

# Smart co-phasing system for segmented mirror telescopes

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## ABSTRACT

Space observations of fainter and more distant astronomical objects constantly require telescope primary mirrors with a larger size. The diameter of monolithic primary mirrors is limited to 10 m because of manufacturing and logistics limitations. For space telescopes, monolithic primary mirrors are limited to less than 5 m due to fairing capacity. Segmented primary mirrors thus constitute an alternative solution to deal with the steadily increase of the primary mirror size. The optical path difference between the individual segments must be close to zero (few nm) in order to be diffraction limited over the full telescope aperture. In this paper a new system that may co-phase 7 segments at once with the light of a star and without artificial one is proposed. First the measuring methods and feedback system is explained, then the breadboard setup is presented and the results are analyzed and discussed, finally a comparison with Keck telescope is performed. This system can be adapted in order to be used in the co-phasing system of future segmented mirrors, its dynamic range starts from several hundred of microns till some tenths of nanometers

**Keywords:** Active optics, phasing, PSF, OTF, FFT

## 1. INTRODUCTION

In space observation, one of the challenges is to observe smaller and fainter objects. This can be achieved by increasing the telescope diameters. So, increasing the primary mirror diameters of the telescopes is the challenge solution but it is technically impossible to manufacture mirrors bigger than 10m in diameter. One solution is to manufacture several smaller mirrors (called segments) and co-phase them so they can behave like a single big mirror. Several co-phasing methods have been developed during the past years to break the 10m barrier.

Also, for space telescopes, the maximum diameter of a single mirror is 5m due to fairing capacity, so folded segmented primary mirrors shall be developed.

This paper describes the results of a light co-phasing setup mounted in laboratory. This setup is able to correct a piston from 200 $\mu$ m to 15 nm based on coarse (200 $\mu$ m to 300nm) and fine (300nm to 15nm) measurement methods.

Both measurements are then chained in a feedback system in order to completely co-phase and keep aligned the segments.

### 1.1 Coarse measurement

In the coarse measurement, a mask is placed in front of the telescope, preferably perpendicular to the collimated rays. This mask samples the incoming light of a star in 7 sub-pupils (round holes) each one in front of each segment. Then the light of all the holes pass through a spectral filter, and finally a CCD sensor records the Point Spread Function (PSF). The coarse measurement analyses the MTF (Modulation Transfer Function) of the OTF (Optical Transfer Function) and it is calculated from the PSF. This method is largely described in [1].It was implemented and tested with a breadboard presented hereafter.

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## 1.2 Fine measurement

The fine measurement uses the same OTF as the coarse measurement, but the analysis is achieved over the PTF (Phase Transfer Function) instead of the MTF. This method is explained in [2] and was implemented and validated with the breadboard presented hereafter.

## 2. CO-PHASING FEEDBACK SYSTEM IMPLEMENTATION

### 2.1 Optical setup

First, the light generated by a Xenon bulb illuminates a pinhole (see Figure 1) to simulate a star.

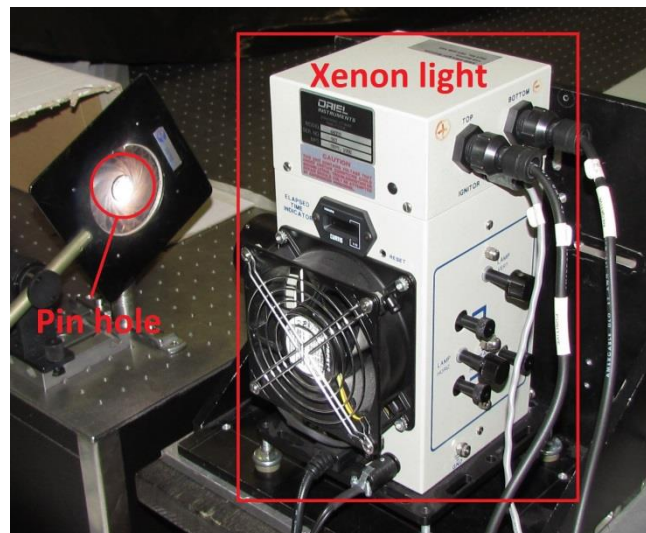


Figure 1. Xenon light and pinhole

The light from the pinhole goes to an off-axis parabola to simulate a telescope primary mirror and a mask to simulate the segments (S1 to S7). They are illustrated in Figure 2. In this case, each sub-pupil covers the entire surface of each segment but in a real telescope, each sub-pupil covers only a small part of each segment.

