An Electro-Acoustic Oil Layer Thickness Gauge

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AN ELECTRO-ACOUSTIC OIL LAYER THICKNESS GAUGE

BY

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ABSTRACT

The testing of spilled-oil recovery systems necessitates the measurement of the thickness of waterborne oil layers. The construction and testing of a successful electro-acoustic oil layer thickness gauge is described. The system determines oil layer thickness by measuring the time interval between acoustic signals reflected from the bottom and top of the layer. The major acoustic and electrical parameters of the systems are given and their effect on the accuracy of the system is discussed, when pertinent. Examples of thickness measurements reduced to graphic form by computer processing are included.

With careful manual operation, layers down to 1 mm are measurable by the system. With automatic data processing, a minimum thickness threshold of 7.5 mm has been realized.

To Dee Anne Lamb and Foster Middleton

Thanks for your patience!

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INTRODUCTION

This thesis describes the design and operation of a system for measuring the thickness of oil layers floating on water. An acoustic technique is used, taking advantage of the impedance discontinuity extant at the upper and lower boundaries of the oil layer.

The specific acoustic impedance (SAI) of any material is defined as the product of its density and velocity, for plane waves.

$$SAI = \rho C, \qquad \rho = \text{density} \qquad C = \text{velocity of acoustic waves in the material} \tag{1}$$

Whenever two materials meet at a boundary, an impedance discontinuity may exist. Acoustic waves incident upon such an interface are partially reflected if the SAI's of the two materials are different. The fraction of the incident energy reflected is given by the reflection coefficient, R.

$$R = \left(\frac{\rho_1 C_1 - \rho_2 C_2}{\rho_1 C_1 + \rho_2 C_2} \right)^2 \tag{2}$$

For the case of acoustic waves normally incident on a water/oil boundary, R is about 0.01. Although 0.01 is not a high reflection coefficient, it is high enough to produce signals easily detectable by a good acoustic receiver. The existence of the reflections from the oil/water and oil/air interfaces is the fundamental principle upon which the thickness gauge is based. Fortunately, the weak oil/water interface reflection is received before the very much stronger oil/air interface reflection (R = 1). The earlier arrival of the weaker of the two signals allows the receiver to be optimized for reception of the weaker signal without concern for the amplifier saturation caused by the stronger signal.

General and specific descriptions of the operation of the layer thickness gauge follow, along with descriptions of some measurement applications not anticipated when the system was constructed.

General System Description

This system measures the thickness of oil layers floating on water by insonifying them with short acoustic pulses, from below, and observing the time interval between the reflections from the oil/water interface and from the oil/air interface.

The major components of the system are the acoustic transducer for sending and receiving acoustic signals, the pulse generator for exciting the transducer, the receiver for detecting the acoustic reflections, and the oscilloscope for measuring time intervals. The components are connected as shown in the block diagram, Figure 1.

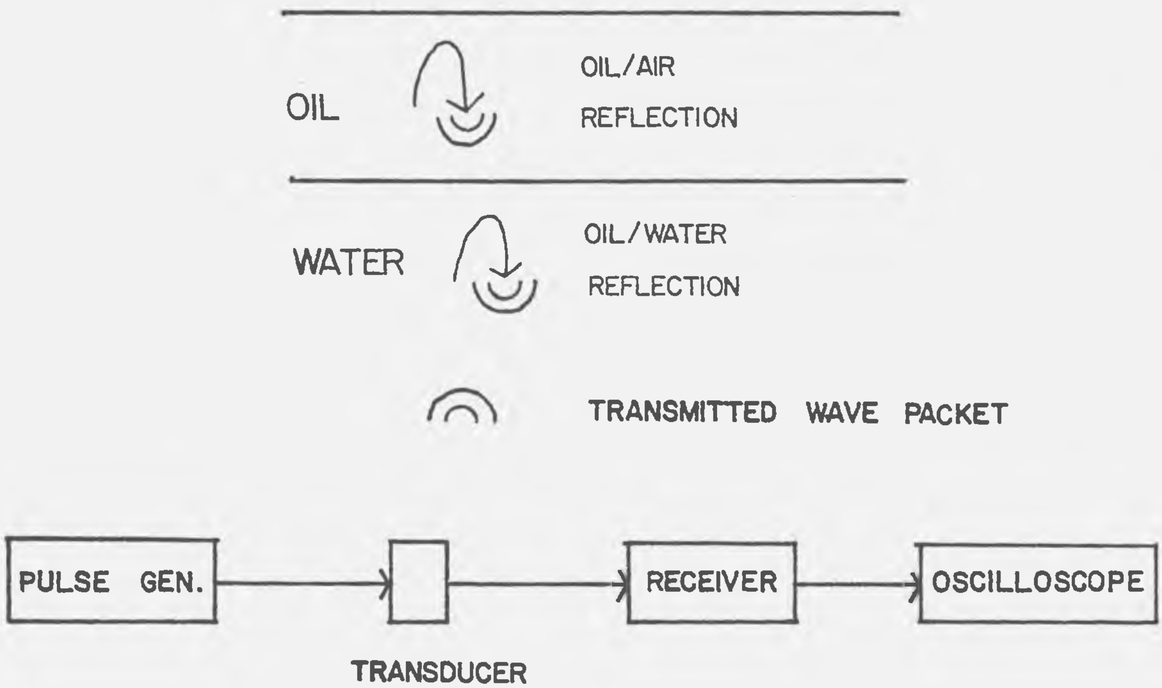


Figure 1

Short (¼ mS) pulses are applied to the transducer, at an arbitrary rate, by the pulse generator. Each electrical pulse causes the transducer to oscillate at its resonant frequency (1 MHz) for several microseconds. This mechanical oscillation is coupled to the water, generating an acoustic wave packet which travels vertically toward the surface of the water. When the wave packet encounters the oil/water interface, a small amount (about 1%) of its energy is reflected back toward the transducer. The remaining energy continues through the oil layer until it encounters the oil/air interface, where nearly all of it is reflected back toward the transducer.

At the transducer, the two reflections are observed as, first, a relatively small one followed by a relatively large one. The transducer converts these two signals to voltage signals for the receiver. If the velocity of longitudinal acoustic waves in the oil is known, layer thickness may be deduced by use of the relation:

$$h = (C_o/2)t \qquad (3)$$

h = oil layer thickness
C_o = acoustic velocity in oil
t = time separation of reflections

Detailed Specifications of System Components

Detailed specifications of the individual components of the measuring system are given here to facilitate the discussion of system operation.

The pulse generator

For this particular application, the pulse generator used is the Hewlett Packard 212-A. It produces pulses of width 0.1-10 microseconds and amplitude 0-100 volts at a PRR (pulse repetition rate) of 50-500 per second. Other pulse generators were tested during the laboratory trials of the system and all were satisfactory, including some homemade ones capable of only 5 volt output amplitudes.

<u>The transducer</u>

Two transducers were fabricated for this system. Both are commercial ferroelectric ceramic discs in aluminum and epoxy housings made at URI. The discs are 19 mm in diameter and one mm thick, with a resonant frequency of 1 MHz. Since 19 mm is about 12.5 wavelengths of 1 MHz acoustic waves in water, these transducers are highly directive, so that the 3-db beamwidth is five degrees (total).

The transducer beamwidth was calculated using the standard equation for the radiation pattern of a circular piston radiator, as given in Bartberger (1965) p. 25.

$$\frac{P(\theta)}{P(o)} = \frac{2 J_1 \left(\frac{\pi D}{\lambda} \sin\theta \right)}{\left(\frac{\pi D}{\lambda} \sin\theta \right)} \tag{4}$$

J_1 = first order Bessel function, first kind

D = transducer diameter

λ = acoustic wavelength, in water, at the frequency for which the directivity is to be calculated.

$P(o)$ = acoustic pressure at a point at range R on the Z axis of the transducer.

$P(\theta)$ = acoustic pressure at a point at range R and at an angular displacement θ from the Z axis (acoustic axis).

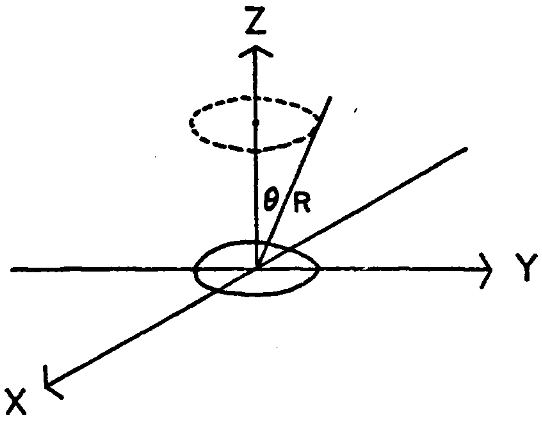


Figure 2

For every value of R and θ, there is a circular locus of points where P = P(θ). Thus the radiation pattern from a circular piston transducer is conical.

Generally, the value of θ where the value of P(θ)/P(0) is 0.707 is defined as one half the beamwidth. At these values of θ the acoustic power, or intensity, I, is one half the value at θ = 0.

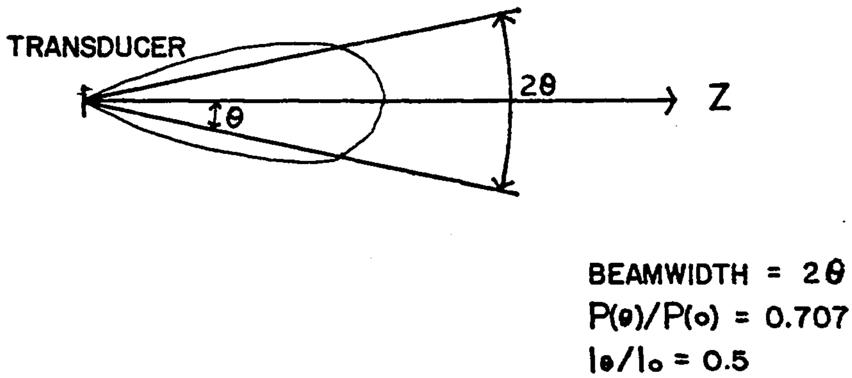


Figure 3

Concentrating the available acoustic energy into a narrow beam raises the acoustic intensity on the axis of the beam by a factor called the directivity index, D.I. (Urick, 1967, p. 48).

$$D.I. = 10 \log\left(\frac{\pi d}{\lambda}\right)^2 \qquad (5)$$

D = piston transducer diameter

The directivity index is the ratio of the on-axis acoustic pressure produced by the directive transducer to the acoustic pressure that would be produced by an omnidirectional transducer radiating the same amount of energy, the two measurements being made at the same range.

