THE DESIGN, CONSTRUCTION AND EVALUATION OF A REAL TIME OPTICAL WAVEFRONT SENSOR

by

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SUBMITTED TO THE DEPARTMENT OF ELECTRICAL ENGINEERING AND COMPUTER SCIENCE IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

May 1, 1988

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ABSTRACT

A theoretical analysis of real time optical wavefront sensors is presented. The interference of two mutually coherent optical fields is described, and the ambiguities which result from the sinusoidal nature of this interaction are examined. A specific real time optical wavefront sensor which will be called the the Sampled, Twyman-Green, Optical Phase Shifting, Digital Interferometer (STOPSDI) was designed, and a bread board version constructed. The major components chosen to make up this system are outlined, and the constraints each of these elements places on the system as a whole are studied. Measurements of several test wavefronts were made with this system. For a nulled interferometer a Strehl ratio of 0.977 was obtained. Comparisons were carried out between data obtained from the ZYGO static phase sensor and the STOPSDI real time wavefront sensor, and the results were found to be virtually identical with a measurement accuracy of .1λ.

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ACKNOWLEDGEMENT


And of course, I would like to thank Jymn Hubbard for being a great guy and making this possible, and Greg Cappiello and Rick Ciliberto for all the help they provided.

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DEDICATION

"The ultimate tragedy is not the brutality of the bad people but the silence of the good people"....Dr. Martin Luther King, Jr.

To all those working for peace and justice around the world.
PREFACE

A real time optical wavefront sensor has many applications: some appropriate, some not so appropriate, and some completely inappropriate. The inappropriate applications stem from the misuse of technology in trying to solve problems where a technical solution is not practical, not economical, and in many cases not possible. The major problems in the world today are political ones and as such require political solutions, not technological ones. Among these problems is the crisis created by the nuclear arms build up. The stockpiling of nuclear weapons not only threatens all life on this planet by making a nuclear holocaust more imminent, but it also takes limited resources away from those in the most need. Quality education for everyone should be a right not a privilege. Affordable housing should be a right not a privilege. Comprehensive health care should be a right not a privilege. Quality day care for all children should be a right not a privilege. Clean water and clean air should be a right not a privilege. Money is being taken from programs which could and should insure these basic rights to all Americans, and is being used to pump up those companies which conduct military research and manufacture the new and exotic weapons systems which threaten our very existence. Through cuts in social programs and increases in the amount of corporate welfare in the guise of military research and development programs carried out by multimillion dollar corporations, money is literally being taken from the poor and being given to the rich. I mention this because the field of adaptive optics has several military applications, one of which is Reagan's "Star Wars" plan. In a utopian society with an infinite supply of expendable resources it would be conceivable to debate the merits of such a weapons system based on its technical infeasibility, its destabilizing effects, its illegality under presents laws and treaties, etc. But in the real world in which we live, the limited resources which are already strained by a huge military budget and a crippling budget deficit make such weapons systems unthinkable. To reduce the threat of nuclear war, nuclear stock piles must be reduced, the development of destabilizing and more dangerous weapon systems which escalate the arms race must be stopped, and treaties must be negotiated to assure a reversal of the arms build up. This is a political problem with a political solution, not a technical one. Adaptive optics has no role in resolving these issues.
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Chapter 1

Introduction

A small space based telescope orbiting just beyond the earth’s atmosphere would be capable of seeing many light years beyond what is presently observable by the largest land based telescope. The images a space telescope would record would not suffer the extreme degradation in quality which occurs during the final few hundred miles in the journey light takes from the edges of the universe to earth’s surface, and which are brought about due to propagation through the turbulent atmosphere surrounding the earth. Of course, a space based telescope would be very expensive to build, position, and maintain, and would be limited in its size and functionality.

An earth based telescope that could peer through the atmosphere without suffering any of the loss in angular resolving power associated with the propagation of light through a turbulent medium, could achieve a resolution close to that of a space based telescope but at a potentially lower cost and with greater flexibility. By determining the effects the atmosphere has on light which propagates through it, these effects could be corrected for either electronically or optically [1].

As an optical signal propagates through the air, phase information is lost to atmospheric disturbances which distort the wavefront profile. Adaptive optics attempts to remove from the wavefront any distortions brought about by atmospheric turbulence. To do this, the way in which the atmosphere is deforming the wavefront must be determined, then this information can be used to correct for aberrations in the wavefront.

As a result, in recent years the field of adaptive optics has emerged as one of the exciting frontiers of modern optics. Its goals, simply put, are to detect aberrations in an optical system, in real time, and to correct for these aberrations, also in real
time, so as to achieve improved system performance [2]. The two elements essential for such a system are a device for sensing optical wavefronts and hence optical aberrations, and a device for altering optical wavefronts and in this way correct for any aberrations. A system employing such elements is capable of compensating for imperfections in its optical components and correcting for continually changing aberrations brought about by such things as atmospheric disturbances in the spaces between components. In optical systems without adaptive capabilities, the space between components has usually been approximated as being uniform and aberration free, but for systems with large distances between elements, or systems which operate under turbulent conditions, the atmosphere can no longer be approximated as ideal and its effects can not be ignored if near diffraction limited operation is to be achieved. In such systems, where the operating conditions are not ideal and are not fully controllable, adaptive optics provides a solution to many problems that arise.

In addition to the above applications, as the ability to grind better and more complicated optical components asymptotically approaches its limit with present technology, adaptive optics provides a means for further improving the performance of a system and making near diffraction limited operation possible. Instead of having to build a perfect lens or other optical element, a near perfect element could be constructed and the techniques of adaptive optics employed to correct for any imperfections in the element and any imperfections that might result from damage to the element. This report examines one solution to one of the major stumbling blocks in implementing an adaptive optical system, the design and implementation of an economical real time optical wavefront sensor.

There are two major groups in which to categorize the use of an optical wavefront sensor. One involves the measuring of unwanted aberrations, such as atmospheric turbulence, which distort an optical signal and degrade system performance, so that these aberrations can be corrected for, and an undistorted wavefront created. Direct line of sight communication systems which attempt to exploit the high bandwidth of the atmosphere, and ground based telescopes which are presently limited in resolving power by distortions brought about by the atmosphere, are characteristic of this set of applications. The other group of applications involves determining the profile of an optical wavefront so as to characterize the medium through which an optical
wave has passed. Unlike the first group of applications where the wavefront profile is not directly what is of interest but is noise which degrades the recording of the actual signal, in this group of applications, the wavefront is the information of interest. Typical applications in this group include the analysis of phase objects such as optical components, biological samples, the atmosphere, etc.

There are many possible implementations for optical wavefront sensors. Most, though certainly not all, rely upon the phenomena resulting from the interference of two optical fields to make wavefront estimations. These systems, known as two beam interferometers, can be cast into two general categories, static and phase shifting interferometers. Each technique has its own set of limitations and applications. Static two beam interferometers, in general, are the simplest to implement, but are incapable of determining the sign of an optical phase term and are sensitive to amplitude fluctuations in the interfering optical fields. Phase shifting interferometers offer greater phase resolution, the ability to determine the sign of the phase, and greater robustness against many forms of noise, in particular, amplitude irregularities. Phase shifting interferometers can be subdivided based on the type of phase shift used. Possible forms of phase modulation include small modulations which are less than $2\pi$, large ramp phase shifts with a scan range that is greater than $2\pi$, and a staircase scan which steps between zero and $2\pi$ [3]. Although the first two methods can operate at relatively high data rates they can not achieve the very high "real time" data rates necessary in many applications. Many phase shifting interferometers which use a staircase scan require the storage of excessive amounts of data, and often can not operate at adequate data rates.

Of the many possible strategies for implementing an optical wavefront sensor, the Sampled, Twyman-Green, Optical Phase Shifting, Digital Interferometer (STOPSDI) employs a staircase pattern to scan the phase of one of the two interfering wavefronts. It does not require the storage of large amounts of data, and although the bread board implementation used for testing and concept demonstration did not operate at the kilohertz data rates essential for analysing most atmospheric disturbances, the principles governing its operation are applicable at significantly higher frequencies. This report is divided into six chapters: (1) an introduction, (2) a theory section which, among other things, explains the principle
of interference and how this phenomena can be used to measure optical wavefronts, (3) a chapter which describes the major design considerations and what is needed to implement the sensor, (4) an outline of the major components used in implementing the STOPSDI system and the limits these components place on the system, (5) a section which examines the results of many of the test cases run on the STOPSDI system, and (6) a conclusion and recommendations section.
Chapter 2

Theoretical Analysis of the Sampled, Twyman-Green, Optical Phase Shifting, Digital Interferometer

There are many possible implementations for an optical wavefront sensor. Although most procedures use the interference pattern formed from a reference wavefront and a test wavefront to characterize the test wavefront, there are many other procedures which do not. The Sampled, Twyman-Green, Optical Phase Shifting, Digital Interferometer does make optical wavefront estimations based on the phenomena of two beam interference. Interferometers can be categorized, depending on the type of reference wavefront used, as either static or phase shifting. Static interferometers use a constant reference wavefront in making wavefront estimations, but suffer from many limitations which are rooted in the sinusoidal characteristic of the interference of light. Phase shifting interferometers circumvent this problem, to some extent, by introducing a controlled phase offset to the reference wavefront, and making measurements as this phase offset is varied. There are many strategies for implementing phase shifting interferometers. They differ in, among other things, the type of phase shift introduced, the method of introducing the phase shift, the amount of data which must be stored, and the amount of processing which must be done on the data after it is collected. These differences determine the quality and the speed at which wavefronts are determined.

One problem common to most forms of interferometry is an ambiguity brought about by the cyclical nature of the expression which describes the output of the interferometer. Without some a priori knowledge about the wavefront being examined or without some assumption which places constraints on the wavefront, this ambi-
guity hampers the measuring of large optical wavefront deviations. Depending on the application and the type of interferometer used, various approaches have been found to overcome this problem. The technique used in this effort is very general, does not require any a priori information about the wavefront, and does not place serious limits on the test wavefront.

