CHAPTER VI

Details of Real-Time Experiment and Results

6.1 Introduction

In order to validate the performance of the simulated Wavefront Sensor using experimental Polarized Shearing Interferometer - based Wavefront Sensor (PSI-WS), Laboratory experiments were carried out at the Photonics Laboratory in Indian Institute of Astrophysics, Bangalore. This Chapter describes the details of the Laboratory experiment needed to execute the phase extraction and wavefront reconstruction algorithm. It justifies the performance and efficiency of the phase extraction algorithm using PSI-WS in real-time. A turbulence simulator using two rotating phase screens is designed for the realization of real observation conditions for Adaptive Optics instrument is described. The Laboratory experimental results which were obtained in the presence of turbulence phase plate are presented. An optical design has been worked out for carrying out the experiments with PSI-WS. The details of the optical layout for the measurements and the experimental procedures adopted are presented. It explains the efficient algorithm for estimation of the errors and reconstruction in an open loop system in the LabVIEW platform.
If the wavefront error is measured once and corrected once, followed by the acquisition of images, operation is said to be in "open loop". This is also necessary for verifying the efficiency of the algorithm for phase estimation and wavefront reconstruction with open loop Adaptive Optics system.

### 6.2 Real-Time Turbulence Simulator

An effort has been put to create a novel means of modelling the spatial and temporal characteristics of phase plates with low cost. A turbulence simulator using two rotating phase screens for a realistic condition was used. Several different technologies using both reflective and refractive methods have been reviewed [69]. The first and natural technique is to use fluid simulators with air or water which is practically complex. Methods such as photo etching [101], near refractive index matching [102] and hair spray [103] have been explored successfully.

As a first step, a phase plate was generated by applying oil and gel between two thin plane parallel glass plates. After the characterization it was found that the phase plate was not matching well with Kolmogorov model. Secondly, hair spray was applied between the two thin plane glass plates. A simple optical experiment has been done in order to characterize the phase plates. So, the implementation of turbulence has been done with hair spray. Hair spray is sprayed on the transparent glass plate in a multiple layer basis with a finite time interval for random turbulence. Two multilayer sprayed glass plates are sandwiched together for better results as shown in the Figure 6.1. For this purpose ordinary hair spray (Gatsby
product) has been used. This product contains a component called amphomer, which resembles resin. Dust issues were avoided by sealing the sprayed surface between two plates. For dynamic turbulence behaviour, the sandwiched glass plates were rotated with 13 rpm. The hair spray also appears to have good longevity, evident by the turbulence characteristics of sprayed glass plates. The actual experiment was performed on anti-vibration isolation table and the components were mounted as per the optical layout.

Figure 6.1: Sample Phase Plate (Two Sprayed Glasses Sandwiched)

6.2.1 Optical Experimental Setup

For this research, a 30 mm primary telescope aperture has been chosen for the design. In the Figure 6.2 extremely simple turbulent simulator setup is shown. Light coming from the source was collimated by a lens and then it was guided to the detector. Now the phase plates were introduced in the collimated beam in order to generate the phase screens as shown in Figure 6.2. Dynamic turbulence was realised by rotating the phase plates with a speed of 13 rpm.
Figure 6.2: Schematic of Optical Layout for Characterising Phase Screens

In the Figure 6.3 the experimental setup is shown with hair spray, gel and phase plate at the anti-vibration table. The collimated beam propagates through the phase plate, and gets distorted. This distorted wavefront was grabbed by PixelFly CCD detector for characterisation of phase screens.

Figure 6.3: The Laboratory Setup used for Characterizing Phase Screen with Hair Spray and Phase Plate

Different intensity scale for different configurations improves the contrast. The Figure 6.4.A and B shows the experimental phase screen, which was obtained with turbulent simulator. The Figure 6.4.A shows the Phase Screen obtained when a plane glass plate without hairspray is inserted in the beam path. The Figure 6.4.B
shows the Phase Screen obtained when a plane glass plate with hairspray is inserted in the beam path. In the laboratory experiment, the phase plates or the phase screens were characterized by measuring the value of the $r_0$ using the Power Spectrum method. The developed turbulence model is based on the Kolmogorov model.

