A Laser Hydrophone

1977

Steven Kenneth Barnoske

*University of Central Florida*

---

Find similar works at: [https://stars.library.ucf.edu/rtd](https://stars.library.ucf.edu/rtd)

University of Central Florida Libraries [http://library.ucf.edu](http://library.ucf.edu)

Part of the Semiconductor and Optical Materials Commons

---

**STARS Citation**

[https://stars.library.ucf.edu/rtd/320](https://stars.library.ucf.edu/rtd/320)

This Masters Thesis (Open Access) is brought to you for free and open access by STARS. It has been accepted for inclusion in Retrospective Theses and Dissertations by an authorized administrator of STARS. For more information, please contact lee.dotson@ucf.edu.
A LASER HYDROPHONE

BY

STEVEN KENNETH BARNOSKE

B.S., Florida Technological University, 1973

RESEARCH REPORT

Submitted in partial fulfillment of the requirements for the degree of Master of Science:
Optical Communications in the Graduate Studies Program of the College of Engineering of Florida Technological University

Orlando, Florida
1977
This report proposes a novel technique for measuring of acoustic fields in water. A Laser Hydrophone is proposed taking advantage of the properties of Total Internal Reflection. A theoretical analysis of the idea is presented followed by a prediction of the operating characteristics of an actual system. Actual data were taken with the proposed system and it is compared to the predicted.
ACKNOWLEDGMENTS

I would like to thank the United States Navy Underwater Sound Laboratory for the loan of the transducer and hydrophone used in this experiment. Without these devices this report would not be possible.

I would also like to thank Dr. Ronald Phillips for his assistance and patience over the last two years. Without him I wouldn't have gotten through.

And lastly I would like to thank my wife without whose endurance I must surely fail.
<table>
<thead>
<tr>
<th>CONTENTS</th>
<th>page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ACKNOWLEDGMENTS</td>
<td>iii</td>
</tr>
<tr>
<td>INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>I. THEORY</td>
<td>3</td>
</tr>
<tr>
<td>II. EXPERIMENTAL ARRANGEMENT</td>
<td>21</td>
</tr>
<tr>
<td>III. PREDICTED RESULTS</td>
<td>30</td>
</tr>
<tr>
<td>IV. PRACTICAL CONSIDERATIONS</td>
<td>35</td>
</tr>
<tr>
<td>V. EXPERIMENTAL RESULTS</td>
<td>38</td>
</tr>
<tr>
<td>VI. DISCUSSION OF RESULTS</td>
<td>43</td>
</tr>
<tr>
<td>VII. CONCLUSIONS</td>
<td>47</td>
</tr>
<tr>
<td>APPENDIX A</td>
<td>49</td>
</tr>
<tr>
<td>APPENDIX B</td>
<td>53</td>
</tr>
<tr>
<td>APPENDIX C</td>
<td>66</td>
</tr>
<tr>
<td>LIST OF REFERENCES</td>
<td>72</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Theoretical Data for TM Sensitivity</td>
<td>54</td>
</tr>
<tr>
<td>2.</td>
<td>Theoretical Data for TE Sensitivity</td>
<td>55</td>
</tr>
<tr>
<td>3.</td>
<td>Theoretical Data for Misalignment - TE</td>
<td>56</td>
</tr>
<tr>
<td>4.</td>
<td>Theoretical Data for Misalignment - TM</td>
<td>57</td>
</tr>
<tr>
<td>5.</td>
<td>Theoretical Data for Comparison of TE and TM</td>
<td>58</td>
</tr>
<tr>
<td>6.</td>
<td>Theoretical Data for Acoustic Intensity vs. Change in Reflectivity at the Critical Angle</td>
<td>59</td>
</tr>
<tr>
<td>7.</td>
<td>Measured Acoustic Signal</td>
<td>60</td>
</tr>
<tr>
<td>8.</td>
<td>Predicted Change in Reflectivity</td>
<td>61</td>
</tr>
<tr>
<td>9.</td>
<td>Signal Processing</td>
<td>62</td>
</tr>
<tr>
<td>10.</td>
<td>Measured Optical Signal</td>
<td>63</td>
</tr>
<tr>
<td>11.</td>
<td>Experimental Changes in R</td>
<td>64</td>
</tr>
<tr>
<td>12.</td>
<td>Data for Measured Misalignments</td>
<td>65</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>--------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>1.</td>
<td>Total internal reflection</td>
<td>4</td>
</tr>
<tr>
<td>2.</td>
<td>Reflectivity near critical angle - TE</td>
<td>8</td>
</tr>
<tr>
<td>3.</td>
<td>Reflectivity near critical angle - TM</td>
<td>8</td>
</tr>
<tr>
<td>4.</td>
<td>TM sensitivity at the critical angle</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>as a function of change in $n_2$</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>TE sensitivity at the critical angle</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td>as a function of change in $n_2$</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Sensitivity to misalignment - TE</td>
<td>11</td>
</tr>
<tr>
<td>7.</td>
<td>Sensitivity to misalignment - TM</td>
<td>12</td>
</tr>
<tr>
<td>8.</td>
<td>Comparison of TE and TM misalignment sensitivity</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>at $N = 0.0003$</td>
<td></td>
</tr>
<tr>
<td>9.</td>
<td>Change in reflectivity vs. acoustic intensity TM</td>
<td>15</td>
</tr>
<tr>
<td>10.</td>
<td>Change in reflectivity vs. acoustic intensity TE</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>polarization</td>
<td></td>
</tr>
<tr>
<td>11.</td>
<td>Acoustic angle of incidence</td>
<td>18</td>
</tr>
<tr>
<td>12.</td>
<td>Phase angle vs. $N$</td>
<td>20</td>
</tr>
<tr>
<td>13.</td>
<td>Water tank</td>
<td>22</td>
</tr>
<tr>
<td>14.</td>
<td>Optics plate and cart</td>
<td>23</td>
</tr>
<tr>
<td>15.</td>
<td>Optics plate arrangement</td>
<td>25</td>
</tr>
<tr>
<td>16.</td>
<td>Prism - Entrance angle for TIR</td>
<td>27</td>
</tr>
<tr>
<td>17.</td>
<td>Detector preamp and signal processing</td>
<td>28</td>
</tr>
<tr>
<td>18.</td>
<td>Measure acoustic signal</td>
<td>31</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>19.</td>
<td>Predicted response</td>
<td>34</td>
</tr>
<tr>
<td>20.</td>
<td>Detected TE signal</td>
<td>39</td>
</tr>
<tr>
<td>21.</td>
<td>Detector calibration</td>
<td>40</td>
</tr>
<tr>
<td>22.</td>
<td>Experimental change in R.</td>
<td>42</td>
</tr>
<tr>
<td>23.</td>
<td>Predicted vs. measured response</td>
<td>44</td>
</tr>
<tr>
<td>24.</td>
<td>Experimental misalignment</td>
<td>46</td>
</tr>
<tr>
<td>25.</td>
<td>Angle of incidence vs. angle of refraction</td>
<td>51</td>
</tr>
</tbody>
</table>
INTRODUCTION

