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FEASIBILITY STUDY  
FOR AN UNDERWATER DETECTION SYSTEM

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ABERDEEN PROVING GROUND, MD<sup>29</sup>  
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by

R. Wayne Masters  
Antenna Research Associates, Inc.  
Beltsville, Maryland 20705

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Final Report

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Aberdeen Proving Ground, Maryland 21005

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PREFACE

This effort was sponsored by the US Army Land Warfare Laboratory, Applied Physics Branch, under the technical supervision of Mr. Louis V. Sargent. This task was designated 07-P-71, Detection of Submerged Targets.

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# UNDERWATER DETECTION SYSTEM

## 1.0 INTRODUCTION

### 1.1 Objective

The objective of the program was to develop a short range electrical detection system which could be mounted under water and automatically detect surface and sub-surface swimmers in fresh-to-salt waters ranging from about 3 to 20 feet in depth. The work was divided into three principal tasks, namely a system design study, a bread-board fabrication and field test, and the fabrication and field testing of a final model.

### 1.2 Review of Preceding Effort

The first two of the three tasks were accomplished and reported in the Final Report, 20 August 1971 (Contract No. DAAD05-71-C-0432). Briefly, the principles of electromagnetic wave propagation in water were reviewed with particular regard for the task at hand, and the available literature was scanned for information on antennas in conductive media. Several different system techniques were considered and analyzed, but all were eventually discarded except the differential cancellation system. This type of system was demonstrated as an unperfected breadboard model both in the contractor's 17-foot diameter circular pool facility and at an open-water location on Spesuti Island at the Aberdeen Proving Ground. The demonstration was very encouraging in the pool, but inconclusive in the open water. The reasons for the difference in performance between the two installations are obscure, but it is known that there existed large differences in water conductivity and boundary conditions, and that the breadboard model was far from optimized, especially for use under field conditions. A water sample from the Spesuti Island site had a measured conductivity of .175 mho/meter, which is within a factor of about two of that of man, so that a

swimmer without scuba tanks would not present much of a target. Considerable data were acquired in the ARA circular pool, and some experience was gained under open salt water conditions during a measurement trip to the Chincoteague Bay area in Maryland.

### 1.3 Additional Results

As a result of the earlier work, a follow-on contract was awarded which permitted an improved model of the underwater detection system to be built and demonstrated which embodied the best combination of design principles and parameters capable of being realized in hardware under the limited circumstances. This system was very responsive in a 16' x 32' x 3' deep rectangular pool of salt water whose conductivity was 3 mho/meter (sea water). The performance was surprisingly good in the brackish open water where the "field exercises" were held, considering the large differences in conductivity and operating conditions between that and the salt water swimming pool where the system was optimally tuned. Not only did the change of conductivity cause a bad antenna impedance mismatch, leading to a system loss in the order of 12 dB, but the enhancing effect of images present in the pool was largely absent. Also, a high background noise level due to mechanical instability of the antennas in the moving water was experienced which prevented a meaningful demonstration of the system in its more sensitive differential detection mode. The mechanical stability is not a basic problem; stakes or weights would probably have solved it for purposes of demonstration. Moreover, the detectability of a swimmer in brackish water is much less than in salt water because the difference in conductivity is less. Detectability depends primarily upon a difference in conductivity between object and medium.

The feasibility of the system was demonstrated without much question, but it was apparent that further development would be required to achieve a substantial increase in coverage and make it fully operational.

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## 2.0 PATH LOSS CALCULATIONS AND MEASUREMENTS

### 2.1 Theory and Calculations

An enormous amount of research has been done concerning antennas in lossy media. Most of it has been stimulated by the need for reliable communications during time of nuclear bomb or other violent military attack. These conditions impose hardening by burial in the earth or, in the case of submarines, deep submergence. In either case the communications problem is primarily one of maximizing the efficiency with which an antenna can launch energy from beneath the surface of the earth into a proper wave traveling above the surface. A direct path through the earth which is large compared to the antenna depth seems to be enormously lossy, compared to the up-and-over path, at all practical frequencies. Interest in so-called buried antennas peaked during the early 1960's, and an excellent reference<sup>1</sup> to the then-current work is the IEEE Transactions Special Issue on Electromagnetic Waves in the Earth. In the lead article, R.C. Hansen<sup>2</sup> presents a broad review of the development of such antennas and includes an extensive bibliography.

Although work has continued<sup>3</sup> on the general subject of antennas in lossy media, not a great deal of information exists as yet in the open literature which bears directly on the basic problems fundamental in the present program. It should be possible, however, to make good use of the work already done. Here, the object is to transfer energy most efficiently between antennas not very far apart in a conducting medium, and in such a way that the energy flow density is maximized in the space between the antennas. This implies an inherently efficient antenna oriented for minimum transfer of energy through the air/water interface. Since the objects to be detected are generally horizontally polarized, it is also implied that the conductive current field produced in the medium by the transmitting antenna should be purely horizontally polarized for maximum perturbation by the target. Also a straight path

through the system should involve a variation in azimuthal direction of the current polarization in order to catch both poorly and highly conducting objects regardless of their orientation. These requirements suggest the horizontal loop as the preferred type. However there is room for question when all the contributing factors are weighted, such as frequency, efficiency, directionality, purity of polarization and interface coupling factor. Perhaps neither is superior in general, and the dimensions of the system would be the deciding factor in a particular application.

R.K. Moore,<sup>4</sup> in an article in the aforementioned Special Issue, concludes that magnetic type antennas (loops) do not suffer increasing losses with decreasing distance from center at the same rate as do electric ones. Speaking with respect to subsurface antennas oriented for optimum transmission to a distant point through the interface, he also concludes that the gain of various small antennas in conducting media is about the same for antenna structures having about the same physical dimensions. In the same light, Hansen<sup>5</sup> states that the most effective antenna is the long wire, that is, an insulated horizontal electric dipole with terminal electrodes. This conclusion is based, no doubt, upon the fact that the wire antenna can be made electrically longer than a loop, so a long one should be a better wave coupler.

Regardless of the type of antenna used, certain factors relating to propagation must be recognized. In water having a conductivity  $\gamma \geq 0.01$  mho/meter, and for frequency  $\leq 2$  MHz, it develops that  $\gamma \gg \omega\epsilon$ , where  $\omega$  is the radian frequency and  $\epsilon$  is the absolute permittivity of the medium. If  $\alpha$  and  $\beta$  are the attenuation and phase propagation constants, respectively, and  $\mu$  is the absolute permeability of the

medium, it follows for a plane wave that the complex propagation constant  $\Gamma$  is

$$\Gamma = \alpha + j\beta \quad (2 - 1)$$

$$= \sqrt{j\omega\mu (\gamma + j\omega\epsilon)} \quad (2 - 2)$$

$$\doteq (j\omega\mu\gamma)^{1/2} \quad (2 - 3)$$

$$= (\omega\mu\gamma/2)^{1/2} (1 + j), \quad (2 - 4)$$

$$\text{or } \alpha \doteq \beta \doteq (\omega\mu\gamma/2)^{1/2}, \quad (2 - 5)$$

Thus, the wavelength  $\lambda$  is determined by  $\gamma$ , and not by  $\epsilon$ . Since skin depth  $\delta$  is the reciprocal of the attenuation constant, one has

$$\lambda = 2\pi\delta = 10^2 (\gamma f_{\text{KHz}})^{-1/2} \quad (2 - 6)$$

$$\delta = 1/\alpha \quad (2 - 7)$$

Similarly, the plane-wave characteristic impedance  $\eta$  of the medium is

$$\eta = \sqrt{j\omega\mu / (\gamma + j\omega\epsilon)} \quad (2 - 8)$$

$$\doteq (\omega\mu/2\gamma)^{1/2} (1 + j) \quad (2 - 9)$$

which has a phase angle of  $\pi/4$  radians. These expressions yield values which are surprising to the uninitiated. For example, the magnitude of  $\eta$  at 400 KHz in water of  $\gamma = 1.0$  mho/meter (brackish) is only 1.777 ohm. The corresponding wavelength is 5 meters, and the skin-depth is 0.83 meters. The attenuation is  $2\pi$  nepers (54.575 dB) per wavelength, or about 3.33 dB per foot. The accompanying graph of Figure 2 - 1 is convenient for determining  $\lambda$  and  $\alpha$  as a function of  $\gamma$  at 400 KHz.

$$\lambda_{400} = 5\gamma^{-1/2} \text{ meters}$$

$$\delta = \lambda/2\pi \text{ meters (neper length)}$$

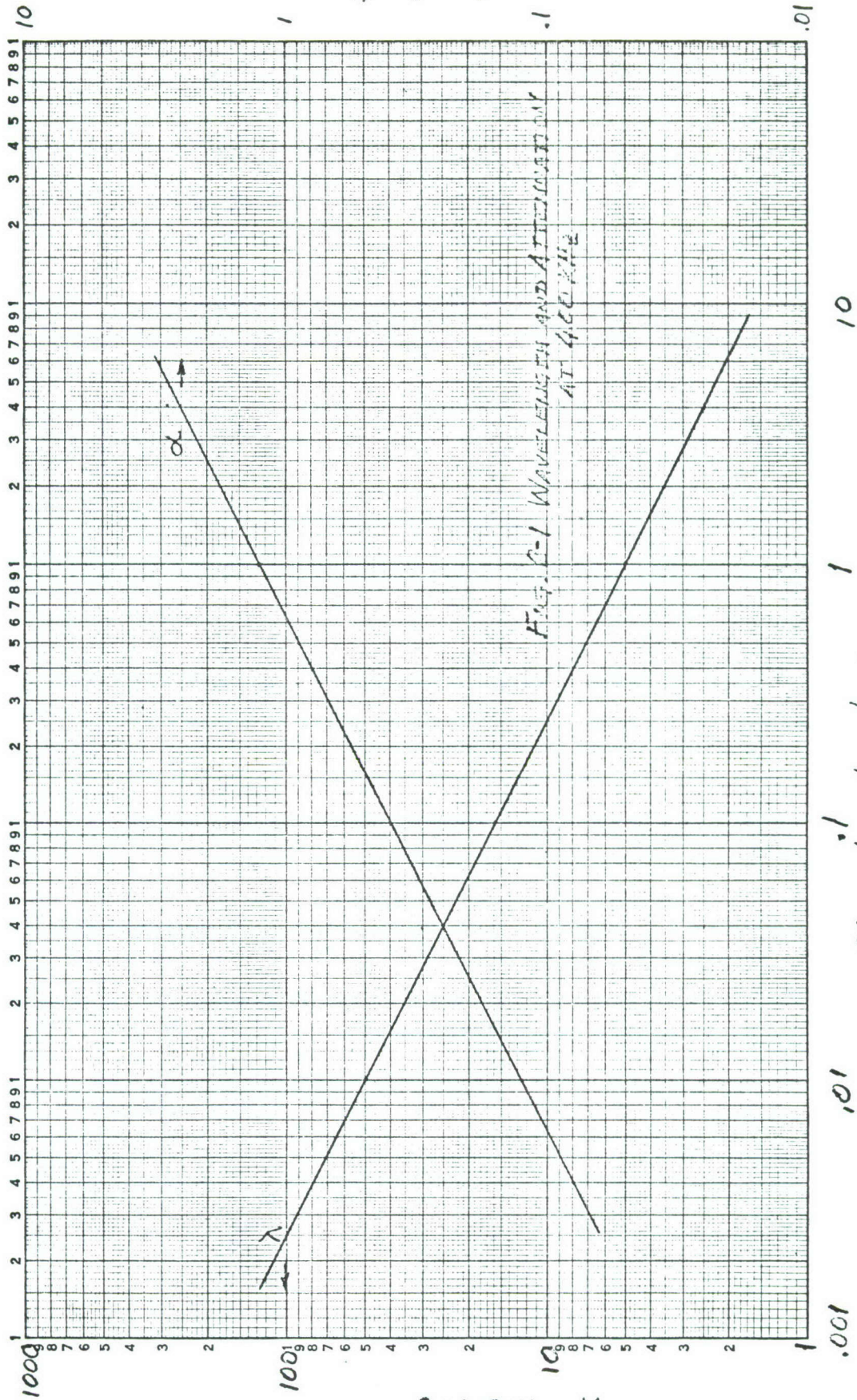


Figure 2 - 1

## 2.2 Measurements

During the month of April 1972, a full week was devoted to obtaining path loss and dipole impedance measurements in the Boca Lake area near Boca Raton, Florida. Pairs of dipoles having lengths of 10 ft., 25 ft., and 50 ft. were used for the tests. These dipoles were fully insulated from the water except for the tip ends which had a conductive surface of approximately two square inches in contact with the water. Each of the dipoles was equipped with a broadband, toroidal balun, exhibiting a 1:1 impedance ratio between input and output terminals. Coaxial cable (RG-58/U) having a length of from 10 ft. to 25 ft. was used to transport signals to and from the dipoles. These coaxial cables were fully insulated from the water by virtue of the vinyl outer jacket.

In each of the measurements, the dipoles were immersed in water having a depth of approximately 6 - 8 ft. The ends of the dipoles were positioned at approximately mid-depth in the water by using wooden stakes of appropriate length that were hammered into the soft bottom of the lake to secure them in place. It was determined by measurement of samples taken from this lake, during both tide periods, that the conductivity of the water averaged about three mhos per meter. The dipoles were oriented parallel to each other as accurately as could be managed under the circumstances accompanying the measurements. Each set of tests was repeated in order to achieve the best possible accuracy. However, taking measurements from two boats in a salt water environment presents an unusual challenge that defies even the best organized and most ingeniously constructed plan. Despite the problems encountered, however, it is believed that the measurements that were made present a reasonably accurate indication of typical losses within both brackish and salt water environments with dipoles of the type used in taking

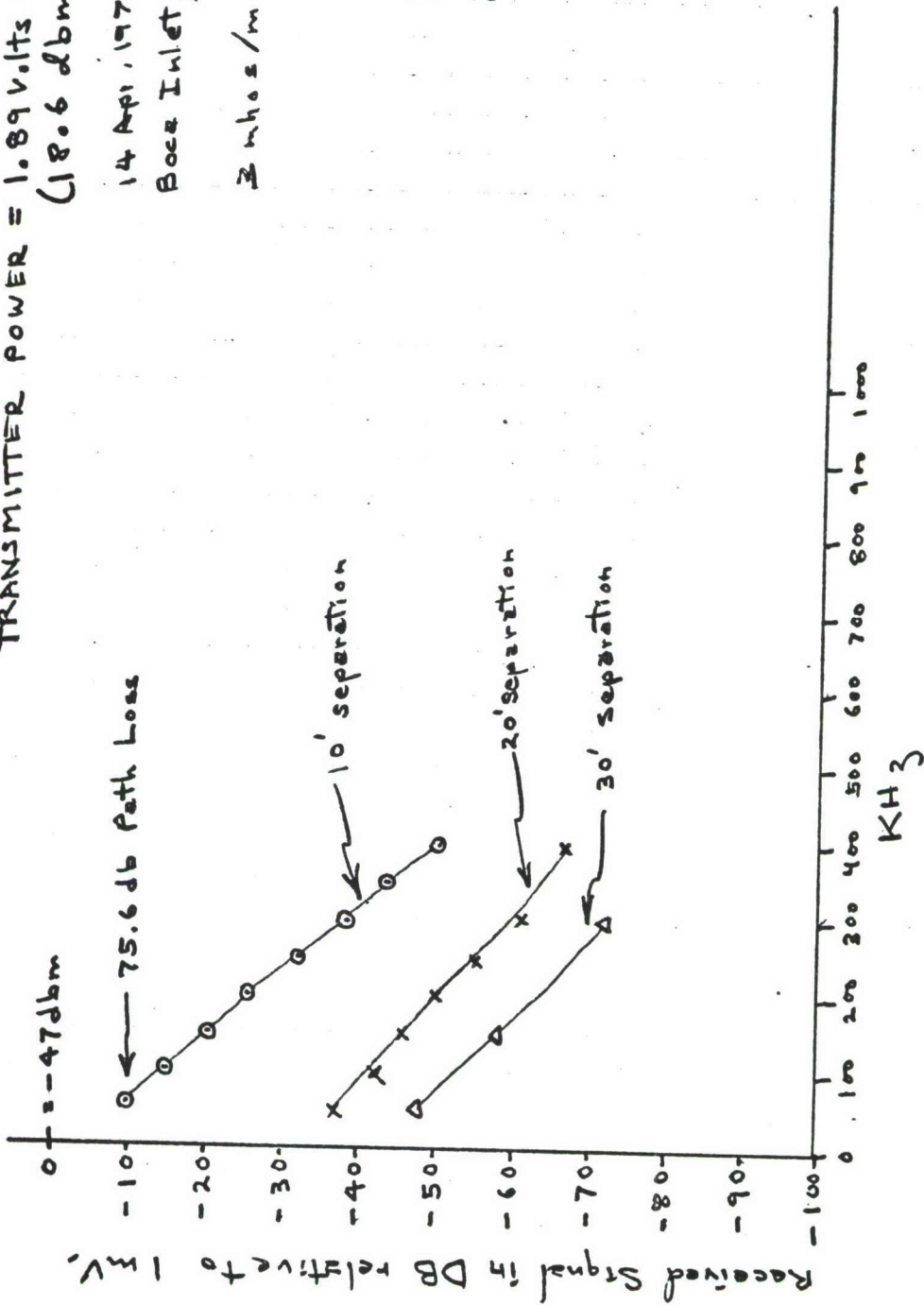
the subject measurements. Figures 2 - 2 thru 2 - 12 depict the results of the measurements made in Boca Lake.

Briefly, the results of the measurements appear to indicate that a dipole having a length of from 20 to 25 ft., operating at a frequency of about 300 to 400 KHz, is perhaps the best overall compromise for a simple underwater detection system in salt and brackish waters. It is obvious from examining the various graphs that no significant difference in path loss was observed between the 25 ft. and 50 ft. long dipoles over a path distance of 50 ft. at 400 KHz. At 200 KHz the difference between the 25 ft. and 50 ft. dipoles was only 4 dB over the same 50 ft. distances. The path loss at 200 KHz was only about 8 dB less than at 400 KHz. However, earlier measurements in the ARA indoor pool seemed to indicate that frequencies in the range of 300 to 500 KHz provided the best detection capability for a human body within salt or brackish waters.

