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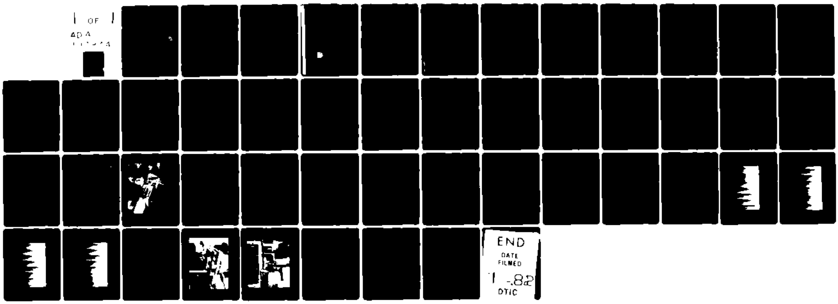

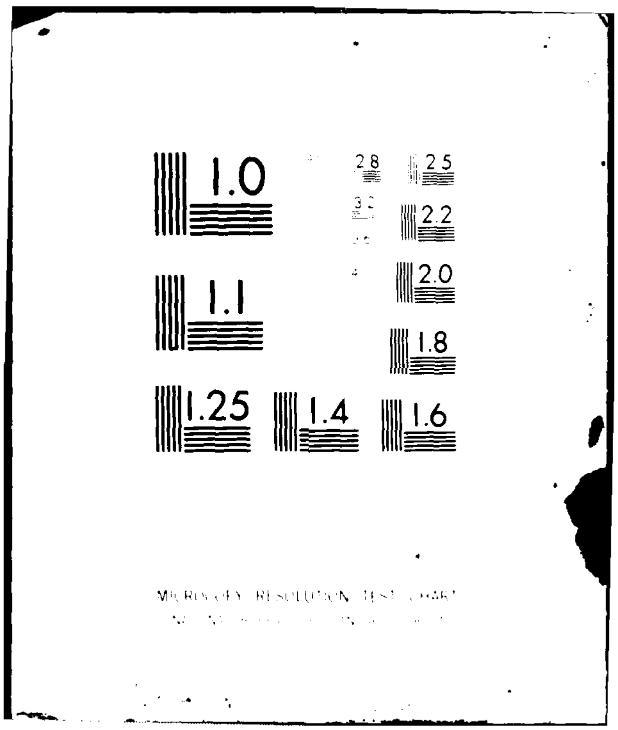
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ANGULAR INTERFEROMETRY – RESOLUTION ENHANCEMENT USING HALF-WAVE PLATES

by

George B. Hept

February 1981

Master of Science Thesis
Massachusetts Institute of Technology

The Charles Stark Draper Laboratory, Inc.
Cambridge, Massachusetts 02139

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ANGULAR INTERFEROMETRY --

RESOLUTION ENHANCEMENT

USING HALF-WAVE PLATES

BY

GEORGE B. HEPT

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(1980)

Submitted to the Department of
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Department of Physics
18 September 1981

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T. T. Chien
Thesis Supervisor

Accepted by ______________________
George F. Koster
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ANGULAR INTERFEROMETRY -- RESOLUTION ENHANCEMENT USING HALF-WAVE PLATES

by

GEORGE B. HFPT

Submitted to the Department of Physics on September 18, 1981 in partial fulfillment of the requirements for the degree of Master of Science in Physics

ABSTRACT

Draper Laboratory is using an interferometer to monitor the rotation of an actively-controlled test platform to .01 arcsec. The resolution of the interferometer needed to be doubled in order to achieve this accuracy goal. The resolution of an interferometer can be doubled by sending the beam back to its target a second time. A method for doing this, analogous to the quarter-wave plate/plane-mirror doubling scheme commonly used in linear interferometry, was designed to double the resolution of the angular interferometer. This method used a combination of half-wave plates and retroreflectors to produce the doubling effect. Some simple, small-scale tests proved that this alternate method worked and that the use of the plates caused no discernible error. A full-scale test on Draper Laboratory test platform showed that doubling the angular resolution was practical and that .01 arcsec accuracy could be achieved.

Thesis Supervisor: Tze-Thong Chien, Staff Engineer, C.C. Draper Lab.

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1.0 INTRODUCTION

Draper Laboratory is conducting a precision pointing and tracking experiment which requires monitoring a test platform's rotation to .01 arcsec. A Hewlett-Packard 5501A Laser Transducer System is being used for this purpose. Since the 5501A was not designed to resolve such a small angle, several methods are being used to enhance its resolution. This thesis will deal with one method for improving the resolution.

1.1 5501A LASER TRANSDUCER SYSTEM

The system consists of a laser, a modular set of optical components, and the associated electronics needed for making measurements using interferometric techniques. Figure 1.1 is a schematic showing the basic electronics and optics common to all the configurations of the system.

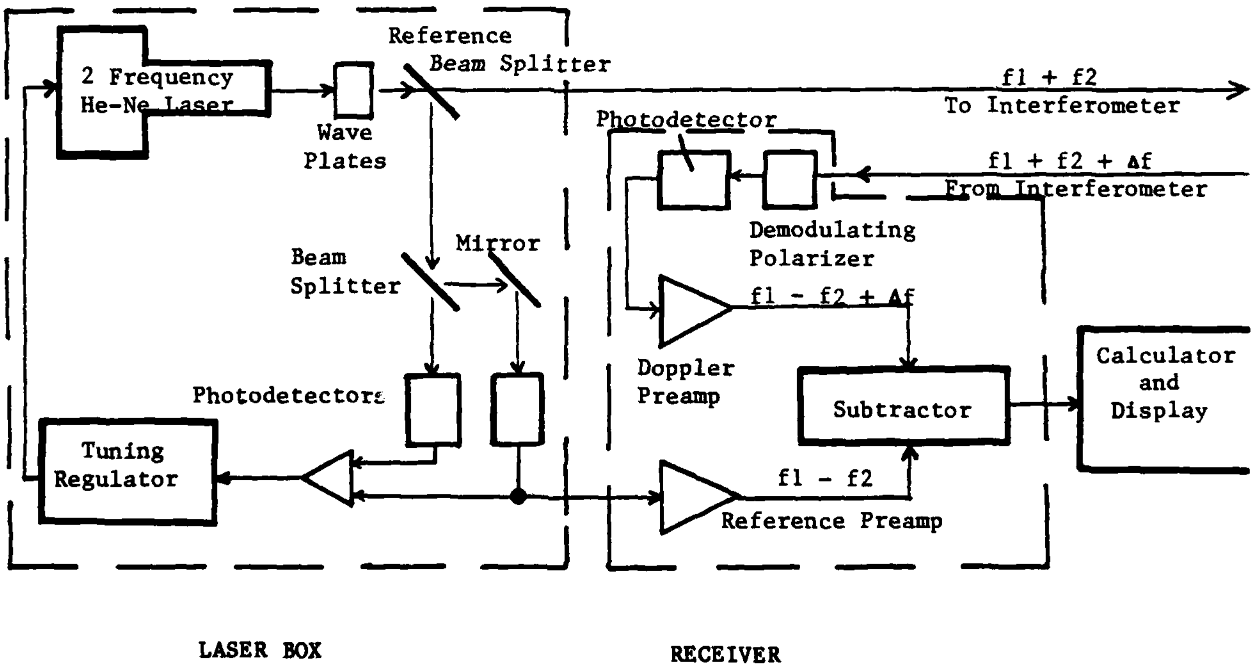


Figure 1.1 Schematic of 5501A Laser Transducer System

The laser itself is a 120 μW He-Ne laser. A small magnetic field splits the transmission line via the Zeeman effect so that the laser emits two beams separated by approximately 2 MHz and centered about 6328 Å. Each of these beams will have orthogonal polarizations and by passing them through an appropriate set of $\lambda/4$ and $\lambda/2$ plates the two beams will come out linearly polarized and perpendicular to each other. The reference beam splitter picks off a part of the beam to be used for laser stabilization and to establish the initial frequency difference. The rest of the beam will leave the laser box and pass through the interferometer optics which will split and then recombine the beam.

After being recombined, the beams enter the receiver. A demodulating polarizer, crossed at 45° to both of the beams, allows the perpendicular beams to interfere. The photodetector will detect the resulting interference signal at the beams' beat frequency. This beat frequency will be the initial frequency difference plus a Doppler shift that was caused by the movement of one or more of the optical components of the interferometer. The subtractor compares the Doppler shifted signal with the reference signal that was picked off earlier in order to determine the actual Doppler shift. This Doppler shift is converted to a velocity which is then integrated to get position.

From here on the laser box and the receiver will be treated as "black boxes" since this thesis will only discuss modifications of the interferometer optics which will be discussed in the next section.

1.2 INTERFEROMETER OPTICS AND BASIC RESOLUTION

Figure 1.2 shows the block diagrams for two of the standard optical configurations of the interferometer which completes the system. Both of these will be discussed in this thesis. The operation of the "Linear Interferometer" is straightforward. The two orthogonally polarized beams from the laser, f1 and f2, hit the polarizing beam splitter. It is transparent to one of the beams, f1, but it reflects the other beam, f2. The reference retroreflector is bolted onto the beam splitter and is assumed to be motionless. Therefore, it merely returns f2 to the beam splitter where it is reflected into the receiver. The measurement retroreflector can move and its movement adds a Doppler shift to f1 according to the formula, $\Delta f/f = 2v/c$, where v equals the velocity of the retroreflector, c equals the speed of light, and f is the frequency of the beam (app. 4.741×10^{14} Hz). The factor two arises from the fact that the apparent speed of the source produced by the moving retroreflector is just twice the speed of the retroreflector itself.[2] The recombined beams, with f1 Doppler shifted, produce an interference signal in the receiver which is transformed into a linear distance.

The resolution of the "Linear Interferometer" is easily obtained. The photodetector senses a change from light to dark which corresponds to a change in f1's path length of $\lambda/2$.[2] Since the beam makes a round trip to the retroreflector, any movement of the retroreflector results in a path length change of twice that movement. Therefore, a change from light to dark, the basic resolution of the photodetector, is caused by a movement of $\lambda/4$ by the retroreflector. Since the laser operates at 6328 Å, the basic resolution is 1582 Å or app. 6.23 μinches.

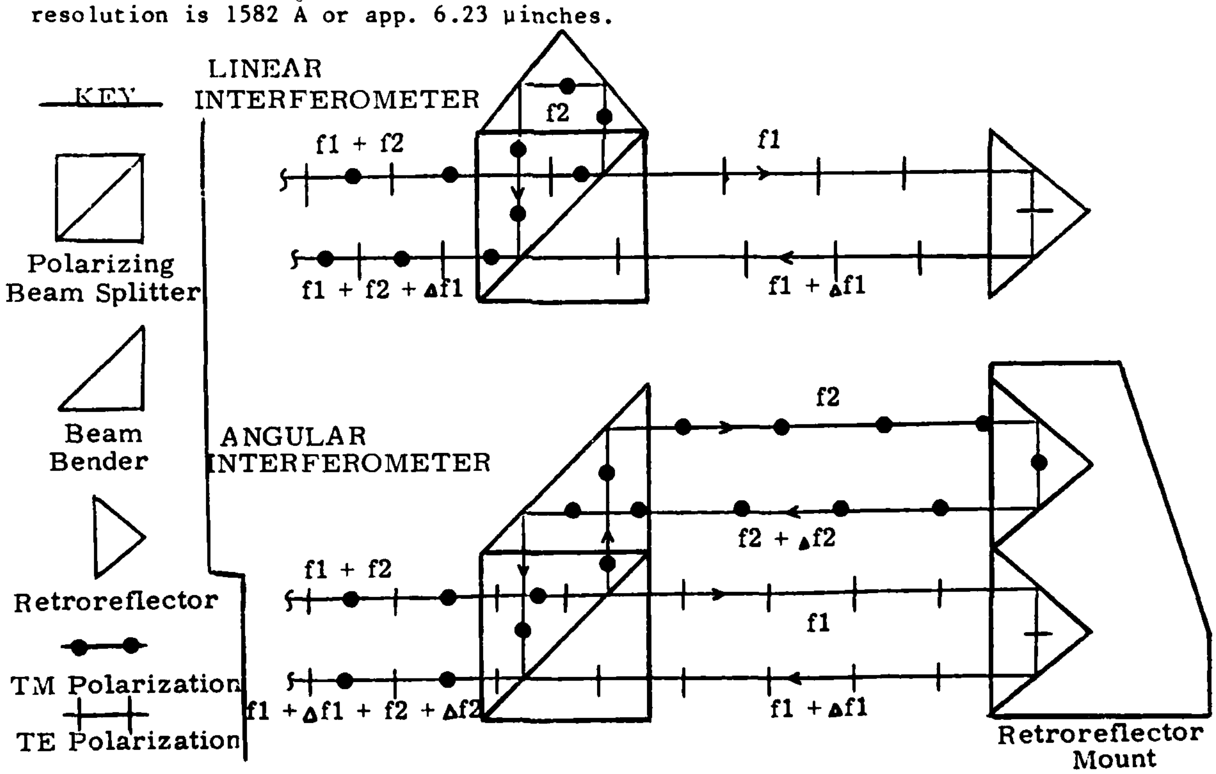


Figure 1.2 Block Diagrams of the "Linear" and "Angular Interferometer"[1]

