Gemini Prime Focus Wavefront Sensor

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ABSTRACT

A Prime Focus Wavefront Sensor (PFWFS) has been designed and built at the Gemini Observatory. The system contains a Shack-Hartmann (SH) wavefront sensor and has been designed to use commercial components. The primary mirror of the 8m Gemini Telescope has a complex active optics system[1,2] that needs to be calculated during commissioning. The wavefront sensor was built to measure the image quality at prime focus, this eliminates the secondary mirror introducing supplementary aberrations. It has been successfully used during commissioning, to test the active optics.

Keywords: wavefront sensor, commissioning, prime focus, Shack-Hartmann

1. INTRODUCTION

The PFWFS is composed of 3 main subsystems (see figure 1):

1) The opto-mechanical assembly mounted on the top end of the telescope. Its function is to position the wavefront sensor relative to the primary mirror and to retain the optics in place.
2) The guiding and image acquisition unit. Its function is to maintain the primary mirror focus image stable during a measurement and record the images before transfer to the analysis software.

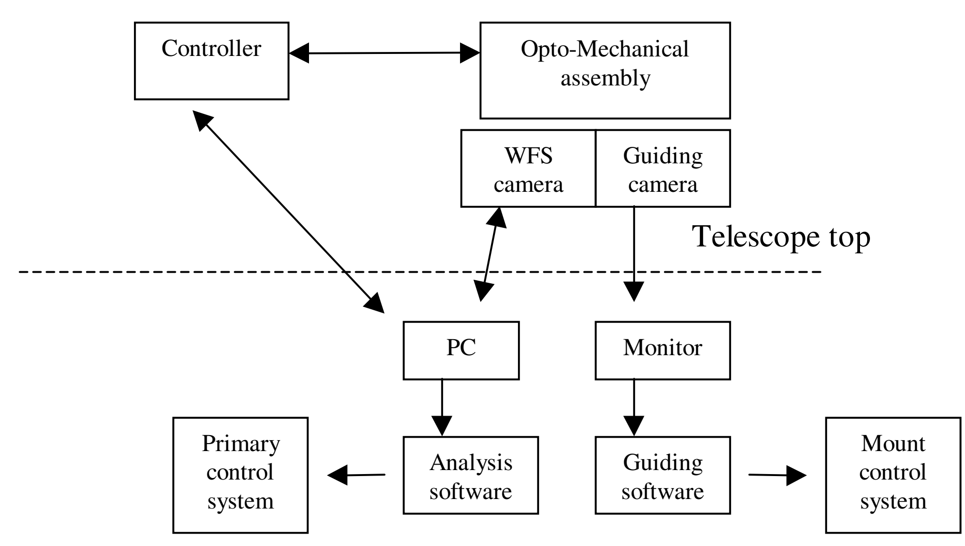

Figure 1: PFWFS overall layout

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3) The analysis software calculates the zernikes. These zernikes are then applied to the primary mirror active optics system to change the shape of the mirror and improve the image quality.

We also developed a calibration bench in order to align and calibrate the prime focus wavefront sensor before mounting it on the telescope. Finally, we explain the nighttime operation of the PFWFS and present some results obtained during commissioning.

2. THE OPTO-MECHANICAL ASSEMBLY

The assembly incorporates 3 axes of translation motion and an aperture wheel. It is designed for installation on the telescope top end, at prime focus (see figure2). A black anodized ring supports the 3 XYZ stages and is attached on the top end using a 3 points interface. The stages are positioned so that they are aligned with the telescope axes. These stages are from the ATS100 positioning stage series, fabricated and calibrated by Aerotech Inc (see table1 for details). They use a 50SMB2 motor and a E1000LD rotary encoder with a 2steps/mm control resolution. They are operated using a Unidex 12 4-axes controller in a 19” rack mount configuration including a DM4001-40-F1 amplifier. It is mounted on the –Y side of the telescope on the top ring, approximately 5 meters away from the stages.