TRANSMITTER POWER = 1.89 volts into 50Ω  
(18.6 dbm)

14 April, 1972  
Boez Inlet, Flz.

3 mhos/m



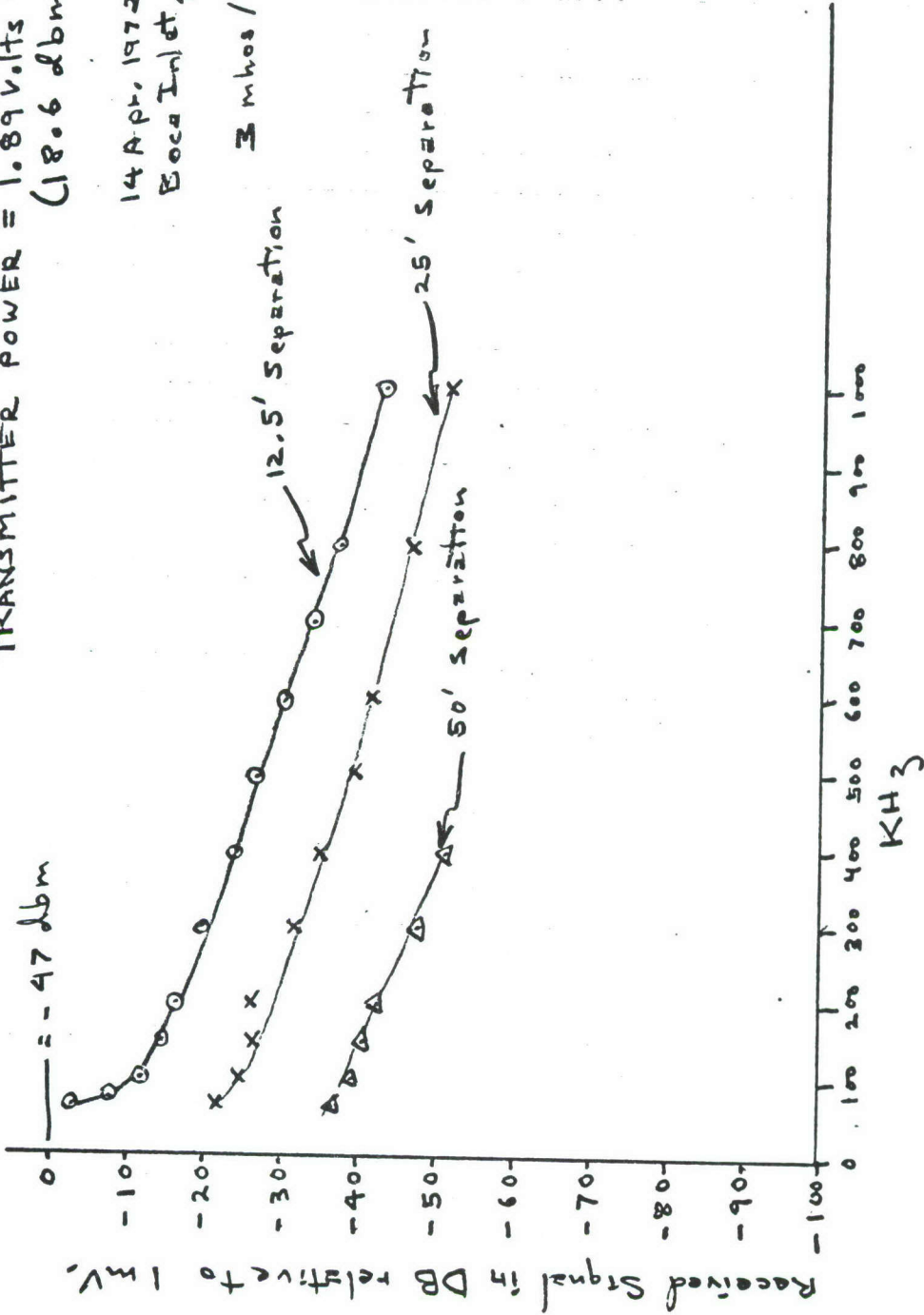
10' LONG DIPOLES IN 2 METER DEEP  
WATER APPROXIMATELY 1 METER BELOW  
SURFACE

FIG. 2-2

TRANSMITTER POWER = 1.89 Volts into 50Ω  
 (18.6 dbm)

14 Apr. 1972  
 Boca Inlet, Fla.

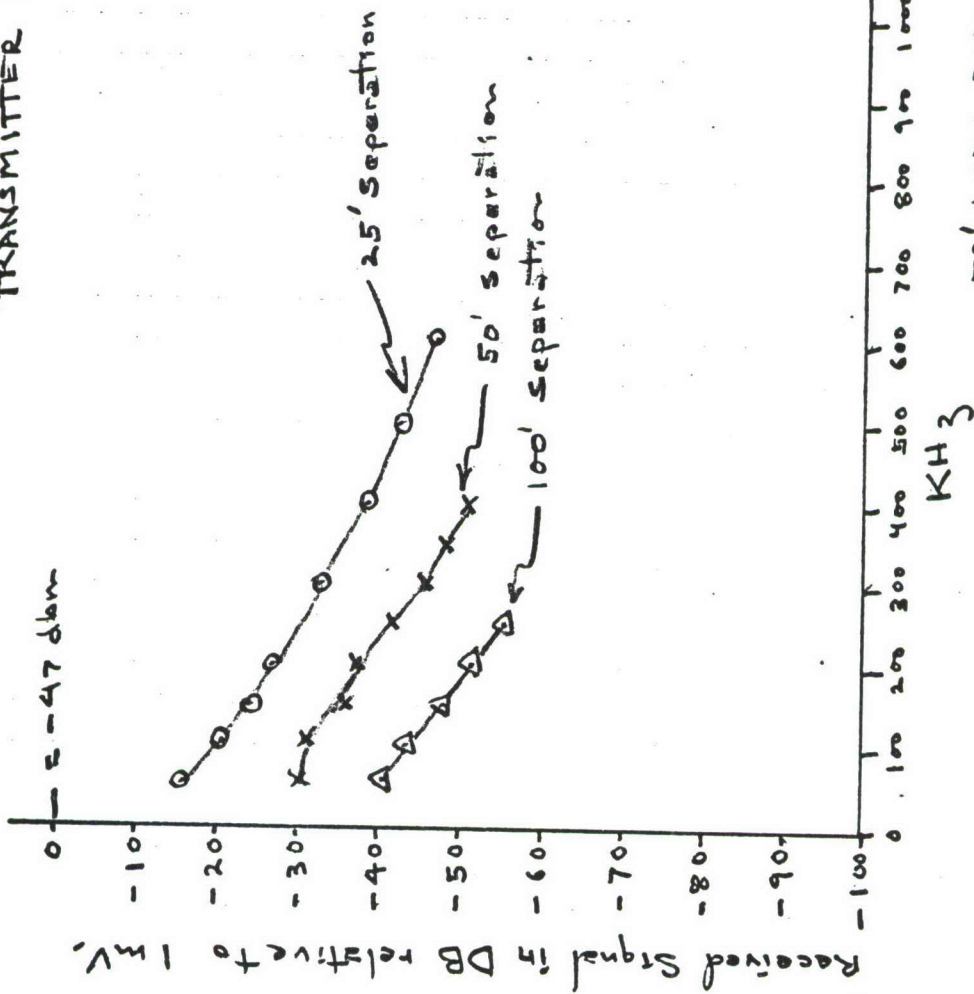
3 mhos/m



25' LONG DIPOLES IN 2 METER DEEP  
 WATER APPROXIMATELY 1 METER BELOW  
 SURFACE.

TRANSMITTER POWER = 1.89 volts into 50Ω  
 (18.6 dbm)

14 Apr. 1972  
 Boca Inlet, Fla.  
 3 mhas/m



50' LONG DIPOLES IN 2 METER DEEP  
 WATER APPROXIMATELY 1 METER BELOW  
 SURFACE.

