1 [illegible]

8-31-1973

Dear [redacted]

As a result of our discussions on 21 August 1973, I am proposing a three phase program designed to:

(1) Establish the effectiveness of electric fish in detecting foreign objects at a distance;

(2) Determine the methods used by electric fish for ranging and location; and

(3) Design equipment systems suitable for replacing electric fish in terms of targeting foreign objects.

I am enclosing a summary of this program. Phase I of the program described herein will correspond to "Phase II" of the program described [redacted] however the tasks have been modified somewhat to better serve the needs of the program. The remainder of the present contract will be used to assess necessary parameters of the electroreceptors system in <u>Gymnarchus</u> and <u>Gnathonemus</u>. Both of these fishes would be used in the Phase I and Phase II of the program recommended above.

I am also enclosing a more detailed description of the experiments to be performed in Phase I of the proposed program and an example of the type of experiments that are appropriate in Phase III. Details on Phase II would depend strongly on the results of the Phase I investigation. I hope that this proposal meets with your approval. Please let me know if you can recommend any added experiments or studies which would aid in the development of a prototype hardware system.

With best wishes,

[redacted]

A PROPOSED THREE PHASE PROGRAM
TO DEFINE HARDWARE ANALOGUES
OF ELECTRIC FISH SENSOR SYSTEM

PHASE I

ESTIMATING THE EFFECTIVENESS OF ELECTRIC FISH IN DETECTING FOREIGN OBJECTS AT A DISTANCE

Perform psychophysiological experiments using different kinds of electric fish in restricted water so as to estimate their ability to identify the existence of foreign objects in this water taking into account electrical discontinuities imposed by the boundaries of that water and the foreign objects placed within it. Specifically, consider the fish as a signal generator and receptor and the use of auxiliary signals which replicate the fish's signals and other signals of specific interest. Compute the expected behavior of such fish in open ocean or fresh waters given typical boundary conditions with respect to depth, topology, inhomogeneity of the water, temperature, and other applicable parameters. Summarize these findings in terms of the ability of these fish to identify foreign objects in a harbor or other natural body of water of interest... foreign objects such as small submarines, torpedoes, scuba divers, skin divers, mines, and others.

More explicitly, determine the sensory capability of individual electric fish in terms of their ability to sense the existence of foreign objects as a function of range, fundamental area, volumetric displacement, differential discontinuity, and so forth. In this regard, use a tank of water at measured temperature and electrolytic conditionts. Retain a fish near one point and insert in the water various objects, discerning the different behavior of the fish as these objects are inserted by concurrently monitoring the electrical field within the water. Specific levels of background noise will be introduced by using a noise generator and measuring the noise amplitude in the tank. Experiments will be performed under normal and extreme noise conditions. From these results, calculate the estimated behavior of such a fish in detecting an object in an infinite water domain and large scale waters with various boundary conditions.

PHASE II

DETERMINING THE METHODS USED BY ELECTRIC FISH FOR RANGING AND LOCATION

Perform detailed experiments wherein the particular characteristics of electric fish are related to their abilities with respect to ranging and location. Particular attention will be focused upon the use of phased arrays of receptors, the fish's ability to determine incremental time lags in the signal, the estimated spectral properties of the signal, the fish's ability to modify the transmitted signal as a reflection of knowledge gained from previous receptions, and so forth. Interpret these findings in terms of specific schematics and data analysis required to synthesize models of the fish's capability, models which when reified would provide signal advantage over the state of the art with respect to such a target as described above.

PHASE III

DESIGN OF EQUIPMENT SYSTEMS SUITABLE FOR REPLICATING ELECTRIC FISH IN TERMS OF TARGETING FOREIGN OBJECTS

Design, fabricate and test experimental apparatus suitable for replicating the above-referenced models. Perform experiments with this apparatus so as to improve its ability in various regards. Make a specific comparison of this capability to that of an electric fish and estimate the utility of such an apparatus in terms of operational situations.

COST ESTIMATE

PHASE I - $	6 months
PHASE II - $	1 year
PHASE III - $	1 year

I. WHAT WE HAVE LEARNED FROM INVESTIGATION OF ELECTRI FISHES AND QUESTIONS WHICH STILL REMAIN

Electric fishes have specialized electric organs: (1) transmitting organs which transmit electric signals modulated and coded in specific ways and (2) receiving organs (electroreceptors) which are part of the lateralis system and detect either (a) discontinuities in the electric field generated by the transmitting organs when the fishes use an active detecting system; (b) changes in the electric field generated by the authorhythmic electroreceptors when the fishes use a passive detecting system and (c) electrical signals emitted by fishes of the same species or of other species, even nonelectric fish which still produce an electric field resulting from their muscular activi during swimming. All this means that electric fishes can navigate, detect, locate and identify living or nonorganic matter and can communicate underwater by means of electric signals and/or electromagnetic detection. The electric power involved is very small. Some of the electric fishes have built-in a jamming avoidance system. Most of them can extract a signal fro a noise that is significantly higher than the signal itself.

and from the data we have from other scientists work, we concluded that unique methods of detection and communication are peculiar to some electric fishes, which could significantly improve our technology if properly applied.

In the appendices to this chapter I summarized the results of the research I have done so far on electric fishes.

SUMMARY OF WORK ACCOMPLISHED

1. One hundred thirty-six fresh water and marine electric fishes were classified; 82 fresh water fishes and 54 marine electric fishes. We collected and correlated data scattered through magazines and the few books having some chapters on electric fishes and data from our own experiments. We listed the locations of specific fishes and prepared maps showing their habitats.

2. Some tropical diseases of the electric fishes were studied. We found a cure for the ulcer-like skin disease of Electrophorus (publ. *Nature*, January 1964) (a cancer-type of skin disease).

3. The anatomy of the electric organs of *Electrophorus*, *Malapterurus*, *Steatogenys*, *Sternarchus*, and *Gymnotus carapo* was studied.

4. Histological preparations were made of the electric organs (Hematoxylin-Eosin staining) and of the electroreceptors in the skin of *Electrophorus* (Bielschovsky-Gross silver impregnation with Cajal counterstaining). Photomicrographs were taken with a Nikon phase-interference microscope.

5. The type of encoding and modulation of the electric signals emitted by electric fishes were studied and classified. (*Electrophorus electricus*, *Gymnotus carapo*, *Sternarchus albifrons*, *Eigenmannia troscheli*, *Gnathonemus petersii*, *Gnathonemus curvirostris*, *Gymnarchus niloticus* and *Malapterurus electricus*.) "Information Processing by Electric Fishes published in the Proceedings of the 1964 Rochester Conference on Data Acquisition and Processing in Biology and Medicine, K. Enslein editor, Pergamon Press, 1965.

6. Behavior experiments were performed with *Sternarchus albifrons*, *Electrophorus electricus*, and *Gymnarchus niloticus*.

7. Proof was brought about the communication ability of electric fishes. Their sensitivity to electric and magnetic stimuli was checked.

8. Exact measurements were made of their discharge; and curves were traced for the *Electrophorus* establishing the voltage, peak power, and average power of its discharge. Curves were traced also for voltage against length of fishes and against weight of fishes.

9. Experiments were performed, and the effect of dc currents on the electric signals of electric fishes has been established for Electrophorus, *Sternarchus*, *Gymnarchus*, *Gnathonemus*, and *Malapterurus*.

10. The effect of changes in temperature of the tank water on the frequency and amplitude of the signals emitted by the electric fishes was investigated and curves traced for temperatures from 18°C to 28°C.

11. The effect of anticholineesterase on the brain of *Sternarchus* was investigated. The change in its behavior and frequency and amplitude of the signal emitted by the fish were studied. The acclimation effect at low (20°C) and high (30°C) temperatures of the tank water on *Sternarchus albifrons* was studied. Comparison with the anticholineesterase is made. (Paper presented at the AAAS meeting, University of California in Berkeley; coauthor with Dr. M. Baslow, University of Hawaii. Only the experiments conducted in our laboratory are mentioned here. Dr. M. Baslow conducted other experiments on Killyfish and other fish at the University of Hawaii, his results are presented as first part of the paper. AAAS paper presented 28 December 1965.)

12. A hypothesis about the way electroreceptors of the electric fishes work was advanced, and experiments were devised to prove the hypothesis.

13. Experiments with moving electrostatic and magnetic fields were conducted. We demonstrated that *Gymnarchus niloticus* is sensitive to a potential gradient of about 0.03 µv/cm, and *Sternarchus albifrons* is only half as sensitive.

14. Alternative explanations of some previous experiments were given in terms of this high dc sensitivity.

15. An explanation in similar terms was given of experiments in which *Gymnarchus niloticus* and *Sternarchus albifrons* were trained to detect a stationary magnet.

16. The mechanisms available for the location of objects by electric fish are reviewed. It is concluded from the results of a critical experiment that *Gymnarchus niloticus* can detect objects by the disturbance of its own electric field in the water.

17. Lissman's derivation of the approximate theory of this method of object location is shown. The effect of the receptors of the perturbing field due to an object depends on the electrical properties of the receptors. In extreme cases, the stimulation of the receptors is proportional either to the potential or to its second derivative. Graphs are given showing the effect of an object on the potential and on its second derivative around the surface of the fish.

18. Experiments are described using Gymnarchus niloticus which (a) confirm that the mechanism of object location employs the detection of the distortion of the electric field produced by discontinuities in this field, and (b) indicate the limits of the sensitivity of the fish.

19. The detection of the second derivative mode of its own emitted signals appears to be the most probable one operating in Gymnarchus. The experimentally determined limits of detection are discussed in relation to the random noise in the receptors circuit. It is concluded that both spatial and temporal integration are likely to be employed.

20. The thresholds for object location and for response to direct currents are compared. It is concluded that the same receptors are probably operating in both cases.

21. Experiments were devised to find the attenuation and distortion of signals similar to the ones emitted by electric fishes in underwater transmission. It is clearly proved that signals are distorted and their shape is close to the derivative of the original signal. In case we can devise a receptor system that can integrate the second derivative of the original signal an improvement of signal-to-noise ratio to about 10:1 is to be expected. Experiments with electromagnetic fields, pure magnetic fields, electric integrators, and magnetic receivers are underway. The results of these experiments may bring us to the recommendation of an absolute new underwater transmitting-receiving system.