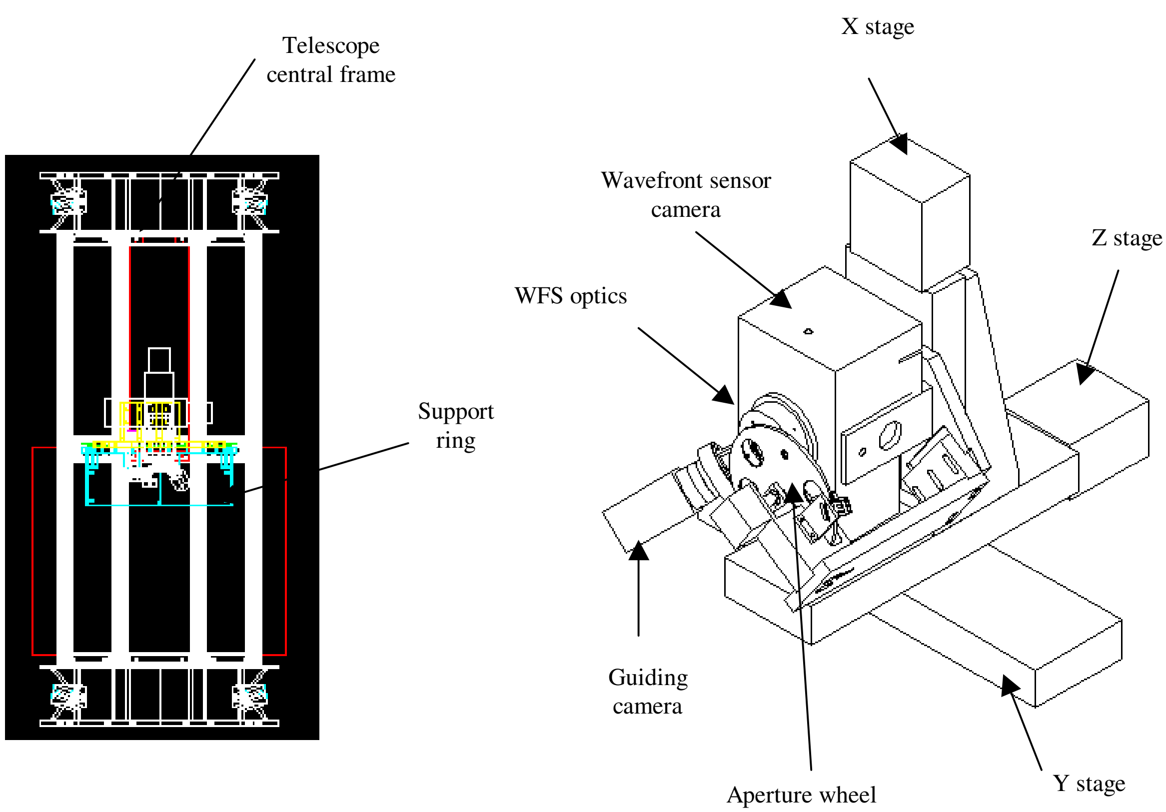


Figure 2: The opto-mechanical assembly.

Stages	*Reference*	*Travel (mm)*	*Max Speed mm/sec*	*Linear resolution (mm)*	*Accuracy (mm)*
X	ATS100-50	50	50	1	2
Y	ATS100-150	100	50	1	5
Z	ATS100-150	100	50	1	5

Table1: Stage specifications

The controller has a hand panel in the front for manual positioning of the stages or it can be controlled from a standard PC using its serial port. The control PC is located at the bottom of the telescope and connected to the controller via cables attached to the telescope structure. A command language enables the user to define small scripts to move the system, for example "in" or "out" of the beam. Instant commands are also available to control the stage in real time.

3. THE GUIDING AND ACQUISITION SYSTEM

The optics

The wavefront sensor optical layout is shown in figure 3. The light from the f/1.8 primary mirror enters the PFWFS and goes through a collimating lens. After the beam is split by the beamsplitter cube, one beam goes to the guiding camera and the other one toward the wavefront sensor. The beam diameter is equal to 8mm. The WFS is a Shack-Hartmann type using lenslet arrays fabricated by Adaptive Optics Associate (AOA). These are standard off-the-shelf monolithic lenslet modules replicated onto glass substrate. The lenslet array 400 (see table 3 for details) has proven to be the most beneficial. It has been very useful when measuring the primary mirror figure either before optimizing its shape or after introducing known aberrations for testing. The other lenslet array proved to be more difficult to use because of its reduced sensitive range. The PFWFS is also designed to accommodate a filter after the lenslet array but it was not used during commissioning.