The measurement of sound pressure, or intensity, in water has been the subject of over thirty years of research. This research has resulted in the compilation of large amounts of data regarding calibration and design of devices to perform these measurements. One thing in common to virtually all of these devices is their dependence upon moving parts. This limits both the linearity of the frequency response, and the maximum useable frequency of these devices. In addition, these devices, which are commonly called hydrophones, require total immersion in the water where the sound field is present. This is necessary to equalize the pressure on both sides of the moving portion of the device. Pressure gradients between the interior and exterior of a submarine, for an example, are often far beyond the maximum tolerable by a normal hydrophone.

A means of measurements of sound fields in water, without moving parts, and able to handle the large constant pressure gradients sometimes encountered, would obviously have certain advantages over present techniques.

An optical method for measuring sound fields,
based on the properties of Total Internal Reflection (TIR), is the subject of this report.
I. THEORY

The basic idea behind the optical hydrophone is to take advantage of the dependence of reflectivity on index of refraction. The phenomenon of Total Internal Reflection is basic and quite well understood. (See Appendix A for discussion of TIR.) Figure 1 shows a curve relating the reflectivity to angle of incidence. The point at which the reflectivity becomes equal to one is known as the critical angle. The critical angle can be found by Snell's Law to be:

$$\theta_c = \sin^{-1} \frac{n_2}{n_1}$$

(where $n_1$ and $n_2$ are the indices of refraction of the first and second mediums respectively). From the above equation it can easily be seen that a change in either or both indices will affect the critical angle. By maintaining a constant angle of incidence, a change in the critical angle will then move the percent of reflectivity curve along the angle of incidence axis, causing a change in reflectivity. The same effect would be caused by a change in the angle of incidence.

It can also be seen in figure 1 that the curves are different for transverse electric and transverse
Figure 1. Total internal reflection
magnetic planes of polarization. The TM polarization is much more sensitive to the angle of incidence than the TE polarization when the angle of incidence is near the critical angle. The TM polarization is, however, also more sensitive to misalignment of an experimental arrangement. For this reason the TE polarization seems the best initially.

It has long been known that the compression and rarefaction waves caused by travelling sound energy in a medium cause a change in the index of refraction. This change in the index of refraction will translate into a change in the reflectivity as discussed previously. In fact it is possible to obtain a correlation directly from acoustic intensity \( I_{ac} \) to a change in reflectivity. Initially it is necessary to relate the acoustic intensity to the change in index of refraction.

Amnon Yari (1971) gives some simple equations relating the quantities of interest to the strain induced in the medium.

Equation 1  \( \Delta n = \frac{n^3Ps}{2} \)

where

\( n = \) index of refraction
\( s = \) strain
\( P = \) photoelastic constant
Equation 2  \[ s = \sqrt{\frac{2I_{ac}}{pV_s}} \]

where \( I_{ac} \) = acoustic intensity
\( p \) = mass density
\( V_s \) = velocity of sound

combining the equations

\[ \Delta n = \frac{n^3 p}{2} \sqrt{\frac{2I_{ac}}{pV_s}} \]

Substituting the following into the equation:
\( p = 1.0 \text{ mg/cm}^3 \) in water
\( V_s = 1.5 \text{ km/sec} \) in water
\( P = .31 \) in water
\( n = 1.33 \) in water

we simplify the equation to:

\[ \Delta n = 2.807 \times 10^{-7} \sqrt{I_{ac}} \]

With the knowledge of how \( I_{ac} \) relates to changes in the index of refraction, it becomes desirable to obtain some information on the magnitudes of these numbers as they relate to changes in the reflectivity. In order to obtain this information some computer models were designed. Appendix B contains some of the data generated by these models along with the data generated by analysis. The models calculated the reflectivity (R)
as a function of \( N = \frac{n_2}{n_1} \).

Separate programs were run for the TE and TM polarizations. Both programs assume the angle of incidence to be 59.099 degrees and let \( N \) vary from 0.856 to 0.858.

Figures 2 and 3 show the generated curves giving calculated reflectivity in the very near vicinity of the critical angle.

From these two curves another pair of curves can be generated. These relate the change in reflectivity to a change in the index of refraction of the second medium assuming that \( n_1 \) remains constant. Figures 4 and 5 illustrate the magnitude of change in \( n_2 \) necessary for a measurable change in the reflectivity. As can be seen from figures 4 and 5 a very small change in \( n_2 \) gives a relatively large change in \( r \).

The first pair of curves can also supply some information about the sensitivity to misalignment. A second angle of incidence can be chosen at a specified angular misalignment to obtain a different relationship between changes in \( n_2 \) and \( R \). A group of computer programs were run at varying angles of incidence. Partial results are contained in Appendix B and illustrated in figures 6 and 7. In addition a direct comparison of TE polarization and TM polarization is shown in figure 8. Figure 8 demonstrates that the TM polarization is more
Figure 2. Reflectivity near critical angle - TE

Figure 3. Reflectivity near critical angle - TM
Figure 4. TM sensitivity at the critical angle as a function of change in $n_2$
Figure 5. TE Sensitivity at the critical angle as a function of change in $n_2$
Figure 6. Sensitivity to misalignment - TE
Figure 7. Sensitivity to misalignment - TM
Figure 8. Comparison of TE and TM misalignment sensitivity at $\Delta N = .0003$
sensitive within angular misalignments of less than one degree and that the TE polarization becomes more sensitive beyond the one degree point. All three figures demonstrate the rapid decrease in sensitivity that occurs with misalignment.