2.1 Analytical Representation of an Optical Disturbance

The set of integral equations, known as Maxwell's equations, used to describe electromagnetic disturbances is

\[
\int_C \vec{E}(\vec{r},t) \cdot d\vec{l} = \int_A \frac{\partial \vec{B}(\vec{r},t)}{\partial t} \cdot d\vec{s},
\]

(2-1)

\[
\int_C \vec{B}(\vec{r},t) \cdot d\vec{l} = \mu \int_A \left[ \vec{j}(\vec{r},t) + \varepsilon \frac{\partial \vec{E}(\vec{r},t)}{\partial t} \right] \cdot d\vec{s},
\]

(2-2)

\[
\int_A \vec{E}(\vec{r},t) \cdot d\vec{s} = \frac{1}{\epsilon} \int_V \rho dV,
\]

(2-3)

\[
\int_A \vec{B}(\vec{r},t) \cdot d\vec{s} = 0.
\]

(2-4)

For free space these equations can be manipulated using two theorems from vector calculus, Gauss's divergence theorem and Stokes theorem, to get two concise vector expressions,

\[
\nabla^2 \vec{E}(\vec{r},t) = \frac{1}{c^2} \frac{\partial^2 \vec{E}(\vec{r},t)}{\partial t^2},
\]

(2-5)

\[
\nabla^2 \vec{B}(\vec{r},t) = \frac{1}{c^2} \frac{\partial^2 \vec{B}(\vec{r},t)}{\partial t^2}
\]

(2-6)

where

\[
c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}.
\]

(2-7)

Because of the way in which the electric and magnetic fields are coupled in free space, analysing either field alone is sufficient to analyse an optical disturbance and to determine the other field if desired. As a result, only the electric field need be considered in the analysis which follows.
2.2 Characterization of Superimposed Electric Fields

Equation (2-5) is an example of the second-order homogeneous linear partial differential equation known as the wave equation, the solutions to which are of the form

$$\mathbf{E}(\mathbf{r}, t) = \mathbf{A}(\mathbf{r}, t)e^{i(\Phi(\mathbf{r}, t) + k \cdot \mathbf{r} - \omega t)}.$$  \hspace{1cm} (2 - 8)

This representation for the electric component of an optical disturbance is linear; that is, $\mathbf{E}(\mathbf{r}, t)$ and its derivatives appear only to the first power. If $\mathbf{E}_1(\mathbf{r}, t)$, $\mathbf{E}_2(\mathbf{r}, t)$, $\mathbf{E}_3(\mathbf{r}, t) \cdots \mathbf{E}_n(\mathbf{r}, t)$ are each individually solutions to the wave equation, then any linear combination of these will also be a solution; i.e.

$$\mathbf{E}(\mathbf{r}, t) = \sum_{i=1}^{n} \mathbf{E}_i(\mathbf{r}, t)$$  \hspace{1cm} (2 - 9)

satisfies the wave equation.

The resultant disturbance at any point in space where two or more light waves overlap is the vector sum of the individual constituent disturbances. This principle, known as the principle of superposition, was first clearly stated by Thomas Young in 1802 [4], and forms the foundation for much of modern optics.

Throughout the remainder of this document the electric field will be treated as a scalar and not a vector. This greatly reduces the mathematical overhead of the expressions that follow and is valid provided all light beams studied are unpolarized or have approximately the same polarization. In addition, the electric field will be time averaged so as to eliminate its optical frequency component which is at a very high frequency ($\sim 5 \times 10^{14}$Hz) and is not of interest for this experiment. Finally, it will be assumed that all the light examined has approximately the same direction of propagation at the point of observation. As a result,

$$\mathbf{E}(\mathbf{r}, t) = A(\mathbf{r}, t)e^{i\Phi(\mathbf{r}, t)}.$$  \hspace{1cm} (2 - 10)

becomes the simplified scalar representation of the electric field.

2.3 An Analytical Model for Optical Detectors

Optical detectors in use today such as CCD arrays, photo diodes, photographic film and the human eye, all measure the energy of an optical field by integrating the
intensity of the incident light over the exposure time. They do not directly measure the amplitude and phase of the field. The intensity of a wave is the amount of energy transported by the wave, that flows per unit time across a unit area perpendicular to the direction of travel of the wave. It is expressed by

\[ I(r, t) = |E(r, t)|^2. \quad (2-11) \]

Integration over the exposure time gives

\[ V(r, t) = \int_0^T I(r, t) dt \quad (2-12) \]

\[ = \int_0^T |E(r, t)|^2 dt \quad (2-13) \]
as the output of a detector observing a given optical disturbance. If the electric field is slowly varying so as not to change over the integration time of the recording medium, the output will be directly proportional to the square of the magnitude of the electric field; the voltage output of a photo detector will be directly proportional to the intensity of the light which is incident on the photosensitive surface of the detector. To reduce the mathematical overhead, the constants of proportionality will be discarded, leading to

\[ I(r, t) = |E(r, t)|^2 \quad (2-14) \]
\[ = A^2(r, t) \quad (2-15) \]
as the expression for intensity as well as for the voltage output of a photocell observing this intensity. As can be seen from Equation (2-15) the magnitude of the electric field can be determined from such a measurement but it is impossible to extract the phase of an optical signal from just a single reading of the intensity of the field. To measure phase, the optical field must first be processed before reaching the detector then the output voltage of the detector may need to be further processed electronically [5].

One technique of optical processing which generates a signal related to optical phase is interferometry [6]. This technique is based on the phenomena which results from the interference of two (or more) optical fields. As was shown earlier, due to the wave nature of light, electric fields obey the principle of superposition. When
two optical fields are combined the electric fields simply add. Since intensity is proportional to the magnitude squared of the electric field, the intensity of two overlapping fields is not simply the sum of the intensities of the two fields but is the magnitude squared of the sum of the two electric fields.

2.4 The Interference of Two Mutually Coherent Fields

The electric fields of two mutually coherent interfering wavefronts can be expressed, using Equation (2-10), as

\[ E_1(\vec{r}, t) = A_1(\vec{r}, t)e^{j\Phi_1(\vec{r}, t)}, \]
\[ E_2(\vec{r}, t) = A_2(\vec{r}, t)e^{j\Phi_2(\vec{r}, t)}. \]  

When these two electric fields overlap, the resulting electric field is found, using the principle of superposition, to be

\[ E(\vec{r}, t) = E_1(\vec{r}, t) + E_2(\vec{r}, t) \]
\[ = A_1(\vec{r}, t)e^{j\Phi_1(\vec{r}, t)} + A_2(\vec{r}, t)e^{j\Phi_2(\vec{r}, t)}. \]  

This leads to the following expressions for intensity:

\[ I(\vec{r}, t) = |E(\vec{r}, t)|^2 \]
\[ = E(\vec{r}, t)E^*(\vec{r}, t) \]
\[ = |A_1(\vec{r}, t)e^{j\Phi_1(\vec{r}, t)} + A_2(\vec{r}, t)e^{j\Phi_2(\vec{r}, t)}|^2 \]
\[ = A_1^2(\vec{r}, t) + A_2^2(\vec{r}, t) + 2A_1(\vec{r}, t)A_2(\vec{r}, t)[e^{j(\Phi_1(\vec{r}, t) - \Phi_2(\vec{r}, t))} \]
\[ + e^{-j(\Phi_1(\vec{r}, t) - \Phi_2(\vec{r}, t))}] \]
\[ = A_1^2(\vec{r}, t) + A_2^2(\vec{r}, t) + 2A_1(\vec{r}, t)A_2(\vec{r}, t) \cos[\Phi_1(\vec{r}, t) - \Phi_2(\vec{r}, t)]. \]  

2.5 Analysis of a Static Two Beam Interferometer

The above expression (Equation (2-24)) is in a very general form. Depending on the type of two beam interferometer used and the nature of the signal to be measured
several simplifying approximations can be made. One possible set of assumptions is that for a static two beam interferometer. In such a system the amplitudes of the two interfering wavefronts are usually assumed to be uniform and time independent, and one of the beams is used as a reference beam and is assumed to have a planar wavefront. These approximations can be written as

\[ A_1(r, t) \approx A_1, \quad A_2(r, t) \approx A_2, \quad \Phi_2(r, t) \approx \Phi_2 \]  

where \( \Phi_2 \) corresponds to a constant phase offset. For simplicity \( \Phi_2 \) is set to zero.

The output intensity, as given by Equation (2-24), can now be simplified and written as

\[ I(r, t) = A_1^2 + A_2^2 + 2A_1A_2 \cos(\Phi_1(r, t)). \]  

Provided the two amplitudes, \( A_1 \) and \( A_2 \), are known, then the phase, \( \Phi_1(r, t) \), can be determined from a single intensity measurement, \( I(r, t) \), but with at least one major limitation; cosine is not a linear function. The cosine of a number is equal to the cosine of the negative of that number; in a simple two beam amplitude splitting interferometer, \( \Phi_1(r, t) \) can not be distinguished from \( -\Phi_1(r, t) \). Without any a priori knowledge about the nature of the wavefront being examined, it is impossible to distinguish a hill from a valley, a positive slope from a negative slope (See Figure 2-1). This type of system has very limited applications. Also, the assumption of uniform amplitudes for the two beams is a very limiting restriction. The output of a laser, in general, has a gaussian amplitude profile. It can be quite difficult to get a uniform amplitude over a large aperture from such a beam, to use in this type of system. To compensate for this electronically could be very complicated. Finally, all measurements are susceptible to noise brought about by amplitude fluctuations in either of the two interfering wavefronts. Unless any amplitude fluctuations in the object being examined are well defined and can be compensated for, the object must be a pure phase object.
2-1.a. Plot of an example fringe pattern observed in the output plane of the interferometer.

2-1.b. Wavefront A: one possible wavefront which might have generated the above fringe pattern.

2-1.c. Wavefront B: another possible wavefront based on the above fringe pattern.

Figure 2-1. Ambiguity of Static Interferometry Which Results in the Same Fringe Pattern for Both a Given Wavefront and Its Conjugate
2.6 Analysis of a Phase Shifting Twyman-Green Interferometer

The Twyman-Green interferometer pictured in Figure 2-2 is a two beam, amplitude splitting, double pass, phase-shifting interferometer. A single monochromatic, coherent light beam emerges from the laser cavity and is immediately filtered, collimated, and expanded to the desired diameter. The widened beam then strikes a beam splitter. Part of the beam is reflected and part is transmitted. The two beams travel two separate paths. The first beam is reflected by the beam splitter, passes through a phase object whose phase profile is to be determined, is reflected by the mirror at the end of the test arm of the interferometer, passes back through the object for a second time, then passes through the beam splitter. The second beam, which provides the reference wavefront, passes through the beam splitter, is reflected by the reference mirror which is controlled by a PZT actuator, then is reflected by the beam splitter where it recombines with the first beam. The reference mirror can be translated back and forth, via a PZT actuator, to introduce a controlled phase shift in the reference wavefront. As can be seen, each beam traverses the length of its arm of the interferometer twice. As a result, beam one passes through the phase object twice. This generates a wavefront with deviations from a planar wavefront which are twice those of the original object. The double pass nature of this interferometer brings a factor of two to the phase terms of the output equation. To keep the expression for the intensity at the output plane of the interferometer in a general form, i.e. independent of the double pass nature of the Twyman-Green interferometer, Equation (2-24) and other related equations are normalized by defining $\Phi_1(\vec{r},t)$ and $\Phi_2(\vec{r},t)$ as twice the phase offsets of arm one and arm two of the interferometer respectively such that this factor of two does not appear in these equations.

The following assumptions are made for this interferometer. The amplitudes of the two interfering wavefronts are assumed not to vary during the measurement of the wavefront. The phase of the object being examined is also assumed to be slowly varying with time compared to the rate of wavefront measurements. Finally, the phase offset introduced by the moveable mirror is assumed to be uniform across the entire aperture. In other words, the mirror is assumed to be flat so that when it is
A beam of light exits the laser cavity, and is expanded and collimated. The beam strikes the beam splitter sending half of the light down arm one of the interferometer and half down arm two. The light is reflected by the mirrors at the ends of each arm of the interferometer, and recombines at the beam splitter. The interference pattern generated at the output plane of the interferometer is sampled by a detector array who's output is $l(\vec{r}, t)$.

