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RESEARCH AND DEVELOPMENT
OF
CACHE MARKER SYSTEM

PHASE II: DEVELOPMENT OF ENGINEERING PROTOTYPE

FINAL REPORT

Contract No. [redacted] 50X1

15 March 1954

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Covering the Period

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ABSTRACT

This report describes the development and construction of an electronic system which will locate exactly the position of a previously buried (or submerged) cache whose approximate position is known. The cache, which may be buried in the ground or submerged in either fresh or salt water, is marked at the time of its concealment by a passive device which is buried with it. This device, called a transponder, is a highly efficient series resonant circuit which is enclosed in a strong watertight case designed to maintain its integrity over a period of years. The transponder is found by means of a portable device, called the detector, which incorporates a low powered oscillator and receiver circuit designed to indicate, by an aural signal, extremely small changes in the Q (figure of merit) of a highly efficient coil which is the sensing element of the detector. When the detector coil is brought near the transponder its Q is lowered and a change in the aural signal is heard by the operator. This system is called the Delta Q System.

This system operates at frequencies between 80 and 100 kilocycles, which are only slightly attenuated by the possible media in which the transponder could be buried. The detector covers this frequency range by 10 bands, each two kilocycles wide. Due to the extremely high Q of the transponders, approximately 380, it is possible to provide 20 discrete transponder frequencies and thus a means for marking 20 different kinds of caches.

For its security the system depends upon the highly frequency-selective circuit of the transponder, the resonant frequency of which must be known within narrow limits in order that it may be detected at the depths at which this system will operate.

The detector will discover a transponder which is buried 5 feet

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deep in soil at a horizontal range of 6 feet. It is then capable of locating its position within three or four inches. The effectiveness of the system is decreased to about 60 per cent when the transponder is submerged in sea water.

A model of the system has been built and operated in the laboratory and tested in the field.

This report includes operating and maintenance instructions.

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1. Introduction

1.1 The Problem

A system is required by means of which the location of a previously buried or submerged object (cache), whose approximate position is known, can be determined with certainty. This cache marker system shall consist of a cache marker (transponder) which is buried in the vicinity of the cache and a detector by means of which the location of the transponder and cache is determined.

1.1.1 Requirements

The requirements of the system that were originally suggested are as follows:

1. The system shall include everything necessary to attain the desired result including a transponder and a means for detecting its location under specified conditions.
2. The system shall be capable of revealing the exact location of the transponder at a radius of 15 feet when the transponder is buried (or submerged) at a depth of 5 feet below the surface of the ground (or water). If this depth cannot be realized, then the depth shall be at least inaccessible to the conventional mine detector. This distance is presently estimated to be 2 feet.
3. The system shall operate reliably in all varieties of soil and under water.
4. A single technique of universal application is desired.
5. The system shall be secure from ordinary attack and from accidental disclosure of the cache to the greatest extent practicable.
6. The system shall be operable by nontechnical personnel.

7. The transponder shall be relatively inexpensive.

8. The transponder shall be passive. Continuously radiating systems are excluded.

9. The transponder shall be of construction estimated to operate reliably 5 to 10 years after being placed as specified in requirement 2.

10. The detection device shall be readily portable by one man and capable of operation without apprehension by a casual observer.

These above requirements are target specifications and represent what was considered to be most desirable at the time that the project was first initiated. Additional operational requirements developed during the course of the work and they are stated in Section 3.1.

1.1.2 Possible Systems

The kind of system that can be used for a cache marker is to a very large extent determined by the nature of the transponder. The requirements for the transponder specify that it be a passive element and that it operate reliably for five to ten years after being buried or submerged. The time requirement rules out the possibility of using batteries because of their limited shelf life. The use of transistors is also ruled out because they need d.c. potentials, their questionable reliability at this time, and because their use would make the transponder expensive to manufacture.

A transponder is suggested that will receive energy from the detector and indicate its presence by transmitting all or part of this energy back to the detector. Consideration must then be given to the various means of transmitting energy and the effects that varieties of soil and water have on transmission.

It was originally proposed that chemical systems be also considered

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if they employed little known or unusual techniques. No systems of this kind were discovered during the course of this project.

1.2 Energy Considerations

The possible success that can be achieved with a cache marker system depends upon the effect the medium in which the transponder is placed has on the ability to transmit to and receive energy from the transponder. The following means of energy transmission were considered.

1.2.1 Acoustical

The absorption factor of sound varies greatly with the kind of medium, being small for water to very large for dry sand. Measurements made of the attenuation of sound in sand and soil at frequencies from 10 to 100 kcs by Nyborg[1] indicate very large absorption factors. The absorption factor was found to depend not only upon frequency and moisture content but also upon the amount of air that was contained in the sand or soil. For mud the absorption factor varied from 25 to 74 db/cm for frequencies from 10 kcs to 35 kcs respectively. For dry soil the attenuation at 10.5 kcs was measured as 10.5 db/cm. The lowest reported absorption factor was about 2 db/cm and for this value the attenuation for one meter would be 200 db which would mean that the amplitude would be attenuated by a factor of 10^{-10}.

The only possibility of using acoustical means for energy transmission lies in the use of very low frequencies. The absorption factor decreases with a decrease of frequency and it is possible that low energy losses will be encountered with frequencies below 100 cps.

1.2.2 Electrical Conduction

The transmission of energy by means of electrical conduction depends on the current distribution that is obtained in the medium. The

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[1] W. L. Nyborg, I. Rudnick, and H. K. Schilling, J. Acous, Soc. Am. 22,442 (1950)

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current distribution depends on the conductivity of the medium, which varies over wide limits from dry sand to salt water. The moisture content of the soil causes the soil conductivity to vary and this would vary with time. Time did not permit an investigation to determine whether a system could be made operable over these wide limits.

1.2.3 Electromagnetic Fields

The attenuation of electromagnetic waves and magnetic fields is small provided the frequency is not too large. The equation for the attenuation of electromagnetic waves as a function of frequency, conductivity and dielectric constant is given in Appendix 4.1. The dielectric constant and conductivity for various soils and water are presented. The attenuation factor is calculated for various media at a frequency of 100 kcs.

1.3 Decision

The use of electromagnetic waves as a means of transferring energy to a transponder appeared to be the means which would most unlikely be unaffected by the medium and one which could be transmitted with the least attenuation. The decision to use electromagnetic waves as the basis for the solution of the problem was based on early measurements of the transfer of energy in air and on calculations which showed that the results obtained in air would be the same that would be obtained in most media, provided that the operating frequency was not too large.

Experiments, which are described in the report on Phase I, measured the amount of energy that could be transferred between two circuits by means of electromagnetic coupling. The apparatus consisted of a signal generator and amplifier driving a series tuned circuit, the coil of which was the radiating element. A similar coil tuned to parallel resonance by a

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capacitor was used to measure the amount of energy transferred. Voltage measurements were made across the second coil, which was placed initially at a distance of five feet from and parallel to the driven coil, and then placed at increasing distances from the first coil along a path perpendicular to a line connecting the coils when they were closest to each other. The data obtained by these measurements indicated that sizable amounts of energy could be transferred by means of coupled circuits.

2. Summary of Phase I Investigations

The work performed during phase I was concerned with developing the transponder and feasible systems for detecting the transponder. Consideration was given to the problem of security in trying to develop a system which required the use of two frequencies for the detection of the transponder. Only the systems whose development was carried on in Phase II are discussed here.