FIG. 2-4

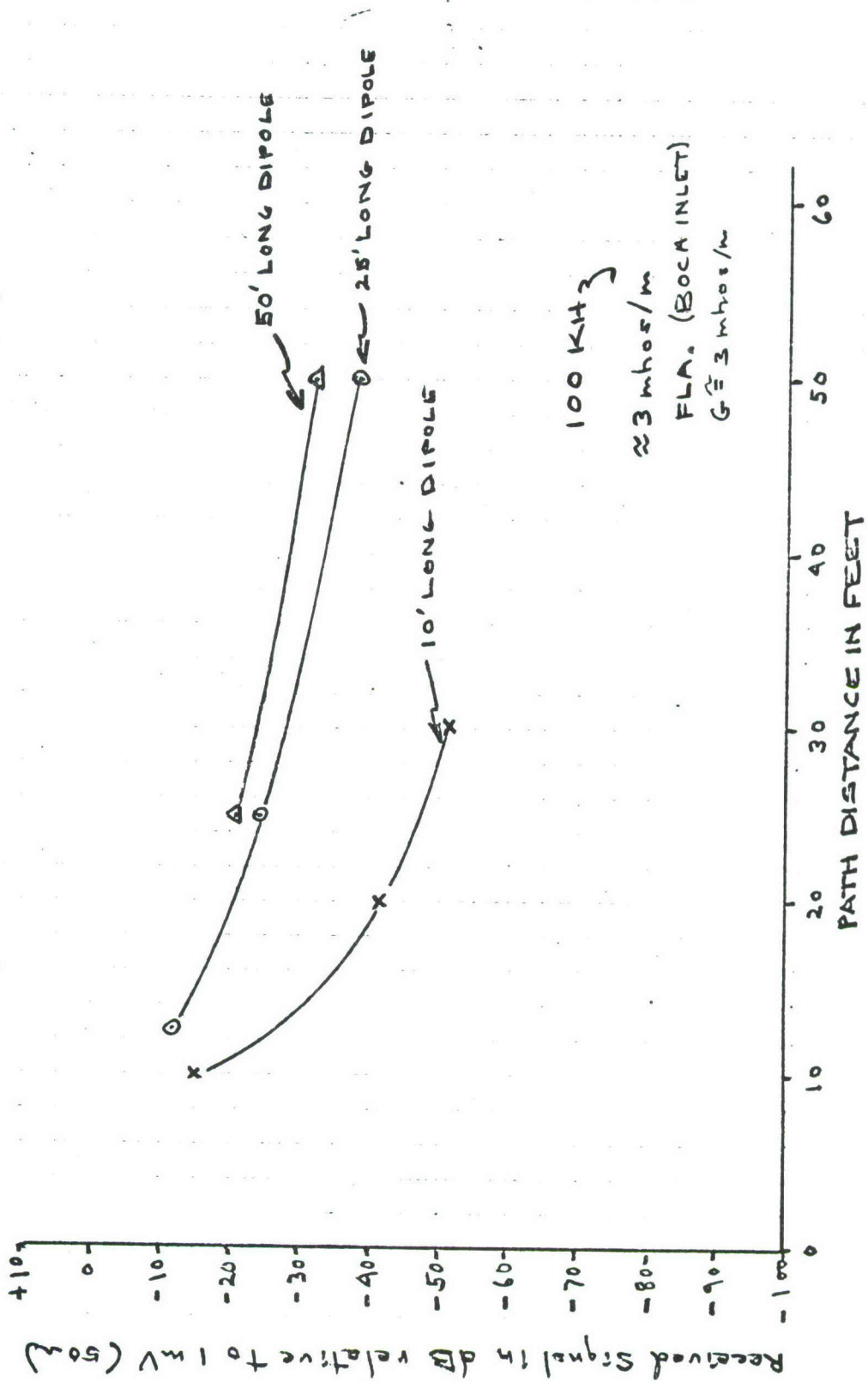


FIG. 2-5

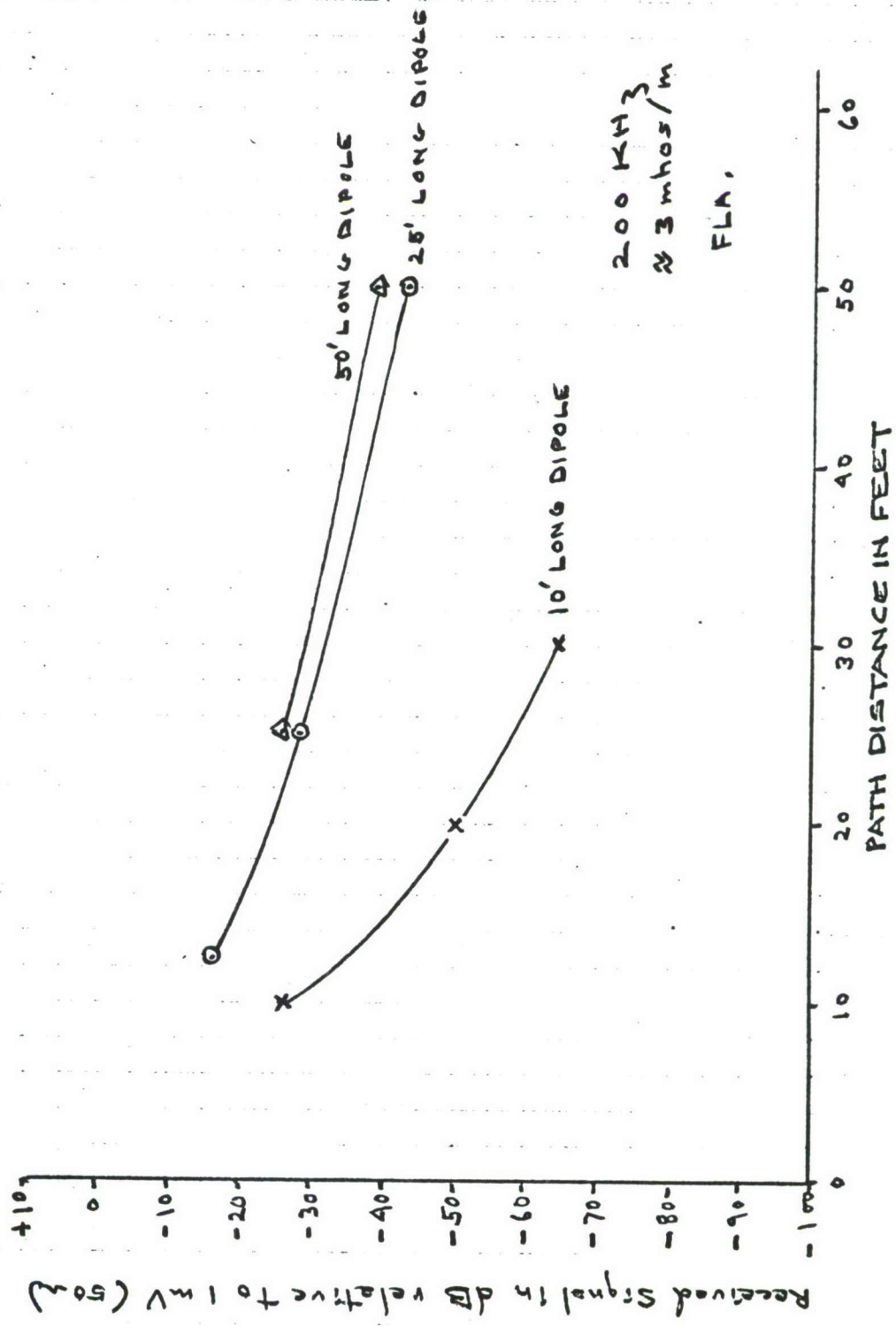


FIG. 2-6

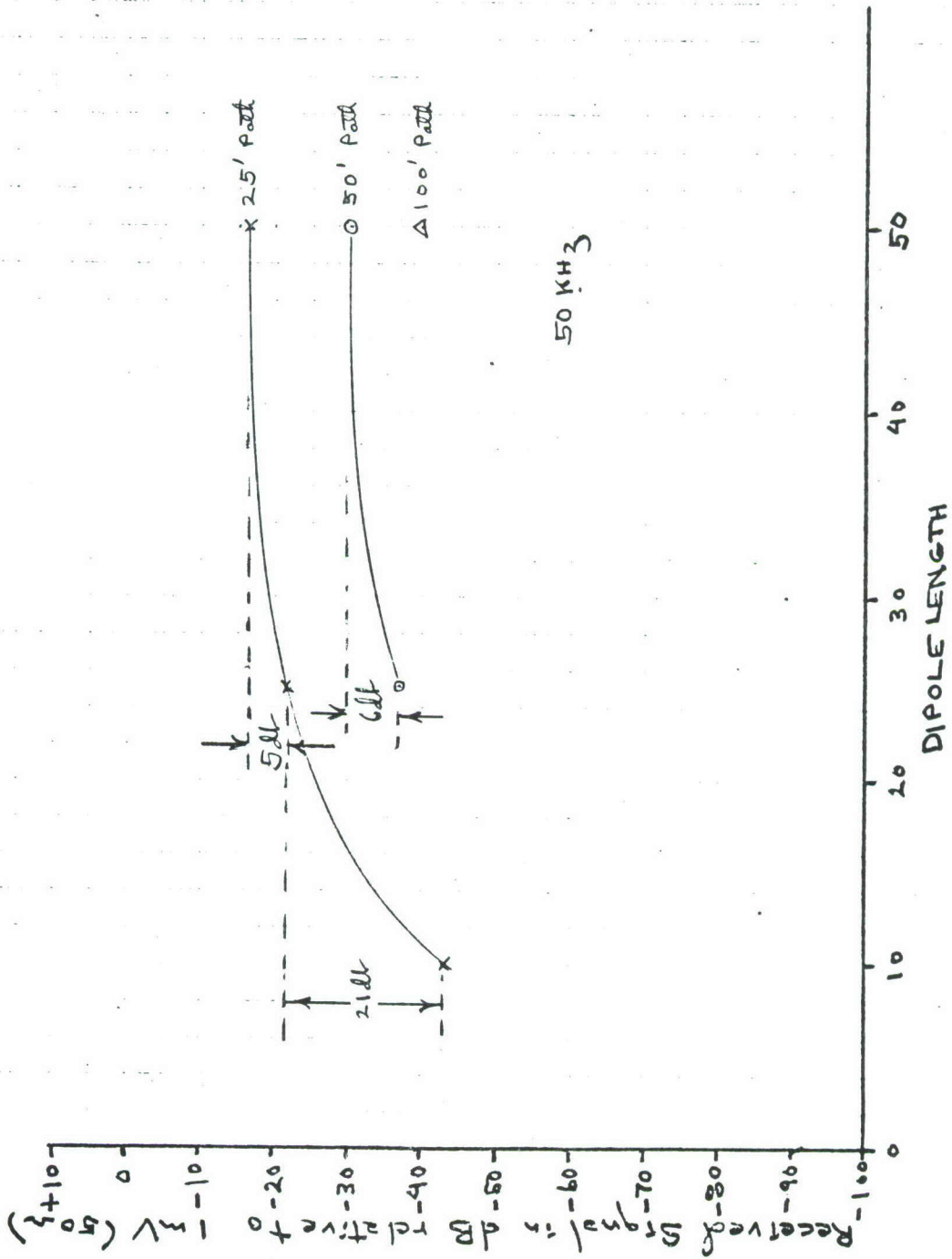


Fig. 2-7

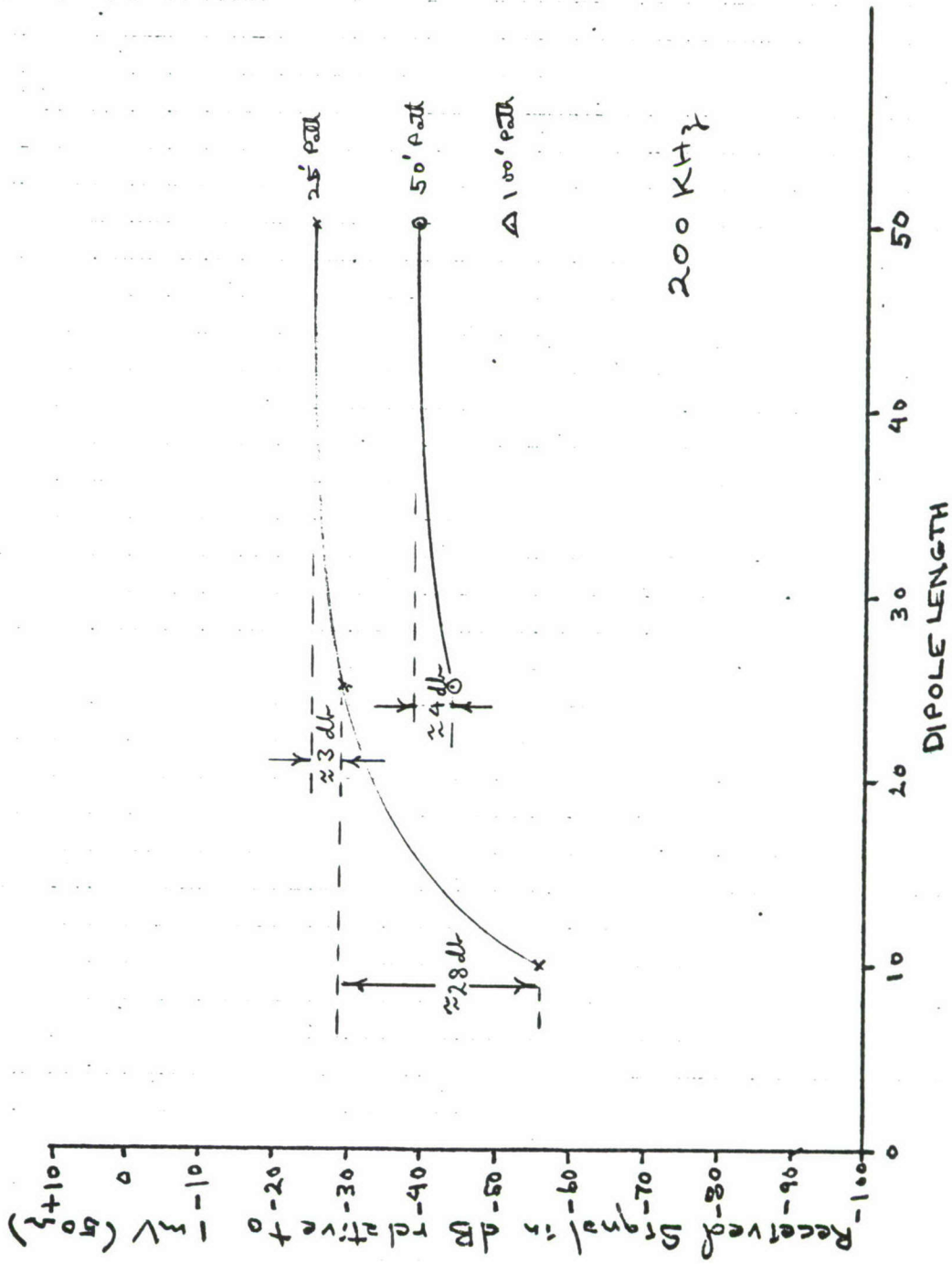


Fig. 2-8

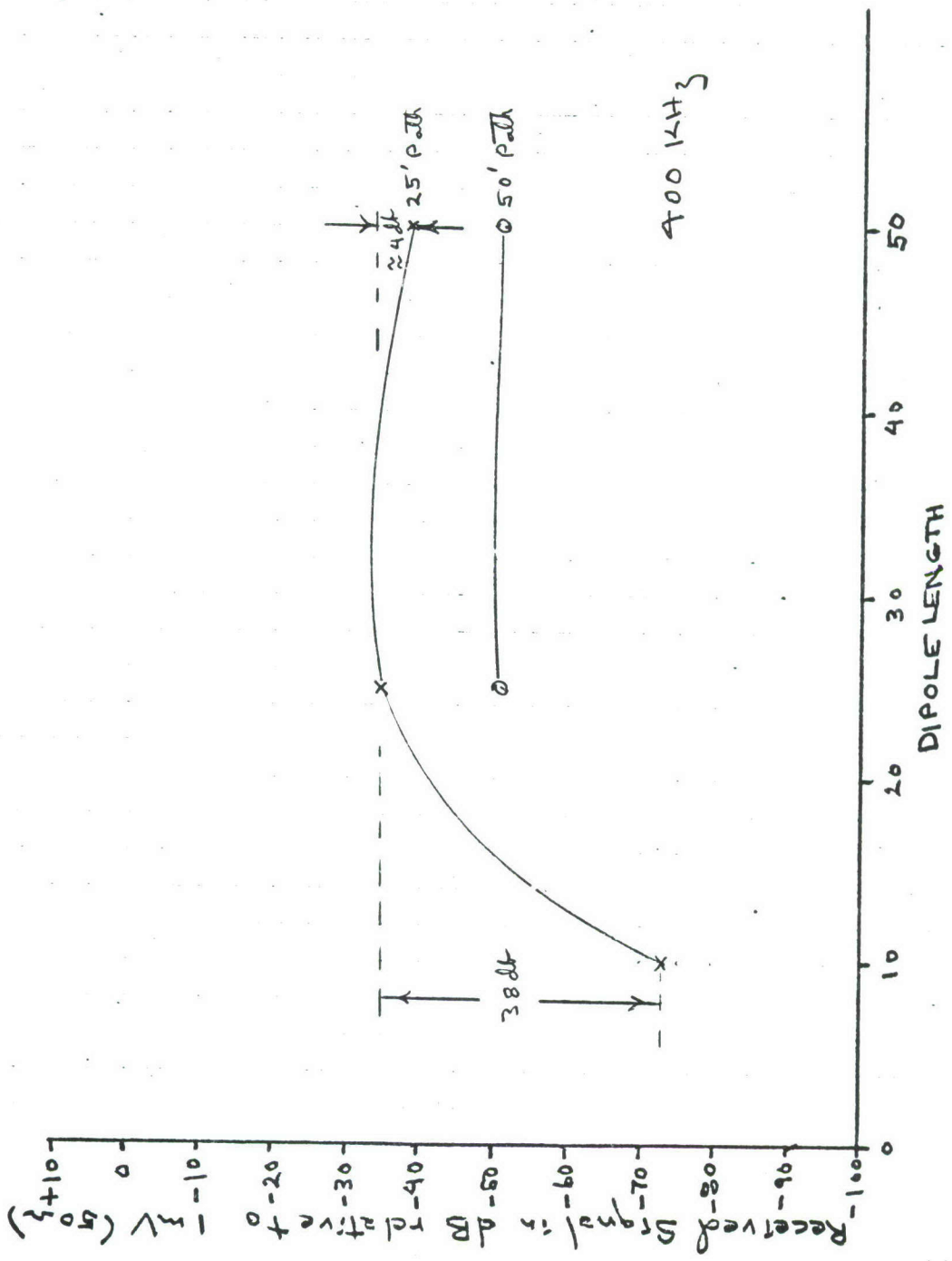


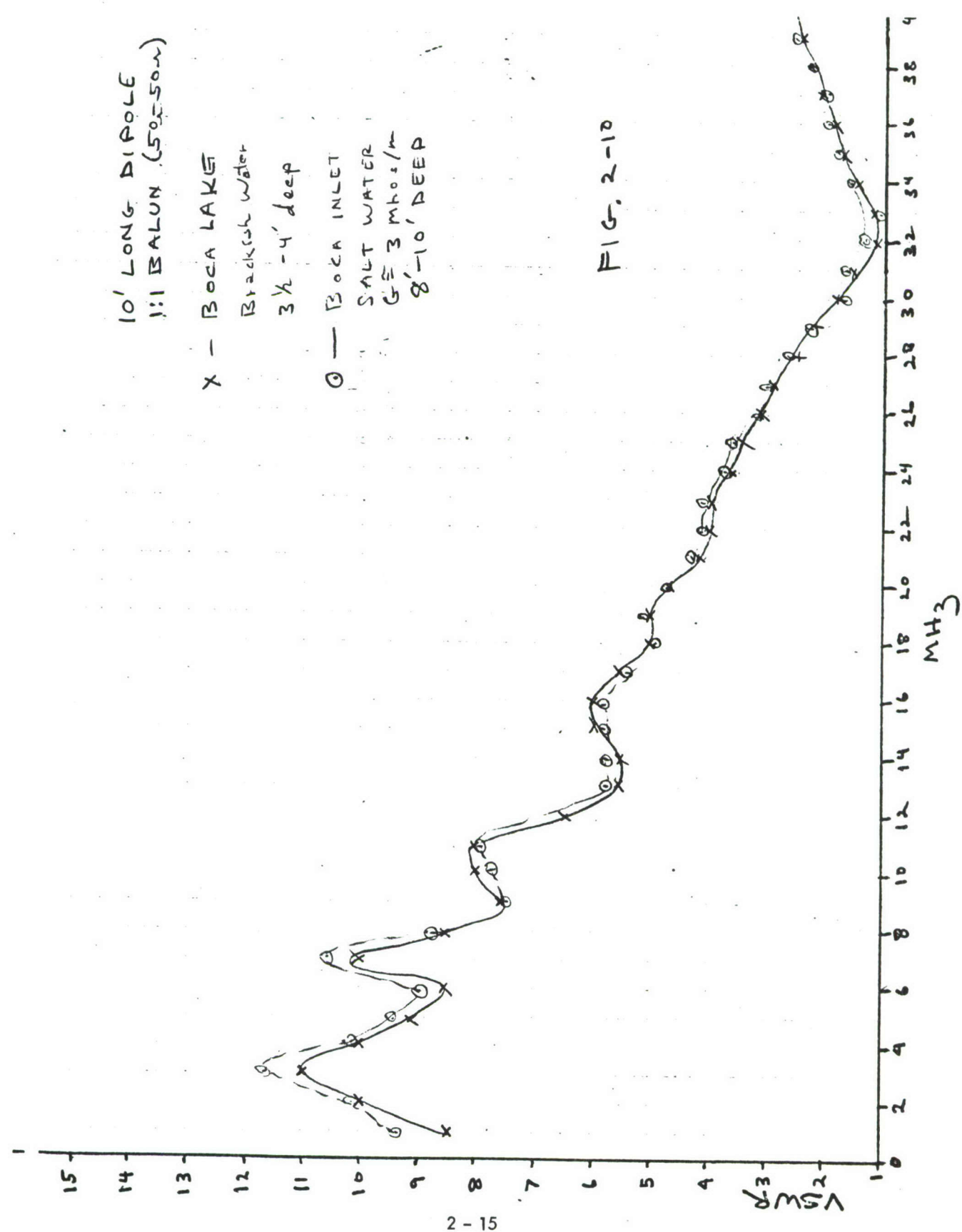
Fig. 2-9

10' LONG DIPOLE  
 1:1 BALUN (50-50m)

X - BOCA LAKE  
 Brackish water  
 3 1/2 - 4' deep

O - BOCA INLET  
 SALT WATER  
 GE 3 MHOS/M  
 8'-10' DEEP

FIG. 2-10



25' LONG DIPOLE  
 1:1 BALUN (50Ω - 50Ω)

X - BOCA LAKE  
 (BRACKISH WATER)  
 3 1/2 - 4' DEEP

O - BOCA INLET  
 SALT WATER  
 G = 3 MILES / hr  
 8' - 10' DEEP

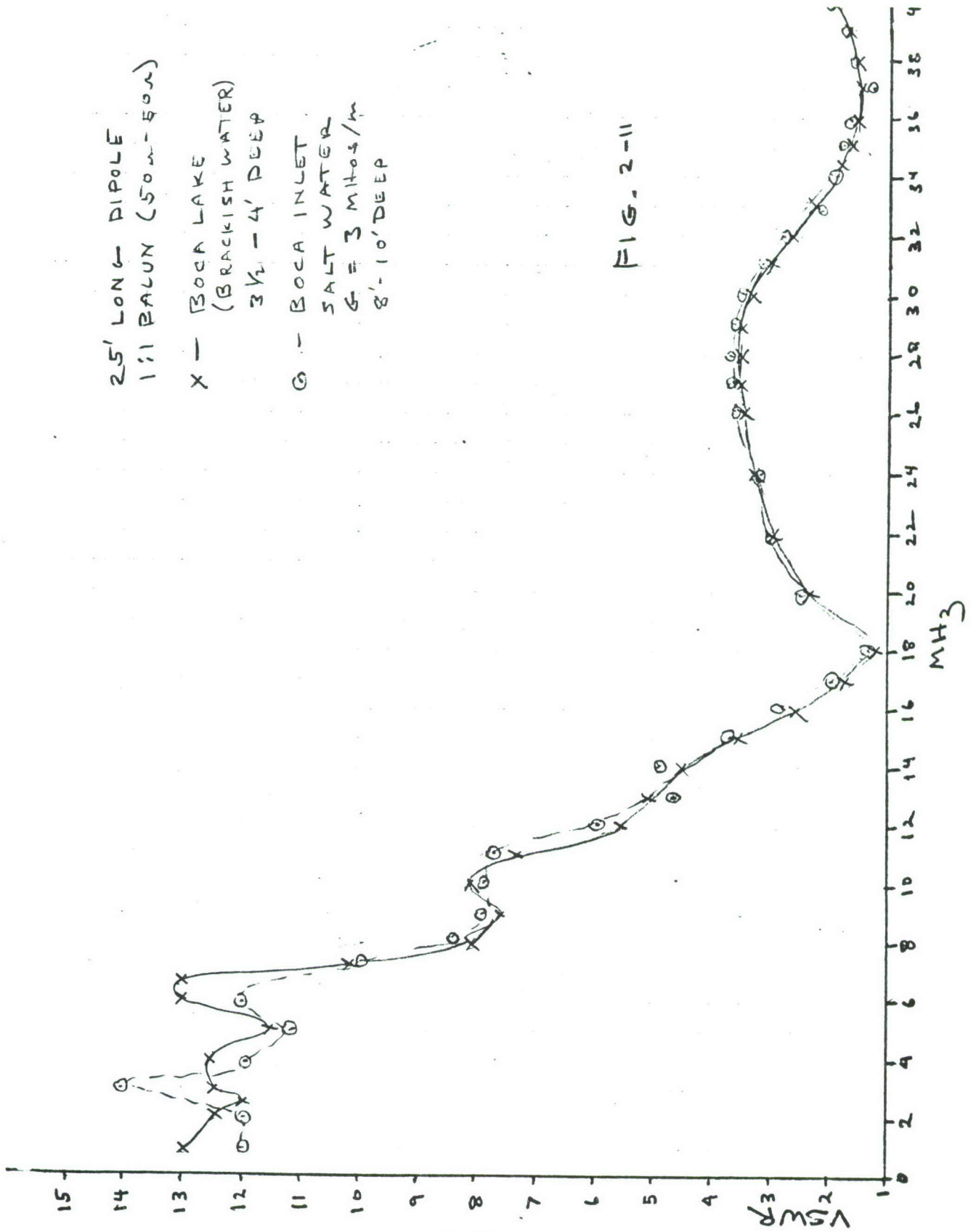


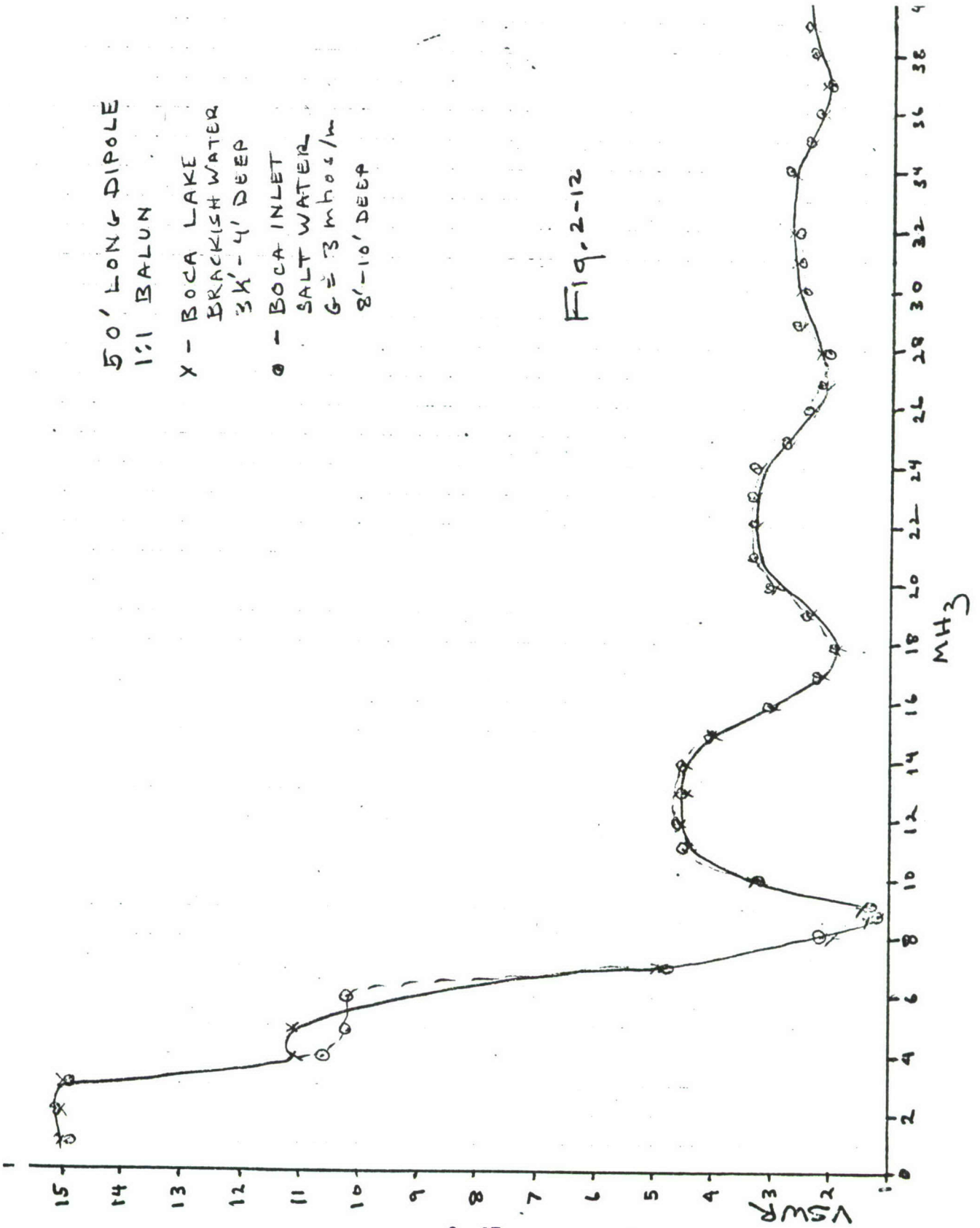
FIG. 2-11

50' LONG DIPOLE  
1:1 BALUN

X - BOCA LAKE  
BRACKISH WATER  
3K' - 4' DEEP

O - BOCA INLET  
SALT WATER  
G = 3 mhos/m  
8' - 10' DEEP

Fig. 2-12



PATH LOSS MSMTS.

POOL = 3.0 mho/m

10 ft. Fiberglass Dipoles - Grounded At ends

Wavetek, B & K, Textron Attenuators, Weston VOM #2

Spacing 10 ft., 20 ft., Depth ~18", Pool Depth 36"

KHz	Path Loss P.L. dB	Path Loss dB
	10 ft. spacing	20 ft. spacing
50		
100	-62.0	-77.0
150	-63.5	-78.0
200	-64.0	-79.4
300	-66.2	
400	-67.5	
500	-68.2	
600	-68.4	
800	-73.3	
1000	-76.25	
1200	-80.00	
1500	-84.0	
2000	-89.0	

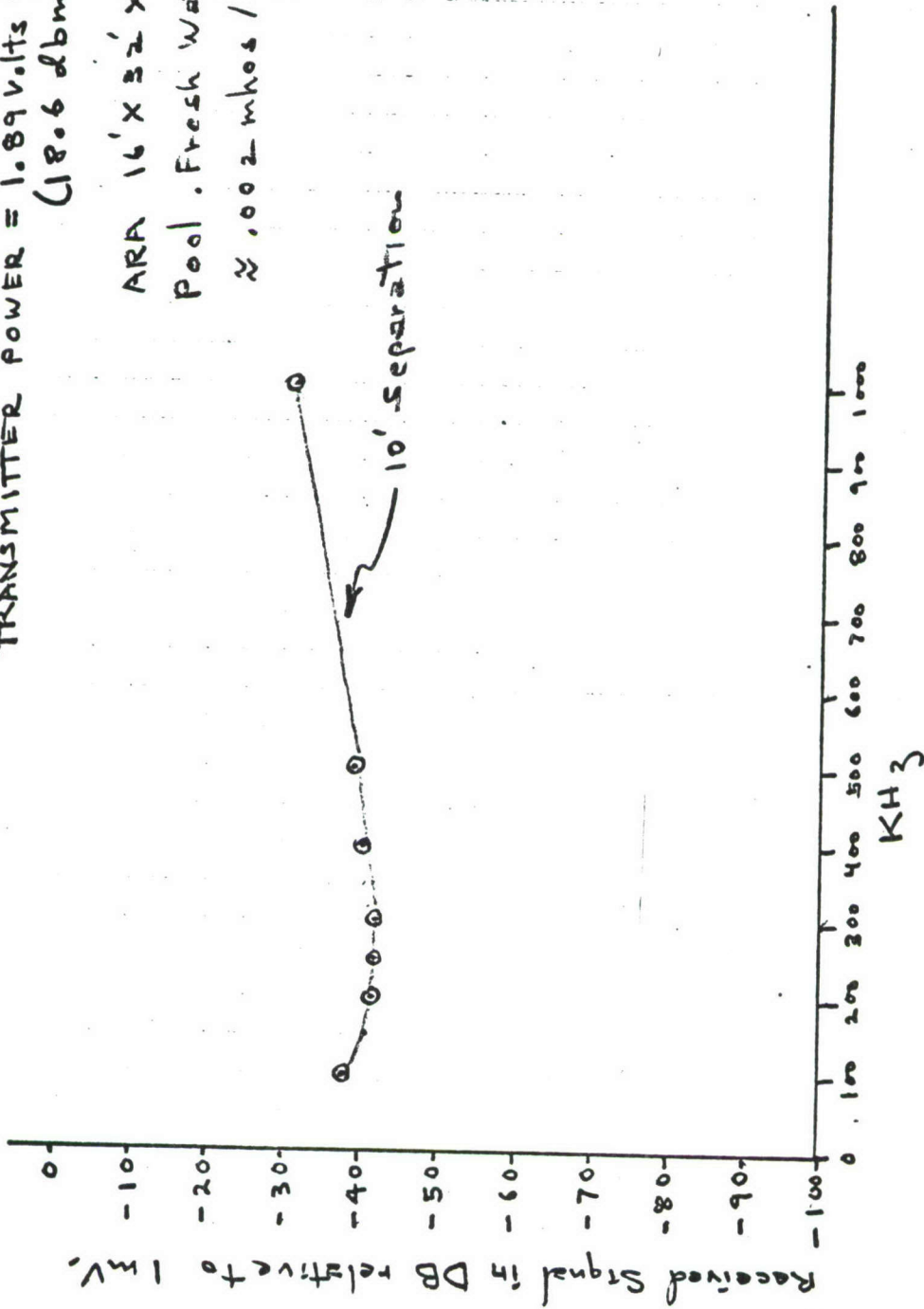
TABLE I

TRANSMITTER POWER = 1.89 Volts into 50Ω  
(18.6 dbm)

ARA 16' X 32' X 3'

Pool. Fresh Water

~ 1,002 mhos/m



10' LONG DIPOLES IN 3' DEEP WATER  
APPROXIMATELY 1.5' BELOW SURFACE.

FIG. 2-13

### 3.0 DESCRIPTION OF THE SYSTEM

#### 3.1 System Design Rationale

The system has been designed in such a way as to embody as many known favorable factors as possible. For example, to minimize the devastating effect of path attenuation upon electro-magnetic waves in a conducting medium it is essential to use a method based on one-way propagation, as contrasted with a two-way (radar-type) system where the path attenuation is effective twice.

Further significant minimization of the path attenuation is accomplished for a given coverage width by using a differential cancellation system which transmits in opposite directions from center to a receiving antenna on each side. The received signals are balanced against each other for a null response in the quiescent state. An unbalanced (i.e., alarm) occurs when the amplitude or phase of one of the signals is sufficiently altered by the entrance of some object in the radio field. It is important that both amplitude and phase are involved, since a system depending upon either one alone is probably less secure. This version of a cancellation system, simple as it may sound, is much superior to one using only a single receiving antenna and a local reference signal from the transmitter to achieve cancellation. For a system of the same outside dimensions, the difference is nominally by a factor of two in the number of dB of attenuation of the transmitted signal upon arrival at the receiving antenna. This difference is very substantial when one considers the high attenuation rate in water even of low conductivity.

In natural waters ranging from rivers to oceans, the attenuation rate for plane electromagnetic waves is  $2\pi$  nepers (54.6 dB) per wavelength. Wavelengths are

relatively short in water of conductivity  $\gamma \geq 0.01$  mho/meter, or greater, as seen from the formula

$$\lambda = 10^2 (\gamma f_{\text{KHz}})^{-\frac{1}{2}}, \text{ (meters)}$$

whence, for example one obtains 5 meters for the wavelength at 400 KHz in water of 1 mho/meter conductivity (brackish). Thus a symmetrical system two wavelengths wide between the two receiving antennas is nominally 54.6 dB above one of the same size using only one receiving antenna. These approximate calculations include only the dispersive aspects of the medium, and neglect entirely the attenuation which would be due to cylindrical or spherical divergence of the waves. This would enhance the difference.

Other system economies of signal include using a configuration which minimizes the volume required to monitor a given passageway so as to maintain maximum energy density, so to speak, at the gate. The cancellation system using two receiving antennas is better in this respect than one in which only one receiving antenna is used, because the transmitted signal does not fill so much volume before arriving at the receiving antenna. That is, the spherical or cylindrical divergence is less. The same reasoning applies for the signal produced by the target.

