TECHNOLOGIES FOR SOLAR INTERFEROMETRY IN SPACE

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ABSTRACT

This paper summarizes, on one part, the results of a 3-telescope breadboard used to demonstrate the cophasing and imaging capabilities of the Solar Imaging Interferometer, SOLARNET, of the Solar Physics and Interferometry Mission (SPI) and, on the other, possibilities for state-of-the-art recombination optics (molecular binding) and novel delay lines using magnetic bearing to achieve unprecedented cophasing quality and ease of interferometric recombination and imaging.

INTRODUCTION

The novel aspect of an imaging interferometer like SOLARNET is certainly to obtain and maintain cophasing of several telescopes over an extended field-of-view. The interferometric concept has evolved since the first complete proposal studied by ESA, SUN/SIMURIS back in 1990–1991 (Coradini *et al*., 1991), to reach maturity with the SOLARNET/SPI concept proposed to ESA recently in answer to the F2/F3 Flexi Missions call in January 2000 (cf. Damé and Derrien, 2002). Despite the detailed design and technical demonstration of cophasing, the mission was not selected, may be because a complete imaging demonstration directly on the Sun was not achieved on ground at that time. Laboratory and Sky demonstrations have now been carried with success and several developments are underway to guarantee a proper spatialization of the interferometer, as will be shown hereafter. Lets hope that in a near future we will have the possibility to use and discover from Solar Interferometers. With a 1 meter baseline or so, a Space imaging interferometer will reach a permanent spatial resolution of 0.01" in the UV over a coherent field-of-view of 40": a definite scientific revolution for Solar Physics.

SOLARNET DEMONSTRATION BREADBOARD

The optical set-up used (cf. Figure 1) for the test and demonstration of the feasibility of Optical Synthetic Aperture (OSA) for solar observation is composed of five parts:

- The white light source and the three telescopes positioned on the vertex of an equilateral triangle.
- Three active mirrors for fine pointing (position is monitored using PSD on active regions).
- Three delay lines (a retro-reflector and a right angle prism) for the OPD (Optical Path Delay) corrections.
- The recombination of the three beams (the entrance and the exit pupils are homothetic) for the large field-of-view imaging.
- The cophasing interferometers that allow to correct the phase errors between the beams ❶ and ❷, and between the beams ❶ and ❸.

COHERENCE AND PHASE CONTROL

The light from the extended source has a large spectral bandwidth, therefore the coherence length is short and interferograms present only a few fringes (cf. Figure 2). In the nominal case, the fringe pattern has the best contrast for the null OPD, which makes it easy to find the fringe pattern and to localize the central fringe (zero OPD). Yet, the interferences are always symmetric around the zero OPD (if the glass crossings are identical for the different beams), and this can be achieved by studying extremes of the different signals.

The interference's signal is modulated by a longitudinal oscillation using one delay line in the reference interferometers. Two lock-in amplifiers use this modulated signal to obtain, at first order, the first and second derivative of the fringes' interference. Thus, the zeros, in the first derivative, correspond to the extremes in fringes signal, and allow an active real-time control of the phase errors between the three telescopes. The second derivative, because of its similarity with the interferogram, permits to select, by its amplitude, the correct fringe (central fringe), to achieve the best possible image in the focal plane of the camera.

