THE SIMURIS INTERFEROMETRIC MISSION: SOLAR PHYSICS OBJECTIVES AND MODEL PAYLOAD

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Abstract. The *Solar Interferometric Mission for Ultrahigh Resolution Imaging and Spectroscopy* (SIMURIS) has recently completed an ESA Assessment Study (Coradini et al., 1991). SIMURIS is a project for *Space Station Freedom* which major aims is to image the Sun with 0.01" resolution in the ultraviolet, and 0.05" resolution in the visible, employing full-field diagnostics, Doppler velocity mapping and Stokes polarimetry.

1 Introduction

SIMURIS (*Solar, Solar System and Stellar Interferometric Mission for Ultrahigh Resolution Imaging and Spectroscopy*) offers an unprecedented opportunity to probe the surfaces and atmospheres of nearby cosmic objects: the Sun, planets and nearby stars. SIMURIS employs advanced interferometric techniques to achieve the very high spatial resolution which is required to observe physical processes at their characteristic scales. It was proposed in November 1989 in response to the Call for Mission Proposals of ESA for the next medium size mission. Selected — in the context of the Space Station — SIMURIS carried an ESA Assessment Study from June 1990 to May 1991, which resulted in an ESA report (Coradini et al., SCI(91)7, August 1991).

The goal of 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, 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.

2 Scientific Objectives

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 SIMURIS 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.

Magnetic loops and other optically thin solar structures will be imaged in the ultraviolet with a resolution of 10 km, appropriate to resolve the steep gradients which exist across magnetic confinements in the chromosphere and corona. In the visible, SIMURIS will resolve solar photospheric structures on 40—50 km scales which correspond to the basic photon mean free path in optically thick conditions.

The SIMURIS instruments primarily concerns are plasma physics, magnetohydrodynamics and radiation hydrodynamics. Their aim is to study complex phenomena caused by the interplay of nonlinear and time-dependent processes which are characteristic of astrophysical plasmas occurring in a wide range of density and temperature (cf. Fig. 1). SIMURIS, SUN in particular, brings sufficient resolution to observe these phenomena near or at the intrinsic scales of the processes, and provides the diagnostics needed for physical interpretation.

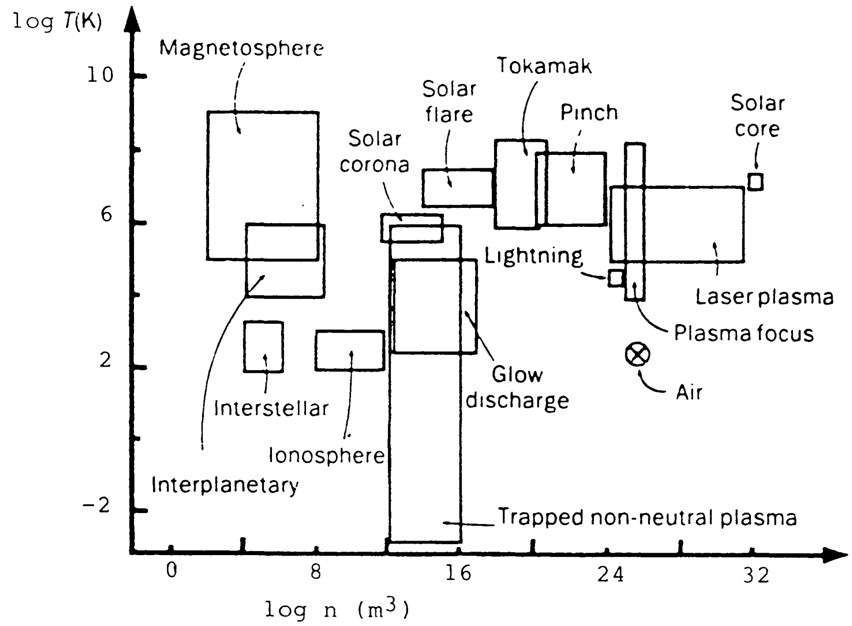

Fig. 1 — Qualitative density-temperature map of plasmas spanning 30 orders of magnitude in density, and 12 orders in temperature (from Petrasso, 1990). Our investigations concern especially the Sun and star conditions indicated: from the solar photosphere to coronal and flare regimes. The diagram also gives constraints on the solar core and stellar internal structure and evolution. In solar system science, solid surfaces, neutral atmospheres as well as ionospheres and magnetospheres, and their interaction with the solar radiation and wind can be investigated.