Figure 2-2. Twyman-Green Phase-Shifting Interferometer
translated back and forth in the x direction it introduces the same phase offset at each point across the aperture making the phase of arm two independent of z and y. The above approximations lead to the following expressions:

\[
A_1(\vec{r}, t) \approx A_1(\vec{r}), \quad (2-29)
\]
\[
A_2(\vec{r}, t) \approx A_2(\vec{r}), \quad (2-30)
\]
\[
\Phi_1(\vec{r}, t) \approx \Phi_1(\vec{r}), \quad (2-31)
\]
\[
\Phi_2(\vec{r}, t) \approx M(t) \quad (2-32)
\]

where

\[
M(t) = \frac{2\pi}{\lambda} 2\pi z(t) \quad (2 - 33)
\]

and \(z(t)\) is equal to the displacement of the reference mirror. This leads to the following expression for the intensity at the output plane of the interferometer:

\[
I(\vec{r}, t) = A_1^2(\vec{r}) + A_2^2(\vec{r}) + 2A_1(\vec{r})A_2(\vec{r})\cos[\Phi_1(\vec{r}) - M(t)] \quad (2-34)
\]
\[
= B(\vec{r}) + C(\vec{r})\cos[\Phi_1(\vec{r}) - M(t)] \quad (2-35)
\]

where

\[
B(\vec{r}) = A_1^2(\vec{r}) + A_2^2(\vec{r}), \quad (2-36)
\]
\[
C(\vec{r}) = 2A_1(\vec{r})A_2(\vec{r}). \quad (2-37)
\]

The intensity at a given sample point in the output plane, \((x_0, y_0)\), which is directly proportional to the voltage output of a detector located at this point, is plotted with respect to \(M(t)\) in Figure 2-3.

The minimum intensity for a point, \((x_0, y_0)\), in the output plane of the interferometer is equal to \(B(x_0, y_0) - C(x_0, y_0)\) and occurs whenever

\[
\Phi_1(x_0, y_0) - M(t) = \pi + 2n\pi \text{ where } n \in \text{ integers}. \quad (2 - 38)
\]

Similarly, the maximum intensity of \(B(x_0, y_0) + C(x_0, y_0)\) occurs whenever

\[
\Phi_1(x_0, y_0) - M(t) = 2n\pi \text{ where } n \in \text{ integers}. \quad (2 - 39)
\]

Equations (2-38) and (2-39) are both linear; consequently, either one alone can be used to solve for the phase of the field in one arm of the interferometer without
\[ I_{\text{Min}} = B(\vec{r}_0) - C(\vec{r}_0) \]
\[ I_{\text{Max}} = B(\vec{r}_0) + C(\vec{r}_0) \]

Figure 2-3. Intensity Observed at a Point \((x_0, y_0)\) in the Output Plane of the Interferometer as a Function of the Position of the Reference Mirror
any of the problems and limitations a static two beam interferometer suffers from, ie. the ambiguity in determining the direction of slope of the wavefront brought about by the nonlinearity of the cosine term, the extreme sensitivity to noise and fluctuations in the amplitude of the light, etc.

The $2n\pi$ term found in both Equations (2-38) and (2-39) is a result of the sinusoidal nature of the intensity at the output plane of the interferometer with respect to the phase of the electric field. If the wavefront under examination only has small fluctuations in phase such that $0 \leq \Phi_1(\vec{r}, t) < 2\pi$, then $n$ can be set to zero and phase measurements can be made without any further information or processing. Of course, $n$ could be set to any arbitrary constant value. This corresponds to a constant phase offset across the entire aperture. Depending on the application this may be desired. For example, if one is interested in the total optical path length difference between the two arms of the interferometer, then a precise value of $n$ could be determined, using some method other than this interferometric technique, and the resulting value of $2n\pi$ could then be added to the wavefront measurements made using this interferometric technique to give the total optical path length difference between the two arms of the interferometer. For the purposes of the experiments described in this report an exact measurement of optical path length differences is not needed; instead, a relative measurement of the wavefront is desired. A phase difference of zero is arbitrarily assigned to one location and all measurements are made with respect to this location.

2.7 Analysis of Ambiguity in Wavefront Estimations

Because a phase offset of $\Phi_1(\vec{r}, t) + 2n\pi$ can not be distinguished from one of $\Phi_1(\vec{r}, t)$, measuring the phase profile of objects with phase deviations larger than $\pi$ becomes complicated as shown in Figure 2-4. When a test object has phase deviations which are larger than $\pi$, the initial phase data, generated by noticing the position of the phase shifting reference mirror which leads to either a minimum or maximum intensity for each point, does not accurately represent the wavefront. To get a true representation of the wavefront, $n$ can not be set to zero, or any other constant, across the entire aperture. Instead, calculations must be made at each
2-4.a. Example of actual wavefront cross section in the x direction at $t = t_0$.

2-4.b. Example of initial phase data cross section corresponding to the above wavefront cross section.

Figure 2-4. Effects of $2n\pi$ Phase Ambiguity on the Initial Phase Data
point in order to determine variations in $n$ across the aperture. As can be seen in Figure 2-5, at each point where $n$ should change value there is a discontinuity in the initial phase data for the wavefront measurement. If the jump is from zero to $2\pi$, then $n$ should be one less than its present value for the next portion of the wavefront up until the next discontinuity. Likewise, if there is a jump from $2\pi$ to zero, then $n$ should be one more than its present value up until the next discontinuity. Of course, this assumes there are no discontinuities in the wavefront being examined. If there are discontinuities, then more data would be needed, which would have to be gotten from some source other than this interferometric data, before an accurate value of $n$ could be calculated. Since most applications are concerned with continuous wavefronts, this is not a serious restriction.

Just as the initial value of $n$ can be set to zero for the case when the wavefront is what is of interest and a constant phase offset is not needed, the $\pi$ term found in Equation (2-38) can be discarded because it too corresponds to a constant phase offset across the entire aperture.

2.8 **Determination of Reference Mirror Scan Profile**

If the position of the phase shifting reference mirror which leads to a minimum or maximum output of the interferometer is known, then Equation (2-38) and Equation (2-39) respectively show that the wavefront in one arm of the interferometer can be determined. To make wavefront measurements $M(t)$ must take on all values from zero, inclusively, to $2\pi$, exclusively, then the mirror position which led to either a minimum or maximum output for a given point in the output plane can be noted. Mathematically, the scan profile of $M(t)$ may not matter but since $M(t)$ corresponds to physically translating a mirror back and forth using a PZT actuator, it is best to keep the scan profile simple and continuous. This leads to moving the reference mirror forward between zero, inclusively, and $\frac{1}{2}$, exclusively, at some constant rate as shown in Figure 2-6. When this pattern is repeated, each tooth of the resulting saw-tooth pattern corresponds to a separate set of phase measurements. As was mentioned earlier, however, discontinuities in the mirror scan pattern should be avoided; therefore, this saw-tooth pattern should be modified into a triangular wave
2-5.a. Cross section of initial phase data with calculated values of the half wavelength boundary crossing number, n.

2-5.b. The wavefront is reconstructed using

\[ \Phi_{\text{Total}}(\vec{r}, t) = \frac{1}{2}[\Phi_1(\vec{r}, t) + 2\pi n(\vec{r}, t)]. \]

Figure 2-5. Determining the Half Wavelength Number, n, Based on Discontinuities in the Initial Phase Data
2-6.a. Scanning the reference mirror forward across half a wavelength at a constant rate corresponds to $M(t)$ going from zero, inclusively, to $2\pi$, exclusively.

2-6.b. Each tooth of the saw-tooth wave corresponds to a separate phase measurement, $\Phi_1(\vec{r}, t_n)$.

Figure 2-6. Ramp and Saw-Tooth Scan Profiles for the Phase Shifting Reference Mirror
To avoid moving the reference mirror over a relatively large distance in the relatively short period of time between phase measurements, a triangular pattern can be used for scanning the reference mirror.

Figure 2-7. Triangular Scan Profile for the Reference Mirror

where each forward scan corresponds to a separate set of phase measurements and each backward scan also corresponds to a separate set of phase measurements (See Figure 2-7). The direction of the mirror scan is of little significance provided the position of the phase shifting reference mirror is monitored.

Notice that since the phase shifting reference mirror introduces a constant phase offset across the entire aperture, measurements can be made in parallel for each point across the aperture. This leads to a complete wavefront measurement of the entire aperture after each mirror scan.

The STOPSDI is implemented using digital circuitry; therefore, the mirror scan profile is modified somewhat as shown in Figure 2-8. As can be seen from the figure, the resolution of the optical phase measurement is determined by the number of steps taken to scan the phase shifting reference mirror from 0 to $\frac{\lambda}{2}$. If the time between each step, $\tau$, is independent of step size, then the number of steps not only determines the resolution of the system but also determines the speed at which consecutive wavefront measurements can be made.
This example reference mirror scan profile is divided into eight equally spaced steps. The mirror is held at each step for the amount of time required for data processing, \( \tau \). The reference mirror scans from zero to one step below \( 2\pi \). Upon completion of the first forward scan, \( \hat{\Phi}_1(\vec{r}, t_0) \), can be determined. After the backward scan, \( \hat{\Phi}_1(\vec{r}, t_1) \), can be determined, and after the subsequent forward scan, \( \hat{\Phi}_1(\vec{r}, t_2) \), can be determined. The time required to measure a wavefront is given by \( \tau \) times the number of steps in the scan.

Figure 2-8. Staircase Scan Profile for the Reference Mirror
2.9 Analysis of the Effects of Using Digital Data

The optical detector used in the output plane to sample the interference pattern of the reference and the object wavefronts consist of an array of discrete photo detectors. This along with the staircase scan profile for the reference mirror, mentioned earlier, lead to a discrete set of sampled digital data for the initial phase data from which the wavefront is determined (See Figure 2-9). Since this digitally sampled data, by its very nature, is not continuous, a more formal statement of the assumption of a continuous wavefront is needed.

Assumption: The phase difference between any two adjacent sample points is always less than \( \frac{\pi}{2} \) and greater than \(-\frac{\pi}{2}\).

Points in the initial phase data where this assumption is violated correspond to changes in the value of \( n \), the half wavelength counter. These changes will be referred to as half wavelength boundary crossings (half wavelength because of the double pass nature of the Twyman-Green interferometer which led to defining \( \Phi_1(\vec{r}, t) \) and \( \Phi_2(\vec{r}, t) \) as twice the phase offset of arms one and two of the interferometer respectively). If the difference in the initial phase data from two adjacent detectors is greater than \( \frac{\pi}{2} \), then a half wavelength boundary has been crossed and \( n \) should be one less than its present value for the next portion of the wavefront up until the next discontinuity. Similarly, if the difference in the initial phase data from two adjacent detectors is less than \(-\frac{\pi}{2} \), then a half wavelength boundary has been crossed and \( n \) should be one more than its present value up until the next discontinuity in the data.

Since the detector array consist of discrete detectors of some finite size the above assumption of a continuous wavefront places a limit on the maximum wavefront deviation that can be measured across a given aperture with a given number of detectors. Of course, a wavefront can be scaled up or down with a lens arrangement so as to fit onto any size detector array; therefore, this limitation is not a very serious one.
2-9.a. Example cross section of the initial phase data generated with an eight step scan for the phase shifting reference mirror. The wavefront used for this example is illustrated in Figure 2-4.a.