From the standpoint of null stability, it can be argued that the symmetrical cancellation system is superior to the one-sided type using a local reference. Changes in water level and salinity will affect the balance much less in the symmetrical system than in the other. The same can be said for electrical interference, although the vulnerability to that is not so great if the system is properly tuned and well filtered.

The choice of operating frequency for a given proposed system is partly a matter of transmission path length and partly a matter of the characteristics of the most probable,

or, rather, the minimum size threat. Certainly, an adequate signal to operate the system must always be present at the receiving antenna, which places an upper limit on frequency for a given size of system in view of the transmitter power, receiver sensitivity and conductivity of the medium. A requirement in any case is for the signal scattered by the target to be large enough at the receiving antenna location to be detectable.

Three separate, but overlapping, frequency ranges must be considered for the system. The first is that for which the path distances are, for the most part, many wavelengths in the medium. The second is that for which the system spans only a very few wavelengths. And the third is the quasi-static case in which the transmission path is less than about  $1/10$  wavelength in the medium.

The first possibility for a choice of frequency can be dismissed almost immediately because of the enormous path attenuation in a conductive medium. The path attenuation increases as the square root of the frequency, whereas the scatter cross section of a given target tends to approach a constant value. The second possibility has its best chance of success at frequencies where the assumed target would reach its first maximum scatter cross section in the physical optics sense. In the case of a relatively good elongated conductor, this should occur when the target size is somewhat less than one-half wavelength. As the frequency decreases, the radar scatter cross section should become Rayleigh, that is, essentially proportional to the inverse fourth power of the wavelength. The third (quasi-static) possibility is essentially frequency independent except for the upper limit roughly imposed by the system size and water conductivity. In this case, all signals decrease approximately as the inverse cube of the distance from the source. The signal produced by the target is proportional to the signal incident upon it and to the cube of its dominant dimension.

The allowable upper limits on frequency in the static case are likely to be very low. For example, the maximum frequency would be about 50 Hz for a symmetrical system having a total span of 40 meters in sea water ( $\gamma = 5$  mho/m). The corresponding upper frequency limit for the same size system in water having a conductivity of only 0.01 mho/m is more like 1 KHz.

It is appropriate here to comment on the obvious with respect to the loop and to the electrode-pair type of dipole at quasi-static frequencies in a conductive medium. Since the detectability of a given target at a given location in the medium is proportional to the current density and polarization at the location, one fundamental factor in determining the type of antenna is the relative efficiency and practicality with which a conductive current field of specified density and polarization can be generated. In the case of the grounded dipole of specified design, this is primarily a matter of maintaining a constant current magnitude at the input terminals, regardless of how low the frequency, including d.c. The situation is not the same for a loop, since the current field must be induced by varying the magnetic flux density. For a loop of given design, the product of frequency and current must be held constant. A loop at steady-state d.c. will not produce a conductive current field in a dissipative medium for any finite value of current. Thus the quasi-static loop may have to be physically large, contain a large number of turns, or carry a large current, any or all of which factors may render the loop impractical compared to a simple grounded dipole.

For the purposes of the feasibility model, a frequency of 400 KHz was chosen which rendered a 5-foot target object approximately one-half wavelength long in water having a conductivity of 3 mho/m. This represents a mid-range choice, since the experimental system is only about 12 feet or so in width, and spans only about one wavelength.

This frequency was also convenient from the standpoint of the electronics. The static case was not seriously considered, but, at the same time, it was not thrown out as a good possibility for some applications.

As to the choice between dipole or loop for the type of antenna, there seems not to be much to govern as long as the properties are satisfactory and suitable to the function of the system. Dipoles were chosen for the ARA feasibility model, primarily because they are more amenable to experimental variation than loops. It is conceivable that loops, being magnetic field devices, might couple more naturally and efficiently to the low-impedance medium than dipoles. This is an area that merits further study.

Loops would be deployed on the same plan as dipoles, lying flat on the bottom and equally spaced in a straight line. This orientation is the most favorable for the detection of an underwater swimmer because all the current stream lines are horizontal loops, whereas those of a dipole possess a vertical component throughout much of the volume, which vertical component probably represents largely wasted energy. Also, the loop in horizontal orientation (axis vertical) is at minimum coupling with respect to the excitation of electro-magnetic waves above the surface of the water, hence practically all of the radiated power is confined to the underwater medium. The opposite is true for the horizontal dipole, which is in the optimum orientation for coupling energy out of the water into a wave above the surface.

In designing antennas for use in a conductive medium, it is important to minimize losses incurred in the antenna itself and in the volume immediately surrounding all conductors. In the case of a dipole grounded to the medium at the ends, this

implies large-surface electrodes and low-loss transmission lines (dipole arms) out to them. The loss in the quasi-transmission lines comprising the dipole arms is minimized by making the wires as large in diameter as practicable and surrounding them with as thick a low-loss dielectric shield as feasibility permits. In the case of a loop, one has the same problem with respect to the wire diameter and its insulation. Also, the loop should be as large in diameter as feasible to minimize near-field eddy current losses due to intense magnetic induction fields perpendicular to and in the plane of the loop. In either case, the antenna impedance must be matched to the transmitter or receiver at some point along the transmission line, the nearer to the antenna the better. The dipoles of the ARA feasibility model were obviously not optimized with respect to efficiency, since the arms consist merely of small-diameter rubber-covered wire.

### 3.2 Power Source

The detection system delivered under the contract is powered by a 400 KHz crystal-controlled r.f. oscillator followed by an amplifier with a 1 KHz modulation. The design objectives were to achieve an average power output of about 1 watt of modulated signal power with as small a package as practicable. The system was to operate on 24 V. d.c. and to have an output impedance of nominally 50 Ohms. These objectives were accomplished for the most part with the exception that a 12 volt system turned out to be more suitable.

The circuit used for the oscillator and amplifier is shown in Figure 3 - 1. The crystal stabilized r.f. output of the oscillator is fed into the gate of a FET, where it is amplified and stored in a tuned circuit. The signal is then introduced

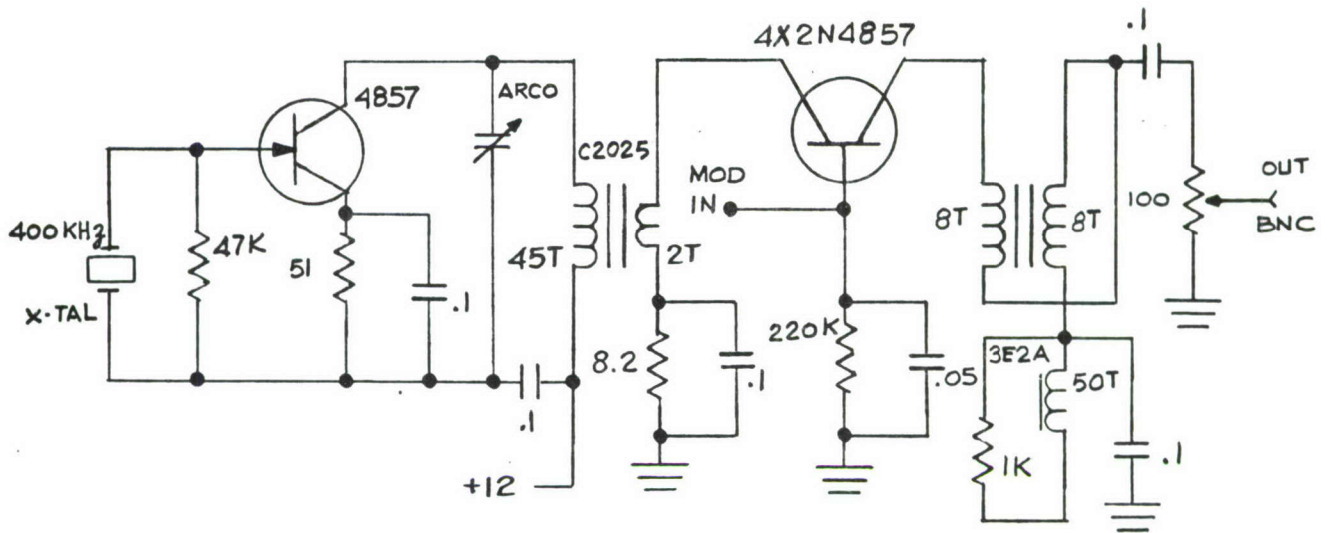


FIG 3-1 OSCILLATOR (400KHz)

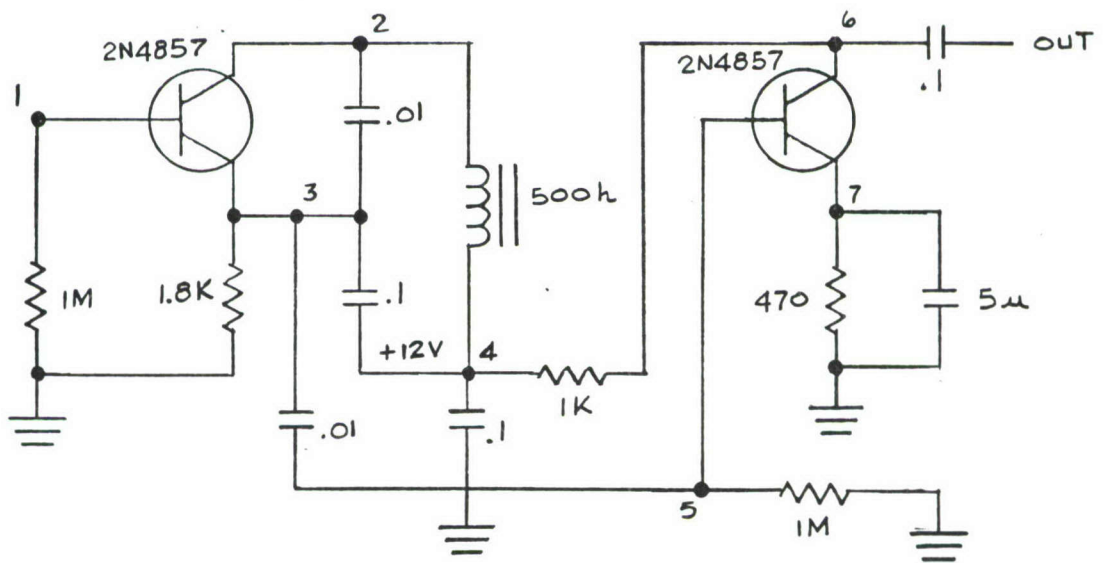


FIG 3-2 MODULATOR (1KHz)

to the source circuit of four FETs working in parallel, at the gates of which is applied the 1-KHz modulation frequency.

The 1-KHz modulator circuit is shown in Figure 3 - 2. It was laid out on a separate circuit board, but included in the same enclosure as the oscillator.

### 3.3 Antennas and their Deployment

The system employs three electric dipole antennas whose construction differs somewhat from that of the half-wavelength dipole ordinarily used in air. One of the dipoles is used to transmit, and the other two are used in phase opposition to receive. The best possible disposition of these three antennas is to place the two receiving dipoles equidistant from the transmit antenna and as far apart from each other as the sensitivity of the system will permit. This plan is shown in Figure 3 - 3.

The reason for this particular arrangement is to achieve the maximum separation between signal paths from the transmit antenna to each of the two receiving ones. It also minimizes the propagation path length, and hence the loss. This yields the maximum difference, or imbalance, signal produced by a body entering the otherwise balanced (nulled) system.

The construction of each of the three dipole antennas is identical in the delivered model, but it is not necessary that the transmit antenna be of the same design as the two receiving ones in a highly developed future design. Each dipole of the delivered model consists of a pair of insulated wires, the ends of which are connected to metal plates about one foot square to provide good electrical contact with the water. Each of the antennas is fitted with an impedance matching balun (Figure 3 - 4) to provide an input impedance of approximately 50 ohms in the salt

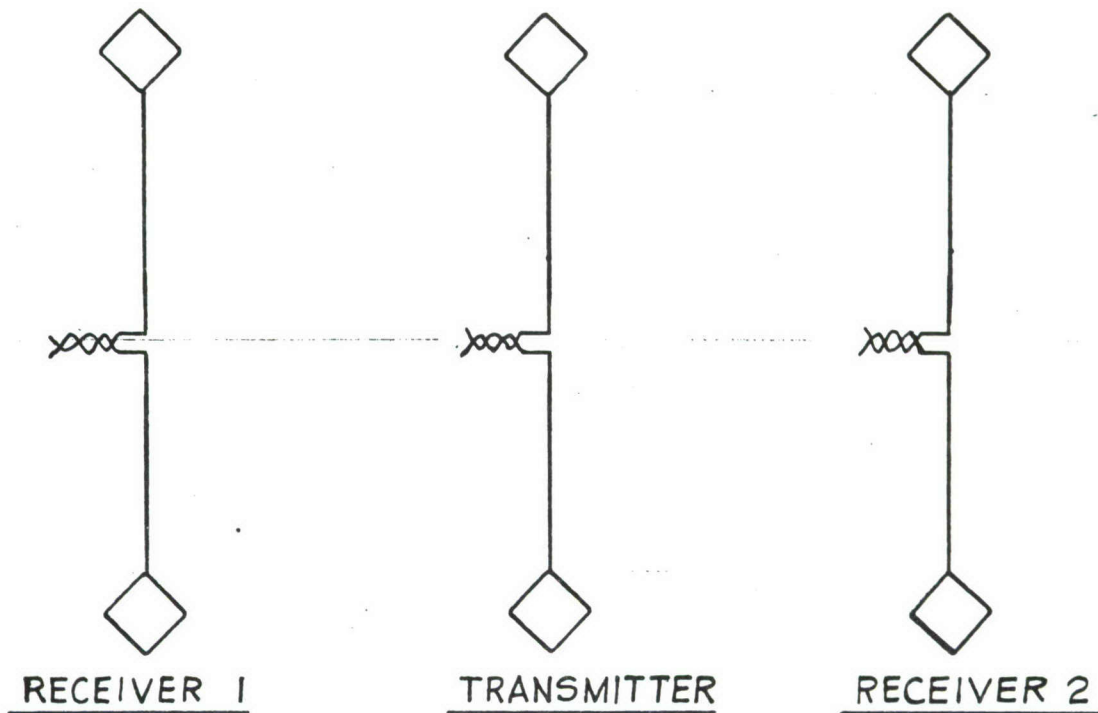


FIG. 3-3 ANTENNA DEPLOYMENT PLAN

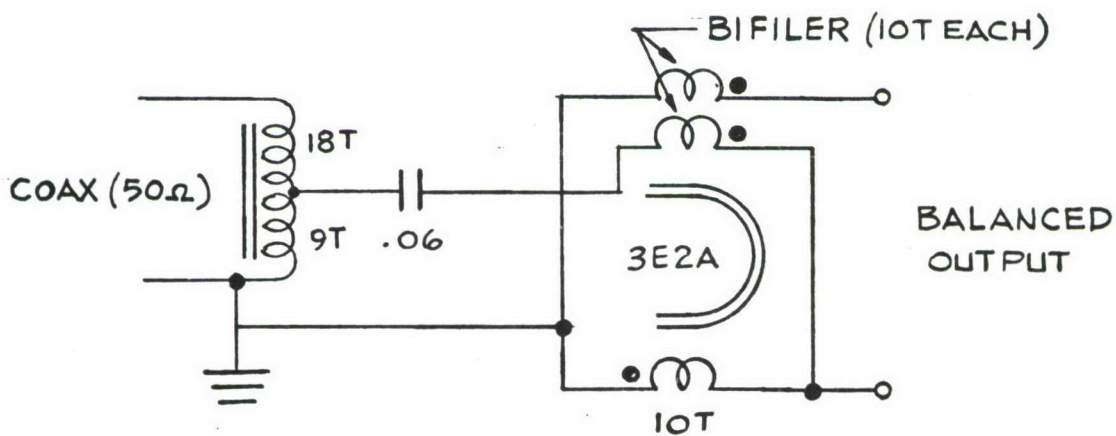


FIG 3-4 BALUN

water swimming pool facility where the conductivity of the medium was 3 mho/meter. For media of different conductivity, the antennas would have to be re-matched to obtain maximum performance. The impedance is a function of the conductivity, dimensions of the dipole, and the frequency.

### 3.4 Combiner and Amplitude/Phase Trimmer (Receiver/Detector)

In order to be able to balance (null) the system initially, when the signals from the two receiving dipoles are combined in the interferometer, a set of phase delay lines and amplitude balancing circuits are incorporated into the detector as shown in Figure 3 - 5 to serve as trimmers. Such trimmers are necessary in order to compensate for the inevitable inaccuracy in placement of the antennas and variations in the geometry of the environment. A transfer switch is provided which facilitates placing the phase delay lines in either arm of the interferometer. This, in effect, doubles the phase trimming range of the delay line system. Seven switches representing phase delays of 0.08, 0.04, 0.02, 0.01, 0.005, 0.0025 and 0.00125 wavelength are provided so that it is possible to vary the relative phase of the two signals by as much as  $\pm 0.15875$  wavelength (i.e., 57.2 degrees, or 1 radian) in increments of 0.00125 wavelength (0.45 degree). The amplitude trimmers are coarse and fine potentiometers, which are operated by knobs. These various controls can be used to achieve a very fine balance (deep null response) of the unperturbed system, and the maximum probability of detecting an intrusion seems to exist when the system is perfectly balanced.

Following the amplitude balancing network, the two signal channels are combined by means of a sum hybrid network, shown in Figure 3 - 6. The output from the hybrid is connected directly to the input of the (80 dB) amplifier.

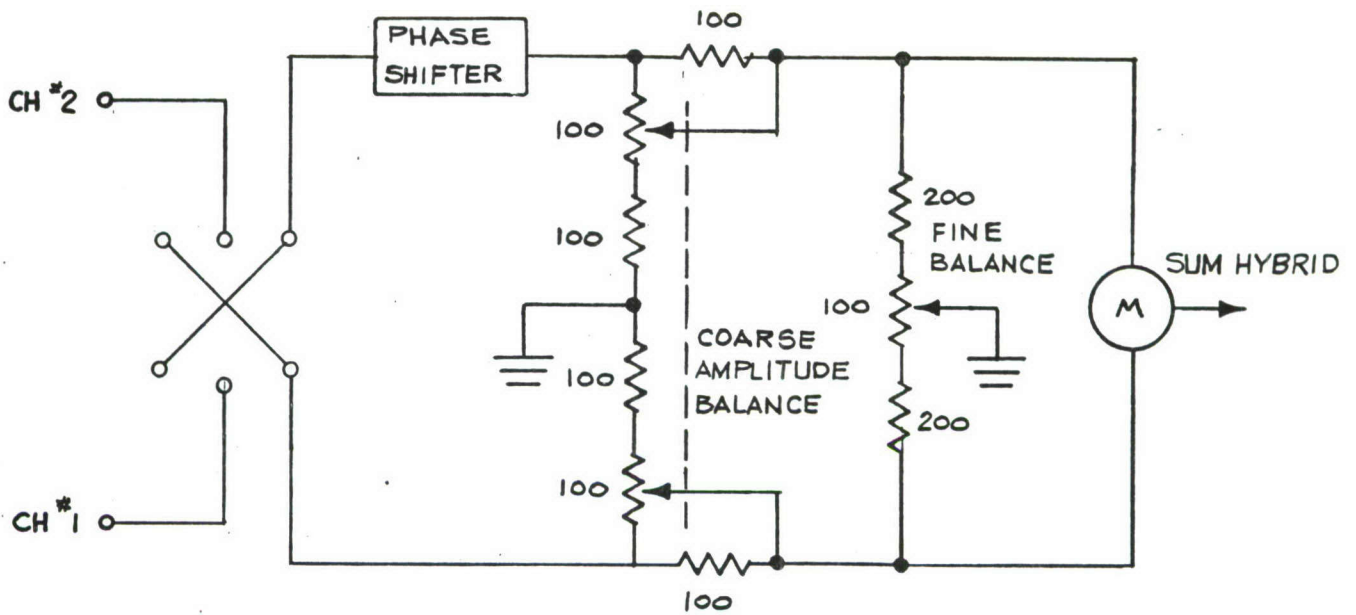


FIG 3-5 RECEIVER NULLING CIRCUIT

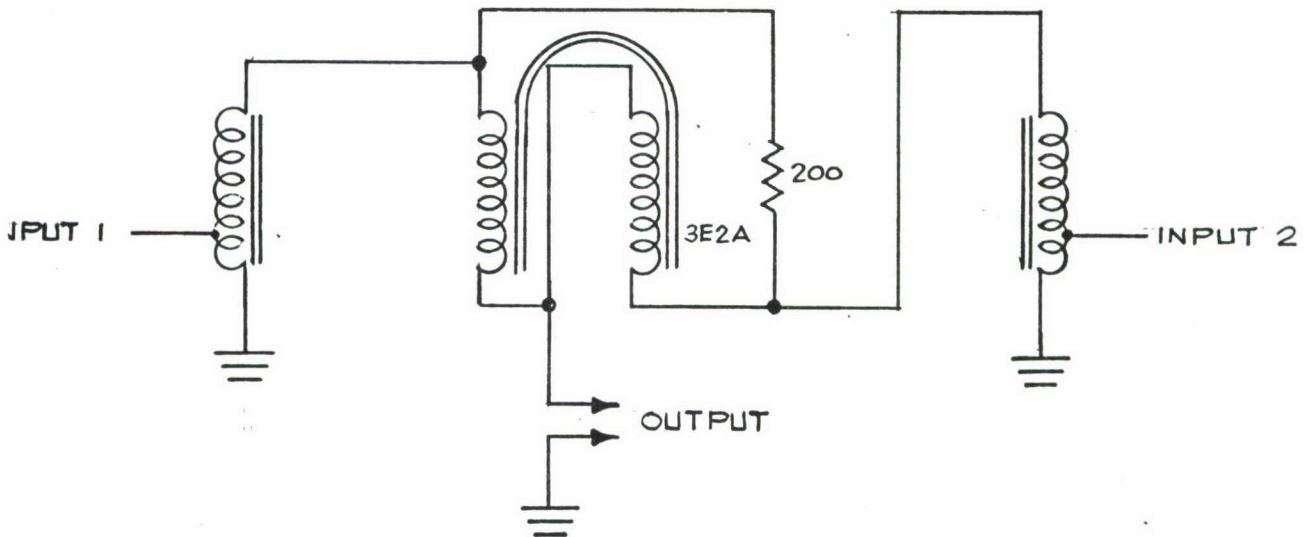


FIG 3-6 HYBRID

### 3.5 Amplifier

A three-stage amplifier capable of 80 dB of amplification is employed to raise the level of the signal out of the interferometer enough to permit processing by the detector-differentiator circuit. The circuit diagram of the amplifier is shown in Figure 3 - 7. To prevent strong extraneous signals from overloading the amplifier, a single-pole band-pass filter is incorporated at the front end of the amplifier. This is, of course, tuned to pass the working frequency of 400 KHz.

