Design of a cophasing system for a space interferometer

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ABSTRACT

The active real-time cophasing of an interferometer, that is, the fulfilment of the condition $\Delta(\mathrm{OPD}) \gg \lambda$ (OPD is the Optical Path Difference between every pair of light beams, each coming from every telescope of the array) is a crucial requirement for high resolution and long exposure image formation. So the optical concept and a possible design of a Cophasing System (CS hereafter) for a space interferometer, e.g. the Multimirror Ultraviolet Solar Telescope (MUST), will be presented.

A collimator and a pair of achromatic wedges are two of its components; the former has the target to collimate light beams which enter in the CS preserving the instrumental errors due to aberrations much less than λ in the Optical Path Lenght (OPL) of the light beams; the latter allows to choose any region of the Field of View (FoV) of the beams by their simple rotation (two degree of freedom correspond to a FoV point) in order to have high contrast features used in telescopes pre-alignement subsystem included in the CS. Ray tracing results on these optical components will be shown. Their tollerance analysis will also be discussed. A mechanical approach for each wedge rotation will be shown together with a preliminary CAD arrangement of the subsystem in a cylinrical package of diameter $\approx$ 300 mm and $\approx$ 100 mm height.

1. INTRODUCTION

The interferometric technique allows to gain high angular resolution in image formation of celestial objects using a few small diameter telescopes opportunely displaced. A non redundant, compact and 2D geometrical configuration of the interferometer, like that of the space-based MUST[1,2,3], offers large baselines and good instantaneous $u-v$ coverage for high angular resolution observation of rapidly evolving events like those of the solar atmosphere (fluxtubes, magnetic canopies, fibrils, spicules, coronal loops, prominences, sunspot umbrae, microflares, microgranulation and so on[4,5]).

Space–based interferometers rely on the absence of the atmosphere and its wavefront perturbations. Following the usual, ground–based, notation virtually $r_0 \rightarrow \infty$. Otherwise, the so called correlation time τ_0 doesn't follow the same behaviour of r_0, and it is determined by spacecraft mechanical and thermal vibrations. Assuming $\tau_0 \approx$ 1sec is a reasonable choice, following the nominal parameters of the Instrument Pointing System (IPS).

Even so, it is much greater than the one imposed by atmosphere turbolence for a ground–based observatory ($\tau_0 \approx$ 10millisec at $\lambda = 500$nm and with a wind velocity of about 10 m s^{-1}). Besides the so called isoplanatic patch is substantially 2π, and the interferometer can be pointed and cophased on any source, even if very much distant from the observed one.

To increase the exposure time over τ_0 two conditions must be fulfilled. All the telescopes of the interferometer have to be mantained absolutely coaligned (pointing) with an angular error less than a fraction of the Airy disc of each telescope. Moreover, the OPD variations between the light beams of every pair of telescopes have to be kept less than a fraction of λ (cophasing) where λ is the minor wavelength of the adopted spectral band. In this way, the fringes pattern formed by all beams is frozen and integration is possible.

The cophasing system of the previous Space Station Freedom version of the MUST interferometer, the Solar Ultraviolet Network (SUN) interferometer, was modified in order to adapt it to its new version.

