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THREE STAGE ATTENUATOR USING GLAN-THOMPSON PRISMS

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Final Report

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PHILLIPS LABORATORY
Space and Missiles Technology Directorate
AIR FORCE MATERIEL COMMAND
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13. ABSTRACT (Maximum 200 words)

Conventional three-polarizer attenuators were developed in the 1960s and had accuracies limited to [illegible] transmittance and, in [illegible], Winters and Roberts determined that at least ten times more accuracy could be obtained using two new types of attenuators which employed either a half-wave or a quarter-wave retardation plate in conjunction with two sheet polarizers. The purpose of the current effort was to test the same concept using extremely high quality optical Glan-Thompson prisms, extremely precise automated stages, and an experimental setup designed to provide accurate measurement for high extinction values, to determine the feasibility of using a three-stage polarizer attenuator with laser sources in the [illegible] to [illegible]-nm range. The device would be used to calibrate experimental signals and/or the transmittance of neutral density filters. The experimental results indicated that the attenuator could only provide uncertainties of [illegible] to [illegible] percent. The photometric accuracy was not tested with natural sources. However, the attenuator was useful in providing practical corrections of a few percent over a wide dynamic range with a simple technique. It can be used to calibrate neutral density filters over a wavelength range from [illegible] to [illegible] nm and an optical density range of nine orders of magnitude.

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Attenuation, Prisms, Transmittance, Three-Polarizer

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FIGURES

1.0 INTRODUCTION

Conventional polarizer attenuators have been used since at least the 1920s. The transmittance of the two-stage polarizer attenuator, where one polarizer is fixed and the other one is rotated, is known as Malus' law:

$$T(\delta)/T(0) = (\cos\delta)^2$$

where $T(\delta)$ is the transmittance of the two polarizers and δ is the angle enclosed by the principal transmittance axes. This device was unreliable if the source was partially polarized or the sensitivity of the detectors varied with the angle of polarization (Ref. 1). Dowell developed the three-stage polarizer attenuator which overcame the defects in the two-stage attenuator (Ref. 2). In Dowell's method the first and last polarizers were stationary with their optic axes parallel and the middle polarizer was rotated. The three-stage polarizer attenuator transmitted an intensity governed by a $\cos^4$ relationship,

$$T(\delta)/T(0) = (\cos\delta)^4$$

To obtain accurate measurements, the extinction ratios of the polarizers and the birefringence of the middle polarizer must be known and accounted for when the attenuator is calibrated. In general, the conventional three-polarizer attenuators utilizing film polarizers were limited to 0.001 transmittance units (Ref. 1).

Several different types of polarizers have been used in the three-stage attenuators. Bennett used sheet Polaroid mounted between distortionless glass plates and determined photometric linearity to better than 0.1 percent (Ref. 3). Mielenz and Eckerle discussed systematic errors due to imperfections in sheet polarizers, setting and alignment errors, and incident beam incidence angle and polarization. They concluded that the accuracy of three-polarizer film attenuators is limited to 0.001 transmittance unit largely because of the unknown birefringence of the middle polarizer. Instead they employed either a half-wave or a quarter-wave retardation plate with a precisely known birefringence and two sheet polarizers and obtained at least 10 times more accuracy than the conventional three-polarizer attenuators (Ref. 1).

Polarization prisms would also avoid the birefringence problem. Mielenz and Eckerle did not pursue the use of prisms because of potentially serious systematic errors caused by their small field angles and because the accurate measurement of the high extinction ratios of good polarizers was difficult (Ref. 1). Bennett tested, but did not use, a good Glan-Thompson prism that deviated the beam by less than 1 min of arc and was a high schlieren quality calcite, because the intensity variation was not symmetric in the four quadrants. He suggested that a prism-type polarizer with adequate performance would have the advantage of a wider, more useful spectral range than was possible with sheet polarizers (Ref. 3).

The current work was based on the same concept and used specially selected high quality optical Glan-Thompson prisms, extremely precise automated stages, and a combination of optical density filters with a lock-in amplifier, to obtain accurate measurements and to determine the feasibility of using a three-stage polarizer attenuator with laser beams in and near the visible range. This device should be effective for independently calibrating experimental signals and transmittance of neutral density filters over a wavelength range from 350 to 2500 nm and over an optical density range of nine orders of magnitude.

2.0 EXPERIMENTAL ARRANGEMENT

2.1 ATTENUATOR DESIGN

The three-stage attenuator was comprised of specially selected high quality optical *Glan-Thompson prisms manufactured by Karl Lambrecht Corporation* (MGT25E10-90), Chicago, Illinois. The calcite prisms are glued at the interface. The optical glue limited the capability of the attenuator at the ultraviolet end of the spectral range, but it also provided better maximum attenuation. The prisms were selected so that one crossed pair would have an attenuation equal to or greater than 10^6:1. The prisms had a wavelength range of approximately 350 to 2500 nm and a tolerance on maximum beam deviation of approximately 6 arc sec.

The prisms were each mounted in precision stages. Two of the stages, manufactured by Klinger Scientific, Garden City, New York, were electronically driven. The first stage was required to accurately return to the 0-deg position and to have a repeatable 90-deg rotation. These criteria were easily met with one of the Klinger stages. The requirements for the second stage (middle polarizer) were the most stringent since this stage was the only one which would rotate after the attenuator was aligned. This stage was responsible for determining the angle "β" with great accuracy. Consequently, the second stage consisted of a Klinger Scientific, Garden City, New York, stage and an encoder. The encoder on the middle stage was accurate to approximately 1 arc sec. The third stage was a manual stage which incorporated both fine and coarse adjustments. Figures 1a, 1b, and 1c show the assembled three-stage polarizer attenuator taken from the top (Fig. 1a), from the front (Fig. 1b), and from the side (Fig. 1c).

(a). Top view.

Figure 1. Three-stage polarizer attenuator.

(b). Side view.

(c). Front view.

Figure 1. Concluded.

2.2 ALIGNMENT OF THE ATTENUATOR

The alignment for the stages was accomplished mechanically by using an optical post which was the same diameter as the prisms. The post was inserted through the mounts (where the prisms would be mounted) and then the mounts were adjusted and tightened down. The post was removed.

Each prism was then individually mounted in each stage position and tested. A target was placed 6 to 8 ft away from the attenuator and then the stage was rotated through 360 deg to ensure that the laser spot remained in the same location on the target. All three prisms performed properly.

An alignment procedure was developed which ensured the first and third polarizers had their optic axes in parallel positions and the second polarizer reached a minimum transmittance when it was crossed with the other two polarizers. The procedures used are described below and depicted in Figure 2. (Note: Prism 1 is mounted closest to the laser source, prism 2 is mounted in the center of the attenuator, and prism 3 is mounted closest to the detector.)

Step 1. Set all of the mounts to their 0-deg position and insert all the prisms in the same approximate orientation.

Step 2. Set prism 3 near the 90-deg or null position.

Step 3. Set prism 2 so that prisms 1 and 2 are exactly 90 deg off (cross polarized). This location should provide an exact null and prism 2 will be in approximately the 90-deg position.

Step 4. Set prism 1 in the same position as prism 2.

Step 5. Return prism 3 to the 0-deg position and adjust it until an exact null is reached (prisms 2 and 3 are crossed polarizers). Lock prism 3 in place.

Step 6. Return prism 1 to its exact original position. At this point, prisms 1 and 2 should be exactly 90 deg offset and prisms 2 and 3 should also be exactly 90 deg offset.

Step 7. Return prism 2 to its 0-deg position. The attenuator should now be set for maximum transmission.