2-9.b. Based on the initial phase data and the assumption of a continuous wavefront, half wavelength boundaries can be calculated and the wavefront determined.

Figure 2-9. Use of Digital Data to Represent the Measured wavefront
Chapter 3

Sampled, Twyman-Green, Optical Phase Shifting, Digital Interferometer Design Considerations

The following is an explanation of the procedure for measuring optical wavefronts using the STOPSDI. As was described earlier and illustrated in Figure 2-2, the phase object to be measured is located in arm one of the interferometer, the reference mirror is translated back and forth in a staircase pattern (See Figure 2-8) to introduce a controlled phase offset in arm two of the interferometer, and a detector array consisting of a 128 by 128 matrix of individual photocells is located in the output plane of the STOPSDI to sample the fringe pattern resulting from optical path length differences between the two arms of the interferometer. The detector array used in the output plane for this implementation only has a single output line through which information from each of the 16K detectors is serially multiplexed. As a result, the reference mirror must be held at each step of its half wavelength scan for a period of time long enough to allow the detector array to output its data and for this data to be processed. This time, required for the detector array data output, is indicated by $\tau$ in Figure 2-8, and is the limiting factor in determining the rate of wavefront measurements.

In the simplest implementation, there are three banks of memory needed for this system. In the actual system, however, a pipelined architecture is used which requires two additional banks of memory but offers a faster system frame rate. Each bank of memory has 16K memory locations with one for each of the detectors in the 128 by 128 array of the output plane of the STOPSDI. One bank is used to hold the intensity information from the detectors, recorded at past positions of the phase.
shifting reference mirror. This data is compared to current intensity information in determining what mirror position leads to the minimum or maximum intensity at a given point in the STOPSDI output plane. Another bank is used to hold information on the position of the reference mirror which leads to the STOPSDI output plane intensity data stored in the first memory bank. The data contained in this bank is referred to as the initial phase data, and upon the completion of a half wavelength scan of the phase shifting reference mirror, this initial phase data is directly related to the phase profile under examination. The third bank is used to hold half wavelength boundary crossing information which is generated based on the data found in the second memory bank.

The STOPSDI system is operated in either minimum or maximum mode. In minimum mode the system determines the minimum intensity for a given sample point in the output plane of the STOPSDI as a function of the position of the reference mirror, and it records the position of the reference mirror which leads to this intensity. Similarly, in maximum mode the system determines the maximum intensity for a given point and the position of the reference mirror which leads to this intensity.

The procedure for making phase measurements is illustrated in Figures 3-1, 3-2, and 3-3. The flow chart of Figure 3-1 illustrates the procedure used to generate the initial phase data which indicates the position of the phase shifting reference mirror that brings about a minimum (or maximum depending on the mode of operation) intensity for each point in the STOPSDI output plane. The reference mirror is scanned, either forward or backward, across half of a wavelength. For a forward scan (i.e. in the +x direction of Figure 2-2), \( d = +1, \ p_0 = 0, \ p_1 = 1 + \text{number of steps in the scan}, \) and for a backward scan (i.e. in the -x direction), \( d = -1, \ p_0 = \text{number of steps in the scan}, \ p_1 = -1. \) The data from the detector array is represented by \( c(x,y), \) and is compared to data stored in memory, \( o(x,y). \) The current position of the reference mirror is indicated by \( m. \) The user sets the mode of operation to either min or max, and with \( L_y \) sets the number of rows of the detector array that are used. The flow chart of Figure 3-2 illustrates the procedure used in determining half wavelength boundary crossings. The initial phase data generated from noting the position of the reference mirror which led to a minimum
(or maximum depending on the mode of operation) intensity for each point in the STOPSDI output plane is represented by the array \( r(x, y) \), and the half wavelength information calculated by this procedure is stored in the array \( h(x, y) \). The wavefront across the aperture is given by: \( \hat{\Phi}_{\text{Total}}(x, y) = \pi[h(x, y) + \frac{\lambda}{2} r(x, y)] \). The flow chart of Figure 3-3 illustrates one implementation of a STOPSDI real time optical wavefront sensor which utilizes a parallel architecture. There are five 16K memory banks used by this system, \( \text{mem}_1(x, y) \), \( \text{mem}_2(x, y) \), \( \text{mem}_3(x, y) \), \( \text{mem}_4(x, y) \), and \( h(x, y) \). \text{part1} and \text{part2} correspond to the procedures outlined in Figures 3-1 and 3-2 respectively. They are executed in parallel. To prevent conflicts between the two procedures when accessing memory, the memory banks are switched back and forth between them. The number of steps taken to scan the reference mirror across half of a wavelength is represented by \( n_s \).

Due to the double pass nature of the Twyman-Green interferometer, stepping the reference mirror across half a wavelength corresponds to introducing a phase shift in arm two of the interferometer going from zero to \( 2\pi \). At each step in this staircase scan the STOPSDI output fringe pattern is sampled and compared to data, generated from measurements at previous positions of the reference mirror, already stored in memory. When the reference mirror is in its initial position, however, there is no data in memory with which to compare the detector array data. In other words, since no other data has been taken yet, all the data measured in this initial position is the maximum and minimum value measured thus far, and is therefore stored into memory. In addition to storing this intensity information, if the reference mirror is scanning forward, in the \(+x\) direction (See Figure 2-8), zeros, indicating the lowest position for the reference mirror, are stored as the current mirror position for each point. If it is going backward, in the \(-x\) direction, then the number which indicates the most extended position for the reference mirror is stored at each point. This number is based on the number of steps in the scan of the phase shifting reference mirror.

Once data from the first scan position has been written to memory and the mirror has been advanced to its next position, comparisons for each sample location can be carried out between the detector array data and the data already stored in memory. In minimum mode, if the data from the detectors is less than that which is already
Figure 3-1. Part 1, Flow Chart of Procedure Used to Determine the Initial Phase Data
Figure 3-2. Part 2, Flow Chart of Procedure for Determining Half Wavelength Boundary Crossings
Figure 3-3. System Flow Chart Depicting the Use of a Parallel Architecture
stored in the corresponding memory location, then the old data in memory is written over by this new data along with the present position of the phase shifting reference mirror. In maximum mode, if the data from a given detector is greater than the data already stored in memory for this point in the STOPSDI output plane, then this intensity data and the present displacement of the reference mirror are written to memory. The reference mirror is again stepped forward (or backward depending on the direction of the scan) and this procedure is repeated until the mirror has stepped across one half of a wavelength.

Upon completion of a scan, the minimum (or maximum depending on the mode of operation) intensity readings for each of the 128 by 128 sample points of the STOPSDI output plane, are stored in memory along with the positions of the phase shifting reference mirror which brought about these intensity readings. This reference mirror position information, as was proven earlier, is directly proportional to the optical phase at each point and is the initial phase data (See Figure 2-9) used to compute the optical wavefront. The intensity information, in a more complicated manner, is related to the amplitude of the light. This amplitude information is useful in performing diagnostics.

The final step in computing the wavefront of an optical disturbance is to determine half wavelength boundary crossings. Since the data is in a 2-dimensional array, it must be scanned for discontinuities in both the x and y directions. This is done by first setting the half wavelength number, \(n\), for sample point \((0,0)\) \(=((\text{column},\text{row}))\) to zero, or any other value if desired. Then, a horizontal scan is performed from location \((0,0)\) to location \((127,0)\). At each point a comparison is made between the initial phase data for a given point and its preceding neighbor. If it is determined that there is a discontinuity in the data and a half wavelength boundary has been crossed, then \(n\) is adjusted accordingly. If there is no boundary crossing, then \(n\) is left unaltered. The newly determined value of \(n\) is stored into memory along side the initial phase data already stored in memory for this point. Together, these two bytes of memory now hold a value which is directly related to the total wavefront deviation for that point. After the horizontal scan is completed, a vertical check is done between location \((0,0)\) and \((0,1)\) to determine if there is a discontinuity in the initial phase data for these two points and to compute the correct half wavelength
number, $n$, for location $(0.1)$ if there is a boundary crossing. This is followed by a horizontal scan from $(0.1)$ to $(127.1)$. This procedure is then repeated with rows 2, 3, 4, etc. until the entire aperture has been scanned and half wavelength numbers have been computed and stored into memory for each point of the STOPSDI output plane. Note that vertical comparisons are only made in the first column, but if the assumption that the object has no phase discontinuities is true, then explicit comparisons are not needed between each point and its neighbors in each column to assure continuous wavelength numbers in the $y$ direction. Of course, this also means the assumption of continuous data in every direction can be relaxed a bit, allowing larger discontinuities in the $y$ direction as long as the data is continuous in the $x$ direction and continuous up and down the first column.

In summary, this wavefront measurement implementation can be separated into two distinct procedures. The first being the generation of the initial phase data based on repeated comparisons of the data stored in memory to the data from the detector array for each step of the staircase scan of the reference mirror (See Figure 3-1). The second procedure being the determination of half wavelength boundary crossings based on the initial phase data generated by the first procedure (See Figure 3-2). Since repeated wavefront measurements are made by the system, a parallel architecture which takes advantage of the two part nature of the process is used to implement the system. While the initial phase data is being generated for one wavefront, boundary crossings are determined for the previous frame of data. Because both procedures will need access to initial phase data information, this parallel architecture requires two additional banks of memory that are switched back and forth between the two parts of the system (See Figure 3-3). Since computing half wavelength boundary crossings only requires one scan of the data array while determining the initial phase data takes as many scans of the complete data array as there are steps in the scan pattern of the reference mirror, the half wavelength numbers are computed much faster than the initial phase data. For the remainder of the frame period after the half wavelength numbers have been calculated, the data is free to be accessed by the user.
Chapter 4

Sampled, Twyman-Green, Optical Phase Shifting, Digital Interferometer Component Specifications

Figure 4-1 gives an overview of the STOPSDI system's electrical interconnections, while Figure 4-2 gives a detailed illustration of the optics and electronics selected for implementing the STOPSDI. The following is a description of the major components used in implementing the wavefront sensor, and the limits these individual components place on the system as a whole.

4.1 NRC Uniphase 1101 Laser

The NRC Uniphase 1101 is a 1.0mW Helium-Neon laser. It has a coherence length of more than one foot.

This laser is used to approximate the monochromatic and coherent light source of the interferometer. The laser has a wavelength of 632.8nm. All wavefront measurements are made in terms of wavelengths and fractions of a wavelength; therefore, laser type plays an important role in determining the resolution of the system. The coherence length determines the maximum optical path length difference that can be tolerated between the two arms of the interferometer. If the optical path length difference exceeds the coherence length, then the light can no longer be approximated as being coherent, and interference fringes are unobtainable.
Figure 4-1. Block Diagram of Major Electrical Interconnections of the System
Figure 4-2. Block Diagram Illustrating Major Components of the System
4.2 Newport Optical Components

The 20Z40 mirror, used for both the test arm and the phase shifting reference mirrors, is a round Pyrex mirror, and has a 2 inch diameter and a maximum peak-to-peak deviation of less than λ/40. The 40Q40 beam-splitter has a 4 inch diameter and is also flat to within λ/40. The T28-50-075 beam expander produces a 2 inch diameter collimated beam.