2.1 Passive Transponder

The function performed by the transponder is that of receiving electro-magnetic energy from the detector and then reradiating energy to the detector. The requirement that the transponder be cheap and be operable after a period of five to ten years rules out the possibility of the use of batteries as a source of energy which is triggered by the energy from the detector and is radiated to the detector. The measurements described in 1.3 showed that a single tuned circuit was an efficient means for absorbing the energy from the detector and reradiating this energy back to the detector. Its simplicity made possible low cost production.

The design requirement for the best transponder is that the Q of the coil be as large as possible. This is based on the following: The size of the coil is determined on consideration of the operational needs and its size is the largest that is permissible. Best transponder means a transponder which will radiate the largest signal for a given magnetic field strength produced in it by the detector.

The problem of transponder design reduces to the design of high Q coils. The factors which determine the Q of a coil of given size are: the kind of wire used, and the manner in which the wire is distributed about the coil. The work of Phase I indicated that a spider web type winding wound with Litz wire gave the highest Q.

2.2 Detector Systems

2.2.1 The Pulsed System

The operation of this system for the detection of the transponder depends on the ringing of the transponder after the output of the transmitter drops to zero. Figure 2.2.1 shows a block diagram for the system. The gate pulse generator supplies pulses to both the transmitter and receiver and synchronizes their operation. The pulse to the transmitter turns the transmitter on thus producing the RF magnetic field. The induced voltage in the transponder causes current to circulate which continues after the transmitter is turned off. At the same time the transmitter is turned on, the receiver is turned off by a pulse from the gate pulse generator. This blocks the transmitter pulse due to direct coupling between transmitter output and receiver input. The receiver is turned on after the transmitter is turned off and it picks up and amplifies the signal produced by the ringing of the traasponder.

The transmitter consists of a pulsed oscillator driving a power amplifier and clamping circuit. The clamping circuit serves to reduce to a minimum the ringing of the tuned transmitter output circuit.

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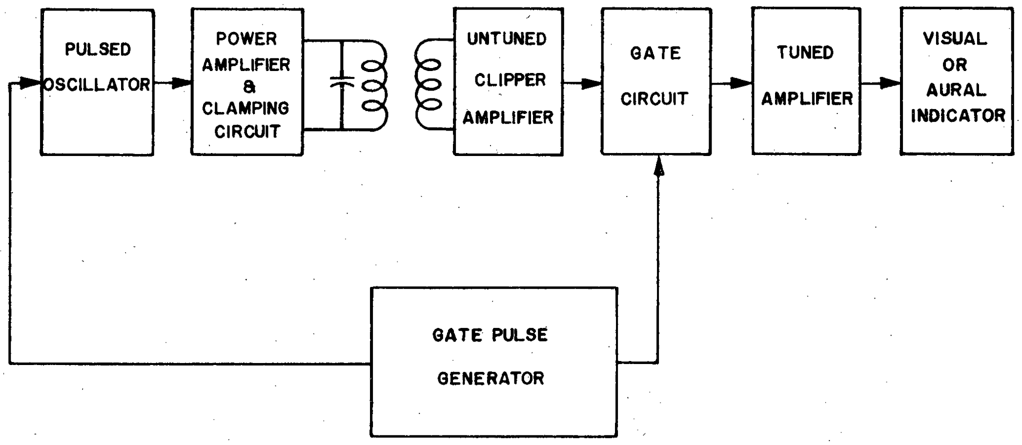

BLOCK DIAGRAM FOR DETECTOR OF PULSE SYSTEM

FIGURE 2.2.1

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The receiver circuit consists of an untuned input circuit followed by untuned clipper amplifiers, a gate circuit which is operated by a pulse from the gate pulse generator, followed by a tuned amplifier. The receiver is prevented from being blocked by the direct signal from the transmitter by the use of the gated amplifier and the clipper circuits which limit the amplitude of the signal that must be handled by this stage. The use of an untuned input prevents ringing of the receiver in the stages preceeding the gated amplifier.

At the end of Phase I this system required additional work to improve the gating circuit, to develop the tuned amplifier and reduce the inherent noise of the gating action. Using the HRO receiver for the tuned amplifier, a maximum range of 11 feet was obtained when the effect in the system was achieved by tuning the transponder.

2.2.2 Crossed Coils System

The crossed coils system consists of a CW transmitter and a receiver, using tuned coils for the transmitter output and the receiver input. The transmitter and receiver coils are oriented so that there is minimum magnetic coupling between the coils. The transmitter field induces a circulating current in the transponder which produces a field which induces a voltage in the receiver coil. This voltage, which is amplified, indicates the presence of the transponder. A block diagram of this system is shown in Figure (2.2.2).

This system was tested during Phase I with the receiver coil oriented with respect to the transmitter coil for a minimum voltage and the output applied to a Tektronix oscilloscope. The transponder was tuned through resonance and the effect was observed on the 'scope as an increase in voltage. With this method the transponder was detectable to a distance of 30 feet.

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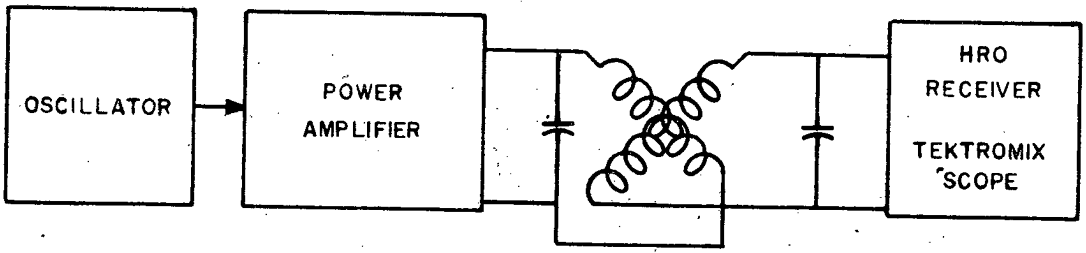

Figure 2.2.2
Block Diagram of Cross Coils

2.2.3 The Balanced Coils System

This system shown in Figure 2.2.3 consists of an oscillator feeding in parallel to power amplifiers which in turn separately feed two parallel-tuned circuits. The inductance of one of the tuned circuits is similar to that used in the crossed coils system, the other is electrically the same but it is magnetically shielded. The receiver is a tuned amplifier to which is applied the sum of the voltages appearing across these two coils. The phase relation between the voltages across the two coils is 180° so that normally the voltage applied to the receiver is at a minimum. The presence of a transponder causes the voltage across the search coil to change due to the change in its Q and this difference is observed in the output of the receiver.

This system did not reach the breadboard stage during Phase I.