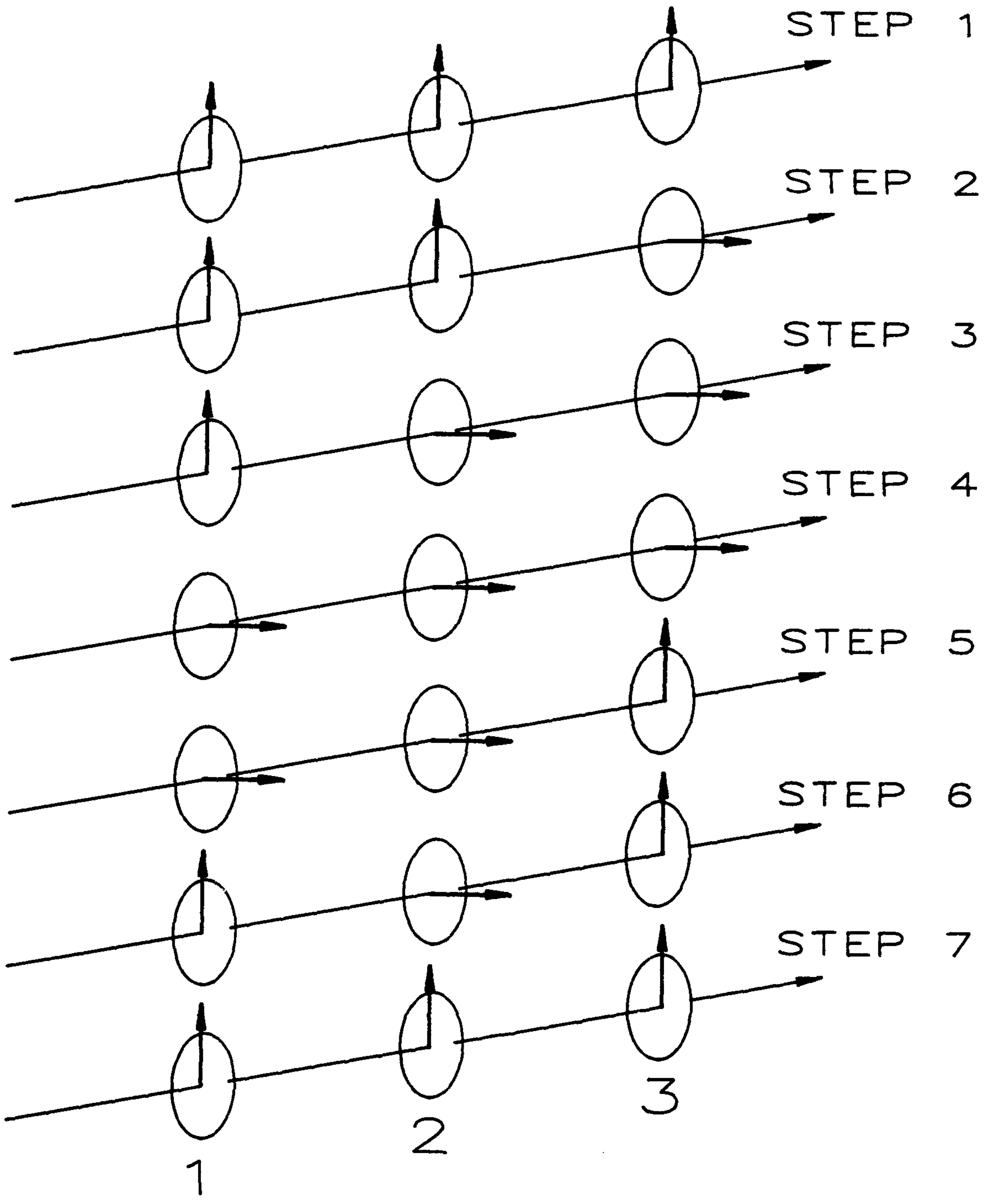


Figure 2. Attenuation alignment procedures.

2.3 EXPERIMENTAL LAYOUT

The three-stage attenuator was then tested in an experimental setup [illegible] range and accuracy. The experimental schematic is shown in Figure [illegible]

The laser was a 5-mW helium-neon laser (633 nm) with an adjustable beam expander. A quarter-wave plate was positioned between the [illegible] attenuator. Consequently, a monochromatic, collimated, [illegible] source was normally incident upon the attenuator. [illegible] properly position the light for the detector

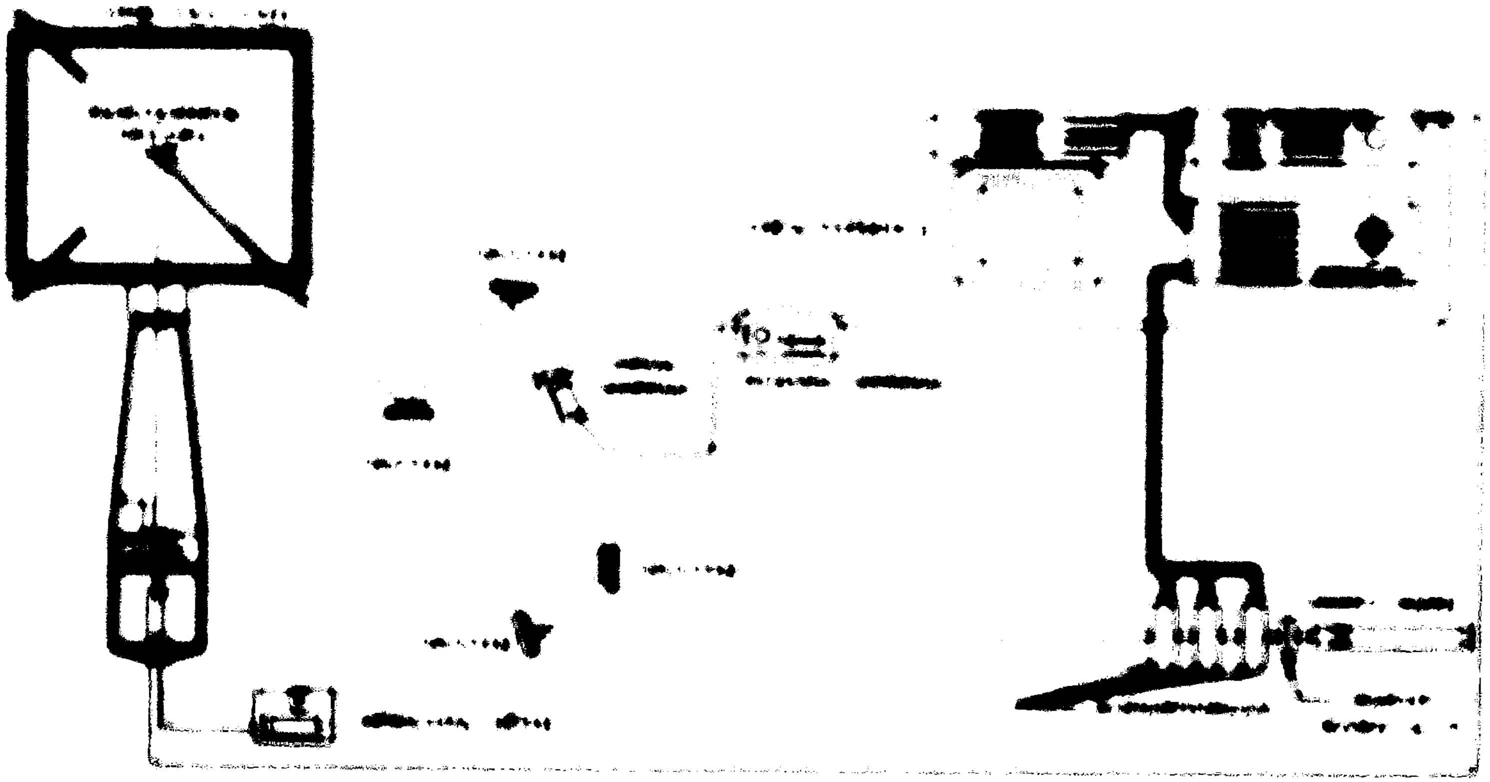
A chopper with reflective blades was used to send part of the beam [illegible] integrating sphere which was coupled to a silicon detector. [illegible] input laser signal and was read on the lock-in amplifier