### 3.6 Differential Signal Detector

The output of the 80-dB amplifier is fed into the differential signal detector, a schematic of which is shown in Figure 3 - 8. This circuit is described beginning at the front end. The shunted ferrite choke serves to short out any low frequency noise below about 50 KHz. The 1-KHz modulation is not affected, since it rides through on the 400 KHz carrier. The diode (1N82) detects the 400 KHz signal, and the following RC  $\pi$ -network stops what is left of the carrier and its overtones while allowing the 1-KHz modulation to pass on to a single stage amplifier. The diode (1N33) detects the 1-KHz signal and charges the  $0.1 \mu\text{fd}$  capacitor by an amount directly proportional to the input signal, that is, the modulation level.

Current now flows through the resistor (10 M) until the series capacitor combination ( $10 \mu\text{fd} - 10 \mu\text{fd}$ ) becomes charged to the same voltage as the  $0.1 \mu\text{fd}$  capacitor. Because of the large time constant (roughly one minute), however, the large capacitor requires a long time to fill. Therefore, the current flowing through the 10 M resistor is nearly proportional to the net change in signal level that has occurred within, say, the last minute. Thus, if within the last minute there had been

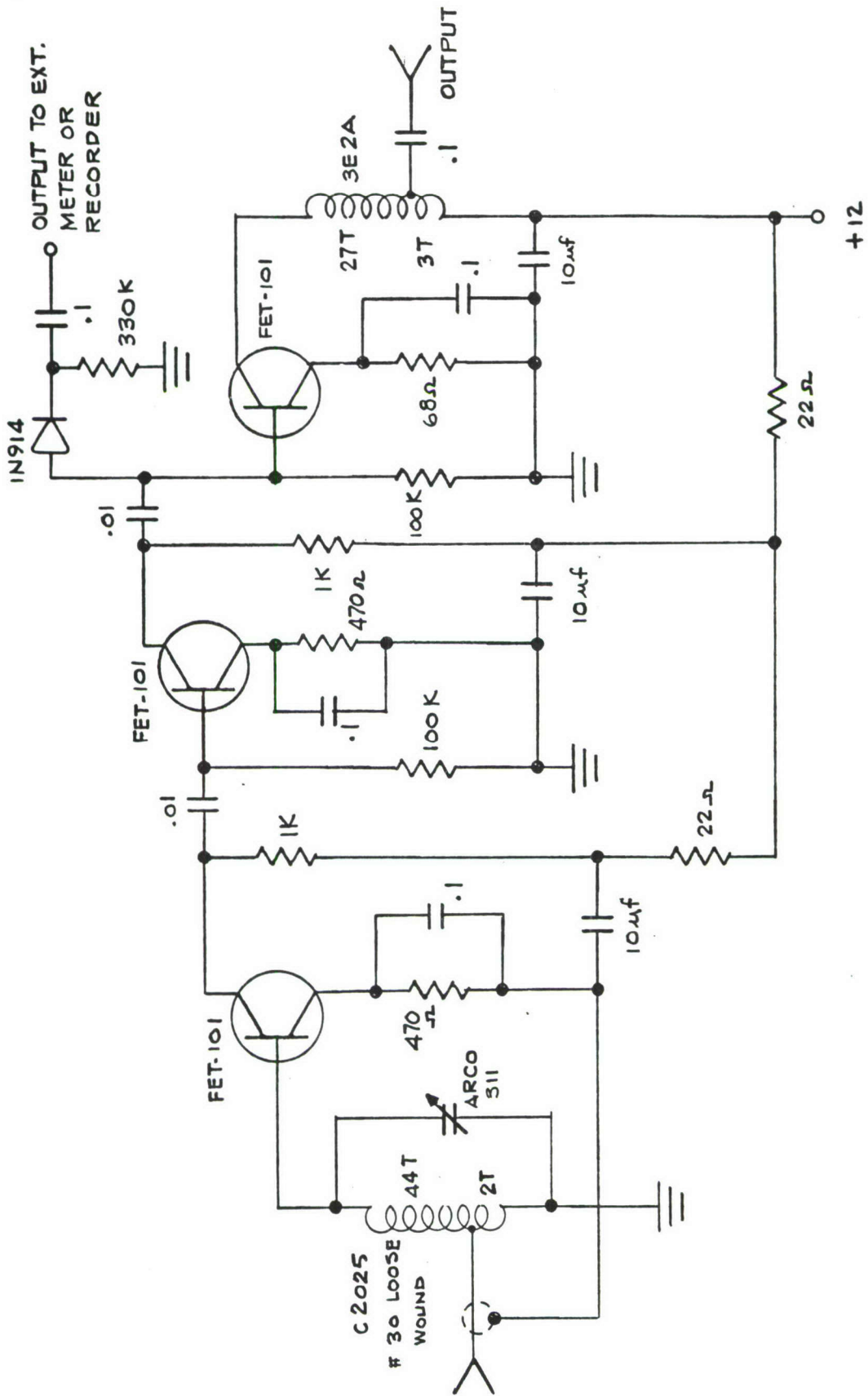


FIG-3-7 AMPLIFIER (80dB)



a net increase in signal level, a voltage would appear at the gate of the upper transistor of the transistor bridge, and the meter would show a positive deflection. If, on the other hand, the net signal level had decreased in the last minute, the deflection would be negative.

## 4.0 SYSTEM PERFORMANCE TESTS

### 4.1 Salt Water Swimming Pool

The performance characteristics of the swimmer detection system were evaluated preliminarily by a series of tests in the ARA salt water pool facility (16' x 32' x 3' deep) prior to larger scale tests in open water. These preliminary tests were designed to determine qualitatively the approximate sensitivity, detection range and the size, shape and material composition of detectable objects. Other parameters such as array size limitations and natural noise levels due to surface waves on the water must be done in a more natural body of water where sharp, plane discontinuities like the insulated bottom and sides of the pool are absent. The conductivity of the salt water in the ARA pool was 3.0 mho/meter, or about 75 percent of that of sea water with average salinity, i.e. 4 mho/m.

Unlike a natural body of water, the boundaries of conductivity in the ARA pool (i.e., surfaces at which the conducting water is terminated by the dielectric walls of the pool) are sharply defined. As Dr. Tami r has pointed out, these boundaries give rise, through internal reflection, to an infinite array of image sources, all of which are in phase with the actual source. A rough calculation at d.c. shows that, for transmission across the pool, one can expect a signal level enhancement in the order of 30 dB. In natural bodies of water, only one sharp discontinuity in conductivity generally exists, namely the air/water interface. The water/bed interface does not ordinarily constitute a sharp discontinuity because the water penetrates to some depth below the physical bottom, and hence one would not expect much reflection there. With only the one good reflecting surface, namely the air/water interface, one might expect signal enhancement in the order of 3 dB over that in an unbounded medium.

The antennas for the in-house tests were arrayed in the water as shown in Figure 4 - 1. Three different types were tried. The first was a set of three rigid fiberglass-encased dipoles, 10 feet long, which were already available from the earlier path-loss investigations. These antennas had baluns incorporated into their mid-points to ensure good electrical balance with respect to their feed cables, and to minimize susceptibility to ground loops, or common mode phenomena. The tips of the dipoles were fitted with metal caps to make electrical contact with the water and to maximize the dipole current moment. Suspended at mid-depth (1.5 feet) in the pool, they were found to work well.

In a second-generation antenna design aimed at making better contact with the water at the dipole ends, and at improving the ease of deployment, the antennas took the form shown in Figure 4 - 2. The dipole arms consisted of extensions of the twisted-pair insulated wire leads, and the electrodes at the tips were standard copper water-tank floats. Lead weights were used with nylon cord to maintain the balls in position at mid-depth of the pool. These dipoles were also about 10 feet long, but the design permitted the length to be varied easily for experimental purposes. The twisted-pair balanced transmission line was converted to coaxial line by means of a balun about 20 feet away from the dipole center so it could be out of the water. This also worked rather well, but it was evident after only a little experimentation with a swimmer in the pool that the electrodes must be held firmly in place. Small motions of the electrodes would cause full-scale deflections of the meter at the monitoring device.

For the third generation dipole design, the copper floats of the second were replaced by a set of 12" square x 1/16" thick aluminum plates, which were allowed

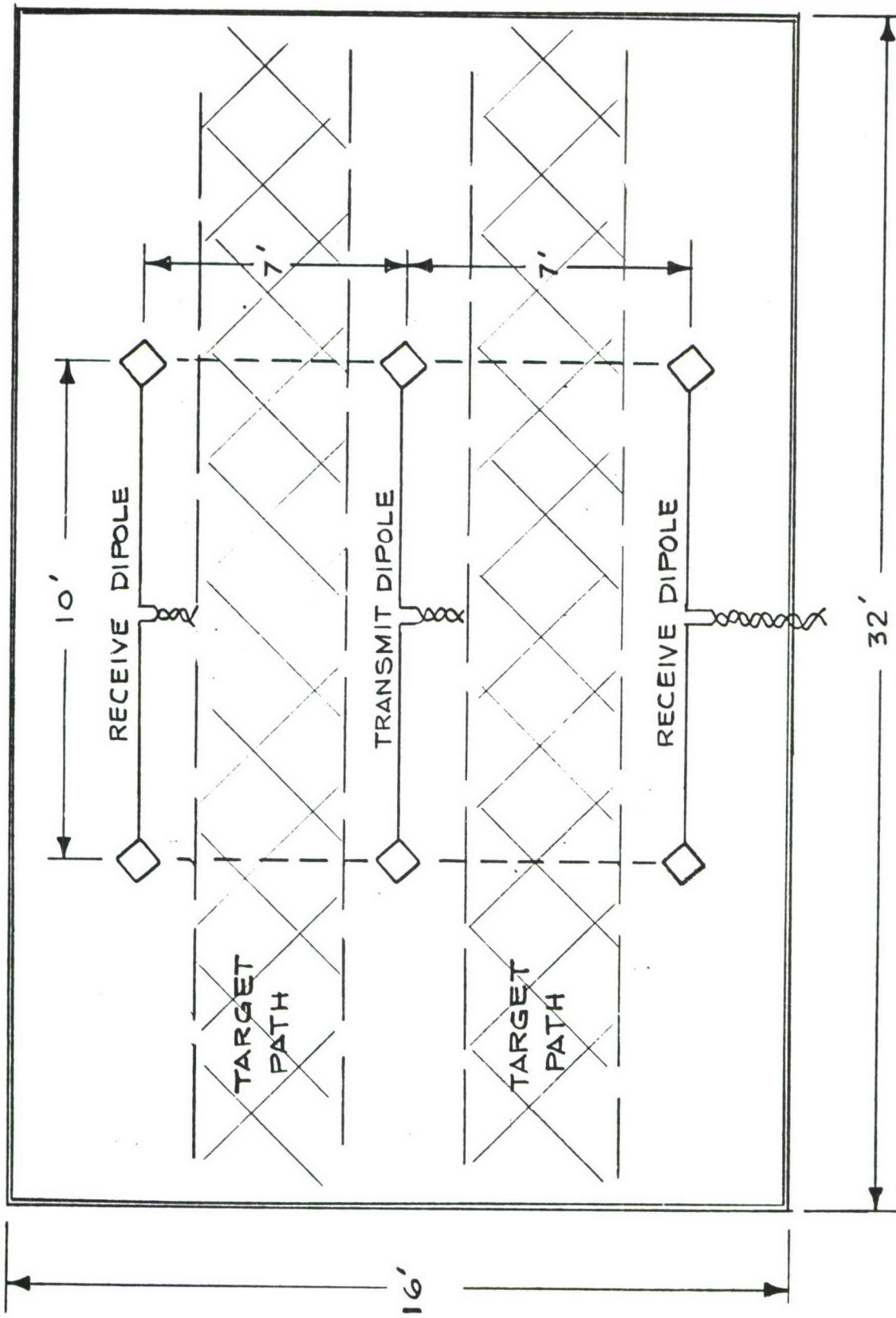


FIG. 4-1 ANTENNA DEPLOYMENT IN SALT WATER POOL

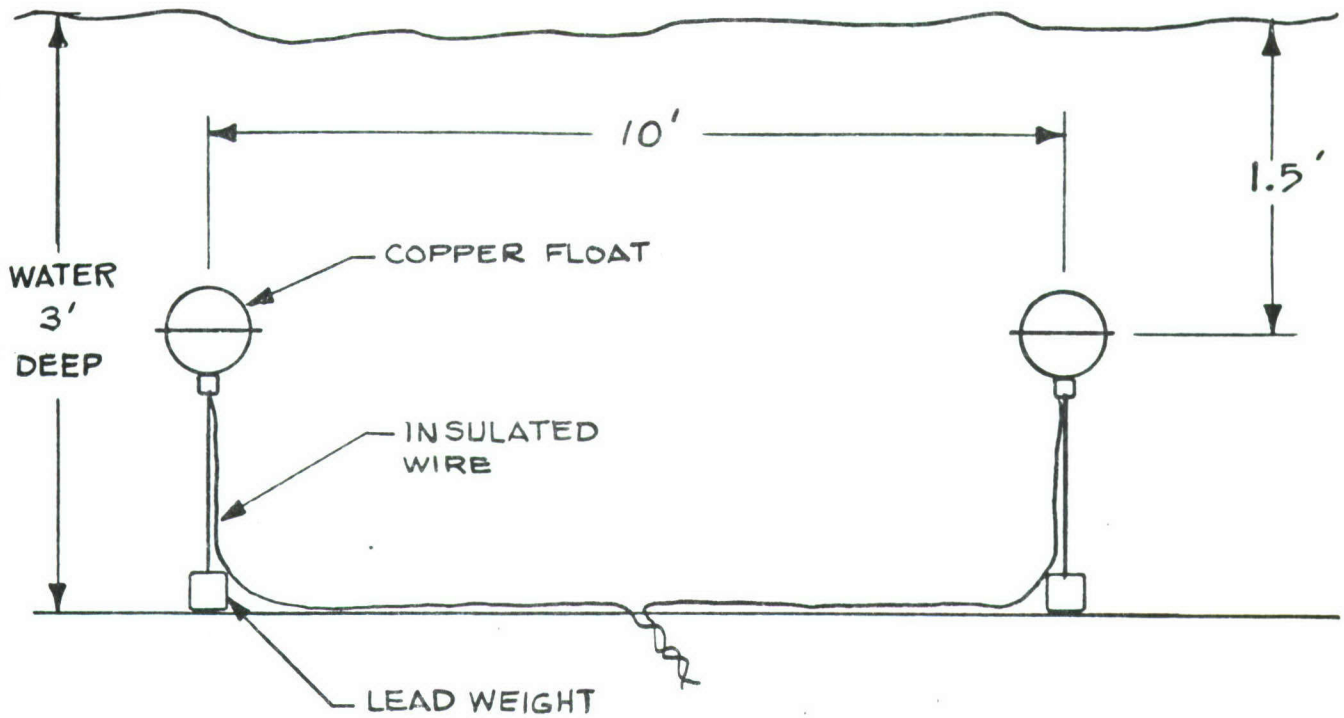


FIG. 4-2 DIPOLE WITH FLOATING ELECTRODES

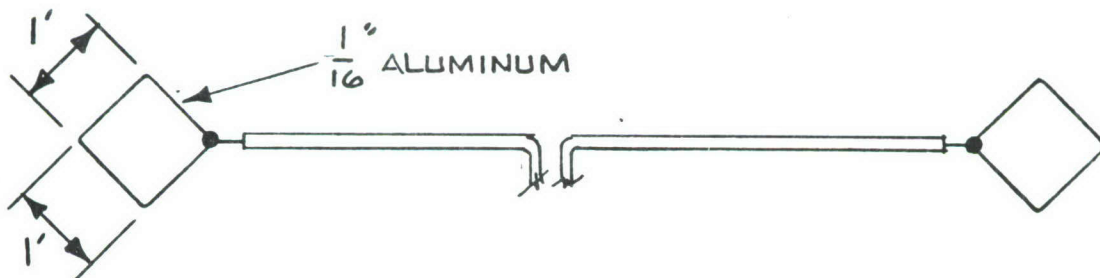


FIG 4-3 DIPOLE WITH ALUMINUM PLATE ELECTRODES

to lie flat on the bottom of the pool as indicated in Figure 4 - 3. This improvement substantially reduced the fluctuations in turbulent water, but did not eliminate them entirely. The action of the water waves on the surface of the pool were responsible for the remaining fluctuations, which was easily demonstrable. It is possible that by going to a longer radio wavelength, one could smooth out some of the effects due to small water waves, however, the detectability of an intruder would also be reduced because his scatter cross-section would be smaller.

The test objects used during the course of the investigation were several in number, and included the following:

- a. Swimmer clad in trunks only
- b. Aluminum tubing 5' x 1" square suspended horizontally by nylon cords from a 2" x 4" wood float of same length
- c. Heavy-duty plastic trash bag partially filled either with salt water or fresh water
- d. Aluminum wire 4' x 1/8" diameter
- e. Aluminum tubing 2' x 1/4" diameter
- f. Fiberglas plate approximately 12" square by 1/16" thick

The floating objects were pulled through the water by means of nylon cords usually along paths indicated in Figure 4 - 1. These paths seemed best for experimental purposes because conducting objects with major dimension aligned with the path were found to produce the maximum electrical disturbance. Oriented crosswise of the indicated path, conducting objects produced significantly less disturbance. Non-conducting objects produced the greatest disturbance when oriented with the maximum cross section perpendicular to the path shown in the figure. This was especially true

of the fiberglass plate, which produced no detectable disturbance when oriented along the path. Whether or not an object will produce a detectable disturbance depends upon its ability to alter the current distribution in the medium. The crosswise conducting rod and lengthwise dielectric plate cannot alter the current distribution very much.

It should be observed that the device is not a motion detector, per se. It is sensitive primarily to perturbations in its electrical environment caused by the appearance of a foreign object having different conductivity than the medium surrounding the antennas, or to a change in position of such an object already present in the vicinity of the antennas, and not primarily to the speed with which the object moves. Of course, a dimensional change in the antenna system itself will also give rise to an alarm signal, but it is assumed that the geometry is stable. For slow changes such as tide levels and salinity variations, an automatic balancing compensator can be developed to keep the system in proper adjustment.

The plastic trash bag was first filled with fresh water about equal in volume to an average man, with the idea of determining whether or not the device could detect such a small mass of fresh water in the salt water medium. Surprisingly, the signal produced was as great as that for the 4-foot aluminum wire. This result was so surprising that it stimulated a few additional tests. A garden hose nozzle was placed in the pool and aimed directly at one of the plates in an attempt to completely envelope the plate with a mass of low-conducting fresh water. The device was monitored throughout the one-minute interval during which the fresh water was turned on, and not the slightest deflection was observed. This result led immediately

to the possibility that the plastic bag, rather than the enclosed water, was responsible for its detectability. To test this concept, the plastic bag was emptied and re-filled with some of the salt water from the pool to assure identical conductivity both inside and outside the bag. Although the salt water filled bag established itself a little deeper below the surface, it occupied about the same volume as did the fresh water. Some trapped air in the bag above the surface kept the bag afloat. When the bag was pulled through the antenna field, about the same deflection occurred as when the bag was filled with fresh water. Thus it was evident that the discontinuity in conductivity was due only to the non-conducting skin of the bag itself. Had the bag been made of a material whose conductivity was about the same as that of the water, it would have been invisible when filled with the salt water and probably quite detectable when filled with fresh water.