2.3 Single vs Double Frequency Systems

During Phase I consideration was given to the development of a

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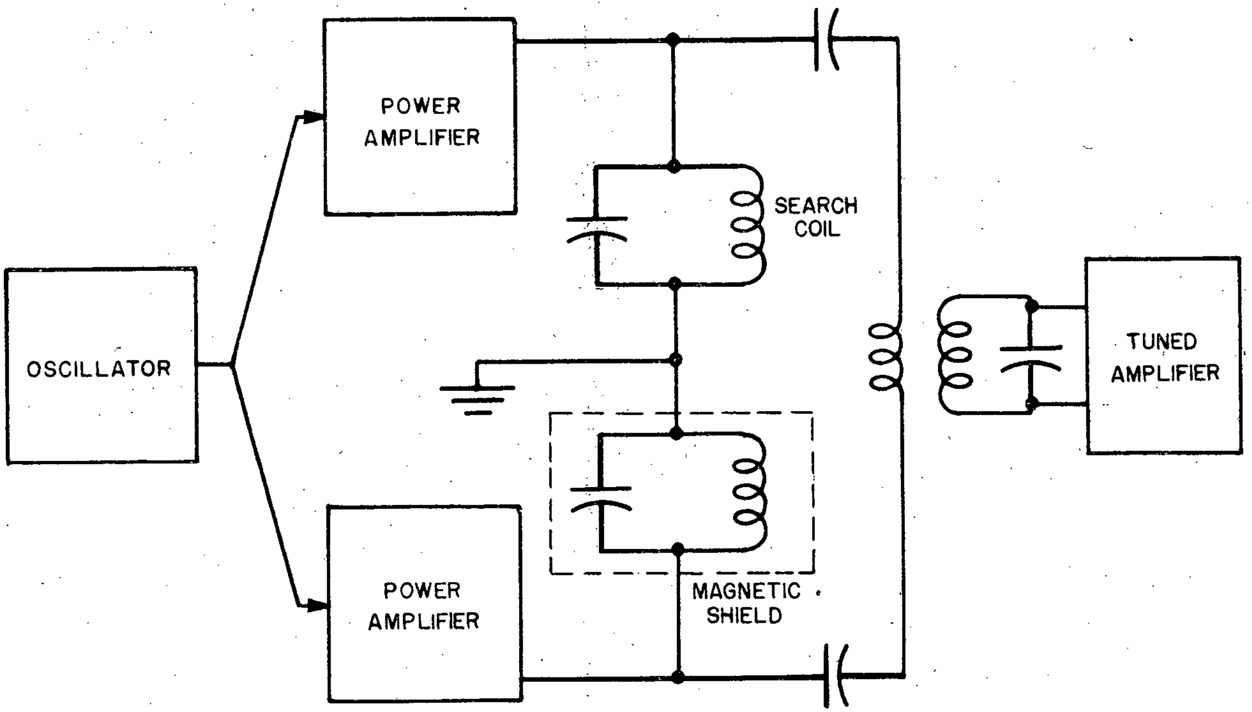

Figure 2.2.3
Block Diagram of Balanced Coils

two-frequency system where the energy from the detector to the transponder is of one frequency and the energy from the transponder to the detector is of another frequency. One of the important reasons for consideration of this kind of system was the great increase in security that could be obtained by requiring the knowledge of two frequencies instead of one for the detection of the transponder. However, if a two frequency system uses a transponder which is detectable by a single frequency detection system then no increase in security is realized. It is because of this that work on two frequency systems was discontinued during PhaseI since it is possible to show that for any system which uses magnetic induction as the means of transferring energy, the transponder is detectiable either at the frequency it accepts energy or at the frequency at which it transmits energy.

The argument for showing that this is the case goes as follows.

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The transmission or reception of energy by means of magnetic coupling requires the use of magnetically unshielded coils which are tuned to resonance at the desired frequency. A two frequency transponder would then consist of two unshielded tuned circuits coupled together by means of a circuit which carries out the frequency conversion process. If a means exists for detecting coils tuned to a single frequency, then a two frequency transponder of the kind described would then be detectable at each of the frequencies for which there is a tuned coil. Single frequency systems have been developed during Phase I which are capable of detecting coils that form part of a resonant circuit. Therefore two frequency systems using magnetic coupling for energy transfer are not better than single frequency systems from a security point of view. In fact the security has been decreased by one-half, approximately.

It might be thought that a two-frequency system would have an advantage over a single frequency system because the receiver could then be tuned to a different frequency than the nearby transmitter. Thus a weaker signal from the transponder could be detected.

Now a new frequency can be generated in the transponder only by some nonlinear effect in its circuit. If the transmitter sends only a single frequency the transponder can generate only harmonics thereof; if the transmitter sends two frequencies the transponder can generate only a sum or difference thereof, or harmonics. But the receiver circuit is not itself linear and precisely the same new frequencies would be generated therein but at a much higher amplitude due to the proximity of the transmitter. Thus an absolutely linear receiver circuit would be required and this linearity would have to hold for large signals. Because of the inherent characteristics of vacuum tubes this cannot be attained.

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In addition, a transponder operating in this fashion would be very inefficient because of the additional loss of energy in the process of conversion to a new frequency.

3. Phase II Work

3.1 Development of Some Operational Features

During the course of the work of Phase II it became clear that to be operationally useful it would be necessary to restrict the dimensions of the transponder in order that it could be fitted into an air drop container. Accordingly transponders were designed to have an outside diameter of 15 inches or less. Another desirable feature was that transponders be designed to be initially fixed-tuned to 20 different frequencies. This would not only provide additional security against enemy detection but would permit the marking by a transponder of a particular kind of cache. To accomplish this the detector was designed to cover a frequency range of 20 kilocycles, (from 80 to 100 kilocycles) which had been determined as adequate to allow for manufacturing tolerances of transponders and frequency shifts due to the media in which the transponders might be buried.

In the early stages of Phase II it became apparent that it would be desirable to investigate some systems not developed in Phase I. Accordingly the contract for Phase II was modified to permit such investigations.

3.2 Rejected Systems

The systems that are described in the sections which follow include those which were developed during Phase I as well as during Phase II. These systems have been rejected either because they inherently do not have the necessary sensitivity for the detection of the transponder or because they are technically or operationally inferior to the Delta - Q system.

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3.2.1 Pulsed System

The principle of this system is described in Section 2.2.1. The work that was done on this system during Phase II was primarily on the receiver circuit. The problem with the receiver circuit was that of separating the transmitted pulse from the pulse received from the transponder. Close coupling between the transmitter output and receiver input caused a large voltage to be induced in the receiver. The problem was that of detecting a much smaller signal from the transponder a short time later. The techniques which were used for handling this situation were those that were developed during Phase I, i.e. the use of clipper amplifiers to reduce the transmitter pulse to the same order of magnitude as the transponder signal and separation of these two signals by means of a gated amplifier.

The clipper amplifier shown in Figure (3.2.1) was developed, which was a considerable improvement over the circuit used in Phase I.