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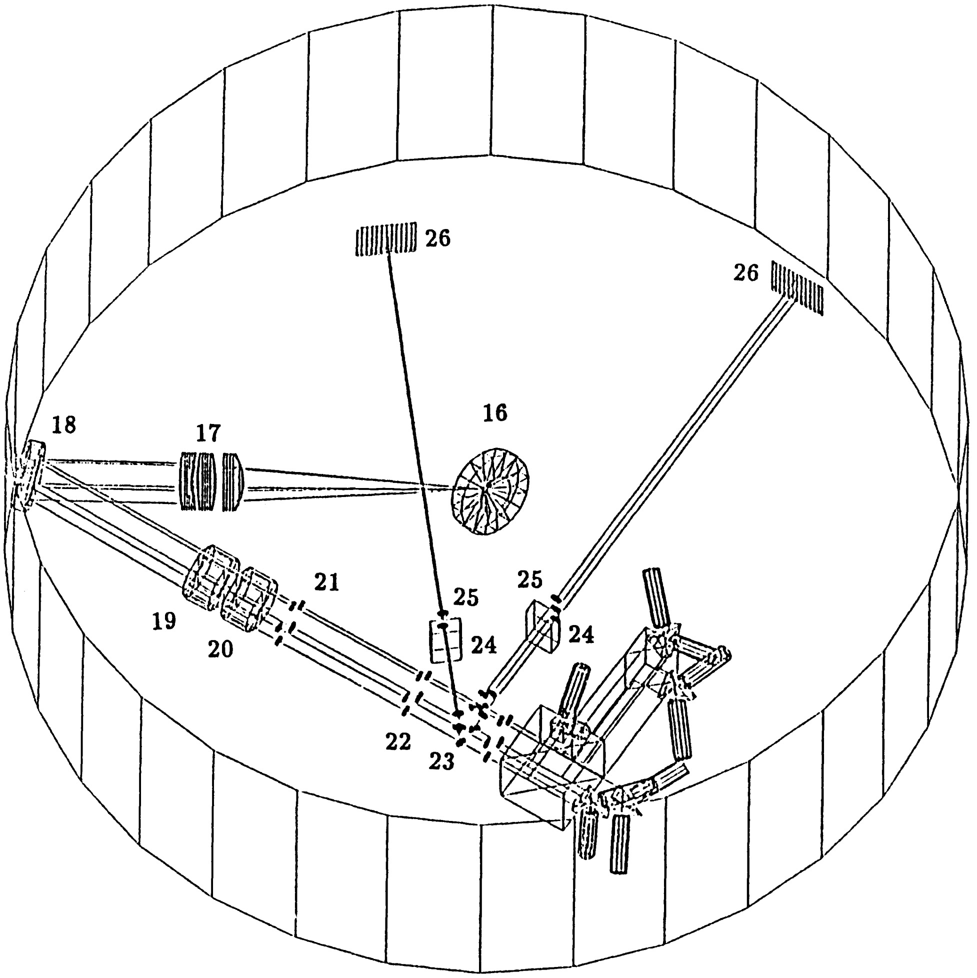

Figure 1: The design of MCS with all its principal components.

2. DESIGN OF MUST COPHASING SYSTEM (MCS)

The MCS has to be contained in a cylindrical box ≈ 30cm large and ≈ 10cm high dislocated at the center of the MUST interferometer. A Ritchey-Chrètien recombination telescope with effective focal length F≈ 750mm focalizes the beams at the center of the box where there is a flat mirror (16) inclined 45° respect to the optical axis and with a diameter of ≈ 15mm. The light corresponding to a sky FoV of ≈ 30″ passes through a pin-hole made in the center of (16) and enters in the focal instrumentation. The pin-hole entrance diameter has to be ≈ 1.5mm and has progressively to increase along the mirror thickness to let all such light to pass. The remaining FoV (≈ 5′) is reflected by (16) towards the lens assembly (17) of the CS which collimates them (see Fig.1).

Because of general optical tolerances, the Golden Rule has to be fulfilled[6,7]. This imposes the optical system formed by the recombination telescope and (17) to be afocal. In this way there are no light losses because such a system have consequently the same f-number.

Preserving the initial geometrical configuration of the entrance pupil (pentagonal) the five beams exiting from (17) are deflected by the flat mirror (18) towards a pair of achromatic rotating wedges (19-20) which allow to choose any region of their FoV. The lens sets (21-22) focalize each beam in the center of the 5 flat mirror+collimator components (23). Two of these need an orientation different from the other three to avoid their superimposition because of the particular entrance pupil geometrical configuration. Infact it doesn't exist any disposition of the mirror (16) around the optical axis which let all the beams to be imaged on the same CCD (26). Each flat mirror of (23) has a pin-hole