The relationship of \( I_{ac} \) to changes in \( R \) can be obtained from figures 4 and 5. Direct application of the derived formula relating \( I_{ac} \) to changes in \( n_2 \) generated curves illustrating the effect on \( R \) caused by changes in \( I_{ac} \). Figures 9 and 10 display this information and thus represent the theoretical performance of the laser hydrophone.

In addition to this basic theory of operation some other interesting considerations deserve discussion.

The detection of amplitude variations in the sound pressure field have been fairly well covered. However, it is important to know something about the frequency characteristics. The changes in \( R \) are dependent on the amplitude of the acoustic wave as it strikes the surface of reflection. This change in the index of refraction must remain constant over the area of reflection in order to obtain predictable results. Since the beam diameter of the laser used to detect the variations in reflectivity is only a few millimeters, an acoustic frequency of hundreds of kilohertz would be necessary before the
Figure 9. Change in reflectivity vs. acoustic intensity TM polarization
Figure 10. Change in reflectivity vs. acoustic intensity TE polarization
acoustic wavelength would be small enough to be significant. And then only if the acoustic wave was at a non-normal angle of incidence would the gradient affect the amplitude response. Since the size of the beam determines the frequency at which response becomes unstable, it is possible to make a device that is independent of frequency up to any desired level simply by focusing the beam down to a small enough spot.

The measurement of the frequency of the acoustic wave is also important. Often times knowledge of the frequency is as important as knowledge of the amplitude. Since the acoustic wave is being detected on a flat surface the detected frequency would appear to depend upon both the incident frequency and the angle of incidence. As seen in figure 11 the relationship would be: detected frequency equals incident frequency multiplied by the cosine of the angle of incidence. In fact, however, that is not the case. Even though the surface of reflection is flat, the actual area of detection will appear to be a point so long as that area is small with respect to the acoustic wavelength. Thus the frequency detection will be linear subject to the same restraints as the amplitude detection.

Another interesting consideration is the possibility of measuring some parameter other than
velocity = $1.5 \times 10^3$ Km/sec

Normal component of velocity = $(1.5 \times 10^3$ Km/sec) (cosine of angle of incidence)

frequency = velocity/wavelength

normal frequency = frequency/cosine of angle

Figure 11. Acoustic angle of incidence
reflectivity. There are two other parameters that vary with the angle of incidence or with changes in $n_2$. One is polarization and the other phase angle.

A computer model of the change in phase angle with $N = n_2/n_1$ was created. Using the same limits as in the amplitude programs, i.e., $N$ varying from .856 to .858 and centering on 59.099 degrees, data were generated. A graph of the results is shown in figure 12. Although these changes could be measured by means of an interferometer it is more difficult to obtain quantitative results. For this reason the analysis of changes in phase was not carried out in detail as was the analysis in changes in $R$.

Changes in the polarization also occur with changes in $n_2$. Measurements of this type may easily introduce undetermined error, however, due to the phase changes mentioned above. A phase retardation will tend to rotate the polarization and introduce signal from another source into the measurements. For this reason the simple change in reflectivity technique was chosen over the polarization method.
Figure 12. Phase angle vs. $N = n_2/n_1$
II. EXPERIMENTAL ARRANGEMENT

In order to verify the basic theory as outlined previously, an experiment was designed. The basic layout is shown in figures 13, 14, and 15. The following discussion addresses itself to those figures. (Appendix C contains actual photographs of the equipment to be described.)

The upper enclosed portion of figure 13 represents the water tank. The tank is approximately 50 inches long by 30 inches wide by 22 inches deep. Mounted to the steel frame of the tank and shown in the lower portion of figure 13 is the optics plate. The optics plate measures approximately 30 inches wide by 18 inches long. All of the optical equipment used in the experiment is mounted to the plate. This was done to insure stability of the laser beam with respect to the detector surface.

Figure 14 is a side view of the water tank. At one end of the water tank, mounted inside, is a sound transducer. This was the source of a known frequency sound pressure field for the experiment. Opposite the sound transducer, mounted through the plexiglass wall of the tank, is the prism. The prism was used to generate a Total Internal Reflection condition with the laser beam at the glass to water interface.
Figure 13. Water tank
Figure 14. Optics plate and cart.
Figure 15 represents the optics plate. Included is the end of the tank to show the relative positions of the optical components to the prism.

The actual experimental arrangement can be divided into three basic segments. The acoustic, optical, and electronic portions of the system have been separated to simplify discussion.

The acoustic portion of the test equipment consists of a J-9 transducer from the United States Navy Underwater Sound Laboratories. This is mounted inside and at one end of the water tank. The transducer requires approximately 20 watts of electrical drive signal in order to achieve maximum output. The drive was achieved by the use of a Krohn-Hite 50 watt power amplifier following a Wave-Tech signal generator. By monitoring the signal with a digital frequency meter it was possible to generate acoustic waves of known frequency and with sufficient acoustic intensity.

The actual acoustic intensity was measured by use of an F-50 hydrophone also on loan from the Navy. This information was used to compare the measured optical signal to the acoustic intensity causing it.

The optical equipment, shown in toto in figure 15, consists of a laser and beam steering and modifying optics. A 1.3 milliwatt helium neon laser is used as the beam source. The beam is taken through a polarizing beam
Figure 15. Optics plate arrangement
splitter which is aligned along the same optical axis as the prism. This makes available the transverse electric polarization with respect to the water to glass interface. The TE polarized beam is then reflected off a high resolution adjustable mirror. This mirror reflects the beam into the prism and allows fine adjustments in the angle of incidence. Figure 16 depicts the beam entering and leaving the prism for operation at the critical angle. The angles given in figure 16 come from direct application of the law of refraction to the materials used in this experiment. Following reflection from the interface the beam is directly incident upon the surface of a P-I-N photodiode. The diode is used to detect the variations in intensity caused by the changes in reflectivity.

The electronic portion of the experiment is concerned with detecting and measuring the output of this photodiode. The output of the photodiode is amplified initially inside the detector module. The photodiode circuit and the following signal processing are shown in figure 17. The output of the detector module is bandpass filtered with a Krohn-Hite variable bandpass filter then amplified by a factor of approximately 100 before final high pass filtering and detection with a wave analyzer.