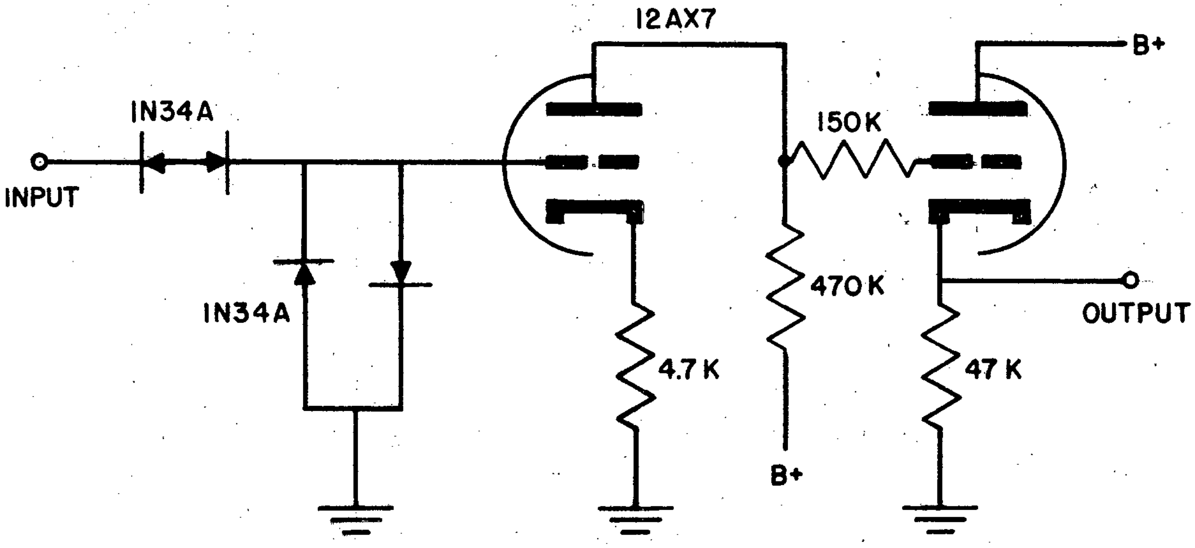

Figure 3.2.1
Clipper Amplifier

This circuit made use of the non-linear characteristics of crystal diodes and had the following amounts of gain for different input signals:

Input voltage	Gain
50 microvolts	10
500 microvolts	8
5000 microvolts	5
0.05 volts	3.5
1.0 volts	0.3
50.0 volts	0.02

Work on this system was discontinued because of technical difficulties in separating the transmitted and received pulses, which would have required extensive circuitry, putting it outside the domain of portability.

3.2.2 Crossed Coils System

The basic difficulty with this system at the state of its development at the end of Phase I was the signal in the receiver coil when the transponder was not present. The magnitude of this residual voltage limits the range of detectability. The signal present in the receiver without the presence of the transponder is due to magnetic and electrostatic coupling between the transmitter and receiver coils. Variation of this signal due the presence of the operation also places a lower limit on the magnitude of the change in signal that can be detected. Further development of this system required reduction in the magnitude of the residual voltage in the receiver coil and stabilization of the coupling with respect to the operator.

The first technique that was tried in order to minimize this residual voltage consisted of taking part of the transmitter signal and passing it through an attenuator and variable phase shift circuit, the idea being to introduce an equal but out of phase voltage to the residual voltage and cancel it out in the receiver circuit. The voltage was taken from the

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transmitter circuit ahead of the output stage so that any changes in the output of the transmitter due to the transponder would not affect the balancing out of the residual voltage. The difficulties with this approach to the problem were the following: The variable phase shift circuit used changed the magnitude as well as the phase; the balancing process depended on frequency and slight changes in frequency completely upset the balance.

Since eliminating the residual voltage in the receiver coil by balancing it out was not feasible, the next technique that was tried was that of trying to minimize the residual voltage by shielding. This technique can only minimize the contribution to the residual voltage due to distributed capacity. However, at best this can only be a compromise since our experience has indicated that really effective electrostatic shielding also results in a marked decrease in the sensitivity of the system because the shielding offers conductive paths for induced currents which both reduce the transmitter output and the signal to the receiver coil.

Reducing the contribution to the residual voltage in the receiver coil caused by magnetic coupling between the transmitter and receiver coils can be accomplished by varying the orientation between the two coils, so that minimum mutual inductance results. The early attempts in this direction were with the receiver coil inside of and with its center coinciding with that of the transmitter coil. This configuration, although lending itself to a more compact design, made the adjusting of the relative coil orientation for minimum mutual inductance extremely critical. Some thought was given to other geometries of the coils which would make the adjustment of relative coil orientation less critical. This consisted primarily of increasing the distance between the two coils. The coil adjustment was made less critical but it introduced the difficulty of coordinating the tuning of the transmitter and receiver circuits because of their physical separation.

3.2.3 Super-regenerative System

The super-regenerative receiver achieves extremely high sensitivity by use of an oscillatory circuit whose feedback is controlled in a manner which causes the circuit to break in and out of oscillation at an super-audible rate. The effect of an incoming signal is to change the duration of the oscillation thus imposing an audio modulation on the otherwise periodic pulses of oscillation. Very weak signals are capable of performing this function because of the extremely high Q of the LC circuit in the region where the circuit is on the verge of oscillating or on the verge of stopping oscillation. This circuit thus combines the function of a transmitter and receiver when the L of the circuit is left unshielded and its field is allowed to radiate. It was thought that, because of these characteristics, the super-regenerative detector could be used for the detection of transponders. During the time that the circuit is oscillating, circulating current is induced in the transponder which continues to "ring" after oscillation in the detector has stopped. This circulating current induces a voltage in the inductance of the detector, causing the period of oscillation to be increased.

Experiments utilizing this type of circuit was carried out. It was found that the system worked, but only for a limited distance. A range of approximately six feet was achieved. Within this range the transponder caused the detector to produce an audible signal. The intensity of this signal did not vary markedly with the changes in distance until a distance of about six feet was reached. Then the audio signal stopped completely. The mechanism which causes the audio signal is not completely understood. No further development has been carried out on this system.

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3.2.4 Boundary Coil System

The Boundary Coil System shown in Figure 3.2.4 uses an oscillator generating a radio frequency signal which is amplitude modulated at an audio rate. A rotating capacitor is used to sweep the frequency of the oscillator by plus and minus 3 kcs and passing through the natural frequency of the transponder. The rate of the rotating capacitor is such as to cause modulation at a very low frequency. The oscillator drives a one-turn insulated wire loop laid on the ground, enclosing the area in which the transponder is believed to be located.

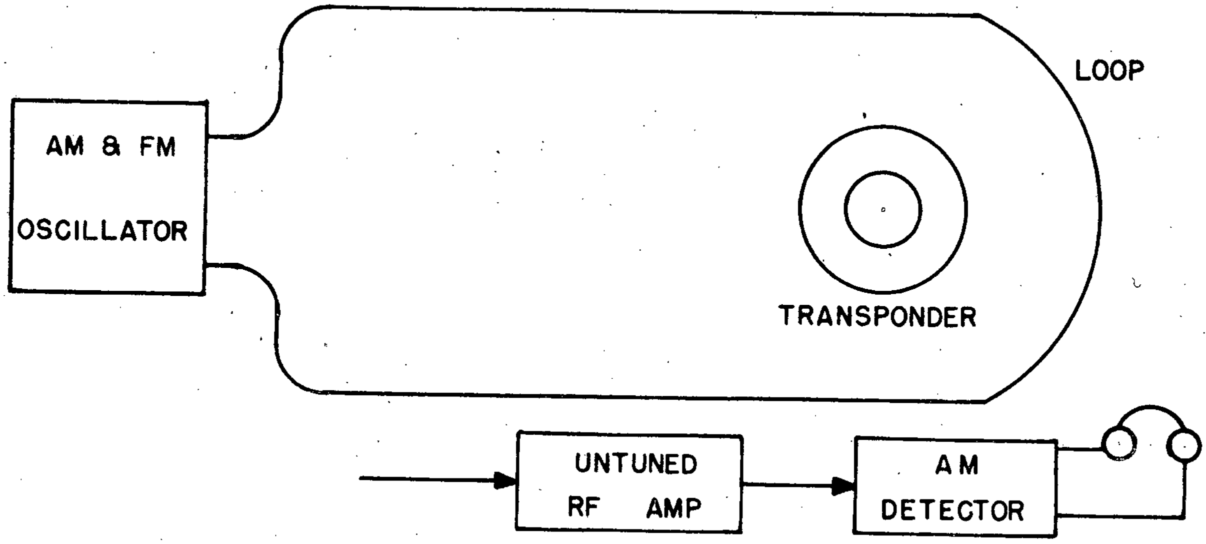

Figure 3.2.4
Boundary Coil System

The detector consists of a three foot length of wire feeding an untuned RF amplifier followed by an AM detector and phones.