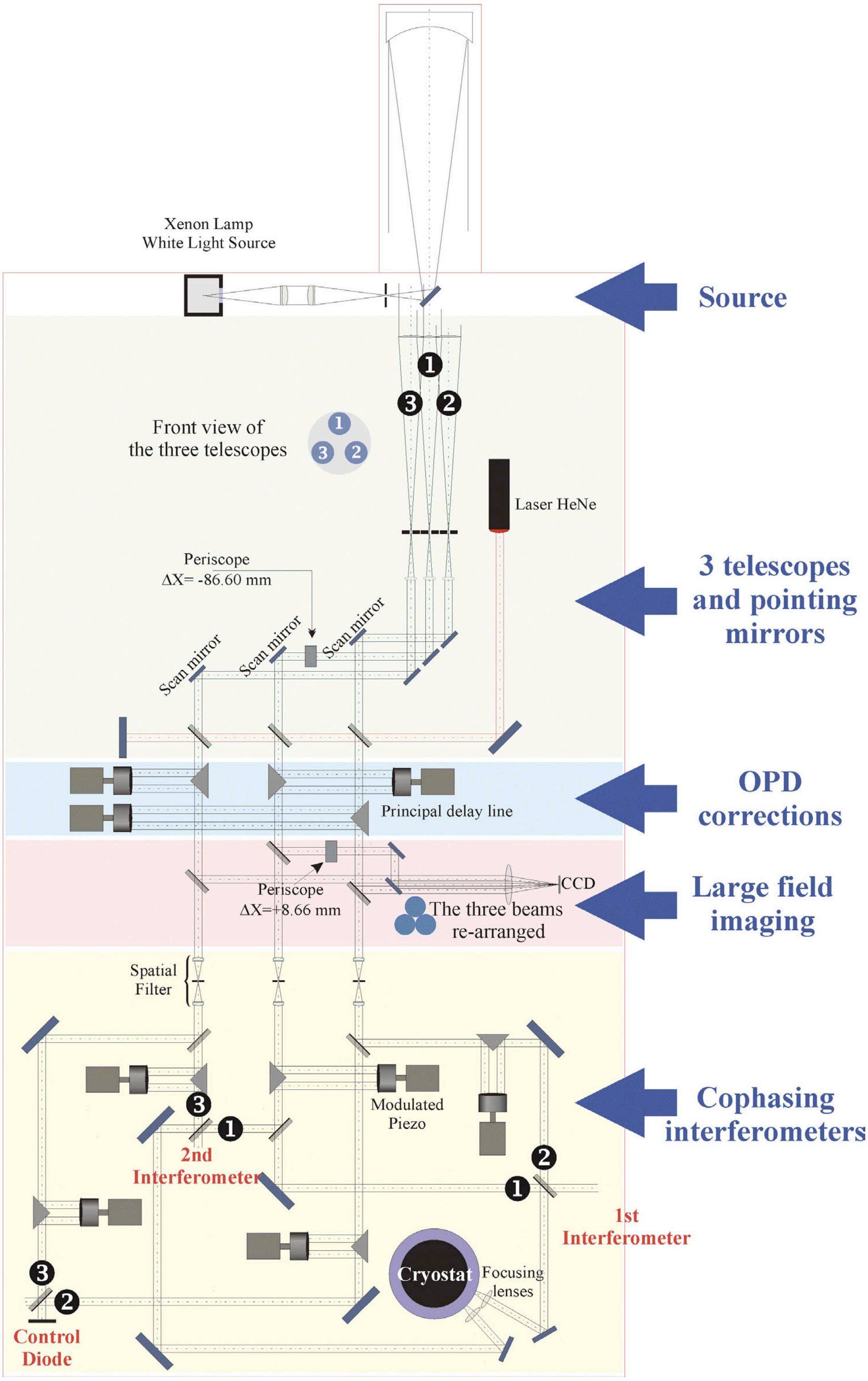

Fig. 1. The 3-telescope laboratory breadboard realized for the demonstration of the SOLARNET concept.

Figure 3 gives such an example of the search of the central fringe: for the two interferometers that control the 3-telescope imaging interferometer we have two curves. The lower one shows the signal issued from the synchronous detection at simple frequency (dark curve) and the signal of the synchronous detection at double frequency (light curve), and this during the Principal Delay Line move. The phase between these two signals is well equal to $\pi/4$ as predicted by a mathematical simulation. The signals' form is not perfect because of the average of multiple measures and the elementary move of the delay line (0.1 µm) which is not infinitely small when using a mechanical table displacement for the acquisition search. The upper curve shows this same signal during the search of the central fringe (null OPD) when the phase control is activated. Then the signal of the synchronous detection at simple frequency is null while the signal of the synchronous detection at double frequency grows until the null OPD is reached when positioned on the central fringe.