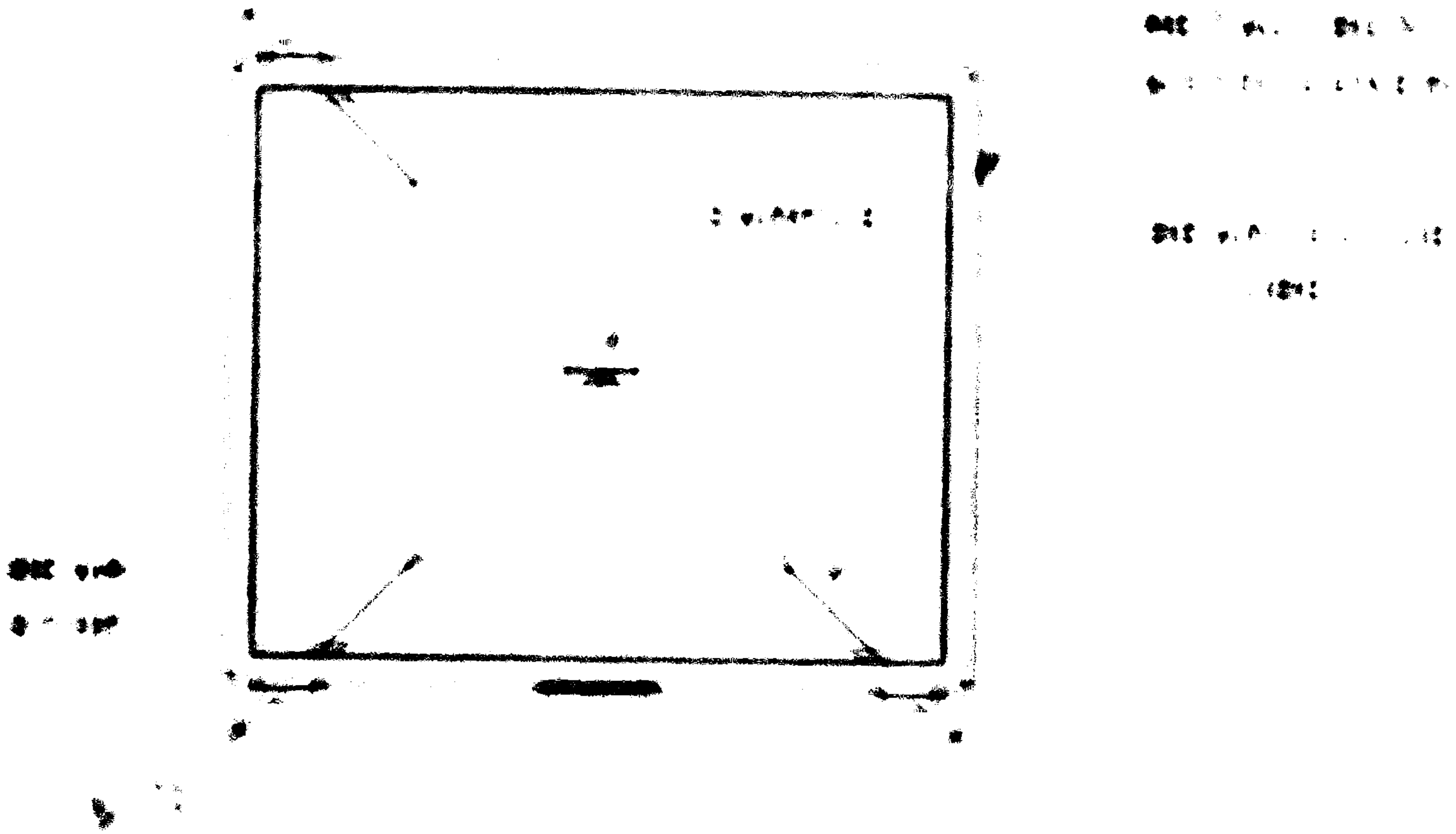
The laser light then entered a utility box measuring 30 x 30 [illegible] in its walls for both the incident and reflected laser light [illegible] caused the laser light to scatter, in this case a [illegible] reflector (Labsphere, Inc., North Sutton, New Hampshire) [illegible] center of the box. The laser beam entered the box at a 45 deg angle [illegible] the sample's normal. A portion of the reflected beam [illegible] the photometer. For alignment purposes, a third hole [illegible] beam could exit when no sample was in place. [illegible] inner wall, were inserted through the small holes in the box [illegible] beam entered and exited the box. Alignment of the laser [illegible] laser beam was adjusted until it appeared to be centered [illegible] the tubes. Figure 4 illustrates the basic setup of the utility box.

The photometer, filter wheel assembly, and photomultiplier [illegible] several capabilities: (1) the ability to scramble the signal [illegible] the ability to focus the beam, (3) the ability to change [illegible] eliminate most sources of stray light, and (5) the ability to [illegible] neutral density filters in the optical train where the light [illegible] axis. Figure 5 provides a ray diagram of the setup. [illegible] housing (Products for Research, Inc., Danvers, Massachusetts) [illegible] radiofrequency shielding, a double window and [illegible] reduction of dark current.

The PMT was connected to a phase lock amplifier. [illegible] was used to obtain data over a six order of magnitude dynamic range. [illegible] orders of magnitude were obtained by attenuating the [illegible] with a National Institute of Science and Technology [illegible] density filter. Consequently, even the weak signals were [illegible] limitation and within the linear range of the photomultiplier

[illegible]





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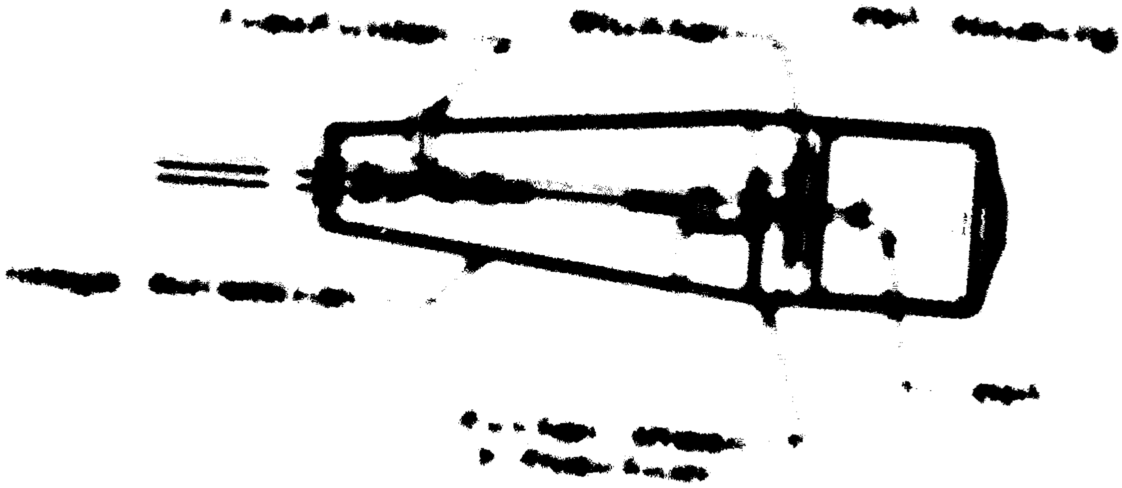