23. The electric organs of Sternarchus albifrons, a South American fresh water weak electric fish, have been studied with emphasis on electroreceptors. The morphological and physiological characteristics of electroreceptors, ampullary and tuberous, were investigated. Special instrumentation required for establishing the role of these electroreceptors in object location, detection and identification has been developed.

24. We have recorded with microelectrodes the autonomous autorhythmic electrical activity of the tonic asynchronous ampullary electroreceptors of the South American weak fresh water electric fish, Sternarchus albifrons. We have also recorded the electrical activity from the asynchronous phasic tuberous electroreceptors and of the synchronous and asynchronous ampullary electroreceptors of the same electric fish, Sternarchus albifrons. Preliminary measurements have been made. The autorhythmic activity of the ampullary electroreceptors has been demonstrated.

The electroreceptors are part of the complex lateralis line system of the electric fishes.

25. The other lateralis line system sensory receptors, like mechanical receptors and displacement receptors, have been discussed as part of a general hybrid object detection, location and identification and recognition system of the fish.

26. A study of the anesthetizing effect of tricaine-methanesulfonate (MS222= FINQUEL) on Sternarchus albifrons has been undertaken by plotting time for the anesthesia and recovery for different specimens. The anaesthetic does effect the pulse-rate and pulse-shape of the discharge of this fish. Anaesthetic other than "Finquel" which does not affect the electric fish's electric organ pulse repetition rate has been found. Also, the effect of D-tubocurarine and the counter-effect of neostigmine has been assessed for Sternarchus albifrons. Finally, some improvements in the microelectrode recording instrumentation have been made.

27. We obtained some specimens of the African weak fresh water electric fish Gymnarchus niloticus. They are supposed to be the most sensitive of all the weak electric fishes known. Together with two specimens about one foot long, we received a number of baby Gymnarchus niloticus about two inches long. The baby electric fish were infected with a Saprolegnia fungus and could not be saved, but we fixed a number of them in buffered formaldehyde and one of them has been cut and mounted in paraffin for histological studies of the electric organs. Preliminary measurements have been made on the communication capability of adult Gymnarchus niloticus.

28. The electric discharge of Malapterurus electricus, an African fresh water strong electric fish, has been measured in and out of water. Its electric organ can discharge bursts of impulses of 100 to 350 volts and currents to about 40 mA. In general they can put an electric power of about 1000 watts per kilogram of electric tissue (1 watt electric power per gram of electric tissue). From our investigation, it can be concluded that electric fishes could use their electric organs (transmitting and receiving) for navigation and communication – in other words, underwater object detection, location and identification using an electromagnetic system of detection.

30. The physical analogs of tonic and phasic electroreceptors have been established. Both are represented by a generator connected to resistances and capacitances in series and in parallel. The difference

between tonic and phasic electroreceptors is that the first ones have one resistance in series with the generator whereas the phasic electroreceptors have a capacitance. The tonic electroreceptors seem to be predominant, maybe like five-to-one, compared to the phasic electroreceptors. The electroreceptors seem to act, to a certain extent, independently of the main electric transmitting organ; at least two out of three different types of electroreceptors are asynchronous and only one type of electroreceptor will synchronize with the main electric organ. It has been found that the complete denervation of the transmitting electric organ does not stop the activity of the asynchronous electroreceptors (both phasic and tonic). The fish is still capable of responding to conductive and nonconductive objects placed near the fish's body. It may affect the total capability in determining certain movements or impair, to a certain extent, its sensitivity in object recognition. Some of the synchronous tonic units are connected to one and the same nerve trunk part of the acoustico-lateralis system but connected to specialized big nuclei in the brain.

The most striking fact about fresh water weak electric fish, besides their spontaneous electric organ, is that all of them are provided with a highly developed lateralis line system. Related to this acoustico-lateralis system is an enlargement of the cerebellum, especially in Gymnarchus niloticus and in mormyrids. The unusual importance of the lateralis system in these fish, compared with other teleosts, is not due to an increase number of "ordinary" lateral line sensory organs, but rather to the existence of a great number of specialized sensory organs within this same system. This is supporting our hypothesis about a hybrid complex underwater object detection, location and identification system used by electric fishes in recognition of prey, predators, and navigation in general. It is recommended that the other lateralis line systems from different fresh water weak electric fishes should be studied with the aim to find out their role in object detection and navigation.

II. CONDITIONING TECHNIQUES APPLICABLE TO THE ELECTRIC RESPONSE AND BEHAVIOR OF SELECTED ELECTRIC FISHES

Summary

A study described in this section is designed to identify the type of conditioning techniques (operant or respondent) applicable to the electric responses of selected electric fishes, with particular attention to those procedures which can be used to assess the "dynamic range" of the response with respect to major electrical parameters. Several additional behavioral studies of electric fishes are also described in some detail.

Introduction

It was mentioned in previous sections of this report that certain fish possess organs capable of generating electrical discharges; and, at least some of these, have electric receptors that are capable of detecting and discriminating among different patterns of discharge. This study is focused on determining the extent to which the electrical responses of selected specie can be brought under the control of respondent (classical, Pavlovian) and/or operant (instrumental, Thorndikian) conditioning techniques. (Skinner,[1] and Keller and Schoenfeld.)[2] The results will then be examined to determine whether or not significant relationships exist between the type of conditioning operations which are applicable to a particular response and physiological data concerning the structure of the organ, the type of tissue from which it was probably derived, the type of neural innervation and control evidenced, its electrical characteristics, and its functioning.

These questions are of considerable interest in behavior science. Viewed as operational definitions (Feigl[3] and Frank[4]) the two sets of conditioning operations subsumed respectively by the labels, "operant conditioning" and "respondent conditioning", are clearly different. The controversy i the literature of the last decade or so concerning the kinds of learning which exist has not usually been at the level of experimental procedures and results (i.e., of operational definitions) here assumed. Instead it has concerned such questions as the possibility of reducing both types of conditioning to a common, usually unobservable, intervening or mediating process; with the nature of the postulated process; or, with the type of theoretical formulation (Estes, Koch, et. al.)[5] considered most promising by the particular "model builder." Skinner[1, 6] for example, prefers the descriptive, operational level and remains aloof from physiological or phenomenological speculations, as well as from the "premature" building of theoretical superstructures. Hull,[7] on the other hand, had as his primary purpose in writing his "Principles of Behavior," the integration of the two types of conditioning operations and results (Spence [8] and endorsed various physiological speculations. Guthrie [9] postulates an underlying process consisting of one-shot, stimulus-response associations resulting from temporal contiguity, and suggests that both types of conditioning follow from it. Estes[10] gave strong impetus to the recent development of stochastic models as a means of achieving the desired integration. Tolman,[11, 12] Woodworth,[13] Birch and Bitterman,[14] and, in a different way, Miller, Galanter and Pribram[15] emphasize perceptual and cognitive processes as more basic. There is no question, however, about the clear distinction between the two sets of conditioning operations at the level of operational definitions--i.e., in terms of laboratory procedures and results. This is the level at which the experimentalist does his work.

For species typically studied in the "animal laboratory," two *almost* mutually exclusive classes of responses can be defined, corresponding to the particular set of conditioning operations which is effective. That is to say, most responses are found to be conditionable by either respondent or operant procedures, usually not both. It has been further observed that responses which can be conditioned respondently typically involve autonomically controlled, smooth muscles; while those accessible to operant procedures always employ striped muscles under central nervous system control.

The empirical relationships between the two types of conditioning procedures are quite complex. Smooth muscle ("emotional") responses are often conditioned respondently in the course of an operant conditioning program. There also exists a small number of striped muscle responses which may be elicited respondently by noxious stimuli (e.g., shock-leg flexion) and which are reinforced operantly by the termination of, or escape from, the noxious stimulation (Skinner).[1] Although the responses--in this case, leg-flexion elicited by shock and leg-flexion as operantly reinforced--are superficially the same, they are best regarded as two different responses with similar topography.

Nevertheless, the association of operant procedures with striped muscles under central nervous system control and of respondent techniques with autonomically controlled, smooth muscle responses, is quite generally valid. Operant techniques are applicable to *all* conditionable striped muscle responses and to *no* smooth muscle responses. Respondent (Pavlovian) techniques are applicable to all conditionable smooth muscle responses and to the relatively small number of specific striped muscle responses for which noxious eliciting stimuli exist.

Differences in the electric organs and associated processes among the various species are particularly interesting when viewed against this background. In terms of origins, for example, most electric organs derive from striped muscle tissue-- caudal, branchial, or ocular, depending on the species-- with the notable exception of *Malapterurus*, where origin is either regarded as a question mark (Grundfest[16]) or hypothesized as glandular (Keynes).[17] The origin in the case of Sternarchus albifrons is nervous tissue. Four different types of electroplaque responses have been identified. The connections between the innervating neurons and the electric organ varies from species to species, as do the relationships of these neurons to the remainder of the nervous system (Grundfest[16]). Moreover, the autonomic nervous system of fish does not exhibit the same degree of differentiation commonly found in mammals (Healy[18]).

In view of these natural variations, it seems worthwhile to determine empirically the type of conditioning operations which can be used to "control" the electric responses of several species, carefully selected on the basis of known structure (and availability) and to relate these findings to the relevant anatomical information.

Since it would not be feasible to include in the investigation every conditioning operation in each of the two sets, emphasis should be placed on those procedures which can be used to assess the "dynamic range" of the response in each case. This will involve determining, not only the mean and distribution, but also the maximum and minimum values of major response parameters, both in the free state and under attainable forms and degrees of environmental and behavioral control. Data obtained in this way can also be correlated with information about the structure and functioning of the respective electric organs. The data will also be relevant to the study of receptor processes.