The transfer function of the detector and pre-amplifier has been measured at a specific chopped frequency.
Figure 16. Prism - Entrance angle for TIR

Oc = 61.45°

n water = 1.33
n prism = 1.514
n air = 1.00

Plexiglass

80.19°
2.36"
28.55°
3.34"
80.19°
Figure 17. Detector preamp and signal processing
By combining this with the calculated frequency response of the pre-amplifier and assuming linearity of the photodiode frequency response in the one to fifteen kilohertz region, a detector module transfer function has been generated. The transfer function for the remainder of the signal processing was determined experimentally by comparison of the measured hydrophone signal both with and without signal processing at each measurement frequency.
III. PREDICTED RESULTS

Using the theory developed in the earliest portion of this paper, it is possible to predict the results of this experiment.

First it is necessary to determine the acoustic intensity inside the tank. When measurements were made using the F-50 hydrophone, it was noted that high amplitude standing wave patterns were present. In order to minimize the effects of this condition an anechoic material was placed along the sides and top of the tank. (A photograph of the material used is included in Appendix C.) This did in fact reduce the standing wave amplitudes but did not eliminate them. Since a complete redesign of the water tank was not feasible, the most that could be done was to make the acoustic measurements as close as possible to the actual point of water to glass interface. At varying frequencies the acoustic intensity at this one point changes at least an order of magnitude due to the changing standing wave patterns. To insure as much reliability as possible, the hydrophone and optical measurement were then taken at the same time at exactly the same frequency.

The recorded hydrophone measurements are shown in Figure 18. These readings can be converted into acoustic
Figure 18. Measure acoustic signal
intensities by use of the hydrophone calibration.

According to NRL Report 7735 (1974), the free field sensitivity of the F-50 hydrophone is:

-205 dB referred to 1 Volt/micropascal

in the frequency range from zero to fifteen kilohertz. From this we can calculate:

\[
20 \log (V/\text{micropascal}) = -205
\]

\[
\log (V/\text{micropascal}) = -10.25
\]

\[
\frac{V}{\text{micropascal}} = 10^{-10.25}
\]

\[
\frac{\text{micropascal}}{\text{micropascal}} = \frac{V}{10^{-10.25}}
\]

\[
\frac{\text{micropascal}}{\text{Pascal}} = (V)(1.7783 \times 10^{10})
\]

In order to get from Pascals to acoustic intensity, which is measured in Watts/square meter, it is necessary to multiply by the velocity of sound in water. Thus

\[
I_{ac} = (V)(1.7783 \times 10^{4})(1.5 \times 10^{3})
\]

or

\[
I_{ac} = (V)(2.6675 \times 10^{7})
\]

The \(I_{ac}\) values corresponding to the hydrophone measurements are shown in figure 18. The actual data are included in Appendix B.

From \(I_{ac}\) direct application of the formula developed in the theory gives the change in index of refraction. These changes in index are then related by use of the computer models to determine the predicted changes in
reflectivity.

In order to finally compare the predicted results to the actual measured results, a graph of $I_{ac}$ and calculated changes in reflectivity is drawn in figure 19.
Figure 19. Predicted response
IV. PRACTICAL CONSIDERATIONS AND DISCUSSION OF PROCEDURE

The actual laboratory procedures were dictated by the limitations of the physical arrangement. The first step in each measurement was to set up the acoustic signal at a constant intensity and known frequency. Due to the extreme sensitivity of the measurements, the frequency had to remain constant for the hydrophone and optical measurement pair. This was due to the presence of frequency dependent standing wave patterns. The technique used was to make three measurements at one time. Two measurements were made with the hydrophone, one with the signal processing and one without. A third measurement was made using the optical system. The first two measurements gave both the acoustic intensity and the gain of the signal processing at the frequency of the measurements. The technique was felt to give the best chance of comparability between the hydrophone and optical signal measurements.

It was determined experimentally that if the frequency was changed and then brought back as close as possible to the original, that the results of any one measurement could not be repeated. However, the relationship between the acoustic and optical signal did seem to be
repeateable. Measurements at various points in the tank showed that the standing wave pattern was shifted even though the frequency was within five hertz of the original. (That is to say, for example, 10,000 Hz instead of 9,995 Hz.)

Noise problems were also encountered with the primary contribution being radiation at sixty hertz. A problem was also encountered with the steel structure of the water tank radiating at the acoustic drive frequency. Both problems were minimized by improved grounding and use of the extensive filters in the signal processing. In addition, the wave analyzer makes measurements only in a very tight crystal filtered bandwidth around the set frequency.

Vibration of the tank walls caused some noise problems which were unaffected by electronic filtering. This condition forced the use of the 3 Kilohertz to fifteen Kilohertz band for measurements. Higher frequency vibrations having much smaller amplitudes than the low frequency vibrations. An even higher frequency would have been used if not for the bandwidth limitations of the electrical drive amplifier and the J-9 transducer. The wall vibrations were still present, however, in the frequency band used. A first surface reflection test made to prove that the signals measured were not due to vibration showed that in fact some of the signal was due to this source. A
modification of the optical arrangement was necessary to eliminate the contribution from this source. The signal contribution due to the vibrations was being caused by movement of the laser beam with respect to the detector face. By expanding the laser beam slightly, it was possible to minimize any signal pickup due to this motion. In fact, after this was done it was impossible to pick up any distinguishable signal due to this source.
V. EXPERIMENTAL RESULTS

Actual measurements made using the TE polarization are tabulated in Appendix B. In order to compare these to the predicted results, it is necessary to first divide out the gain of the signal processing and then compare the data to the detector-pre-amplifier calibration. The measurements taken with the hydrophone both with and without the signal processing are in Appendix B along with the calculated gain of the signal processing. By using these gains the actual detector module outputs have been calculated and these are shown in figure 20.

The detector module calibration is a combination of measured and calculated quantities. Figure 21 shows the measured amplitude response of the detector module in the amplitude region of the experimental results. The calculated frequency response is also in figure 21. Since the frequency response of the pre-amplifier is virtually flat for the region of the tests, the amplitude response can be used to convert directly from voltage to optical intensity. These optical powers divided by the unmodulated beam power at the detector will then give the percent amplitude change measured, which can be directly compared to the anticipated changes in reflectivity.
Figure 20. Detected TE signal
Figure 21. Detector Calibration
Figure 22 displays the change in reflectivity that would produce the measured results.