The transducer used in the oil layer thickness gauge has a directivity index of 32 db, or factor of nearly 1600. This illustrates the capability of generating high acoustic intensities with relatively low power electrical drivers when directive transducers are used.

In the receiving mode, the narrow beam transducer rejects interference arriving from directions in which it is not sensitive, raising the signal/noise ratio of the system. For the oil layer thickness measurement application, a highly directive transducer must be used to assure that only a small area of the boundary is insonified. Otherwise a confusing combination of echoes would be received from directions off the axis of the transducer. The effect of such off-axis signals is to increase the apparent length of the received pulses. If the apparent length of the oil/water reflected pulse is allowed to increase, even by a small amount, it will begin to overlap the oil/air pulse and make the interval timing problem difficult or impossible.

Received pulse length is a crucial parameter in the determination of the ultimate minimum layer thickness detection threshold.

Transducer fabrication details

For reasons of expediency, the transducers described here were assembled with aluminum housings. A machinable plastic or cast epoxy housing would be preferable because of the corrosion potentials usually

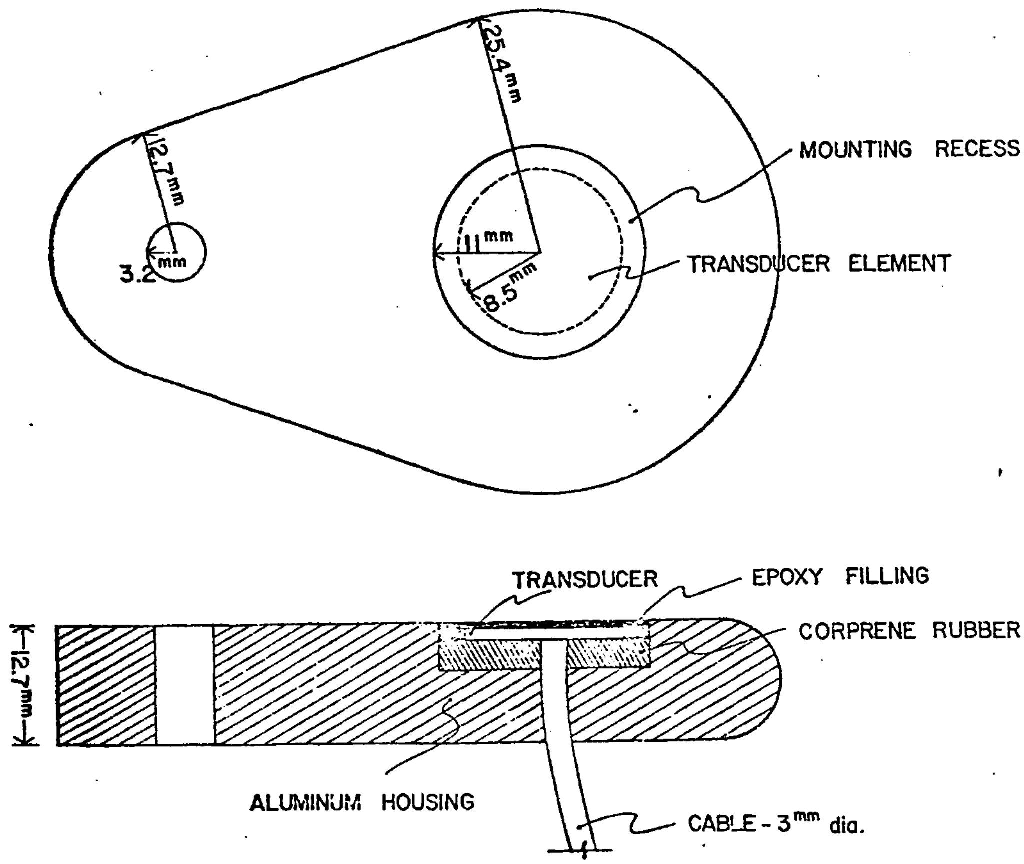


Figure 4

existing in hastily assembled laboratory and field test situations. Figure 4 shows the construction of the transducers.

The Emerson & Cumming 2741 LV epoxy casting resin used to waterproof and secure the transducer assembly is worthy of note. By adjusting the catalyst/resin ratio one may produce a casting that is "soft", "semi-rigid", or "rigid". As an attempt to partially isolate the transducer buttons from shock and abuse, the structure behind and beside the buttons was secured and sealed with semi-rigid material and a very thin

(0.5 mm) outer layer of rigid material was cast over the whole transducer mounting recess. Apparently this method is reasonable, since one of the transducers has survived being dropped, stepped on, and submerged for four weeks in fresh water and six weeks in sea water.

Each transducer has an RG-174 miniature coaxial cable permanently attached. Cable lengths of five, ten and 100 meters have been used with no observable difference in results.

Acoustic measurements indicate a transmitting response of 106 db//1 µP/volt @ 1 meter and a receiving sensitivity of -200 db//1V/ µP for these units. (1 µP = 1 micropascal.)

<u>The receiver</u>

Acoustic signals are easily generated but not always so easily received, especially at very low levels. The receiver, therefore, usually presents the most critical design problems when a new acoustic system is contemplated. This receiver is quite simple and entirely adequate to meet the demands placed upon it by oil layer thickness measurements. In that sense it is successful.

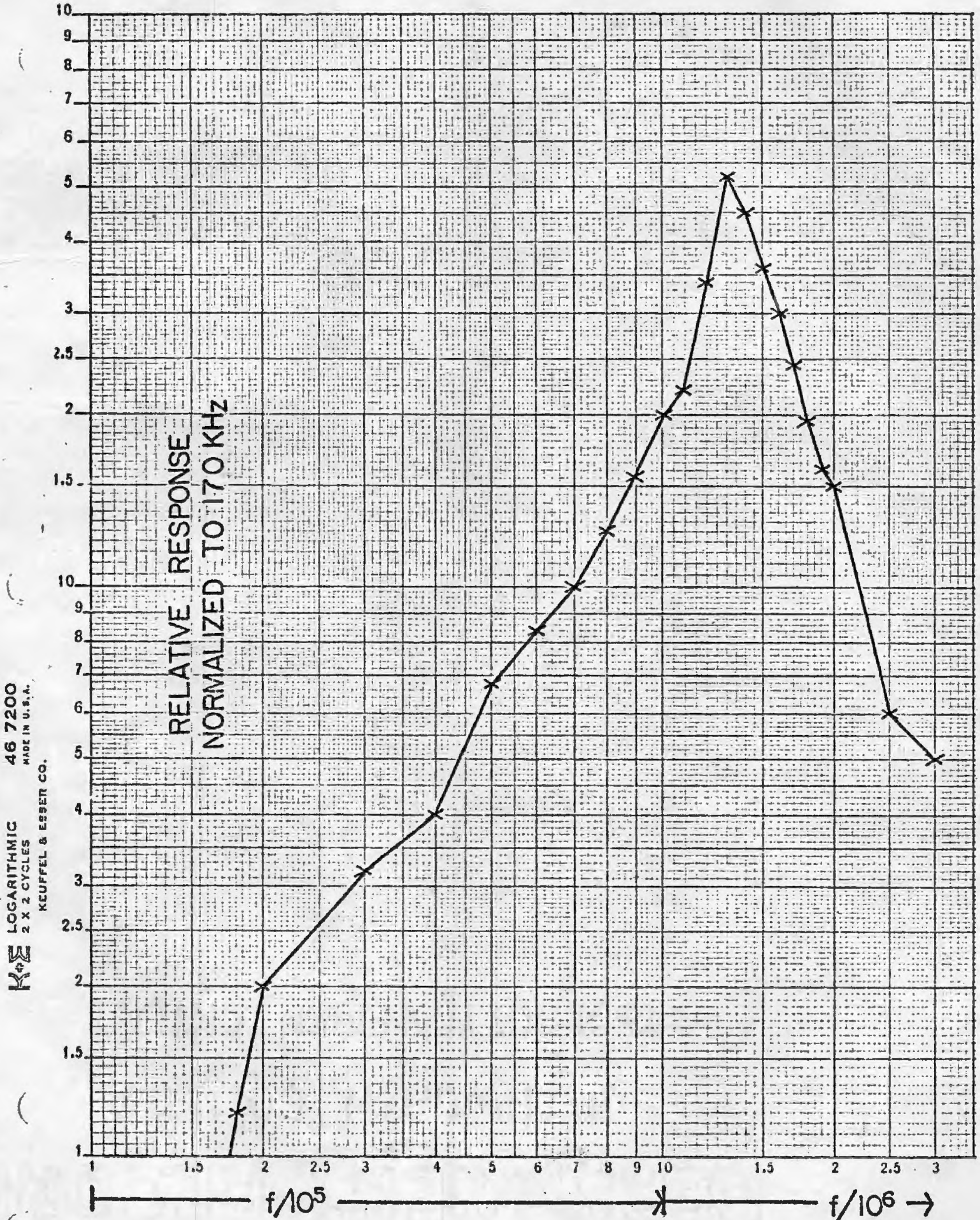
To meet the schedule imposed by the experimental program involved, it was necessary to use commercial operational amplifiers to realized most of the gain needed to make the voltage analogs usable. Considerable time was spent in the selection and testing of "low-noise", wideband operational amplifiers. None were sufficiently "low-noise" to serve as the receiver input stage, so a one transistor, discrete component amplifier was designed. Mochenbacher, (1962) gives useful advice and design equations for achieving low noise amplification. The suggestions dealing with biasing and impedance setting were instrumental in the expeditious design of the input stage.

At the output of the first stage the signal amplitude is sufficiently large to override the noise of the operational amplifier used as the second stage (Philbrick Nexus 1321).