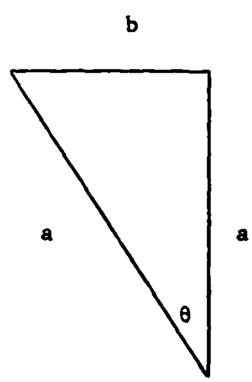
The "Angular Interferometer" is the configuration being used by Draper Laboratory to monitor the rotation of the stabilized platform. The beam bender is used to bring both of the beams out in parallel. This configuration works like the "Linear Interferometer" except that both of the retroreflectors move and cause a Doppler shift in both of the beams. Therefore, the beat frequency of the interference signal now becomes $(f2 + \Delta f2) - (f1 + \Delta f1)$. Because of this, a translation of the retroreflector mount will not be measured by the system. This is because $\Delta f1$ will equal $\Delta f2$ giving a beat frequency of $(f1 - f2)$ which the electronics interprets as no movement. However, if the assembly is rotated about an axis perpendicular to the plane of the retroreflector's centers, one retroreflector will move relative to the other. Since the distance between the retroreflectors is fixed and known, this new beat frequency caused by the relative movement can be translated into a rotation.

The smallest angle that can be resolved by the "Angular Interferometer will cause a change from light to dark in the interference pattern. This will happen when the relative movement between the two retroreflectors equals the minimum resolvable linear distance, which has already been calculated to be 6.23 μin. Since the distance between the retroreflectors is known to be 2.063 in., the minimum resolvable angle can be found using the Law of Cosines and the small angle approximation:

a = distance between retroreflectors = 2.063 in.

b = minimum resolvable distance = 6.23 μin.

θ = minimum resolvable angle



$$2a^2 - 2a^2\cos\theta = b^2$$
$$2a^2(1 - \cos\theta) = b^2$$
$$2a^2(1 - \sqrt{1-\sin^2\theta}) = b^2$$
$$2a^2(1 - [1 - \theta^2/2]) = b^2$$
$$2a^2(\theta^2/2) = b^2$$
$$\boxed{\theta = b/a}$$

θ = 3.02 μrad
= .6 arcsec*

*1 arcmin = 1/60°; 1 arcsec = 1/60 arcmin = 1/3600°

2.0 RESOLUTION ENHANCEMENT

Draper Laboratory's accuracy goal is .01 arcsec. In order to achieve this goal the calculated θ of .6 arcsec needs to be improved by a factor of 60. Hewlett-Packard offers a "Resolution Extender" for the 5501A System that can improve the resolution by x15 by using a phase-lock loop technique. Using this "Resolution Extender", the "Angular Interferometer" can resolve angles as small as .04 arcsec. Hewlett-Packard has also tested a x36 resolution extender that would allow angles as small as .02 arcsec to be resolved, however, the technique is considered unreliable by Hewlett-Packard engineers.[3]

Even using the new "Resolution Extender", the resolution still needs to be at least doubled in order to achieve the accuracy goal of .01 arcsec. One way that was tried to achieve this was to off-line average every ten measurements. This offered a possible $\sqrt{10}$ resolution improvement but it was unsuccesful because the jitter frequency of the laser was too low.[4] Another approach was suggested by the equation for θ calculated in the last section, $\theta = b/a$. By doubling a, the distance between the retroreflectors, θ could be reduced by half. In practice, this scheme encountered some difficulties, such as sensitivity to length variations due to temperature changes, and any further lengthening of a was ruled out.[5]

This thesis will deal with another scheme for resolution improvement that was also suggested by the equation, $\theta = b/a$. The resolution of the "Angular Interferometer" can also be doubled by halving the minimum resolvable distance, b. This will also decrease θ by half. This can be done by sending the beam back to the retroreflector a second time. In an earlier section, it was concluded that the minimum distance that could be resolved was $\lambda/4$. But, since the beam will now make two round trips to the retroreflector, any movement of the retroreflector will now cause a path length change of four, instead of two, times that movement. Therefore, the minimum resolvable distance will now be $\lambda/8$ or 3.16 μin.

2.1 LINEAR RESOLUTION DOUBLING USING QUARTER-WAVE PLATES

Halving the minimum resolvable difference by sending the beam back for a second round trip is often done in linear interferometry by using λ/4 plates and plane mirrors. Hewlett-Packard, in fact, uses this method in its "Plane-Mirror Interferometer", which is another possible configuration of the 5501A system. It is depicted below in figure 2.1.

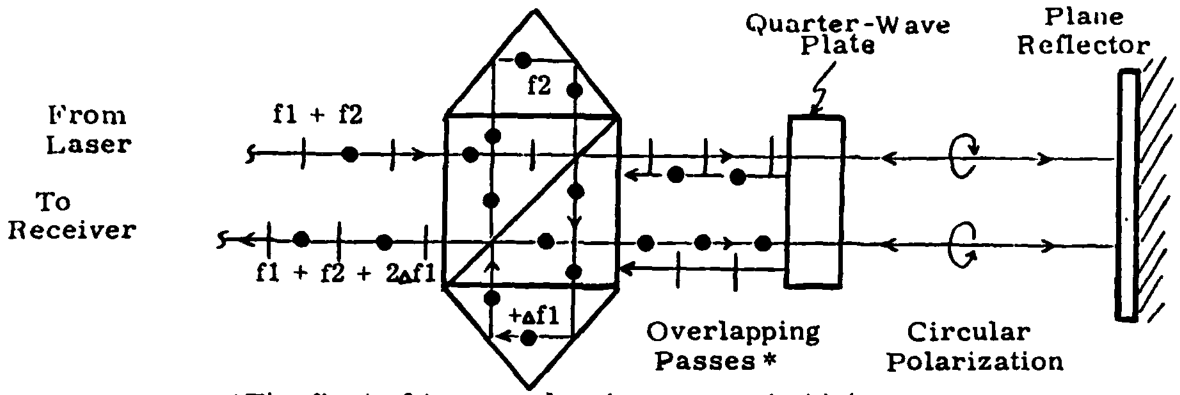


Figure 2.1 Block Diagram of the "Plane-Mirror Interferometer"[1]

The "Plane-Mirror Interferometer" is basically the "Linear Interferometer" with a plane mirror substituted for the retroreflector and with a λ/4 plate inserted in f1's beam path. There is also an additional non-moving retroreflector that is bolted onto the polarizing beam splitter opposite the usual stationary retroreflector. Its principle of operation is based on the fact that the beam's two passes through the λ/4 plate will rotate its plane of polarization by 90°. To do this, the λ/4 plate is oriented at 45° to the beam's plane of polarization so it will resolve the beam into two orthogonal linearly polarized components of equal amplitude and equal phase.[2] While passing through the λ/4 plate, one of these components will be retarded in phase by π/2 radians. Hence, the emerging light will be circularly polarized. When the circularly polarized light hits the mirror, it will be reflected with the same sense of rotation.[6] However, because of the reversed sense of the light, the polarization's "handedness" will change. In other words, right-handed circular polarization will become left-handed and vice-versa. On the beam's return pass through the $\lambda/4$ plate, the reversed circular polarization will be changed to a linear polarization that is perpendicular to the beam's initial polarization.[2]

For the particular case of the "Plane-Mirror Interferometer", the f1 beam initially has transverse electric (TE) linear polarization which is transmitted by the beam splitter. By the time it has returned to the beam splitter, it has been changed to transverse magnetic (TM) linear polarization which is reflected by the beam splitter. Therefore, with the aid of the new stationary retroreflector, f1 is sent back to the moving mirror. On its second round trip, it is restored to TE polarization so that it can be transmitted by the beam splitter in order to go to the receiver. Since the f1 beam makes two round trips before being recombined with f2, the resolution of the "Plane-Mirror Interferometer" is double that of the normal "Linear Interferometer".[1]

2.2 APPLICATION TO ANGULAR INTERFEROMETRY

It should also be possible to double the "Angular Interferometer's" resolution in a similar manner. There are two important differences though. The first difference is that both beams must make two round trips to their retroreflectors. This is because the receiver detects the difference ($\Delta f1 - \Delta f2$). In the "Linear Interferometer", $\Delta f2$ was assumed to be zero so there was no sense in doubling it. But, in the "Angular Interferometer", both retroreflectors move and cause a non-zero Doppler shift in both of the beams. Therefore, in order to double the angular resolution, $\Delta f1$ and $\Delta f2$ must be doubled. The second, and more troublesome, difference is that the retroreflectors cannot be replaced by plane mirrors. This is because the retroreflector's ability to always return a beam parallel to its incident direction is needed. In the "Plane-Mirror Interferometer", the plane mirror also did this because it was kept at normal incidence. But, to be used in the "Angular Interferometer", the mirrors would have to be put on the rotating mount. As the mount rotated, the beams would be reflected away from the interferometer.

However, if we continue to use retroreflectors, the $\lambda/4$ plate scheme will no longer work. To see why, we have to look at the effects that retroreflectors have on beam polarization. Figure 2.2 (a) shows the face of a retroreflector with its symmetric axis normal to the paper. Real edges are drawn as full lines and their backward virtual reflections as dotted lines.

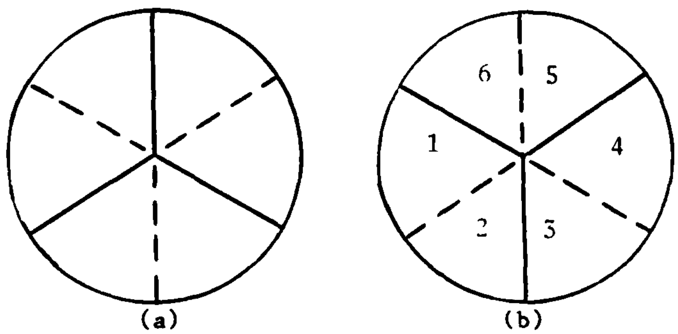


Figure 2.2 Symmetric Face of a Retroreflector

When an incident beam of light hits a retroreflector, it makes three reflections before emerging. It will hit one of the sextants labeled in figure 2.2 (b) and then proceed to another sextant across the nearest real edge. It will then be reflected over to the sextant opposite to the one it initially hit befroe leaving the retroreflector. For example, a beam that is initially incident on sextant 3 will be reflected first to sextant 2. There it will be reflected a second time to sextant 6 where it will be reflected a third time before leaving the retroreflector.

The above discussion is based on a paper by Edson R. Peck of Northwestern University entitled "Polarization Properties of Corner Reflectors and Cavities". In it, he also mentions that since each of these three reflections is oblique (versus the one normal reflection in the "Plane-Mirror Interferometer"), "phase shifts are dependent upon the polarization of the light. If the incident light is polarized, the emergent light is generally in a different state of polarization."[6] This is because the reflections will affect the TE component of any polarization differently than its TM component. If the retroreflectors are hit with circularly polarized light, which consists of equal TE and TM components out of phase by $\pi/2$, the emerging polarization would be dependent upon the inital orientation of the retroreflectors and on the angle of incidence. The $\lambda/4$ plate scheme would only work if the retroreflectors consistently reversed the "handedness" of the circular polarization as the mirror did. But, since the angle of incidence would change in the "Angular Interferometer" as the mount rotated, the polarization emerging from the retroreflectors would be constantly changing. Only in very specific circumstances would the two retroreflectors be aligned correctly to allow the $\lambda/4$ plate scheme to work. The $\lambda/4$ plate scheme cannot, therefore, be directly applied to the "Angular Interferometer".