Experimental tests were also made at various optical misalignments. Steps of one-third of a degree were used since no detectable signal could be found beyond the two-thirds of a degree point. Graphs of these data are included with the discussion of results.
Figure 22. Experimental change in $R$
VI. DISCUSSION OF RESULTS

Figure 23 shows the predicted and measured response. The measured response is orders of magnitude down from the predicted response. In fact, the two curves do not even always follow each other in their excursions.

When the measurements were being taken, it was noted that the standing wave patterns had very large intensity gradients near the walls. Thus even though the hydrophone was directly in front of the prism and as close as physically possible, it was impossible to insure that the field intensity seen by the hydrophone and the prism were in fact the same. The difference in some places in the shape of the predicted and measured curves can probably be attributed to this condition.

The extreme difference in amplitude between the predicted and measured result could be due to a number of factors. It is not unlikely that the technique used to calibrate the detector module was suspect. The technique of chopping the known signal and then measuring the amplitude of the output square wave is adequate for most conditions. The actual experimental situation, however, had the detector exposed to a large constant level of light while measuring a much smaller sinusoidal signal. This could
Figure 23. Predicted vs. measured response
have driven either the detector of the pre-amplifier into saturation.

It is also possible that even with the careful adjustments made, the optical alignment was in error. This could make a large change in sensitivity, as much as an order of magnitude or more. The theoretical discussion of misalignment shows the extreme sensitivity to this condition. Also the curves in figure 24 show measured misalignments from what was thought to be the critical angle. These curves along with the experimental data contained in Appendix B are indicative of the variations in sensitivity that could occur.

Either or both of these conditions could contribute to the extremely small signals measured. It is also possible that the standing wave patterns had a null along the walls of the tank that was impossible to detect with the hydrophone because of its size.
Figure 24. Experimental misalignment
VII. CONCLUSIONS

It is the opinion of this author that even though the experimental results did not quantitatively verify the theory, the very existence of experimental data is verification for the principle. It is further thought that an extension of this research on the basis of these results is called for.

A number of improvements and/or changes have been suggested by the results of this research.

Experiments involving the simple amplitude variations used in this research could be undertaken. The information accumulated in this report along with the assistance of professionals in the acoustics field should allow the design of an experiment free from the standing wave conditions which plagued this research.

In addition, other techniques of measurement are possible. By the use of two polarizers, both aligned in the same plane, any rotation of polarization should show up as an increase in the light passing through the second polarizer. This technique has the advantage of eliminating the high level of constant illumination encountered in this research.

It has also occurred to this author that possibly at
very high frequencies, in the megahertz range, a frustrated total reflection system might work. The phenomenon of frustrated total reflection is beyond the scope of this paper, but in short it takes advantage of the existence of the electromagnetic field of the reflected light in the less dense medium even though no light intensity is transmitted into the medium. A system based on this principle would not be as sensitive to the angle of incidence as the critical angle system used in this research.

The principles of total internal reflection may possibly be applied to the problem of measuring sound pressure in ways that have not occurred to this author. The multitude of possible applications and lack of research into this area demand an extension of these ideas.
APPENDIX A

TOTAL INTERNAL REFLECTION

When a ray of light in an optically dense medium is incident on a surface which is the interface with a less dense medium we see two effects. First is a reflection of a percentage of the light back into the medium at an angle given by Snell's Law. This states that the angle of incidence is equal to the angle of reflection, or

\[ \theta_i = \theta_r. \]

Second is a refraction of the remaining light (that which is not reflected) into the less dense medium. This occurs at an angle given by the law of refraction. The law of refraction relates the refracted angle to the incidence angle as a function of the two indices of refraction.

\[ n_1 \sin \theta_1 = n_2 \sin \theta_2 \]

As the angle of incidence increases the angle of refraction also increases approaching ninety degrees (see figure 25). When the angle of refraction reaches ninety degrees and for all angles beyond that we have what is called total internal reflection. So called because the refracted intensity in the less dense medium is zero while the reflected intensity is equal to the incident intensity. The angle of incidence at which the angle of refraction equals exactly
Figure 25. Angle of incidence vs. angle of refraction
ninety degrees is called the critical angle. The critical angle can be found from the Law of Refraction. By substituting ninety degrees for \( \theta_2 \) we get

\[
\begin{align*}
\eta_1 \sin \theta_1 &= \eta_2 \\
\sin \theta_1 &= \frac{\eta_2}{\eta_1}
\end{align*}
\]

and

\[
\theta_1 = \sin^{-1} \frac{\eta_2}{\eta_1}
\]

since

\[
\theta_1 = \theta_c
\]

then

\[
\theta_c = \sin^{-1} \frac{\eta_2}{\eta_1}
\]
<table>
<thead>
<tr>
<th>$\Delta N$</th>
<th>$\Delta R$</th>
<th>$\Delta n_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00000805</td>
<td>0.010593</td>
<td>0.00000532</td>
</tr>
<tr>
<td>0.00002105</td>
<td>0.047499</td>
<td>0.00001390</td>
</tr>
<tr>
<td>0.00003405</td>
<td>0.067317</td>
<td>0.00002249</td>
</tr>
<tr>
<td>0.00007205</td>
<td>0.104963</td>
<td>0.00004759</td>
</tr>
<tr>
<td>0.00011105</td>
<td>0.131133</td>
<td>0.00007335</td>
</tr>
<tr>
<td>0.00015005</td>
<td>0.152049</td>
<td>0.00009911</td>
</tr>
<tr>
<td>0.00018905</td>
<td>0.169858</td>
<td>0.00012487</td>
</tr>
<tr>
<td>0.00022705</td>
<td>0.185520</td>
<td>0.00014997</td>
</tr>
<tr>
<td>0.00026605</td>
<td>0.199604</td>
<td>0.00017573</td>
</tr>
<tr>
<td>0.00030505</td>
<td>0.212436</td>
<td>0.00020149</td>
</tr>
</tbody>
</table>
TABLE 2
THEORETICAL DATA FOR TE SENSITIVITY