The two-foot aluminum rod and the fiberglass plate were used as indicated in Figure 4 - 4 to probe the fields near the dipoles, with predictable results as to the dependence of detectability upon orientation. The most sensitive regions were those immediately surrounding either of the receive antennas, i.e., around the wires comprising the arms of the dipoles themselves and especially around the terminating electrodes. Only the region within a radial distance of about one skin depth (0.4 m) from the dipole wires was very sensitive, and somewhat farther away at the end plates. This supports the theory that the dipole arms at low frequency in a conductive medium are analogous to short sections of lossy coaxial transmission line whose outer shells comprise about one radial skin depth of the medium. Changes in condition of the shell affect the response.

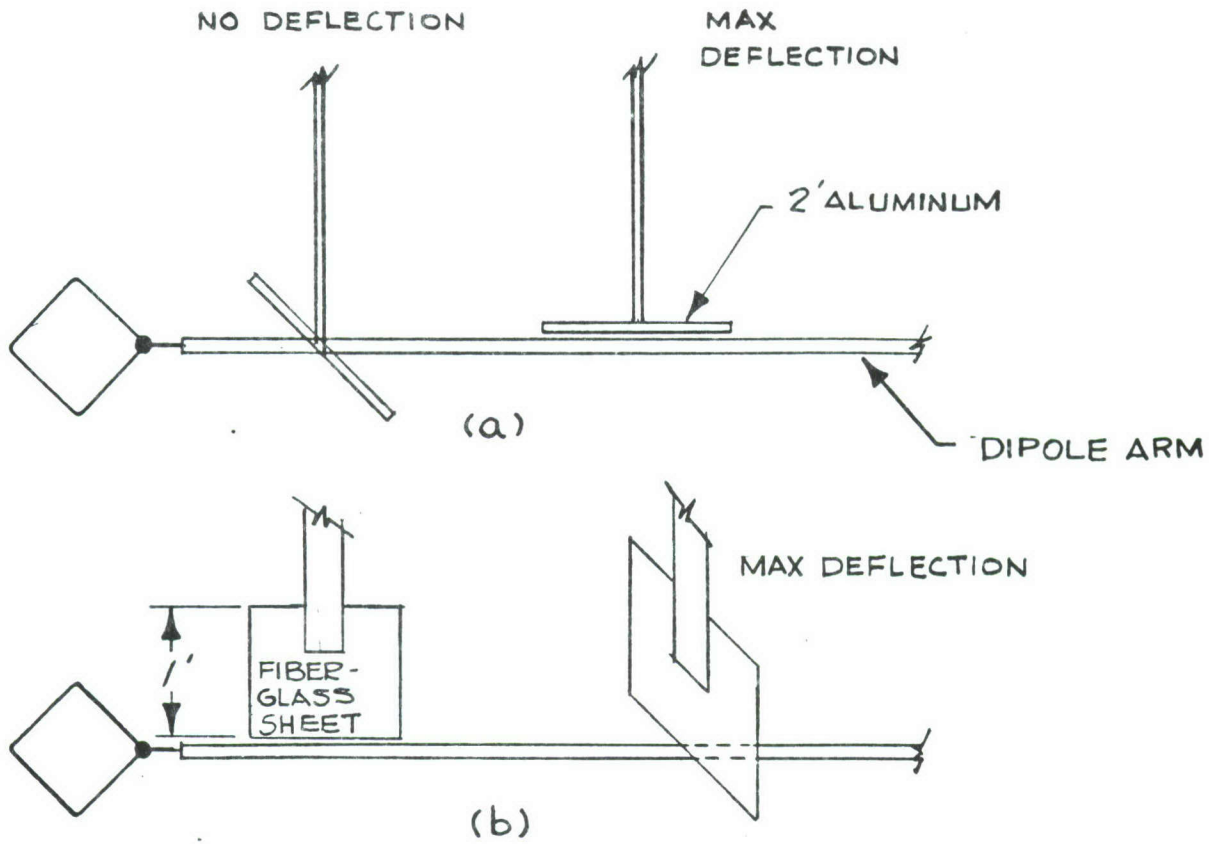


FIG 4-4 METHOD OF PROBING

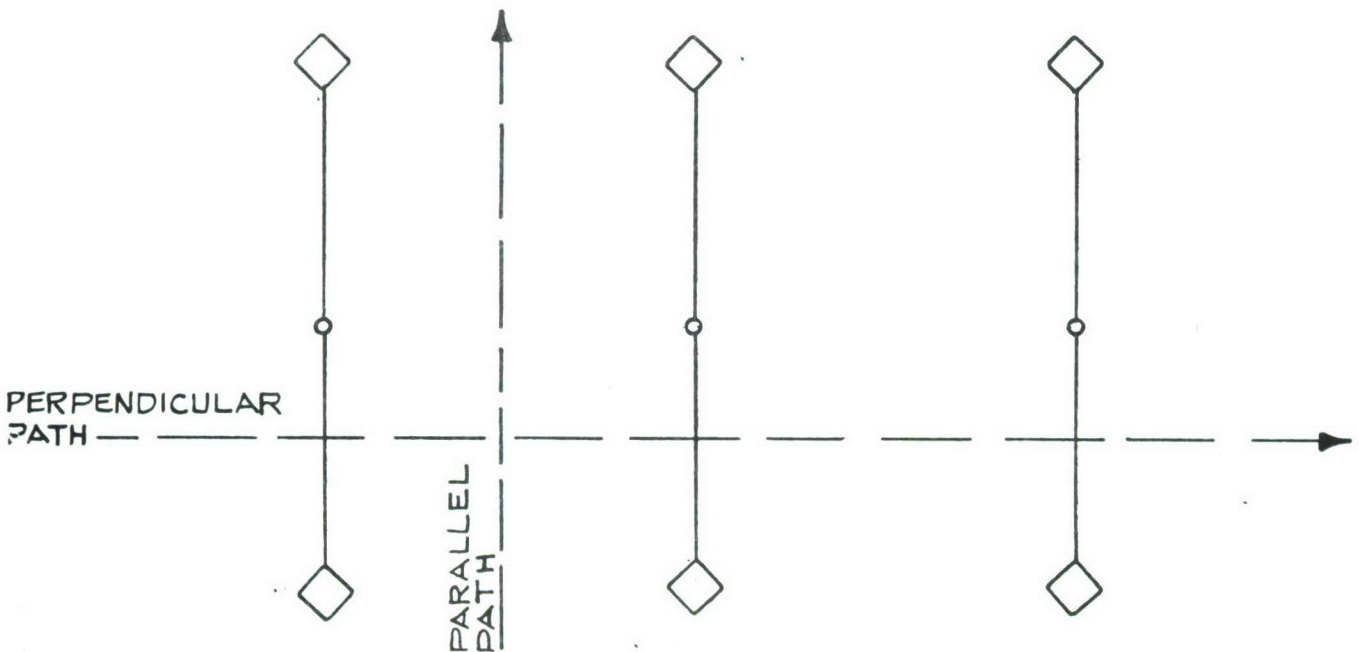


FIG 4-5

The region of lesser sensitivity, but still very active, was the space between the antennas. This region extended a short distance, say about a meter, beyond the ends of the dipoles.

Finally, a six-foot swimmer, clad in swim trunks only, swam down one of the lanes through the antenna field. Meter deflection was about 80 percent of full scale. It was found that if he swam directly above the center (transmitting) dipole, he could nearly escape detection.

At this juncture in the investigation a variable attenuator was placed in the system between the transmitter and the transmitting antenna balun. With 30 dB reduction in transmitter power, the detector showed about 20 percent of full scale deflection when the 5-foot aluminum tube was pulled through the antenna field. When the system is deployed in waters where there is only one sharp reflecting surface, namely the air/water interface, it is conceivable that as much as 30 dB of sensitivity with respect to that of the pool could be lost due to the lack of multiple reflections.

Although these tests were very encouraging, the over-all behavior of the system was as if it were not performing anywhere near its full capability. Having already stabilized the antennas themselves against mechanical motion, and reduced local power losses at the dipole ends by means of the larger-area plates, further improvements were sought. The antennas were tuned as near as practicable to a 50-ohm impedance in the salt-water swimming pool environment, and the twin-leads to the dipoles were tightly twisted to minimize changes in impedance due to mechanical motion of the leads. Also, three more switches (making a total

of seven) were added to the detector unit to permit a finer adjustment on relative phase in optimizing the balance of the system. Terminals were added to permit the direct connection of a 12-volt battery power supply, and a pair of banana-plug jacks were installed to permit measurement of the 1000 Hz signal from which the d.c. meter indication is derived.

These simple measures produced so much more response with the same 400 KHz signal generator that the plastic bag test now produced an off-scale indication of the d.c. meter. The fiberglass test plate was now easily detected at the surface of the pool, and long wavelength undulations generated on the surface of the water in the pool were sufficient to produce off-scale indications of the meter. Thus it now appeared that the system was capable of detecting man-sized objects in open water of conductivity either much greater or much less than that of the object, when deployed over approximately the same area as in the pool. It must be kept in mind that a system tuned for maximum power transfer in a medium of one conductivity will not function optimally in a medium of different conductivity. The antennas must be well-matched in the medium in which they are intended to be used in order to achieve the best performance. Considerable tolerance is allowable on the degree of mismatch, say a 3.0:1 VSWR, which is a fair amount of leeway.

#### 4.2 Open Brackish Water (Black Marsh Pier)

##### 4.2.1 Swimmer Detection Tests

Open water field tests were held with the assistance of APG personnel in an area known as Black Marsh, located on the western shore of Chesapeake Bay a few miles north of Baltimore, Md. The dipole antennas were deployed off the lee side

of a concrete barge in the same pattern as in the salt water pool, except the spacing was about ten feet instead of six. This wider spacing rendered the path attenuation between the transmitting and receiving antennas about equal for the two cases. The barge served both as an instrumentation platform from which to work and as a break-water for waves arriving from the open bay. The wave height in the area was about six inches on the average, and the visibility below the surface was poor. Buoys were attached to each of the dipole end-plates to mark their locations, while the location of the diver at depth was known only after a time lapse by the bubbles released.

It has already been mentioned that the detectability of an object underwater by electrical means depends primarily upon the difference in effective conductivity from that of the medium. Other factors include size, shape, orientation and location with respect to a fixed reference in the system. The water conductivity at the Black Marsh site was measured at 0.94 mho/meter by the method described in the Appendix. This is approximately 2.5 times that of the human body (0.38), whereas the difference for salt water is a factor of 8 to 12. Thus, the detectability of a swimmer in the open brackish water was expected to be much lower in general than for the same swimmer in salt water. The results generally supported these predictions.

It was originally planned to measure the amount of deflection from the null on the detector meter as a function of the position of the swimmer or other target in the antenna field. This was seen to be impractical almost immediately, and a strip chart recorder was used instead for the permanent data taking. The recorder high input impedance was connected directly across the receiver meter terminals and adjusted to write half scale when the receiver meter indicated full scale ("null adjust" mode). The recorder scale was calibrated in one-dB steps by means of a precision

attenuator in the transmission line between the transmitter and the transmitting antenna. The chart speed for the duration of the tests was two millimeters per second.

The dipoles, each 14 feet in length (plate to plate), were initially spaced 10 feet apart. Basically, the swimmer used only two different paths through the array. These are denoted as "parallel" and "perpendicular" with respect to the dipole orientation, and illustrated in Figure 4 - 5. Traverses were made both on the surface of the water and on the bottom. No further refinement was made as to the location of the swimmer or the other targets. The swimmer was equipped with swim trunks, upper half of a wet suit, fins and face mask. No SCUBA gear was worn during the first part of the tests. The same tests were then repeated with the swimmer wearing standard single-tank SCUBA gear. The results are summarized in Table I I.

The raw data in strip chart form and accompanying description are included in the Appendix. It is clear therein that there was considerable difficulty in keeping the system balanced. Also, there were sudden losses of the null which were probably the result of a bump or nudge from the swimmer in passing.

Both the aluminum tube and the water-filled plastic trash bag, which were useful targets in the swimming pool tests, were pulled through the array on parallel and perpendicular paths on the surface of the water. Neither of them was detected.

All the data in Table II, which are direct read-outs from the recorder tapes, were taken with the receiver in the "null adjust" mode. Background interference was so great that the system could not be used in the "detect" (differential) mode. It was not realized at the time, but the probable cause of the interference was a transfer of motion from the buoys attached by cords to the dipole end-plates, and not reflections from the water waves themselves. If the interference had been due to

OBSERVED DEFLECTION FROM NULL (dB) DUE TO TARGET

Path of Swimmer	Swimmer No Scuba Gear		Swimmer with Scuba Gear	
	On Surface	Near Bottom	On Surface	Near Bottom
Parallel & between dipoles	-	9 dB	-	6 dB
Perpendicular & across dipoles	7 dB	13 dB	-	> 15 dB
Parallel 4 feet outside array	no data	-	no data	no data
Perpendicular 4 feet outside array	no data	6 dB	no data	no data

TABLE II - Results of Tests at Black Marsh on 27 September 1973

NOTE: Water depth - 7 feet

reflections from the small waves that existed, one would think the plastic bag and aluminum tube test targets just under the surface would have been detected easily.

Finally the spacing between the dipoles was increased from 10 to 15 feet. Several attempts were made to bring the receiver to a null balance after minor adjustments in the location of the dipole plates, without much success. Time and swimmer endurance ran out before a satisfactory null could be obtained.

#### 4.2.2 Impedance of Submerged Dipole

As a check on the efficiency of the detection system, an impedance measurement was made on one of the antennas while it was immersed. The measurement was made through the balun which was designed to produce 50 ohms resistance when the antenna was installed in the salt water swimming pool (conductivity = 3 mho/meter). The impedance was found to be approximately  $Z = 10 - j75$  ohms, representing a large impedance mismatch with respect to 50 ohms resistance. This corresponds to a reflection loss of 6.5 dB, which loss must be taken fully at the receiving antenna and approximately at the transmitting antenna for a total of about 12 dB. Such losses can be practically eliminated by designing the antennas for an impedance match in range of conductivity of the medium in which they are to work.

## 5.0 CONCLUSIONS

1. An underwater electronic swimmer detection system has been built, and the feasibility of such a system has been successfully demonstrated. Although it was tuned for peak performance in a salt water swimming pool, the system worked surprisingly well in brackish ( $\gamma = .94$ ) open water where the contrast in conductivity with a swimmer was not large.
2. The detectability of a swimmer, or other target, depends on size and the difference in effective conductivity between him and the medium.
3. The size of the "window" that can be protected is primarily a function of the conductivity of the water and the scattering coefficient of the target in the medium. Other factors also enter, such as transmitter power, receiver sensitivity, inherent background noise levels and environmental conditions.
4. The system must be mechanically stabilized against motion in order to function satisfactorily in any installation. Motion of the electrodes or other current carrying antenna components under water is equivalent to the entrance of an object into the protection zone.
5. It is theoretically possible to camouflage a swimmer sufficiently well by adjusting his "effective conductivity" that he might pass through the system undetected.
6. More development is needed to reduce the system to practical operational status.

7. For maximum results, the system should be designed specifically for the individual application, although considerable latitude can be tolerated without serious degradation in performance. Items requiring attention include choice of frequency, size, type and quality of antenna element, and impedance matching of the antennas to the transmitter and receivers.

## 6.0 RECOMMENDATIONS

1. It is recommended that additional work be done to determine the practical size limitations of a system incorporating the various improvements indicated in the present study. As one particular objective, any additional work should include a determination of the conditions, if any, for which a quasi-static system would be superior to a dynamic one, in which frequency is a consideration. Also, the characteristics of loop antennas should be investigated for their merits in comparison with dipoles for application in an underwater detection system. Implied in this, of course, is study toward maximizing the antenna efficiency and the working out of optimum design techniques.

2. One simple recommended improvement, which can easily be made in the present feasibility model, is to add a filter to reject fluctuations outside the desired frequency pass-band for optimum detection. This would permit the more sensitive "DET" mode to be used. Another recommendation is to improve the impedance match of the dipoles to the rest of the system for the specific value of the conductivity of the water in which the system is to be used. Additional improvements can be made by upgrading the inherent efficiency of the dipoles.

## 7.0 APPENDIX

### 7.1 Operating Procedure for the System

(1) Set up the three-antenna array as shown in Figure 4 - 1, with the transmitting antenna in the center position. The dipoles must be fixed in place so no part can move, and care should be taken to place the receiving dipoles equidistant from the transmitting dipole.

(2) Bundle the dipole transmission line leads together along the line of centers of the dipoles, and bring them out of the array on the bottom perpendicular to one of the outside dipoles. These leads may not be permitted to cross or approach a dipole at a slant angle because undesirable cross-coupling between elements will occur. Connect each pair of dipole leads to the dual-terminal side of a balun (small blue box with three coaxial terminals), but do not connect the baluns to the transmitter or receiver yet.

(3) Both the receiver and transmitter operate from a 12 V d.c. power supply. The receiver has a built in circuit to convert 115 V a.c. to 12 V d.c., but the transmitter does not. If a 115 V a.c. source is not available, terminals are provided on the receiver for a 12 V d.c. supply. In any event, the transmitter and the receiver should not be powered from the same source in order to avoid possible ground loops.

(4) Alignment - The transmitter has a tank circuit which must be tuned to resonance with the 400 KHz crystal. This can be done with a level-monitoring device such as a cathode ray oscilloscope connected to the output terminals. A small screwdriver can be used through the access hole provided in the

transmitter chassis to maximize the output. A 100-ohm potentiometer has been provided at the transmitter output to control the output level for convenience in alignment or any other purpose which may require it. It is set for minimum signal when the transmitter adjustment is completed, preparatory to a receiver adjustment.

Next the receiver is turned on with no connections made to the input ports 1 and 2. With the mode switch set in the detect "DET" position (see Figure 7 - 1, Receiver Panel), adjust the balance potentiometer "BAL" on the side of the chassis so that the meter indicates the mid-scale zero.

After adjusting the transmitter and receiver gains to minimum setting, and placing the mode switch to "NULL ADJ", connect a piece of 50-ohm coaxial cable from the transmitter output to either receiver input, and adjust the gains so that the meter reads about half scale deflection to the right. Use a screwdriver to adjust the tuning "TUNE" for maximum meter deflection. Reduce gains as resonance is approached to prevent pegging the meter.

(5) Achieving the Null Balance - After the system has been tuned up, the transmitter should be connected to the center dipole through the balun as mentioned in step (2), and the gain set for maximum output. If the receiving dipoles have been properly placed, the received signal should be the same on each of them. This is checked by alternately connecting each one to the same receiver input port, with the receiver gain control set low enough to ensure an on-scale reading. The mode switch should be in the "NULL ADJ" position for this test. The meter readings should be within 20 per cent of each other for the two dipoles. If they are not, the placement of the center dipole should be altered until the two received signals do agree within the tolerance.

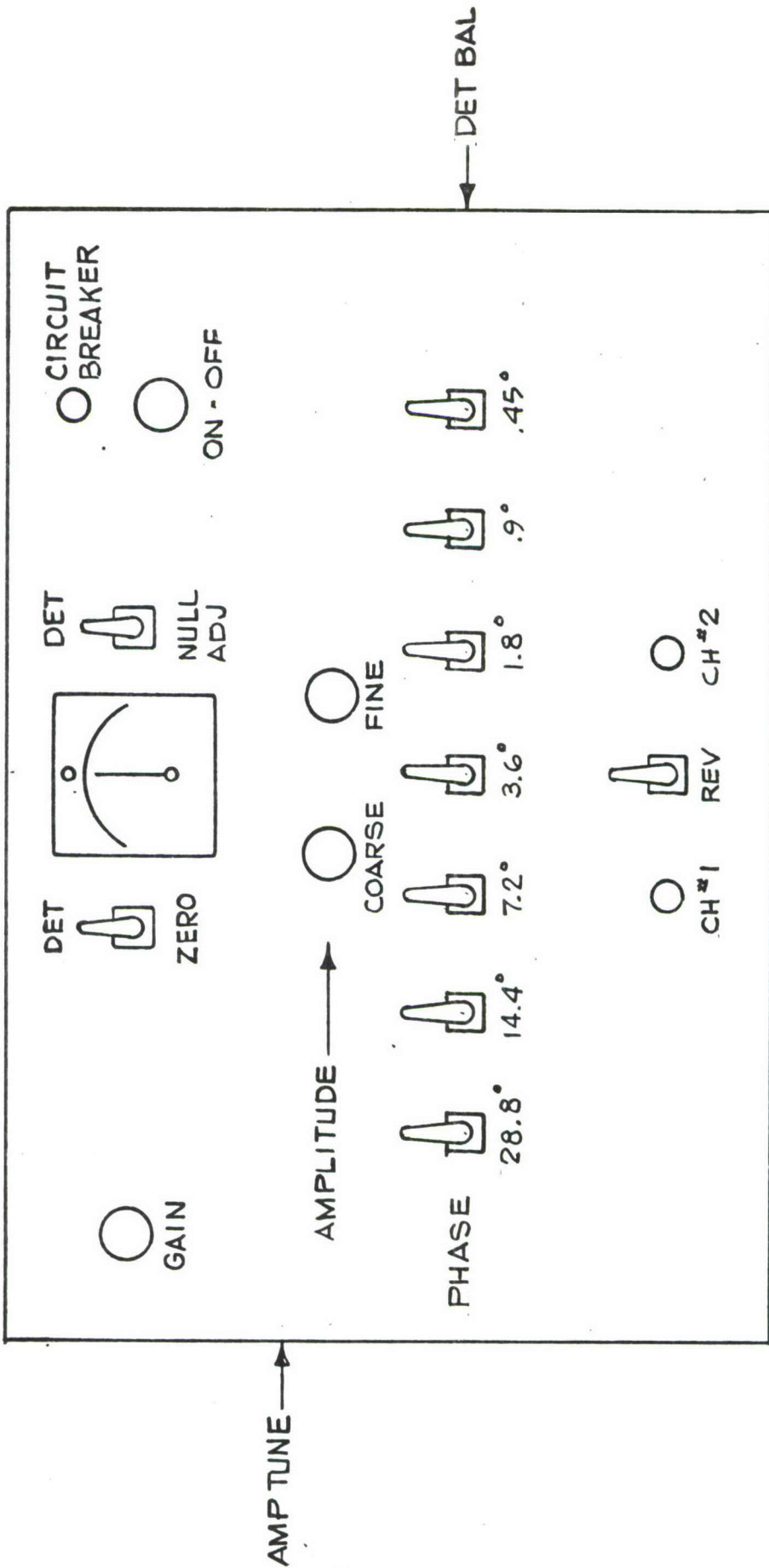


FIG 7-1 RECEIVER PANEL

Set the amplitude control knobs at about mid-range, and throw all seven of the phase switches in the upward position. Phase delay is introduced by throwing the switches downward, and the reversing switch "REV" determines which receiving antenna line requires the delay. Connect both receiving antennas to the receiver with equal length cables, and observe whether the signal indication increases or decreases when the second dipole is connected. If the signal increases, the dipoles are incorrectly phased, and the polarity of one of the receiving dipoles must be reversed. This is done by interchanging the red and black leads at the balun. Set the "REV" switch in whichever position produces the smaller response, and proceed to make alternate amplitude and phase adjustments to null the response. As the null is approached, the receiver gain should be increased until it is maximum. If the response fails to decrease when phase delay is introduced, the "REV" switch is thrown to the other position, and the nulling procedure continued.