2.3 ANGULAR RESOLUTION DOUBLING USING HALF-WAVE PLATES

Because the multiple reflections in a retroreflector may change the phase relationship between any polarization's TE and TM components and therefore change the polarization, it did not seem possible to use retroreflectors in any scheme which involves changing the polarization. But, in the special case of purely TE or TM polarization, there is no second component to get out of phase. There may still be a change of phase but, since it will only be in one component, it will not change the plane of polarization. In fact, we knew from the "Angular Interferometer" configuration that a retroreflector will return TE polarization if it is hit with TE polarization, no matter the angle of incidence.[1] The same is true for TM polarization. Therefore, the polarization effects of the retroreflectors will be consistent and simple if they are only hit with TE or TM polarization.

This can be done by using a $\lambda/2$ plate instead of a $\lambda/4$ plate. A $\lambda/2$ plate is also a retardation plate. The difference is that it will retard one component of the polarization by π radians instead of $\pi/2$, as a $\lambda/4$ plate will. If it is aligned at 45° to the plane of polarization, it will rotate the plane of polarization by 90°[7] instead of producing circular polarization like the $\lambda/4$ plate. Therefore, the $\lambda/2$ plate can be used to change TE polarization directly to TM polarization and vice-versa. Now we can use the basic idea behind the "Plane-Mirror Interferometer" for the "Angular Interferometer". The $\lambda/2$ plates can be used to rotate the beams' polarization by 90° on each pass and the polarizing beam splitter can be used to return the two beams to their retroreflectors a second time before being recombined. This will double the angular resolution.

Figure 2.3, on the next page, shows the beam paths for the modified "Angular Interferometer". Note that, like the "Plane-Mirror Interferometer" configuration, only one extra bolted-on retroreflector is needed. The main differences are that two wave plates are now needed (one for each beam) and that the beams only pass through the plates once on each trip (so the plates cannot be centrally mounted). Although the beam paths look complicated, their analysis is simple. This is because the beams are always in either TE or TM polarization and the effects of the beam splitter, beam bender, and retroreflectors on these two basic polarizations are known from analyzing the standard interferometer configurations. These effects are listed below in table 2.1. Both the f1 and the f2 beam can be followed through figure 2.3 by using the table and by knowing the initial states of polarization (TE for f1 and TM for f2).

Table 2.1 Optical Component Effects on TE and TM Polarization

OPTICAL COMPONENTS	TE	TM
Polarizing Beam Splitter	Transmits	Reflects
Retroreflector	Reflects	Reflects
Beam Bender	Reflects	Reflects
$\lambda/2$ Plates (at 45°)	Changes to TM	Changes to TE

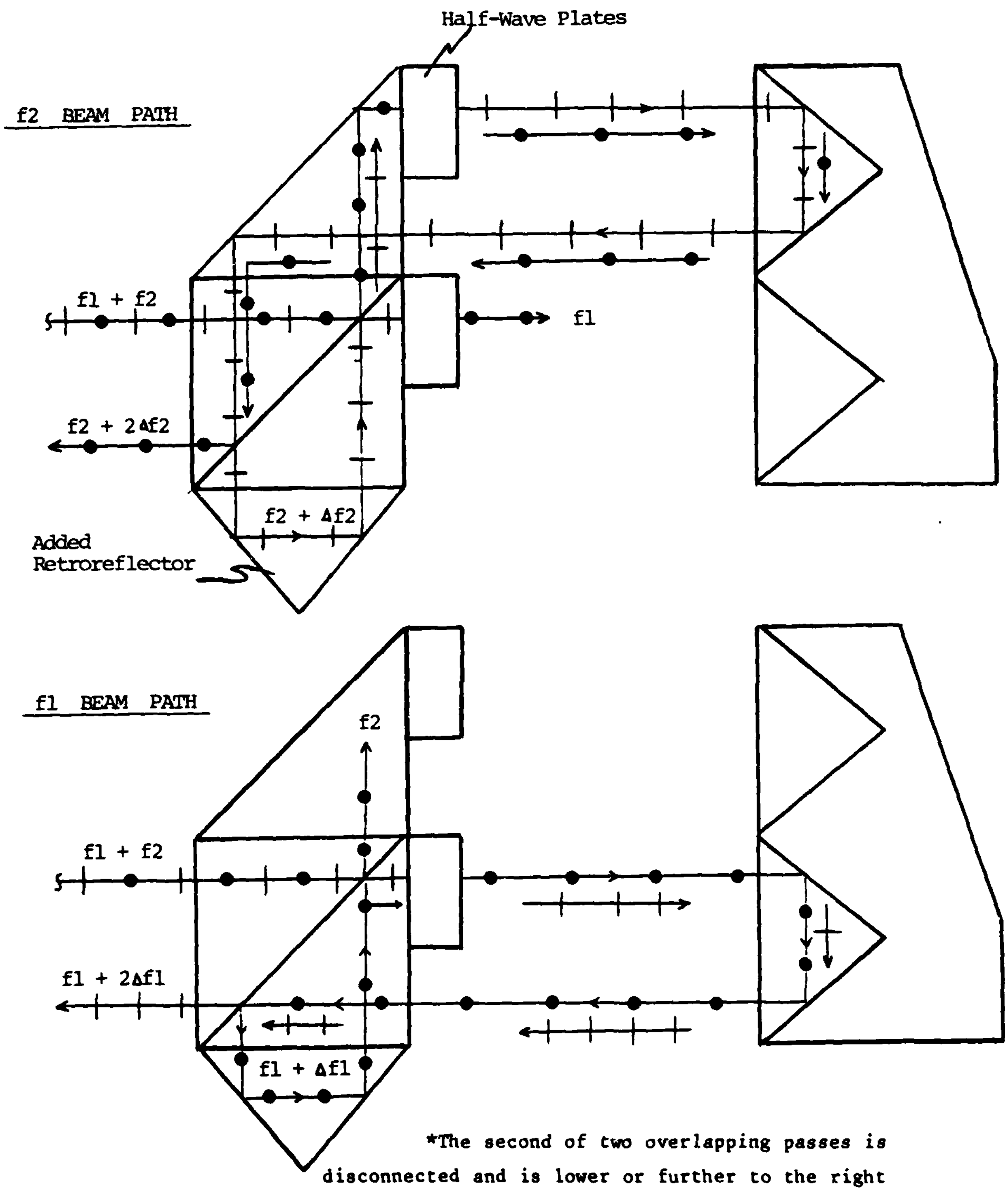


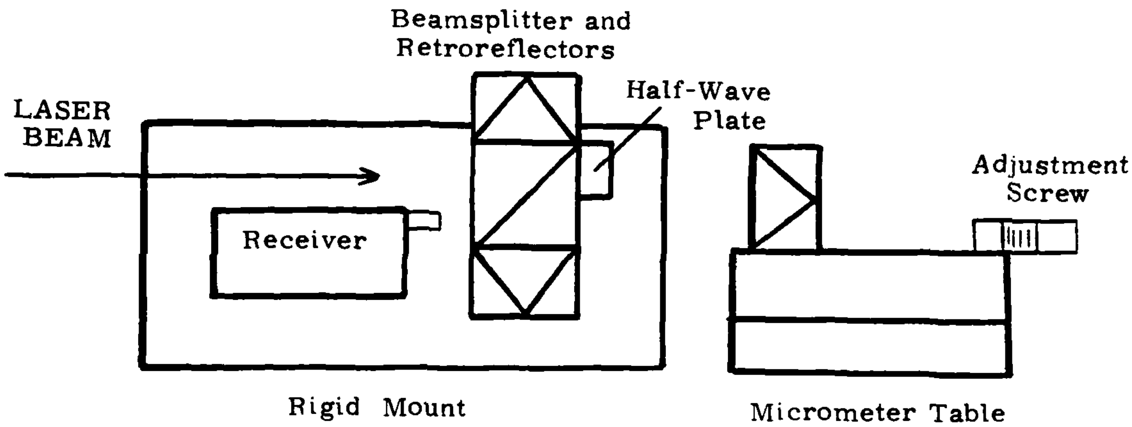
Figure 2.3 Beam Paths for the Modified "Angular Interferometer"

3.0 EXPERIMENTAL VERIFICATION

Although the 90° rotation of the plane of polarization by $\lambda/2$ plates is standard practice, its use for this application is not. So, although no problems were foreseen from a theoretical standpoint, we decided to run some small-scale tests to ensure the practicality of the concept. These tests were done while the rather large and complicated test platform at Draper Laboratory was still being built and tested. The verification was divided into two tests. The first one will be called the "feasibility test" and its purpose was to determine if there were any major problems or large errors introduced by the installation of the $\lambda/2$ plates. This test was also used to gain some experience in the practical problems that would be involved with using the $\lambda/2$ plates, such as how to properly align them. The second test will be called the "accuracy test" and its purpose was to insure that the use of the plates introduced no error greater than the basic resolution of 6 μinches.

3.1 FEASIBILITY TEST

The basic purpose of the feasibility test was not to test the overall design concept but merely to determine if the $\lambda/2$ plate scheme worked as conceived. A block diagram of the test set-up is shown in figure 3.1. Note that the set-up is a linear, not an angular, interferometer, and that it only uses one $\lambda/2$ plate to produce the doubling effect instead of two. However, it is much simpler to set up and use and, most importantly, we found it much easier to accurately duplicate a linear motion than an angular motion. Because of these advantages, and because it uses the same basic principles as those envisaged for the modified "Angular Interferometer", we decided to conduct the tests using a linear interferometer set-up. The beam paths are also shown in figure 3.1. Note that the f1 beam makes two trips to its retroreflector before being recombined with f2 at the receiver. The receiver determines the Doppler shift and the computer software translates it into a linear distance. However, the Doppler shift is now double what would normally be expected so the computer will interpret a movement of "x" as a movement of "2x".



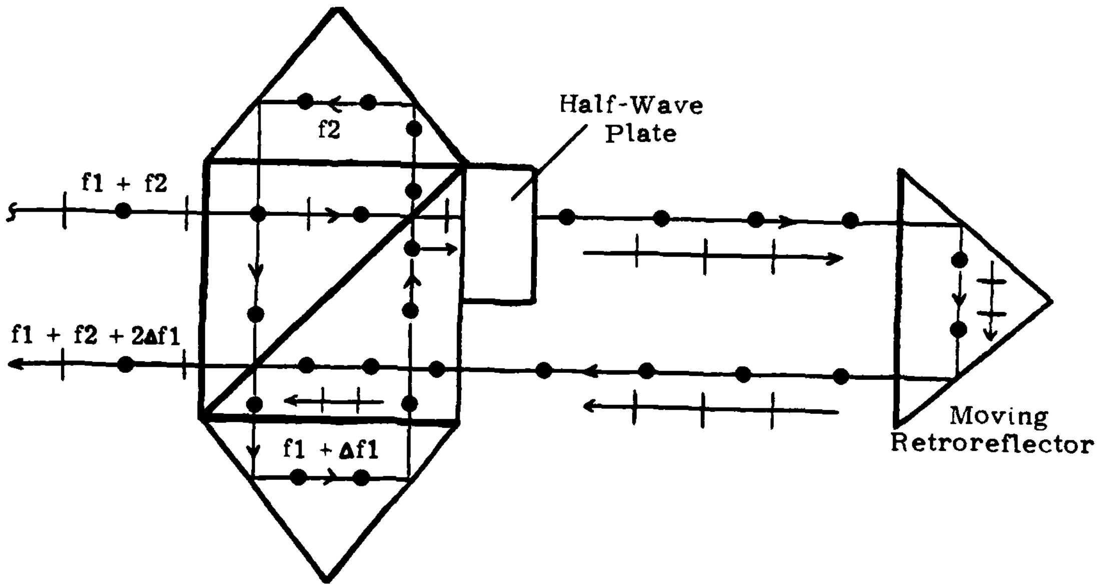


Figure 3.1 Block Diagram and Beam Paths for the Feasibility Test

This now provides a straightforward test of the $\lambda/2$ plate scheme. First, a standard measurement would be made without the plate. Then the plate would be inserted and the measurement would be retaken. The measurement with the plate should be double that of the standard measurement. Several possible problems were to be looked at using this test, such as, how difficult would it be to align the plate, will ground movements and vibrations ruin this alignment, will the extra trip make alignment of the beams more difficult, and, most importantly, will the wave plate introduce any obvious error.