<table>
<thead>
<tr>
<th>$\Delta N$</th>
<th>$\Delta R$</th>
<th>$\Delta n_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>.00000805</td>
<td>.007810</td>
<td>.00000532</td>
</tr>
<tr>
<td>.00002105</td>
<td>.035196</td>
<td>.00001390</td>
</tr>
<tr>
<td>.00003405</td>
<td>.050017</td>
<td>.00002249</td>
</tr>
<tr>
<td>.00007205</td>
<td>.078404</td>
<td>.00004759</td>
</tr>
<tr>
<td>.00011105</td>
<td>.098324</td>
<td>.00007335</td>
</tr>
<tr>
<td>.00015005</td>
<td>.114359</td>
<td>.00009911</td>
</tr>
<tr>
<td>.00018905</td>
<td>.128096</td>
<td>.00012487</td>
</tr>
<tr>
<td>.00022705</td>
<td>.140242</td>
<td>.00014997</td>
</tr>
<tr>
<td>.00026605</td>
<td>.151217</td>
<td>.0017573</td>
</tr>
<tr>
<td>.00030505</td>
<td>.161262</td>
<td>.00020149</td>
</tr>
</tbody>
</table>
TABLE 3
THEORETICAL DATA FOR MISALIGNMENT - TE

<table>
<thead>
<tr>
<th>$\Delta N$</th>
<th>$\Delta R$</th>
<th>$\Delta n_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001</td>
<td>0.0022</td>
<td>0.000066</td>
</tr>
<tr>
<td>0.0002</td>
<td>0.0043</td>
<td>0.00013</td>
</tr>
<tr>
<td>0.0003</td>
<td>0.0065</td>
<td>0.00020</td>
</tr>
<tr>
<td>0.0004</td>
<td>0.0088</td>
<td>0.00026</td>
</tr>
</tbody>
</table>

$\Delta N$ | $\Delta R$ | $\Delta n_2$ |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001</td>
<td>0.0011</td>
<td>0.000066</td>
</tr>
<tr>
<td>0.0002</td>
<td>0.0021</td>
<td>0.00013</td>
</tr>
<tr>
<td>0.0003</td>
<td>0.0031</td>
<td>0.00020</td>
</tr>
<tr>
<td>0.0004</td>
<td>0.0042</td>
<td>0.00026</td>
</tr>
</tbody>
</table>

$\Delta N$ | $\Delta R$ | $\Delta n_2$ |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001</td>
<td>0.0006</td>
<td>0.000066</td>
</tr>
<tr>
<td>0.0002</td>
<td>0.0012</td>
<td>0.00013</td>
</tr>
<tr>
<td>0.0003</td>
<td>0.0018</td>
<td>0.00020</td>
</tr>
<tr>
<td>0.0004</td>
<td>0.0024</td>
<td>0.00026</td>
</tr>
<tr>
<td>$\Delta N$</td>
<td>$\Delta R$</td>
<td>$\Delta n_2$</td>
</tr>
<tr>
<td>-----------</td>
<td>-----------</td>
<td>------------</td>
</tr>
<tr>
<td>0.0001</td>
<td>0.0023</td>
<td>0.000066</td>
</tr>
<tr>
<td>0.0002</td>
<td>0.0044</td>
<td>0.00013</td>
</tr>
<tr>
<td>0.0003</td>
<td>0.0066</td>
<td>0.00020</td>
</tr>
<tr>
<td>0.0004</td>
<td>0.0090</td>
<td>0.00026</td>
</tr>
</tbody>
</table>

$58^\circ$

<table>
<thead>
<tr>
<th>$\Delta N$</th>
<th>$\Delta R$</th>
<th>$\Delta n_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001</td>
<td>0.0010</td>
<td>0.000066</td>
</tr>
<tr>
<td>0.0002</td>
<td>0.0019</td>
<td>0.00013</td>
</tr>
<tr>
<td>0.0003</td>
<td>0.0028</td>
<td>0.00020</td>
</tr>
<tr>
<td>0.0004</td>
<td>0.0038</td>
<td>0.00026</td>
</tr>
</tbody>
</table>

$57^\circ$

<table>
<thead>
<tr>
<th>$\Delta N$</th>
<th>$\Delta R$</th>
<th>$\Delta n_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0001</td>
<td>0.0005</td>
<td>0.000066</td>
</tr>
<tr>
<td>0.0002</td>
<td>0.0010</td>
<td>0.00013</td>
</tr>
<tr>
<td>0.0003</td>
<td>0.0014</td>
<td>0.00020</td>
</tr>
<tr>
<td>0.0004</td>
<td>0.0019</td>
<td>0.00026</td>
</tr>
</tbody>
</table>

$56^\circ$
TABLE 5
THEORETICAL DATA FOR COMPARISON OF TE AND TM

<table>
<thead>
<tr>
<th>Misalignment</th>
<th>TE - ΔR/ΔN</th>
<th>TM - ΔR/ΔN</th>
</tr>
</thead>
<tbody>
<tr>
<td>1°</td>
<td>21.6</td>
<td>22.0</td>
</tr>
<tr>
<td>2°</td>
<td>10.3</td>
<td>9.3</td>
</tr>
<tr>
<td>3°</td>
<td>6.0</td>
<td>4.6</td>
</tr>
</tbody>
</table>

Misalignment sensitivity at ΔN = .0003
<table>
<thead>
<tr>
<th>( I_{ac} ) (watts/m²)</th>
<th>( \Delta R )</th>
<th>( I_{ac} ) (watts/m²)</th>
<th>( \Delta R )</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.5921 ( \times 10^2 )</td>
<td>.010593</td>
<td>3.5921 ( \times 10^2 )</td>
<td>.007810</td>
</tr>
<tr>
<td>2.4523 ( \times 10^3 )</td>
<td>.047499</td>
<td>2.4523 ( \times 10^3 )</td>
<td>.035196</td>
</tr>
<tr>
<td>6.4196 ( \times 10^3 )</td>
<td>.067317</td>
<td>6.4196 ( \times 10^3 )</td>
<td>.050017</td>
</tr>
<tr>
<td>2.8745 ( \times 10^4 )</td>
<td>.104963</td>
<td>2.8745 ( \times 10^4 )</td>
<td>.078404</td>
</tr>
<tr>
<td>6.8286 ( \times 10^4 )</td>
<td>.131133</td>
<td>6.8286 ( \times 10^4 )</td>
<td>.098324</td>
</tr>
<tr>
<td>1.2467 ( \times 10^5 )</td>
<td>.152049</td>
<td>1.2467 ( \times 10^5 )</td>
<td>.114359</td>
</tr>
<tr>
<td>1.9790 ( \times 10^5 )</td>
<td>.169858</td>
<td>1.9790 ( \times 10^5 )</td>
<td>.128096</td>
</tr>
<tr>
<td>2.8546 ( \times 10^5 )</td>
<td>.185520</td>
<td>2.8546 ( \times 10^5 )</td>
<td>.140242</td>
</tr>
<tr>
<td>3.9194 ( \times 10^5 )</td>
<td>.199604</td>
<td>3.9194 ( \times 10^5 )</td>
<td>.151217</td>
</tr>
<tr>
<td>5.1527 ( \times 10^5 )</td>
<td>.212436</td>
<td>5.1527 ( \times 10^5 )</td>
<td>.161262</td>
</tr>
</tbody>
</table>
### TABLE 7