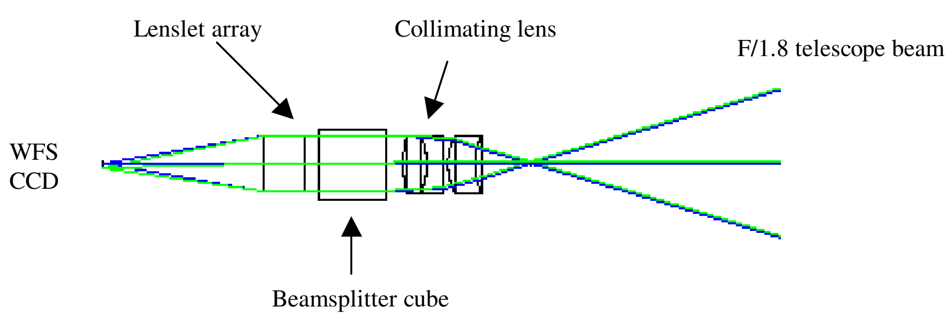


Figure 3: Shack-Hartmann wavefront sensor optical layout.

Optical element	*Reference*	*Specification*
Collimating lens	Melles Griot 06GLS 003	Foc = 14.5mm Clear aperture = 8mm
Cube beamsplitter	Melles Griot 03BSC 003	Size 10mm
Lenslet array 250	AOA 250-18-SX	Foc=18mm Lenslet shape; square Lenslet size = 250mm Illuminated lenslets = 32x32
Lenslet array 400	AOA 400-24-SX	Foc=24mm Lenslet shape; square Lenslet size = 400mm Illuminated lenslets = 20x20

Table 2: WFS optics

Optical element	*Reference*	*Specification*
Mirror	Melles Griot	Size Angle = 22.3 degrees
Focusing lens	Melles Griot 01LAO 019	Foc = 25mm Clear aperture = 12mm

Table 3: Guider optics

The guiding optical layout is shown on figure 4. The collimated light coming out of the beamsplitter cube is reflected on a folded mirror and directed towards the focusing lens.

The guiding and image acquisition system

The guiding camera is composed of a Pulnix TM-7 series camera on which is mounted a standard C-mount objective with the focusing lens. The field of view is around 20 arcsec on the sky. The images are displayed on a UNIX Sun station. The guiding software calculates the centroid coordinates of the star image in a user-defined guiding box, and sends offsets directly to the telescope mount to keep it centered in that

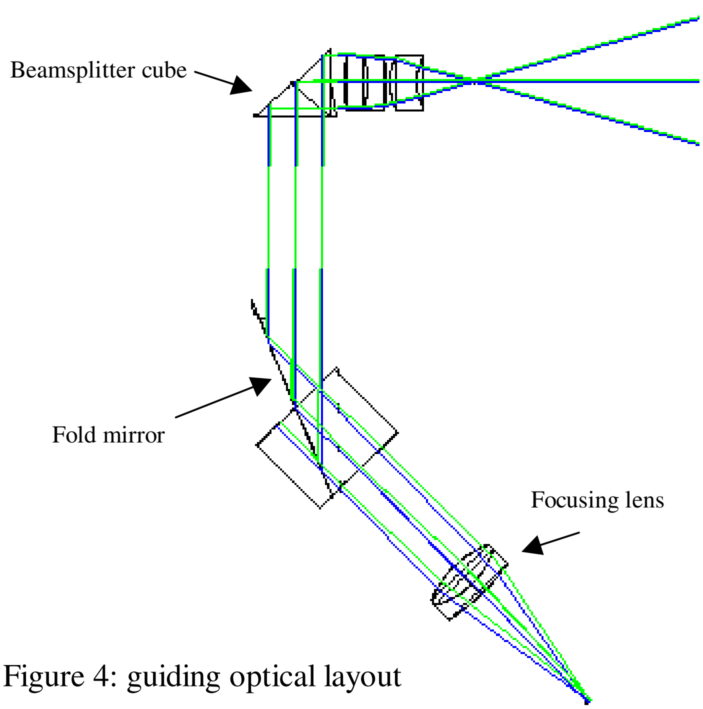


Figure 4: guiding optical layout

box. The overall frequency of the system is between 5 and 10 Hz, which was sufficient for this wavefront sensor.