Capacity coupling was used between all stages to make the receiver broadly peaked about the operating frequency. Emphasis was placed on obtaining a low noise figure to minimize the necessity of filtering and the associated distortion. Figure 5 is a graph of the gain versus frequency characteristic of the complete receiver. When used in the field tests, the receiver gain was set at about 90 db. Its maximum usable gain is about 110 db. Higher gain could be realized by adding shielding and better decoupling circuits.

Output lines are provided after the first, third, and fourth stages of the receiver. When used with the signal discriminator and synchronizing logic unit (described later) these outputs provide signals at the various levels required by the logic circuits. The output of the first stage triggers a logic level synchronizing pulse generator at the time of the outgoing acoustic pulse. The synchronizing pulse is used as a time zero reference point for subsequent timing operations.

The output of the third stage triggers the oil/air interface detector in the logic unit. At this point in the receiver circuit the oil/water interface signal is below the amplitude threshold of the logic unit's response. The oil/air interface signal, however, is much (ten times) stronger and, therefore, triggers the oil/air interface detection circuit very nicely.



Receiver frequency response

Figure 5

The output of the fourth (last) stage of the receiver triggers the oil/water interface detector in the logic unit and may be displayed on an oscilloscope and/or recorded on magnetic tape for subsequent analysis. In normal operation, the fourth receiver stage is overdriven by both the oil/water and oil/air interface signals. Operating this stage as a fast recovery amplitude limiter normalizes the amplitude of both output pulses over 60 db range of input signal amplitudes. Amplitude normalization is essential for efficient use of digital logic type timing circuits and also for effective use of oscilloscope timing techniques.

Receiver construction details

The receiver for the oil layer thickness measuring system was hand wired on perforated epoxy electronic circuit board. No uniqueness is claimed for its design or construction. It is, nevertheless, very effective, having operated for several months with no electronic or mechanical malfunctions. For detailed schematic diagrams of the receiver, see the appendix.

The receiver circuit board was mounted in a conventional 7"x17"x3" aluminum chasis. The chasis served to support and protect the receiver circuit board, support the necessary plugs and switches, and contain the batteries used as the power supply.

The logic unit

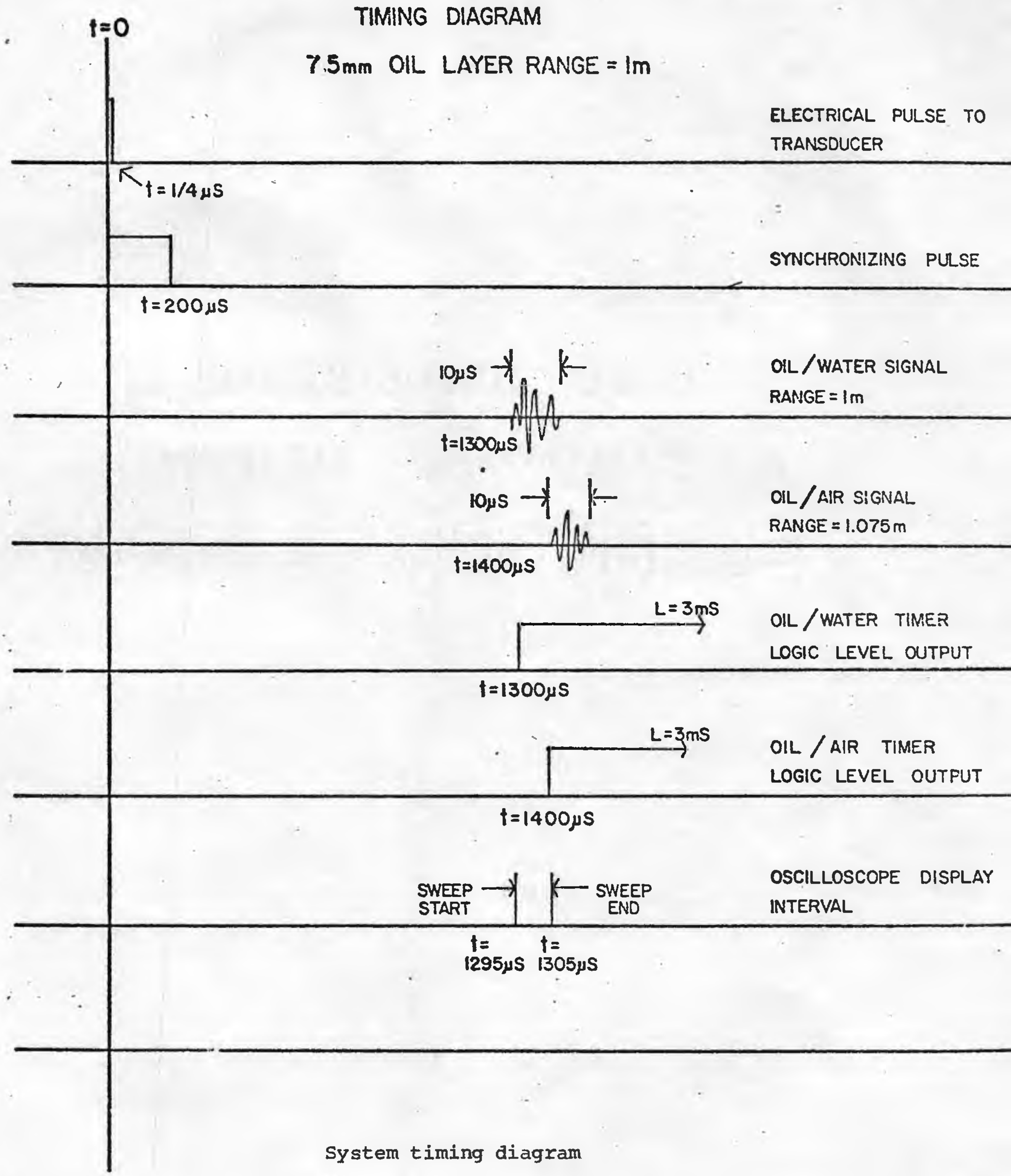
The logic unit of the oil layer thickness measuring system contains three subsystems. They are: synchronizing pulse generator, oil/water interface detector/timer, and oil/air interface detector/timer. A by-product of the interface timing operation is the capability of using the oil/water or oil/air interface signals as synchronizing pulses. In this mode of operation, the logic unit can suppress interface pulse arrival time variations caused by waves on the surface of the water body under study, be it laboratory tank, outdoor test tank or ocean.

The logic unit is composed of three monstable, retriggerable multivibrators. The first of these multivibrators, the synchronizing pulse generator, is triggered by the output of the first stage of the receiver at the start of each transmitted pulse. It generates a positive logic level pulse that serves as a time reference for recorded data and as the time zero point for oscillographic observation of received signals.

The second and third monostable multivibrators are used to generate timing pulses coincident with the reception of the two interface signals. One produces a logic pulse when the receiver output first reaches some minimum level, corresponding to the arrival of the oil/water interface signal. The output produced by this stage upon reception of an oil/water interface signal activates the next logic stage, which produces another logic pulse when the output of the third stage of the receiver reaches some minimum level, corresponding to the reception of an oil/air interface signal. The time separation of the outputs of these two logic stages corresponds to the time separation of the two interface signals. The logic pulse outputs are available at output jacks for connection to any sort of timing system, recording system, or computer.

The oscilloscope

Any oscilloscope with delayed sweep capability may be used to measure the pulse separation time corresponding to oil layer thickness, see Figure 6. The delaying capability is required to allow observation of the two interface pulses with sufficient time resolution to accurately



System timing diagram

Figure 6

determine their separation. In practice, the time interval between transmission of the acoustic pulse and the reception of the interface pulses may be several orders of magnitude larger than the time interval between the two interface pulses. For example, if the transducer were one meter below a 10 mm oil layer the total travel time of the acoustic pulse reflected from the oil/water interface would be 1.3 ms and the time separation of the interface signals would be 0.013 ms. Measuring a pulse separation of 0.013 ms on a scale of 0-2 ms is unreasonable and highly inaccurate. Instead, by delaying the initiation of the horizontal sweep of the oscilloscope for 1.3 ms and displaying a range of 1.3 to 1.4 ms a separation of 0.013 ms would then appear as 13 percent of the length of the horizontal axis of the oscilloscope trace, readable to perhaps five to ten percent accuracy. Obviously, further expansion of the time scale is possible if more accurate results are required.

The foregoing discussion of timing technique assumes that the water surface is flat, still, and horizontal. Note that 30 cm waves will introduce a variation of $\pm$ 0.040 ms in the arrival time of the interface pulses. If displayed on a time axis of 1.25-1.35 ms, received signal pulses would move in synchronism with the waves, between the 1.26 ms and 1.34 ms points. This sort of movement not only makes visual reading of the pulse separation very tedious, but also severely limits the maximum time sensitivity that may be used while keeping both pulses within the time frame visible on the oscilloscope screen.

If waves exist in a real experimental situation, their effect on the timing system may be substantially reduced by using the logic level output of the oil/air interface detector as the sweep trigger pulse and setting the sweep delay interval equal to the pulse repetition period. Under these conditions, one received signal starts the sweep and the next one is displayed on the screen. Time displacements caused by waves are limited, therefore, to a maximum excursion proportional to the water surface displacement occurring during the interval between the two transmitted pulses. At a pulse repetition rate of 100/s, the repetition period is 10 ms. Given waves of one second period, a maximum amplitude excursion of four percent of the total wave height could be expected to occur in 10 ms, to a first approximation (triangular waves). Note that the wave suppression factor is proportional to wave period. Longer waves are attenuated more effectively than shorter ones.

The Laboratory Trial

After the fabrication of the first transducer, the concept of the oil layer thickness gauge was tested in a one gallon plastic jar. (See Figure 7.) Layers of number six and number two fuel oil were insonified at a range of about ten cm. With a 60 volt drive pulse and the maximum available oscilloscope sensitivity (10 mV/cm) the oil/water interface reflection could just be detected. These results were encouraging and sufficiently informative to serve as the basis for a first approximation of oil/water boundary reflectivity. Given an estimated oil/water boundary reflectivity, the acoustic and electronic parameters of the prototype layer thickness gauge were specified.