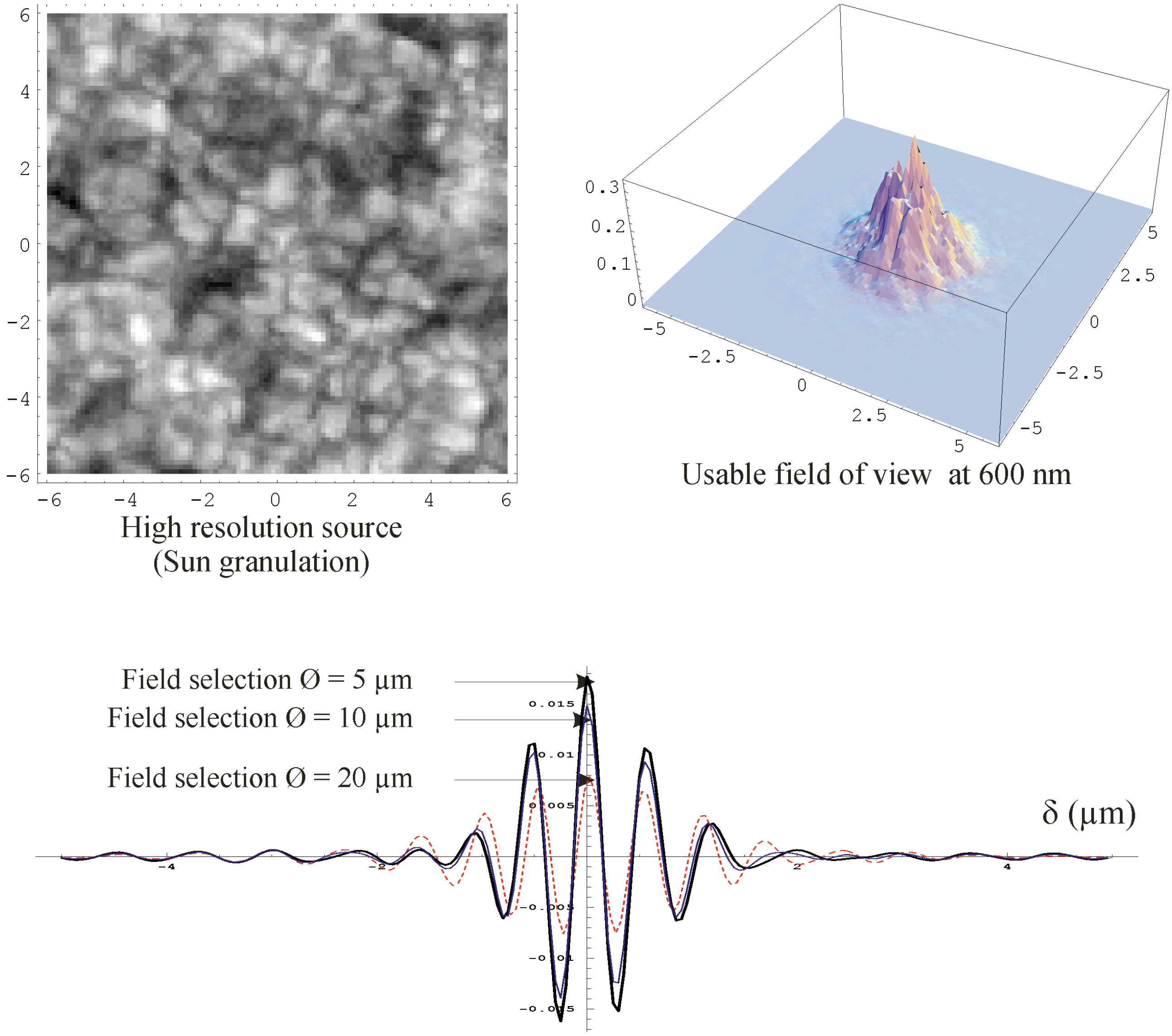

Fig. 2. Fringes pattern for a high-resolution white light source and a spatial filter.

RESULTS

Although the fringe signal was not maximized (low contrast, about 12%, due to spatial coherence), we were able to perform measures at very low fluxes using sets of neutral densities. The major results obtained are summarized in Figure 4.

The experimental values (dots) are coherent with the curve drawn on this figure. The curve is an experimental simulation of the two principal noise sources:

- Electronic noise for the very low flux measures.
- Noise of the white light source for the high flux measures that limits the apparent quality of the phase control (which is, then, necessarily better).