The amount of phase delay per switch progresses geometrically from switch to switch by a factor of two per step, starting from the smallest (0.00125 wavelength, or 0.45 electrical degree) at the extreme right. By proper combination of switches, one can introduce any phase delay from 0 to 57.15 degrees into either one or the other receiving transmission lines in increments of 0.45 degree.

When the receiver has been nulled, it is ready for swimmer detection. Objects whose conductivity differ significantly from that of the water are potentially detectable, provided that the scattered signal received is above the noise level of the system. Set the mode switch in the differential detection "DET" position, which will usually cause an off-scale deflection of the indicating needle, either negative or positive. This initial offset is removed, and the pointer reset to zero, by depressing the meter zero switch "MTR ZERO" for a few seconds. This discharges a storage capacitor in the circuit.

## 7.2 Test Data Remarks on Black Marsh Strip Charts

The chart speed was maintained at 2 mm per second throughout. The trace is proportional to meter deflection of the detector in the "null adjust" mode. Thus, minimum trace reading corresponds to a null on the device (about 10 mm above zero on the chart), and full scale deflection of the detector meter corresponds to 30 mm on the chart. The chart has been marked by encircled numbers to identify the events of interest. The following remarks describe these events:

(15) Chart calibration in one-decibel steps.

(1) Swimmer near bottom, path between and parallel to the dipoles. About 9 dB deflection. Swimmer had no SCUBA equipment.

(2) Same as (1) except swimmer was at the surface. No deflection was observed. Following this event, a small amount of drift away from the null condition was noted, and the system was readjusted to a null.

(3) Same as (1). Deflection was about 10 dB.

Following this event, the system began to drift away from the null condition. Restoring adjustments were made, but drifting continued. The swimmer nevertheless made a pass near the bottom in a direction perpendicular to the dipoles and about four feet outside the array. He was not detected. Readjustment to null was done twice while the system continued to drift. The drift was assumed to be due to the flow of water over the dipoles and the action of wind and waves on the styrafoam floats which were attached to dipole end-plates by nylon cords.

(4) Swimmer near bottom; path perpendicular to dipoles over center of array. About 13 dB deflection. Event followed by more drift and readjustment.

(5) Same as (4), but swimmer at the surface. Deflection about 7 dB.

Event followed by more nulling of detector, while swimmer donned SCUBA equipment.

(6) Same path as in (1). Deflection about 6 dB.

(7) Same as (2). No detection.

(8) Same as (4). Detected signal greater than 15 dB.

(9) Same as (5). No detection. Following this event, the swimmer brushed one of the dipole plate buoys, after which the system began to drift out of its null adjustment.

(10) Swimmer on the bottom, path parallel to the dipoles, but four feet outside the array. No detection. System was drifting at the time.

(11) Swimmer on the bottom, perpendicular to the dipoles and four feet outside the array. About 6 dB deflection for first half of traversal, no response for the last half.

(12) An aluminum tube about one meter long and one inch in diameter was suspended about three feet below the surface from a wooden two-by-four float, and pulled through the array by means of a nylon cord long enough to permit the swimmer to be clear of the array before the rod entered. Here, the rod was pulled through parallel to and between two adjacent dipoles. This target was undetected.

(13) Same as (12), except that the path was perpendicular to the dipoles and through the center of the array. Again, the aluminum tube was undetected.

(14) A heavy-duty plastic trash bag was loaded with about 20 gallons of water from the antenna test area to prepare a similar test target as was used in the swimming pool. It was pulled across the array both parallel and perpendicular to the dipoles without detection.

Both the rod and the plastic bag were highly detectable in the salt water swimming pool. The difference is undoubtedly due to the significant difference in depth of water and to other differences mentioned elsewhere in the text.

After event (14) the system began to drift rapidly. The cause was not known, but was assumed to be a shifting in position of one or more of the dipoles. It appeared that a shift in position of a dipole plate, or its connecting wire, of as little as an inch would completely destroy the null condition.

(15) Calibration in one-decibel steps. This was accomplished by turning the receiver gain almost to minimum sensitivity and disconnecting one of the receiving dipoles from the detector unit. A variable attenuator placed at the transmitter output was used to mark the one-decibel levels on the chart.

At this point, the spacing between the dipoles was changed from 10 to 15 feet.

(16) The swimmer made a pass along the bottom, parallel to and between dipoles, and was not detected.

(17) Repeat of (16). It appeared that the swimmer kicked one of the dipoles, which accident was followed by a period of inability to achieve balance again.

(18) Swimmer again nudged a dipole, this time while on the bottom along a path perpendicular to and over the center of the dipoles. There was some evidence of detection.

(19) Repeat of (18). Swimmer again brushed against a dipole.

End of tests. Time runs out, and the swimmer is cold and tired.

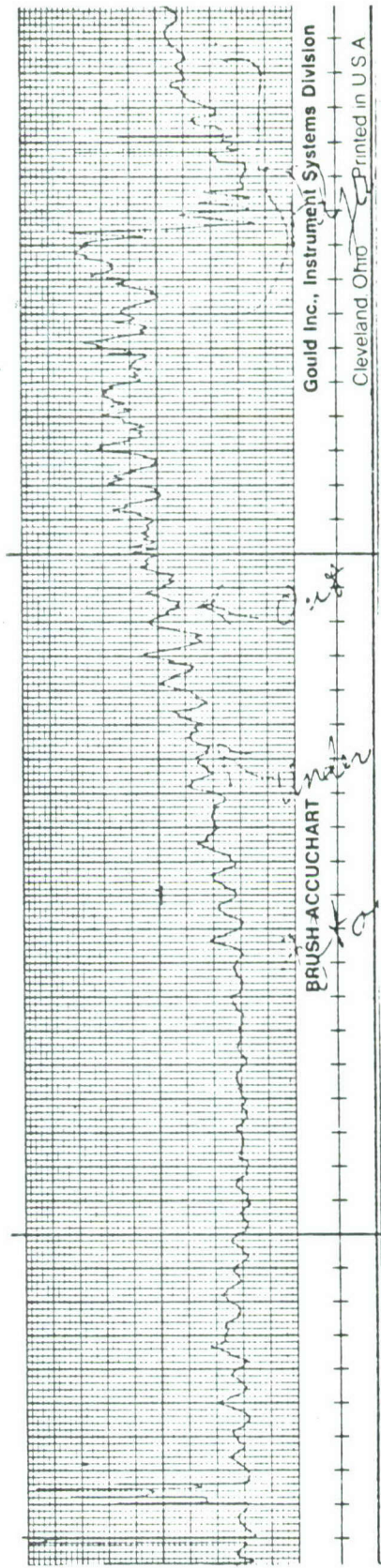
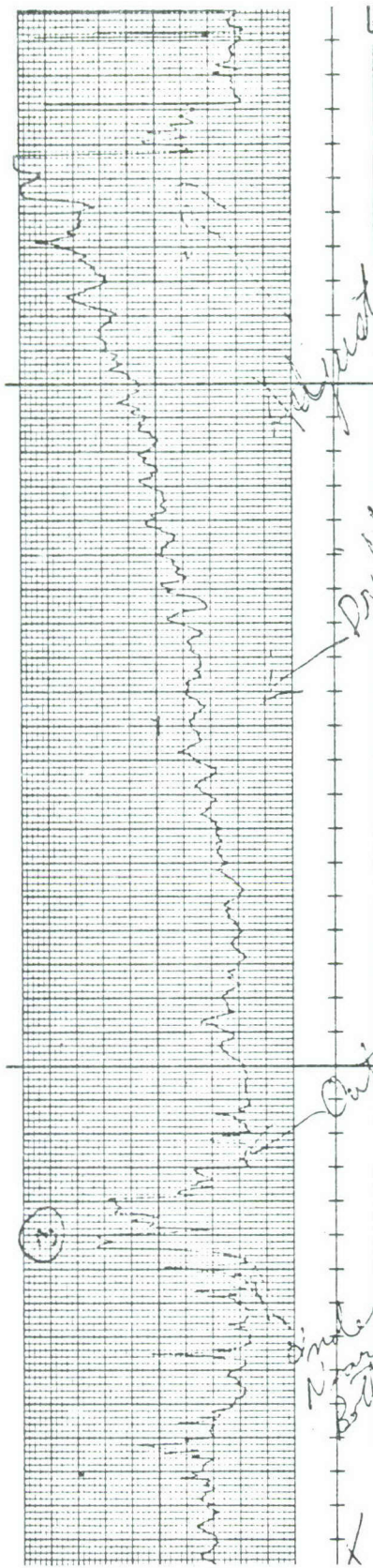
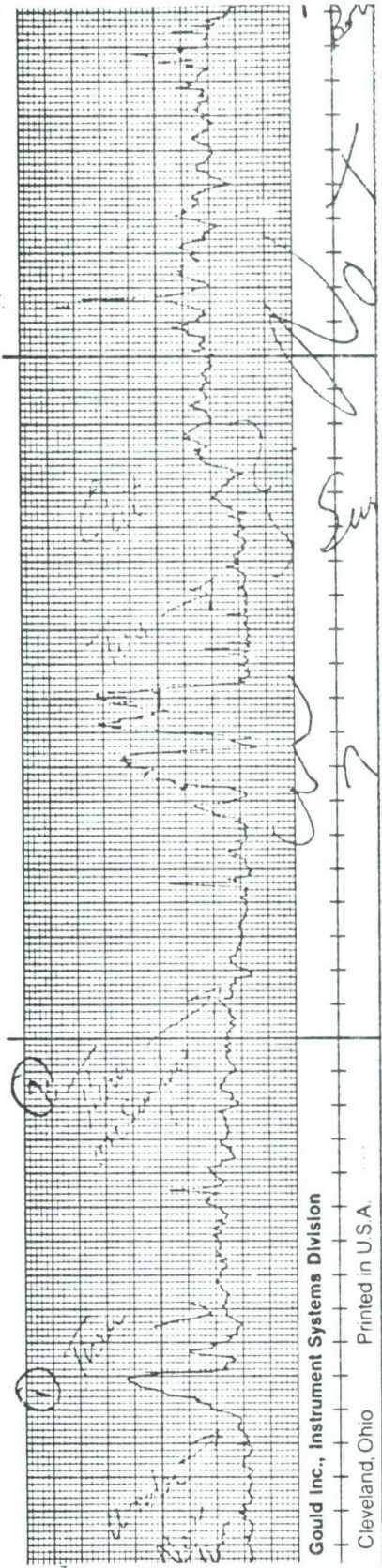


Figure 7 - 2(a)

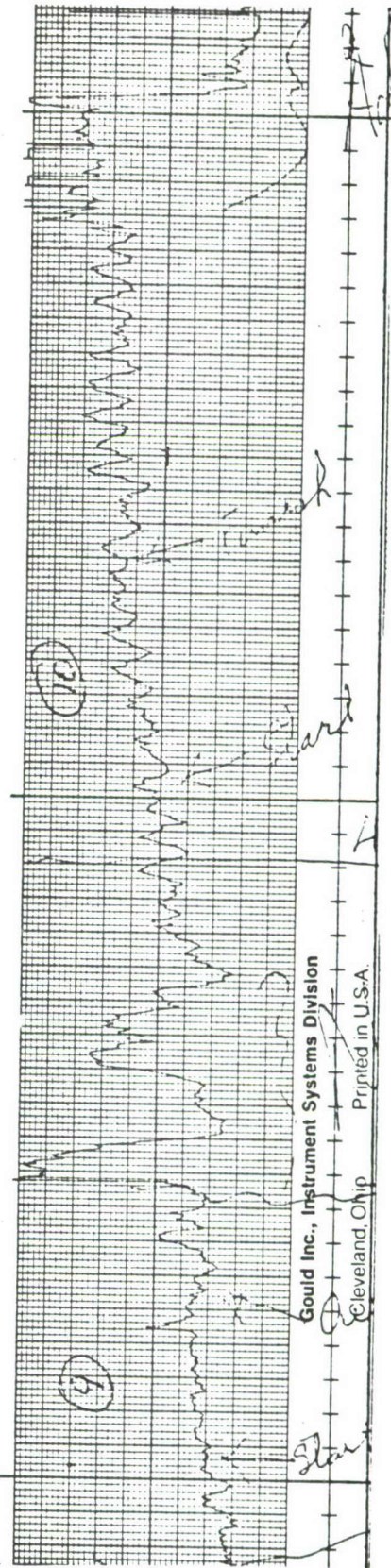
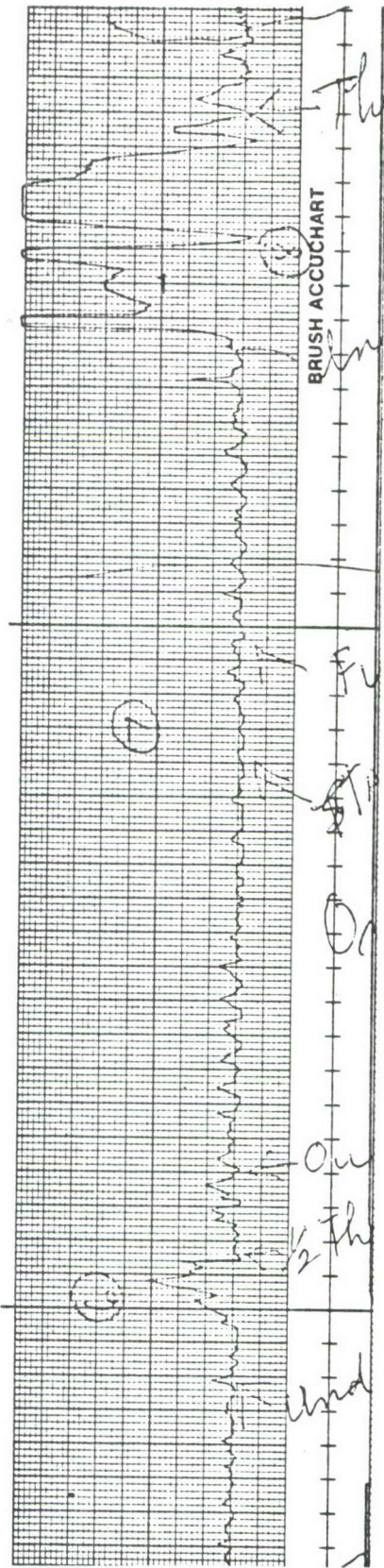
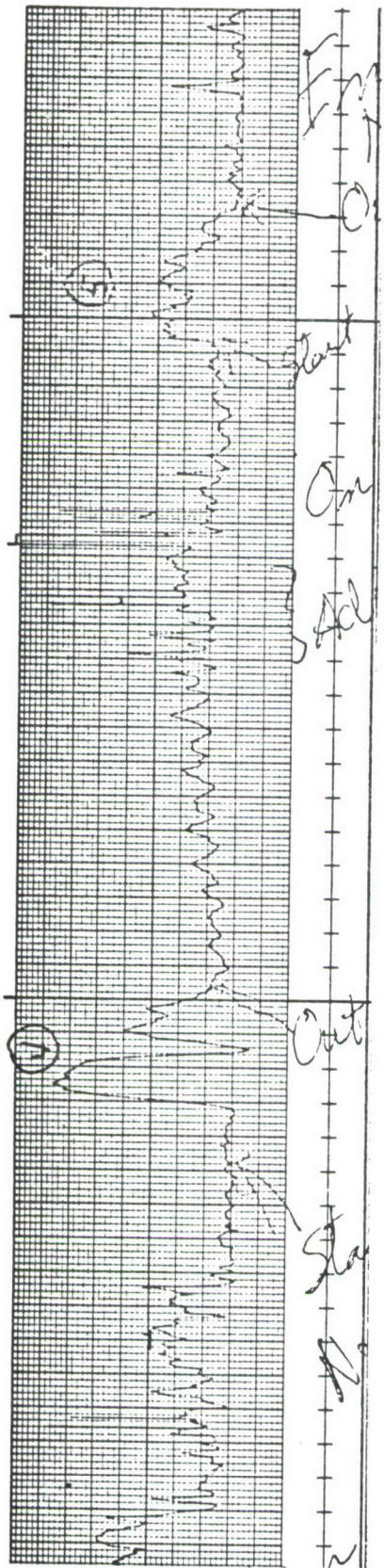
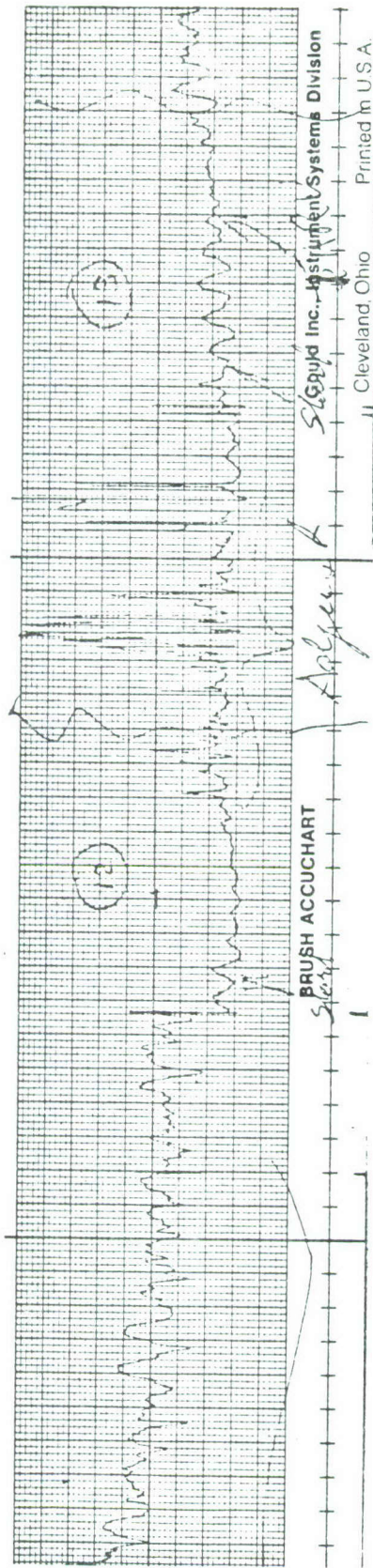
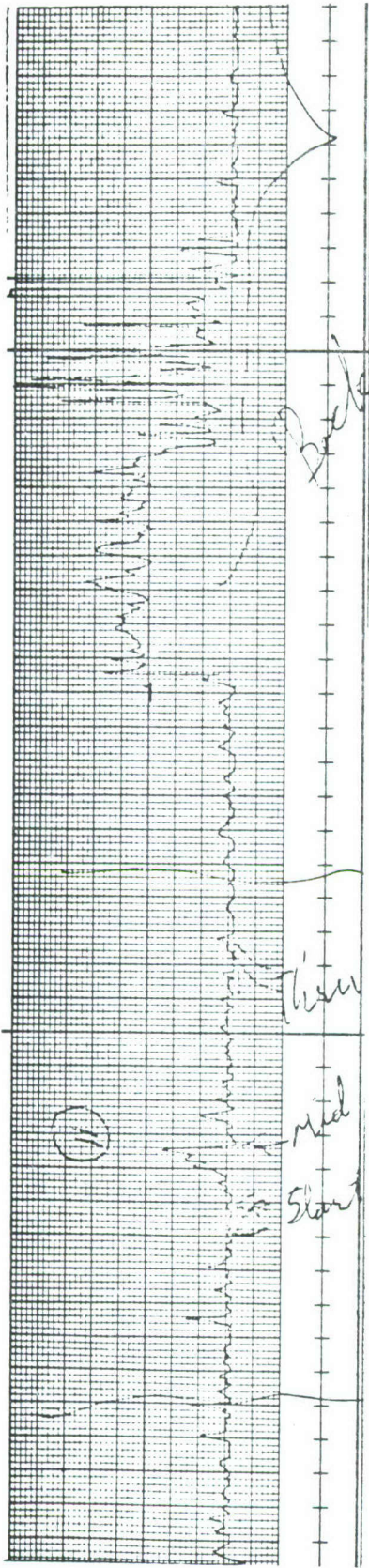