After construction of the first prototype receiver, acceptable results were obtained in the test jar, but when the prototype logic system was built on the same circuit board, excessive logic signal leakage

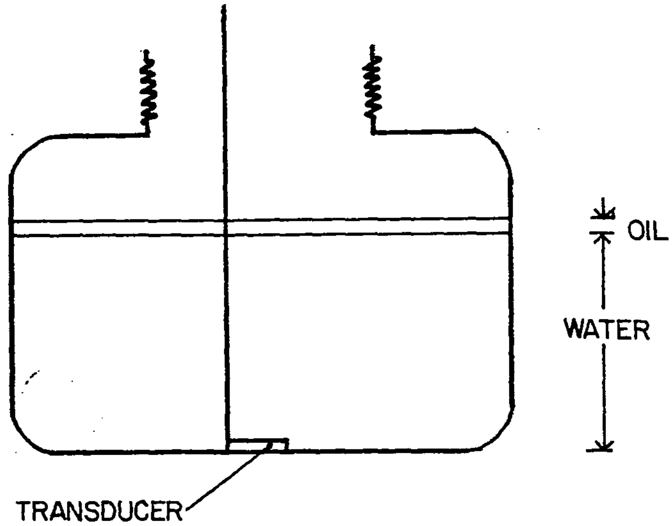


Figure 7

into the receiver occurred. At that time another system with separate receiver and logic modules was constructed. Except for minor circuit modifications and amplifier substitutions the second receiver is still in use.

As soon as the second receiver board was finished, the transducer was moved to a test tank deep enough to allow testing of the system at a range of about a meter. It was in this tank that the thorough testing and refinement of the system was performed. It was large enough (18 cm x 90 cm x 122 cm) to allow testing of the time normalization system by simply rocking the tank to simulate waves.

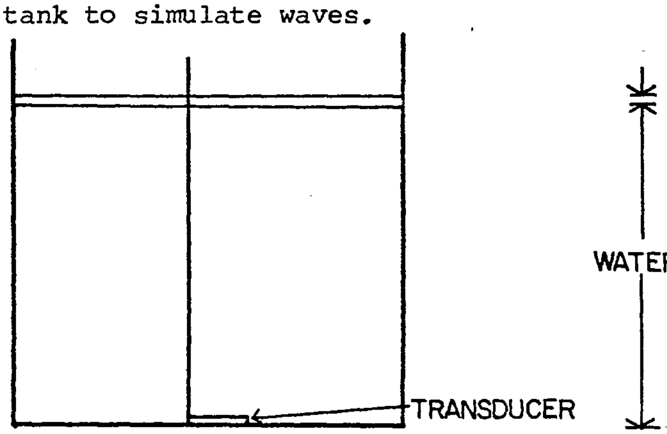


Figure 8

The large-tank test yielded an accurate value of the reflectivity of the oil (number six)/water interface (-21.3 db//reflectivity of oil/air interface). When the test tank was rocked, to simulate waves, a reflected signal amplitude range of about forty db (factor of 100) was observed. Although final adjustment of the system parameters was made emperically at the field test site, the wave induced signal variation measurement was very useful because it provided a minimum design goal for the system's final amplitude normalization capability. The final version of the receiver can normalize the oil/water interface signal over a range of sixty db (factor of 1000).

Accuracy

The accuracy of measurements made with the oil layer thickness gauge depends primarily upon three factors: the applicability of the physical model, the calibration of the electronic timing system, and the skill of the operator.

The physical model

As illustrated in Figure 1, the thickness gauge is assumed to measure the time separation between pulses reflected from the oil/water and oil/air interfaces. The assumption represents the *a priori* acceptance of a physical model of the system in which the acoustic wave packet impinges on both interfaces at normal incidence, producing reflections at two points on the acoustic axis of the transducer. In reality, the finite width of the acoustic beam produces reflections from other points on the interfaces, but all such off axis reflecting points are farther from the transducer than the on axis ones and, therefore, their signals are received later than the on axis ones. Off axis reflections are not a source of error if only the first arrival of signals from the respective interfaces is considered. There are no apparent shortcomings of the physical model just described. The two reflections are received, as expected, when an oil layer exists. The reflectivity of the oil/water interface was measured experimentally and the result agrees well with theoretical predictions. There are, of course, no other sources from which the acoustic signals may originate.

Having accepted the physical model as described, one parameter must be specified: the velocity of the longitudinal acoustic waves in the oil layer. Equation 3 shows that the accuracy of any thickness measurement will be directly proportional to the accuracy of the acoustic velocity parameter specification. For the field work described in this thesis, tabulated velocity data, Weast, ed. (1968), were believed to be sufficiently accurate. For precise determinations, samples of the particular oils involved should be collected and analyzed with a velocimeter to determine precise velocity figures.

<u>The timing calibration</u>

The timing system used as a basis for oil layer thickness measurements is the horizontal sweep generator of a high quality oscilloscope. Casual checks of the accuracy of the oscilloscope's sweep generator, comparing it to a quartz crystal oscillator, suggest that it is more than an order of magnitude better than any reasonable accuracy goal that might be sought for thickness measurements.

<u>The operator</u>

When thickness data are read from the oscilloscope there will always be an error component introduced by the operator, the magnitude of which will depend upon the sweep rate setting of the oscilloscope. If any particular pulse pair can be displayed with a separation of one half the total display interval, the time separation will span 25 scale marks and be readable to one half mark or two percent. Layers thinner than about 15 mm must be measured at less than half scale display separation. The operator induced errors rise in approximately inverse proportion to the layer thickness.

The Field Trial

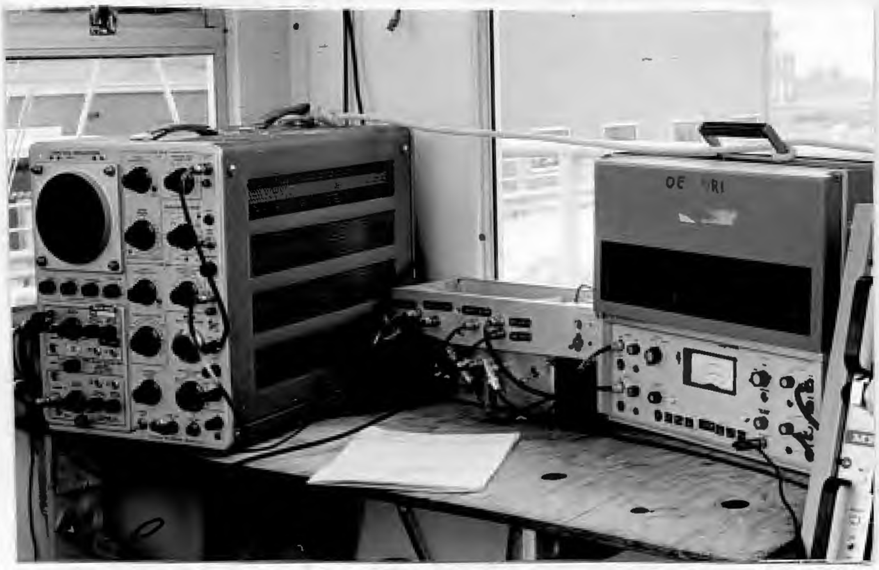
The U.S. Coast Guard is engaged in a substantial program to test and evaluate oil spill detection and cleanup apparatus. One of these tests involved the deposit and recovery of an oil layer in a large test tank. The recovery was effected by two different oil spill cleanup devices. In each case, it was necessary to measure the thickness of the oil layer encountered by the device under test, so that the recovery efficiency of the device could be determined. The oil layer thickness gauge, as previously described, was used to monitor the thickness of the oil layer deposited by the distribution system. This successful monitoring project served as the field trial of the gauge.

The field trial was conducted at the U.S. Environmental Protection Agency's OHMSETT facility in Leonardo, New Jersey. The 20 x 200 meter test tank at the OHMSETT site is large enough to allow full scale tests of many oil spill recovery devices under more or less realistic conditions. The tank is outdoors, so wind and sun can influence the test environment, and there is a wave generator to make waves up to about two feet in amplitude. At-sea recovery conditions are simulated by towing the device under test along the long dimension of the tank to correspond to towing by a boat. The towing force is provided by a transverse bridge rolling on rails at each side of the tank. On the bridge is a fluid distribution system and an instrumentation shelter so that the device under test can be studied in its own frame of reference. Figure 9a is a photograph of the tank and bridge system. Figure 9 is a photograph of the thickness gauge system set up in the instrumentation shelter on the bridge.

In addition to the layer thickness measuring equipment, Figure 9 shows a Hewlett-Packard 3960A magnetic tape recorder in place at the test site. Tape recordings of the receiver output were made for subsequent automatic data processing by the Ocean Engineering Department's computer system. The technique and results of the computerized data processing are described in a separate section.

Oil layer thickness measurements were made about five meters "behind" the oil distribution system, at the opposite side of the bridge, where the oil layer was stabilized at a reasonably uniform thickness. The acoustic transducer was mounted on an iron bracket about one meter below the water surface. The bracket was carefully positioned to insure normal incidence of the acoustic signals upon the oil layer, see Figure 9b.

Many tests were run with this setup, with considerable success. A Tektronix 535 oscilloscope and a Dumont oscilloscope camera were used to observe and record oil layer thickness data at the field test location. Figure 10 is a photograph of the oscilloscope screen, showing interface signals corresponding to a 12 mm oil layer thickness. The



Thickness gauge equipment at the field site

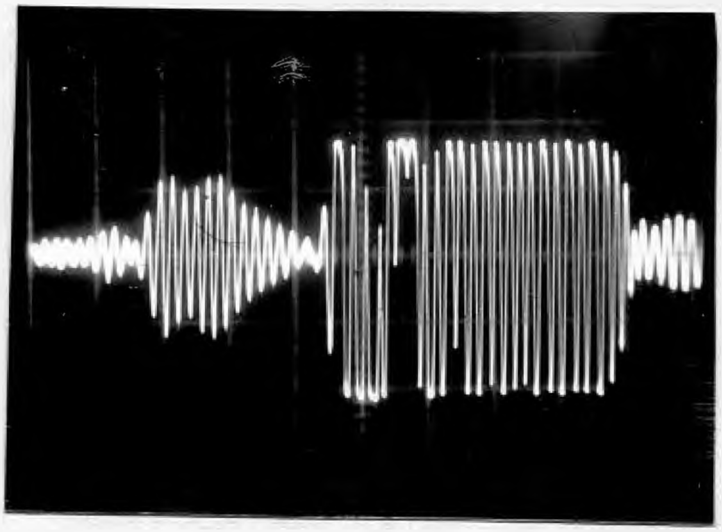
Figure 9

The OHMSETT tank

Figure 9 a

The transducer and bracket installed at the field site

Figure 9b



Reflection signals from a 12 mm oil layer
X = 5 μS/DIV, Y = 2 Volts/DIV

Figure 10

picture serves as evidence of the proper functioning of the oil layer thickness gauge. For the majority of the tests, the receiver was operated at a gain of 86 db. This figure represents a compromise value between the conflicting requirements of wide dynamic range and a low minimum thickness detection threshold. Under the experimental conditions described, the effective duration of the acoustic signal is about ten microseconds, corresponding to a thickness threshold of 7.5 mm.