The detector, which cannot detect the FM portion of the signal, will give a steady signal when in the vicinity of the loop but not in the vicinity of the transponder. The transponder, which is a very high Q resonant

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circuit, demodulates the FM portion of the signal from the oscillator. If the detector is brought in the vicinity of the transponder, a pulsating signal will be heard due to the reradiated energy as the oscillator sweeps through the resonant frequency of the transponder.

In the first test a single loop of wire was strung around the room at a height of about six feet above the floor. With this arrangment, the range of detectability was only 18 to 24 inches.

In a second test untuned loops, about 18 inches in diameter, were used as antennas with the oscillator and detector, respectively. With this arrangment somewhat greater range, four feet, was obtained; but direct coupling between the oscillator and receiver coils introduced difficulties which could not be controlled.

Another experiment was made using the same arrangment as in Figure 3.2.4, except that audio frequency amplitude modulation was not used. The FM modulation should have been heard in the phones when the detector was in the vicinity of the transponder. However, the oscillator paralyzed the receiver and thus swamped the weaker signal coming from the transponder. No further work was done on this system.

3.2.5 The Balanced Coils and Balanced Bridge Systems

These two systems are discussed together because they are basically the same kind of system. The balanced coils system uses a transmitter consisting of an oscillator driving two amplifiers with parallel input and pushpull output. The output circuits consist of two tuned circuits which are connected so as to have the voltages apposing each other. This is shown in Figure 3.2.5 (a). The receiver input is the difference between these two voltages, which is adjusted for a minimum when not in the presence of the transponder.

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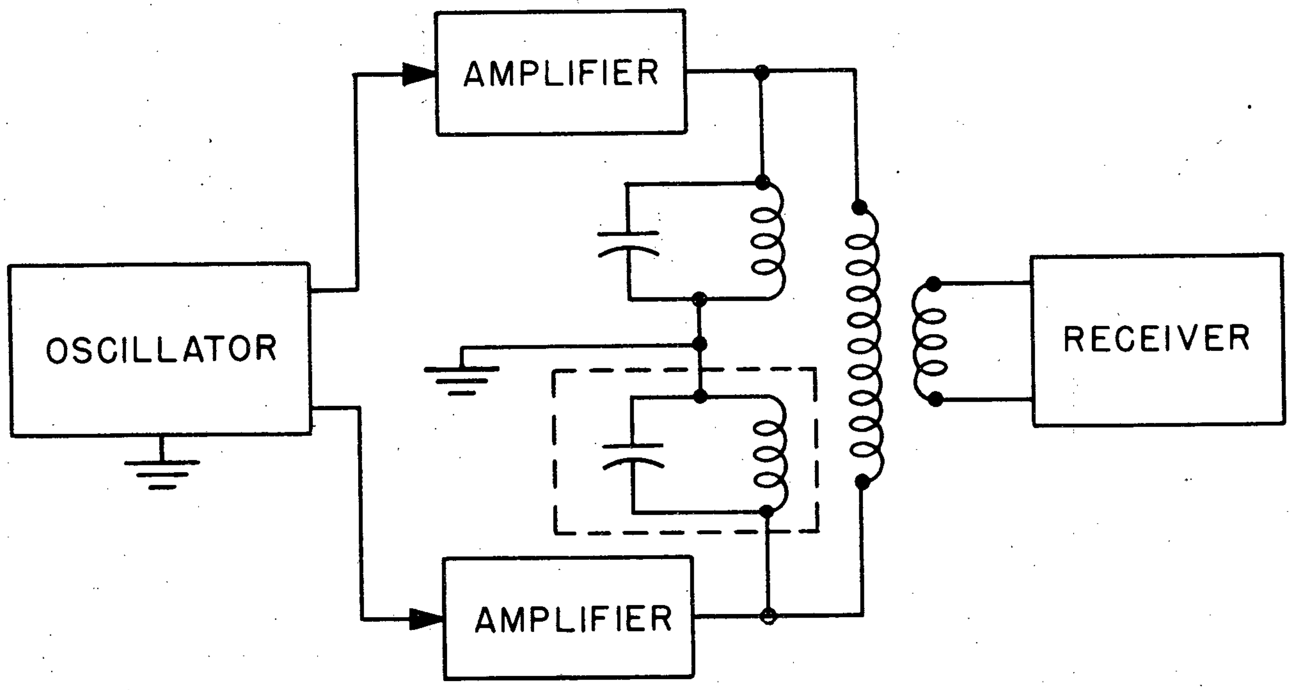

FIGURE 3.2.5(a) BALANCED COILS SYSTEM

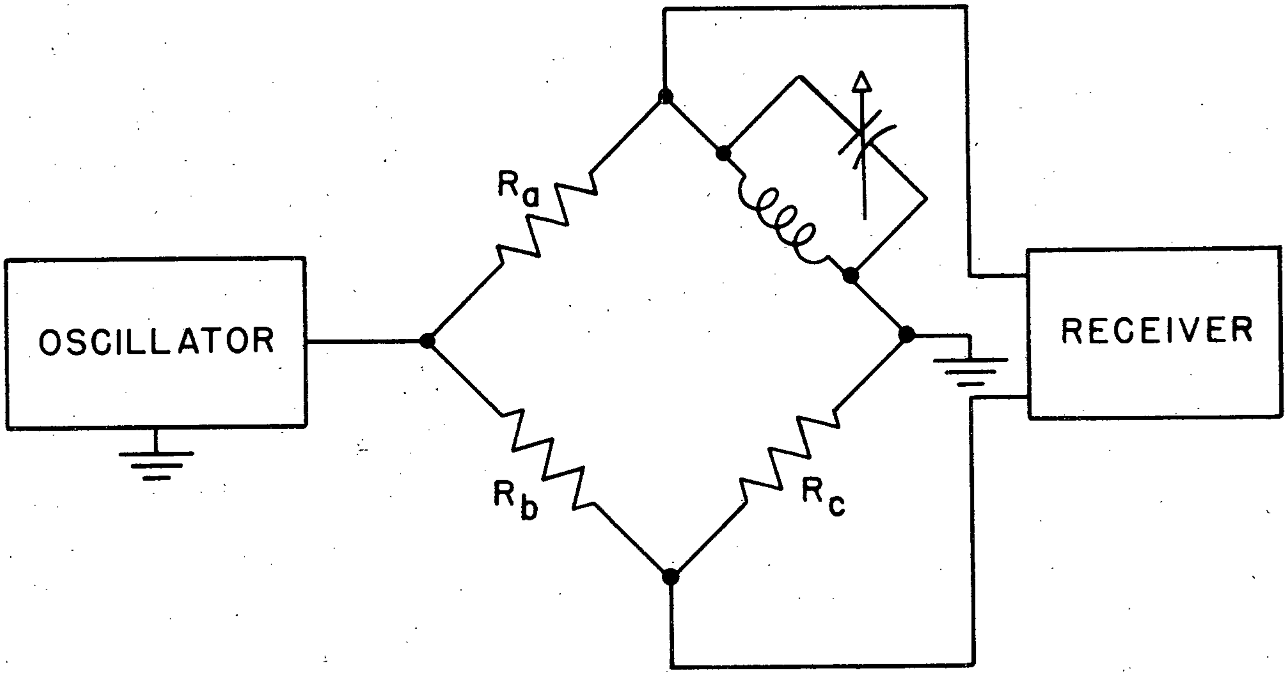

FIGURE 3.2.5(b) BALANCED BRIDGE SYSTEM

The difficulty that was encountered with this system was the high degree with which the electrical properties of the shielded coil have to match the unshielded coil. No successful breadboard circuit of this system was achieved.

