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SIMURIS: A UV AND XUV MISSION FOR HIGH RESOLUTION SOLAR PHYSICS

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ABSTRACT

Advances in electronics and servo-control allow to envisage extremely high spatial resolution observations of the Sun through the use of a compact array of phased telescopes. We present the SIMURIS Mission *(Solar Interferometric Mission for Ultrahigh Resolution Imaging and Spectroscopy)* which is the first to propose high resolution ultraviolet imaging coupled to high time and spectral resolutions through the use of an interferometric array of five 20 cm telescopes feeding a subtractive double monochromator tunable over a large spectral range and providing narrow band filtergrams. In addition to the ultraviolet imaging interferometer SIMURIS has soft X-ray and EUV imagers and spectrometers for complete coverage of the solar atmosphere.

MISSION CONTEXT

The *Solar Ultraviolet Network* (SUN), a linear interferometer of 2 meters baseline, with 4 telescopes of Ø20 cm, was the first proposed interferometric experiment in Space at visible and ultraviolet wavelengths aimed at reconnaissance of solar features at angular scales below 0.1 arcsec. It was proposed to ESA in November 1989 as the major instrument of the SIMURIS Mission in answer to the Call for the Next Medium Size Mission (M2). The SIMURIS Mission was accepted in the context of the Space Station and started an Assessment Study which was completed in August 1991 /1/. ESA agreed to proceed with a Phase A but the changing context of the Space Station did not allow to restart it up to recently.

In May 1993 we proposed, in answer to the ESA Call for the Medium Size Mission M3, a satellite version of the SIMURIS mission /2/. In this framework, the proposed solar interferometer was the *Multi-mirror Ultraviolet Solar Telescope* (MUST), a 5 telescopes circular array (5 x Ø20 cm telescopes on a Ø71 cm baseline). Though considered (and being placed) by the ESA Solar System Working Group, SIMURIS was finally not retained in the seven ESA M3 Assessment Studies. Nevertheless, the same interferometric configuration of 5 telescopes is the baseline of the studies which are continuing in the Space Station context for use of Attached Payloads on the *External Viewing Platform* (EVP). The EVP is a small platform with no pointing capacities placed at the end-cone of the Columbus European module. Accommodation constraints and viewing limits prevented from using the SUN design on the EVP (SUN was using the *Instrument Pointing System*, a platform allowing a line-of-sight rotation of 180°, which cannot be accommodated on the EVP). The more compact design of MUST, along with its specific support for pointing, the Hexapod, was studied by ESA /3,4/ and can be accommodated on the EVP. The Hexapod concept, used on the Ø2 m German Hexapod-Teleskop, could also be used on ground to point an optical solar interferometer of small baseline (less than 2 meters) and was also proposed for a Lunar version of the solar interferometer /5/. With moderate work, The reduced SIMURIS payload developed for the EVP could also be accommodated (with an Hexapod pointer) on other platforms, either US or Japanese.

SCIENTIFIC RATIONALE FOR SOLAR INTERFEROMETRY

Considerable evidence suggests that all scales of the Sun' structures, as well as other interesting astrophysical objects, are coupled to small-scale processes associated with intermittent magnetic fields and turbulent stresses. Though the minimum temperature gradient scale across structures in the solar atmosphere (chromosphere and corona) might in principle be 25 cm (ion gyroradius), it will probably be smeared out by plasma micro-instabilities (such as drift waves), and the relevant minimum observable scale is more realistically of the order of 10–30 km. 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 or in X-ray (multilayer telescopes are limited to 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 (e.g. 70 cm) we have the appropriate, *scientifically justified*, spatial resolution for both the UV (25 km at Lyman Alpha 1200 Å) and the visible / near UV (80 km in the Ca II K line 3963 Å).

A breakthrough in high spatial resolution observations (25 km is 30 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 localization 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. Fig. 1 summarizes these objectives and their characteristic scales. A detailed description of these objectives can be found in /6,7/ and in the SIMURIS Report /1/ (available from ESA).