These optical components are assembled into a Twyman-Green interferometer. To some extent, the quality of wavefront measurements is only as good as the quality of the optics used in making the measurements. However, since aberrations brought about by the optics can be measured by examining an empty interferometer, these imperfections can be subtracted from future measurements, canceling any effect they might have had on the measurement. The optics need not generate a perfectly planar wavefront provided any deviations created from a planar wavefront do not exceed the phase resolution limits of the system.

4.3 Swarovski Optik NOVA Telescopic Sight

The Swarovski Optik NOVA telescopic sight is a 3-12x56 telescopic zoom lens.

The lens is used to focus the 2 inch diameter output beam of the interferometer down to a 0.302 inch diameter beam, the size of the active area of the detector array used to sample the interferometer output fringe pattern. This lens must be of comparable quality to the other optical elements of the system because any warping by this lens, of the combined interfering wavefronts is projected directly onto the detector array, and results in a distortion of all measurements.

4.4 Queensgate Instruments DIGITAL PIEZO

The Queensgate Instruments DIGITAL PIEZO actuator consists of a stack of discrete piezo electric transducers. Because the basic piezo electric stack exhibits hysteresis, non linearity and creep there is no simple relationship between the scan offset and the voltage on the piezo. To compensate for this, inside the stack of the DIGITAL PIEZO a parallel-plate capacitance micrometer is mounted. As the
transducer expands or contracts the spacing between the plates of the micrometer changes. Using a high frequency bridge the capacitance micrometer is continuously compared to a high stability reference capacitor, and the difference signal is demodulated, amplified and fed back to the piezo elements. This forms a servo-control loop with high gain and fast response time. A digitally controlled offset signal of 14 bit resolution is applied to the measuring bridge to scan the DIGITAL PIEZO. The range of the actuator is 10µm with a nominal step size of 0.6nm.

The reference mirror is mounted to the DIGITAL PIEZO which is used to step this mirror across one half of a wavelength, 316.4nm, introducing a controlled phase shift in arm number two of the interferometer.

4.5 EG & G Reticon MC9128D Modular Camera

The two-dimensional image sensor in the MC9128D modular camera consists of individual photodiodes arranged in a 128x128 square matrix. The active area of the sensor measures 0.302 inch on each side with the photodiode center-to-center spacing for both axes equal to 60 micrometers. Pixel rates up to 8 MHz and corresponding frame rates up to 380 frames/second can be achieved when using the entire detector array. The pixel rate is equal to the clock input rate, and each line is sequentially scanned or skipped depending on the mode of operation. The photodiodes have a saturation exposure of 0.155µj/cm² at 2870°K and signal to noise ratios of 100 : 1 for saturated to peak dark pattern and 1000 : 1 for saturated to random pixel. The sensor photo response uniformity is ±10% of the saturated output at 50% of saturation.

The camera is placed in the output plane of the interferometer and samples the output intensity resulting from the two interfering wavefronts created by the interferometer. The signal to noise ratio and the saturation exposure set limits on the minimum and maximum intensity of light that can be analysed by this system. The maximum clock rate of the camera limits the data acquisition rate to 8 MHz.
4.6 Analog Devices MATV-0811 8-Bit Video A/D Converter

The MATV-0811 analog-to-digital converter is an 8-bit A/D converter which operates at video frequencies. It is self contained including input buffer, encoder, reference, timing, and buffered parallel output. It has a relative dc accuracy of 0.2% of full scale, \( \pm 1/2 \) LSB when operating over the frequency range of dc to 11 MHz and 8-bit accuracy is guaranteed monotonic. The unit occupies 21 cubic inches and is housed in a metal case which shields the circuits from external RF interference and aids in efficient heat dissipation. The circuitry is pipelined and has a conversion time of \( 150 \pm 20 \) ns and a conversion rate of 11 MHz. The signal to noise ratio (rms signal to rms noise) is guaranteed to be at least 58 dB.

The MATV-0811 converts the analog camera output data into a digital signal that can be processed by the system electronics. The operating conversion rate is selected by the user, based on existing light levels, to be 1, 2, 4, or 8 MHz which are all well within the capabilities of this device. Because the MC9128D modular camera has a signal to noise ratio of only 100 : 1, the eight bit resolution of this A/D converter is more than adequate to properly convert the analog camera output into a digital signal.

4.7 74S225 Asynchronous First-In First-Out Memory

The 74S225 is a Schottky-clamped transistor-transistor logic 16x5 first-in-first-out memory which operates from dc to 10 MHz. The data is loaded and emptied on a first-in-first-out basis through asynchronous input and output ports. Both the word length and FIFO depth are expandable.

The 74S225 works in conjunction with the MATV-0811 analog-to-digital converter. Since this A/D converter is pipelined it does not operate synchronously with the rest of the circuitry of the wavefront sensor. The 74S225 is used as a data buffer to hold up certain signals until the A/D converter has finished its processing.
4.8 IDT71981S CMOS Static RAM

The IDT71981S is a 65,538 bit high-speed static RAM organized as 16Kx4. It has an access time of 35 ns and a maximum power consumption of 605 mW. All inputs and outputs are TTL-compatible and operate from a single five volt supply. Fully static asynchronous circuitry is used, which requires no clocks or refreshing for operation, and provides equal access and cycle times.

The IDT71981S is used to store 8 bits of intensity information, 8 bits of mirror position information, and 8 bits of wavelength number information for each of the 16K detectors of the MC9128D located in the output plane of the interferometer.

4.9 Industrial IBM PC MBA 402 I/O Cards

The MULTIBUS Adaptor consists of two cards. One fits inside the IBM PC AT and the other fits inside a MULTIBUS card cage. The two cards are interconnected with two ribbon cables. Address mapping permits the PC AT to directly address MULTIBUS memory as though it were PC AT memory. The resulting target address in MULTIBUS address space is determined by DIP switches. Another set of switches selects the range of PC AT I/O addresses that are mapped to MULTIBUS I/O. The MULTIBUS Adaptor contains 32K bytes of dual port concurrent access static RAM. The RAM can be mapped into any unused PC AT address space and into any unused MULTIBUS address space.

These I/O cards are used to interface the STOPSDI circuitry, which is in MULTIBUS format, to the IBM PC AT. Similar cards can be used to interface the sensor to other computer systems.

4.10 System Specifications

The specifications for the above components which makeup the STOPSDI wavefront sensor define the specifications for the system as a whole.

- Minimum resolvable OPD .................. 1.2 nm.
- Maximum resolvable OPD .................. 19993.6 nm.
- Maximum system clock rate ................ 8 MHz.
System frame size ................. 128x128, 128x64, 128x32, ..., 128x2.
System frame rate ............... clock frequency/(frame size x number of steps).

4.10.1 Minimum Resolvable Optical Path Length Difference

The Digital Piezo has a nominal step size of .6nm but is controlled by a seven bit data word from the wavefront sensor. As a result, the Digital Piezo is not the limiting factor in determining the minimum resolvable phase. Instead, it is the seven bit word size which sets the minimum step size for the PZT, and hence the minimum resolvable optical path length difference, to

\[
\min\{\text{OPD}\} = \frac{\lambda}{2 \times 2^7} = \frac{312.4\text{nm}}{256} = 1.2\text{nm} = .01\text{rad}
\]

4.10.2 Maximum Resolvable Optical Path Length Difference

The maximum resolvable optical path length difference which can be detected by the wavefront sensor is defined by the number of detectors in the MC9128D detector array, hence the number of samples. The assumption of a continuous wavefront states that the maximum phase difference between any two adjacent detectors, due to the double pass nature of Twyman-Green interferometer, is \(\frac{\pi}{2}\). Consequently, the maximum phase difference across either axis of the detector arrays 128 by 128 detectors is 64\(\pi\). This corresponds to a maximum optical path length difference of 32\(\lambda\) or 9996.8 nm across a single axis and 19993.6 nm across the entire aperture.

4.10.3 System Frame Rate

The maximum clock rate for the MC9128D is 8 MHz, and the circuitry of the wavefront sensor allows the user to set the clock rate to either 1, 2, 4, or 8 MHz. The MC9128D has a single output line through which all of its data is multiplexed. This single line creates the major bottleneck in determining the rate of wavefront measurements. Presently, there is no detector array, commercially available, that has
an output line for each detector of the array or even two or three output lines for the array, instead of one, through which data is passed. If such an array were available, this would greatly increase the rate at which wavefronts could be determined by facilitating the use of a much more parallel architecture for the system than what is possible with the MC9128D. If there were two output lines, for example, the system could operate twice as fast. If there was one line for each row or column of the array, the system could operate over one hundred times as fast, and in the ideal case, if there was an output line for each detector, then the system frame rate becomes independent of frame size; for a 128x128 array this corresponds to a frame rate which is over 16000 times as fast as that possible with the MC9128D.

The user specifies the height of the detector array, i.e. the number of samples in the y direction. A smaller array size means less data and a faster frame rate. The electronics of the wavefront sensor limit the array size to 128 points in the x direction by 128 (which corresponds to a full frame of data), 64, 32, 16, 8, 4 or 2 in the y direction. The user also specifies the number of steps taken to scan the reference mirror across half a wavelength. The electronics limit the number of steps to 128, 64, 32, 16, 8, 4 or 2 steps per half wavelength. The smaller the step size, the greater the resolution of the sensor but the slower the sensor frame rate. The user trades off step size for frame rate based on the needs of a given application.

The single output line of the MC9128D and the user specified clock rate combine with the user specified frame size to set the time it takes for a frame of data to be passed as output from the detector array (τ in Figure 2-8) and processed by the system. This detector array frame rate along with the number of steps taken to scan the phase shifting reference mirror across half a wavelength gives the maximum rate at which wavefront measurements can be made. Table 4-1 outlines the STOPSDI system frame rate as a function of the frame size and the number of steps in the reference mirror's scan.
Table 4-1. System Frame Rate (Hz) vs. Frame Size and Number of Steps in the Reference Mirror's Scan, with a System Clock Rate of 8 MHz

<table>
<thead>
<tr>
<th>ns</th>
<th>128x2</th>
<th>128x2</th>
<th>128x8</th>
<th>128x16</th>
<th>128x32</th>
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<tr>
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<td>1302</td>
<td>710</td>
<td>372</td>
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<tr>
<td>4</td>
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<td>1736</td>
<td>1116</td>
<td>651.0</td>
<td>355.0</td>
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<td>95.25</td>
</tr>
<tr>
<td>8</td>
<td>1202</td>
<td>868.0</td>
<td>558.0</td>
<td>325.5</td>
<td>177.5</td>
<td>93.01</td>
<td>47.63</td>
</tr>
<tr>
<td>16</td>
<td>601.0</td>
<td>434.0</td>
<td>279.0</td>
<td>162.8</td>
<td>88.75</td>
<td>46.50</td>
<td>23.81</td>
</tr>
<tr>
<td>32</td>
<td>300.5</td>
<td>217.0</td>
<td>139.5</td>
<td>81.38</td>
<td>44.38</td>
<td>23.25</td>
<td>11.91</td>
</tr>
<tr>
<td>64</td>
<td>150.2</td>
<td>108.5</td>
<td>69.75</td>
<td>40.69</td>
<td>22.19</td>
<td>11.63</td>
<td>5.953</td>
</tr>
<tr>
<td>128</td>
<td>75.12</td>
<td>54.25</td>
<td>34.88</td>
<td>20.34</td>
<td>11.09</td>
<td>5.813</td>
<td>2.977</td>
</tr>
</tbody>
</table>

ns = number of steps in the reference mirror's scan
Chapter 5

Results and Discussion

A bread board model of the STOPSDI was constructed and tested. What follows is a sampling from the many test cases which were run. For all of the sample cases listed, unless otherwise specified, the data was taken with the wavefront sensor in minimum mode, with a clock rate of 4 MHz and with a phase shifting reference mirror step size of 19.2 nm which is approximately $\frac{\lambda}{32}$, and the entire array, 128x128, was used. A 32x32 subset of the data, consisting of every fourth point both horizontally and vertically, was then processed by the FRINGE software package for analysis.