The balanced bridge system is shown in Figure (3.2.5(b)). The oscillator drives the bridge circuit which is made up of resistors for three of the legs of the bridge with the detector coil forming part of a parallel resonant circuit as the fourth leg of the bridge circuit. Comparing this circuit with that shown in Figure (3.2.5(a)), R_a and R_b have replaced the two amplifiers and the shielded coil which makes up one of the parallel tuned circuits has been replaced by R_c. These substitutions are possible because all that is required of these circuits is that they supply a voltage to balance out the voltage that is developed across the detector coil. The balanced bridge system is a simplification of the balanced coil system because there is one less tuned circuit to consider. There still remain two problems with this system. One is the distributed capacity across the resistive components which makes them frequency sensitive, and the other is one which is basic with all of the systems, namely the tracking between the frequency determing circuits of the oscillator and the bridge circuit.

A breadboard arrangment of the balanced bridge circuit was tested with a certain degree of success. Obtaining a good null was difficult because of distributed capacity of the wiring of the circuit. Consideration of the mechanism by which this system operates led to a system which did away with the problem of distributed capacity of the wiring.

The field which is set up by the coil of the detection system induces a voltage in the coil of the transponder and thus causes circulating currents. These circulating currents of the transponder produce a field which induces a voltage in the detector coil and it is this voltage with which we are concerned. In the balanced coils system and in the balanced bridge system, this induced voltage is indicated by a change in the voltage appearing across the parallel resonant circuit containing the detector coil. This change in voltage we attribute to the field produced by the transponder and we let it go at that. However, the whole process of induced voltages can be expressed in terms of the mutual inductance that is present between the detector coil and the transponder coil.

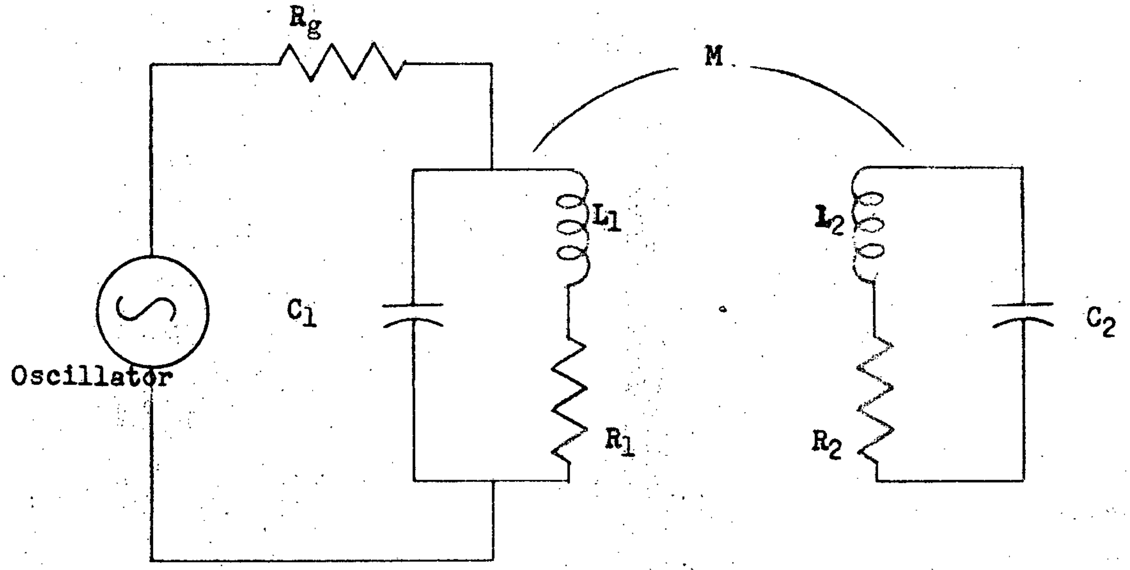

Figure 3.2.5 (c)

Consider the circuit shown in Figure 3.2.5 (c). An oscillator with internal impedance R_g drives a parallel resonant circuit made of L_1, C_1, and R_1 which represents the total resistance of the parallel circuit. Coupled to this circuit by means of the mutual inductance M is the parallel circuit consisting of L_2, C_2, and R_2. For the case where M is zero the impedance of the parallel resonant circuit in series with R_g can be expressed as Q_1wL_1 where Q_1 is the ratio wL_1/R_1 and w is the angular frequency. For the case where M is not zero the impedance of the circuit in series with R_g will be altered and for the special case where both parallel circuits are resonant to the same frequency, the change will be in the value of R_1. Thus R_1 will consist of the value that it has when M is zero plus the term w^2M^2/R_2 which is due to the current which is caused to flow in the second circuit. This change in R_1 results in a change in Q_1. The results is a change in the impedance of the first circuit. That is, the impedance of the parallel circuit in series with R_g is lowered and the voltage that is developed across this circuit is correspondingly lowered. The presence of the second resonant circuit (transponder) lowers the Q of the first resonant circuit. The basis of the Delta-Q system is a technique for measuring small changes in Q.

3.3 Delta-Q System

3.3.1 Development

The work on the balanced coils system and the balanced bridge system led to consideration of the problem in terms of coupled circuits rather than in terms of the back and forth transfer of energy. The realization that the effect of the transponder could be described as a change of Q of the detector coil led to the following experiment. A coil was connected to a Model 160-A Boonton Q-Meter and the Q-Meter was adjusted to read the Q of the coil. This is accomplished by setting the oscillator to the desired frequency, (in this case about 100 kcs) and then tuning to resonance the capacitor of the Q-Meter which is in series with the coil whose Q is being

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measured. A second coil was then tuned to resonance for the same frequency and as the coil was tuned through the operating frequency of the Q-Meter, a dip in the voltmeter reading which indicates Q was observed. This change in the Q was observable at distances of about eight feet with the planes of the coils parallel and their centers on a line perpendicular to these planes. The results of this experiment indicated that further work in evaluating this system was desirable.

The next step in the development of the Delta-Q system was a careful examination of how the Q-Meter operates and from an understanding of this, how the measurement of the change in Q can be made more sensitive.

The Boonton Q-Meter consists of an oscillator, a variable air capacitor, and a vacuum tube voltmeter which reads the voltage developed across the variable capacitor. The output of the oscillator is supplied by means of loop coupling, to a 0.04 ohm resistor. The oscillator is capable of supplying up to half an ampere of current through this resistor. The inductance, which is connected to the Q-Meter for measurement of its Q, completes a series circuit with the variable air capacitor. This circuit is driven by the voltage developed across the 0.04 ohm resistor.