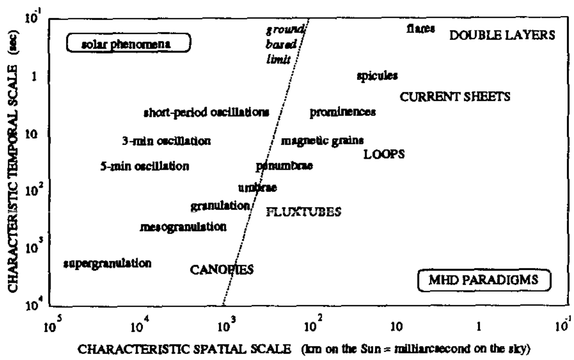

Fig. 1. Solar physics requirements: space-time characteristics of solar phenomena (small print) and paradigms of magnetohydrodynamics (capitals). The axes specify intrinsic scales, corresponding to desirable resolution. The dotted line is the ground-based optical resolution limit, including new techniques (adaptive optics). This figure portrays the main reasons why solar physics needs interferometers in Space. Altogether, this figure displays quite fortunate circumstances. The magnetic structuring of the outer solar atmosphere is faithfully encoded in short-wavelength diagnostics of which the line formation is optically thin. The proximity of the Sun translates into shortness of the required baselines compared to non-solar astrophysics. A meter suffice for all phenomena because the smallest (e.g. flare kernels) are also best observed at the shortest wavelengths. Thus, Space observation with relatively modest baselines suffices for solar physics.

If the need for high spatial and spectral resolutions is commonly agreed, the question is why an interferometer and not a single-dish large telescope. The answer is that the required measurement needs exceed the limitations of conventional instrumentation — a 0.7–1 m telescope diffraction-limited in the far UV is, in practice, exceedingly difficult to construct — but also, that even if possibly perfect, a meter class telescope would be more costly and difficult to control and assemble.

The Michelson interferometric approach represents significant advantages over diffraction-limited large telescope imaging. Only small telescopes are necessary and their small secondary mirrors can act directly as active pointing mirrors, without requiring intermediate optics for this purpose. Telescopes larger than 50 cm cannot be polished to the specification of $\lambda/8$ at Lyman α (120 nm) while small ones can. The Hubble Space Telescope, a 2.4 m mirror, even if of perfect figure, is still a factor 10 away (0.1 arcsec rather than 0.01 arcsec) from its diffraction limit in the far

UV due to the residual ripples left on its surface by the polishing process /8/. Interferometry requires to control the residual optical path delays between telescopes but this, consequently, guarantees a perfect '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 thermal cycling in orbit.

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 the one developed for the astrometric programs) result in very reasonable cost and mass which open solar interferometry programs to the small satellites programs currently envisaged by CNES and NASA (Small or Medium Explorer programs). The Reduced SIMURIS Payload adapted to small platforms and satellites is presented in Table 1 (XUV Spectrometers and Solar Irradiance monitoring instruments could be envisaged in addition for completeness as a solar observatory).

TABLE 1. Model Payload of the Reduced SIMURIS Mission.

	Instrument	Wavelength range (Å)	Resolutions: spatial (arcsec) and spectral (Å)	Field-of-view (": arcsec) (': arcmin)	Optical characteristics
High Spatial Resolution Imager	MUST (Multi-mirror Ultraviolet Solar Telescope)	1170 — 2000 1300 — 2800 2800 — 4000	0.03" / 0.03 Å 0.12" / ~200 Å 0.08" / 0.01 Å	10" x 10" 30" x 30" 20" x 20"	Five Ø20 cm Gregory telescopes on a baseline of Ø0.7 m followed by two double monochromators in cascade
High Temperature Imager	XUVI (Extreme Ultraviolet Imager)	Fe XX/XXIII 133 Fe IX/X 173 Fe XII/XXI 192 Fe XIV 211 He II 304	0.5" / ~10 Å	8' x 8'	5 x Ø10 cm Ritchey-Chrétien telescopes with selectable multilayers
Large Field and Survey Imager	HRTRC (High Resolution Transition Region Camera)	Lyman α 1216 C IV 1550 Continuum 1600 Continuum 2200	0.25" / ~10 Å 0.25" / ~0.5 Å " 0.25" / ~10 Å	2.5' x 2.5'	Ø20 cm Gregory telescope with filter wheel (including a FP filter for the C IV)