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3.0 DATA INTERPRETATION AND EXPERIMENTAL RESULTS

3.1 EXPERIMENTAL RESULTS

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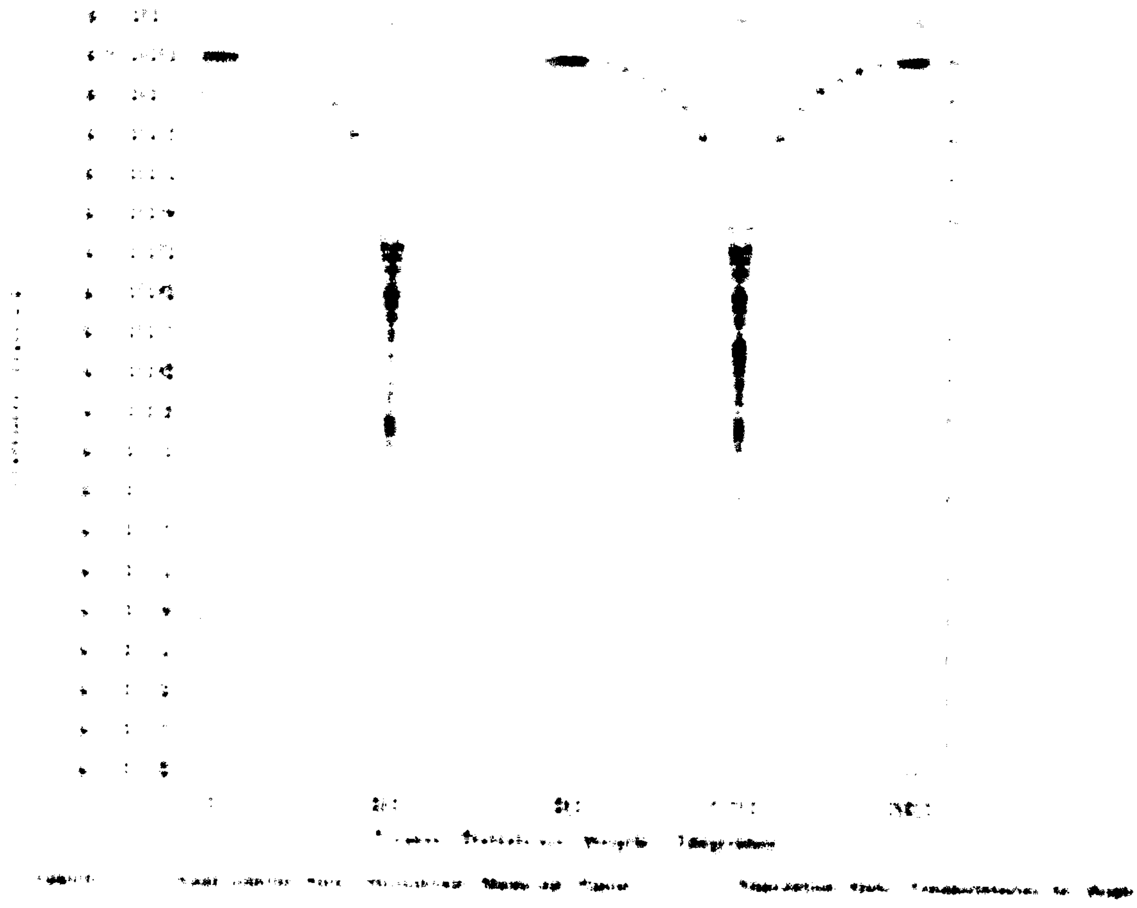


Figure 6 Experimental and theoretical transmittance versus the prism rotation angle

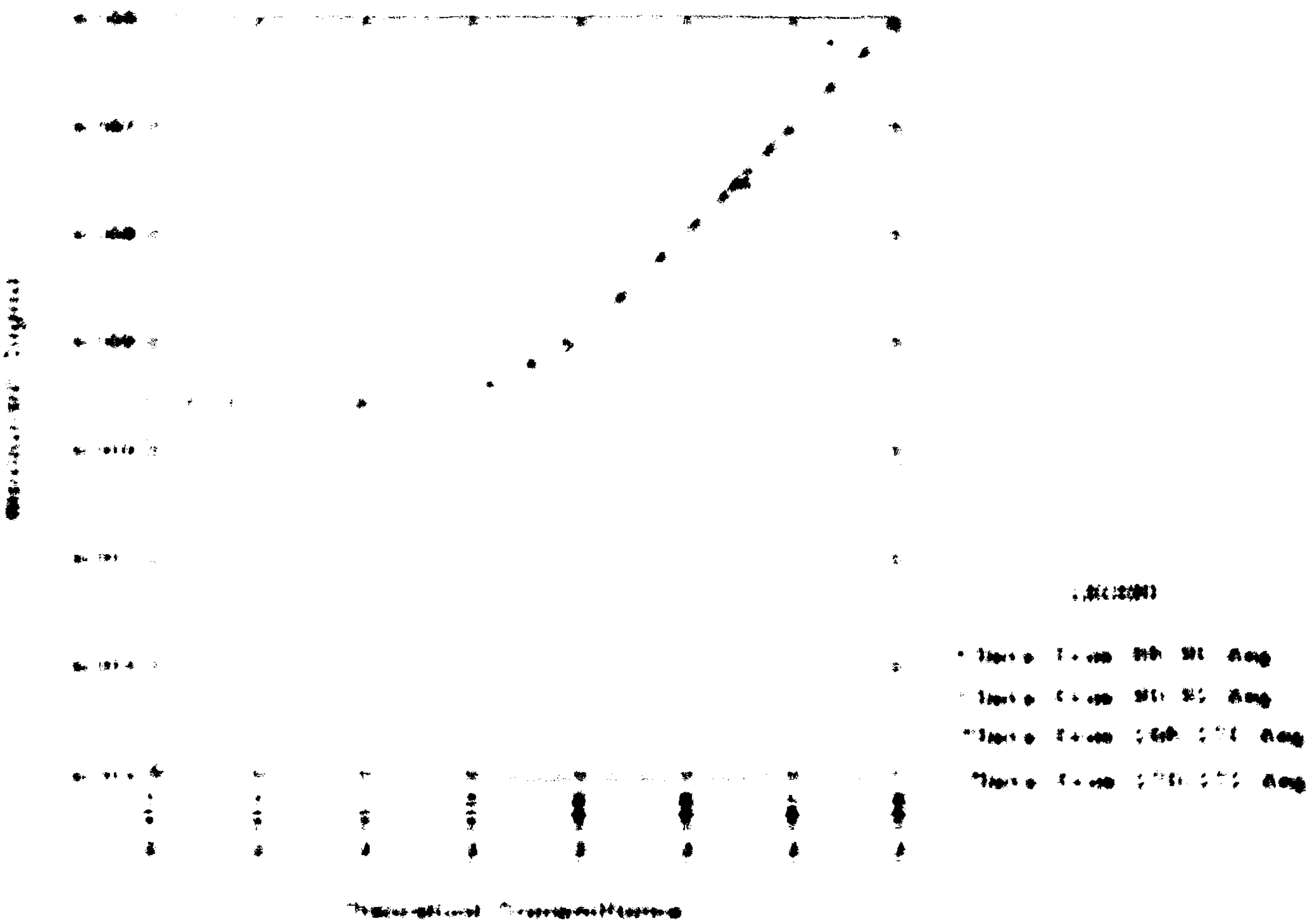


Figure [illegible] Measured signal versus theoretical transmittance for data in the vicinity of 90 and 270 deg.