For measurement of Q at a particular frequency, the oscillator is adjusted to this frequency and the variable air capacity is adjusted until the voltmeter in parallel with it indicates maximum voltage. This voltage reading can be calibrated directly in Q because the voltage developed across the capacity of a series circuit at resonance is equal to the voltage applied to the series circuit times the Q of the circuit. The effect on the Q of the variable air capacitor is negligible since its contribution to the series resistance is very small. It is then only necessary to calibrate the voltage applied to the series circuit. This is accomplished by means of a

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thermocouple ammeter which reads the current through the 0.04 ohm resistor to indicate the mutiplying factor for the voltmeter to indicate Q directly.

The 0.04 ohm resistor is sufficiently low in value to prevent any impedance presented by the series circuit, which is in parallel with it, from having any effect on the operation of the oscillator.

The effect of the reflected impedance of a tuned circuit on the Q-Meter can be determined by considering Figure 3.3.1 (a) where L_2, C_2 and R_2 form the transponder, M is the mutual inductance between L_1 and L_2 and L_1 and R_1 are the detector coil and its resistance which is connected to the Q-Meter made up of the oscillator, the very low resistance, and C_1 paralleled by the VTVM. At resonance $X_1 = X_c$ and the current through the series circuit is given by e/R_1 where e is the voltage applied to the series circuit.

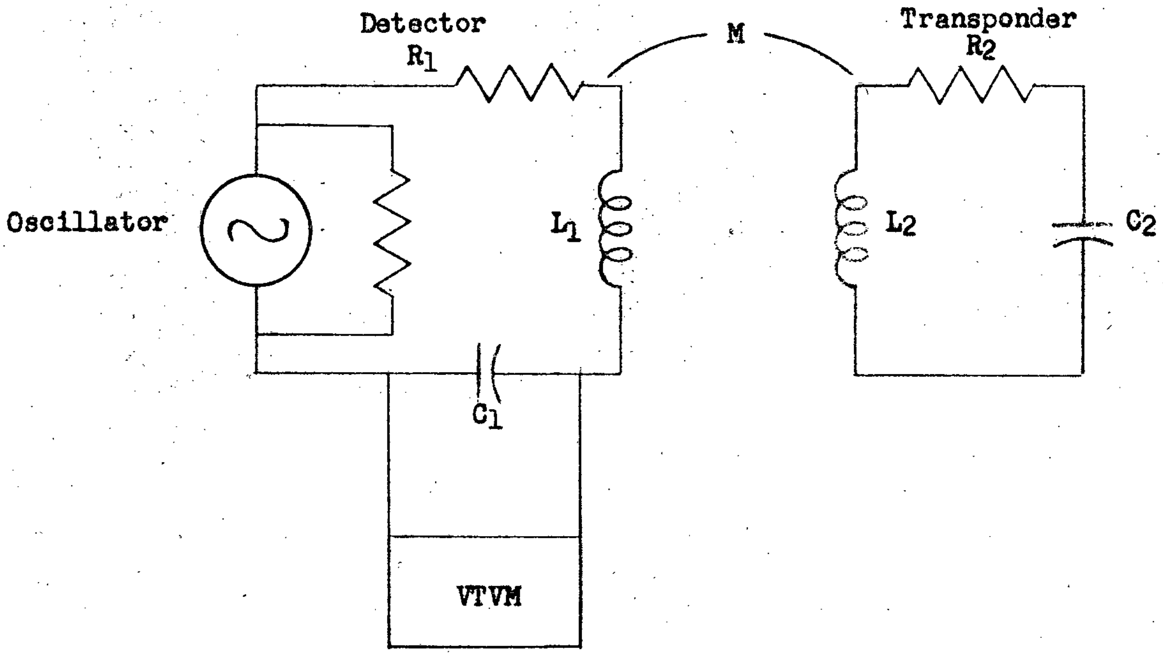

Figure 3.3.1 (a)
Basic Circuit of the Delta-Q System

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The voltage applied to the vacuum tube voltmeter is given by the current times the impedance or $(e/R_1)X_1$. The current of the series circuit will be reduced by the impedance change due to the transponder and is given by $e/(R + w^2M^2/R_2)$. Then the voltage change across L_1, due to the transponder, which we want to be a maximum is

$$eX_L/R_1 - eX_L(R_1 + W^2M^2/R_2)$$

Factoring out the common term eX_L/R_1 the expression

$$\frac{eX_1}{R_1}\left[1 - \frac{1}{1 + \frac{W^2M^2}{R_1R_2}}\right]$$

is obtained. The term outside the brackets can be written as eQ_1 and the term in the brackets can be written as

$$\frac{W^2M^2}{1 + \frac{W^2M^2}{R_1R_2}}$$

$M = K\ L_1L_2$ where k is the coefficient of coupling. Making this substitution,

$$\frac{\frac{k^2W^2L_1L_2}{R_1R_2}}{1 + \frac{k^2W^2L_1L_2}{R_1R_2}}$$ is obtained.

The Q of the detector coil is $\frac{WL_1}{R_1} = \frac{XL}{R1} = Q_1$

The Q of the transponder is $\frac{WL_2}{R_2} = Q_2$

The term in the brackets can thus be written as

$$\frac{k^2Q_1Q_2}{1 + k^2Q_1Q_2}$$

and the change in voltage due to the transponder can be expressed as

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$$eQ_1 \left[\frac{k^2 Q_1 Q_2}{1 + k^2 Q_1 Q_2} \right]$$

In order for this term to be as large as possible, e, Q_1, and Q_2 should be as large as possible. This means that the Q of the detector coil and of the transponder coil should be as large as possible. The driving voltage from the oscillator should be as large as possible. The advantage obtained by increasing e can only be realized if the amplifier to which the voltage across C_1 is applied, is one which can amplify only the changes in voltage without amplifying the whole signal.

The next step in the development of the Delta-Q system was the design and construction of an amplifier which looked at only the peaks of the signal. This was accomplished by the use of a cathode follower with the cathode biased considerably beyond cutoff, permitting only the peaks of the signal to cause current to flow. The circuit of the amplifier is shown in Figure 3.3.1 (b). The cathode follower which is biased to cutoff is followed by two stages of amplification. The signal is then fed to an amplifier with sufficient bias so that only the peaks of the signal are applied to the following stage which is a cathode follower. The output of the cathode follower is rectified and amplified by a dc amplifier. The output of the dc amplifier is fed to another cathode follower which is used to operate a dc microammeter.