It is important to study the types of conditioning techniques which are applicable to the electric responses of selected electric fishes, with some emphasis on those procedures which can be used to assess the "dynamic range" of the response in each case. Possible relationships between the type of conditioning operations found applicable and the type of neuromuscular process involved, will be sought. It should be noted that the relationship discussed between the two classes of conditioning and the two major subdivisions of the neuromuscular system in higher animals is not an integral part of behavior theory itself, or even of Skinner's version of it. It is rather at the level of an observed "coincidence" between the two operationally distinct sets of conditioning procedures (which are part of behavior theory) and a set of facts concerning the morphology of the organisms which are conditioned (which facts are not a part of behavior theory). Data pertaining to the "dynamic range" will be examined in the light of known or readily ascertainable facts about the respective electric organs.

Behavioral Research

The behavioral research should be executed in two stages. The first will be concerned with identifying the category of conditioning operations which can be used to control the electric response. The second will consist of utilizing this control to determine the "dynamic range" of the response.

Determination of the Kind and Degree of Behavioral Control which is Attainable over the Electric Responses of Selected Species.

This stage will involve answering the following closely related questions for each species and each response:

Does the electrical response occur as a reflex to a discoverable and definable class of unconditioned stimuli?

Can the response be conditioned using respondent (classical, Pavlovian) procedures?

Can the response be conditioned using operant (instrumental, Thorndikian) techniques?

The procedures employed to answer these questions will include the following:

1. Study each "electric response" as a "free operant."

   The "spontaneous" emissions of the fish have to be studied under the range of environmental conditions (temperature, light, sound, electromagnetic shielding, etc.) in which the subsequent conditioning studies will be undertaken. (Ferster;[19] Schoenfeld, Antonitis, and Bersh;[20] Reed[21]) The distribution of all significant response parameters, including occurrence in time for the non-continuous case, will be obtained. Since the responses of strong electric fish may not occur as free operants (i. e., in the absence of specific eliciting stimuli), the bulk of these data will probably concern parametric variations in the continuous emissions of weak electric fish. Some of the information gathered at this stage will be useful in determining the nature and degree of experimental control necessary to ensure the desired precision in subsequent behavioral measurements.

2. Record gross or general activity of the fish.

The "gross" or "general" activity of the fish has to be recorded on a continuous basis during all experimental sessions (Bull[18]) in which movement by the fish is possible, including the foregoing "free operant" study. A relatively simple set of floats and microswitches could serve as the sensing device for this purpose.

A relationship between emission frequency and momentary activity and stimulation has been asserted to hold for certain Gymnotidae and for Mormyridae. The inclusion of the general activity measure will permit us to determine whether such a relationship exists and, if so, to specify its precise form. Other uses of this measure will be evident as the study proceeds.

3. Determine the effects on behavior of selected stimuli.

The stimuli to be presented will be carefully selected to represent the range of modalities and parametric values known or thought to be within the receptive capabilities of the organism or of special interest to the investigation. Variations in electrical response parameters, in the general activity measure, and in other describable behaviors will be observed and recorded. Other techniques (Ash[23] and Thorpe[24]), will include the investigation of unconditioned respondents (Kuroda[25]), associated with each stimulus and the effects of stimulus presentations on a free operant other than the electrical response.

One of the objectives of this step is the identification of neutral stimuli which are suitable for use as "conditioned stimuli" in respondent conditioning and as "discriminative stimuli" and "secondary reinforcers" in operant conditioning. A sufficient number of "primary reinforcing stimuli" will be sought for use in manipulating the strength of selected operants.

Lastly, an effort will be made in this step to identify "unconditioned stimuli" which are capable of eliciting the electric response of strong electric fish and, possibly, of producing variations in the continuous emissions of weak electric fish, prior to any conditioning operations. Such eliciting stimuli retain their association with the response despite the application of extinction procedures.

4. Condition the electrical response.

The specific procedures to be followed will depend upon the outcome of the foregoing steps. If eliciting stimuli are found, we would expect the paradigms of respondent conditioning to be applicable, assuming the response can be conditioned at all. On the other hand, if the response (e.g., spontaneous parametric variations in the continuous case) is found to occur as a "free operant," in the absence of specific eliciting stimuli, then either operant techniques will apply or the variations will exhibit the properties of "behavioral oscillation" (Hull).[7]

Because of the existence of the "operant-respondent overlap," discussed earlier, it would be desirable to check the possibility of operant conditioning whenever a noxious eliciting stimulus for the electrical response is found; and, to seek a noxious eliciting stimulus even if operant techniques have been successfully applied to a (topographically similar) response.

From the literature dealing with electric fish, one would expect to find:

a. That a class of eliciting stimuli exists for the strong electric response in each species. Pavlovian procedures are therefore likely to be found applicable. Nevertheless, the possibility that these responses are accessible to operant procedures should also be checked.

b. That the continuous emissions of those knifefishes whose responses have been shown to be temperature-correlated may not be conditionable. It has been suggested that the control centers for these responses may be isolated neurologically from the necessary sensory inputs. However, Bennet and Grundfest[26] report a transient increase in the rate of response in *Gymnotus carapo*, one of the species used in establishing the temperature-frequency relationship, immediately following a tap on the tank. A systematic and full-scale attempt to condition this fish is therefore indicated.

c. The weak responses of those gymnotid and mormyrid species in which frequency (and perhaps other parameters) is said to be highly variable and dependent upon the activity and excitation of the fish, are likely to be conditionable operantly.

The failure of Longo and Bitterman[27] to find increased resistance to extinction in fish (Telapia macrocephala) following partial reinforcement --a consistent finding in the animal laboratory-- illustrates the need for caution in generalizing results over too wide a segment of the phylogenetic scale and possibly over too wide a range of experimental operations, time schedules, etc.

On the other hand, Dews[28] (1959) was impressed by the similarity of his results in conditioning lever manipulation in the octopus to those typically obtained with "higher" organisms. Noting that the octopus evolved independently of vertebrates since Cambrian times (500 million years ago), he commented that operant conditioning must be a very old and fundamental learning process.

Generally speaking, it is expected that the resemblances among species will far outnumber the differences. Nevertheless, it is only through research with the particular species, responses, and experimental procedures of interest that clear answers to such questions can be obtained.

Determination of the "Dynamic Range" of Each Electrical Response

The objective of this stage is to "push" response parameters, singly and in selected combinations, to their upper and lower limits.

It is at this point that the differences between operant and respondent conditioning bears most critically on the proposed research. Only operant procedures provide the type and degree of control necessary to "shape" responses in the desired manner. The main procedure available for this purpose, namely "response differentiation," consists in making reinforcement contingent upon the emission of responses progressively approximating the desired values. (See for example, the oft-quoted study of Hays and Woodbury, initially reported by Hull.)[7]. In addition, the manipulation of reinforcement schedules (Ferster and Skinner[29]) can be used to "compress" two or more discrete responses in time.

On the other hand, the control over the parameters of those responses which can be conditioned only respondently, is generally limited to those variations in magnitude and latency associated with changes in the intensity, number and rate of conditioned and unconditioned stimuli, with the number of extinction trials, and with certain extraneous or "conflicting" stimulations (Hilgard and Marquis).[30] These techniques permit neither the "shaping" of responses nor the degree of control over response parameters that is attainable with operant conditioning. Nevertheless, the data describing response variations which accompany these respondent procedures, will serve to define the dynamic range to the extent that such definition is possible with responses accessible only to Pavlovian techniques.

This section began with a discussion of concepts and methods that we would use to determine the kind and degree of behavioral control that could be achieved over the electric responses of selected species. This question was seen to reduce to the task of determining the particular set of conditioning operations (operant or respondent) which are applicable in each case. The procedure for getting the necessary information involved studying the electric response as a "free operant;" recording the general activity of the fish on a continuous basis during experimental sessions; determining the effect of selected stimulus presentations on general activity and on specific responses, primarily as a means of identifying a sufficient number of neutral and reinforcing stimuli for experimental purposes and to identify such specific, eliciting, "unconditioned " stimuli for the electrical response as may exist; and, attempting to condition the electrical response operantly, respondently, or both, as appropriate.

The method of exploring the dynamic range of electrical responses was seen to depend critically upon the type of conditioning operations to which the response is accessible.

These two efforts --determining the set of conditioning operations applicable in each case and using this information to ascertain the limits with respect to selected response parameters-- are the core of the mentioned behavioral research.

In the next part of this section certain related behavioral research studies are described. These indicate the wide range of questions to be answered through research with respect to the behavior of electric fishes. Following this, we shall turn our attention to some questions of "experimental design."

Other Behavioral Studies

As physical facilities and experimental techniques are developed, in the course of conditioning the electrical response and determining its dynamic range, it will become economical to utilize the resources for additional research along the same or related lines. Among the additional studies deserving of consideration are those concerned with object location, object identification, warning and other intraspecies "communications," thresholds of electrical reception, receptor location and certain additional conditioning experiments.

Illustrative studies in each of these areas are described below.

Object Location

It has been stated that Gymnarchidae, Mormyridae, Gymnotidae, Electrophoridae, Sternarchidae, and Rhamphichthyidae use their weak electrical responses for direction finding and navigational purposes. Studies such as the following would yield relevant data.

Obstacle avoidance tests. The fact that electrically and magnetically sensitive fishes avoid or attack metal objects might provide a basis for duplicating the approach employed by Griffin[31] with bats and Kellogg[32] with porpoises. Accordingly, metal wires would be strung vertically, and perhaps horizontally, across a tank and the organism enticed or "persuaded" to swim through. The diameter, spacing, and number varied systematically over a series of determinations. Contacts with the wires would be detected and counted as errors. Electrical responses and general activity would be recorded throughout. An essential feature of such experimentation is the careful elimination, or control, of all extraneous (including non-electrical) cues which might possibly be useful to the organism in avoiding the obstacles (Lissman and Machin[33]).

The primary value of such a study would probably be as a demonstration that a particular fish actually does use its electrical system for navigational purposes. Scores obtained in the test situation could also be used to compare the performance of the same fish under different conditions, as for example, to assess performance decrements associated with experimentally induced impairment or isolation of the electroreceptor function. On the other hand, comparisons based on scores attained by fish differing in size, species, and perhaps other factors would be somewhat tenuous.

