (SUN)

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ABSTRACT

The SUN experiment is a UV and visible Space Interferometer aimed at ultra-high resolution in the solar atmosphere. It has been proposed to ESA as part of the SIMURIS Mission Proposal which has recently been accepted for an Assessment Study in the framework of the Space Station. The 4 x 20 cm telescopes of the SUN linear array are non-redundantly placed to cover a 2 m baseline, and the instrument makes full use of stabilized interferometry potential, the 4 telescopes being co-aligned and co-phased on a reference field on the sun. After a brief outline of the scientific objectives, the concept of the instrument is described, and its image reconstruction potential is illustrated.

INTRODUCTION AND MISSION CONTEXT

The SIMURIS Mission (*Solar Interferometric Mission for Ultrahigh Resolution Imaging and Spectroscopy*) was proposed to ESA in November 1989 /1/ in the framework of the next M2 Mission (Medium size "Blue" Mission), and accepted in February 1990 for an Assessment Study. It is dedicated to ultrahigh resolution imaging and spectroscopy of the solar atmosphere from the convection zone to the high corona. As such, it has two major instruments : the *Solar Ultraviolet Network* (SUN), an interferometer capable of **10 km resolution** on the sun, and the *Imaging Fourier Transform Spectrometer* (IFTS) which provides multi-spectral 2D velocity fields in the solar atmosphere.

The SIMURIS payload is intended to perform from the Space Station European Pointing System (EPS). The EPS is existing hardware which has been flown on Spacelab2 with measured performances of pointing stability and accuracy at the 1 arcsec level /2/. The improved electronics and control system under development by DORNIER (under ESA contract) should provide Space Station performances of

0.35 arcsec or better. Through a full rotation (3°/s rate) around its line-of-sight (a unique capacity of the EPS), it allows the SUN instrument to synthetize a 2D high resolution image in 1 minute. The EPS is currently planned as a facility to be provided to Astronomers. It could be implemented on one of the attachment point of the Space Station as soon as in 1998. One should notice that, to experiments which require a significant power, a high precision pre-pointing and a significant telemetry, the Space Station provides an excellent environment.

SCIENTIFIC OBJECTIVES

The high spatial and spectral resolutions of SUN/SIMURIS allow to address in details the major fields of study of the solar atmosphere : physics of coronal loops, plasma heating and thermal inputs of flares and microflares, fine magnetic field structures in the UV and in the visible (flux tubes ; magnetic field confinement), prominences, and the dynamics of granulation (convection). These objectives will be achieved through high resolution images (and velocity fields for broad lines) of coronal loops, flare kernels, prominences, internal flux tube structure, granules and magnetic vortex, with a spatial resolution allowing to access the ultimate process scale of most events. 10 km on the sun (0.01 arcsec spatial resolution) is the first "macroscopic" scale to observe since it grossly corresponds to the photon mean free path in the solar atmosphere. Higher resolutions (microscopic scales like the ion gyroradius ≈ 1 m) cannot be easily observed by a remote observing instrument since the natural "agitation" will probably thermalize the observed plasma.

A fundamental cause for both small and large scale evolution and activity in stellar atmosphere is the presence of magnetic fields. Observations (e.g. /3/) and theoretical studies suggest that all the spatial scales of the observed solar structures are coupled to small scales processes linked to the discontinuities and constraints in the magnetic field with a scale of ~ 3 to 30 km. Accordingly, the fine scale structures cannot be regarded as unimportant complications of otherwise simple phenomena.

INSTRUMENTAL CONCEPT

The SUN interferometer consists in 4 telescopes of 20 cm in diameter, positioned non-redundantly such as to cover a 2 m baseline. The high spatial resolution performances (10 km - 0.01 arcsec on a 4 x 4 arcsec^2 field on the sun) are completed by an **uninterrupted wavelength coverage from the C III line at λ 1175 Å to the near infrared Ca II triplet at 8662 Å**, thanks to a triple stage Double Grating Spectrometer (DGS). The SUN UV filtergrams will be obtained with 0.1 to 100 Å spectral bandwidth ; in the visible, spectral resolutions up to 60 mÅ allow to measure magnetic fields directly. A general view of the instrument is given in /5,6/ ; the general characteristics of the instrument (dimensions, mass, telemetry) are summarized in this issue (SIMURIS /4/). The "compact" configuration of SUN (Optical Transfer Function without "holes"), and the phase stabilized approach, allow to perform direct imaging by linear deconvolution techniques ; SUN therefore provides "snap shot" images of 0.01 x 0.1 arcsec resolution in a fraction of a second, or a full high resolution image (0.01 x 0.01 arcsec) by aperture synthesis, but in a 1 minute process. SUN is a fully stabilized interferometric concept in which both the pointing and the phase in between distant telescopes are controlled actively. In the following we briefly recall the different sub-systems and functions, insisting on the co-phasing which is at the heart of the SUN design, and which is unique to interferometric instrumentation.