In order to do the test, we had to find a way to align the axis of the wave plate at the correct angle to change the plane of polarization by 90°. The simplest method, and the one we hoped to use, would be to "eyeball" a minimum at the receiver after inserting the wave plate and removing the two stationary retroreflectors. By doing this, the f2 beam will be reflected up to the ceiling. And, as the $\lambda/2$ plate is rotated, the f1 beam's plane of polarization will be rotated from TE to TM polarization and the TM component will be reflected down to the floor. When the axis is properly aligned at 45°, the f1 beam will be entirely changed to TM polarization and there will be a minimum at the receiver. It was fairly easy to establish a minimum visually but this did not always produce the most "useful" signal when the stationary retroreflectors were put back in place.

A useful signal is one that can be interpreted by the computer software. It is indicated by a small green LED on top of the receiver that lights up when the receiver detects an appropriate interference signal. If the LED is out, or is blinking, it means that the signal is either too weak or is too incoherent. After setting a minimum, the LED was often found to be blinking so a measurement could not be made. A simple visual inspection showed that there was no dramatic loss of power (the system can stand a 95% power loss[1]) or severe misalignment. In order to try and understand what was happening, the output of the photodetector was monitored with an oscilloscope. Without the plate, the photodetector put out a steady signal. After a minimum was visually established, with the plate in place, the photodetector put out a jittery signal that occasionally dipped to zero. By slowly rotating the plate about the established point, a signal could usually be established that was much steadier though still jittery.

Hewlett-Packard's manual for the 5501A system says that dirt on the optics or changes in the refractive index of the air can "break the beam for a second" and cause enough incoherence to prevent a measurement.[1] This seemed to be a reasonable explanation for the jittery signal. The problem could not be changes in the air or dirt on the interferometer optics because the output signal was so steady without the plate. This left dirt on the plate itself as the probable culprit and, indeed, after a careful cleaning of the wave plate, a useful signal could always be produced at the visually established minimum. However, we still found that the optimum angle did not always produce the most useful, or steadiest, signal. There turned out to be a rather large amount of allowed error in the angle that would produce the doubling effect. This is why we were able to produce a useful signal, before cleaning the plate, by "fiddling" with the alignment. It was possible to move the beam to a cleaner part of the plate while staying within the margin for error. From this, we concluded that, barring any problems (such as dirty optics), it was possible to visually determine the correct alignment for a useful, doubled signal. However, to maximize the "usefulness" of the signal (which you might want to do in a low-power situation, for instance), you could "fine-tune" the alignment angle by monitoring the photodetector's output on an oscilloscope and watching for the steadiest signal.

3.2 RESULTS AND ERROR ANALYSIS

In order to make the measurements, we set a zero position and then moved the micrometer through one turn of its adjustment screw. Earlier measurements by Draper Laboratory had indicated that ground noise was significant at our level of accuracy[5] so ten measurements were taken after each turn and were then averaged. The system was then re-initialized and the wave plate was inserted. The micrometer was then moved through the same turn and ten more measurements were sampled. Table 3.1 shows a typical set of results. It is obvious, from the table, that an approximate doubling did take place.

Table 3.1 Typical Set of Results from Feasibility Test

Standard Results Without Plate	Doubled Results With Plate
25019*	50102
25031	50121
25025	50102
25031	50108
25025	50108
25025	50127
25031	50108
25025	50108
25025	50127
25031	50108
AVG: 25027	50111

*All measurements in µinches

We had only expected an approximate doubling because of ground noise and because of the difficulty of exactly reproducing the initial linear movement. The linear movement was obtained by lining up two marks on the micrometer screw and then rotating the screw through 360° until the marks were realigned. The alignment was done visually and no special care was taken since we were just trying to confirm a crude doubling. Assuming that we were able to return the mark to within half a degree of its original position, then, in the worst case, two measurements should be within 1/360 of each other. This assumes that the first turn is half a degree off in one direction while the second turn is half a degree off in the other direction. Since one turn gave a reading of 25000 µin., an error of 70 µin. should be expected from this reproducibility error.

The error from the random ground noise must also be added to to this in order to get the total error. The ground noise was found, using our set-up, to be a high-frequency jitter of 6-18 µin. Again assuming a worst case, the initial measurement could have an error of -18 while the doubled one would have an error of +18. Therefore, an error of 36 μin. can be expected from the ground noise alone. But, since we were averaging over ten measurements in each case, an improvement of approximately $\sqrt{10}$ can be assumed in this error. Therefore, a conservative estimate of the total error should be 85 μin.

In the results listed in Table 3.1, the standard measurement was 25027 μin. Halving the doubled measurement of 50111 μin. equals 25055.5 μin. There is a difference of 28.5 μin. between the two, well within the expected error. In fact, all of the sets of measurements that were made were within 85 μin. of each other. This does not confirm that the plate introduces no error into the system but it does show that the basic concept works and that there is no large error or bias introduced by the plate, which is what we hoped to do in this first experiment.

3.3 ACCURACY TEST

Because of their stringent accuracy requirements, Draper Laboratory wanted verification that there was no error introduced by the plate down to the basic resolution of 6 μinches. To do this, the reproducibility error of 70 μin. obviously had to be eliminated. The ground noise error also had to be substantially reduced. Draper Laboratory had been using heavy piers surrounded by hundreds of pounds of sand and concrete to bring the ground noise level down to their accuracy needs. Such a procedure is expensive and time-consuming. The reproducibility error would be even tougher to solve because, to verify our measurements, we would need a system more accurate than the one we were trying to develop. So, instead of trying to defeat these two problems, we designed an experiment to accomodate them. Since we were merely trying to verify the accuracy of the doubling effect, we decided that instead of trying to make two highly accurate measurements of a fixed distance, we would make two simultaneous measurements of the same movement.

In theory, we could do this by splitting the reference signal and sending it to two separate receivers. We would also have to hit the moving retroreflector once with the f1 beam and then split it. Then we would allow part of that beam to go to a receiver and use the wave plate to send the other part back to the retroreflector for a second trip, after which it would go to the second receiver. There would, of course, be no reproducibility error in this scheme and ground noise error would be eliminated for the part of the path that the singled and doubled f1 beam had in common. This would reduce the ground noise error to the amount of movement that could occur in the time that it took for the f1 beam to make its second trip. Since the round trip to the moving retroreflector is only about .2 meters, the f1 beam's transit time is: $[.2/(3 \times 10^8)]$ or approximately one nanosecond. We assumed any ground noise on this time scale to be negligible.

In practice, we were unable to use this scheme. We were able to design a configuration that would make the simultaneous measurements using a 50/50 and a 33/67 beamsplitter that were part of the 5501A system (Hewlett-Packard provides them so that the beam from a single laser can be split and used to measure movement along several different axes). But both of these beamsplitters had a loss of about 10% and our scheme involved multiple passes through them. There were also, of neccesity, several wasted beam paths. Because of this, even assuming perfect alignment and no other losses, both receivers would be receiving less than the minimum required power of four microwatts.

Instead of trying to increase the laser's power or modify the standard Hewlett-Packard optics, we decided to use a variation of this idea which was simpler and might still meet our accuracy needs. We decided to simultaneously measure the movement of two retroreflectors that would be bolted together on a rigid mount so that their motion would be coupled. We did this by taking the equipment that was already set-up and used in the feasibility test and adding an auxiliary set of interferometer optics in parallel and offset by the distance between the retroreflectors in the mount designed for the "Angular Interferometer". This mount was bolted to the micrometer table and was used to couple the motion of the two retroreflectors. Figure 3.2 depicts a block diagram of this set-up to help identify the separate pieces in the photograph in figure 3.3. The laser box, the beamsplitter and beam bender (used to bring the beams out in parallel), the two receivers, the two sets of interferometer optics, the retroreflector mount and the wave plate can all be seen in the photograph.

EQUIPMENT LIST

a) Laser Box
b) 50% Beam Splitter
c) Beam Bender
d) Receivers
e) Interferometer Optics
f) λ/2 Plate
g) Retroreflector Mount
h) Micrometer Table
i) Adjustment Screw
j) Rigid Mounts

Note: Figure is not drawn to scale. It is only an identification aid for the photo on the next page.

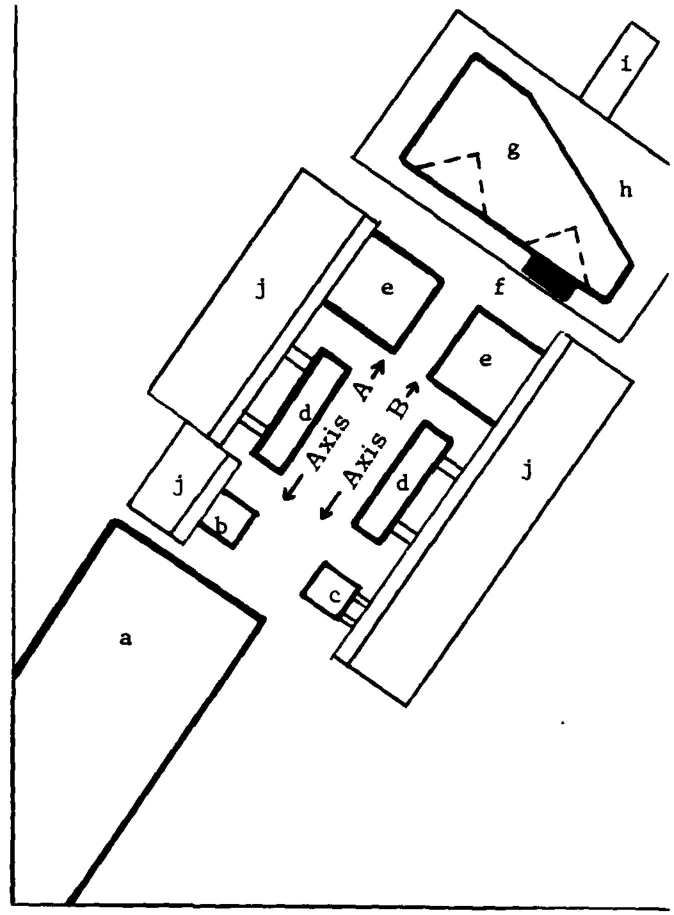


Figure 3.2 Block Diagram of the Accuracy Test Set-Up

The mount was assumed to be a rigid body so that the ground noise and reproducibility errors would still be eliminated. However, if the micrometer movement was not purely translational, a new and possibly significant error would be introduced. Any rotation caused by the micrometer movement would result in one of the retroreflectors moving further than the other. We had no way to directly detect such a rotation nor to eliminate it. We decided to try and estimate it by making several measurements without the plate installed. If there was no error caused by a rotation, then the readings from the two axes should be identical (assuming that rotation is the only major source of error). If there was an error, then we would expect a similar, but doubled, error in the measurements made with the plate (assuming the rotation to be consistent). Any additional error would be assumed to be coming from the installation of the plate. This should allow us to separate any error caused by the plate from any error caused by the rotation.