**MEASURED ACOUSTIC SIGNAL**

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Signal</th>
<th>$I_{ac}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 Kc</td>
<td>42 mV</td>
<td>$1.1 \times 10^6$</td>
</tr>
<tr>
<td>14 Kc</td>
<td>6.6 mV</td>
<td>$1.8 \times 10^5$</td>
</tr>
<tr>
<td>13 Kc</td>
<td>25 mV</td>
<td>$6.7 \times 10^5$</td>
</tr>
<tr>
<td>12 Kc</td>
<td>12.5 mV</td>
<td>$3.3 \times 10^5$</td>
</tr>
<tr>
<td>11 Kc</td>
<td>19 mV</td>
<td>$5.1 \times 10^5$</td>
</tr>
<tr>
<td>10 Kc</td>
<td>8.3 mV</td>
<td>$2.2 \times 10^5$</td>
</tr>
<tr>
<td>9 Kc</td>
<td>7.2 mV</td>
<td>$1.9 \times 10^5$</td>
</tr>
<tr>
<td>8 Kc</td>
<td>16 mV</td>
<td>$4.3 \times 10^5$</td>
</tr>
<tr>
<td>7 Kc</td>
<td>14 mV</td>
<td>$3.7 \times 10^5$</td>
</tr>
<tr>
<td>6 Kc</td>
<td>15 mV</td>
<td>$4.0 \times 10^5$</td>
</tr>
<tr>
<td>5 Kc</td>
<td>12.5 mV</td>
<td>$3.3 \times 10^5$</td>
</tr>
<tr>
<td>4 Kc</td>
<td>5 mV</td>
<td>$1.3 \times 10^5$</td>
</tr>
<tr>
<td>3 Kc</td>
<td>1.8 mV</td>
<td>$4.8 \times 10^4$</td>
</tr>
<tr>
<td>Frequency</td>
<td>$I_{ac}$ (watts/m²)</td>
<td>$\Delta n_2$</td>
</tr>
<tr>
<td>-----------</td>
<td>--------------------</td>
<td>--------------</td>
</tr>
<tr>
<td>15 Kc</td>
<td>$1.1204 \times 10^6$</td>
<td>$2.9713 \times 10^{-4}$</td>
</tr>
<tr>
<td>14 Kc</td>
<td>$1.7607 \times 10^5$</td>
<td>$1.1779 \times 10^{-4}$</td>
</tr>
<tr>
<td>13 Kc</td>
<td>$6.6688 \times 10^5$</td>
<td>$2.2924 \times 10^{-4}$</td>
</tr>
<tr>
<td>12 Kc</td>
<td>$3.3344 \times 10^5$</td>
<td>$1.621 \times 10^{-4}$</td>
</tr>
<tr>
<td>11 Kc</td>
<td>$5.0683 \times 10^5$</td>
<td>$1.9985 \times 10^{-4}$</td>
</tr>
<tr>
<td>10 Kc</td>
<td>$2.214 \times 10^5$</td>
<td>$1.3208 \times 10^{-4}$</td>
</tr>
<tr>
<td>9 Kc</td>
<td>$1.9206 \times 10^5$</td>
<td>$1.2302 \times 10^{-4}$</td>
</tr>
<tr>
<td>8 Kc</td>
<td>$4.2680 \times 10^5$</td>
<td>$1.8339 \times 10^{-4}$</td>
</tr>
<tr>
<td>7 Kc</td>
<td>$3.7345 \times 10^5$</td>
<td>$1.7155 \times 10^{-4}$</td>
</tr>
<tr>
<td>6 Kc</td>
<td>$4.0013 \times 10^5$</td>
<td>$1.7757 \times 10^{-4}$</td>
</tr>
<tr>
<td>5 Kc</td>
<td>$3.3344 \times 10^5$</td>
<td>$1.621 \times 10^{-4}$</td>
</tr>
<tr>
<td>4 Kc</td>
<td>$1.3338 \times 10^5$</td>
<td>$1.0252 \times 10^{-4}$</td>
</tr>
<tr>
<td>3 Kc</td>
<td>$4.8015 \times 10^4$</td>
<td>$6.1511 \times 10^{-5}$</td>
</tr>
<tr>
<td>Frequency</td>
<td>With Processing</td>
<td>Without Processing</td>
</tr>
<tr>
<td>-----------</td>
<td>----------------</td>
<td>--------------------</td>
</tr>
<tr>
<td>15 Kc</td>
<td>3.2 V</td>
<td>42 mV</td>
</tr>
<tr>
<td>14 Kc</td>
<td>560 mV</td>
<td>6.6 mV</td>
</tr>
<tr>
<td>13 Kc</td>
<td>2.3 V</td>
<td>25 mV</td>
</tr>
<tr>
<td>12 Kc</td>
<td>1.2 V</td>
<td>12.5 mV</td>
</tr>
<tr>
<td>11 Kc</td>
<td>1.9 V</td>
<td>19 mV</td>
</tr>
<tr>
<td>10 Kc</td>
<td>830 mV</td>
<td>8.3 mV</td>
</tr>
<tr>
<td>9 Kc</td>
<td>760 mV</td>
<td>7.2 mV</td>
</tr>
<tr>
<td>8 Kc</td>
<td>1.7 V</td>
<td>16 mV</td>
</tr>
<tr>
<td>7 Kc</td>
<td>1.5 V</td>
<td>14 mV</td>
</tr>
<tr>
<td>6 Kc</td>
<td>1.6 V</td>
<td>15 mV</td>
</tr>
<tr>
<td>5 Kc</td>
<td>1.25 V</td>
<td>12.5 mV</td>
</tr>
<tr>
<td>4 Kc</td>
<td>500 V</td>
<td>5 mV</td>
</tr>
<tr>
<td>3 Kc</td>
<td>170 mV</td>
<td>1.8 mV</td>
</tr>
<tr>
<td>Frequency</td>
<td>Detected Signal</td>
<td>Actual Detector Module Signal</td>
</tr>
<tr>
<td>-----------</td>
<td>----------------</td>
<td>-----------------------------</td>
</tr>
<tr>
<td>15 KHz</td>
<td>90 mV</td>
<td>1.1812 mV</td>
</tr>
<tr>
<td>14 KHz</td>
<td>28 mV</td>
<td>0.330 mV</td>
</tr>
<tr>
<td>13 KHz</td>
<td>75 mV</td>
<td>0.8152 mV</td>
</tr>
<tr>
<td>12 KHz</td>
<td>40 mV</td>
<td>0.4166 mV</td>
</tr>
<tr>
<td>11 KHz</td>
<td>120 mV</td>
<td>1.2 mV</td>
</tr>
<tr>
<td>10 KHz</td>
<td>72 mV</td>
<td>0.72 mV</td>
</tr>
<tr>
<td>9 KHz</td>
<td>55 mV</td>
<td>0.5210 mV</td>
</tr>
<tr>
<td>8 KHz</td>
<td>115 mV</td>
<td>1.0823 mV</td>
</tr>
<tr>
<td>7 KHz</td>
<td>100 mV</td>
<td>0.9333 mV</td>
</tr>
<tr>
<td>6 KHz</td>
<td>220 mV</td>
<td>2.0626 mV</td>
</tr>
<tr>
<td>5 KHz</td>
<td>80 mV</td>
<td>0.8 mV</td>
</tr>
<tr>
<td>4 KHz</td>
<td>80 mV</td>
<td>0.8 mV</td>
</tr>
<tr>
<td>3 KHz</td>
<td>110 mV</td>
<td>1.1647 mV</td>
</tr>
</tbody>
</table>
TABLE 11
EXPERIMENTAL CHANGES IN R