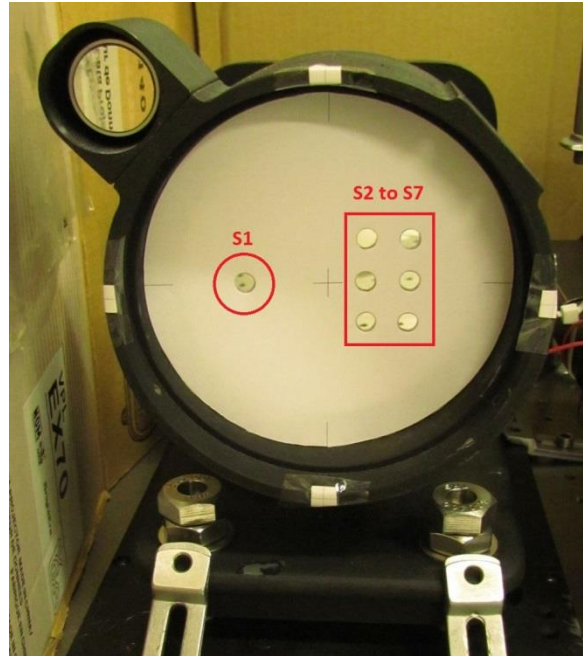


Figure 2. Off-axis parabola and mask for 7 segments used in the coarse and fine measurements.

The light of the segments S2 to S7 goes to the left flat mirror (see the Figure 3) and the light of S1 goes to the right flat mirror. The S1 mirror can be moved by a piezo-electric actuator in order to adjust the Optical Path Difference (OPD or piston error) between the light from S1 and the other segments. The corner cube is used with an Agilent HP5519A interferometer to compare and verify the measurements. The piezo-electric actuator is hidden behind the S1 mirror so it cannot be seen on the picture.

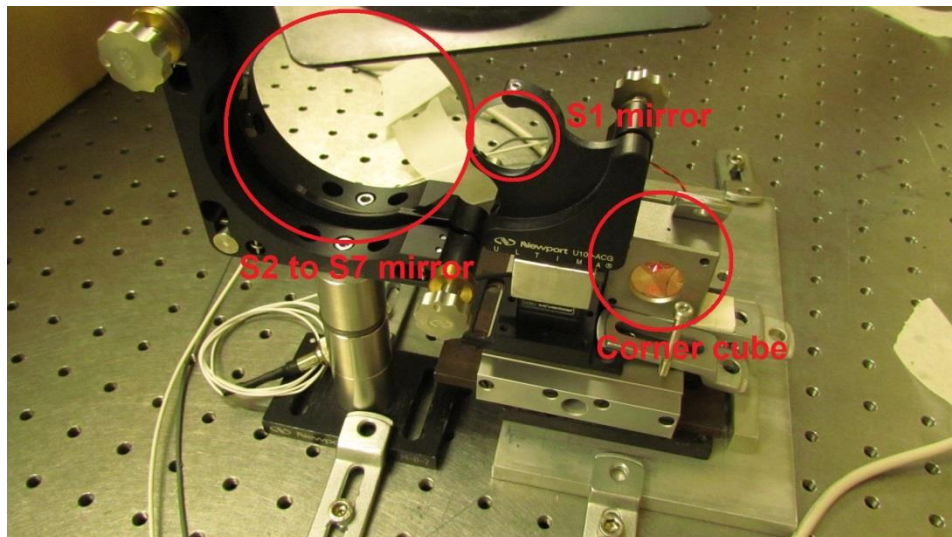


Figure 3. Flat mirrors and corner cube

The light from the flat mirrors converges to the CCD camera passing through three different filters (see Figure 4), one at a time. In this way, the CCD records the PSF of the segments S1 to S7.

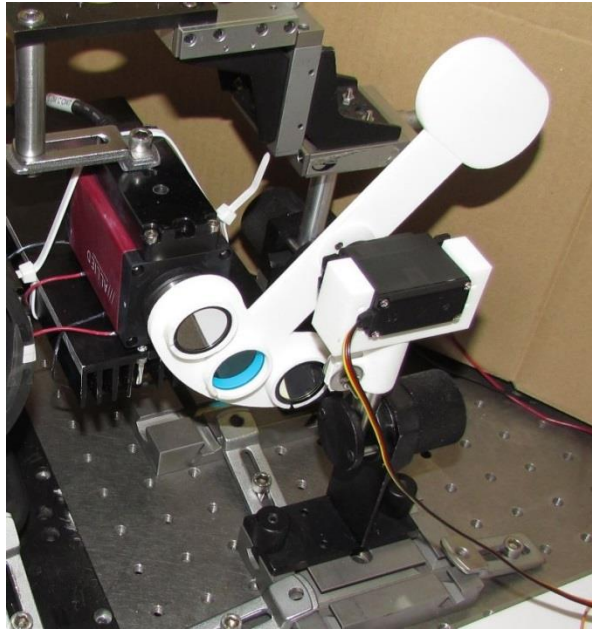


Figure 4. Filter wheel and camera

The piezo-electric actuator and the filter wheel (Figure 4) are controlled by a PC using the control card shown in Figure 5.