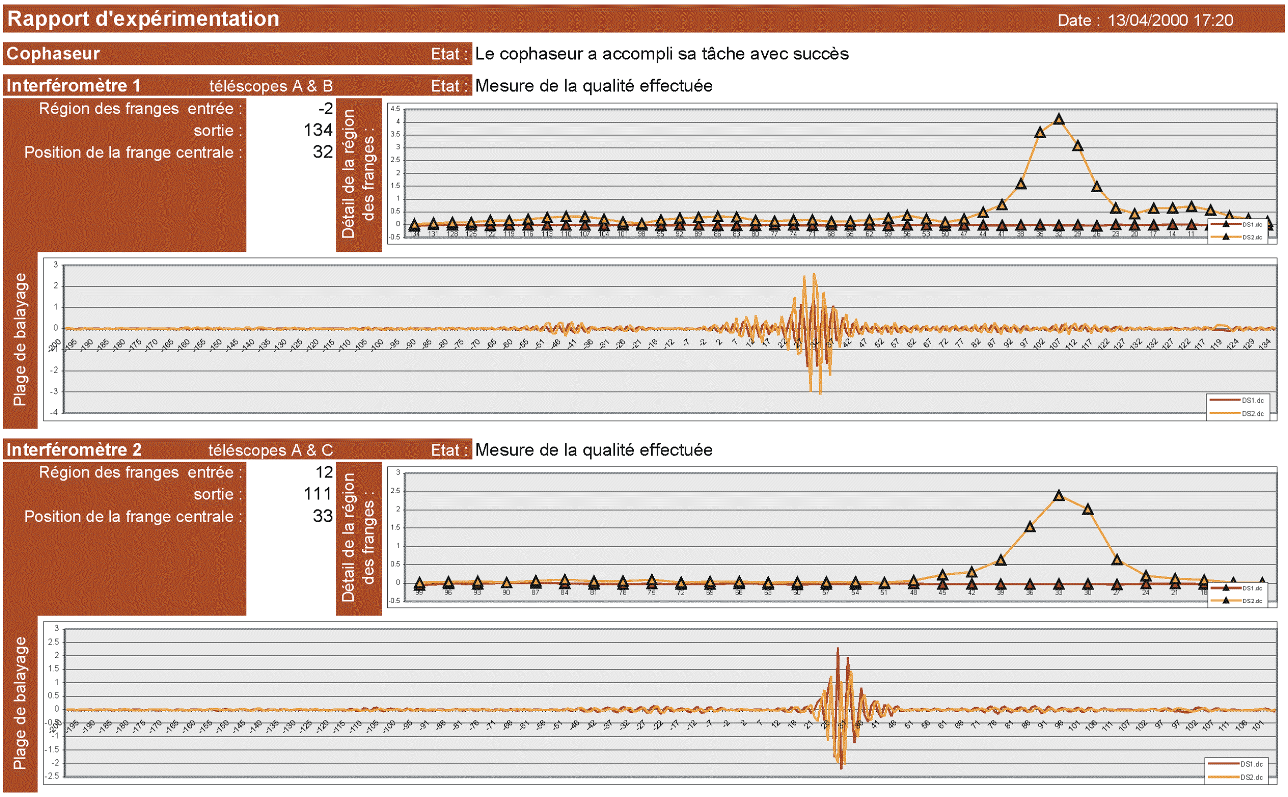

Fig. 3. Control interface of the 3-telescope breadboard of SOLARNET.