What are the basic process scales occurring in the solar atmosphere and what are the dimensions of the structuring they cause in the solar plasma? These questions determine the importance of very high spatial — and temporal — resolutions.

The physical processes at work in the solar atmosphere have a wide range of temporal and geometrical scales. Very large structures exist but nevertheless, current research concentrates on structuring and processes at small scales. The reason is that large-scale explanations have completely failed to explain even globally present phenomena such as coronal heating or solar wind acceleration. On the other hand, the smallest spatial scales of the solar plasma at which basic processes occur remain unobservable. This is the case for the particle gyro-radius and the Debye length and also for MHD surface waves, current sheets, double layers, *etc.*, down to scales on the order of centimeters. It is unlikely that these leave direct signatures in emergent ensemble-radiation; however, such microscopic scales do determine the larger-scale processes which produce the dynamical structuring of the atmosphere. Examples are magnetic reconnection, shock waves, current dissipation, *etc.* Between the longest and the shortest are the scales of interest, both physically important and observable. Ionization times of a few seconds and recombination times of a few minutes exist in many coronal structures. Waves such as fast and Alfvén modes have periods of a few seconds. Damping lengths range from a million kilometers down to a few kilometers, depending on the strength of the magnetic field. Loop resonance periods are between 10 and 100 s, depending on their lengths. Plasmoid accelerations occur on 10 to 20 km spatial scales and 1-10 s temporal scales.

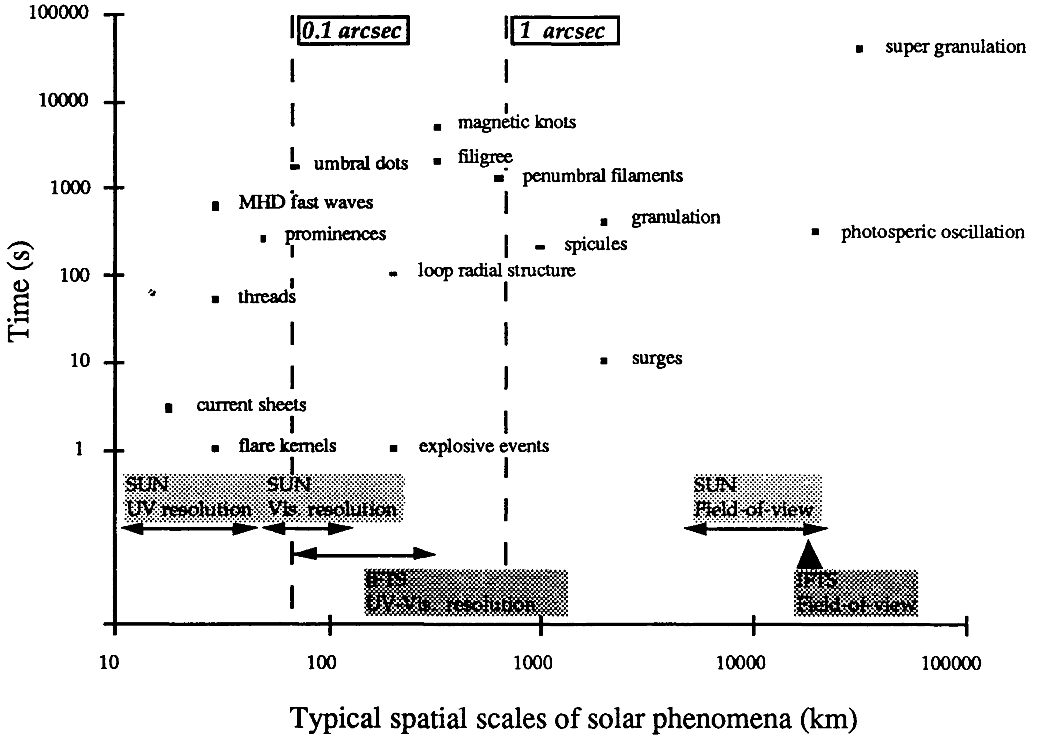

Fig. 2 — Typical scales of solar phenomena and characteristics of the SIMURIS core instruments, SUN and IFTS.