Directional adjustments in output. The possibility that the electrical output pattern is adjusted directionally to the location of the "target" object might be worth checking in those weak electric fish with diphasic (e.g., Gymnotus Carapo) and triphasic (e.g., Sternarchus Albifrons) responses. This could be done by developing a technique for introducing "supraliminal" objects (e.g., metal slugs) at carefully selected points in the space around the fish, with suitable precautions to preclude extraneous cues, and examining the electrical response patterns for possible adjustment to the location (and perhaps nature) of the stimulus objects.

Object separation thresholds. Another assessment of the resolving power of the receptor system might consist in training the animal to discriminate between the presentation of a *single cylindrical object* and *two spatially separated half-cylinders.* Three points in a horizontal plane through the center of the totally or partially confined fish and equidistant from its surface would be chosen. The fish would be trained to make the required discriminative response to stimuli presented at any one of the three selected points. This discrimination training can be accomplished by conditioning a (non-electrical) respondent or operant to the presentation of the single cylinder at any one of the three points. Another response (or extinction of the first one) would be linked with the presentation of the two half-cylinders. Stimulus presentations would be randomly sequenced with respect to type (single cylinder or two halves) and location in the test field. Initially the two half-cylinders would be separated by an easily discriminable distance, with one member located at one of the three points and the other displaced to one side or the other, parallel to the surface of the fish. The displaced half would be brought closer to one located exactly at the selected point, as the conditioning proceeded. The separation threshold would be exhibited by plotting log latency (Schlosberg and Solomon [34]; Blackwell and Schlosberg [35]), or other appropriate response measure, against separation distance for each of the three points. Observable behaviors will also change around the threshold of discrimination (Pavlov[36]).

Object Identification

It has been seriously suggested that weak electric fish may use the electrical process for species, perhaps even for sex, recognition. It would not be difficult (theoretically) to devise experiments to test these hypotheses. Some minimum data bearing on species and sex recognition could be initially collected as opportunities present themselves in the course of other studies. After this has been done, the other experiments could follow.

It will be relatively simple, on the other hand, to develop an adaptation of Kellogg's preferred food identification test.

Warnings and Other Intra-species Communications

The assertion that a particular species utilizes warning signals implies that one member of the species, when presented with a negative (primary or perhaps even secondary) reinforcing stimulus, will emit signals to which other members of the same species respond appropriately. The Fringe-Jumber[37] studies of specific sounds to repel starlings nicely illustrates the method with primary reinforcers. The technique can be generalized to include a wide range of stimulus presentations to a fish whose signal output is recorded. Changes in the electrical emissions, general activity, or other behavior of other fish stimulated by the recordings would be recorded and compared quantitively and qualitatively with the responses to stimulation of the kind applied directly to the first.

In a similar way, Church[38] employed a modified Estes-Skinner[39] technique to study the effect on an intermittently reinforced (FR 4:1--Forster and Skinner[29]) response. When the squeals, etc. of a shocked rat were followed immediately by shock to the observing rat, such squeals came to function as an anxiety producing stimulus (Schoenfeld[40]). The squeals of another rat under shock thus became sufficient by themselves to depress the rate of bar pressing. Rats not so conditioned exhibited a temporary depression in response rate, following the initial presentations of the squeals, etc., which quickly adapted out--i.e., extinguished.

Threshold Determinations for Electrical Receptors

There exists a considerable number of techniques which can be adapted readily to the determination of electrical thresholds for any species selected for study. These techniques all involve conditioning the organism to respond differently to the presence or absence of stimulation (absolute thresholds) or to two stimuli which differ with respect to some parameter (difference thresholds). Since there is no restriction on the responses which can be linked discriminatively to stimulus-presence or to a particular parameter-difference, any convenient operant or respondent may be chosen.

For this reason, the question of type of conditioning operation, which is so critical in attempting to gain control over a particular response, presents no problem at all for threshold determinations. Here, it is important only to select from the repertoire of the organism a response that is readily conditioned and easy to work with (record, quantize, etc), and one which will not contaminate the threshold determinations --e.g., by causing uncontrollable variations in the distance between the receptor and the stimulus-object, or by otherwise inducing significant changes in the perceived electrical field. Such decisions can be made best after one has had opportunity to observe and conduct preliminary trials with a given species and organism.

The following are illustrative of the operant and respondent techniques which may be adapted to the task of determining absolute and differential thresholds of electrical stimulation in selected species:

1. Operant techniques.

Lissman[33] trained *Gymnotus carapo* to feed when a stationary magnet was mounted just outside its aquarium. The prototype for for this widely used discrimination training procedure may be represented in the following paradigm:

$$S^D \longrightarrow [R] \longrightarrow S^R$$

$$S^{\Delta} \longrightarrow [R] \not\longrightarrow S^R$$

The first line indicates that the "discriminative stimulus" (indicated by S^D, read and sometimes written as "essdee," in this case the presentation of the magnet) is followed by (indicated by arrow) the set of responses that we are attempting to condition (indicated by [R], in this case approaching the food) which in turn is followed by "positive, primary reinforcing stimuli" (indicated by S^R, in this case the food).

The second line represents the fact that responding (approaching the feeder, etc.) in the absence of the magnet (S^{Δ}, read and sometimes written as "essdelta") is *not* followed by ($\not\longrightarrow$) reinforcement (S^R, i.e., food).

The first process, reinforcement in the presence of S^D strengthens the response to the point where the response rate increases even in the absence of the magnet (i.e., in the S^{Δ} condition). This, of course, is "generalization." The second process serves to extinguish responding in the S^{Δ} condition. As a result of these two processes operating concurrently, the animal learns to respond in the presence of the discriminative stimulus and not to respond in its absence. In a similar way, Deterline[41] conditioned African mouthbreeders to manipulate a lever, with the brighter of two lights as the S^D.

The following are illustrative of the numerous variations on the general procedure which are possible.

a. Instead of merely witholding S^R (e.g., food) for responses under S^{Δ}, Lissman[33] punished such responses by chasing the fish away from the food with a wire fork and, on occasions, the fish was "knocked on the snout with one end of this wire fork." Punishing responses made in the absence of the discriminative stimulus (i.e., in the S^{Δ} condition) is generally to be avoided. It contributes little or nothing to the learning and has undesirable, "emotional" side effects.

b. Punishing stimuli may be used without prolonged emotional effects when the set of responses, [R], is reinforced by avoidance or immediate termination (Schoenfeld[40]) of a noxious or punishing stimulus (i.e., a primary negative reinforcing stimulus), instead of by the procurement of a positive reinforcer.

Blackwell and Schlosberg[35] used this technique for determining absolute thresholds. They trained rats to cross a grid, [R], to procure food. The rats received a shock when they crossed during periods of silence (S^{Δ}), but avoided this noxious stimulus by crossing during the presentation of a tone of one of several frequencies. Percent occurrence and log latency of responses were used to determine the stimulus thresholds. As a more recent example, Murphy and Harris[42] adapted the Mowrer-Lamoreaux[43] "shuttle box" technique to assess auditory threshold changes resulting from head exposure to X-rays in rats.

c. The procedures may be adapted for the determination of difference thresholds and for decision-making studies by substituting two or more different stimuli in place of the stimulus-presence (S^{D}) and the stimulus-absence (S^{Δ}) pair in the paradigm.

Sutherland (e.g., Refs. 44 and 45) trained octopi to attack one class of geometric figures (e.g., squares) and to refrain from attacking another class (e.g., rectangles). He used food to reinforce "correct" responses and, in some studies, also used shock in addition to no food for "incorrect" responses. Lissman[33] trained Gymnarchus Niloticus to discriminate between two opaque containers of aquarium water, differing electrically because of the inclusion in one container of a glass tube, 0.2 cm diameter. The proper approach response was reinforced with food; an incorrect choice received the no-food-wire-fork-treatment, mentioned earlier.

d. The Ratliff-Blough technique consists essentially in training an animal to make one response (e.g., depress a lever) in the presence of the stimulus (S^{D}) in order to obtain positive reinforcement. Each such response attenuates the signal by some known amount. When the signal dissappears below the organism's threshold, the animal shifts to another response (e.g., a second lever), by means of which each response amplifies the signal in known increments. When the signal reappears (i.e., reaches a suprathreshold value), the animal returns to the first lever, where responses are again reinforced.

The procedure is an adaptation of a standard psychophysical method variously called the "method of limits" (originally by Kraepelin and recently, for example, by Woodworth and Schlosberg[46]), the "method of minimal changes, and the "method of serial exploration" (Woodworth[46]), It was employed by Bekesy[47] to measure auditory thresholds in humans.

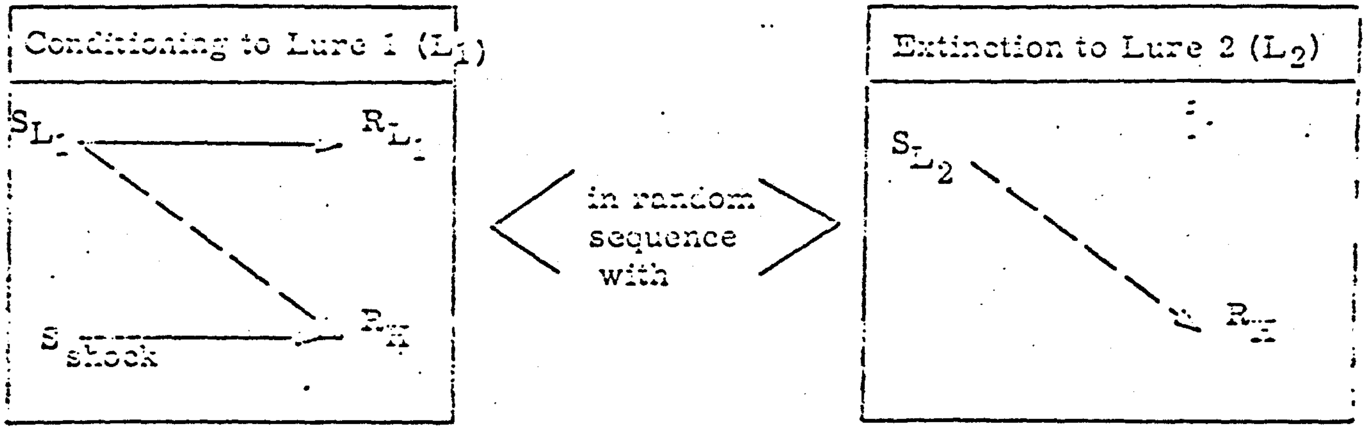
As applied to lower organisms, the procedure requires careful manipulation of reinforcement schedules and the establishment of complex reinforcement contingencies, making it time consuming and perhaps beyond the capacity of some species of interest to this proposal.