The wavefront sensor camera is a Photometrics Sensys K1600 camera. It has a high-speed mechanical shutter to select the camera integration time. The camera is connected to a 12bit video card on a PC which stores the images. In the acquisition software called Vwin, we wrote a script to average and format the WFS images before sending them to the data analysis software. We average the images so that we get a better measurement of the mirror shape, without taking into account the atmospheric turbulence.

Cameras	*Pixel number*	*Pixel size (mm)*	*Pixel scale on sky (arcsec)*	*Number of Pixels per lenslet*	*Comments*
Pulnix TM-7	768x494	8.4x9.8	0.07x0.08		Interline transfer
Photometrics Sensys K1600	1536x1024	9x9	Lenslet 250: 0.1 Lenslet 400: 0.08	Lenslet 250: 28 Lenslet 400: 44	12 bit cooled CCD

Table 4: Cameras characteristics. The field of view per lenslet is 2.9 arcsec for the lenslet array 250 and 3.5 arcsec for the lenslet array 400

4. THE DATA REDUCTION SYSTEM

The software package used for analyzing the wavefront sensor data is called WaveLab written by Adaptive Optics Associates, Inc., a United Technologies company. WaveLab is a Shack-Hartmann wavefront sensor data analysis system that permits any Shack-Hartmann test data to be converted to wave fronts. The software uses a graphical interface that makes standard data reduction straightforward and also provides a command line interface for customized data handling.

WaveLab is an extension to the tcl scripting language and Gemini has taken advantage of the capability of customizing the scripts to handle the data in a specialized way. Gemini has written some in-house tcl scripts, allowing for a friendly user interface, by doing so, it has made data reduction quick and easy. The tcl scripts will take a specified image and allow the user to interact with the image. By creating one mask, it can be stored and used to reduce all subsequent images, provided no physical changes are made, such as a lens change. Figure 5 shows the GUI used to begin the WaveLab data reduction process.

The tcl script allows the user, file manipulation, setup varies parameters, do calibrations, make OPDs and fit Zernikes. It has various tools, which lets the user manipulate the image format and files, as well as several engineering tools. Once the user has created the necessary files needed for data reduction, they can be saved to a configuration file. From that point on, the configuration file can be saved and each night it can be loaded into wavelab. The user can run up the software, load the configuration file and start making OPD images and fitting Zernikes almost immediately.

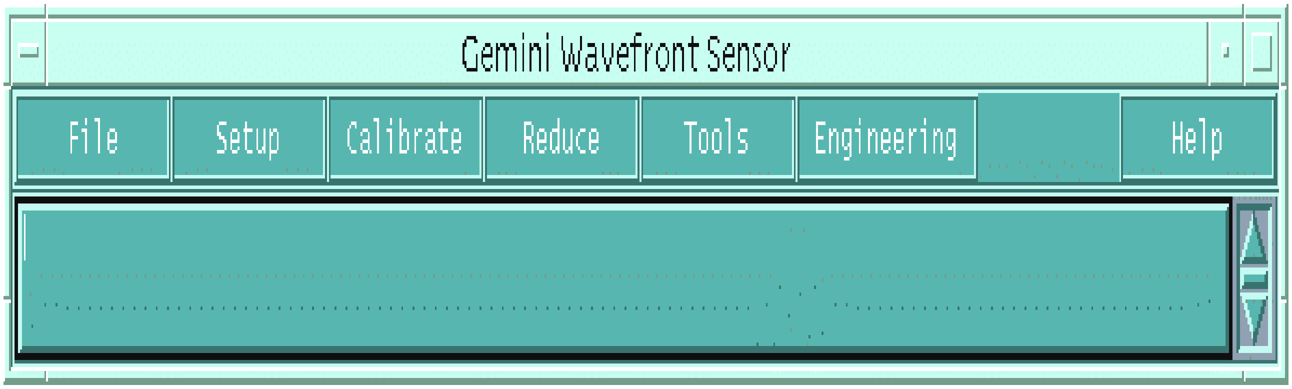


Figure 5: The graphical user interface used to begin the data analysis.