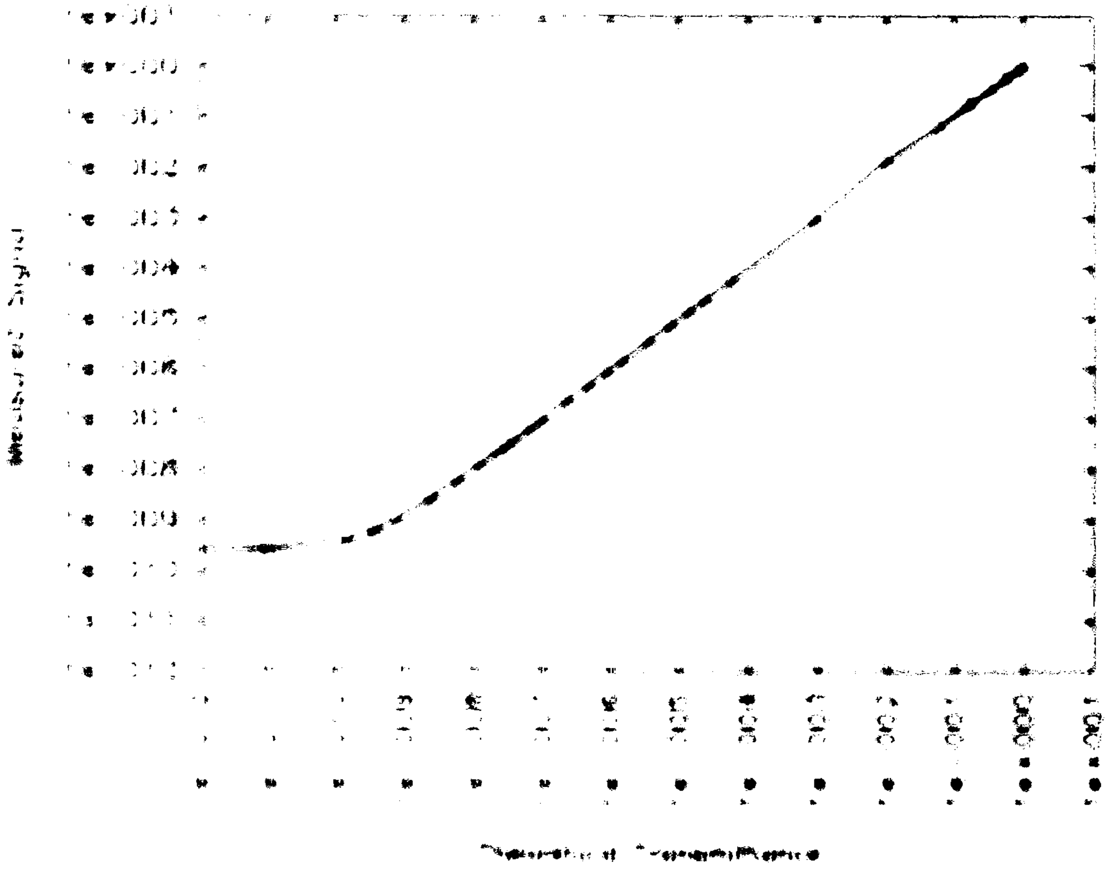
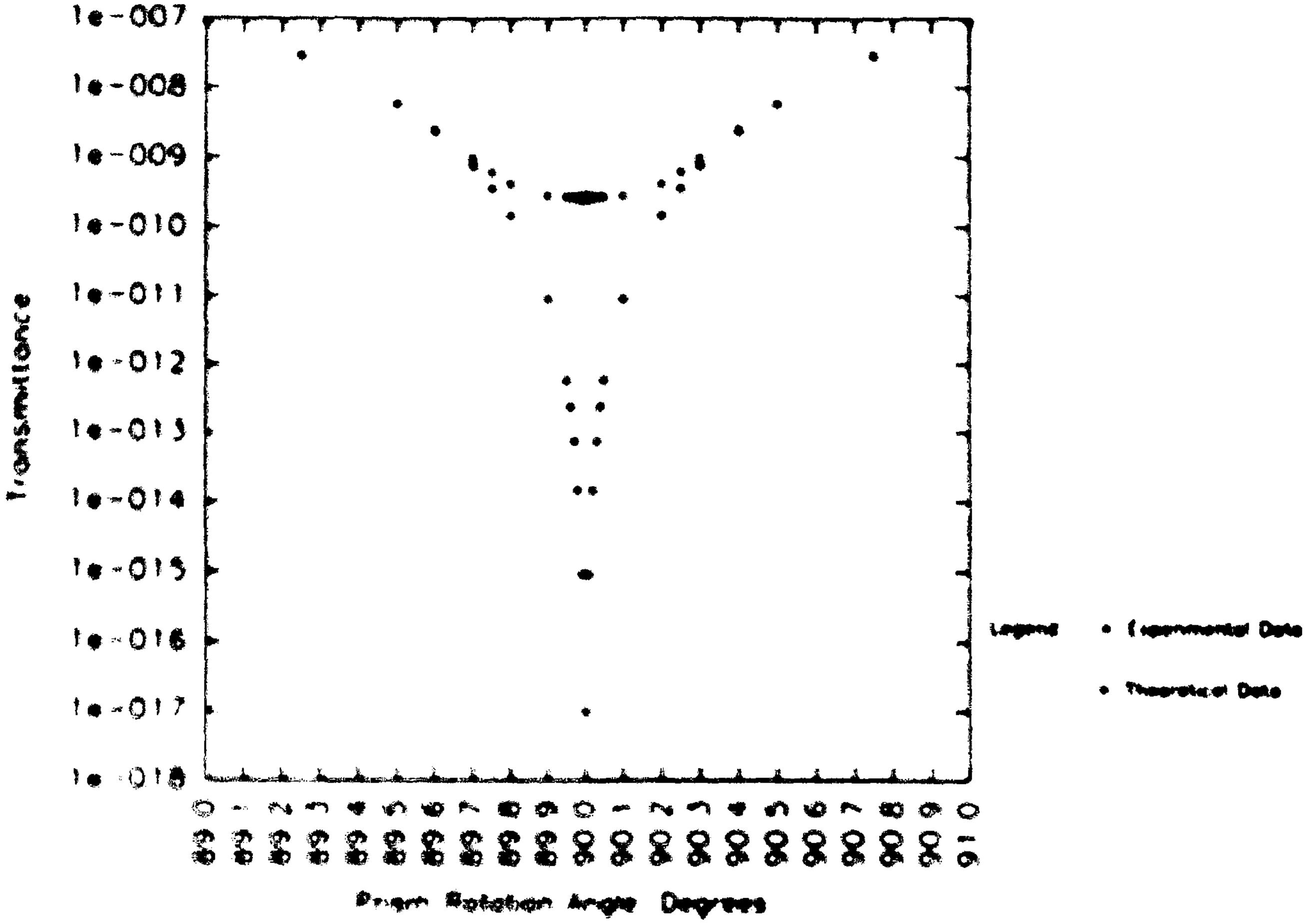
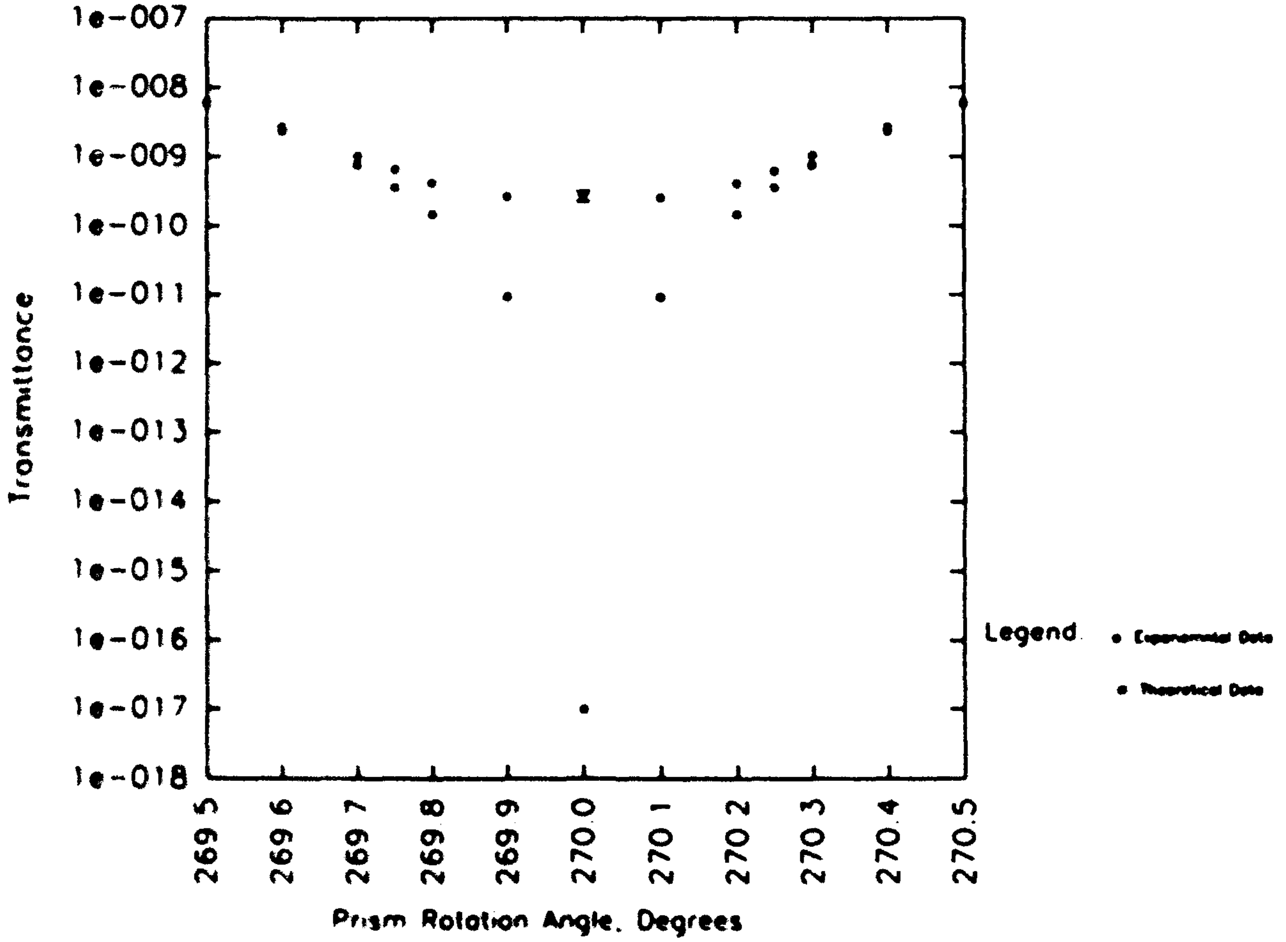