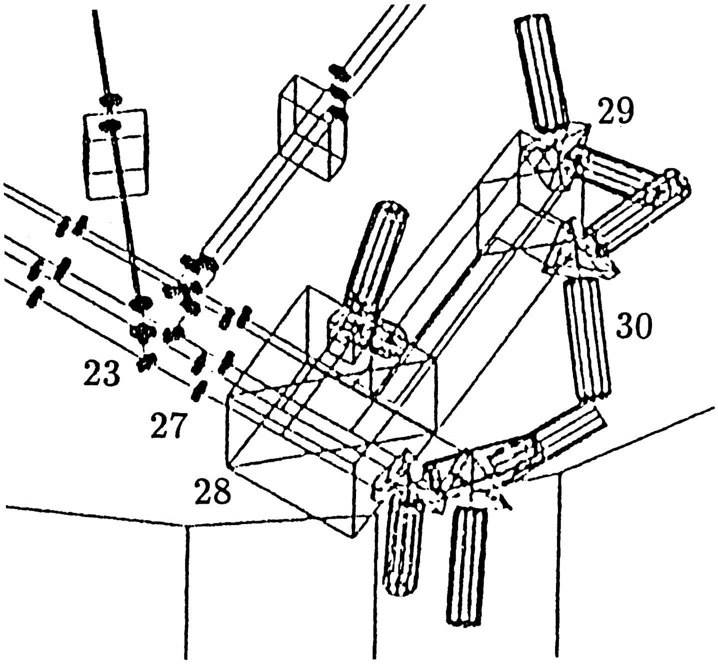

Figure 2: Reference interferometers in the MCS. The spectral band is wide $\Delta\lambda \approx 400$nm centered at $\lambda_0 \approx 600$nm. This leads to a coherence length $l_c \approx 1\ \mu$m.

large enough to let only the light corresponding to a FoV equal to an Airy disk of telescope to pass. This allows to improve fringe contrast in the following reference interferometers.
The remaining FoV ($\approx 30''$), hopefully characterized by a lot of high contrast features is reflected towards the pre-alignement system composed by (23), filters (24), objectives (25) and CCDs (26) where FoV images are formed to be successively compared. From this comparison a precision in relative pointing of telescopes of $\approx 0.1''$ is possible by secondary mirrors positional active correction. Optimization of fringe pattern contrast on the focal plane by more accurate corrections let a final pointing precision of $\approx$ 3mas to be gained.
The light coming from the focus in the center of each pin-hole of the flat mirrors of (23) is collimated by the lens set (27). Each beam is splitted by the beamsplitter array (28) to form pairs corresponding to adiacent telescopes (see Fig.2).

Each beam's pair enters the piramidal beamsplitter (29) while the OPL of a single one is modulated at a frequency $\gg 1/\tau_0$ with an oscillating wedge. At the edge of (29) there are two optical components (30) including Brewster plate polarizers, which increase fringe contrast, and SiO photodiodes measuring interference signal intensities to apply synchronous detection technique in order to detect OPD variations[8,9,10,11]. If such Δ(OPDs) $> \lambda$, an electrical signal is send to corresponding delay lines in order to compensate 'them in real time making the fringe pattern frozen.

3. LENS ASSEMBLY OPTICAL ANALYSIS

Ray tracing simulations have been made for (17) and (19-20) optical components of MCS. Details can be found elsewhere[12].

The lens–assembly has been studied in some deep detail. Solutions ranging from a singlet to 6 lenses has been optimized. In some occasions an estensive global optimization has been performed. In a few cases, asphericization has been introduced.

In Fig.3 some solutions has been sketched together with the Airy disk performances. The scale for the spot diagrams is the same other than the doublet, clearly unable to fulfill the required performances.

Even if the spot diagram gives a prompt idea of the optical quality of an optical system. Performances test and optimization has been performed with the goal of minimization of σ_w and σ_{OPD}.