It should be noted, however, that the procedures have been used successfully with pigeons (Ratliff and Blough[48], Blough[49]), rats (Gourevitch, Hack, and Hawkins[50]) and starlings (Adler and Dalland[51]). Threshold determinations are in terms of the stimulus dimension varied, thus avoiding the more troublesome (Frick[52]) aspects of changes in rate, percent occurrence, and latency as applied to operant conditioning. The feasibility of using this approach should be explored whenever operant procedures are being considered for threshold measurements.

The foregoing will suffice to illustrate the use of operant discrimination procedures for the determination of absolute and differential thresholds.

2. Respondent techniques.

An experiment included in McCleary's study of interocular transfer provides a recent example of the use of respondent techniques for threshold measurements in fish. The typical Pavlovian (Pavlov[36]) pattern for discrimination training will be recognized in the following representation of McCleary's procedure:



The response (R_H) which was conditioned was an alteration in heart rate --normally rather stable in fish-- elicited by a tail-shock as stimulus (S_{shock}). By pairing the shock in proper temporal relationship with a fishing lure (S_{L_1}), a conditioned reflex developed, indicated by the diagonal line, and involving a change in heart rate in response to the lure (L_1) alone. The conditioned response in this case is a deceleration in heart rate, which is different from the unconditioned response to shock. (See also Notterman.[53]) The complexities of conditioned heart rate with animals and humans serves as a warning against too hasty an identification of the conditioned and the unconditioned responses in respondent conditioning. With fish, there is the additional fact that the heart has only vagal i innervation. As one would expect, this response generalizes to the second lure (L_2), as shown on the right side of the diagram. By presenting L_2 alone, i.e., without shock, in a random sequence with the regular conditioning trials, the conditioned response to L_1 is strenghened while that to L_2 diminishes, and the fish comes to respond discriminatively to the two lures.

The same basic procedure can be used to establish a respondent discrimination between two stimuli differing only in some particular parameter (difference thresholds) or between stimulus-presence and stimulus-absence (absolute thresholds). (For several examples, see Ash[23].)

Unconditioned responses to test stimuli have also been used. Kuroda[25] looked for respiration changes in newts as an indication of sensitivity to such stimuli as pistol shots, tuning forks and whistles. Murphy and Harris[42] investigated the pinna reflex to sound in the rat, "with at least as good repeatability as in the normal human audiogram."

The fact that respondent techniques can be used with constrained and "instrumented" fish makes these techniques particularly suitable for the study of electrical receptors. They enable control over the orientation of the fish with respect to test objects and eliminate changes in electrical fields which might be associated with movement through the tank.

3. Electrophysiological techniques.

   As more is learned about the location and structure of the electrical receptors of these fish and about the afferent pathways involved, it will become possible to utilize electrophysiological techniques both to verify the function of the suspected receptor and to estimate thresholds.

   Wever and Vernon's studies of hearing in snakes[54] and in bats;[55] the investigation of the eye and optic lobes in the chick embryo by Peters, et al.;[56] and the work of Dr. Robert Doty, Professor at the Center for Brain Research at the University of Rochester, provide contemporary examples.

The Location of Electrical Receptors

Information about the electrical receptors of these fish is discussed elsewhere in this report.

Additional Conditioning Studies

Among the numerous conditioning experiments that could be conducted, the following appear to be interesting:

1. Experiments necessary to clarify the results of the main investigation, including those control studies mentioned in the following section on Experimental Designs.

2. Experiments which repeat, with the species and responses included in the main investigation, a good cross-section of the prototypical experiments conducted in the "animal laboratory." The results would provide additional data on the phylogenetic generality of the conditioning operations, data and relationships obtained with other, usually higher, organisms.

Experimental Designs

The reliability of data related to all significant conclusions has to be established appropriately, using the best techniques available in each set of circumstances. This would always involve careful analysis of the "process" under investigation, identification of the relevant variables, a proper choice of the measures to be used to represent the dependent and independent variables, selection of variables to be controlled or randomized, the removal of sequential effects, and other experimental procedures and techniques, designed to minimize error variances and to remove bias or contamination.

Some problems can be anticipated along these lines. For example, with some species, size and procurement difficulties will probably restrict the number of "subjects" which can be used in a given experiment. This will exclude from consideration many of the more elegant and efficient experimental designs found in such standard references as Cochran and Cox,[51] Dixon and Massey,[52] Edwards,[53] Goulden,[64] Kempthorne,[61] and Lindquist.[62] It will be necessary in such circumstances to shift emphasis to designs which permit each individual to serve as his own control, to repetition of measurements on the same organisms, and to other experimental stratagems and cross-checks as are found in Skinner,[1] Ferster and Skinner,[29] and Sidman.[63] Whenever feasible, strong preference will, of course, be accorded those designs which assign probabilistic warrantees to assertions relevant to the particular investigation.

Another problem which may be encountered is failure to achieve any form of control over the occurrence of, or over the parametric variations in, the electrical response of a given species. This would represent the most difficult outcome to interpret and would raise such questions as: Were the reinforcements, other stimuli, etc., appropriate to the organism? Was the emotional or physical condition of the organism such as to adversely affect learning? Was the task set to the organism too difficult --i.e., would some other choice have worked out differently? Were the environmental conditions and other laboratory arrangements unsuitable in any way? Were the conditioning techniques competently applied? Etc.

Careful observation of the organisms' behavior in the course of attempting conditionings will usually provide some relevant evidence.

In addition, it will be highly desirable, with every species, to select a convenient respondent (e.g., McCleary[64]) and a convenient operant response (e.g., Bently,[65] Deterline[66]) to serve as a kind of control. Then, if a particular conditioning paradigm fails to yield the expected results, as applied to the electrical response, the procedures used could be "checked out" using the appropriate alternate response. (Similarly, in studies of the electrical receptor, an alternate set of non-electrical discriminative stimuli would be used as a check on procedures when needed.)

Through these and other means, the kind of reproducibility and precision in results that characterizes the best scientific research in the behavioral sciences will be achieved.