![Sample Phase Screen](image)

Figure 6.4: Sample Phase Screen Obtained with Phase Plate at $D/r_0 = 1.5$

### 6.2.2 Power Spectrum Calculation

A way to estimate the Fried parameter is to measure the power spectrum of the phase distortions. The relationship between the phase fluctuation power spectrum $W(f)$ and the Fried parameter $r_0$ [104] is given by:

$$W(f) = 0.0028\left(r_0^{-5/3} f^{-11/3}\right)$$

(6.1)

where $f$ is the spatial frequency. $W(f)$ is related to the OPD $\delta$, by
\[ W(f) = \alpha \cdot \langle |FFT(\delta)|^2 \rangle \cdot (\lambda/2\pi)^2 \]  \hspace{1cm} (6.2)

where FFT is the Fast Fourier Transform, \( \langle |FFT(\delta)|^2 \rangle \) is the spectral energy and \( \alpha \) is the co-efficient converting the spectral energy in power spectrum. \( \alpha = N_{\text{tot}} \cdot \tau^2 \) where \( N_{\text{tot}} \) is the total number of pixels in the image and \( \tau \) is the size of the pixels. Using the above equations in LabVIEW, the fried parameter is obtained as a function of \( f \) and \( r_0 \) value is calculated. It is matching well with the value of \( r_0 \) calculated using the Zernike Polynomial method as well as the OTF method.

A turbulence simulator at low cost in Photonics laboratory was developed and experimented with several records of the fringe pattern image for phase plate evaluation. After characterisation of phase plate it was found that the phase plate is matching well with Kolmogorov model. Also a comparative analysis was attempted at the laboratory by both simulation and real time experimentation. In the Figure 6.5 phase variance is plotted against Zernike index \( j \), for experimental data, simulation data and theoretical data of Kolmogorov model. Theoritical data is analysed from equations 6.3 and 6.4,

\[ W^*(r) = \sum_l a_l Z_l(r) \]

\hspace{1cm} (6.3)

\[ \sqrt{\langle a_l^2 \rangle} = \sqrt{N_l} \cdot \left( \frac{D}{r_0} \right)^{5/6} \]

\hspace{1cm} (6.4)

where \( \langle a_l^2 \rangle \) is the phase variance, \( D \) is the Telescope diameter and \( N_l \) is the Noll Coefficients [34].
By knowing, the Zernike expansion of the distorted wavefront over a circular aperture the Fried parameter for each Zernike order $i$ was calculated. The Figure 6.5 shows the measured phase variance for Zernike modes from 2 to 11. First mode called piston was not considered. In this graph Kolmogorov theoretical model, experimental data and simulation data are compared and it is found that all the three data match well. The Laboratory setup for the measurement using Polarization Shearing Interferometer is shown in Figure 6.6.

![Figure 6.5: Comparison Graph for Kolmogorov Theoretical Model, Experimental Data and Simulation Data](image)

![Figure 6.6: Photograph of the Actual Setup](image)
6.3 Experimental Setup of Polarized Shearing Interferogram

In the laboratory an attempt was made to simulate the turbulence phase screen and to study its effect on the PSI-WS and to evaluate the Fried's parameter. A method of Wavefront Sensing using a PSI has been developed in the Photonics Laboratory. It uses the Babinet Compensator as a convenient and suitable optical device to create the shearing of wavefronts in two orthogonal directions simultaneously. Babinet Compensators are made up of birefringent material. These are best suitable optical devices to produce shearing wavefronts. The approach made here is to separate the two orthogonally polarized beams and analyze the beams with an analyzer.

An efficient approach for Shearing Interferometry is to separate the two beams by Polarization using birefringent prisms. This class of interferometer is called Polarization interferometer [105]. Lateral Shearing Interferometer normally uses two orthogonal shear directions to measure the slope in two directions in order to reconstruct a two-dimensional wavefront. In the laboratory experiment, Babinet Compensator based Polarization Shearing Interferometer was used as explained in [48]. In [48] the Polarized Shearing Interferometer using two crossed Babinet Compensators has been explained. A single interferogram can be efficiently used for slope finding of the wavefront.

In the Laboratory setup a collimated beam was derived from a light source using a beam expander and a collimating lens. The collimated beam first passes
through the test bench where the turbulence phase plates were used for analysing study. A special adapter was fabricated to house the phase plate. Then it falls on the Polarization Shearing device. The device consisting of two crossed Babinet Compensators was introduced on either side of the focus. Neutral Density (ND) filters were used in order to minimize the intensity of the light. The Pixel fly camera has been used to grab the noisy interferometric fringe pattern (at different turbulence strength phase plates) in the computer. The main parameters in designing the optical system are the position of the Babinet compensator and the detector array size.

The schematic of the optical layout for PSI-WS of wavefront sensing experiment at the Laboratory is given in the Figure 6.7. The phase plate was introduced in the optical setup for realistic turbulence and the noisy interferometric image was recorded into the CCD Detector. The aberrated noisy interferometric fringe pattern image recorded due to the turbulent phase plate as shown in Figure 6.10.