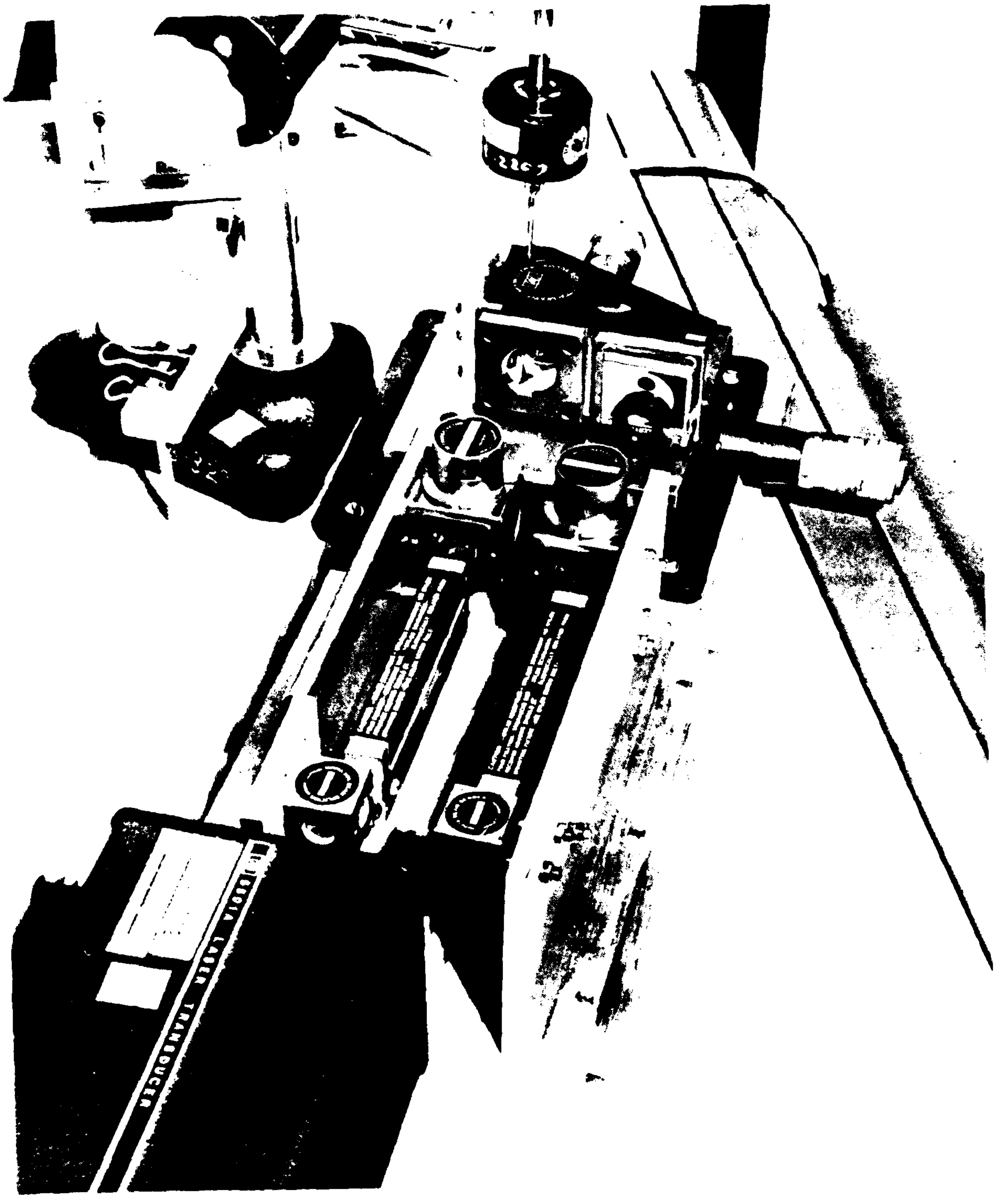


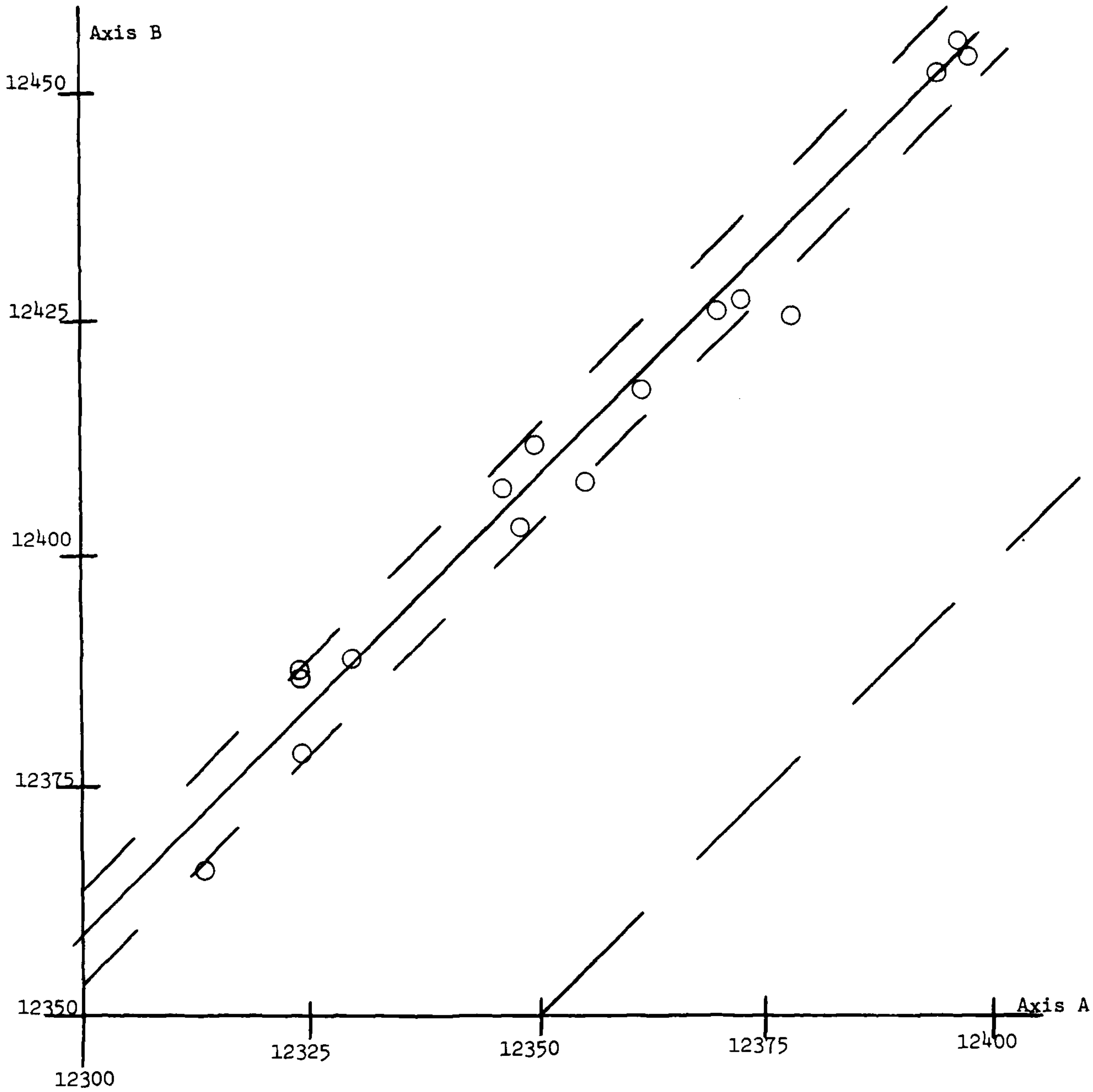
Figure 3.3 Photograph of the Accuracy Test Set-Up

3.4 RESULTS AND ANALYSIS

The first result noticed was that ground noise was still a problem. Even though both retroreflectors were equally affected by the ground noise, it was still possible for a one quanta (6 μin.) error to be caused by the ground noise. For example, an error of 15 μin. might register on one axis as 12 μin. and on the other as 18 μin. This problem was minimized by once again taking ten samples after each measurement and then averaging. With this $\sqrt{10}$ improvement, the ground noise error was assumed to be acceptable at less than 2 μin.

As mentioned in regard to the feasibility test, we were only able to duplicate a movement with the micrometer to within app. 70 μin. Because of this, we were not able to simply reproduce one measurement in order to determine the micrometer bias. So, we decided to try and duplicate a nominal measurement of 12350 μin. (as measured by axis A) while intending to use data from any points within the 12300 - 12400 range. After getting several points, a line could be fit to the points using linear regression and the bias would be determined from the line and not from an individual point. We assumed that this line would represent a pure bias so we expected a slope of 1.0. The actual line had a slope of 1.0034 in accordance with this assumption. Figure 3.4 shows the values of axis B plotted against the values of axis A. Each of the points represents ten samples of one movement averaged over the ground noise. The long dashed line represents the line for zero bias (both axes identical). The solid line represents the average of each of the points' individual biases and the short dashed lines represent one standard deviation from that average. The averaged bias was 58.3 μin. with a standard deviation of 4.6 μin. This meant that, although the bias was not exactly reproducible, it was consistent enough to make this test useful because we were only looking for errors greater than 6 μin.

The actual test consisted of doubling one axis and then comparing its halved value to the standard value of the other axis. The plate could be switched between axes without being realigned so that we could run the test with axis A doubled and then with axis B doubled. This provided a good test for any bias introduced by the installation of the plate. If the



Both axes scaled in μinches

Long dashed lines represent the zero bias line

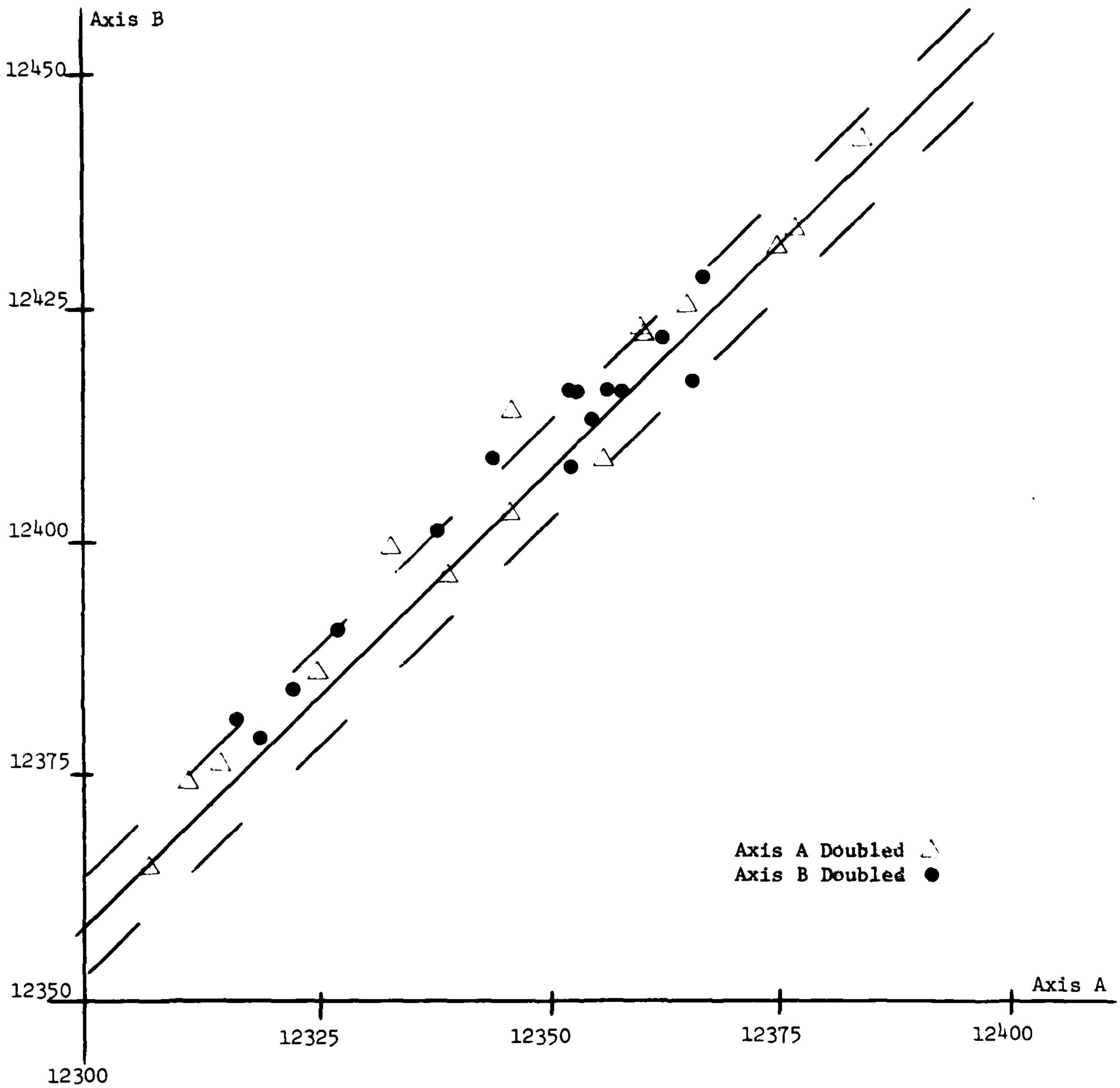
Solid line represents averaged bias of 58.3 μin.

Short dashed lines represent one σ of 4.6 μin.

Figure 3.4 Graph for Micrometer Bias Used in Accuracy Test plate did introduce a bias, it would add to the micrometer's bias when the plate was on axis B (with the larger values). But it would subtract from the micrometer bias, by the same amount it had previously added, when the plate was installed on axis A (with the smaller values). Therefore, any bias introduced by the installation of the plate should be readily detectable because it will show up as a symmetric error about the calculated micrometer bias when the average bias values are compared.