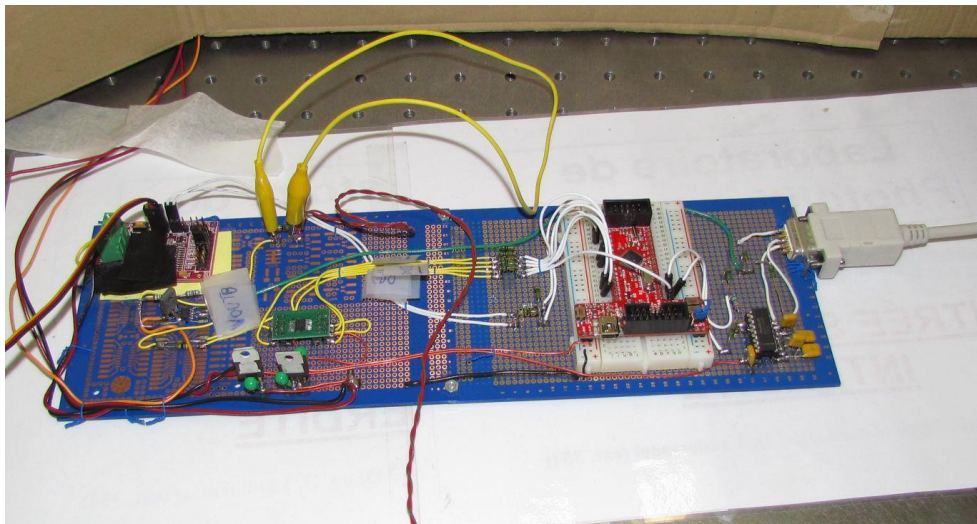


Figure 5. Control card

## 2.2 Coarse measurement implementation

The coarse measurement was implemented by calculating the absolute value of the amplitude of the Fast Fourier Transform of the PSF (See the MTF in Figure 6) and measuring the height of the red circled peaks.



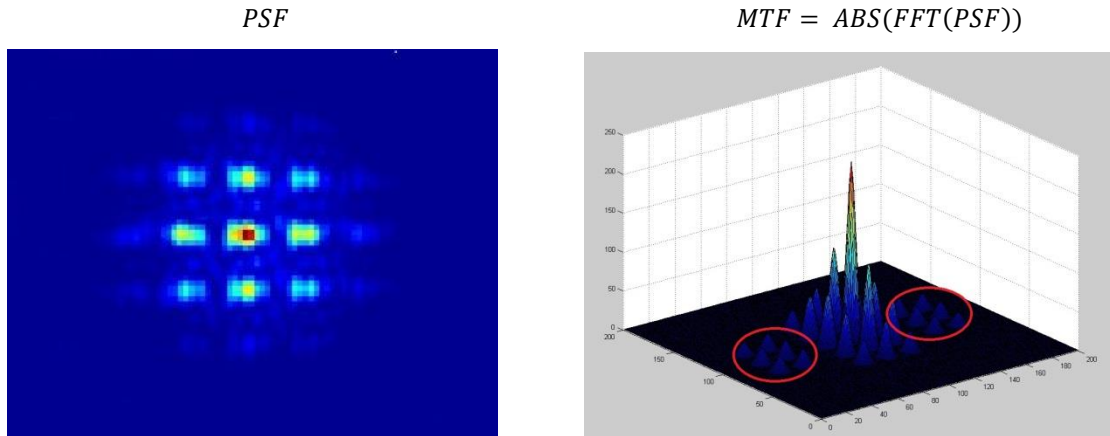


Figure 6. PSF (left) and MTF (right) used in the coarse measurement

### 2.3 Fine measurement implementation

The fine measurement was implemented by calculating the argument of the Fast Fourier Transform of the PSF (see the PTF in Figure 7) and measuring the average height of the yellow dotted peaks.