Figure 8. Measured signal versus theoretical transmittance for the entire data set



(a) Angles near 90-deg

Figure 9 Data plot of the transmittance versus the prism rotation angle.



(b) Angles near 270 deg.

Figure 9. Concluded.

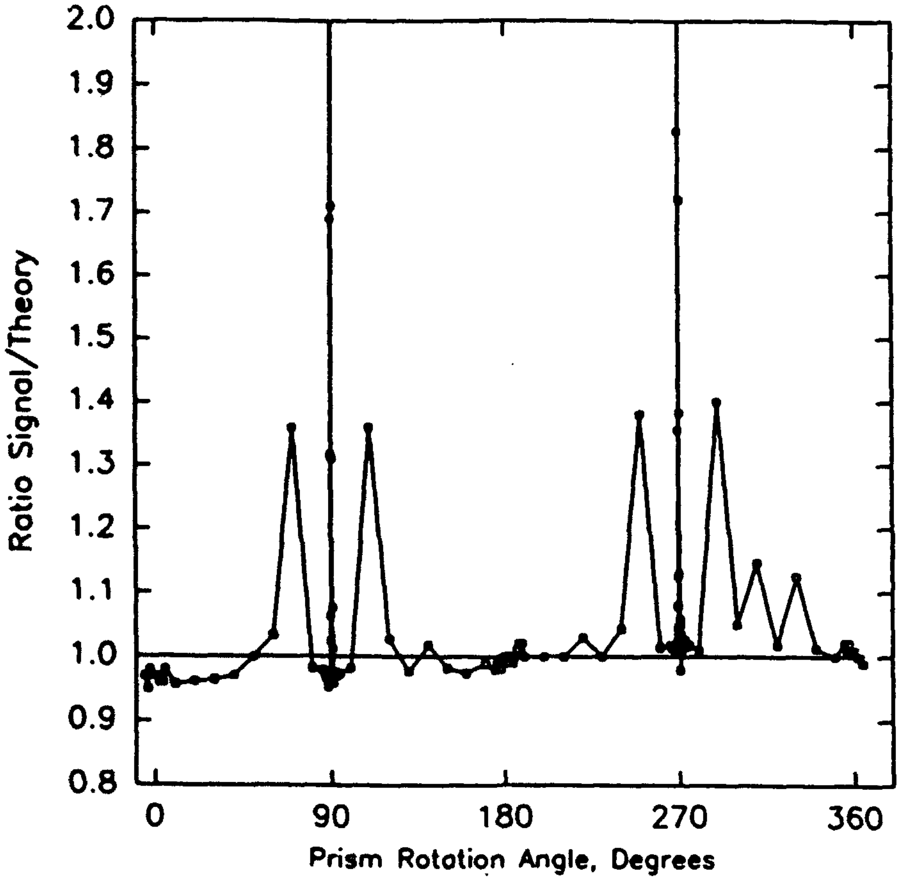


Figure 10. Ratio of the experimental transmittance to the theoretical transmittance versus the prism rotation angle.

3.2 EXPERIMENTAL ERROR

3.2.1 Measurement Error

There were several sources of measurement and random error present throughout the experiment. These errors include nonlinearity in the phase lock amplifier, noise from the photomultiplier, stray light in the optical train, variation in the lock-in amplifier reading, and drift in laser power. No attempt was made to control the laser power.

3.2.2 Systematic Error

Data collected around the 0-, 90-, 180-, and 270-deg angles indicated significant systematic errors. The major errors include drift in the laser signal from the beginning to the end of the data run and slight alignment errors in the prisms. The drift was noticed in the signal from the beginning to the end of the data runs. In addition, the equipment was left for several 30-min intervals without altering the equipment setting and experimental data did change slightly with time. Alignment errors are noticed in the lack of perfect symmetry in data around the 0- and 360-deg points. In addition, there was a small double hump pattern around the 90- and 270-deg points. Additional systematic errors would include the temperature change in the room affecting the laser detector or the electronics and small inaccuracies in the mechanized center stage.

4.0 CONCLUSIONS

The three-stage polarizer attenuator, with the advanced Glan-Thompson optical prisms, the extremely precise automated stages, and an experimental setup which allowed accurate measurements of high extinction ratios, was capable of providing attenuation of a laser beam for nine orders of magnitude with uncertainties of 1 to 2 percent. This attenuator was useful in providing practical accuracies of a few percent over a wide dynamic range with a simple technique. The data were symmetric throughout all four quadrants. The attenuator can be used to calibrate neutral density filters over a wavelength range from 350 to 2500 nm and over an optical density range of nine orders of magnitude. These results were obtained with laser sources only, and no corrections were made for drift in the laser power or signal processing.

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2. Dowell, J. H., J Sci Instrum, Vol. 8, p. 382, 1931.