5. THE CALIBRATION BENCH

The calibration bench (Figure 6) gives a f/1.8 output beam, same as the primary mirror. It is composed of a He-Ne laser with a beam expander, a focusing lens and a spatial filter. It includes also a polarizer to control the beam intensity. A XYZ stage assembly supports the wavefront sensor. The calibration bench is used before mounting the wavefront sensor on the telescope to measure the reference positions of the lenslet array spots, and to get a reference position on the guider. For an order of accuracy, we obtain usually between 2 and 3nm RMS on the wavefront by taking multiple reference images during one calibration on the wavefront sensor. If we compare reference images taken over different months, we obtain around 20 to 30nm RMS on the wavefront. This accuracy is good enough for measurements that are well above 100nm RMS.

Component	*Reference*	*Comments*
HE-NE laser	Melles Griot 05 LHP 111	1mW power output
Polarizer	Melles Griot 03 FPG 001	
Focusing lens	Melles Griot 04OAS012	F=10.8mm
Spatial filter	Melles Griot 04 PPM 001	2mm diameter

Table 5: calibration bench components.

6. NIGHTTIME OPERATIONS

First, we pointed to a bright star to align the PFWFS relative to the primary mirror, using a screen mounted on the PFWFS. Then, we centered it on the optics using the XYZ stages and tested the guider. Once the beam is lined up with the alignment camera, wavefront sensing can begin. Usually a star with a magnitude of 6-8 in the visual is chosen. Integrations begin and the data is reduced using WaveLab in real time. One major advantage of using the PFWFS is the minimum of optics the beam has to be directed along. This makes analysis of the primary mirror much easier.

The first image collected is usually made into a Mask image, shown in Figure 7. It uses data obtained from starlight to identify the subapertures on the light sensor plane and to match them to subapertures in the pupil's plane. Generally, reference data include the effect of the system's optics on the light beam. Also, we verify the XY orientation of the pupil image relative to the primary mirror axes by vignetting the telescope pupil with the dome.