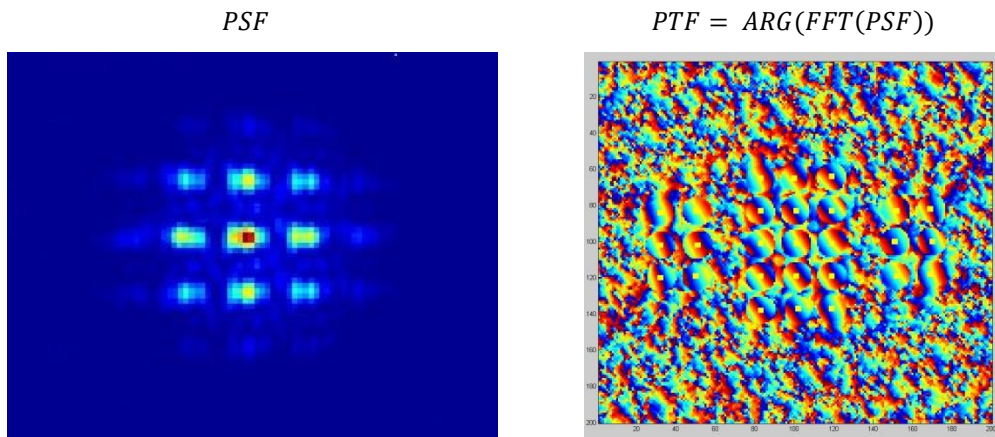


Figure 7. PSF (left) and PTF (right) used in the fine measurement

### 2.4 Feedback system implementation

The feedback system was implemented in the following way: The PC records the PSF with the CCD camera and then calculates the MTF and PTF from the PSF. After that, it measures the peaks of the MTF and PTF (coarse and fine measurements, respectively) and sends the information of the coarse measurement to the piezo-electric actuator in order to correct the piston error. When the coarse measurement of the first filter reaches 0, the PC changes to the second filter and it measures again. When the coarse measurement of the second filter reaches 0, the PC changes to the third filter and it measures again. When the coarse measurement of the third filter reaches 100nm, the PC changes back to the first filter and measures again but this time it measures the peaks of the PTF. Finally It performs measures and corrects the piston from the fine measurement indefinitely in order to maintain the piston error to less than 15nm.

### 3. RESULTS

Table 1 illustrates the measurements achieved with the system when the whole co-phasing is finished.

Table 1. Results of piston measurements after the co-phasing is finished. Average of 50 measurements (Left column), standard deviation (Center column), HP5519A measurement (Right column, this measurement have a known Standard Deviation of 10nm).

<b>Average (nm)</b>	<b>2xStdDev (nm)</b>	<b>HP5519A (nm)</b>
1	8	-2
0	14	-12
1	16	1
1	10	1
0	12	-2
1	12	-2
0	14	-2
-1	14	-1
0	16	-21

The measurements performed with the system here above presented show good correlation with a interferometer (HP5519A) uses as standard. The average of the measurements does not exceed +/- 1nm so it is more precise than the co-phasing requirements (typical wavelength of  $550\text{nm}/40=13.75\text{nm}$ ).

However, the 2 x Stdev of 16nm is related to the xenon light instabilities.

## 4. COMPARISON WITH KECK

The following table has been adapted from [8] in order to compare the Keck measurement system to the system described in this paper.

Table 2. Comparison with Keck telescope system

Procedure Name	Narrowband SH	Fine Measurement	Broadband SH			Coarse Measurement			PDS
			+/-30	+/-3	+/-1	+/-164	+/-16	+/-0.6	
Special Instrumentation	Yes	Yes	Yes			Yes			No
Pupil Registration	Yes	Yes	Yes			Yes			No
Iterative	No	No	No			No			Yes
Capture Range ( $\mu\text{m}$ )	0.100	+/-0.300	+/-30	+/-3	+/-1	+/-164	+/-16	+/-0.6	0.400
Accuracy (nm)	6	1	1000	100	30	30000	3000	100	40
Number of Exposures	1	1	11	11	11	1	1	1	11-12
Execution Time (min)	20	1	30	30	30	1	1	1	45
Star Magnitude	5	-	4	5	6	-	-	-	3-4
Central Wavelength (nm)	852	632.8	891	870	700	632.8	560	507	3310
Filter FWHM (nm)	30	1.22	10	100	200	1.22	9.4	210	63

The Fine Measurement is comparable with the Narrowband SH system and the Coarse Measurement is comparable with Broadband SH system.

Additional assessment shall be realized in order to estimate the required Star Magnitude.

The execution time is significantly less but the exposure time used in the system is 0.3s in comparison with 30s for the Keck system.

## 5. CONCLUSIONS

A very compact and light system has been presented. The uncertainty of this system is well below the co phasing requirements. These qualities allow his use on space as well as on ground-based telescopes. However in order to be implemented on ground-based telescopes, an additional system capable to correct for the atmospheric turbulence is necessary.

The system speed and precision can be improved using high speed camera and optimized piezo-electric controller card.

The described system has several advantages in comparison with the Keck telescope system but additional assessment shall be realized to validate it in a real segmented telescope.

## REFERENCE LINKING

- journal paper: [1] Simar, J.F., Single wavelength coarse phasing in segmented telescopes, Applied Optics, Vol. 54, Issue 5, pp. 1118-1123 (2015).
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