Figure 3.5 shows the results of the accuracy test. The solid line and the dashed lines are the same as those in figure 3.4 and they represent the calculated micrometer bias of 58.3 μin. with a standard deviation of 4.6. The points again represent ten samples of one measurement averaged over the ground noise. The triangles are the points taken when axis A was doubled and the dark circles are the points taken when axis B was doubled. In each case, the halved value of the doubled measurement is graphed against the standard value of the other axis. As can be seen in the graph, most of the points lie within one standard deviation of the calculated micrometer bias. Both of the averaged bias values for these points were app. half a standard deviation away from the micrometer bias of 58.3 μin. (60.1 μin. when axis A was doubled, 60.9 μin. when axis B was doubled). Both of their standard deviations were also similar to the value without the plate installed of 4.6 μin. (3.9 μin. when axis A was doubled, 3.5 μin. when axis B was doubled).

The bias values with the plate installed were not symmetric about the value without the plate, as we would have expected them to be if the plate added a bias. Both of the values were within the bounds of the error that was expected from the micrometer rotation inconsistency. Therefore, we concluded that, to the degree of accuracy which we could measure, the installation of the plates introduced no observable error. The way was now clear for a full-scale test on the "Angular Interferometer" monitoring Draper Laboratory's stable platform.



Both axes are scaled in μinches

Solid line represents previously calculated bias value of 58.3 μin.

Short dashed lines represent a σ of 4.6 μin. (previously calculated)

Figure 3.5 Graph of the Micrometer Bias with the λ/2 Plate Installed

4.0 FULL SCALE TEST

Although the $\lambda/2$ plate performed well in the small-scale tests, it was essential that the doubling scheme be tested on the actual set-up before making a decision on its use. This was because, despite the fact that the same basic concept is used to double the "Angular Interferometer's" resolution, there are also several important differences from the small-scale tests to be considered in the actual set-up. The differences included the use of two plates and much longer path lengths, which would make alignment of the beams more difficult. Also, f1 and f2 will overlap once before going back to the retroreflectors a second time. In the linear tests f1 and f2 overlapped on themselves but never on each other. After hitting the extra stationary retroreflector in the modified "Angular Interferometer", however, the two beams follow the same path until they are again separated by the beam splitter (see figure 2.3). This was not expected to be a problem since the two beams have orthogonal polarizations during that time so they should not interfere, but it was a new factor to be considered. Another new factor was that the "Resolution Extender" was going to be used, making the receiver more sensitive to error. These, and other unforeseen, potential problems all needed to be investigated. The two questions that needed to be answered were would the plates produce the doubling effect and, if the other resolution enhancement techniques were working, could we achieve .01 arcsec resolution.

4.1 "ANGULAR INTERFEROMETER" TESTING, RESOLUTION VERIFICATION

The "Angular Interferometer" being used by Draper Laboratory was measuring the rotation of a large, active-controlled test platform built by Goerz Optical Company. It could be rotated through small angles via a precision torque motor and Draper Laboratory used it primrarily for testing gyroscope accuracy. The desired rotation could be input from a control panel and the current angular position could be read off an LED display that was also on the panel. Angular changes as small as .0001° could be input and monitored on the LED display but, because of ground jitter and noise in the electronics, the table was only stable to app. .0005°. This could be seen by watching the LED display which showed the final displayed digit to be constantly changing and therefore unreliable. So, although angular changes as small as .0001° could be input, the table's motion could only be monitored to app. .001° using its built-in equipment.

As stated previously, Draper Laboratory wanted to monitor the platform rotation to .01 arcsec which is about 360x smaller than .001°.* That is why the "Angular Interferometer" was being used. The retroreflector mount was put along a radius of the table. The interferometer optics were put on another stable, stationary pier about a meter away and the laser box was put on a third pier. By the time the experimental verification of the plates was finished, this set-up was being successfully tested with a 4-inch separation retroreflector mount and the x15 "Resolution Extender". As mentioned in section 2.0, this was supposed to give an accuracy of .02 arcsec. To verify this accuracy, the receiver's output was connected to software that merely recorded the number of "pulses" counted by the receiver (one for each fringe in the detected interference pattern) as the table moved. Because there was a lot of ground and electronic noise error, these pulse counts were averaged over a number of points, as was done in the small-scale tests. This was done automatically by the computer. It would sample a specific number of points (up to 512) at a specified sampling frequency (up to 1600 Hz). Its output included a graph of the points and the averaged value, standard deviation, and range (maximum and

*I wish to make a note here on angular measurements. The accuracy of gyroscopes is customarily measured in arcsec, hence the reason Draper Laboratory's goal is in those units. Unfortunately, the table was designed to use degrees as its input and output, and, later, I will refer to the "Angular Interferometer's" sensitivity in units of nanoradians. This is not done purposely to be confusing, although it is. It was done out of convenience (you get nice round numbers to use for comparison when you use nanoradians), for necessity (as in the design of the table), or for custom (as in the gyro accuracy convention). Where I feel it is necessary, I will translate between units. For the most part, I will use the units that were actually used in the testing. A good rule of thumb to use when looking at these measurements is: .01 arcsec ≈ 50 nanoradians ≈ 3×10^{-6} degrees.

minimum values) of the points. If this averaged value is multiplied by the assumed resolution of .02 arcsec (100 nanoradians), it will give the value of the unknown angle that the table moved through. Instead, the input angle was assumed to be known in this case. By dividing the known angle by the averaged number of pulses, you get the sensitivity of one pulse. This is a way to directly verify the basic resolution of the "Angular Interferometer", which is the same as the sensitivity of one pulse. Using this procedure, Draper Laboratory verified that their basic resolution was approximately 100 nanoradians (.02 arcsec) per pulse.

4.2 MODIFIED "ANGULAR INTERFEROMETER" TEST RESULTS

We used this same procedure to verify the doubling effect in the modified "Angular Interferometer" and to verify that we could achieve an accuracy of .01 arcsec (50 nanoradians per pulse). The test itself was much like the small-scale feasibility test. We took several measurements without the plates and then repeated the measurements with the plates installed, expecting to see the same doubling as in the linear tests. A typical test consisted of initializing the set-up at some arbitrary angle. We used 271.1350°. The software counter was set to 160 pulses at initialization and any time the counter went below zero it automatically reset to 160 pulses. This caused a small problem because the noise was on the same order as 160 pulses. To prevent the ground noise from resetting our counter in the middle of a set of measurements, we moved the table forward .005° to 271.1400° and took our first set of measurements there. We could not use this movement as our known angle since we did not take an averaged reading at 271.1350°. This meant that,although we knew the table was nominally set at 271.1350° when the counter was set at 160, the position was actually 271.1350° plus or minus the ground movement at that particular instant. We averaged 512 points at 100 Hz at 271.1400° and then commanded the table to move to 271.1450°. We then took the averaged value of another 512 points. By subtracting the averaged value at 271.1400° from the averaged value at 271.1450°, we knew the number of pulses caused by a movement of .005°. From that number, we could easily get the pulses per degree which could be changed to nanoradians per pulse.

The computer output for the standard measurements is shown in figures 4.1 and 4.2. Figures 4.3 and 4.4 show the computer output for the measurements taken using the modified "Angular Interferometer". The graph in each figure represents the individual values of all 512 points. The averaged value is indicated by the dashed line. There is no scale and the bottom of the graph does not equal zero, it is just below the minimum value. To get an idea of the scale, refer to the averaged, maximum, and minimum values given at the top of the graph. The standard deviation (SIGMA) is also given there. For instance, in figure 4.1 the dashed line represents 1151.1 pulses. The maximum value is 1221.0 pulses, about 70 pulses higher and it appears to be the third peak in the graph. The minimum value of 1076 is about 75 pulses lower than the average and it occurs right before the peak, at the bottom of the page. Therefore, the graph is about 150 pulses wide and is app. centered on 1151. With this in mind, you should be able to get a feel for the scale. For instance, you could estimate the error in the last 250 points or so to be about 35 pulses. The graph is only included so the reader can get an idea of the noise problem and a better feeling for the measurements. The only information that we were really concerned with was the average value and the standard deviation. The standard deviation was important to us because we did not want to use any paritcularly noisy measurements. These could be caused by small movements in the lab or large movements outside the lab (e.g. someone coming in through the door or starting up another machine in the lab or even a large truck passing on the nearby street).

Taking the average from figures 4.1 and 4.2, we found the normal resolution without the plates to be:

$$1 \;/\; \{[(2049.6 - 1151.1) \;/\; (.005)] \times [(180 \;/\; \pi) \times 10^{-9}]\}$$

This expression equals 97.12 nanoradians per pulse, near the exact expected value of 96.96 nanoradians per pulse for .02 arcsec accuracy.

Taking the average from figure 4.3 and 4.4, we found the doubled resolution of the modified "Angular Interferometer to be:

$$1 \;/\; \{[(3944.3 - 2161.1) \;/\; (.005)] \times [(180 \;/\; \pi) \times 10^{-9}]\}$$

This expression equals 48.94 nanoradians per pulse, near the exact expected value of 48.5 nanoradians per pulse and app. half the previous value. This confirmed both that the modified "Angular Interferometer" worked as planned and that it was possible to achieve .01 arcsec accuracy.

To get a better idea of the accuracy that we could obtain, we ran the same test only we took measurements every .001° from 271.1400° to 271.1450° and then back to 271.140°. We ran it back to see how accurately the table could repeat a measurement. The results from this test are shown in the table below. All counts are averaged over 512 points taken at 100 Hz.

Table 4.1 Pulse Counts for .001° Increment Measurements

Input Angle	Standard Count	Difference	Doubled Count	Difference
271.1400°	1039.8	------	2212.8	------
.1410°	1213.8	174	2550.4	338
.1420°	1399.0	169	2929.3	379
.1430°	1568.7	169	3299.0	370
.1440°	1739.3	171	3634.8	335
271.1450°	1927.5	188	3988.9	354
.1440°	1739.4	188	3637.1	352
.1430°	1566.1	173	3294.0	343
.1420°	1395.6	171	2935.0	359
.1410°	1208.8	187	2558.5	377
271.1400°	1028.9	180	2209.7	349
	Error: 1%	AVG: 177	Error: .3%	AVG: 355.6

The averaged standard count value turns out to be 98.61 nanoradians per pulse and the averaged doubled count turns out to be 49.08 nanoradians per pulse. This turns out to be an error between the two of less than .5%, which is about the accuracy with which the table can repeat a movement.