The pointing is performed on the solar limb with a double quad-cell ecartometry set up. Precision expected is at the level of the one achieved by the SOUP instrument on board Spacelab2, i.e. 3 milliarcsec /2/. Pointing on any structure at the limb or on the disk is done through the use of an offset introduced by a diasporameter type of device (two wedges) placed before the ecartometer. This device, which also rotates, has the advantage to keep the offset angle while the EPS is rotated around the line-of-sight to synthetize an image. Further details on the system can be found in /5/.

The cophasing is achieved on a restricted field on the disk, corresponding to an Airy disk size in the visible optical wavelength range (4000 Å from 0.4 to 0.8 μm) in which the stabilization is done. From a reflection on the entrance slit/field mirror (16) of the spectrometer (cf. Fig. 1) the 4 beams are collimated by a lens assembly (17). The outlined four element configuration of this lens assembly is just an indication of the design problems that are expected when trying to meet the requirements on image quality over the field of view at the sky (5 x 5 arcmin).

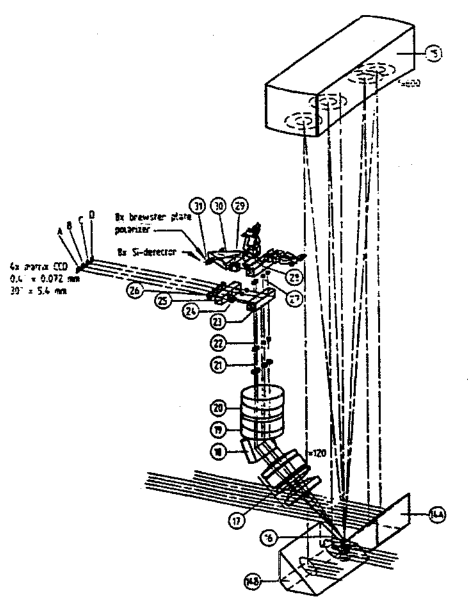


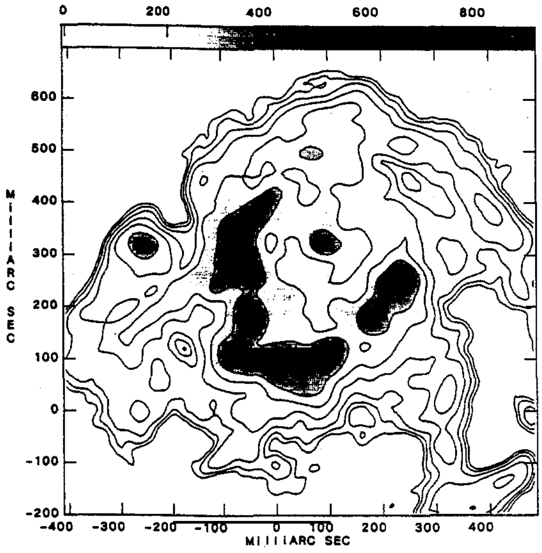
Fig. 1. Co-phasing system. The 4 beams are sent through pinhole fields of 0.4" × 0.4" (with an adjustable pointing, and after a diasporameter). They are then directed by couples to the Differential Synchrone Interferometers which monitor the OPD fluctuations (and possess, each, an adjustable delay line).

The beam (now 4 mm × 40 mm : 4 beams) is reflected by a flat mirror to the two identical achromatic transmission wedges (19) and (20). For any desired off-axis angle, up to 2.5 arcmin at the sky, the two individually adjustable wedges will be able to bring the selected off-axis field of view to an on-axis situation with respect to the following optical system starting with the four small lenses (21). The wedge concept for the off-axis co-phasing has the same advantages as the sun limb sensors (rotation of the pair of wedges over exactly the same angle as the spacecraft 180 degrees rotation for mapping purposes). The 4 mm diameter parallel beams are focussed on 4 pinholes of the beamsplitter (23) by the 4 adjustable lenses combinations (21) and (22). The lenses are used to adjust the 4 beams in one direction on the pinholes of optical element (23). These pinholes correspond to a field of view at the sky of 0.4 arcsec, the Airy disk of a single telescope in the visible, to suppress phase information of eventual extended structures. The relatively large field of view reflected at beamsplitter (23) provides 4 images to ease the pre-alignment of telescopes to 0.1 arcsec. The 4 transmitted beams are collimated by 4 lenses (27) before being splitted into 4 combinations of 2 beams by the beamsplitter-prism assembly (28).