Additional scales of small size and short duration are set by the steepness of the gradients across solar structures. Such steep gradients probably occur across magnetic field lines and in regions of high vorticity, both in the photosphere and in the higher atmosphere. Resolving the fine structure of a coronal loop, for example, requires about 0.02 arcsec resolution; similarly, photospheric fluxtubes are thought to have diameters of order 100 km, corresponding to 0.1—0.2 arcsec and requiring about five to ten times better resolution for studies of internal structure.

Even the vertical stratification scales are not much larger. The density scale height in the plane-parallel models measures only about 50 km; the actual stratification has probably steeper gradients according to numerical granulation simulations.

These characteristic spatial and temporal scales of solar atmospheric phenomena are summarized in Fig. 2 along with the SIMURIS instruments capabilities. Imaging at process scales if achieved in all cases. More detailedness on the scientific objectives can be found in the SIMURIS ESA Assessment Study Report (Coradini et al., 1991).

Table 1 — Far UV lines for fine structure and dynamical studies

Line	Wavelength (Å)	Te (K)	Specific Interest
C III	1175	70 000	Transition zone
S X	1196	1.2 10^6	Corona (density diagnostic)
	1213	"	"
Lyman α	1216	20 000	Coronal loops (+ chromospheric studies in the wings)
N V	1243	1.5 10^5	Flares
Si III	1301	35 000	Density diagnostic
O I	1302	10 000	Chromosphere (fluorescence with Ly β)
	1305	"	"
	1306	"	"
Mg V	1324	2.5 10^5	Active regions & active loops
C II	1335	30 000	Filaments & prominences
	1336	"	(evidence of sub-arcsec fine structures)
Fe XII	1349	1.5 10^6	Flares
Fe XXI	1354	1.1 10^7	Flares
O V	1371	2 10^5	Flares (impulsive phase "clock")
Si IV	1394	50 000	Strong line
O IV	1401	1.2 10^5	
	1405	"	Density diagnostic
	1407	"	"
Si VIII	1440	8 10^5	Plages & activity
Fe X	1464	$> 10^6$	Hot line: coronal Loops
Fe XI	1467	$> 10^6$	"
C IV	1548	10^5	Strong line: transition zone
C IV	1551	"	(ratio –> opacity)
Cont.	1600	4200	T. min. fine structure (Bright Points)
He II	1640	30 000	Sunspots (high chrom. but with coronal contribution)

Measuring physical processes requires physical diagnostics: mapping temperature, density, velocity and magnetic field. These mappings use selected spectral lines at widely different wavelengths. The ultraviolet supplies good temperature, density and velocity diagnostics (cf. Tables 1 and 2); photospheric lines provide maps of photospheric flows and of the magnetic field, either of the longitudinal component by measuring Stokes V profiles or full vector maps if all Stokes parameters are evaluated. Such maps have to cover a wide area around the structure of interest. Evolutionary changes must be followed; the magnetic field topology and flow patterns have to be known with sufficient spatial extent to model boundary conditions. In the ultraviolet, imaging must be achieved with narrow spectral passbands selecting specific spectral lines. Visible passbands may be larger but narrow-band imaging is highly useful in selecting spectral features such as the CN bandhead, Ca II H and K, the Mg b lines and Hα which span the lower atmosphere in formation heights.

Table 2 — Line pairs for density and temperature diagnostic studies

Line	Wavelength (Å)	Ne (electrons/cm^3)	Te (K)
Si VIII	1445/1440	$1.0\ 10^7 - 1.0\ 10^9$	$7.9\ 10^5$
S X	1213/1196	$2.0\ 10^8 - 2.0\ 10^{10}$	$1.2\ 10^6$
C III	1247/1175	$1.0\ 10^9 - 1.0\ 10^{10}$	70 000
Si III	1312/1301	$1.0\ 10^9 - 1.0\ 10^{11}$	35 000
O IV	1407/1405	$3.0\ 10^9 - 3.0\ 10^{11}$	$1.2\ 10^5$

To access the higher temperature regimes, the spectral coverage of SIMURIS is completed by a set of multi-layered telescopes with a typical aperture of 10 cm, and working in XUV wavelengths. Because the UV and visible light is rejected, it is safe to use a Ritchey-Chretien telescope offering the wide field necessary for full disk imaging. Lines of Fe IX to XXIV for instance span the temperature range 10^6 - $2\ 10^7$ K and, as in the EIT instrument on-board SOHO (see Delaboudinière et al., 1988), one could also add an He II channel at 30.4 nm. A tentative list of lines is proposed in Table 3: one could design one telescope per wavelength — at the cost of a high number of detectors — or, as in EIT, one could divide the optics into several parts with their specific multilayers, a line being selected with an entrance rotating mask. A spatial resolution of one arcsec would require a large detector; a good compromise is a set of two telescopes: the first one, working in the above four bandpasses with a limited field-of-view but a pixel size as small as 0.3 arcsec, and the second one in He II with a pixel size of 3 arcsec but a wide field-of-view. The NIXT solar picture at 17.3 nm (Walker et al., 1988) is a beautiful example of the bulk of information provided by EUV imaging. If the reflectivity is sufficient, Si or Mg lines at shorter wavelengths could also be studied.