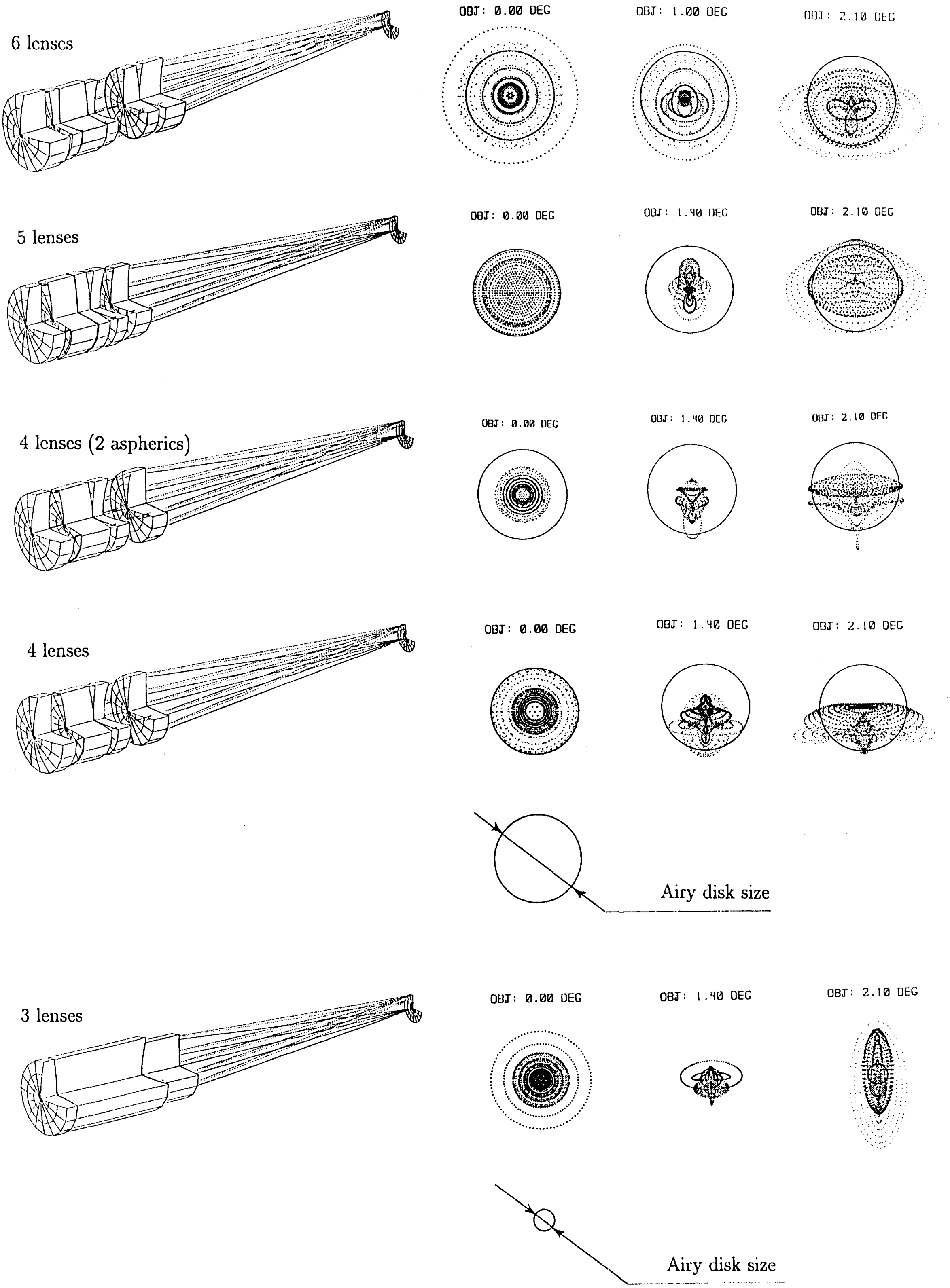

Figure 3: Layout and corresponding spot–diagram for some examples of solutions found during the MCS design.