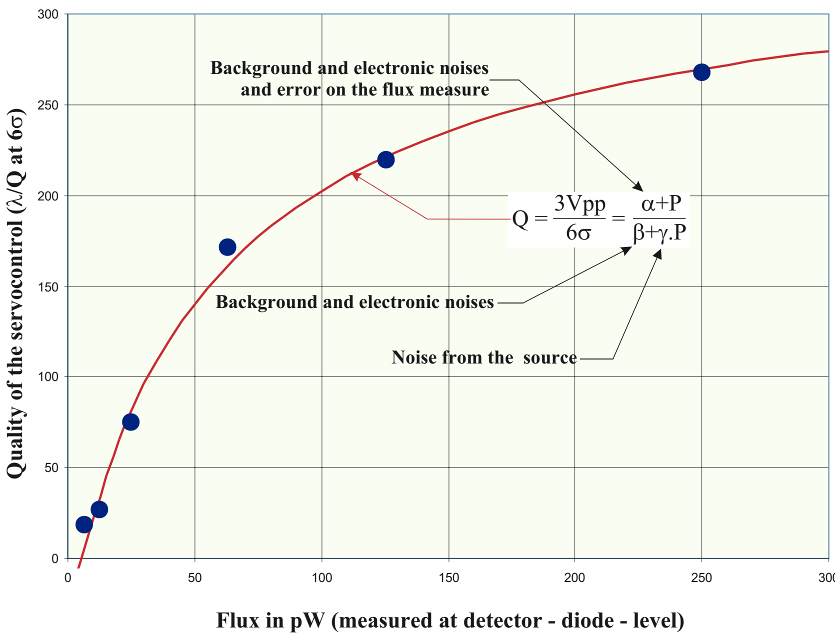

Fig. 4. Stability of the phase control (quality is expressed at 6σ) as measured at low fluxes.

Concerning imaging potential, Figure 5 shows the result of the effective phasing of the beams when imaging with three telescopes the white light source. As can be noticed, the diffraction limit is achieved in this case with the gain of spatial resolution nicely illustrated (note also the six secondary peaks of the diffraction figure).

Thus, this breadboard has demonstrated that an excellent phasing quality can be achieved despite a fairly poor optical quality of the interfering beams (astigmatism, residue of differential glass crossed, etc.). It is worth recalling that a phase quality of $\lambda/6$–$\lambda/8$ is sufficient to allow an excellent numerical reconstruction of the solar images with dynamics of several hundreds.

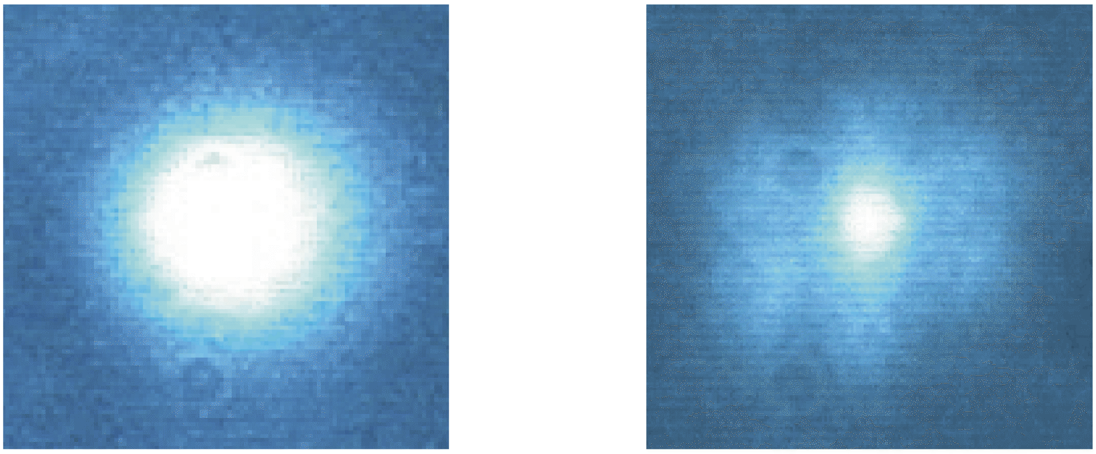

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Fig. 5. Cophasing of the three telescopes in white light (Airy patterns).

THE 3-TELESCOPE BREADBOARD AT MEUDON OBSERVATORY

The laboratory results of the 3-telescope breadboard were excellent, making worth and possible to reproduce the conditions of solar imaging by SOLARNET very adequately (to the exception of fine pointing which cannot be achieved – because of atmospheric turbulence, on the solar limb). The experiment had already been moved to the "Grand Sidérostat de Foucault" at Meudon Observatory during summer 1995 and during the period from June 1996 to March 1997 (cf. Damé *et al*., 1998a & b) to demonstrate, with success, the cophasing using two telescopes, both on stars (Altair, Arcturus) and extended objects like planets (Mars, Jupiter) or the Sun, yet with much difficulty at that time by lack of fine pointing. In the Solar case the contrast was very low (about 4%) but we nevertheless cophased the two telescopes with a measured stability of $\lambda/140$ (at $\lambda_{ref} = 550$ nm).