Table 3 — Possible lines' choice in the XUV

Wavelength (nm)	Ion	Formation Temperature (K)
17.3	**Fe IX/X**	10^6
19.2	**Fe XII / XXI**	$1.5 — 20\ 10^6$
21.1	**Fe XIV**	$2.5\ 10^6$
13.3	**Fe XX / XXIII**	$12 — 16\ 10^6$

3 Model Payload

To meet its ambitious scientific goals, SIMURIS must deliver unprecedented spatial resolution of fast-evolving, tiny structures while at the same time providing a complete set of plasma diagnostics. The requirements are:

- 10 milliarcsecond spatial resolution;
- full-field imaging;
- free wavelength tunability from the UV (120 nm) to the visible;
- simultaneous observation in the UV and the visible;
- high spectral resolution to isolate lines, and to measure velocities and magnetic fields.

	Instruments	Wavelength range (Å)	Resolutions: spatial (arcsec) and spectral (Å)	Field-of-view (": arcsec) (': arcmin)	Optical characteristics
High Spatial Resolution Imager	**SUN (Solar Ultraviolet Network)**	1170 — 2000	0.012" / 0.1 Å	6" x 6"	Four Ø20 cm Cassegrain telescopes, Double Monochromator with 6 channels, and Fabry Perot in the 500 — 800 nm channel
		1300 — 2800	0.06" / ~ 200 Å	30" x 30"	
		2800 — 4800	0.028" / 0.1 Å	7" x 7"	
		4800 — 5000	0.05" / ~ 200 Å	25" x 25"	
		5000 — 8000	0.05" / 50 mÅ	13" x 13"	
		8000 — 11000	0.08" / ~ 10 Å	20" x 20"	
High Spectral Resolution Imager	**IFTS (Imaging Fourier Transform Spectrometer)**	1200 — 2000	0.1" / 30 mÅ	25" x 25"	Folded Gregory telescope Ø40 cm, Double Monochromator, and two channels FTS
		2500 — 9000	0.1" / 10 mÅ	25" x 25"	
High Temperature Imagers	**EUVT (Extreme Ultraviolet Telescopes)**	Fe XX/XXIII 133	0.6" / ~ 10 Å	5' x 5'	Ø10 cm Ritchey-Chrétien telescope, selectable multilayers
		Fe IX/X 173			
		Fe XII/XXI 192			
		Fe XIV 211			
Large Field and Survey Imagers	**UVC (Ultraviolet Camera)**	Lyman α 1216	0.6" / ~ 100 Å	2.5' x 2.5'	Ø10 cm Gregory telescope with filter wheel (including a FP filter)
		C IV 1550	0.6" / ~ 8 Å		
		Continuum 1600	"		
	HLT (Helium II Telescope)	He II 304	3" / ~ 15 Å	Full Sun	Ø10 cm Ritchey-Chrétien telescope (multilayered)

Table 4 — Summary of SIMURIS Model Payload Characteristics

These objectives can only be realized by space observation; SIMURIS fulfills them requirements with two major instruments:

- the *Solar Ultraviolet Network* (SUN), achieving the highest spatial resolution;
- the *Imaging Fourier Transform Spectrometer* (IFTS), having high spectral capabilities.

SUN will be the first short-wavelength interferometer in space. It implements active real-time cophasing on an offset reference for imaging on extended and complex objects with unprecedented angular resolution of 0.01" in the ultraviolet and 0.04" in the visible. SUN observes simultaneously in three monochromatic passbands, each variable in width from 0.1 to 100 Å, throughout the ultraviolet and visible. The high spatial resolution is obtained instantaneously in one direction of the imaged field-of-view ($\geq 6 \times 6$ arcsec^2); rotational aperture synthesis adds high resolution in the other directions, typically within 1 minute of time. SUN will be the first two-meter telescope reaching the diffraction limit in the ultraviolet. As such, in addition to its scientific breakthrough in solar physics and astrophysics, it is a precursor demonstrating interferometric techniques to future space interferometers.