5.1 Examination of Interferometer Output Amplitude Profile

Before the wavefront data is scrutinized, some analysis of the amplitude profile of the light at the output plane of the STOPSDI is in order. For this purpose, measurements were taken with approximately three wavelengths of tilt in the x direction and with the wavefront sensor first in maximum mode then in minimum mode. As can be seen from Figure 5-1, the maximum intensity for much of the array has many of the detectors operating close to saturation. The amplitude is fairly uniform across most of the array but does drop off significantly near the edges. This is characteristic of the gaussian amplitude profile of laser beams. Because the STOPSDI wavefront sensor makes measurements based on relative minimum and maximum intensity readings for each detector, however, the amplitude fluctuations across the aperture have little effect on any wavefront measurements. The important thing is that all detectors are exposed to some level of light which is above the threshold required for good signal to noise and which varies sinusoidally as the
reference mirror is scanned back and forth.

Figure 5-2 is a plot of the amplitude profile with the sensor in minimum mode. Ideally, if the beam splitter of the interferometer (See Figure 2-2) is a 50/50 beam splitter and the object being examined is a pure phase object, then the minimum intensity for each point in the output plane should be zero (See Equations (2-35), (2-36) and (2-37)). Most of the data is in fact zero but there are many points were the data does not reach zero. There are two reasons for this. The first is that the two interfering wavefronts do not have the same amplitude profiles. The two wavefronts will never completely cancel in points where the amplitudes are not identical and the minimum intensity observed will have some none zero value. This leads to the random bright spots found scattered throughout the aperture and the slight constant offset across parts of the aperture. The second factor is based on the discontinuous staircase scan pattern for the phase shifting reference mirror. If the position of the reference mirror which should give a minimum output for a given point is located between two of the steps of the scan, then the two wavefronts will never perfectly cancel, even if they have equal amplitudes. This will lead to some none zero intensity reading, and is evident by the ridges which can be seen in Figure 5-2. This error term is proportional to the amplitude of the wavefront under examination and is more pronounced near the center where the amplitude is stronger. The ridges form vertical lines which correspond to lines of constant phase (recall that the phase profile was set to approximately three wavelengths of horizontal tilt).

In comparing Figure 5-1 to Figure 5-2 one notices that the maximum intensity readings are always much greater than the minimum readings. This is a good check for determining if the wavefront is covering the entire array, or if stray light which is not modulated by the phase shifting reference mirror is incident on part of the array.

5.2 Examination of Problem Amplitude Profiles

To get the maximum dynamic range for intensity measurements, the detector array should be operated over its entire linear range. Because of possible fluctua-
Figure 5-1. Recording of Maximum Amplitude Profile at Output Plane of the Interferometer
Figure 5-2. Recording of Minimum Amplitude Profile at Output Plane of the Interferometer
tions in the amplitude of the light source or amplitude changes in arm two of the
interferometer brought about from using a test object which is not a pure phase
object, care must be taken to assure an appropriate level of light is incident on each
detector across the array. If the amplitudes of the two wavefronts are very large,
then the detectors of the array will saturate, and if the system is being operated in
maximum mode, the position of the reference mirror which should lead to a unique
maximum intensity can not be distinguished from neighboring positions which also
saturate the detector and have the same saturated output. If there is two little
light, then the difference between the minimum and maximum intensities could be
to small to detect.

5.2.1 Insufficient Light to be Recorded by the Detector Array

There is a minimum intensity level which can be measured by the detector array
located in the STOPSDI output plane. If either or both of the light levels of the two
arms of the interferometer drops below this level, then detection becomes impossible.
5-3 illustrates the effect of insufficient light in both arms of the interferometer. The
intensity for a given point in the output plane of the STOPSDI is plotted as a
function of the position of the reference mirror. If there is insufficient light in only
one arm of the interferometer, then this curve is shifted up to a different DC level
which corresponds to the intensity of the stronger signal; however, there is still no
unique minimum or maximum. This could be the result of using an object in arm
number one of the interferometer which was not a pure phase object and which
reduced the amplitude of the light in this arm by more than what the system could
tolerate.

5.2.2 Saturation of the Detector Array Elements

If the intensity levels of light incident on the array are such that for some part
of the reference mirror scan some of the detectors of the array are saturated, then
the system can not be operated in maximum mode, but successful data aquisition
can be obtained in minimum mode (See Figure 5-4). As long as the amplitudes of
the two interfering wavefronts are approximately equal, then the minimum intensity
CHAPTER 5. RESULTS AND DISCUSSION

Figure 5-3. Results of Insufficient Light Levels

Figure 5-4. Effect of Saturation on Intensity Recordings at a Point \((x_0, y_0)\) in the Output Plane of the Interferometer
should be close to zero even if the maximum intensity saturates the detector array. As a result, when making phase measurements, it is best to operate the system in minimum mode.

5.2.3 **Vertical Blooming Across the Detector Array Elements**

The detectors of the MC9128D detector array have been approximated as being independent of one another, but in the actual array, there is some coupling between the detectors of each column. When any detector of a column is being operated well beyond the saturation level, charge from that detector bleeds out into the other detectors of that column. This can result in detectors which have incident light levels well within the linear range of the detector saturating (See Figure 5-5). A feature, characteristic of this type of amplitude problem, is the ability of the system to measure horizontal tilt when the amplitude of the light is high but the inability to measure vertical tilt. Horizontal tilt results in a vertical fringe pattern with a uniform amplitude up and down each column of the array. If one detector is saturated, then all the detectors in that column should be saturated, and the vertical blooming has little impact other than to lower the saturation level a bit. Vertical tilt, however, results in horizontal fringes. Consequently some detectors of a column will be at there minimum intensity level, for a given position of the reference mirror, while others are saturated. The saturated detectors will leak charge into the unsaturated detectors causing them to also saturate. The entire column will saturate and the wavefront can not be measured.

5.3 **Analysis of a Nulled Interferometer**

The first wavefront measurement to be analyzed is that for a nulled interferometer. This is the case when there is no object in either arm of the interferometer and the interferometer is aligned with no tilt in either of the interfering wavefronts; there are no fringes in the output plane. This measurement gives a good indication of the quality of the optics, and the data from this measurement can be subtracted from future wavefront measurements to cancel the effects of imperfections in the optics.
Figure 5-5. Effect of Vertical Blooming on the Intensity Profile
The data is summarized in Table 5-1. There is still some tilt to the wavefront which indicates that the interferometer was not perfectly nulled. The tilt is not indicative of the quality of the optics but the accuracy of the alignment. The Strehl ratio was found to be 0.977 and gives a good indication of the optical quality of the system. Repeated measurements of this wavefront were taken, and comparable results were obtained each time. A plot of the wavefront is given in Figure 5-6.

5.4 Analysis of a Small X/Y-Tilt

A tilted wavefront is convenient to analyze because an actual phase object is not needed to generate the wavefront. Instead, the test arm mirror just needs to be tilted to give the desired results. By doing simple fringe counting, one can get an approximate value for the amount of tilt in the wavefront with which to compare the measured data.

The interferometer was first nulled, then the test arm mirror was tilted in the horizontal and vertical direction introducing tilt in both directions of the wavefront of arm number one. With the phase shifting reference mirror held still, approximately four diagonal fringes were observed across the aperture indicating the tilted mirror corresponded to a phase object with approximately two wavelengths of tilt. Data was taken and processed by the FRINGE software package. The results outlined in Table 5-2 confirmed these observations. Figure 5-7 is a plot of the wavefront.

5.5 Analysis of a Large X-Tilt

With a detector array size of 128 by 128 sample points, the assumption of a continuous wavefront sets a limit of 64\(\lambda\) as the maximum peak to peak deviation across the aperture that can be measured by the system. This corresponds to a perfectly flat wavefront with 32\(\lambda\) of tilt in both directions. In such a wavefront there is a \(\frac{\lambda}{2}\) phase difference between each adjacent detector which results in a half wavelength boundary crossing between each detector. If there is any noise in the data, then the half wavelength boundary crossings will be miscalculated, creating large differences between the actual wavefront and the measurement. This extreme
Table 5-1. Summary of FRINGE Results for a Nulled Interferometer

The wavefront deviation is measured in units of waves (wavelength = 0.633 microns) with tilt and defocus measured from the diffraction focus.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAW</td>
<td>0</td>
<td>0.041</td>
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<tr>
<td>PLANE</td>
<td>2</td>
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<tr>
<td>SPHERE</td>
<td>3</td>
<td>0.024</td>
</tr>
<tr>
<td>4H ORDER</td>
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<td>0.024</td>
</tr>
<tr>
<td>6H ORDER</td>
<td>15</td>
<td>0.023</td>
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<td>8H ORDER</td>
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Strehl Ratio = 0.977 at Diffraction Focus

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Fourth Order Aberrations

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<td></td>
<td></td>
<td></td>
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Residual Wavefront Variations Evaluated at Data Points

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<thead>
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<th>MIN</th>
<th>SPAN</th>
<th>STREHL</th>
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Residual Wavefront Variations Over Uniform Grid

<table>
<thead>
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<th>MIN</th>
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<th>STREHL</th>
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RMS Calculated from Zernike Coefficients = 0.029

Zernike Polynomial Coefficients

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Figure 5-6. Measured Wavefront Profile for a Nulled Interferometer
Table 5-2. Summary of FRINGE Results for a Wavefront with a Small Degree of Tilt

The wavefront deviation is measured in units of waves (wavelength = 0.633 microns) with tilt and defocus measured from the diffraction focus.

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<tr>
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Strehl Ratio = 0.991 at Diffraction Focus

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</tr>
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</table>

Residual Wavefront Variations Evaluated at Data Points

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<th>MIN</th>
<th>SPAN</th>
<th>STREHL</th>
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Residual Wavefront Variations Over Uniform Grid

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RMS Calculated from Zernike Coefficients = 0.243

Zernike Polynomial Coefficients

-0.4465  -0.1900  0.0000  -0.0019  -0.0085  0.0019  -0.0032  -0.0019  -0.0009
-0.0002  -0.0042  -0.0010  0.0014  0.0009  -0.0005  -0.0004  -0.0036  0.0016
 0.0017  0.0013  0.0017  -0.0008  -0.0002  -0.0001  0.0010  -0.0004  -0.0010
 0.0006  -0.0009  -0.0005  -0.0003  -0.0003  -0.0001  0.0000  0.0003  -0.0001
Figure 5-7. Plot of a Slightly Tilted Wavefront
sensitivity to noise makes such wavefronts unmeasurable. A more reasonable limit on the maximum deviation which is measurable must take into account the effects of increased noise sensitivity with increased tilt.