Fig. 6. The "Grand Sidérostat de Foucault" and the 3-telescope breadboard demonstrator at Meudon Observatory. The entrance window, the three refractors and the periscope can be seen in the back.

During summer 2000 we therefore reinstalled the optical set-up at Meudon Observatory, but now with its 3 telescopes (with 3 active mirrors for fine pointing) instead of the 2 telescopes previous experimentation. Imaging capabilities and performances are under investigation and first results are promising (although cophasing imaging and cophasing quality are currently limited by the fine pointing possibilities achievable on ground).

EVOLUTION OF THE SOLARNET OPTICAL SET UP

Beside the 3-telescope cophasing and imaging demonstrations, another significant progress that was achieved in 2000 is the miniaturization/spatialization of the three reference interferometers by the use of optics assembled by molecular binding. Indeed, the present reference interferometers represent large dimensions (1.1 x 1.5 m^2) – incompatible with space assets – while the dimensions of the miniaturized block now under realization is less than 20 x 30 cm^2 (cf. Figure 7), suitable for a space mission like SOLARNET. The miniaturized block of the 3 reference interferometers is to be delivered by June 2001 and its test with the 3-telescope breadboard will be carried afterwards. A very complete analysis of this block is given in Derrien's PDH Thesis (Derrien, 2000). Special polishing tricks are used during assembly to minimize the OPD differences between the beams so that the three output interferograms are automatically phased.