IFTS will be the first Fourier transform spectrometer to provide two-dimensional spectroscopy in the UV. It extends state-of-the-art Fourier transform spectrometry into the vacuum ultraviolet and from single-element to a full two-dimensional detection. It provides diagnostics, including maps of velocity and magnetic field strength, which combine high spatial resolution (0.1" in the ultraviolet, 0.4" in the visible) with high spectral resolution (up to 10 mÅ) on a 25×25 arcsec^2 field-of-view.

Together, SUN and IFTS provide the means to study astrophysics processes at high resolution simultaneously in very different regimes and with diverse diagnostics. They are complemented by instruments with larger field-of-view, including EUV multi-layer telescopes to provide diagnostics of high-temperature plasmas (cf. Table 4).

The SIMURIS payload will be accommodated on the *Instrument Pointing System* (IPS). The IPS is a precision pointing platform which demonstrated sub-arcsec pointing accuracy and stability when flown on Spacelab2. It permits pointing of all instruments to any target of interest over a wide viewing angle and has the important capability of full rotation around the line-of-sight, which is essential for aperture synthesis. Depending on target geometry, SIMURIS will be rotated for aperture synthesis or used in its snap-shot linear-resolution mode. SIMURIS is intended to be operated from Space Station Freedom. It fits well on the IPS which can be accommodated on the Space Station with minor modifications. The current implementation possibility under investigation is an External Viewing Platform appended to the Columbus Attached Pressurized Module (APM).

3.1 The Solar Ultraviolet Network (SUN)

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.

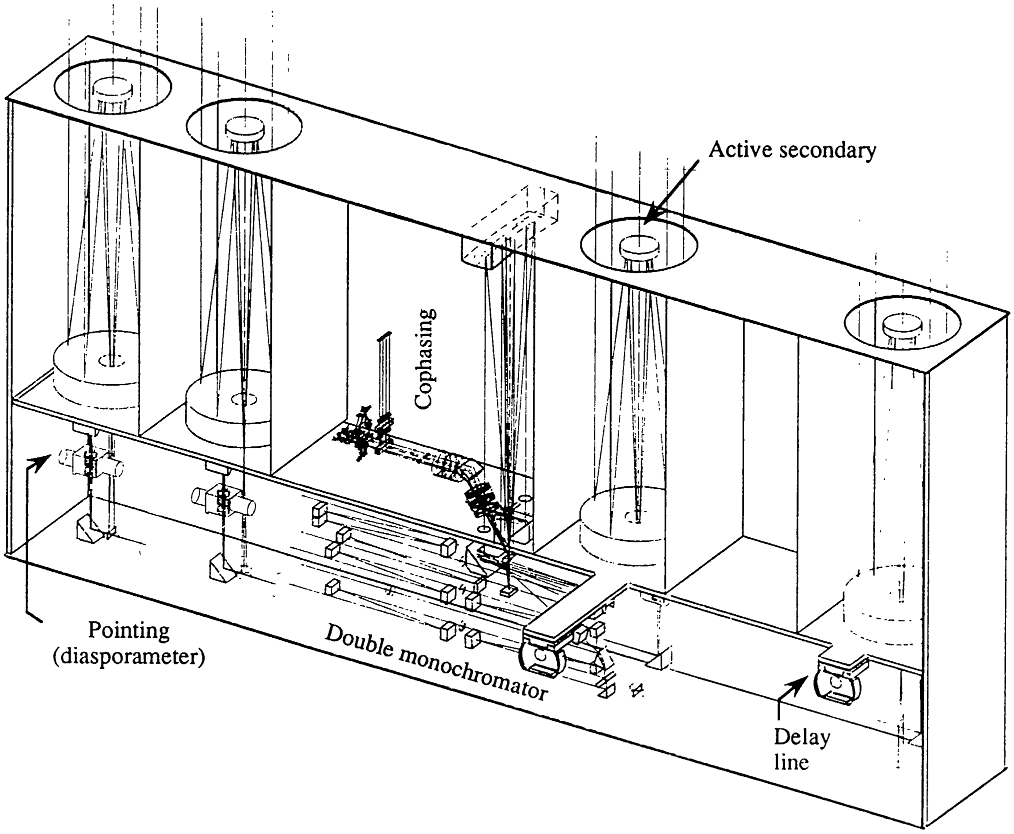

Fig. 3 — General optical layout of the SUN interferometer. Note the use of the space in between the central telescopes of the non-redundant configuration for the recombination mirror (top) which focalizes the beams on the entrance slit of the triple stage subtractive double monochromator (center and 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, 1992) demonstrate that such cophased arrays can properly observe complex and extended objects, and reconstruct images with dynamical range ≥ 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 (Damé, 1992, 1991, Damé et al., 1991b).