Measurements were made with different degrees of tilt. The data in Table 5-3 is for the largest $x$-tilt consistently measurable before noise became a serious problem. The wavefront is illustrated in Figure 5-8.

5.6 Analysis of a Large Y-Tilt

The above procedure was repeated except with vertical tilt instead of horizontal tilt. The results are outlined in Table 5-4 and Figure 5-9.

5.7 Analysis of an Atmospheric Disturbance

With the interferometer nulled, a hot plate was placed under arm number one of the interferometer, and a small jet of air was blown across the plate. This created a continually changing atmospheric turbulence above the plate as the phase profile to be measured by the system. All of the other test cases examined thus far involved static phase objects. This is the first wavefront measurement where the real time nature of the sensor is essential. The results are given in Table 5-5 and Figure 5-10.

For the test cases which examined tilted wavefronts it was possible to compare the STOPSDI data to results expected based on simple fringe counting. For this case, however, there is nothing to compare with the data, and only a "snapshot" of instantaneous phase data was analysed. A more comprehensive test would be to examine a known rotating phase object placed in the test arm of the interferometer. This would give numbers that could be compared to the known measurements when the object is stationary. The set up for such an experiment, however, was not available.

5.8 ZYGO Interferometer Comparison

A low quality optical flat was examined using the ZYGO static wavefront sensor, and was then placed into the STOPSDI real time optical wavefront sensor. Data
Table 5-3. Summary of FRINGE Results for a Wavefront with a Large Amount of Tilt in the X-Direction

The wavefront deviation is measured in units of waves (wavelength = 0.633 microns) with tilt and defocus measured from the diffraction focus.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAW</td>
<td>0</td>
<td>0.896</td>
</tr>
<tr>
<td>PLANE</td>
<td>2</td>
<td>0.022</td>
</tr>
<tr>
<td>SPHERE</td>
<td>3</td>
<td>0.021</td>
</tr>
<tr>
<td>4H ORDER</td>
<td>8</td>
<td>0.019</td>
</tr>
<tr>
<td>6H ORDER</td>
<td>15</td>
<td>0.018</td>
</tr>
<tr>
<td>8H ORDER</td>
<td>24</td>
<td>0.018</td>
</tr>
<tr>
<td>COMPLETE</td>
<td>36</td>
<td>0.017</td>
</tr>
</tbody>
</table>

Strehl Ratio = 0.982 at Diffraction Focus

<table>
<thead>
<tr>
<th>Magnitude Waves</th>
<th>Angle Deg</th>
<th>Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.553</td>
<td>2.3</td>
<td>TILT</td>
</tr>
<tr>
<td>-0.016</td>
<td></td>
<td>DEFOCUS</td>
</tr>
<tr>
<td>0.022</td>
<td>-47.1</td>
<td>ASTIGMATISM</td>
</tr>
<tr>
<td>0.027</td>
<td>-109.7</td>
<td>COMA</td>
</tr>
<tr>
<td>-0.014</td>
<td></td>
<td>SPHERICAL ABERRATION</td>
</tr>
</tbody>
</table>

Residual Wavefront Variations Evaluated at Data Points

<table>
<thead>
<tr>
<th>PTS</th>
<th>RMS</th>
<th>MAX</th>
<th>MIN</th>
<th>SPAN</th>
<th>STREHL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1024</td>
<td>0.896</td>
<td>1.529</td>
<td>-1.604</td>
<td>3.133</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Residual Wavefront Variations Over Uniform Grid

<table>
<thead>
<tr>
<th>PTS</th>
<th>RMS</th>
<th>MAX</th>
<th>MIN</th>
<th>SPAN</th>
<th>STREHL</th>
</tr>
</thead>
<tbody>
<tr>
<td>697.</td>
<td>0.771</td>
<td>1.459</td>
<td>-1.487</td>
<td>2.946</td>
<td>0.000</td>
</tr>
</tbody>
</table>

RMS Calculated from Zernike Coefficients = 0.776

Zernike Polynomial Coefficients

<table>
<thead>
<tr>
<th>1.5509</th>
<th>0.0648</th>
<th>-0.0060</th>
<th>0.0002</th>
<th>-0.0097</th>
<th>0.0014</th>
<th>-0.0058</th>
<th>-0.0025</th>
<th>0.0003</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.0001</td>
<td>0.0003</td>
<td>0.0002</td>
<td>0.0016</td>
<td>0.0008</td>
<td>0.0000</td>
<td>-0.0011</td>
<td>-0.0022</td>
<td>0.0008</td>
</tr>
<tr>
<td>0.0008</td>
<td>0.0002</td>
<td>0.0032</td>
<td>0.0019</td>
<td>0.0021</td>
<td>0.0022</td>
<td>0.0031</td>
<td>0.0016</td>
<td>-0.0013</td>
</tr>
<tr>
<td>0.0003</td>
<td>0.0001</td>
<td>-0.0006</td>
<td>-0.0005</td>
<td>-0.0011</td>
<td>-0.0007</td>
<td>-0.0007</td>
<td>-0.0011</td>
<td>0.0001</td>
</tr>
</tbody>
</table>
Figure 5-8. Plot of a Wavefront with a Large Amount of X-Directed Tilt
Table 5-4. Summary of FRINGE Results for a Wavefront with a Large Amount of Tilt in the Y-Direction

The wavefront deviation is measured in units of waves (wavelength = 0.633 microns) with tilt and defocus measured from the diffraction focus.

<table>
<thead>
<tr>
<th>N</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAW</td>
<td>0</td>
</tr>
<tr>
<td>PLANE</td>
<td>2</td>
</tr>
<tr>
<td>SPHERE</td>
<td>3</td>
</tr>
<tr>
<td>4H ORDER</td>
<td>8</td>
</tr>
<tr>
<td>6H ORDER</td>
<td>15</td>
</tr>
<tr>
<td>8H ORDER</td>
<td>24</td>
</tr>
<tr>
<td>COMPLETE</td>
<td>36</td>
</tr>
</tbody>
</table>

Strehl Ratio = 0.977 at Diffraction Focus

<table>
<thead>
<tr>
<th>Magnitude Waves</th>
<th>Angle Deg</th>
<th>Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.256</td>
<td>-92.5</td>
<td>TILT</td>
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Fourth Order Aberrations

<table>
<thead>
<tr>
<th>Magnitude Waves</th>
<th>Angle Deg</th>
<th>Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.013</td>
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<td>0.006</td>
<td>-58.1</td>
<td>ASTIGMATISM</td>
</tr>
<tr>
<td>0.014</td>
<td>-122.4</td>
<td>COMA</td>
</tr>
<tr>
<td>-0.009</td>
<td></td>
<td>SPHERICAL ABERRATION</td>
</tr>
</tbody>
</table>

Residual Wavefront Variations Evaluated at Data Points

<table>
<thead>
<tr>
<th>PTS</th>
<th>RMS</th>
<th>MAX</th>
<th>MIN</th>
<th>SPAN</th>
<th>STREHL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1024</td>
<td>0.725</td>
<td>1.270</td>
<td>-1.488</td>
<td>2.758</td>
<td>0.000</td>
</tr>
</tbody>
</table>

Residual Wavefront Variations Over Uniform Grid

<table>
<thead>
<tr>
<th>PTS</th>
<th>RMS</th>
<th>MAX</th>
<th>MIN</th>
<th>SPAN</th>
<th>STREHL</th>
</tr>
</thead>
<tbody>
<tr>
<td>697</td>
<td>0.623</td>
<td>1.195</td>
<td>-1.186</td>
<td>2.381</td>
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RMS Calculated from Zernike Coefficients = 0.628

Zernike Polynomial Coefficients

<table>
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<th>Coefficient</th>
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<tbody>
<tr>
<td>-0.0541</td>
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<tr>
<td>-1.2538</td>
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<td>-0.0045</td>
</tr>
<tr>
<td>-0.0005</td>
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<tr>
<td>-0.0019</td>
</tr>
<tr>
<td>-0.0046</td>
</tr>
<tr>
<td>-0.0011</td>
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<td>0.0008</td>
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<td>0.0071</td>
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<td>-0.0002</td>
</tr>
<tr>
<td>-0.0002</td>
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<tr>
<td>0.0000</td>
</tr>
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</table>
Figure 5-9. Plot of a Wavefront with a Large Amount of Y-Directed Tilt
Table 5-5. Summary of FRINGE Results for a Wavefront Distorted by Atmospheric Turbulence

The wavefront deviation is measured in units of waves (wavelength = 0.633 microns) with tilt and defocus measured from the diffraction focus.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAW</td>
<td>0</td>
<td>0.089</td>
</tr>
<tr>
<td>PLANE</td>
<td>2</td>
<td>0.085</td>
</tr>
<tr>
<td>SPHERE</td>
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<td>0.084</td>
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<tr>
<td>4H ORDER</td>
<td>8</td>
<td>0.064</td>
</tr>
<tr>
<td>6H ORDER</td>
<td>15</td>
<td>0.046</td>
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<tr>
<td>8H ORDER</td>
<td>24</td>
<td>0.037</td>
</tr>
<tr>
<td>COMPLETE</td>
<td>36</td>
<td>0.026</td>
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</table>

Strehl Ratio = 0.755 at Diffraction Focus

<table>
<thead>
<tr>
<th>Magnitude Waves</th>
<th>Angle Deg</th>
<th>Designation</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>0.195</td>
<td>0.015</td>
</tr>
<tr>
<td></td>
<td>-18.6</td>
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</tr>
<tr>
<td></td>
<td>0.114</td>
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<tr>
<td></td>
<td>-0.023</td>
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</tr>
</tbody>
</table>

Residual Wavefront Variations Evaluated at Data Points

<table>
<thead>
<tr>
<th>PTS</th>
<th>RMS</th>
<th>MAX</th>
<th>MIN</th>
<th>SPAN</th>
<th>STREHL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1024</td>
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<td>0.267</td>
<td>-0.287</td>
<td>0.555</td>
<td>0.730</td>
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</tbody>
</table>

Residual Wavefront Variations Over Uniform Grid

<table>
<thead>
<tr>
<th>PTS</th>
<th>RMS</th>
<th>MAX</th>
<th>MIN</th>
<th>SPAN</th>
<th>STREHL</th>
</tr>
</thead>
<tbody>
<tr>
<td>697.</td>
<td>0.078</td>
<td>0.193</td>
<td>-0.178</td>
<td>0.371</td>
<td>0.788</td>
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</table>

RMS Calculated from Zernike Coefficients = 0.078

Zernike Polynomial Coefficients

<p>| | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0085</td>
<td>0.0631</td>
<td>0.0051</td>
<td>0.0937</td>
<td>-0.0544</td>
<td>-0.0179</td>
<td>-0.0651</td>
<td>-0.0245</td>
<td>0.0836</td>
<td></td>
</tr>
<tr>
<td>-0.0390</td>
<td>-0.0489</td>
<td>-0.0178</td>
<td>0.0057</td>
<td>0.0368</td>
<td>0.0121</td>
<td>-0.0330</td>
<td>-0.0368</td>
<td>-0.0493</td>
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</tr>
<tr>
<td>0.0127</td>
<td>-0.0023</td>
<td>0.0046</td>
<td>-0.0125</td>
<td>-0.0180</td>
<td>-0.0101</td>
<td>-0.0454</td>
<td>-0.0486</td>
<td>-0.0166</td>
<td></td>
</tr>
<tr>
<td>-0.0010</td>
<td>0.0069</td>
<td>-0.0025</td>
<td>0.0031</td>
<td>-0.0004</td>
<td>0.0022</td>
<td>0.0022</td>
<td>0.0020</td>
<td>-0.0001</td>
<td></td>
</tr>
</tbody>
</table>
Figure 5-10. Plot of a Wavefront Distorted by Atmospheric Turbulence
was taken and compared to the ZYGO data. This test gives precise data with which to compare the accuracy of wavefront sensor data, and characterize the system performance.