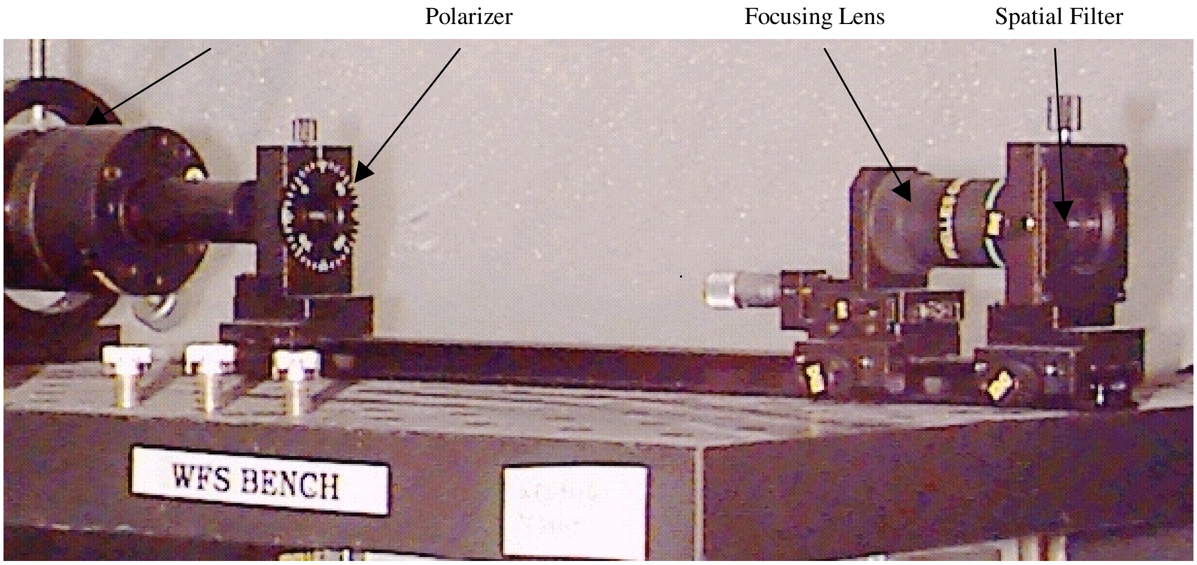


Figure 6. WFS Calibration Bench.

Once this is completed another image is taken and after checking the OPD's to make sure everything has been set up correctly, images are taken and Zernikes are fit to the incoming data. Once the Zernikes are calculated, they are then put into the adaptive optics (aO) software and the forces are adjusted. More data is collected, reduced and applied to the forces until the root mean square of the optical path difference (OPD) is within the Gemini specs. All this can be accomplished within a relatively short period of time.

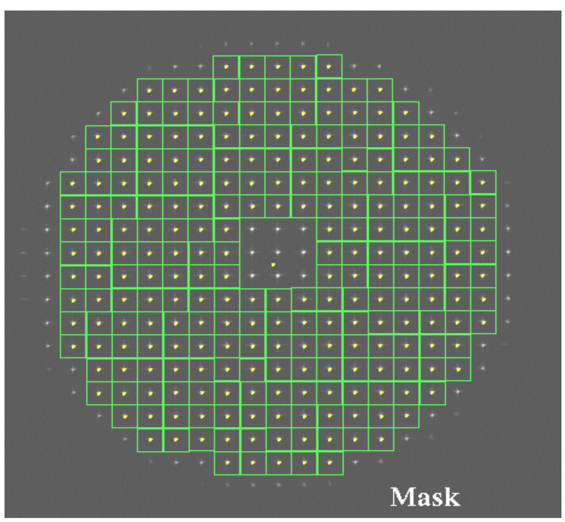


Figure 7: Mask image made from a telescope image, and positioned over a calibration image.

7. RESULTS FROM GEMINI COMMISSIONING

We present results taken on the Gemini 8m telescope during commissioning last August 1999 and September 1999. Presented are vector maps, optical path differences and elevations tests.

Vectors maps are plotted to show the slope of the spots (see figure 8). They all point in the same direction, provided no zernikes are removed. If they fail to do so, there is most likely something wrong with the wavefront sensor set up. We also present a vector map showing what they look like after having tip/tilt and focus removed. The vector maps are then turned into OPDs. The zernikes values are calculated from these images and applied into the primary mirror control system. After multiple iterations, the image quality is improved. Figure 9 is an example of such a result, where the RMS was reduced to 0.177 micron.