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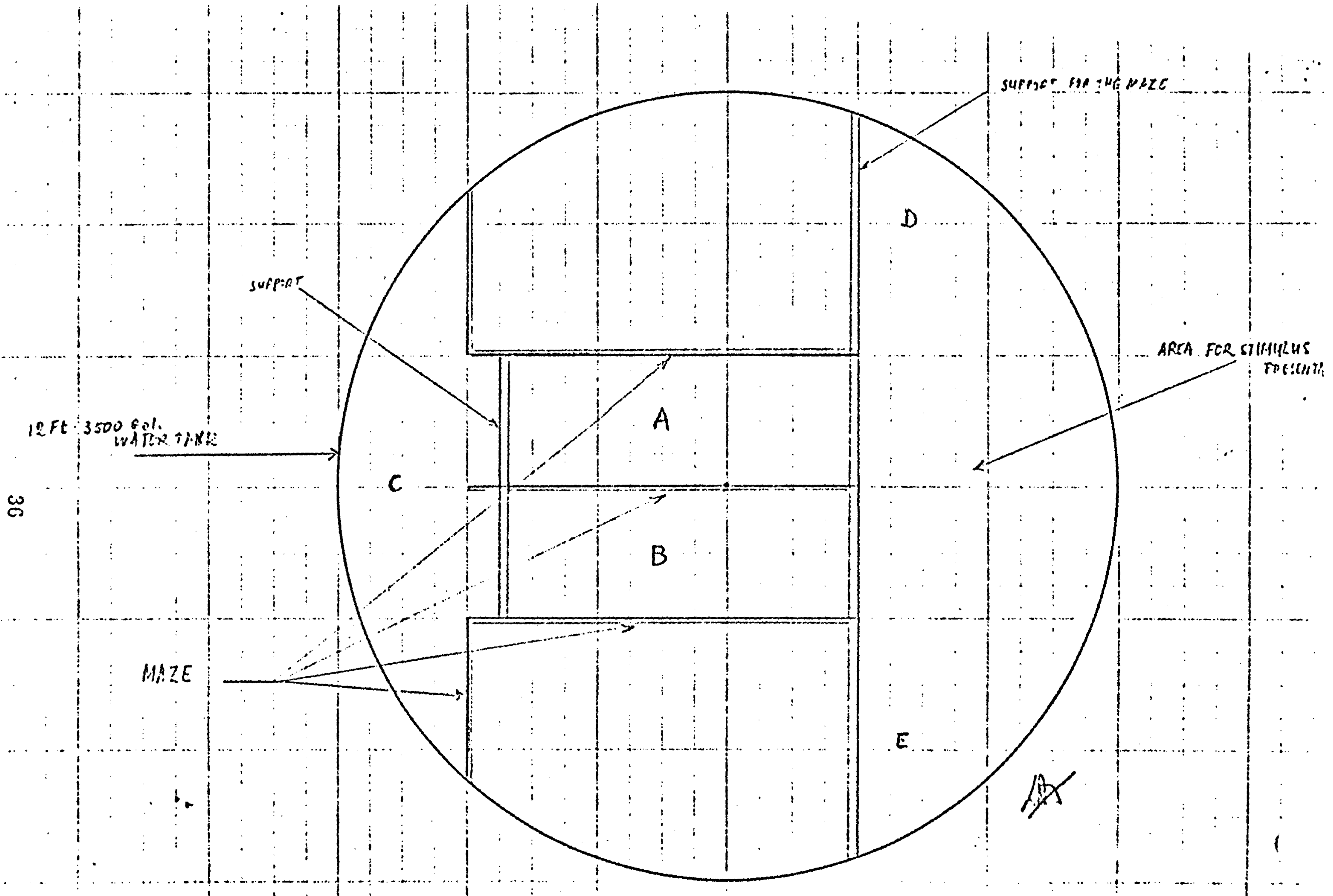
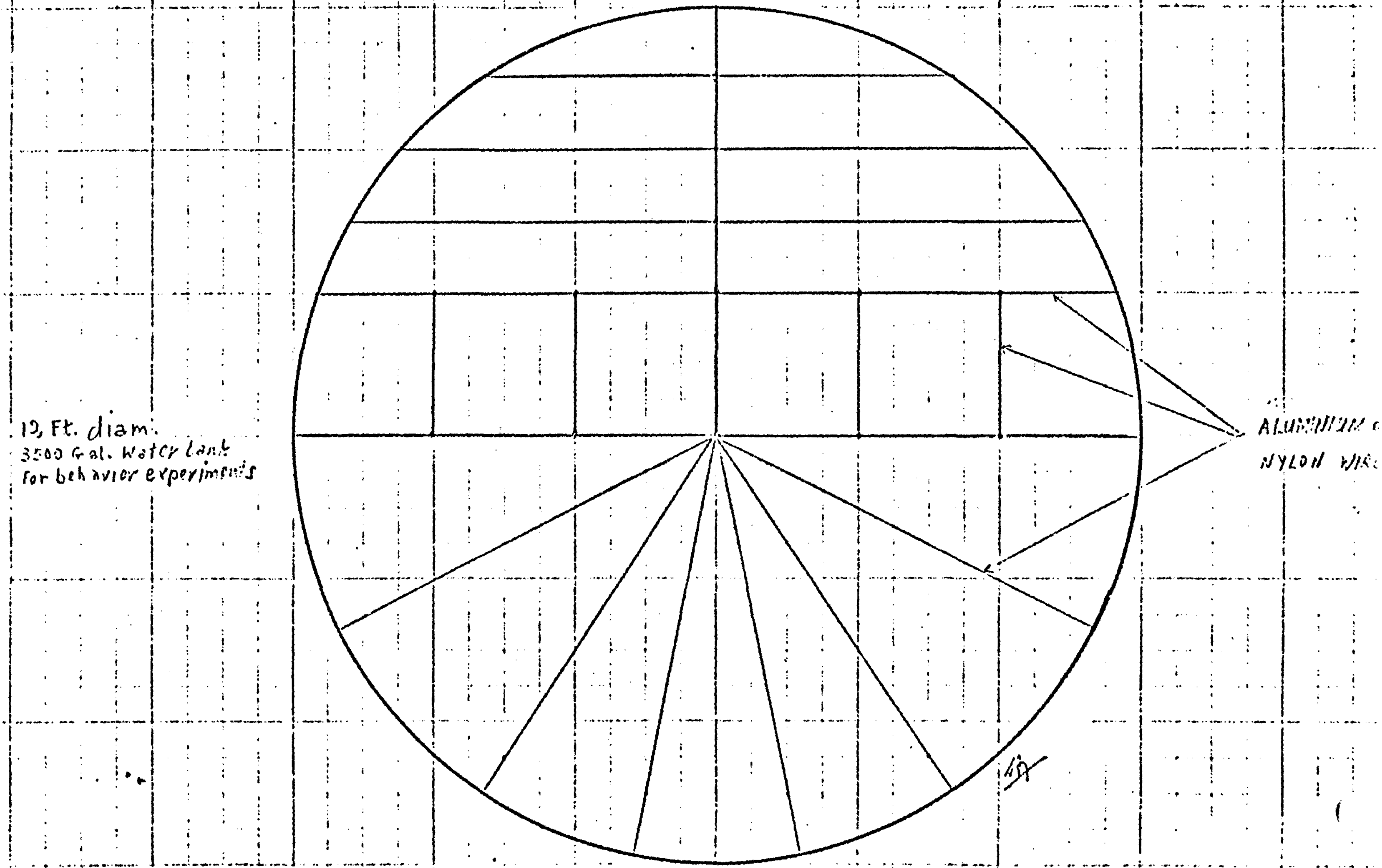
III. PROPOSED BEHAVIORAL STUDY OF ELECTRIC FISHES WITH EMPHASIS ON OBJECT DETECTION, LOCATION, AND IDENTIFICATION (PHASE I)

Three different kind of experiments are proposed with the aim to assess the ability of electric fishes to detect, locate and identify objects underwater. The first system is designed to use as a subject, a weak fresh-water African electric fish Gymnarchus niloticus. A maze has been designed (Figure 1) to be built in a water tank of 12 feet in diameter and 4 feet in height. The maze has two channels supported by bars on the tank. The fish located at C will be presented with a stimulus in the form of objects (metallic, nonmetallic, magnetic and nonmagnetic) of different sizes either moved from D to E or from E to D. The reaction of the fish and its choice of the channel will indicate how well the subject would detect different objects of different textures and sizes. The fishes are freely swimming. The second system, (Figure 2) is designed to prove the ability of electric fishes to avoid obstacles like fine aluminum wire or nylon thread. The African electric fish Gymnarchus niloticus and the South-American electric fish Sternarchus albifrons would be used. Both fishes are blind and use their electric transmitting-receiving system for navigation. Gymnarchus has a very steady frequency (around 300 Hz) and Sternarchus has a steady frequency (around 750 Hz) provided the water temperature is held constant. The fishes would be presented with stimuli (attractants and repellents) and their behavior will be monitored by filming it. The fishes are freely swimming. The third system is designed for variable rate of pulses electric fish species like the South American fish Gymnotus carapo or the African fish Gnathonemus petersii. The subject will be confined to plexiglass tube with holes and two electrodes (at the head and at the tail). The impulses emitted by these fishes will be amplified and monitored with an oscilloscope and a frequency counter. Objects (metallic and nonmetallic) of different sizes would be presented from different distances and their effect on the fishes pulse rate will be recorded. Graphs will be plotted relating material, size, and distance to the pulse rate as compared with the steady-state pulse rate. These fishes increase the pulse rate when an object disturbs their electric field generated by the transmitting organ and received by the electroreceptors in the skin of the fish.

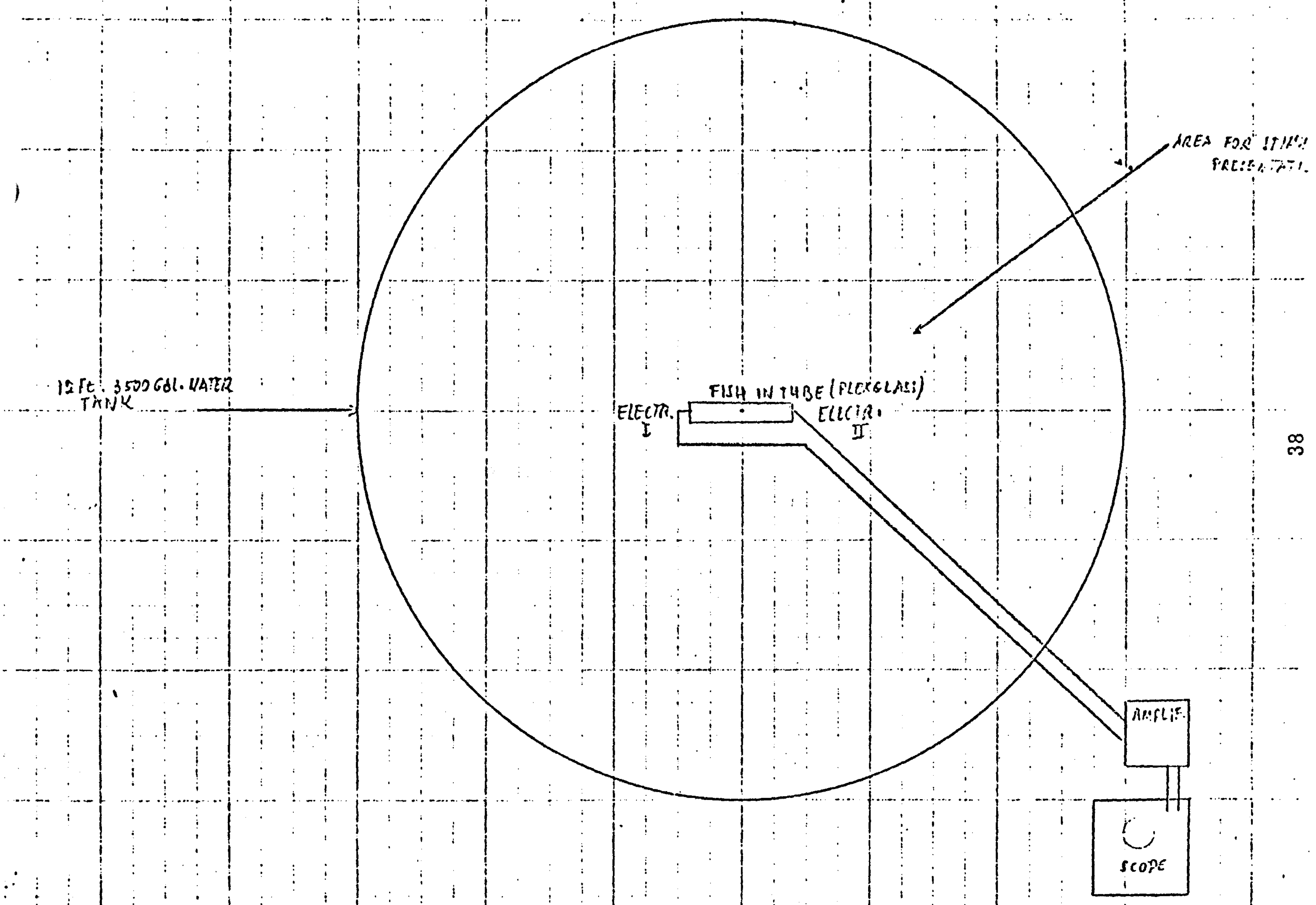
It is hoped that these three sets of experiments will show the sensitivity and range of detection of different objects by electric fishes.