MUST: AN IMAGING SOLAR INTERFEROMETER

To study the ultimate fine structure of the Sun, a solar interferometer needs to *image* an extended field-of-view (FOV) covered with complex structures. And, since many structures of interest are evolving rapidly (in 1 second or even less, cf. Fig. 1), this imaging cannot be achieved by classical long-baseline interferometry techniques where fringes' visibilities are being measured sequentially. This prompts to design an interferometer with *instantaneous imaging* capability i.e., to choose a 'compact' array. 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 modulation transfer function of the array. Image restoration is, in this case, based on a direct deconvolution. Image reconstruction performances of MUST are reported in Damé /9/ (see references herein for earlier work). In most respects, MUST imaging performances are similar to single-dish telescopes (short exposures of 40 ms in flares for example).

The other important requirement is to control the residual optical path delays between the telescopes to a fraction of a wavelength, i.e. to 'cophase' the interferometer. This allows all the recorded fringes to be used *instantaneously*, since not affected by phase errors (thus allowing a robust image reconstruction approach). The consequence of importance brought by this cophased approach is that, permanently, we have the insurance of a perfect 'wavefront' (stable transfer function), the telescopes of the array being controlled to their optimum phase position. Cophasing performances have been demonstrated in laboratory to be better than $\lambda/300$ in the visible (peak-to-peak, i.e. superior to $\lambda/50$ in the UV in any case) in conditions representative of the solar case (reference objects are extended solar structures that are diaphragmed internally) /9/. Since then, cophasing in laboratory tests is performed at $\lambda/400$ on flux 10000 times smaller than the solar available flux...

Another important issue is the focal plane instrument spectral bandwidth. Image reconstruction simulations which we perform are working on filtergrams' data, i.e. on non-dispersed narrow band-passes data. Adding spectral dispersion would produce extra complexity: overlapping fringes patterns — and their noise — over the 2D field at the different free wavelength bands allowed in the output. To limit observations to narrow-band filtergrams we use a double monochromator (DM) in which the dispersions of the two gratings are subtractive. This concept has been studied in details /6/ (e.g. tolerance to chromatic shear /10/) and simplified (2 DM, three channels) for MUST (cf. Table 1).

CONCLUSION

The SIMURIS payload has evolved over 5 years since the first proposal to ESA in 1989. In particular, the Solar Ultraviolet Interferometer has been reduced in size and complexity while providing better spectral and temporal resolutions than ever: 30 mÅ spectral resolutions are achievable altogether with 40 ms time resolution on imaging field-of-views of 10 x 10 $arcsec^2$ thanks to the compact 2D configuration of the interferometer. Spectroheliograms, velocity fields and polarimetry are also possible with a moderate increase in complexity. In parallel, a large effort on laboratory work has shown our ability to *cophase two telescopes* on extended and complex solar objects by using a synchronous detection technique. Further laboratory tests are still necessary at system level (multi-telescopes control case) but most of the feasibility demonstration is now behind us.

SIMURIS as a whole and complemented with Solar Spectrum and Solar Irradiance monitoring instruments can directly be considered for Space Station opportunities or future Medium Size Missions of ESA. The solar UV interferometer MUST with its 5 small aperture telescopes (≈ Ø20 cm) and an angular resolution of 0.03 arcsec of the fine ultraviolet structures of the solar atmosphere, could also be envisaged for a Small or Medium Explorer Mission since, even when complemented with a soft X-ray imager, the payload would not exceed a total weight of 250 kg.

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