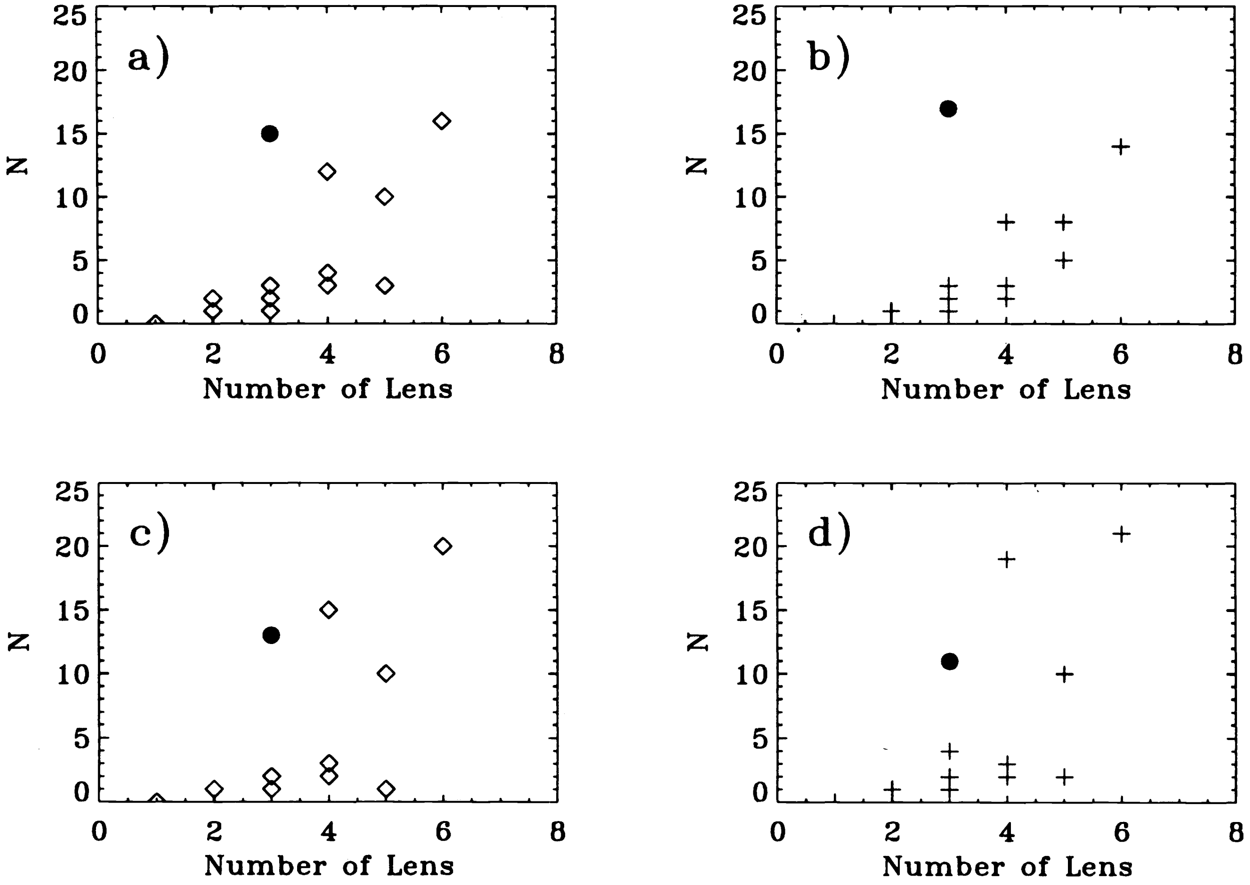

Figure 4: Fraction N of wavelenght (120 nm) vs. number of lenses employed corresponding to: **a)** σ_w for the on–axis case; **b)** σ_{OPD} for the on–axis case; **c)** σ_w for the off–axis case and **d)** σ_{OPD} for the off–axis case; the filled circle corresponds to the two concave aspherical lenses triplet T4XAFS1.

These two quantities are described in the following. It is to be recalled that the beams collected by each telescope is only a small portion of the entrance pupil of the lens assembly.

- σ_W
  It is the sum of the single rms of each of the small subpupil on the lens assembly, covered by the light incoming from each single telescope in the interferometer;

- σ_{OPD}
  It is the rms of the differences between each couple of wavefronts incoming on the lens assembly, related each one to a single telescope of the interferometer.

It is interesting to note that the rms of a spot diagram (usually used a merit function for lenses group optimization) has not, strictly speaking, the same minima location of σ_w and σ_{OPD}. The differences, moreover, changes changing the dispositions of the interferometric pupil input.

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