Maze for Behavior and Object Location Experiments with Electric Fishes



Wire Maze for Behavioral Experiments and Object Avoidance by Electric Fishes



Experimental Set-Up for Variable Frequency Electric Fishes (Gymnotus carapo, Gnathonemus

IV. AN EXAMPLE OF HARDWARE ANALOGUE EXPERIMENT TO SIMULATE OBJECT DETECTION BY ELECTRIC FISH (PHASE III)

It is possible to simulate an equivalent sensory system of electric fishes responding to different stimuli underwater. A system with a double feedback mechanism can be envisaged: (1) one represented by a constant frequency electric field transmitting system operating on the phase-synchronous electroreceptors responding to discontinuities in the electric field or to changes in the phase relationship transmitter-receptor; and (2) another one represented by a variable frequency transmitting system responding to disturbances in the field between transmitter and receptor with a change of the frequency of the transmitting electric organ. To this we could add an independent dual autorhythmic receptor system: (a) responding with the increase or decrease of the authorhythmic frequency depending on movement direction of the disturbance in the electric field; and (b) responding with a change in the latency depending on the magnitude of the disturbance, and also distinguishing between conductive and non-conductive objects.

A simulation of the electric fish object detection system would make it possible to find out how models of the physical analogs of the sensors could be integrated in object or organism location, detection and identification. The range and sensitivity of the system could be assessed and improvements could be made. As a first step toward this simulation we present a measurement plan for an experiment in Phase III of our investigation, to build and check the first of the above mentioned mechanisms for detecting, locating, and identifying objects underwater by means of a phase detector system sensitive to changes produced by discontinuities in the electromagnetic field.

Systems and equipment for detection and location of objects in a seawater or freshwater medium have to be designed from the standpoint that the medium is lossy and has a high dielectric constant. Consequently, the wavelength of a signal transmitted through the water medium is different that that of a signal of the same frequency transmitted through free space. Attenuation and scattering are also different from the values for free space.

The advantage of using a phase comparison, position determining system is evident because the precision of our measurements depend on the phase measurement precision capabilities independently of the frequency used. This gives us the possibility of using low frequency combined with a highly accurate phase measurement.

In free space we have the well-known relation between the speed of light c, the frequency of an electromagnetic wave being propagated f, and its wavelength

$$c = f \cdot \lambda \text{ (for all } \lambda \text{ in free space)}$$

In seawater, this formula cannot be used because the propagation velocity of an electromagnetic wave is different than the value of c in free space. Moreover, the propagation velocity in water changes with frequency and is not a constant. It is represented by the relation

$$s = F\,'\lambda' \quad \text{where } S = \text{Function } (\lambda^2)$$

** s = speed of propagation in water dependent on the electrolyte medium.
f = frequency (Hz)
λ' = wavelength in water (meters)

The signal travels a distance D in the time T where:

$$T = \frac{D}{s}$$

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* Taken from D. L. Nichols reports from the U.S. Navy Underwater Sound Laboratory, New London, Connecticut.

s. is dependent of f and λ'. With respect to time zero the phase of the rated signal advances through the angle $2\pi fT$. The received signal therefore behand the signal at the signal generator by $2\pi fT$. If this phase lag could neasured, the range could be calculated. The basic equation for phase-nparison distance measurement is

$$\rho = 2\pi fT = 2\pi f \frac{D}{s}$$

ere ρ is the measured phase difference between the reference signal and the gnal which has traversed the distance to be measured. In terms of the stance traveled,

$$D = \frac{s\rho}{2\pi f} = \frac{\rho\lambda'}{2\pi}$$

hase measurement can be based on: (1) the multiplication of two cosines or sines) and integration over one period of the function; or, (2) by determining he instants at which the reference and text signal cross zero in the same direction and measuring the time between the zero crossings. The phase angle is then $2\pi f T$, where T is the time between zero crossings.

We have chosen some hypothetical parameters for a phase disturbance detection and location system. The values chosen may have to be modified according to our findings during checking, experimenting, and making measurements in a scaled model in fresh water, sea water, and mixed fresh and seawater. The parameters for our system that have to be scaled down are:

Transmitter: f = frequency = chosen between 5000 Hz and 1000 Hz

ℓ = length of the antenna made of a water column in sea water = between 22 m and 50 m

p = endplates for the antenna feeding between 25 and 50 cm diam., silver silver chloride plates on Monel-metal 1/8 in. thickness; plates will be fed by coaxial cable in a coppertube 1/2 in. diam., 1/16 in. wall thickness sprayed with a teflon coating of minimum 1/32 in. thickness.

Transmitter power effective delivered at the endplates = 1 kW. Transmitter

› be in a screened room, double copper mesh, with a good ground to an endent ground. Transmitter has to be crystal controlled.

.ntenna depth = 3 to 5 m under the surface of sea level.

ʀeceivers: Instead of dipole antennas, low-loss toroids will be used, tuned to between 5000 Hz and 1000 Hz frequency fed into matched lines and to low-noise linear amplifiers. The amplifiers have to be non-phase distort type. Phase active networks connected to the amplifier will correct for exact 180° phase opposition of the toroids' output. The output from the phase-corrective networks will be fed into a variable high-gain (decade amplifier) differential amplifier where the output will be monitored by a scope and a null detector. Differences of 0.001% may be possible to be detected at the highest gain.

Scaled Model: George Swain* tried an experimental toroidal antenna scaled to small diameters for frequencies of 1.5, 2.0, 3.0, 4.0 and 7.0 MHz in a solution of NaCl of 0.285 moles per liter and a conductivity of 2.8 mhos per meter at 25° C in a tank 3.5 m in diameter and .55 cm deep.

George R. Swain: Antennas in or at the Surface of a Conducting Medium at 'LF, Report EE-116 of the E. E. S. Univ. of New Mexico, Albaquerque, '. M. (1964).

t is proposed to use a plastic tank 12 ft. in diameter and 4 ft. deep for ed down experiment with fresh and seawater.

We will increase the frequency to 400 kHz corresponding to a wavelength vater of 2.25 m; also ten times smaller than one of the hypothetical values. endplates of the antenna will be 8 cm in diameter (about 1/10 of the surface the hypothetical plates). The power of the transmitter will be decreased 100 W at the end plates. Antenna should be submerged to a depth of from to 50 cm.

Receiver antenna will be made of corresponding toroids for the frequency f 400 kHz. The ratio of the attenuation between a signal of 5000 Hz at 22 m nd 400 KHz at 2.2 m distance will be calculated and the factor applied to the esults of the measurement.

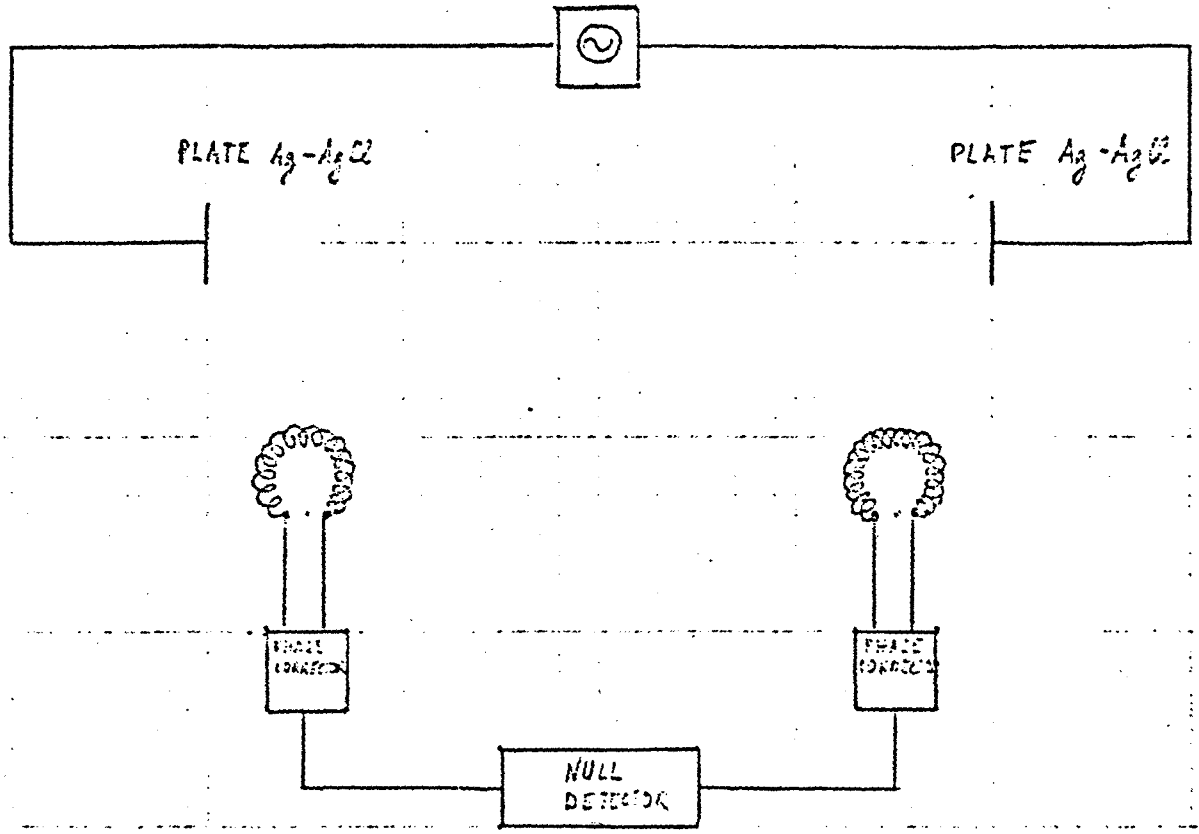
A piece of cotton filled, cotton covered, and partly isolated cotton body with a volume of one-tenth that of a human body and with similar conductance will be used to find out the phase deviation produced in the field in different positions between the transmitter and the receiver antennas at different depths.

A device for making artificial measurable waves on the water surface will be used to produce scaled down waves.