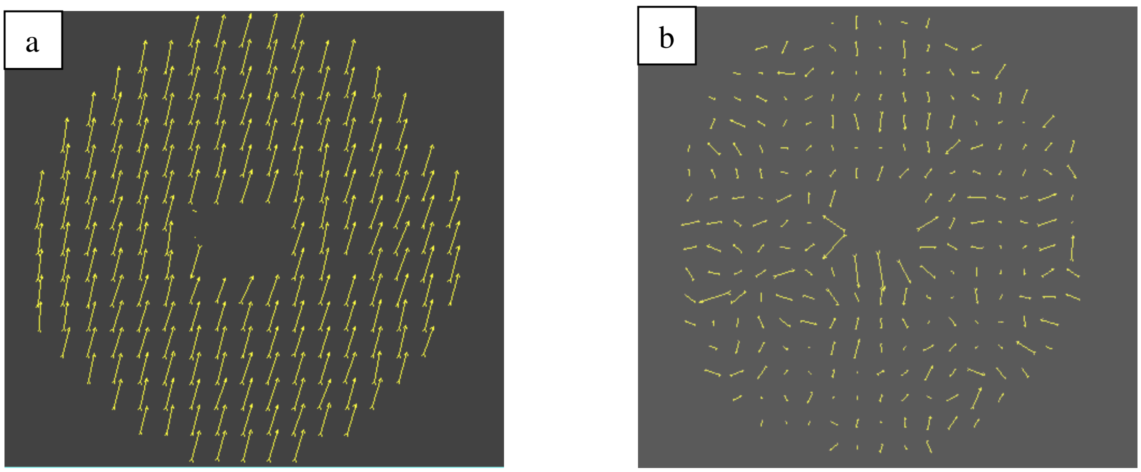
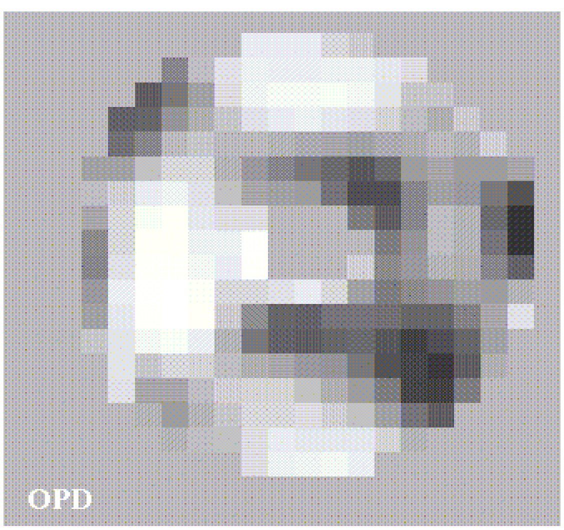


Figure 8: (a) Vector map with no tip/tilt and focus removed, (b) vector map with tip/tilt and focus removed.



ZERNIKES values:

2	-0.170246	# rcos(t) (X Tilt)
3	0.034938	# rsin(t) (Y Tilt)
4	-0.004357	# 2r^2-1 (Focus)
5	-0.123626	# r^2cos(2t) (0 Astigmatism)
6	0.114531	# r^2sin(2t) (45 Astigmatism)
7	0.204063	# (3r^2-2)rcos(t) (X Coma)
8	-0.066433	# (3r^2-2)rsin(t) (Y Coma)
9	0.018060	# 6r^4-6r^2+1 (Spherical)
10	-0.073964	# r^3cos(3t)
11	-0.050465	# r^3sin(3t)
12	-0.109250	# (4r^2-3)r^2cos(2t)
13	-0.054909	# (4r^2-3)r^2sin(2t)
14	-0.014879	# (10r^4-12r^2+3)rcos(t)
15	-0.020338	# (10r^4-12r^2+3)rsin(t)
16	-0.028788	# 20r^6-30r^4+12r^2-1
17	0.039307	# r^4cos(4t)
18	-0.012580	# r^4sin(4t)
19	-0.013830	# (5r^2-4)r^3cos(3t)
20	-0.018696	# (5r^2-4)r^3sin(3t)

Figure 9: OPD image with a RMS of 0.177nm, and corresponding zernikes.

The PFWFS was also used to determine the evolution of the primary mirror shape versus elevation. In this case, we maximize image quality at the zenith, by dialing out the lower order zernikes and making measurements without using the active optics. Figure 10 shows the results obtained during another night, for astigmatism and coma. You can see the strong variation of 0 astigmatism versus elevation, and the same for Ycoma.