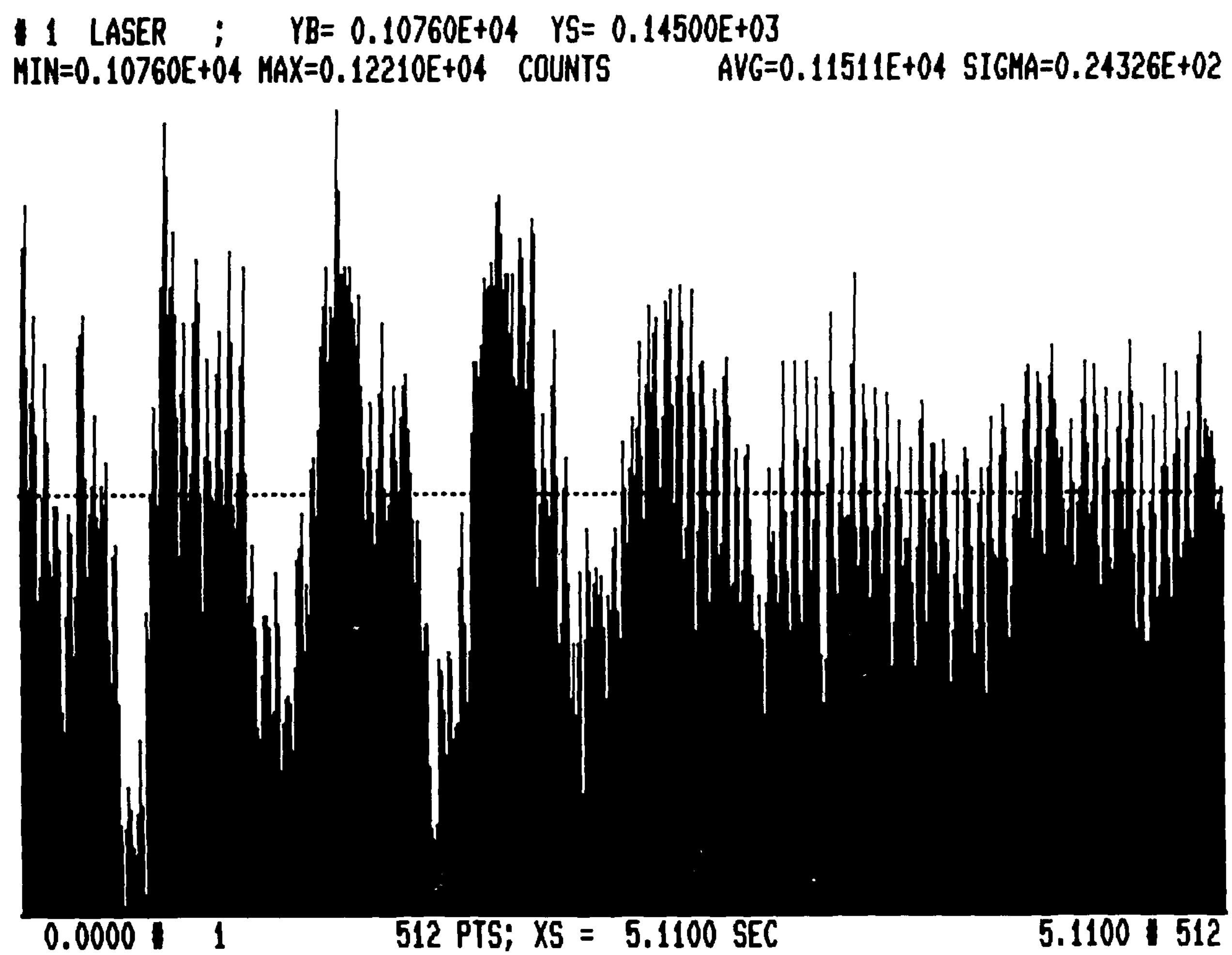


Figure 4.1 Computer Output for Standard Measurement at 271.1400

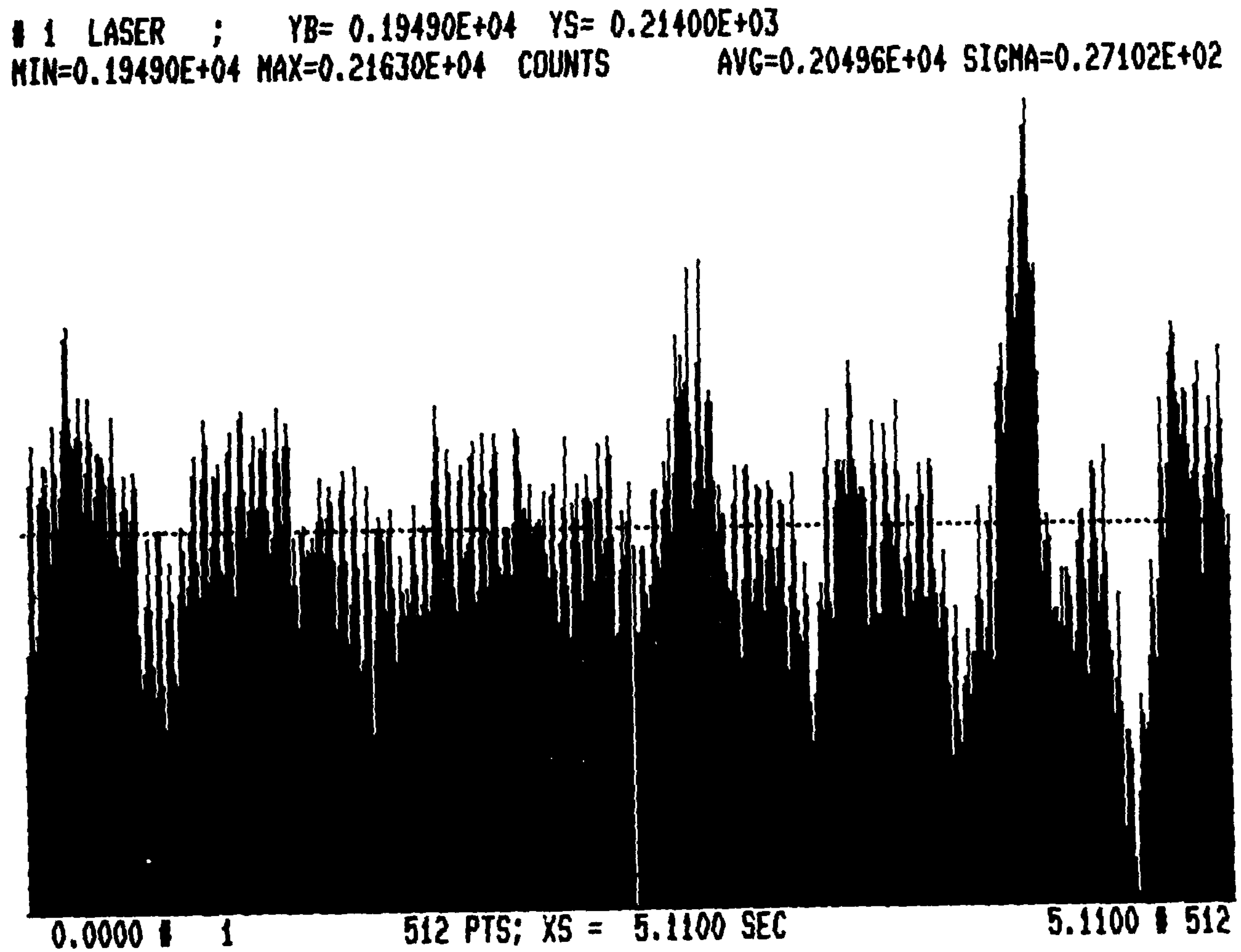


Figure 4.2 Computer Output for Standard Measurement at 271.1450

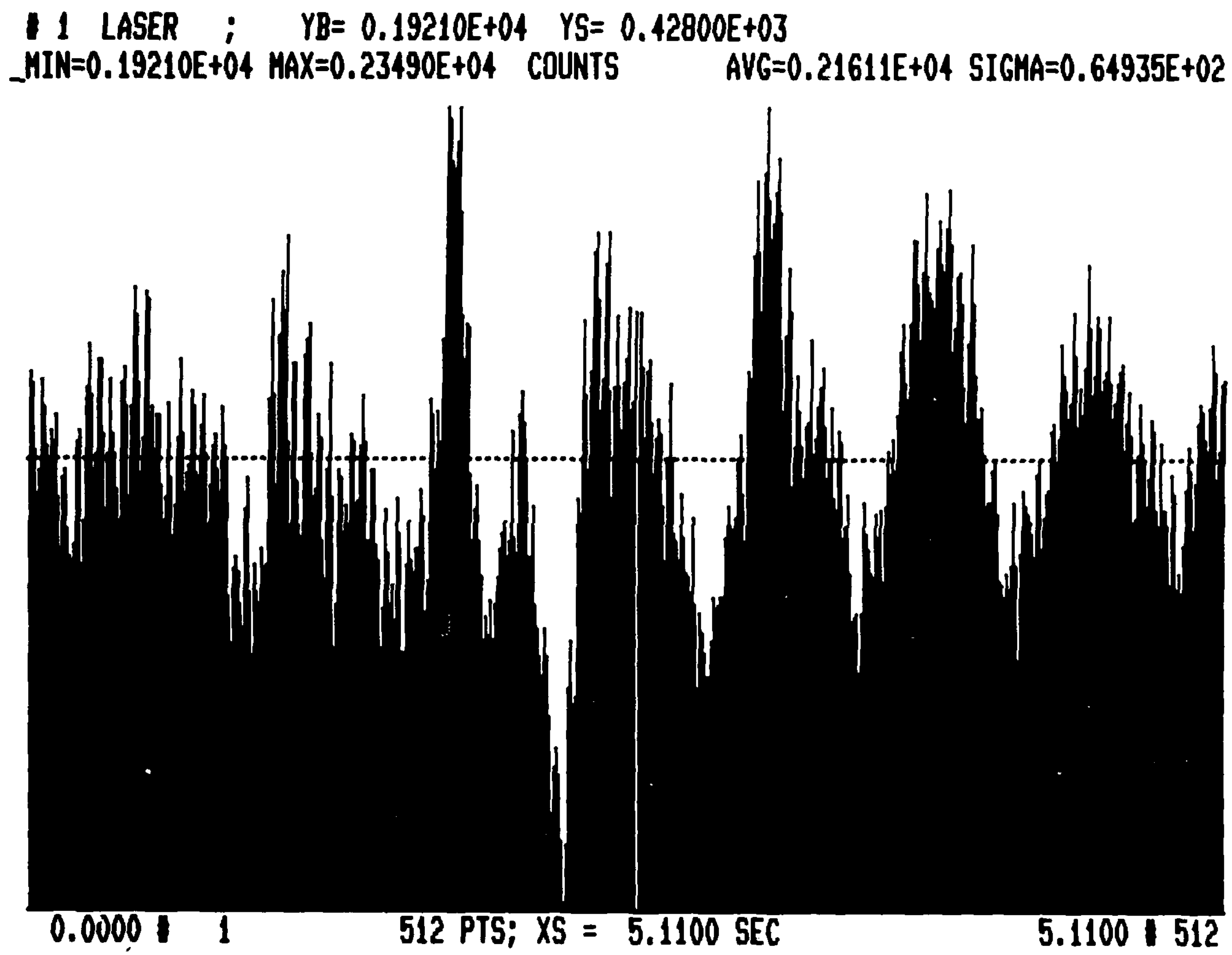


Figure 4.3 Computer Output for Doubled Measurement at 271.1400

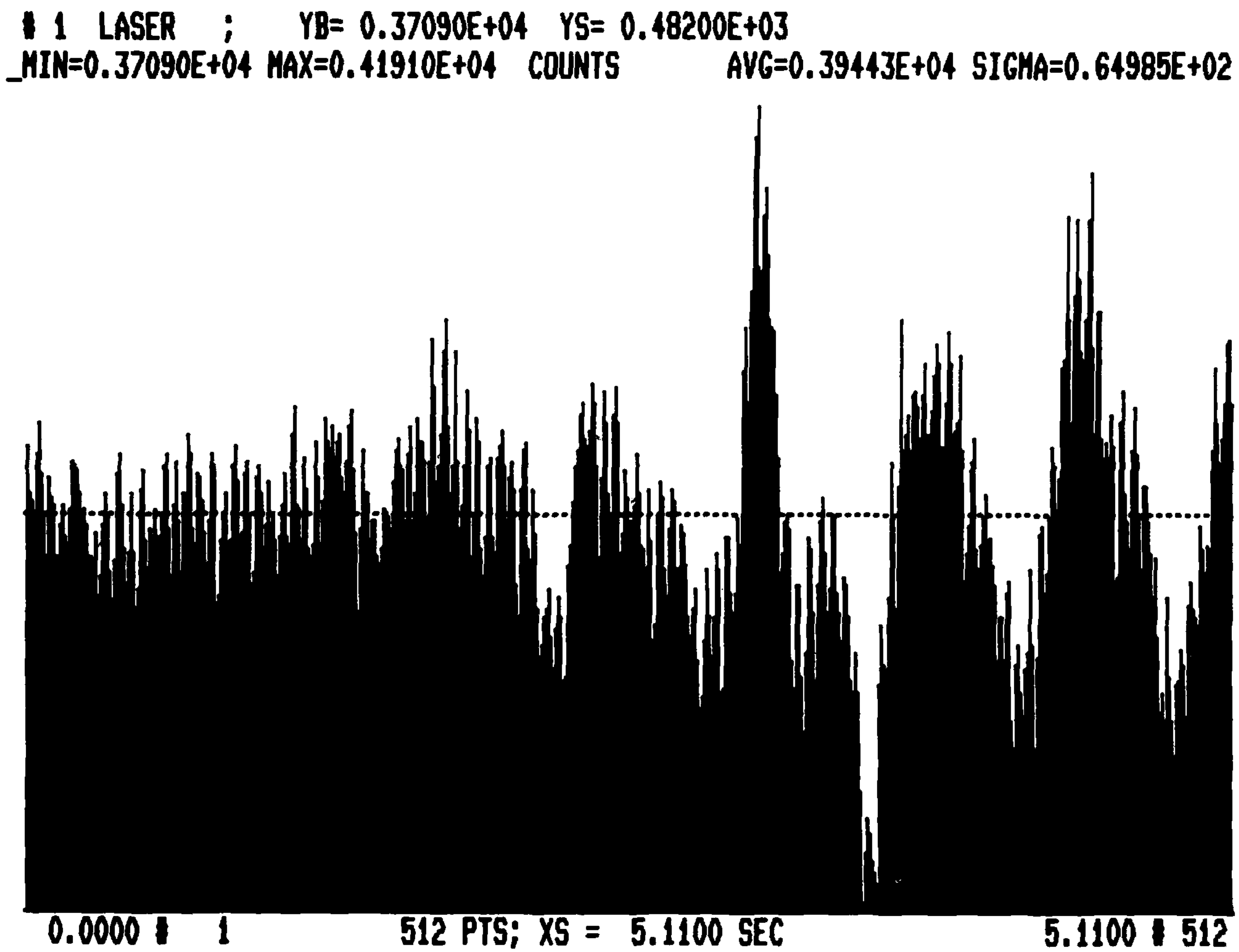
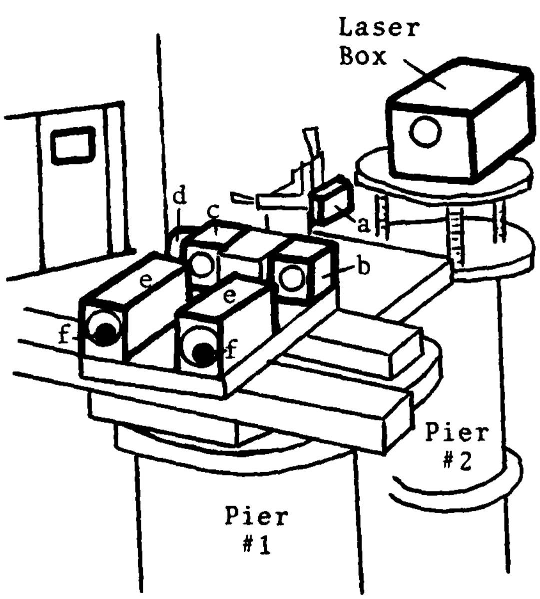