The threshold figure is the layer thickness necessary to produce a pulse spacing greater than the duration of the oil/water pulse. It is determined largely by the receiver gain setting, because, as the gain is increased, more of the exponentially decaying pulse envelope is amplified to values within the amplitude window of the timing system. The ultimate minimum thickness threshold is obtained at a gain setting that does not produce amplitude limiting of the oil/water interface signal. Under this condition, the amplitude of the oil/air interface signal will be above the level necessary to produce limiting and an operator can measure the interval between the start of the oil/water signal and the onset of limiting of the oil/air signal. Observations of intervals of one period (1.5 microseconds) have been made, corresponding to a thickness threshold of about 1.1 mm.

Unfortunately, the variability of acoustic signal strength caused by waves, turbulence and debris necessitates the use of about forty db of limiting, raising the thickness threshold to the 7.5 mm range, when continuous thickness measurements are desired in the presence of waves or other disturburances. It should be noted that neither of the two thickness thresholds mentioned above are inherent physical limitations of the concept. They are, rather, limitations imposed by the electronics as arranged for these tests. Since the tank tests involved oil layers well above the 7.5 mm threshold, the existence of the threshold presented no difficulty in terms of the test results.

Automatic Data Processing

During the field trials, oil layer thickness data were recorded on magnetic tape for later automatic reduction and display at URI. The synchronizing pulse and the two signal pulses, after rectification, were recorded with a Hewlett Packard 3960A instrumentation recorder.

Oil layer thickness data

At URI, the recorded data were analyzed using a Nova 1200 computer, a Versatec D1100A printer, and other components of the Ocean Engineering data processing facility. The synchronizing pulse, recorded on its own tape track, serves as a time reference for the computer just as for the oscilloscope during field observation. Thickness data are read by the computer using a program originally developed for seismic profiling. The amplitude of received signal pulses is stored in the computer memory whenever the leading edge derivative of a data or noise pulse exceeds some preset value. If two data pulses exist on the magnetic tape, their leading edges will produce two derivative signals, separated by a time equal to the original pulse separation.

The two derivative signals are displayed, in graphic form, on the Versatec printer. Given good data on the magnetic tape, the Versatec chart displays a continuous representation of oil layer thickness.

Two factors limited the effectiveness of the automatic data processing scheme described above: the limited bandwidth of the tape recorder and the limited conversion rate of the analog-to-digital converter in the computer system. The bandwidth of the tape recorder influences the minimum thickness threshold of the automatic data processing system because the risetime of reproduced pulses is lengthened by the recording process. The manufacturers specification of bandwidth for the tape recorder is 70 KHs, at the -3 db point. The observed risetime is 8 microseconds, much longer than the observed 4 microsecond risetime of the rectified data pulse.

Given the ten microsecond effective pulse length and 7.5 mm thickness threshold discussed in the "field trial" section, a conservative estimate for the thickness threshold of the automatic system is 10.5 mm, corresponding to an 8 microsecond risetime, 4 microseconds of the data pulse, and 2 microseconds for the data pulse to decay to 3/4 of its maximum amplitude. After the first data pulse has decayed to about the 3/4 amplitude point, the leading edge of the second data pulse can produce sufficient derivative signal to be printed on the chart.

The thickness scale of the graphic output is determined by the conversion rate of the analog-to-digital converter. There are 1024 recording points across the Versatec printer chart. At the maximum conversion rate available, 30,000/S, each point corresponds to a time interval of 33 microseconds. To maintain usable time resolution in spite of the 33 microsecond sampling interval, the magnetic tape was run at a playback speed of 1/16 of the record speed. This reduces the effective sample interval to 33/16 or 2.06 microseconds and the effective thickness resolution to 0.75 x 2.06 = 1.54 mm.

Obviously this resolution of 1.54 mm could be improved by further reduction of the tape playback speed or by an increase of the sampling rate. With the limited tape recording system available, however, there was little incentive to improve the system's time resolution. The error contributed by the resolution limitation of the system as operated during the field trial is, at worst, (½)(1.54/10.5) or 7.3 percent. This resolution error is, of course, a result of the digital processing scheme. In addition to resolution related error, the automatic data processing scheme suffers from errors in the assumed velocity of the same magnitude as those discussed in the subsection on the physical model. The minimum layer thickness threshold figures discussed previously for oscillographic and computerized data reduction schemes are representative of the capability of the layer gauge as operated during the field trial.

Interpretation of the Computer Graphic Data Presentation

Figure 11 is a section of the graphic data presentation produced by the automatic data reduction system. Referring to Figure 11, the longitudinal axis has a scale of one second/inch, determined by the pulse repetition rate of the system (100 pulses/second) and the line spacing of the plotter (100 lines/inch). The transverse axis has a much larger time scale of 206 microseconds/inch. Data are displayed as event time after the transmitted pulse (transverse) versus time (longitudinal). The transverse scale represents 0 to 2109 microseconds or, in distance units, 0.75 x 2109 = 1582 mm. Note that the 100 line/inch specification applies to both axes of the printout, because "lines" are in fact simulated by a transverse array of 1024 writing points 0.254 mm apart. The scale of the transverse axis may, therefore, be expressed as 6.08 mm sound path distance per mm. on the chart.

Data taken during the field trial produce a chart showing a water surface line at about the half-scale point on the transverse axis. If an oil layer existed there is a parallel line corresponding to the oil/air interface. The spacing of these two lines represents the oil layer thickness, at the scale factor calculated above.

An Unexpected Application of the Thickness Gauge

One of the oil spill cleanup devices tested during the field trial concentrated oil in a holding basin before pumping it to a storage tank. During the field trial, the author suggested installing a second thickness gauge transducer within the holding basin to monitor the thickness of oil there.

Computergraphic data presentation

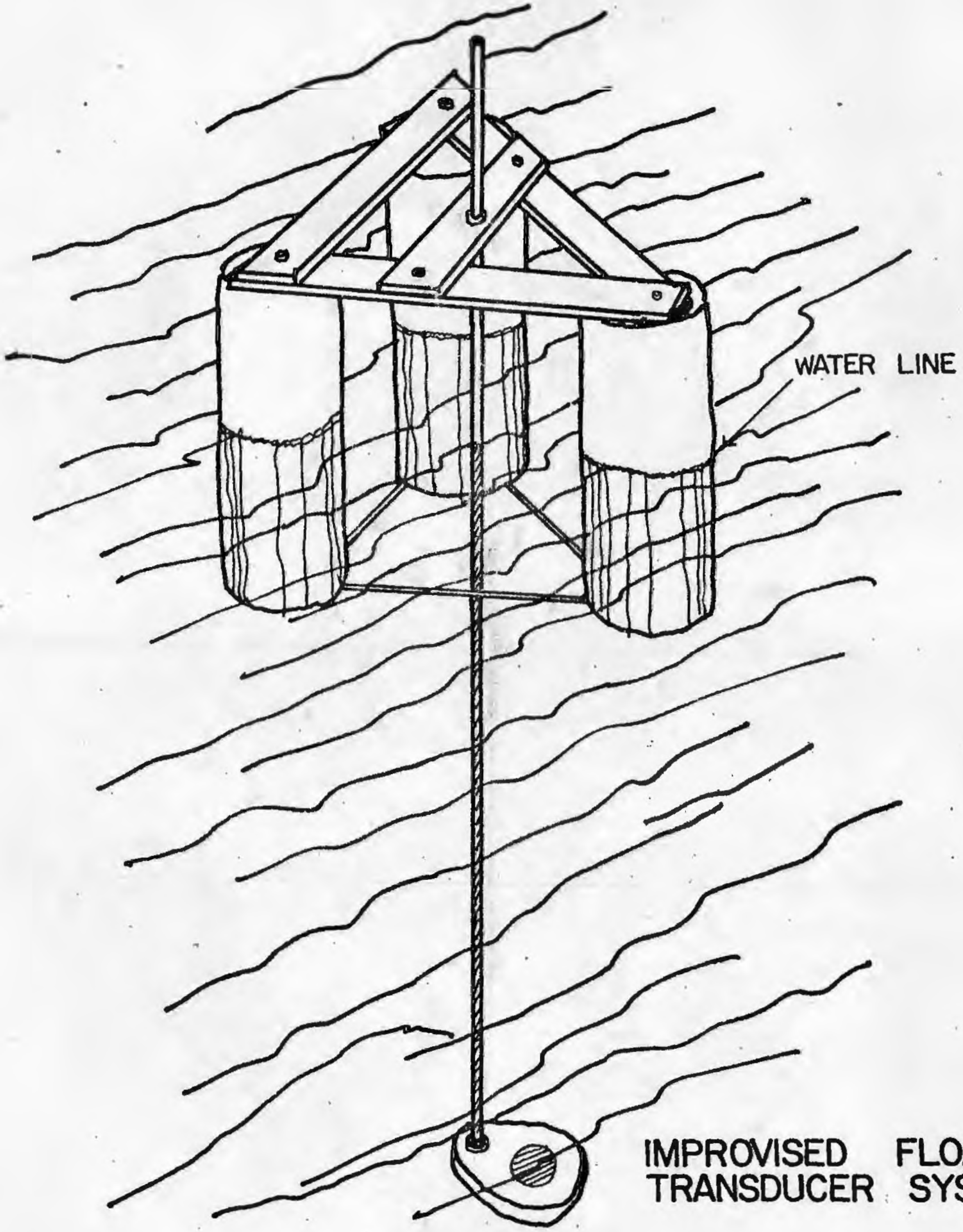
Figure 11

The basin oil layer thickness is an important operating parameter for that system because, if it is too thick, the recovery efficiency of the apparatus is reduced and, if it is too thin, excessive water is picked up with the recovered oil; diminishing the oil storage capability of the storage tank.