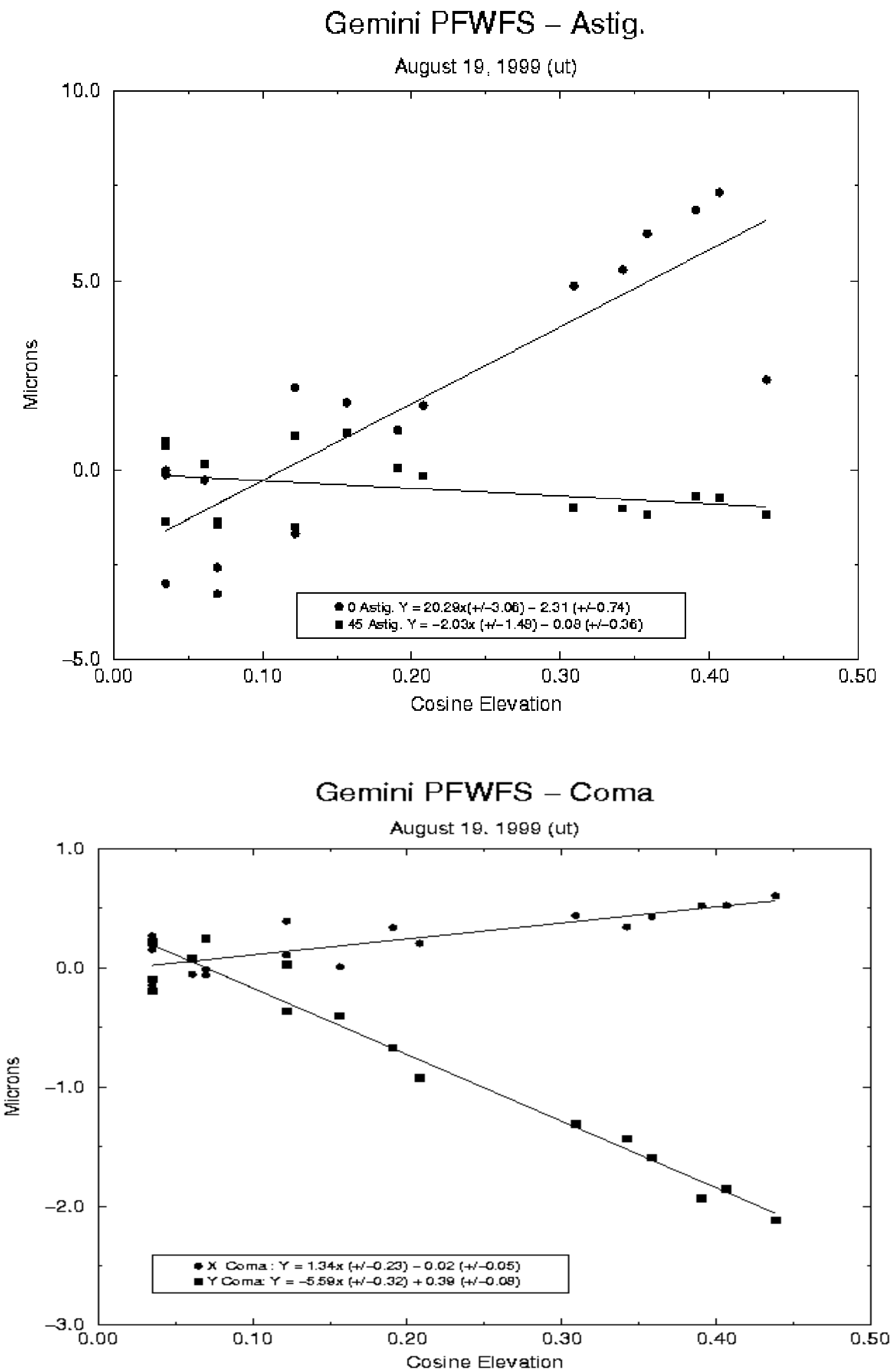


Figure 10. Astigmatism and coma results.

8. CONCLUSION

This paper described the Prime Focus Wavefront Sensor used during commissioning of the Gemini 8m telescope. Mainly designed and fabricated using off-the-shelf components, this is an instrument with a relatively low financial overhead and low maintenance. Its robust performance gave us the ability to measure most of the primary mirror control system characteristics repeatedly. After mounting of the secondary mirror on the telescope and because of the PFWFS's good performance, the PFWFS was not stored on the shelf but easily transformed into a Cassegrain Focus Wavefront Sensor (CFWFS) to continue wavefront measurements of the whole telescope.

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9. REFERENCES

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2. M. K. Cho and L. M. Stepp, "Effect of Gemini primary mirror position, relative to the lateral support, on mirror fatigue", *SPIE Proc.* **4003** [4003-19], 2000.