The ZYGO data is listed in Table 5-6 and Figure 5-11, and the STOPSDI data is in Table 5-7 and Figure 5-12. It is very difficult, if not impossible, to measure the exact same region of the optical flat and to have it aligned in precisely the same manner for the measurements by the two different systems. Consequently, one cannot expect a precise match between the two sets of data. By examining the data, it is obvious that a slightly larger region of the optical flat was observed by the ZYGO than by the STOPSDI. As a result, the span of the ZYGO measurement is larger than that of the STOPSDI. Also, the Zernike coefficients are slightly different. From the angle of the astigmatism and coma it is clear that the object was rotated slightly for the ZYGO measurement. The tilt terms are indicative of the alignment of the two interferometers. They do not give information about the optical flat phase profile. There is a close match between all of the data from the two measurements, and based on the wavefront contour plots, there is a measurement accuracy of at least .1λ. After initializing the ZYGO it took several seconds for the phase profile to be determined. For the STOPSDI real time wavefront sensor, however, the object was simply placed in arm one of the interferometer and the phase profile was recorded in .083 second.
Table 5-6. Summary of FRINGE Results, Generated with the ZYGO Static Wavefront Sensor, for a Test Optical Flat

The wavefront deviation is measured in units of waves (wavelength = 0.633 microns) with tilt and defocus measured from the diffraction focus.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>PLANE</td>
<td>2</td>
<td>0.133</td>
</tr>
<tr>
<td>SPHERE</td>
<td>3</td>
<td>0.098</td>
</tr>
<tr>
<td>4H ORDER</td>
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<td>0.015</td>
</tr>
<tr>
<td>6H ORDER</td>
<td>15</td>
<td>0.008</td>
</tr>
<tr>
<td>8H ORDER</td>
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<td>0.005</td>
</tr>
<tr>
<td>COMPLETE</td>
<td>36</td>
<td>0.003</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Magnitude Waves</th>
<th>Angle Deg</th>
<th>Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.305</td>
<td>-267.9</td>
<td>TILT</td>
</tr>
<tr>
<td>0.111</td>
<td></td>
<td>DEFOCUS</td>
</tr>
<tr>
<td>0.437</td>
<td>82.2</td>
<td>ASTIGMATISM</td>
</tr>
<tr>
<td>0.068</td>
<td>-83.4</td>
<td>COMA</td>
</tr>
<tr>
<td>-0.042</td>
<td></td>
<td>SPHERICAL ABERRATION</td>
</tr>
</tbody>
</table>

Fourth Order Aberrations

Residual Wavefront Variations Evaluated at Data Points

<table>
<thead>
<tr>
<th>PTS</th>
<th>RMS</th>
<th>MAX</th>
<th>MIN</th>
<th>SPAN</th>
<th>STREHL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1349</td>
<td>0.128</td>
<td>0.343</td>
<td>-0.168</td>
<td>0.511</td>
<td>0.521</td>
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</tbody>
</table>

Zernike Polynomial Coefficients

-0.0057  0.2578  0.1445  -0.2163  0.0590  0.0041  -0.0271  -0.0062  -0.0175
0.0225  0.0137  -0.0003  0.0000  0.0126  -0.0052  -0.0129  0.0004  -0.0006
-0.0095  0.0054  0.0024  -0.0031  -0.0023  0.0000  -0.0016  0.0108  -0.0056
0.0006  -0.0030  0.0028  -0.0060  -0.0026  -0.0033  -0.0029  -0.0012  0.0060
Figure 5-11. Plot of ZYGO Interpretation of a Test Optical Flat
Table 5-7. Summary of FRINGE Results, Generated with the STOPSDI, for a Test Optical Flat

The wavefront deviation is measured in units of waves (wavelength = 0.633 microns) with tilt and defocus measured from the diffraction focus.

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>RAW</td>
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<td>0.176</td>
</tr>
<tr>
<td>PLANE</td>
<td>2</td>
<td>0.119</td>
</tr>
<tr>
<td>SPHERE</td>
<td>3</td>
<td>0.081</td>
</tr>
<tr>
<td>4H ORDER</td>
<td>8</td>
<td>0.026</td>
</tr>
<tr>
<td>6H ORDER</td>
<td>15</td>
<td>0.015</td>
</tr>
<tr>
<td>8H ORDER</td>
<td>24</td>
<td>0.013</td>
</tr>
<tr>
<td>COMPLETE</td>
<td>36</td>
<td>0.012</td>
</tr>
</tbody>
</table>

Strehl Ratio = 0.774 at Diffraction Focus

<table>
<thead>
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<th>Angle Deg</th>
<th>Designation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.223</td>
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<tr>
<td>0.209</td>
<td></td>
<td>DEFOCUS</td>
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<td>0.346</td>
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<td>0.079</td>
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</tr>
<tr>
<td>-0.042</td>
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<td>SPHERICAL ABERRATION</td>
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</table>

Residual Wavefront Variations Evaluated at Data Points

<table>
<thead>
<tr>
<th>PTS</th>
<th>RMS</th>
<th>MAX</th>
<th>MIN</th>
<th>SPAN</th>
<th>STREHL</th>
</tr>
</thead>
<tbody>
<tr>
<td>1024</td>
<td>0.119</td>
<td>0.302</td>
<td>-0.174</td>
<td>.476</td>
<td>0.570</td>
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</table>

Residual Wavefront Variations Over Uniform Grid

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<th>SPAN</th>
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RMS Calculated from Zernike Coefficients = 0.105

Zernike Polynomial Coefficients

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Figure 5-12. Plot of STOPSDL Interpretation of a Test Optical Flat
Chapter 6

Conclusions and Recommendations

As winds blow solar heated air about the earth, small temperature fluctuations arise throughout the atmosphere. These temperature differences result in variations in the index of refraction and hence the speed at which light propagates through different sections of the atmosphere. Consequently, as an optical wave propagates through the earth's atmosphere, its wavefront becomes distorted. Adaptive optical systems provide the means for overcoming limitations brought about by such atmospheric distortions of a wavefront. A real time optical wavefront sensor is a crucial component of such a system.

The STOPSDI was shown to operate as a real time optical wavefront sensor. With a sampling array size of 128 by 128 data points and a phase resolution of $\frac{2\pi}{16}$ the system can operate with a system frame rate as high as 47.63 Hz, and by compromising phase resolution or the number of sample points (hence spatial resolution), the system frame rate can be pushed even higher without any changes to the electronics or optics of the system. The phase profile of a low quality optical flat was characterized using a ZYGO static phase sensor, and the results were compared to measurements made with the STOPSDI. The two measurements were found to be comparable except for one major difference, it took several seconds for the ZYGO to analyse the flat but it only took the STOPSDI about .08 second to make the same measurement. In many applications, such as adaptive optics, this real time nature of the sensor is essential.

From space based telescopes which need to monitor and correct for thermal and gravitational stress on their optical elements, to systems making phase measurements from on top of an optical work bench, there are many applications for real
time optical wavefront sensing technology. The Sampled, Twyman-Green, Optical Phase Shifting, Digital Interferometer is suitable for many of these applications and with various modifications can be used for many other applications. There are many improvements, some simple while others more complex, that could be made to the hardware to more fully exploit the theory behind the operation of this sensor.

6.1 Development of an Improved Parallel Architecture

The most significant change which would drastically improve the system is to build a detector array with more than a single data output line. By making a more parallel architecture feasible, this would dramatically increase the system frame rate. Ideally, minimum and maximum detection circuitry and a register to hold information on the position of the reference mirror could be integrated, along side each detector, onto a single device. Since each detector would have its own minimum and maximum phase detection circuitry, the intensity information need never be digitized and a compact analog comparator could be used to determine the minimum or maximum intensity. When given the right input, the output of this super chip would be the phase profile of the incident light instead of the intensity.

6.2 Improved Half Wavelength Boundary Crossing Scan

A modification which is simple to implement and which would make the system more flexible to use would be to modify the scan procedure that checks for half wavelength boundary crossings. The present system starts at one side of the data array and scans across each row and down the first column. A better scan procedure would start in the middle column and scan out to both sides of the array and scan down the middle column. The amplitude of the light near the edges of the data array was shown to be much less than that near the center, and it was found that these areas of low light levels were more susceptible to noise. In the present system, the first column, which is in one of the high noise regions, is scanned when checking for vertical half wavelength boundary crossings. As a result, these checks are more susceptible to noise than if the checks were carried out down the middle column,
which has the strongest light level. Also, if an object to be examined needs to be clamped into place, with this modified scan procedure the object could be held on its sides, and the data from the edges could be discarded with no effect on the valid data from the center of the aperture.

6.3 Check for Points With Low Light Levels

Another simple modification which makes the system more versatile is to check for points on the detector array which are not exposed to a proper signal. This could be done by monitoring each point of the array to see if the incident light level ever changes as the reference mirror is scanned across half of a wavelength. If it does not change, then it is either not receiving any light, it is receiving too much light and is therefore always saturated, or it is receiving stray light that is not modulated by the reference mirror. In any case, these points that received improper input could be tagged and then ignored when determining half wavelength boundary crossings. Since the present system does not have this feature, the phase object under test must cover the entire aperture to assure that each point receives a valid input. With this modification, however, the test object need only cover part of the aperture, and the rest could be masked off. This makes it much easier to measure objects of various shapes, and to mount these objects in arm number two of the interferometer when making measurements.

6.4 Use of a Multiple Pass Interferometer

The Twyman-Green interferometer is a double pass interferometer. As a result, the phase of the light exiting arm one of the interferometer has deviations from a planar wavefront which are twice those of the phase object under examination. Also, the reference mirror need only scan across half of a wavelength to get a scan in phase from 0 to 2\pi. If a triple pass interferometer were used instead, for example, then the reference mirror would only have to scan across one third of a wavelength to get a full 2\pi scan. The DIGITAL PIEZO used to translate the reference mirror is capable of making much smaller steps than those presently used with the double pass
interferometer when making high speed measurements. A smaller scan length with
the same number of steps but with a smaller step size means a higher resolution
measurement without a decrease in frame rate. If the higher resolution is not
needed, then fewer but larger steps can be taken to scan the shorter distance, and
a higher frame rate can be achieved. With a triple pass interferometer instead of a
double pass interferometer, \( \frac{3}{2} \) boundary crossings must be checked for instead of \( \frac{1}{2} \)
boundary crossings. This means the maximum phase deviation measurable across a
given number of detectors is smaller but the resolution and/or frame speed can be
higher.
References