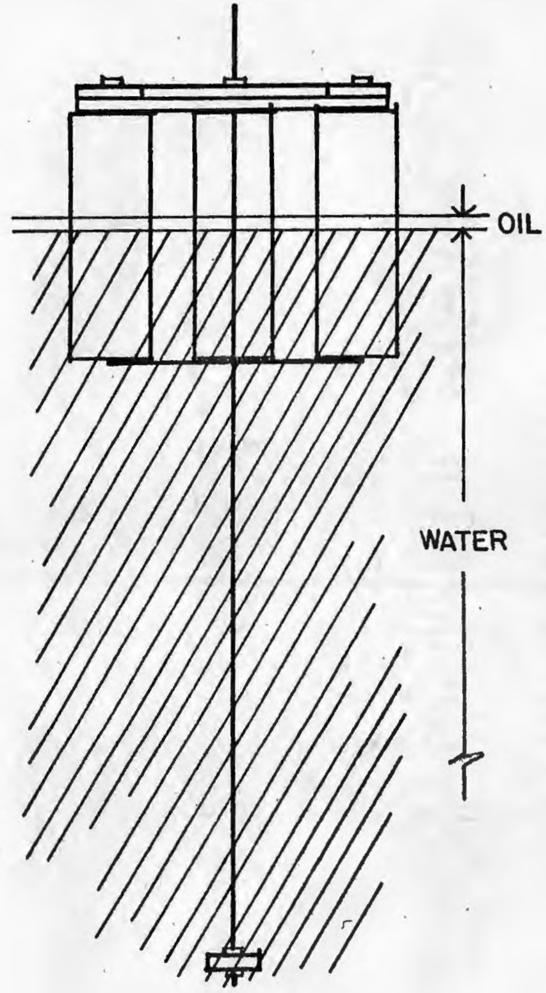
Since the collection basin was made of flexible fabric, there was no stable point at which the thickness gauge transducer could be attached. To hold the transducer below the oil layer, and to diminish the effect of waves, a small buoy was constructed from scrap materials available at the test site, as in Figure 12. The three column configuration was used to allow the transducer a clear view of the fluid surface and to provide some decoupling of high frequency surface disturbances. It was successful, as the chart shown in Figure 13 illustrates.

Since the basin thickness measurement was made from only about 40 cm below the fluid surface, the basin and platform mounted transducers were simply operated in parallel. Both transmitted at the same time and the latest possible signals from the basin transducer were received after an elapsed time of 530 microseconds (400 mm). The fluid surface signal from the platform mounted transducer appears much later, at about 1330 microseconds, corresponding to the one meter depth of the platform transducer.

No problems were encountered during the two-transducer operations except for the necessity of compromise in receiver gain settings to resolve both layers effectively. Figure 13 shows that this was possible. Basin oil layer thicknesses up to at least 305 mm were measurable.

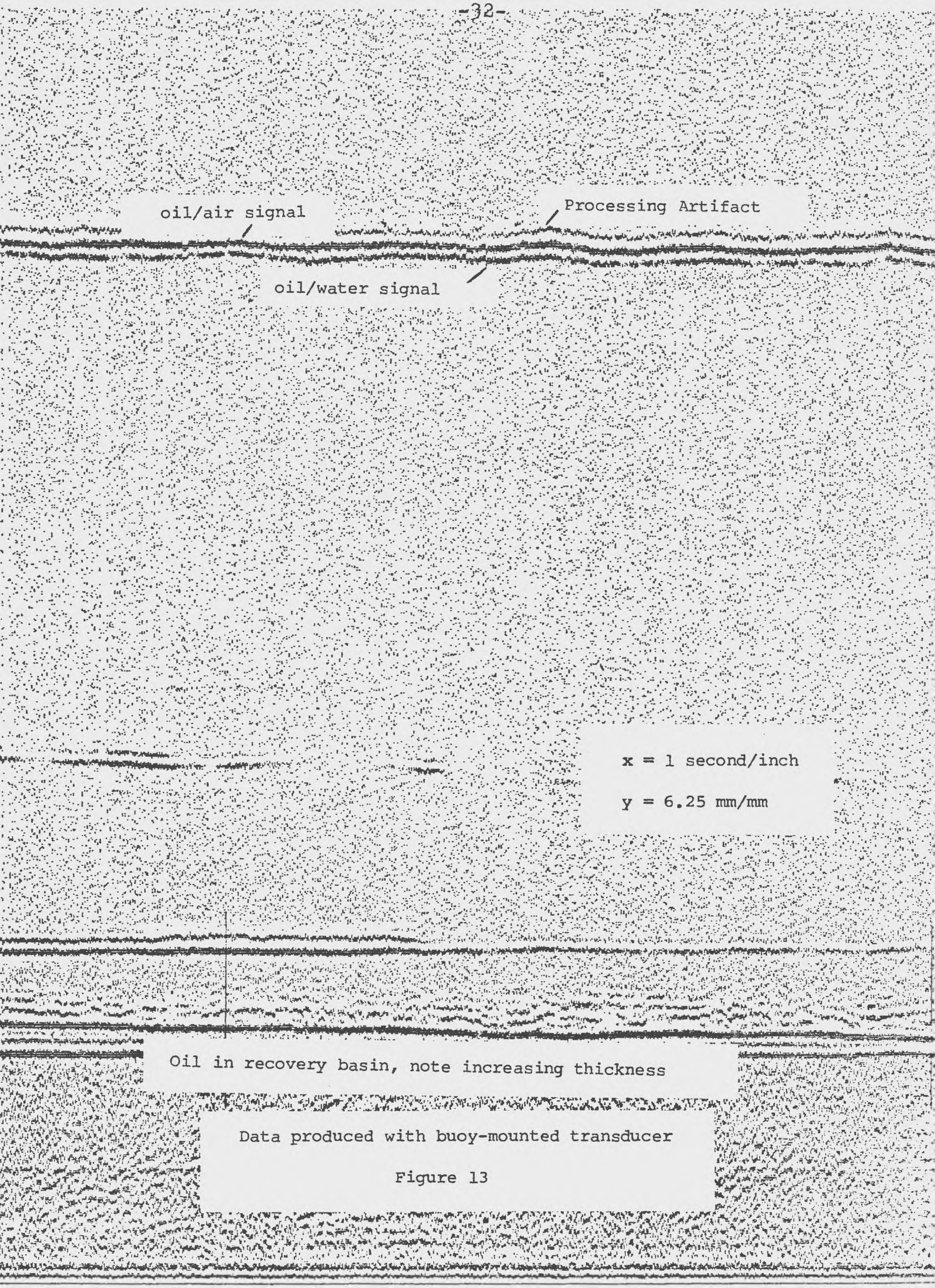


IMPROVISED FLOATING TRANSDUCER SYSTEM



TRANSDUCER

Figure 12



Data produced with buoy-mounted transducer

Figure 13

CONCLUSIONS AND RECOMMENDATIONS

The oil level thickness gauge just described worked beyond the expectations of all who were concerned with its development. The time resolution and detection thresholds of the system are parameters that are measurable and, to some extent, selectable by the operator of the system.

The measured value of the reflection coefficient of oil/water boundaires is near the theoretical value, as expected. Wave turbulence and floating debris all caused signal strength variations, as did aeration and emulsification of the oil. All these variations were handled adequately by the gauge, principally because of the inclusion of sufficient gain capability to achieve amplitude normalization of the receiver output signals.

The use of a buoy-mounted transducer to measure oil layer thicknesses in the concentration basin of a recovery device suggests the desirability for further development of the buoy mounted system for use in a form of quasi-remote sensing. The buoy should carry a complete thickness gauge and a radio transmitter, and be dropped from airplanes, helicopters or ships to measure the thickness of oil layers resulting from accidents at sea.