![Figure 6.7: A Schematic of Laboratory Setup for PSI-WS](image)
The experimental setup consisted of Light Source, Imaging optics, Polarizer, two Babinet Compensators, Analyzer, CCD camera, Control electronics, Control algorithm, Computer and Deformable Mirror. The PixelFly Camera has been used as a detector. By using the above setup in Laboratory, the aberrated noisy interferometric image (due to phase plate) was grabbed continuously using PixelFly Camera. The noiseless interferogram was also recorded in the camera when the phase plate was not inserted into the beam path.

6.3.1. Light Source

A collimated Laser Diode with operating wavelength of 635nm and having 1 mW power light source was used in this experiment. Its beam size is 3 mm. It can withstand large temperature variations. All modules maintain an Optical-to-Mechanical alignment better than 20 mrad.

6.3.2 Imaging Optics

It contains Plano-convex lenses with size 30 mm, mirror, with focal length of 50 mm, Pellicle beam splitter of 2 μm size (with reflection 85 and transmission 92 %) and neutral density filters.

6.3.3 Polarized Shearing Interferometer Wavefront Sensor Device

The Polarization Shearing Interferometer device consists of a Polarizer (P), an Analyzer (A) and two Babinet compensators (BC) and it is introduced in between the re-imaging optics.
6.3.4 Babinet Compensator

The Babinet Compensator is widely used as an effective optical device for the measurement of retardation between the ordinary ray (o) and extraordinary ray (e) (i.e) to study the degree of birefringence. A Babinet Compensator can be adjusted to provide a variable path difference. The Babinet Compensator consists of paired quartz wedges, of small wedge angle, which are cut in such a fashion that one is positioned with the optic axis parallel to the edge, while the other has the axis perpendicular to the edge. The optical path difference in each wedge increases from the edge to the base and the birefringence has opposite values in the wedges. The extraordinary axes of the two plates are perpendicular to each other so the roles of the ordinary and extraordinary ray are reversed as the light travels through one plate and then the other. The optical specifications of the Babinet Compensators are given in the Table below:

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<table>
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<tr>
<td>Aperture</td>
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<tr>
<td>Wedge Angle</td>
<td>5 degrees</td>
</tr>
<tr>
<td>Material</td>
<td>Quartz</td>
</tr>
<tr>
<td>Surface accuracy</td>
<td>λ/20</td>
</tr>
<tr>
<td>Refractive Index</td>
<td></td>
</tr>
<tr>
<td>Ordinary Ray</td>
<td>1.54424</td>
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<tr>
<td>Extra-ordinary Ray</td>
<td>1.55335</td>
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Table 6.1: Optical Specifications of Babinet Compensator

A phase difference or retardation that is accumulated in first wedge may be partially or completely cancelled out by second wedge. A dark fringe appears where the net optical phase difference through the compensator becomes zero and a bright fringe appears when the phase difference is π and continues in a direction at right
angles to the zero line as the distance increases. Between crossed Polarizer’s, dark and bright bands are observed in monochromatic light at a separation distance of one wavelength of optical path difference. A typical Babinet Compensator prisms showing the preferential direction of the optic axis in each prism is shown in Figure 6.8.A and BC produced fringe pattern is shown in Figure 6.8.B.

![Figure 6.8.A: Typical BC](image)

![B: Fringe Pattern from BC](image)

### 6.3.5 The CCD Camera

The PixelFly QE Charge Coupled Device (CCD) camera has been used to grab the image which has a high performance digital 12bit camera system. The PixelFly has extraordinary quantum efficiency with up to 65%. The system consists of an ultra compact camera head, which either connects to a standard Peripheral Component Interface (PCI) or a compact PCI board via a high speed serial data link. The available exposure times range from 5µs to 65s. Digital temperature compensation is integrated instead of a space consuming thermo-electrical cooling unit. It has a resolution of 640x480 pixels. The details relating to specifications of the PixelFly camera are given in Table 6.2.

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Details Specifications

<table>
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<th>Details</th>
<th>Specifications</th>
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<tr>
<td>Camera Resolution</td>
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<tr>
<td>Pixel Size</td>
<td>9.9 µm² x 9.9 µm²</td>
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<tr>
<td>imaging frequency, frame rate</td>
<td>177 fps</td>
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<tr>
<td>Dynamic Range</td>
<td>12 bit</td>
</tr>
<tr>
<td>pixel scan rate</td>
<td>20 MHz</td>
</tr>
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Table 6.2: PixelFly Camera Details