<table>
<thead>
<tr>
<th>Frequency</th>
<th>Signal</th>
<th>Optical Intensity</th>
<th>$\Delta R$</th>
</tr>
</thead>
<tbody>
<tr>
<td>15 Kc</td>
<td>1.1812 mV</td>
<td>.02386 mV</td>
<td>.003 %</td>
</tr>
<tr>
<td>14 Kc</td>
<td>.330 mV</td>
<td>.00666 mV</td>
<td>.001 %</td>
</tr>
<tr>
<td>13 Kc</td>
<td>.8152 mV</td>
<td>.01647 mV</td>
<td>.0025 %</td>
</tr>
<tr>
<td>12 Kc</td>
<td>.4166 mV</td>
<td>.008415 mV</td>
<td>.0013 %</td>
</tr>
<tr>
<td>11 Kc</td>
<td>1.2 mV</td>
<td>.02424 mV</td>
<td>.0037 %</td>
</tr>
<tr>
<td>10 Kc</td>
<td>.72 mV</td>
<td>.01454 mV</td>
<td>.00237 %</td>
</tr>
<tr>
<td>9 Kc</td>
<td>.5210 mV</td>
<td>.01052 mV</td>
<td>.00162 %</td>
</tr>
<tr>
<td>8 Kc</td>
<td>1.0823 mV</td>
<td>.0218 mV</td>
<td>.00354 %</td>
</tr>
<tr>
<td>7 Kc</td>
<td>.9333 mV</td>
<td>.01885 mV</td>
<td>.0029 %</td>
</tr>
<tr>
<td>6 Kc</td>
<td>2.0626 mV</td>
<td>.04166 mV</td>
<td>.0064 %</td>
</tr>
<tr>
<td>5 Kc</td>
<td>.8 mV</td>
<td>.01616 mV</td>
<td>.00248 %</td>
</tr>
<tr>
<td>4 Kc</td>
<td>.8 mV</td>
<td>.01616 mV</td>
<td>.00248 %</td>
</tr>
<tr>
<td>3 Kc</td>
<td>1.1647 mV</td>
<td>.023527 mV</td>
<td>.00362 %</td>
</tr>
</tbody>
</table>
TABLE 12
DATA FOR MEASURED MISALIGNMENTS

<table>
<thead>
<tr>
<th>Frequency</th>
<th>$1/3^\circ$</th>
<th>$2/3^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>52 mV</td>
<td>11 mV</td>
</tr>
<tr>
<td>14</td>
<td>19 mV</td>
<td>4 mV</td>
</tr>
<tr>
<td>13</td>
<td>39 mV</td>
<td>8 mV</td>
</tr>
<tr>
<td>12</td>
<td>14 mV</td>
<td>Noise</td>
</tr>
<tr>
<td>11</td>
<td>39 mV</td>
<td>11 mV</td>
</tr>
<tr>
<td>10</td>
<td>21 mV</td>
<td>9 mV</td>
</tr>
<tr>
<td>9</td>
<td>11 mV</td>
<td>Noise</td>
</tr>
<tr>
<td>8</td>
<td>27 mV</td>
<td>9 mV</td>
</tr>
<tr>
<td>7</td>
<td>25 mV</td>
<td>9 mV</td>
</tr>
<tr>
<td>6</td>
<td>50 mV</td>
<td>12 mV</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Noise</td>
<td>Noise</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX C

DETECTOR CALIBRATION

Amplitude Response

<table>
<thead>
<tr>
<th>Optical Intensity</th>
<th>Voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 microwatts</td>
<td>.24 V</td>
</tr>
<tr>
<td>9 microwatts</td>
<td>.38 V</td>
</tr>
<tr>
<td>14 microwatts</td>
<td>.50 V</td>
</tr>
<tr>
<td>24 microwatts</td>
<td>1.08 V</td>
</tr>
</tbody>
</table>

Frequency Response

\[
\text{Gain} = \frac{1}{5.1 \times 10^{-12} S} \quad \text{Gain} = \frac{5.1 N}{1+.612 S} \quad \text{Gain} = \frac{2.397 S}{1+.0612 S}
\]
Complete Test Lay out

Water Tank
Optical Plate

Signal Processing Equipment
Anachoic Material on Surface of Water in Tank
J-9 Transducer - mounted
LIST OF REFERENCES