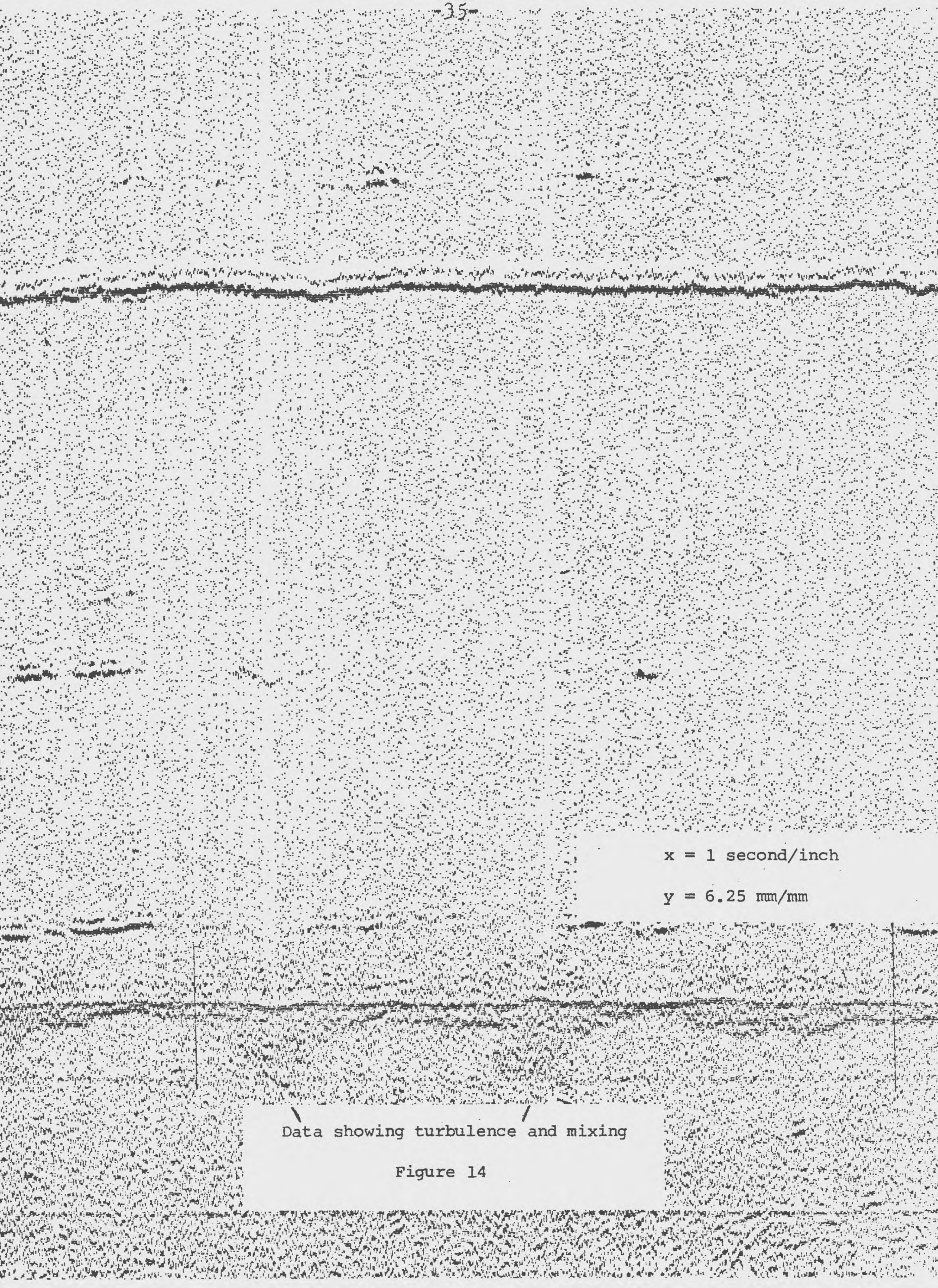
The wave measuring capability of the system should be exploited in applications in wave studies using bottom or spar buoy mounted systems. By measuring from a point near the water surface, very small waves can be measured with an accuracy exceeding that of any physical contact system. The acoustic wave sensor and the hydrostatic sensor are the only types which can avoid penetration of the air/water interface, and the acoustic system is much less susceptible to low pass filtering of the data by the water column. Manual measurements of basic wave parameters have been made from graphic outputs of the present system. For automatic data processing of wave data, the simple measurement of the time interval between the outgoing pulse and the surface reflection would be recorded in digital form. The range of time intervals thus recorded would correspond to wave amplitude, to the accuracy of laboratory timing systems, which is very high (10^{-4} or better).

Another area of research in which the oil layer thickness gauge should be employed is in the study of the dynamic behavior of oil layers in waves. The capability of producing a continuous record of layer thickness facilitates the observation of layer thickening or thinning as a function of relative position on a wave.

Mixing phenomena are observable with the wave gauge because oil entrained in water, or water entrained in oil, create regions of diffuse reflectivity which are observable on both the oscilloscope and the computer-graphic data displays. In the development of oil recovery systems, this mixing process is of great importance to the prediction of the behavior of an oil layer. Such predictions, based on wind, wave, and meteorological data, as well as oil behavior data, are crucial to the achievement of fast, efficient recovery. See Figure 14.

<u>Specific wave measurement applications</u>

The timing system of the layer thickness gauge may be used to measure the separation between the transducer and a fluid surface, as a function of time, as mentioned previously. Figure 15 is an example of a wave record made at the field test site. The particular waves shown in Figure 15 are about 40 cm in amplitude, with a period of about three seconds.

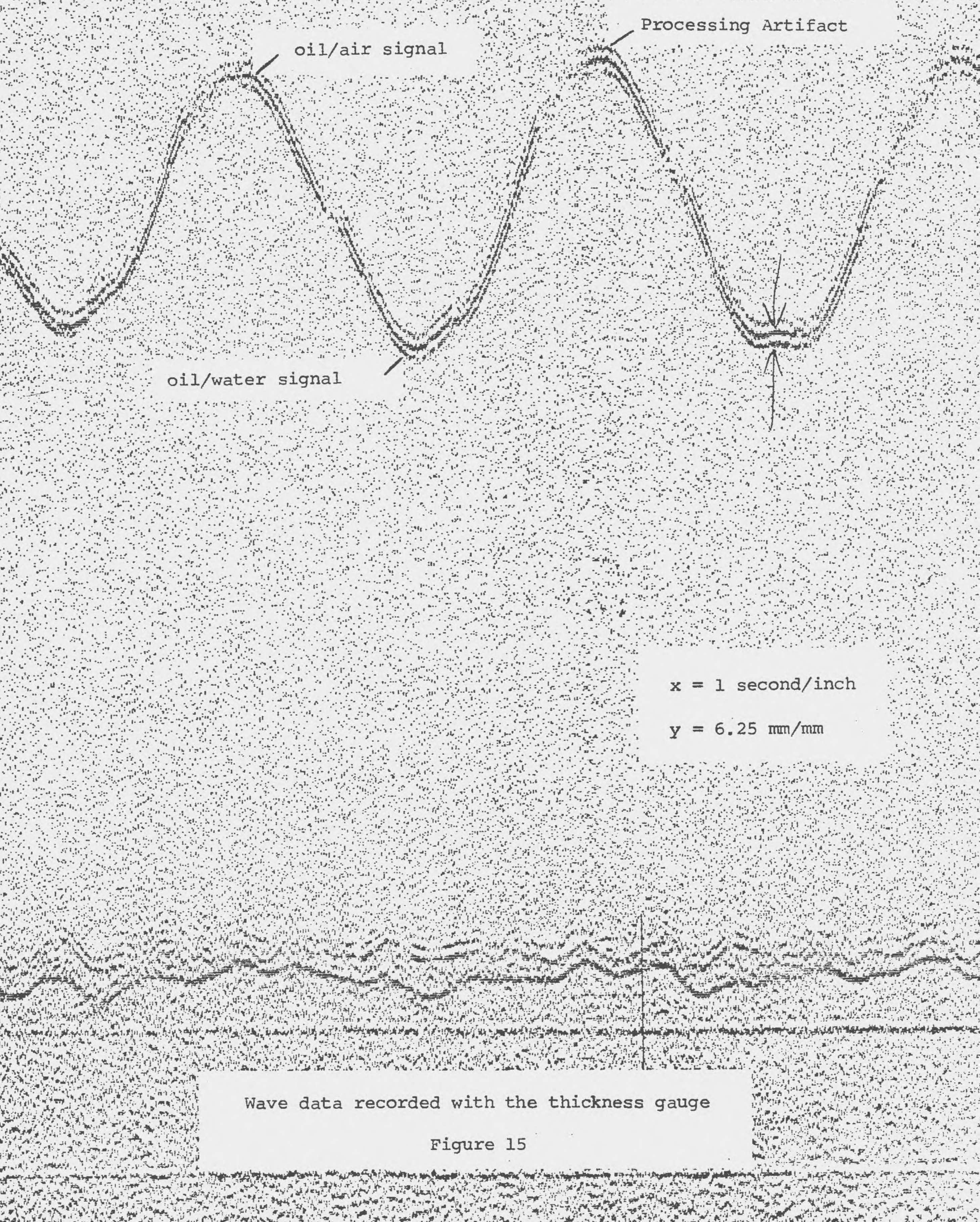


Data showing turbulence and mixing

Figure 14

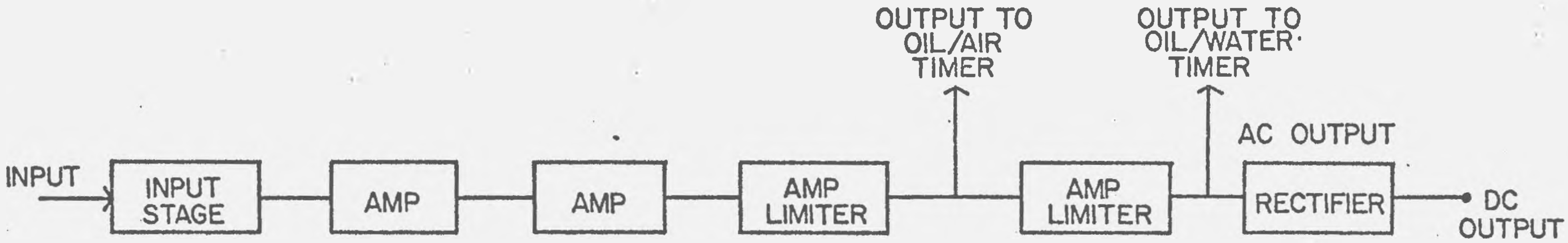
Obviously, the wave amplitude is readily readable from this record. With expansion of the transverse axis of the chart, much smaller waves could be measured.

At the scale of Figure 15, the system is usable for the measurement of waves up to 1.5 meters in amplitude. Such a scale would be useful for most estuarine wave monitoring, as well as for large scale model tank applications. With scale exapnsion of the transverse axis, and a narrower acoustic beam, waves only a few centimeters long could be measured. For example, a one degree beam, at a range of 10 cm insonified a circular area .2 cm in diameter. Such a beam should be suitable for waves greater than about 20 cm long.