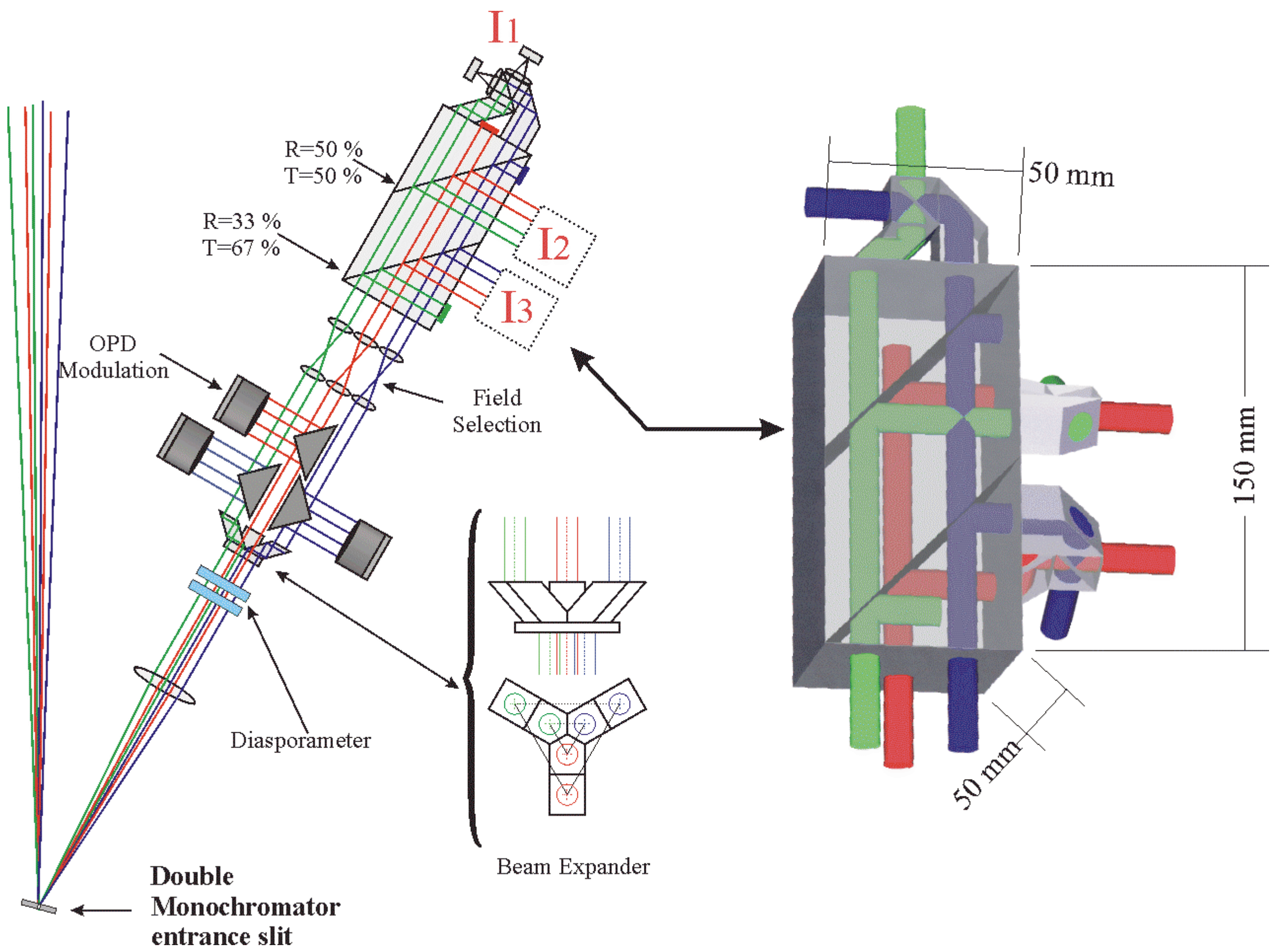

Fig. 7. Miniaturization of the three reference interferometers obtained by molecular binding.

OPTIMIZED DELAY LINE CONCEPT

The delay lines are at the center of the cophasing process and, as such, deserve special attention. Classical approaches using cat-eyes or 3-mirror retroreflectors on piezoelectrics and mechanical table have been shown feasible, both by our breadboard (cf. Damé *et al.*, 1999) and the ESA effort carried through the Optical Aperture Synthesis Technology Research Program. On the other hand, the two needs that they express, on one hand, acquisition-search on a large distance (table) and, on the other, fine cophasing on a wavelength scale, can be combined together using a magnetic suspension approach like the one developed by A. Preumont's team and Micromega Dynamics.

In order to demonstrate the effectiveness of magnetic bearings for high accuracy, long stroke devices, a breadboard based on commercially available components has been developed (cf. Figure 8). The magnetic bearing (MECOS-T3336) provides guidance over 5 degrees-of-freedom while the piston movement is sensed by a laser interferometer (HP-5578A) and actuated by a voice-coil (ETEL-T2530). The control law is implemented in a DSP board (dSPACE DS-1102) and the GUI is implemented on MATLAB™. Both feedback and feedforward control laws have been implemented. Feedback provides stability, step responses and wide-band disturbance rejection. Feedforward can be used to cancel harmonic perturbations (if a correlated reference signal is available).

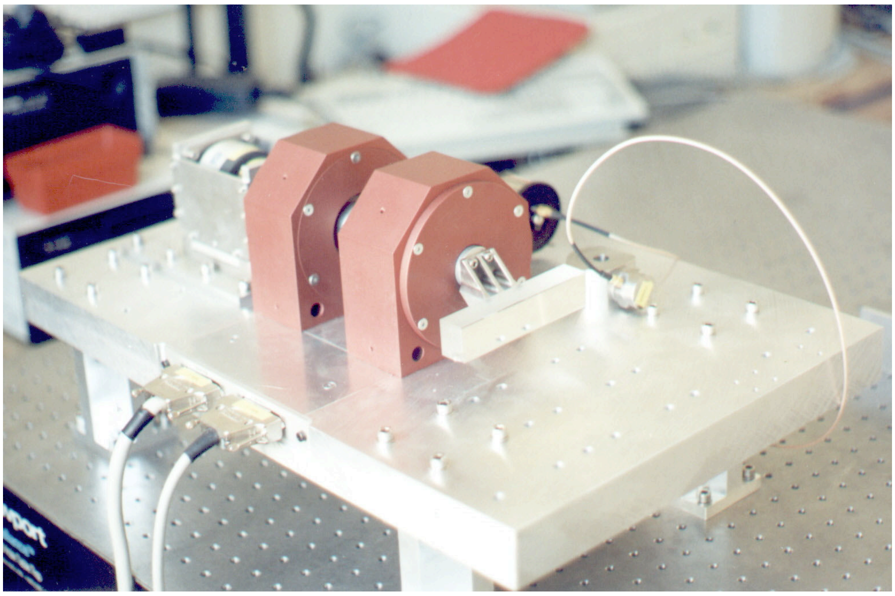

Fig. 8. Magnetic bearing optical delay line.