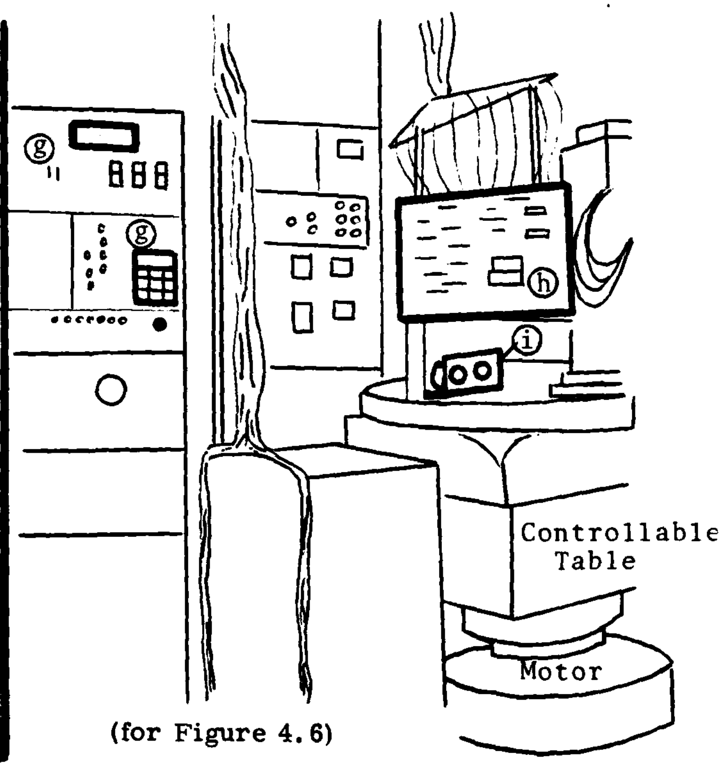
Figure 4.4 Computer Output for Doubled Measurement at 271.1450

4.3 THE MODIFIED "ANGULAR INTERFEROMETER"

The actual set-up that was used in this full-scale test is shown in the photographs on the following pages. The block diagrams on this page are meant to be used to help identify the individual components in the photographs. The laser box and the receiver are the same type as the ones used in the small-scale tests. All of the optical components are slightly larger and more precise than their counterparts in the small-scale tests. The plates are mounted in the end blocks of the planned evacuated tubes (to be discussed in the next section) and are the same as those tested using the linear set-up. Most of the table itself can be seen in figure 4.6 and the torque motor's electronics and control panel can be seen in the background.



(for Figure 4.5)



(for Figure 4.6)

a. Receiver	d. Retroreflector	g. Input and Output Panels
b. Beam Bender	e. End Blocks	h. Modified Motor Electronics
c. Beam Splitter	f. $\lambda/2$ Plates	i. 4-inch Retroreflector Mount

Figure 4.5 The Modified "Angular Interferometer"

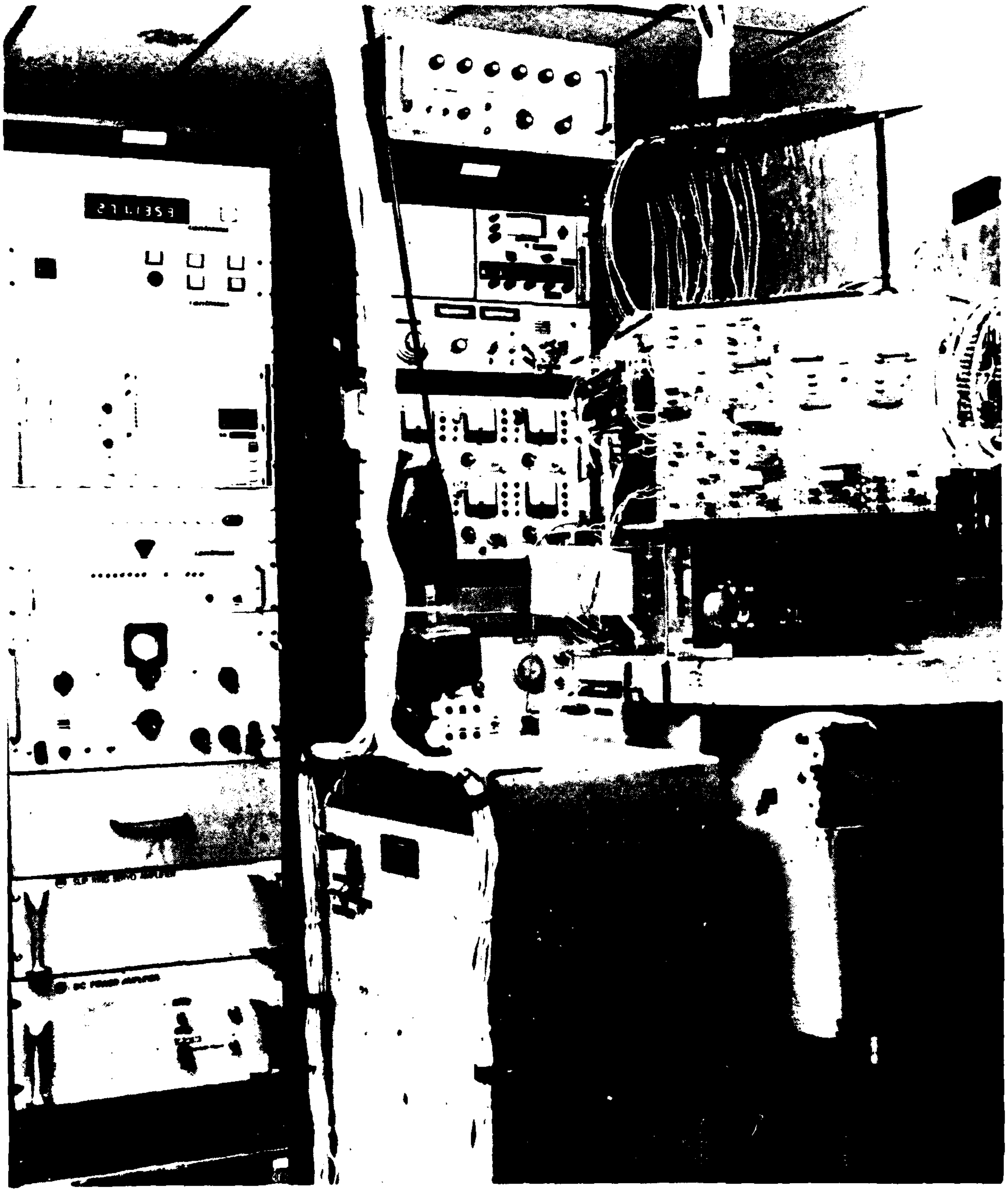


Figure 4.6 Monitored Test Stand and Associated Electronics

5.0 CONCLUSIONS AND RECOMMENDATIONS

Some practical problems that we encountered during the full-scale test should be considered before making the plates a permanent part of the system. One problem is that the modified "Angular Interferometer" is more difficult to align than the standard set-up. The beam paths are longer and therefore more sensitive to misalignment. The fact that f1 and f2 overlap makes it difficult to adjust one beam without ruining the alignment of the other beam. And, lastly, if the beam is to exactly duplicate its first trip, it must hit the extra retroreflector symmetrically about its center. To do this, the beam must hit the beam splitter symetrically about its center. This is a desirable and often convenient alignment in the standard "Angular Interferometer" but any positioning of the beam is satisfactory as long as the two beams overlap at the receiver. In the modified "Angular Interferometer", the symmetric alignment becomes a neccessity. This is not especially difficult but it does put an added constraint on the system.

Another problem to be considered is power loss. Using the given losses for each component, we had only expected a power loss of 31% in the modified "Angular Interferometer", not much worse than the expected 12% loss in the standard configuration. In actuality, because of unexpectedly large losses in the interferometer optics and one of the wave plates, our losses were nearly doubled to 25% for the standard set-up and 64% in the modified "Angular Interferometer". The signal is still useful up to a loss of app. 70%. We were above that figure but we were close enough so that a very large jump in the jittery signal could break the beam for an instant and reset the whole system, making a whole set of measurements useless. At such low power, it was necessary to maximize the "usefulness" of the signal, as we did in the small-scale tests. If the one plate with the large loss (10%) is replaced with one that has a working anti-reflection coating (the other plate lived up to expectations with a less than 1% loss), the loss can be reduced to 52%. The photodiode's ouitput would probably still need to be maximized in order to get the most useful signal but this loss should allow an acceptable margin of error, since the beam rarely broke (app. once an hour) at a power loss of 64%.

One other potential problem arises from a design modification that Draper Laboratory may make in their set-up. They are considering placing two evacuated tubes between the interferometer optics and the retroreflectors. This will greatly reduce the path length (the effective length of an evacuated tube is zero) and should eliminate any noise in the signal from air turbulence and changes in the refractive index of the air. Current plans call for the tubes to be sealed at the ends with Brewster windows for minimum loss at the interface. In the standard "Angular Interferometer", f1 and f2 stay in either TE or TM polarization so a window can be designed specifically for each beam to cut its losses to near zero. But, in the modified "Angular Interferometer", the plates change the polarizations to the perpendicular polarizations for the second trips. This perpendicular polarization will suffer a 20% loss on hitting the Brewster window designed for the other polarization (actually, since the beam will already have lost nearly 40% of its power, the effective loss will only be about 10%). Normal flat glass plates cannot be used as a compromise for the two polarizations even though the loss would be cut to 4%, because that loss would be for both polarizations. Since the beam's first pass will be at nearly full power, the total effective loss for a flat plate would be about 6% for the two trips. Since their would be two windows for each tube, and the beams would have to pass through each window twice per trip, these losses are prohibitively high. The only acceptable solution is to replace the Brewster windows with flat plates that have anti-reflection coatings. This would reduce the loss to less than 1% per pass.

Throughout the testing, I saw no practical difficulties that would prevent the use of the plate in normal operations. Therefore, since the full-scale test proved that .01 arcsec accuracy could be achieved with the modified "Angular Interferometer", I see no reason Draper Laboratory should not use it. The small-scale accuracy test and the full-scale test showed that there was no discernible error introduced by the plates in producing the doubling effect. Therefore, my conclusion is that the half-wave plate/retroreflector scheme works as well for angular interferometry as the quarter-wave plate/mirror scheme works for linear interferometry.

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