6.4 Results

The laboratory experimental results which were obtained with open loop Adaptive Optics in the presence of turbulence phase plate are presented in this section. Turbulence was simulated by using a sandwiched phase plates. In phase plate hair spray was sprayed in a multiple layers. The collimated beam was passed through turbulent phase plate and due to this distorted wavefront was sensed by PSI Device. The setup was shielded by a glass window in order to minimise the air turbulence. As shown in the Figure 6.9 light passes through a phase plate (which is rotated at 13 rpm for dynamic turbulence behaviour) simulated at the Laboratory. This distorted wavefront was sensed by a PSI-WS and the grabbed images were continuously tested with the five proposed algorithms. The software for capturing the interferometric images in CCD and analysis of the interferometric image was developed in the LabVIEW platform. Using this optical and experimental setup a typical interferogram has been obtained in a PixelFly Camera.
6.4.1 Steps for Data Acquisition in LabVIEW

The algorithm was developed for image capturing in PixelFly camera for phase extraction. The developed algorithm was used to acquire the image continuously and was taken for data reduction procedures. Steps to grab the images from PixelFly camera in LabVIEW are given below:

1. Initialize the PixelFly interface board and camera head. Initialization must be done once for camera in the system.

2. Call Get parameters function which returns camera type, resolution, current gain, binning settings, etc. for the camera.

3. Configure the camera for operating mode, trigger mode, exposure time, binning and pixel depth.
4. Call Get Size function which returns maximum and current resolution along with the pixel depth for the camera configuration.

5. Allocate an image buffer in computer memory. The size of the buffer is specified as the number of bytes required.

6. Map a specified buffer into main memory space, starting at the "buffer address" output. "Buffer address" is then used by the image transfer routines.

7. Start a camera acquisition sequence, placing the camera in wait state until hardware or software trigger is received.

8. Place a buffer in the acquisition queue. If the specified buffer is already in the queue, an error is generated. The queue can hold up to 32 buffers. Once the data has been transferred from the camera to the buffer it is removed from the queue, and the next data transfer will use the next buffer in the queue.

9. Trigger an exposure. If the PixelFly is in internal trigger mode, the exposure starts as soon as this trigger is called. In external trigger mode, the PixelFly waits for a transition on the external trigger input before exposing.

10. Return the status of the selected buffer including information on queue position.
11. Obtain an image from a buffer and return it as a 2-D array of 12 bit integers.

An array of U16 integers must first be defined that matches the horizontal and vertical dimensions of the image in the buffer. This data format can be used for BW images using the "Array to IMAQ image" to convert this array to an image.

Figure 6.10: The Recorded Interferometric Image

The Figure 6.10 shows the interferometric fringe record of the Polarization Shearing Interferometer obtained in the Laboratory using PixelFly camera, when turbulence strength was $D/r_0 = 1.5$. The fringe pattern in the interference is continuously changing due to the atmospheric fluctuations (due to the phase plate). This changing pattern is a representation of the distortions over telescope pupil plane. The task is to measure these distortions in real time. The software was developed in such a way that measures the errors in the wavefront and displays the wavefront error in real time keeping the cost and time as main factors. After
capturing the noisy interferometric image from the PixelFly CCD Camera, the five proposed algorithms were tested and their performance were evaluated based on noise removal accuracy and speed. The CFWL algorithm performed superior than the other four algorithms.

Figure 6.11.A: The 1D Noisy Interferogram

Figure 6.11.B: The Compressed 1D Noisy Interferogram with Unique Peak and Valley Identification

6.12: Reconstructed Wavefront
6.13: Zernike Co-efficient

The Figure 6.10 is one of the noisy interferometric fringe pattern image which is grabbed in the PixelFly Camera. The Figure 6.11 shows its noisy one dimensional (1D) data where one cannot locate the peak and the valley as it contains multiple peak and valley. The Figure 6.11.B shows the compressed and average plot of the noisy data with unique peak and valley identified by CFWL algorithm. The extracted fringe and reconstructed wavefront is shown in Figure 6.12 and the respective Zernike coefficients are shown in Figure 6.13. The unwrapped phase data were fitted into Zernike Polynomial and the wavefront has been reconstructed in continuous mode with 35 milliseconds timeframe in real-time experiment at the Laboratory.

6.5 Conclusion

The simulation results are tested with real time experimental setup with low cost turbulence simulator. For both simulation and real time experimentation in the Laboratory, the phase screen was compared and it was found to match well. Due to the technical problems prevailing in the Deformable Mirror, the closed loop
correction system was not completed successfully. In real-time, the estimation of wavefront error and reconstruction by implementing the five proposed algorithms with reduced time limit were achieved. Based on the result obtained in the laboratory and analysis, the CFWL algorithm outperforms the others similar to the simulation result discussed in Chapter IV and Chapter V.