Axial Positioning Performance

The stroke is 5 mm, the positioning resolution is 12 nm_{rms} (over 100 Hz) and the closed-loop bandwidth is 100 Hz. The latter was mainly limited by the control structure interaction. Due to the saturation of the actuator, the settling time of the step response depends on the amplitude of the command (Figure 9). In the required configuration, the Optical Delay Line works in a perturbation rejection mode and the achieved sensitivity to perturbation is – 60 dB at 10 Hz (cf. Figure 10).

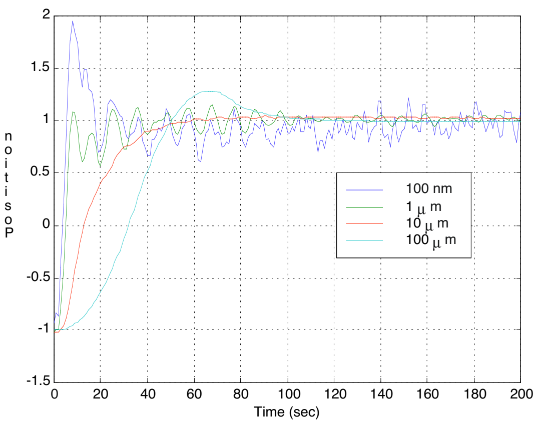

Fig. 9. Step responses.

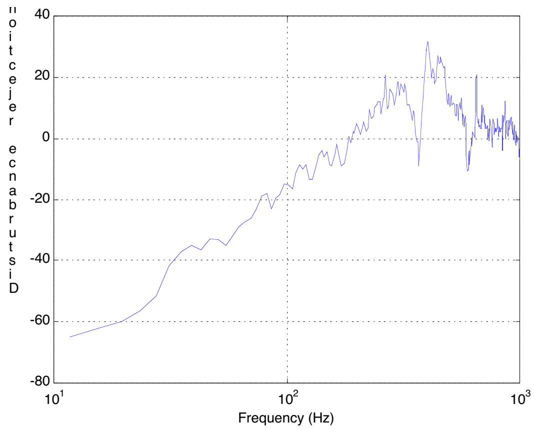

Fig. 10. Sensitivity to perturbations.

Future improvements

The breadboard shown on Figure 8 is based on an off-the-shelf magnetic bearing system. This system was initially designed for high speed rotating machines. It was enough to demonstrate the concept but it is not really adequate for a high-stroke / high-resolution device:

- *Control electronics*: the control law of the MECOS magnetic bearing are implemented on fast DSP chips because balance control of the rotor requires adaptive, digital controller;
- *Power electronics*: the high power required for the high speed magnetic bearing can be obtained from current controlled PWM driver, unfortunately these are quite noisy (ripple) for high precision system;
- *Bias current*: as mentioned previously, the required power can be drastically reduces by using permanent magnets for the bias flux.

Future works will tackle these points by:

- Investigating the use of simple analogue controllers for the magnetic bearing;
- Developing a magnetic bearing system using permanent magnets for the bias current;
- Investigating magnetic bearing configuration for the control of several degrees-of-freedom (i.e. Tip-Tilt)

At present, developments of the delay lines are on hold, both at ESA and CNES, although this simplifying approach combining quality and reliability is certainly worth further investigations.

CONCLUSION

Solar interferometry is certainly a complex endeavor. However as long as cophasing and imaging on extended objects is concerned, laboratory and sky experimentations on the 3-telescope SOLARNET breadboard have demonstrated their possibilities and performances. Further promising developments (miniaturized reference interferometers for the phase measure, magnetic bearings delay lines) are yet under development and should soon make the opportunity to use Solar interferometers in Space even more attractive and easier to implement.

ACKNOWLEDGEMENTS

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