Figure 7 - 2 (b)



BRUSH ACCUCHART

Siemens Instrument Systems Division  
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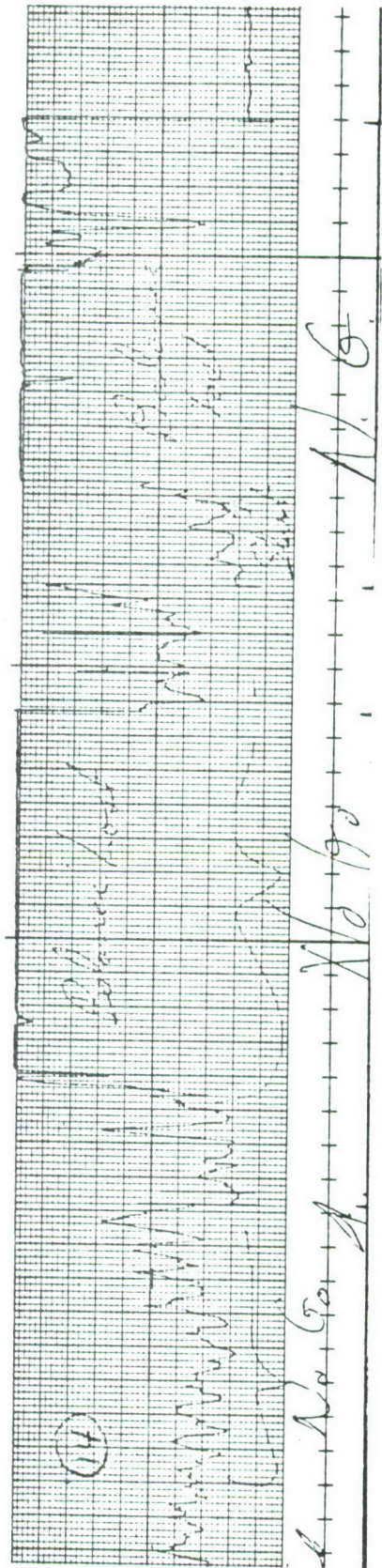


Figure 7 - 2(c)

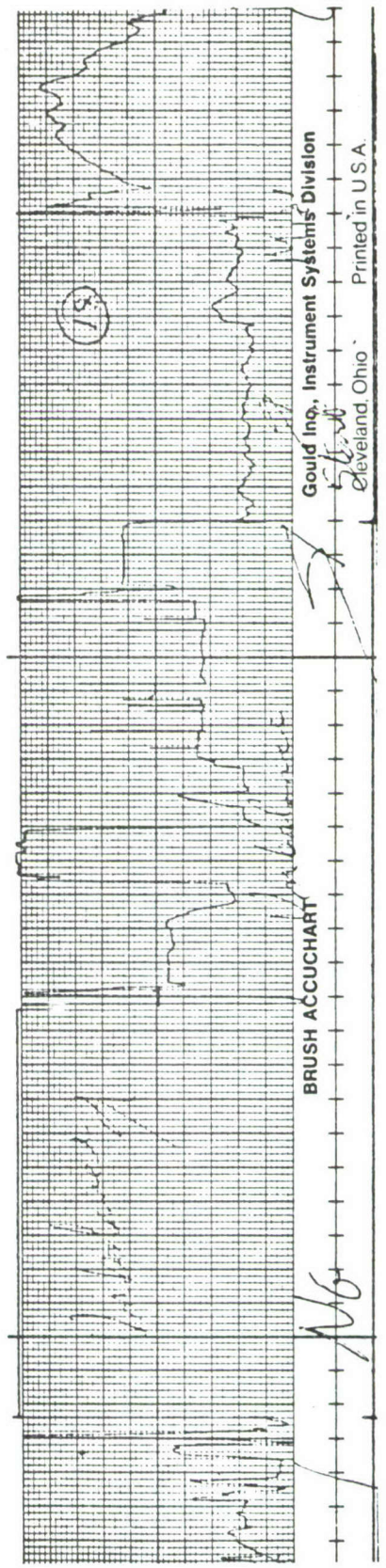
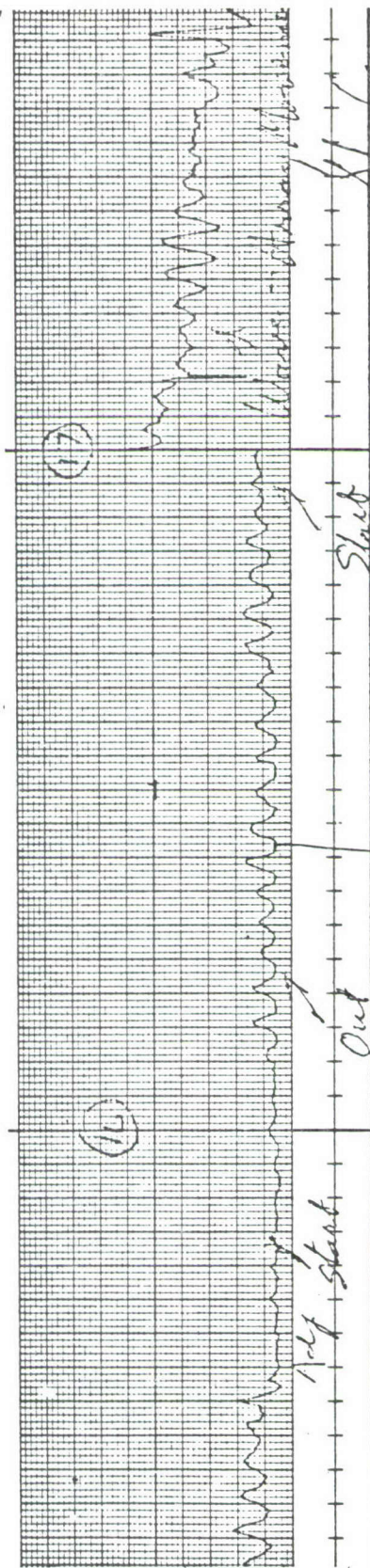
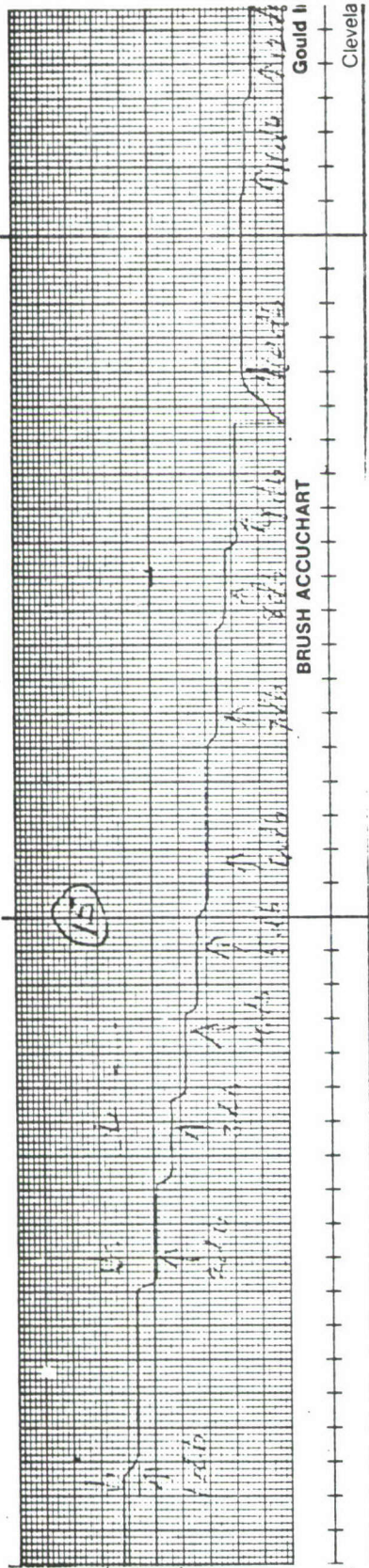


Figure 7 - 2(d)

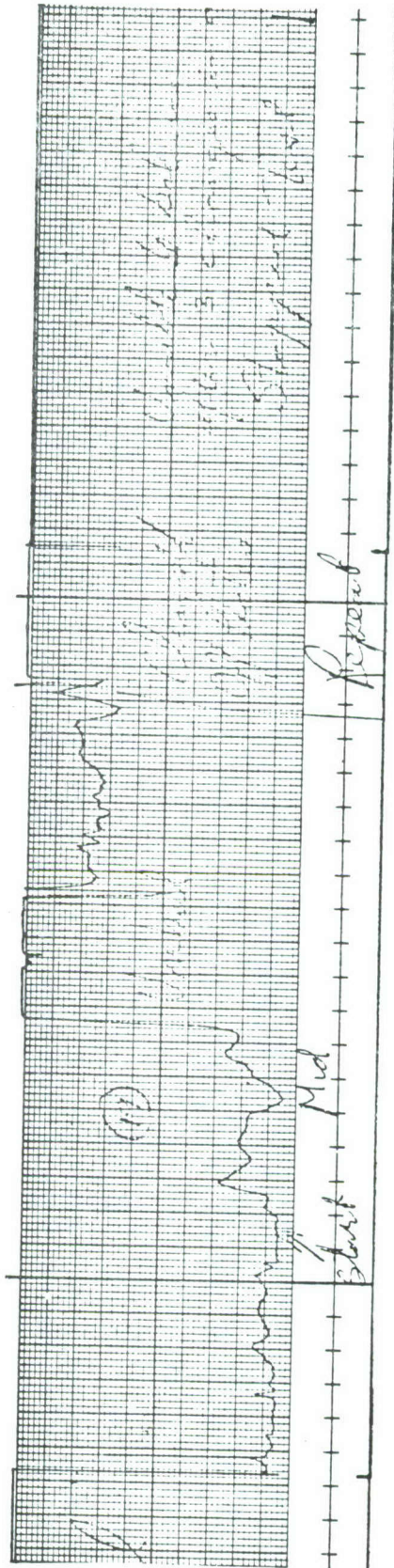


Figure 7 - 2(e)

### 7.3 Equivalent Man

According to Dalziel<sup>6</sup>, a value of 500 ohms is commonly used as the minimum resistance of the human body between two major extremities at or below about 1000 Hz. The extremities are taken to mean the hands and the feet. Presumably this is for a person of average proportions. A path from both hands to both feet would only be half this, or 250 ohms. Because of the significant difference between the average cross section of the limbs and of the torso, the minimum resistance between the top of the head and the two feet should be less than half that from both hands to both feet, or approximately 100 ohms.

Consider, now, a smaller than average man of 1.5 meter height and average cross section of 0.04 sq. meters. His head to feet resistance R is

$$R = \rho H/A \quad (1)$$

where  $\rho$  is the resistivity, H is height and A is equivalent cross-sectional area.

From these approximate dimensions and an assumed resistance of 100 ohms, one finds

$$\rho = 2.67 \text{ ohm-meter,}$$

or 
$$\gamma = 0.37 \text{ mho/meter. (estimated) } \quad (2)$$

A measurement made between the wet hands of one of the project workers at 500 KHz yielded a resistance value of 500 ohms (armspread approximately 1.5 meters and equivalent diameter of 0.10 meter, including chest). Dalziel mentions that the resistivity of the human body actually decreases by as much as 50 per cent in going from 50 Hz to 50 KHz, which non-linear characteristic is explained as being due to the cellular structure of the body. At 500 KHz, the

so-called skin-effect begins to assert itself, and the resistance starts to increase with frequency. At any rate, the measurements on the worker yielded

$$\begin{aligned} \rho &= 2.62 \text{ ohm-meter} \\ \nu &= 0.38 \text{ mho/meter. (measured)} \end{aligned} \quad (3)$$

While neither of these estimated and measured results may be taken as very accurate, the agreement between them is convincing enough to conclude that the human body (with conductive contacts) has an effective conductivity less than 1/10 that of seawater, about the same as brackish water, and more than ten times that of fresh water. Thus, a system which depends upon a discontinuity in the conductivity of the medium to detect an underwater swimmer will work best either in seawater or fresh water, and poorest in brackish water.

A large intruder will, of course, create a stronger disturbance in the medium than a small one, all other conditions being equal. The sphere of about equal volume to the smaller-than-average man mentioned above is 0.5 meter in diameter. A large man of 1.9 meter height and effective cross section of 0.09 square meters would be equal in volume approximately to a sphere having a diameter of 0.7 meters. An average man would be about equal in volume to a sphere of diameter 0.6 meters. The geometrical shape is not especially important in improving a representative equivalent, so long as the dimensions do not exceed those of a human.

Since a man is practically an insulator in seawater, and considerably less than a wavelength in height at 400 KHz, an easily realized electrical equivalent to an average man in seawater is a heavy-duty plastic trash bag containing about 3 cubic feet or 22 gallons of water. The bag represents an insulating barrier of the

required volume at the frequency of interest. Such a model was actually found to be about equivalent to one of the project workers in the laboratory at ARA where the measured conductivity of the water was 3.2 mho/meter. No difference in response was found when the fresh water in the bag was replaced with an equal volume of the more conductive water of the facility. The handling was easier, however, with fresh water because of its tendency to float.

#### 7.4 Method of Conductivity Measurement

A simple technique for measuring the conductivity of water of various levels of salinity employs an electrically-short, open-circuited section of coaxial transmission line, and an r.f. impedance meter which will operate at or below about 1 MHz.

The d.c. conductance  $G$  between two electrodes in an infinite homogeneous conducting medium of conductivity  $\gamma$  is proportional to the Capacitance  $C$  between the same two electrodes in an infinite homogeneous dielectric medium of permittivity  $\epsilon$ .

The relationship is<sup>7</sup>

$$G/\gamma = C/\epsilon$$

The capacitance of a coaxial transmission line of circular cross section is

$$C = 2 \pi \epsilon h / \ln (b/a) \quad , \quad (2)$$

where  $a$  and  $b$  are the radii of the inner and outer opposed surfaces respectively; and  $h$  is the length of the section. Then

$$G = 2\pi \gamma h / \ln (b/a) \quad , \quad (3)$$

and the resistance  $R$  between the cylinders is simply the reciprocal of  $G$ . Thus, for a cylinder of fixed dimensions, one has

$$\begin{aligned} \gamma &= \ln(b/a) / 2\pi Rh \\ &= K/R \end{aligned} \quad (4)$$

The constant K is different for sections of different proportions.

Cylinders of very short electrical length must be used at or near the frequency of the proposed system to achieve accurate results because the input impedance otherwise becomes complex, and the resistive component is not an accurate measure of the desired resistance. The following table gives the dimensions of a set of cylinders suitable for use with the Hewlett-Packard Model 4815 RF Vector Impedance Meter, and indicates the approximate upper limit of conductivity for which they apply at about 0.5 MHz. These cylinders have been used to measure values of conductivity as low as .0016 mho/meter (creek water after a storm), which is about what one should expect for the sample taken. Agreement is also good for a prepared sample of standard seawater (salinity = 35). One should make an additional measurement with the next shorter cylinder when one is near its approximate limit of applicability.

TABLE III  
Design Constants for Conductivity Measuring Cylinders

No.	b (in)	a (in)	h(m)	K	approx. upper limit mho/meter
1	1.384	.500	.25	.648	0.01
2	1.384	.250	.10	2.720	0.07
3	1.384	.250	.05	5.440	0.50
4	1.384	.187	.02	15.900	6.00

## 7.5 Formula for Salt Water of Given Conductivity

Using the ARA test apparatus described elsewhere, it was found experimentally that the conductivity of a water solution of NaCl is an exponential function of the amount of salt dissolved per unit volume, at least for the practical range,  $0.05 \leq \gamma \leq 6.00$  mho/meter. The experiment was done by diluting a known solution 50 per cent for each successive measurement, and using more cylinders for verification as they became applicable. More explicitly, the empirical result was

$$\gamma = 2.410 S^{7/8} \quad (S \text{ in lbs/cu.ft.}) \quad (1)$$

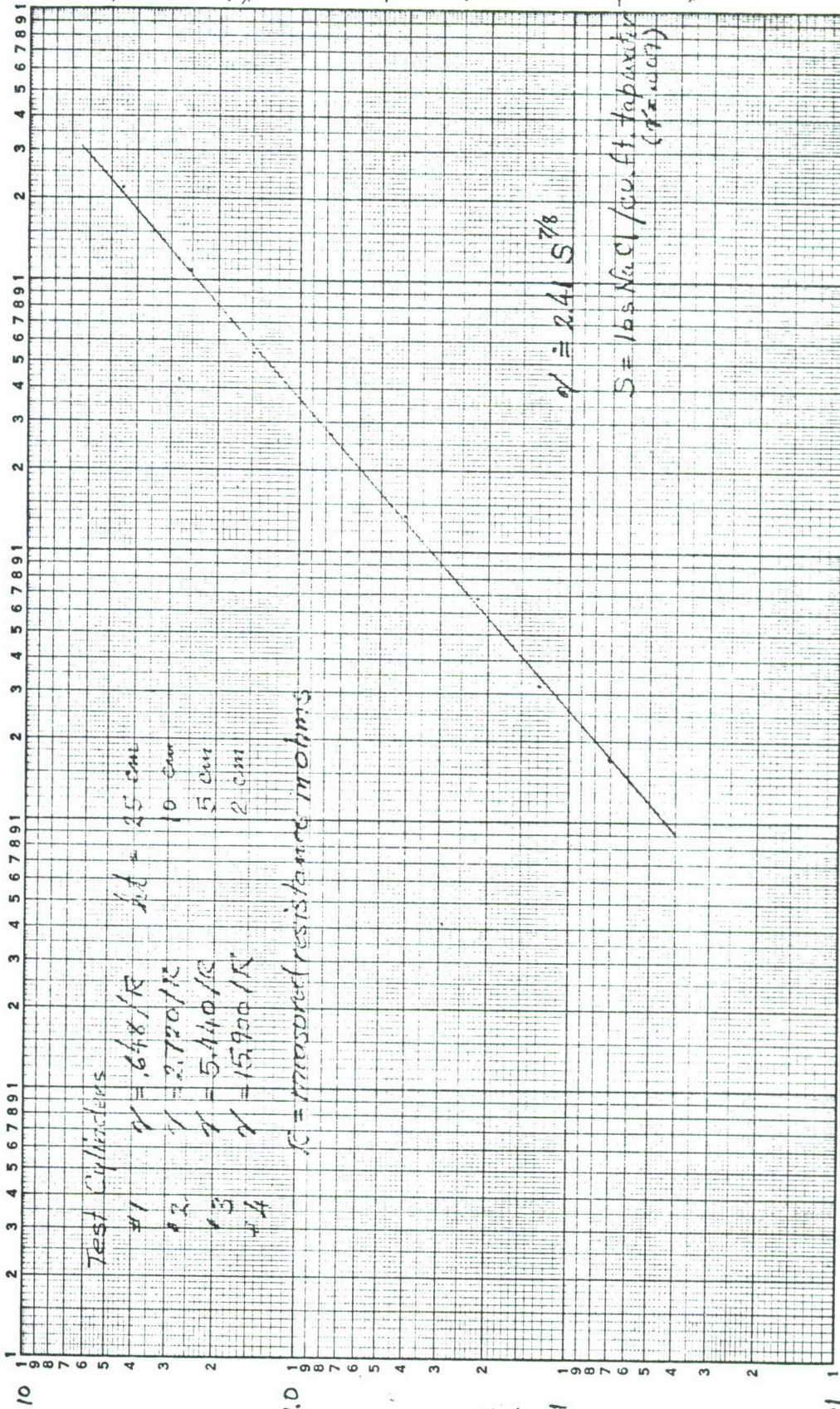
or

$$\gamma = 0.213 S^{7/8} \quad (S \text{ in gm/liter}) \quad (2)$$

Standard seawater has a salinity of 35, which means that its conductivity is the same as that of a solution of 35 grams of NaCl in one liter of pure water. Actually, seawater varies in salinity from about 34 to 37, with extremes of 30 and 47 (Sargasso Sea, Red Sea, Arctic Sea, etc.). The above formulae yield a conductivity of 4.78 mho/meter for water having a salinity of 35 which is very close to the nominal value<sup>8</sup> of 5 most commonly used.

The accompanying chart is a plot of eq. (1), with an indication of the approximate limit on the conductivity below which the various ARA test cylinders yield accurate results.

$\gamma$  = Conductivity - Mho/m



Applicability limits for Test Cylinders

#1  
#2  
#3  
#4

$\gamma = 2.415\%$   
 $S = 16.018 \text{ gm/cc (1 lb/cu.ft.) (approx.) (rho x unit)}$

Test Cylinders  
 #1  $\gamma = 6.48/R$   $ht = 25 \text{ cm}$   
 #2  $\gamma = 2.720/R$   $10 \text{ cm}$   
 #3  $\gamma = 5.440/R$   $5 \text{ cm}$   
 #4  $\gamma = 15.900/R$   $2 \text{ cm}$   
 $C = \text{measured resistance in ohms}$

S - Pounds

(1 lb/cu.ft. = 16.018 gm/cc)  
 (1 gm/cc = 0.6243 lb/c.f.)

Figure 7-3 Salinity Chart

11/10/72

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