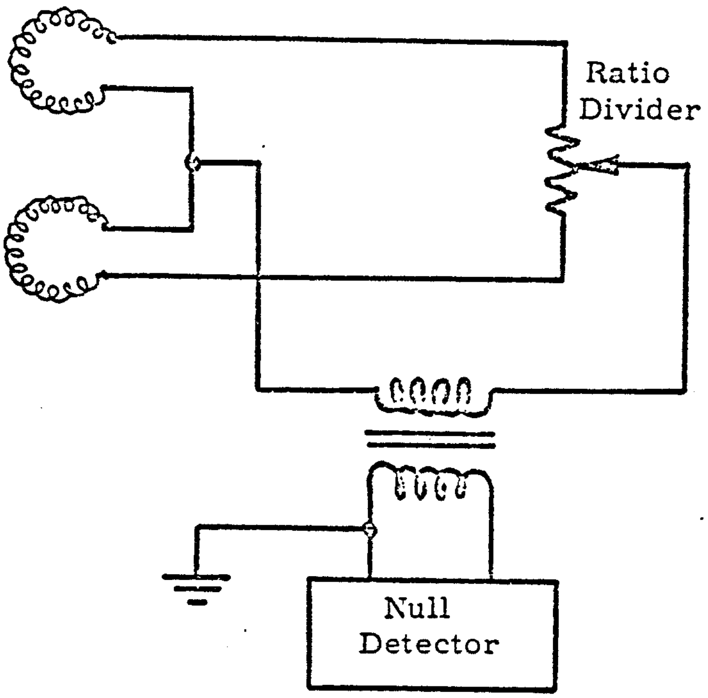
A random-noise generator will be used to simulate natural noise which will be added to the signal for different S/N ratios. Polarization and position change of the toroids will be checked to find out if it is possible to reduce the unwanted effects of water movement and noise.

The temperature and the salinity with respect to the conductivity of the water will be continuously monitored and recorded during experiments.

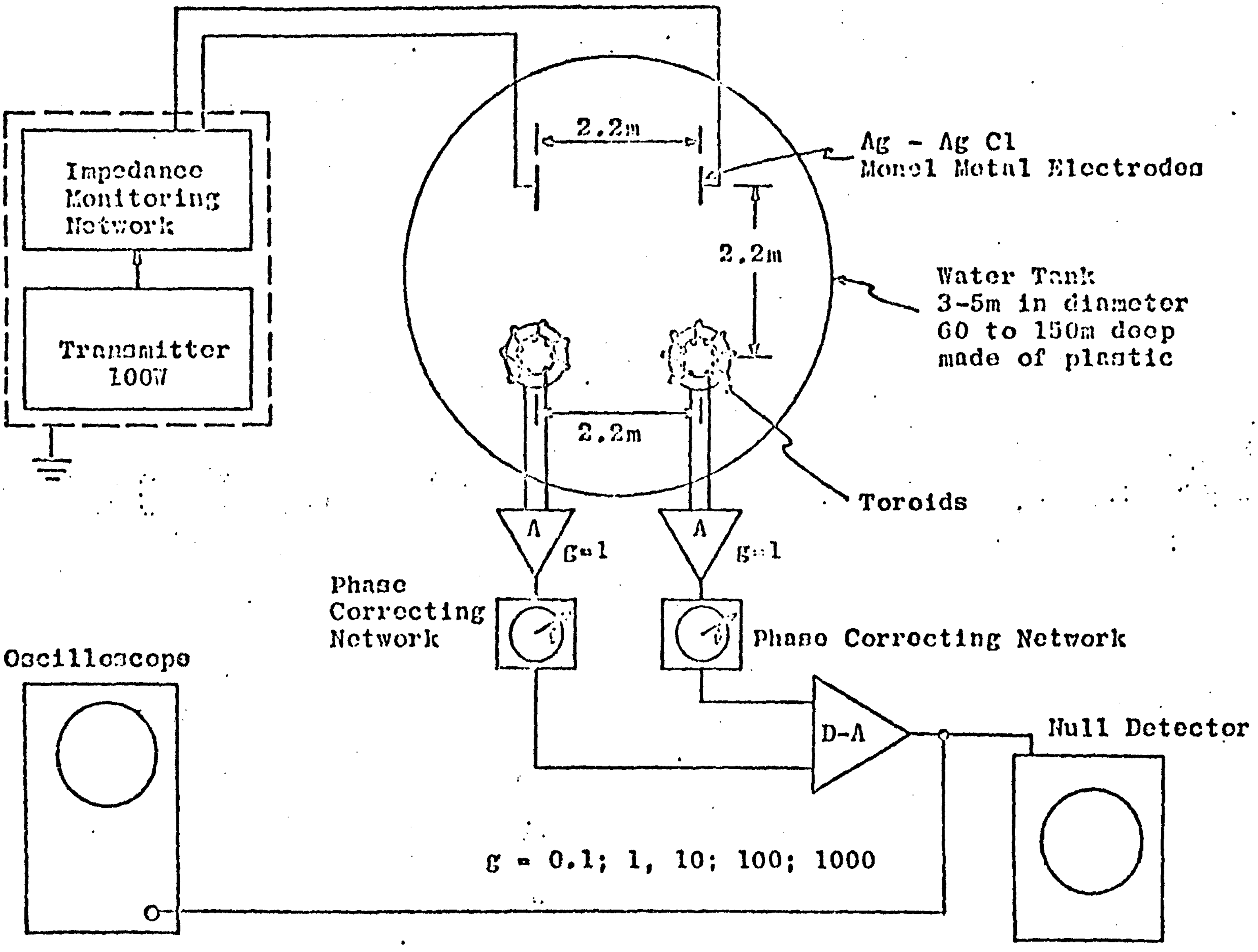
Receiver and transmitter antenna will be checked under steady positions and small movements to determine the effect of moving the antennas on the onse of the system. Q-factor of the toroids in air, fresh water, and ater will be measured. The ratio between deviation produced by waves or noise and the one produced by the object will be determined in order ecide if a full-scale experiment is warranted.



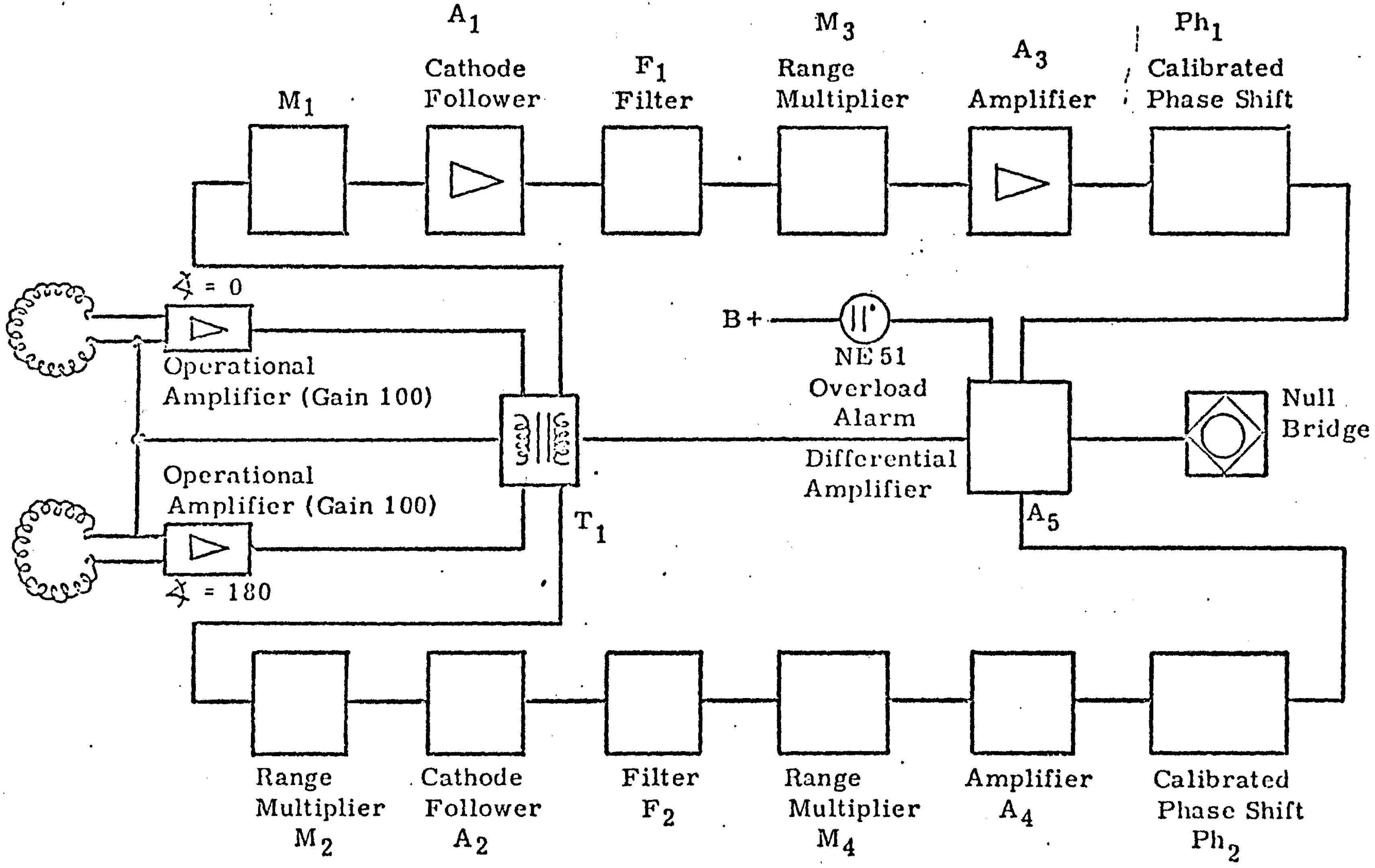
Simplified Block-Diagram of an Underwater Phase-Detector System Used to Detect and Locate Objects



Example of a simple ratio bridge.



Scaled Down Model for Experimenting Purpose of a Phase Discrimination Object Detection and Location System in Fresh and Seawater



Proposed experimental set-up for demonstration of the "System for Detection and Location of Objects in a Seawater or Freshwater Medium."