3. Bennett, H.E., "Accurate Method for Determining Photometric Linearity," Applied Optics, Vol. 5, No. 8, August 1966.

APPENDIX A

RAW DATA COLLECTED

FILTER WHEEL POSITION	[illegible]	[illegible] READING	FILTER WHEEL POSITION	[illegible]	[illegible] READING
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[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
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[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
[illegible]	[illegible]	[illegible]		[illegible]	[illegible]

FILTER WHEEL POSITION	θ (°)	LOCK-IN READING	FILTER WHEEL POSITION	θ (°)	LOCK-IN READING
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

FILTER WHEEL POSITION	θ (°)	LOCK-IN READING	FILTER WHEEL POSITION	θ (°)	LOCK-IN READING
3	266.00	67.2 ± 0.3 µV	1	269.90	26.7 ± 0.3 µV
1	266.00	2.41 ± 0.005 V	1	270.00	26.0 ± 0.3 µV
1	266.50	1.42 ± 0.005 V	1	270.10	26.5 ± 0.1 µV
1	267.00	0.7[illegible] ± 0.0005 V	1	270.20	41.4 ± 0.05 µV
1	267.50	0.370 ± 0.0005 V	1	270.30	106.4 ± 0.05 µV
1	268.00	151 ± 0.5 mV	1	270.40	272 ± 0.5 µV
1	268.25	[illegible].0 ± 0.05 mV	1	270.50	0.632 ± 0.0005 mV
1	268.50	48.3 ± 0.05 mV	1	270.60	1.28 ± 0.005 mV
1	269.00	9.53 ± 0.005 mV	1	270.70	2.33 ± 0.005 mV
1	269.10	[illegible] ± 0.005 mV	1	270.80	3.87 ± 0.005 mV
1	269.20	3.[illegible] ± 0.005 mV	1	270.90	6.2[illegible] ± 0.005 mV
1	269.30	2.31 ± 0.005 mV	1	271.00	8.57 ± 0.005 mV
1	269.40	1.[illegible] ± 0.005 mV	1	271.[illegible]	48.9 ± 0.05 mV
1	269.50	0.[illegible] ± 0.0005 mV	1	271.70	80.1 ± 0.05 mV
1	269.60	[illegible] ± 0.5 µV	1	272.[illegible]	152 ± 0.5 mV
1	269.70	[illegible] ± 0.5 µV	1	27[illegible]	0.272 ± 0.0005 V
1	269.80	[illegible] ± 0.2 µV	1	2[illegible]3.[illegible]	0.700 ± 0.0005 V

FILTER WHEEL POSITION	θ (°)	LOCK-IN READING	FILTER WHEEL POSITION	θ (°)	LOCK-IN READING
1	273.50	1.42 ± 0.005 V	3	360.00	2.78 ± 0.005 V
1	274.00	2.41 ± 0.005 V	3	361.00	2.76 ± 0.005 V
3	274.00	66.9 ± 0.05 µV	3	362.00	2.75 ± 0.005 V
3	275.00	163 ± 0.5 µV	3	363.00	2.73 ± 0.005 V
3	280.00	2.40 ± 0.005 mV	3	364.00	2.71 ± 0.005 V
3	290.00	30.0 ± 0.05 mV	3	365.00	2.70 ± 0.005 V
3	300.00	171 ± 0.5 mV	3	0.00	2.76 ± 0.005 V
3	310.00	0.488 ± 0.0005 V	3	1.00	2.76 ± 0.005 V
3	320.00	0.862 ± 0.0005 V	3	2.00	2.73 ± 0.005 V
3	330.00	1.55 ± 0.005 V	3	3.00	2.71 ± 0.005 V
3	340.00	2.20 ± 0.005 V	3	-1.00	2.77 ± 0.005 V
3	350.00	2.50 ± 0.005 V	3	-2.00	2.78 ± 0.005 V
3	355.00	2.77 ± 0.005 V	3	-3.00	2.77 ± 0.005 V
3	356.00	2.79 ± 0.005 V	3	0.00	2.66 ± 0.005 V
3	357.00	2.79 ± 0.005 V	1	89.50	0.380 ± 0.0005 mV
3	358.00	2.79 ± 0.005 V	1	89.60	256 ± 0.5 µV
3	359.00	2.79 ± 0.005 V	1	89.70	100 ± 0.5 µV

FILTER WHEEL POSITION	θ (°)	LOCK-IN READING	FILTER WHEEL POSITION	θ (°)	LOCK-IN READING
1	89.80	42.2 ± 0.05 μV	1	90.500	0.591 ± 0.0005 mV
1	89.90	29.3 ± 0.05 μV			
1	89.95	28.0 ± 0.05 μV			
1	89.96	27.8 ± 0.05 μV			
1	89.97	27.6 ± 0.05 μV			
1	89.98	27.7 ± 0.05 μV			
1	89.99	28.1 ± 0.05 μV			
1	90.00	28.3 ± 0.05 μV			
1	90.01	28.0 ± 0.05 μV			
1	90.02	27.8 ± 0.05 μV			
1	90.03	27.8 ± 0.05 μV			
1	90.04	27.7 ± 0.05 μV			
1	90.05	27.5 ± 0.05 μV			
1	90.100	28.7 ± 0.05 μV			
1	90.200	42.6 ± 0.05 μV			
1	90.300	99.8 ± 0.05 μV			
1	90.400	259 ± 0.5 μV			

APPENDIX B

REDUCED DATA

β	TRANSMITTANCE COS^4 β	EXPERIMENTAL VALUE	NORMALIZED EXPERIMENTAL VALUE
-5.00	0.98	2.62E00 ± 0.01	0.95E00
-4.00	0.99	2.61E00 ± 0.01	0.94E00
-3.00	0.99	2.69E00 ± 0.09	0.97E00
-2.00	1.00	2.70E00 ± 0.09	0.97E00
-1.00	1.00	2.70E00 ± 0.08	0.97E00
0.00	1.00	2.70E00 ± 0.11	0.97E00
1.00	1.00	2.69E00 ± 0.07	0.97E00
2.00	1.00	2.68E00 ± 0.06	0.96E00
3.00	0.99	2.67E00 ± 0.04	0.96E00
4.00	0.99	2.63E00 ± 0.01	0.95E00
5.00	0.98	2.67E00 ± 0.01	0.96E00
10.00	0.94	2.51E00 ± 0.07	0.90E00
20.00	0.78	2.08E00 ± 0.02	0.75E00
30.00	0.56	1.51E00 ± 0.05	0.54E00
40.00	0.34	0.92E00 ± 0.02	0.33E00
50.00	0.17	0.47E00 ± 0.02	0.17E00
60.00	0.06	1.72E-01 ± 0.05E-01	0.62E-01
70.00	0.01	3.77E-02 ± 0.08E-02	1.36E-02
80.00	9.09E-04	2.48E-03 ± 0.07E-03	8.93E-04
85.00	5.77E-05	1.57E-04 ± 0.06E-04	5.65E-05
86.00	2.37E-05	6.44E-05 ± 0.2E-05	2.32E-05
86.50	1.39E-05	3.75E-05 ± 0.04E-05	1.35E-05
87.00	7.5E-06	2.02E-05 ± 0.03E-05	7.27E-06
87.50	3.62E-06	9.67E-06 ± 0.16E-06	3.48E-06
88.00	1.48E-06	3.93E-06 ± 0.03E-06	1.41E-06
88.25	8.70E-07	2.32E-06 ± 0.01E-06	8.35E-07
88.50	4.70E-07	1.26E-06 ± 0.01E-07	4.54E-07