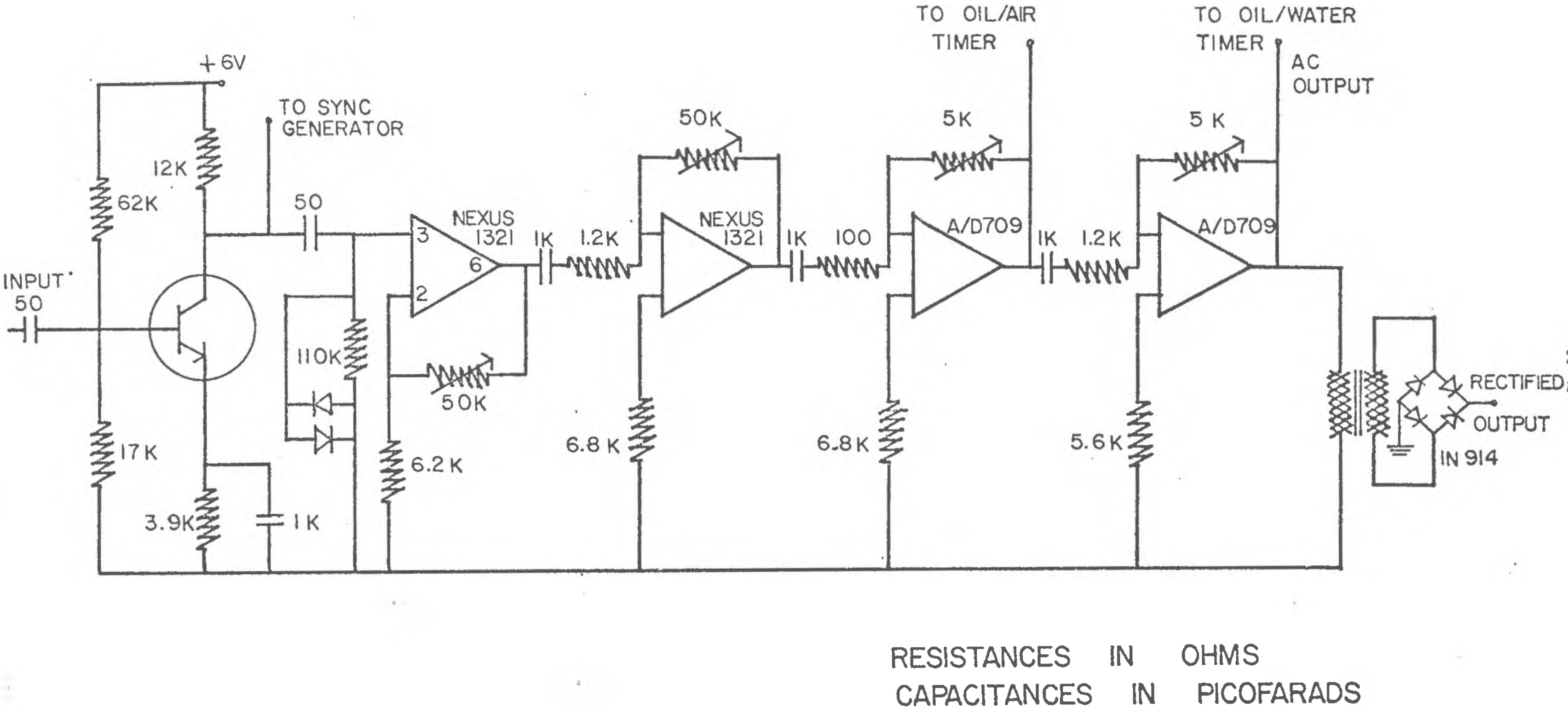
Wave data recorded with the thickness gauge

Figure 15



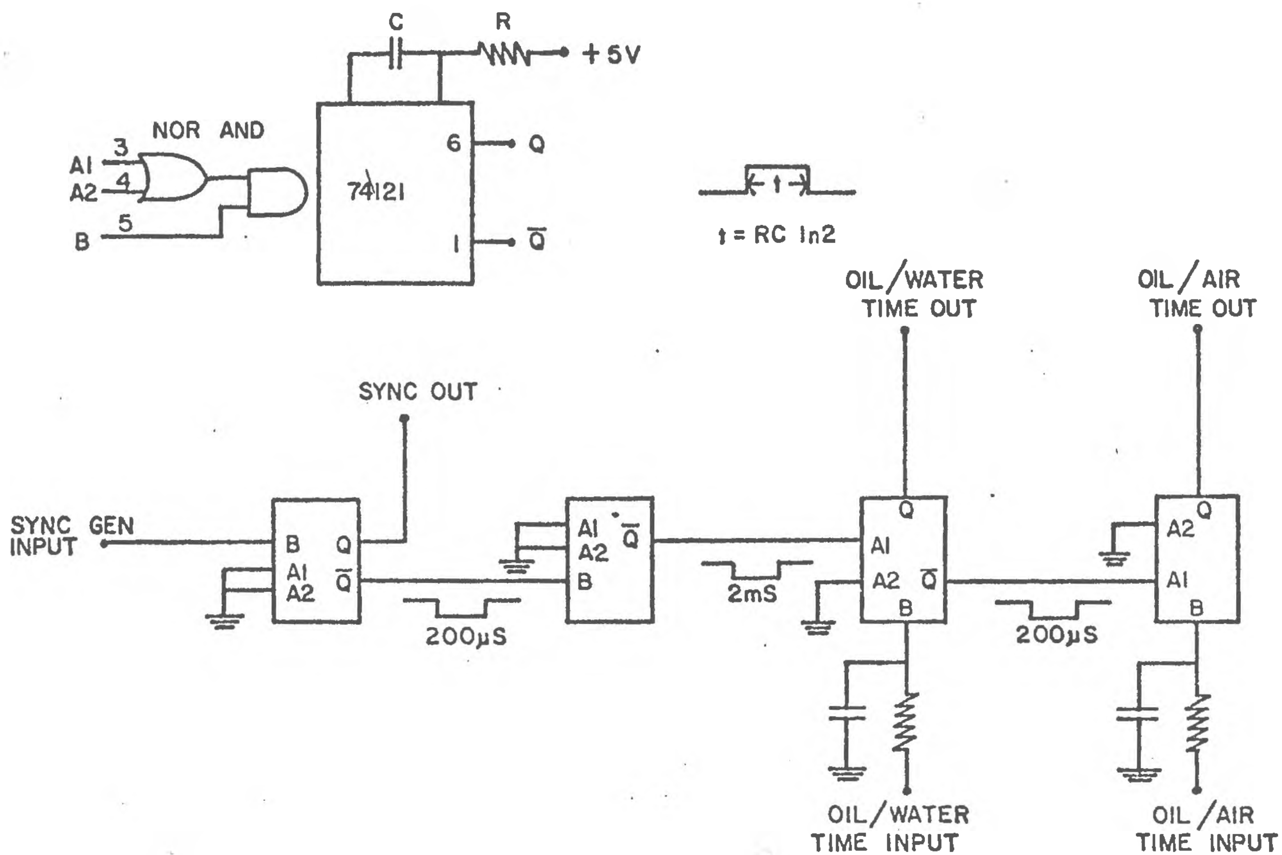
Receiver block diagram

Figure 16



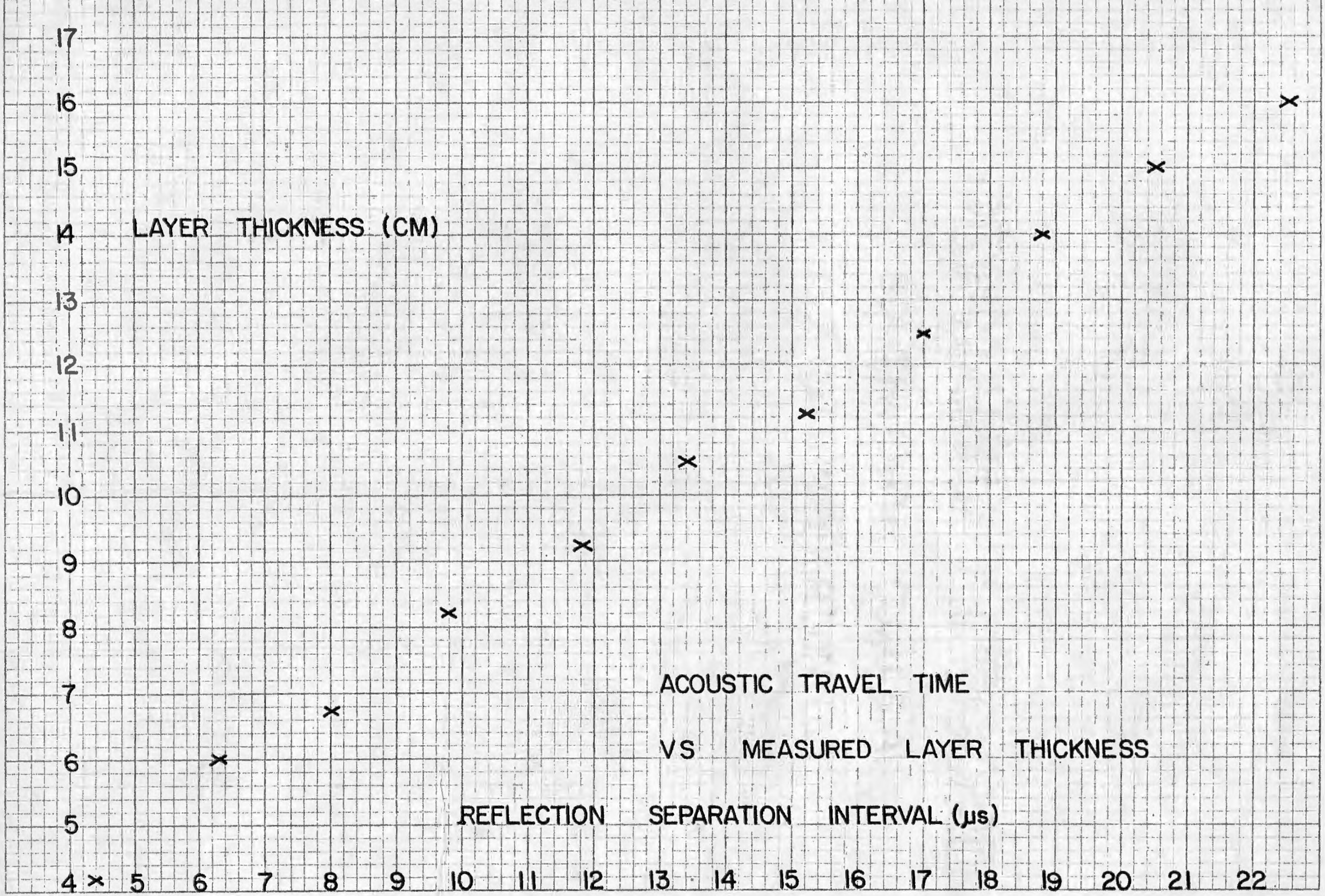
Receiver schematic diagram

Figure 17



Logic unit functional diagram

Figure 18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LAYER THICKNESS (CM)
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ACOUSTIC TRAVEL TIME
VS MEASURED LAYER THICKNESS
REFLECTION SEPARATION INTERVAL (μs)

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