One further particularity of SUN is the use of a reference object for both cophasing and pointing of the telescopes. This allows excellent low-flux performance necessary for faint UV lines, and also for Stellar and Galactic programs since the light from the object can be integrated for minutes when the array is cophased. 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).

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. Indeed, adding spectral dispersion to interferograms 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.]

How to obtain such narrow bandwidths 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 (cf. Damé et al., 1992). An intermediate slit 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 — while the quality is maintained over the entire field of view, 6 x 6 arcsec^2, i.e. while the diffraction spot is smaller than the diffraction spot of the telescope array — the magnification introduced in the DM allows to keep the one of the telescopes small which is essential for the interferometric recombination .

3.2 The Imaging Fourier Transform Spectrometer (IFTS)

IFTS combines spectral resolution with two-dimensional spatial imaging. The instrument itself is a scanning Michelson interferometer in which the entrance aperture is imaged onto an array detector so that each element of the detector receives light from a particular small element of the field of view — in this case 0.05 arcsec^2. When one mirror (in practice a retroreflector) of the interferometer is scanned in the usual way for Fourier transform spectrometry each detector element records an independent interferogram, the Fourier transform of which gives the spectrum for that particular part of the field of view. The spectral region of primary interest is in the vacuum ultra-violet (VUV) from about 1600 Å to Lyman alpha (1215 Å). A spectral resolution of about 0.1 Å is required to obtain true line shapes, and in order to study the dynamics on the scale of the spatial resolution the time for a single scan must be limited to a few seconds.

In the last decade FTS has been successfully used through the visible and into the UV region as far as 1800 Å, which is the present state-of-the-art short wavelength limit. The SIMURIS IFTS design is based on the VUV prototype developed at Imperial College. The essential modifications for SIMURIS are the replacement of the single detector by a CCD, the extension of the short wavelength limit of the instrument, and the spectral selection. In FTS the noise from all the spectral elements seen by the detector is distributed right through the spectrum. It is therefore important to exclude all spectral elements not of interest. For this reason a double grating monochromator is placed between the telescope and the IFTS. A spectral line or a set of lines can be isolated by a slit or mask in the intermediate focal plane of the monochromator so as to enhance the signal to noise ratio for the selected line(s). Two output signals of complementary phase are available from the interferogram; one will be focused on a solar-blind detector for VUV operation and the other on a visible region detector for the range 3000 — 9000 Å.

For SIMURIS there are three important characteristics of FTS that are not available from a grating spectrometer. First, two-dimensional spatially resolved spectrometry is possible without rastering. Second, spectral and spatial resolution are independent, not coupled by the slit width. Third, the spectral resolution (depending only on the scan length) is flexible and can be changed from one observation to another.

4 Conclusion

The SIMURIS mission pioneers space interferometry at short wavelengths. Its outstanding improvement in spatial resolution combined with its comprehensive spectral diagnostics represents a major scientific and technical breakthrough. SIMURIS will open a new frontier for astrophysics advent its selection for a mission to *Space Station Freedom.*

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DISCUSSION

Serio: I understand that the simulations you have presented to demonstrate the meeting of pointing requirements, have used nominal Space Station oscillating amplitudes. Due to the uncertainty of actual oscillating modes, do you envisage any critical inconvenients, if they have higher amplitudes and different frequencies than those planned?

Damé: The new structure of the Space Station should be stiffer and therefore better than the preceeding one. Amplitude differences by a few cm and frequency differences by a Hz or a few Hz are acceptable by the Instrument Pointing System (IPS) which, onboard the Space Station, will be equipped with a new stellar sensor at 100 Hz sampling. The SIMURIS instruments have an active stabilization in real-time of both pointing and phase and, as long as the IPS pointing excursions are less than 20 arcsec, the performances are not affected.