In each of the eight beams transmitted by (28), a pair of compensating wedges (29) is introduced. One of the wedges in each combination of two beams can be moved so that the phase relation between the two beams can be adjusted. Finally the beams of the two beams combinations are mixed by the 4 beam-combiners (30), that consist in two cemented prisms. The 2 output beams are directed to single element silicon detectors (diodes). These detectors "see" the interference signals of the two mixed beams. By the displacement of the wedges (29) the "white light fringe" can be acquired. The stabilization is achieved through synchronous detection, the wedges being modulated at a determined frequency. Laboratory experiments on white light fringe pattern acquisition and stabilization have been performed /6,7/, and appear to be highly successful : acquisitions were performed at a S/N ratio of only 2 in between the fringe amplitude and the noise. Note that having 4 telescopes doesn't change the method since, into the 4 Differential Synchronous Interferometers, only two telescopes interferometry is performed (and in pupil plane, which relaxes the initial co-alignment tolerances). The technique is optimized for fringe acquisition and tracking and performances better than $\lambda/10$ are anticipated at UV wavelengths.

The detection is achieved in a Double Grating Spectrometer (DGS). The system is presented in /5/. In the latest version /1/ a pupil anamorphose in entrance of the DGS allows to reduce the beams openings, such as to provide continuous UV to IR wavelengths coverage. The spectral resolution can be as high as 0.1 Å (line width of most UV lines), but the system is designed for nominal use at 1 Å or more.

The image reconstruction uses the Radio Astronomy already developed methods, with limited changes in the algorithms since the dispersion has been removed by the DGS. Specific to the optical domain is the photon noise which modifies the notion of independent measurements as compared to the Radio domain. The Optical Transfer Function (OTF) of the SUN instrument is so compact (nearly equivalent to a full size pupil) that, in practice, only a linear deconvolution is performed to weight the high and low frequency contents of the OTF. Maximum Entropy deconvolution could afterwards be applied to the resulting "dirty map" image but does not bring much due to the important u,v plane coverage of SUN. Both instantaneous images (with high resolution on one axis) and synthetized images (which need a one minute exposure time due to the 3° per second maximum rotation rate of the EPS) are possible. Fig. 2 shows one selected example of image reconstruction performed on an artist view of what a solar structure (like a flux tube) could be at 0.01 arcsec spatial resolution.



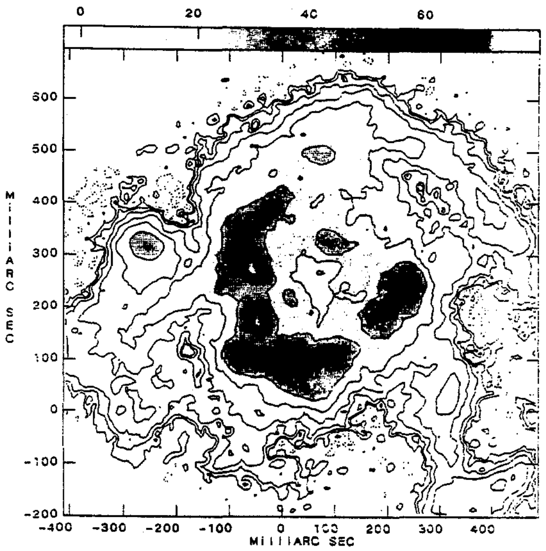


Fig. 2. Model (left) and image reconstruction ("dirty map", right) made from 60 interferograms (180° rotation by 3° steps), accounting for photon noise, and phase errors. The field is 1 x 1 arcsec and the maximum flux in a single pixel (of 7 x 7 milliarcsec) is 10^5 ph/s/pix. Important residual phase errors of $\sigma = 30°$ have been introduced (i.e. a $\lambda/12$ distribution of independent errors in between each telescope at each rotation step which corresponds to peak-to-peak **errors amplitudes, at $\pm$ 3 σ, of $\lambda/2$)**. Most of the geometry and the details are correctly reproduced down to about 1000 ph/s/pixel. In this example the structure was extended, but in case of isolated structures without "background", the correct geometry and flux can be estimated down to 100 ph/s/pix /8/.

CONCLUSION

SUN/SIMURIS is certainly the most prospective experiment for the study of the solar atmosphere from the intergranular lanes and convective vortex in the low photosphere to the coronal loops fine structure and disruptions above the solar limb. As such, it is however a complex instrument which benefits from the latest available developments in electronics, active optics and image reconstruction techniques. All these critical techniques are currently being investigated in laboratory, and the preliminary results obtained are definitively encouraging of our capacity to built and control the system. As the next significant step to demonstrate of the feasibility of the "interferometric machine", a representative 4 telescopes breadboard of the overall concept is currently being studied, eventually for a balloon flight.

Solar Interferometry, proposed for an ESA Mission, has been accepted for an Assessment Study in view of its tremendous potential of problem-solving and discoveries ; it is expected that the advent of such possibilities of high spatial resolution observations will be stimulating enough to justify a first Space Mission before the end of this century.

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