β	TRANSMITTANCE COS^4 β	EXPERIMENTAL VALUE	NORMALIZED EXPERIMENTAL VALUE
88.75	2.26E-07	6.06E-07 ± 0.04E-07	2.18E-07
89.00	9.28E-08	2.50E-07 ± 0.03E-07	9.00E-08
89.25	2.94E-08	7.98E-08 ± 0.14E-08	2.87E-08
89.50	5.80E-09	1.65E-08 ± 0.06E-08	5.94E-09
89.60	2.38E-09	7.04E-09 ± 0.02E-09	2.53E-09
89.70	7.52E-10	2.75E-09 ± 0.02E-09	9.90E-10
89.75	3.62E-10	1.70E-09 ± 0.03E-09	6.12E-10
89.80	1.48E-10	1.16E-09 ± 0.03E-09	4.18E-10
89.90	9.28E-12	8.06E-10 ± 0.03E-10	2.90E-10
89.95	5.80E-13	7.70E-10 ± 0.01E-10	2.77E-10
89.96	2.38E-13	7.65E-10 ± 0.01E-10	2.75E-10
89.97	7.52E-14	7.59E-10 ± 0.01E-10	2.73E-10
89.98	1.48E-14	7.62E-10 ± 0.01E-10	2.74E-10
89.99	9.28E-16	7.73E-10 ± 0.01E-10	2.78E-10
90.00	0	7.60E-10 ± 0.45E-10	2.74E-10
90.01	9.28E-16	7.70E-10 ± 0.01E-10	2.77E-10
90.02	1.48E-14	7.65E-10 ± 0.01E-10	2.75E-10
90.03	7.52E-14	7.65E-10 ± 0.01E-10	2.75E-10
90.04	2.38E-13	7.62E-10 ± 0.01E-10	2.74E-10
90.05	5.80E-13	7.56E-10 ± 0.01E-10	2.72E-10
90.10	9.28E-12	7.89E-10 ± 0.01E-10	2.84E-10
90.20	1.48E-10	1.17E-09 ± 0.01E-09	4.21E-10
90.25	3.62E-10	1.72E-09 ± 0.06E-09	6.19E-10
90.30	7.52E-10	2.74E-09 ± 0.01E-09	9.86E-10
90.40	2.38E-09	7.12E-09 ± 0.01E-09	2.56E-09
90.50	5.80E-09	1.63E-08 ± 0.01E-08	5.87E-09
90.75	2.94E-08	7.84E-08 ± 0.05E-08	2.82E-08

θ	TRANSMITTANCE COS^4 θ	EXPERIMENTAL VALUE	NORMALIZED EXPERIMENTAL VALUE
91.00	9.28E-08	2.49E-07 ± 0.02E-07	8.96E-08
91.25	2.26E-07	6.08E-07 ± 0.03E-07	2.19E-07
91.50	4.70E-07	1.27E-06 ± 0.01E-07	4.57E-07
91.75	8.70E-07	2.36E-06 ± 0.04E-07	8.50E-07
92.00	1.48E-06	3.99E-06 ± 0.03E-06	1.44E-06
92.50	3.62E-06	9.75E-06 ± 0.07E-06	3.51E-06
93.00	7.50E-06	2.02E-05 ± 0.01E-05	7.27E-06
93.50	1.39E-05	3.74E-05 ± 0.03E-05	1.35E-05
94.00	2.37E-05	6.41E-05 ± 0.01E-05	2.31E-05
95.00	5.77E-05	1.56E-04 ± 0.01E-04	5.62E-05
100.00	9.09E-04	2.48E-03 ± 0.02E-03	8.93E-04
110.00	0.01	3.78E-02 ± 0.05E-02	1.36E-02
120.00	0.06	1.71E-01 ± 0.03E-01	6.16E-02
130.00	0.17	0.46E00 ± 0.07E-01	1.66E-01
140.00	0.34	0.96E00 ± 0.02E00	3.46E-01
150.00	0.56	1.53E00 ± 0.01E00	0.55E00
160.00	0.78	2.12E00 ± 0.05E00	0.76E00
170.00	0.94	2.59E00 ± 0.06E00	0.93E00
175.00	0.98	2.68E00 ± 0.06E00	0.96E00
176.00	0.99	2.71E00 ± 0.03E00	0.98E00
177.00	0.99	2.72E00 ± 0.01E00	0.98E00
178.00	1.00	2.73E00 ± 0.05E-01	0.98E00
179.00	1.00	2.75E00 ± 0.01E00	0.99E00
180.00	1.00	2.77E00 ± 0.03E00	1.00E00
181.00	1.00	2.76E00 ± 0.01E00	0.99E00
182.00	1.00	2.75E00 ± 0.01E00	0.99E00
183.00	0.99	2.74E00 ± 0.03E00	0.99E00

θ	TRANSMITTANCE $\cos^4\theta$	EXPERIMENTAL VALUE	[illegible]
184.00	0.99	2.73E00 ± 1.[illegible]	[illegible]
185.00	0.98	2.73E00 ± 1.[illegible]	[illegible]
186.00	0.98	2.7[illegible]E00 ± 1.[illegible]	[illegible]
187.00	0.97	2.7[illegible]E00 ± 1.[illegible]	[illegible]
188.00	0.96	2.72E00 ± 1.[illegible]	[illegible]
189.00	0.95	2.[illegible]E00 ± 1.[illegible]	[illegible]
190.00	0.94	2.61E00 ± 1.[illegible]	[illegible]
200.00	0.78	2.1[illegible]E00 ± 1.[illegible]	[illegible]
210.00	0.56	1.[illegible]E00 ± 1.[illegible]	[illegible]
220.00	0.34	0.[illegible]E00 ± 1.[illegible]	[illegible]
230.00	0.17	0.[illegible]E00 ± 1.[illegible]	[illegible]
240.00	0.06	[illegible]	[illegible]
250.00	0.01	[illegible]	[illegible]
260.00	9.09E-04	[illegible]	[illegible]
265.00	5.77E-05	[illegible]	[illegible]
266.00	2.37E-05	[illegible]	[illegible]
266.50	1.39E-05	[illegible]	[illegible]
267.00	7.50E-06	[illegible]	[illegible]
267.50	3.62E-06	[illegible]	[illegible]
268.00	1.48E-06	[illegible]	[illegible]
268.25	8.70E-07	[illegible]	[illegible]
268.50	4.70E-07	[illegible]	[illegible]
268.75	2.26E-07	[illegible]	[illegible]
269.00	9.28E-08	[illegible]	[illegible]
269.10	6.09E-08	[illegible]	[illegible]
269.20	3.80E-08	[illegible]	[illegible]
269.25	2.94E-08	[illegible]	[illegible]

θ	TRANSMITTANCE COS² θ	EXPERIMENTAL VALUE	NORMALIZED EXPERIMENTAL VALUE
269.30	[illegible]	[illegible] ± [illegible]	[illegible]
269.40	[illegible]	[illegible] ± [illegible]	[illegible]
269.50	[illegible]	[illegible] ± [illegible]	[illegible]
269.60	[illegible]	[illegible] ± [illegible]	[illegible]
269.70	[illegible]	[illegible] ± [illegible]	[illegible]
269.75	[illegible]	[illegible] ± [illegible]	[illegible]
269.80	[illegible]	[illegible] ± [illegible]	[illegible]
269.90	[illegible]	[illegible] ± [illegible]	[illegible]
270.00	0	[illegible] ± [illegible]	[illegible]
270.10	[illegible]	[illegible] ± [illegible]	[illegible]
270.20	[illegible]	[illegible] ± [illegible]	[illegible]
270.25	[illegible]	[illegible] ± [illegible]	[illegible]
270.30	[illegible]	[illegible] ± [illegible]	[illegible]
270.40	[illegible]	[illegible] ± [illegible]	[illegible]
270.50	[illegible]	[illegible] ± [illegible]	[illegible]
270.60	[illegible]	[illegible] ± [illegible]	[illegible]
270.70	[illegible]	[illegible] ± [illegible]	[illegible]
270.75	[illegible]	[illegible] ± [illegible]	[illegible]
270.80	[illegible]	[illegible] ± [illegible]	[illegible]
270.90	[illegible]	[illegible] ± [illegible]	[illegible]
271.00	[illegible]	[illegible] ± [illegible]	[illegible]
271.25	[illegible]	[illegible] ± [illegible]	[illegible]
271.50	[illegible]	[illegible] ± [illegible]	[illegible]
271.75	[illegible]	[illegible] ± [illegible]	[illegible]
272.00	[illegible]	[illegible] ± [illegible]	[illegible]
272.50	[illegible]	[illegible] ± [illegible]	[illegible]
273.00	[illegible]	[illegible] ± [illegible]	[illegible]

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