The breadboard model of the Delta-Q system was tested for range. No provision was made for tuning this early model and the testing proceeded as follows. First the oscillator was set to a frequency of about 100 kcs, and then the tuned circuit in the input of the amplifier was tuned to exactly the same frequency. A transponder was then tuned to this same frequency and

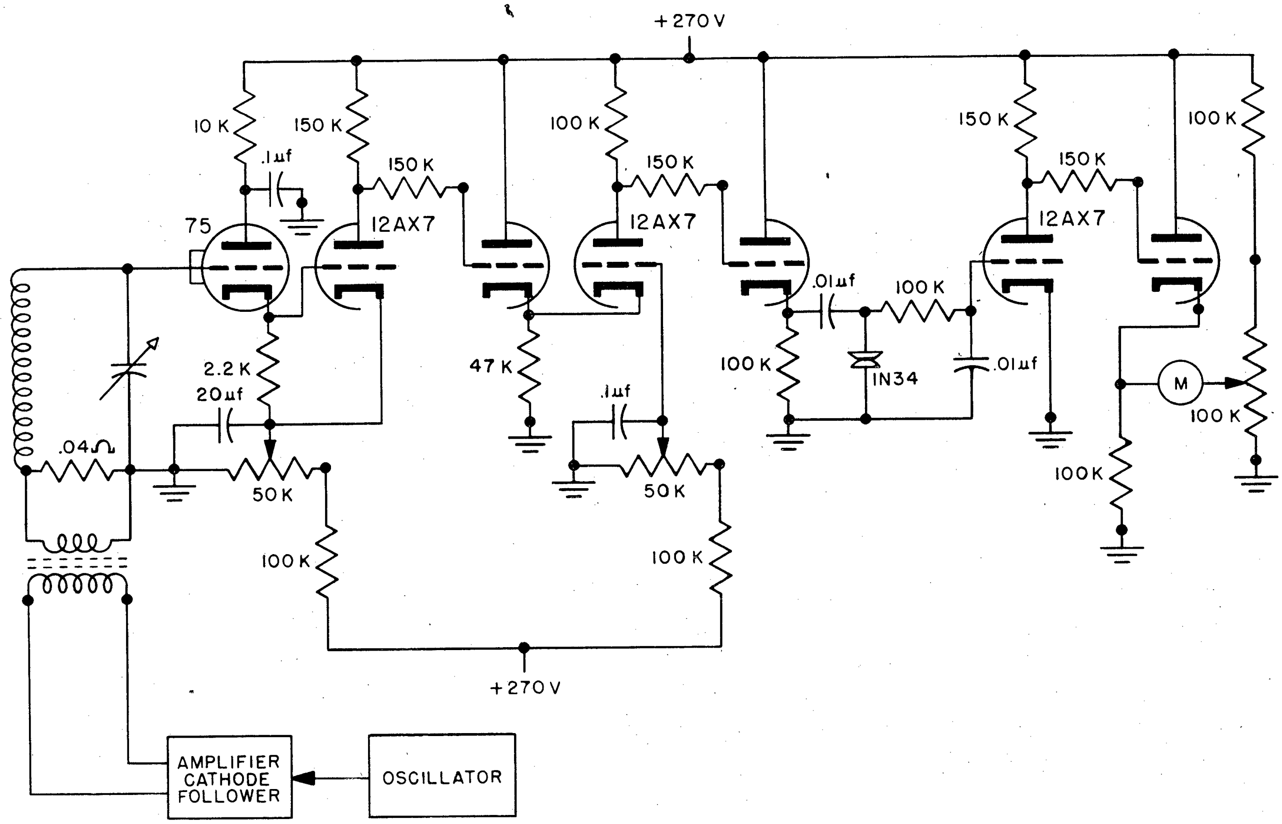

FIGURE 3.31(b) FIRST DELTA-Q SYSTEM DETECTOR

the effect was observed on the meter indicator. As the transponder tuned through the operating frequency of the detector, a sharp dip was observed in the meter reading. The distance between the detector coil and the transponder coil was increased until the dip in the meter reading was no longer observed. This occured at a distance of greater than twenty five feet. During the course of this experiment it was observed that the meter reading was extremely sensitive to changes in position of people located within a few feet of the detector coil. This was cuased by the changes in distributed capacity. This aspect of the detection system played an important role in limiting the sensitivity and range of detectability. At the time it was thought that shielding could greatly minimize this effect.

The next step in the development of the detection system was that of building a portable model of the detector. This model incorporated the amplifier tested in the breadboard model and in addition used a ganged tuning control for the oscillator and receiver circuits to permit adjusting this circuit to exact resonance. Testing of the circuit showed that tracking errors were sufficient to cause false indications since a tracking error caused the same indication as that of a transponder. These false indications could always be resolved by the adjustment of the small capacitor in the receiver circuit.

The technique of using the detector played an important part in determing the development. It was thought at this stage in the development that continous tuning of the detector as the search was carried on would be the mode of operation. As experience was gained in using the detector it was determined that continous tuning was not necessary. While it was thought necessary, several methods were devised for solving this tracking

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problem.

The basic solution to the tracking problem consisted of placing in parallel with the capacitor of the receiver circuit a capacitor whose value of capacitance varied periodically with time. This varied the resonant frequency of the receiver circuit about the operating frequency of the oscillator. If the frequency of the oscillator is that of the transponder, then the receiver circuit will pass through this frequency at least once and probably twice during the cycle of the varying capacitor.

In the first model of the detector the rotating capacitor was driven by a modified clock motor taken from an eight-day traveller's clock. This obviated the use of battery power. This method turned out to be expensive because of the amount of work needed to modify the clock and build the rotating capacitor. Furthermore the clock motor was not very reliable, having a tendency to stop when held in certain positions. It was later decided to abandon the use of the clock motor when a method of achieving the same result was developed which did not require much battery power.

The second method consisted of using a vibrating capacitor made by modifying an earpiece of a pair of headphones. This was accomplished by placing an O ring of insulating material and an extra diaphram of non-magnetic material on top of the magnetic diaphram. Holes were drilled in the non-magnetic diaphram to prevent loading of the magnetic diaphram. The two diaphrams insulated from each other by the O ring formed the plates of the vibrating capacitor, the variation in capacitance being obtained by the change in spacing which occurs when the earphone is driven by an ac signal. The driving current for the earphone was supplied by a type 1U4 vacuum tube used as an amplifier with its grid signal obtained from a neon tube relaxation

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oscillator. This method for obtaining the varying capacitor worked well.

In the course of the development of the detector an investigation was made of having the frequency of the oscillator varied instead of that of the receiver circuit. This was found to be a more satisfactory way of solving the tracking problem mainly because of the less stringent requirements on the Q of the varying capacitor.

In addition to solving the tracking problem, the varying capacitor whether in the form of the rotating capacitor or in the form of the vibrating capacitor produced an audio modulation of the signal. This enabled the receiver circuit to use RC coupled amplifiers instead of untuned RF amplifiers and in addition gave the audio modulation necessary to produce aural indication.

The final form of the detector of the Delta-Q system utilizes an amplitude modulated oscillator without any provisions for frequency modulation. The main tuning capacitors track over small portions of the band with proper adjustment of the fine tuning capacitor. This method of using the detector will require tracking over only small portions of the band.

3.3.2 Detector

3.3.2.1 Theory of Operation

The operation of the Delta-Q system detector is based on the impedance that is reflected by a tuned circuit, the transponder, into a series circuit resonant at the same frequency, by means of magnetic coupling. The Q of the series resonant circuit is altered by this reflected impedance. The change in voltage developed across this circuit is used to indicate the presence of the transponder.

The detector consists of three main circuits; an amplitude modulated

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oscillator which drives the series resonant circuit, a frequency determining circuit for the oscillator and for the series resonant circuit, and the amplifier which amplifies the changes in voltage across the series resonant circuit caused by the transponder.

The oscillator, which is of the Hartley type, is amplitude modulated by an audio signal in order to give an aural indication. The output of the oscillator which is supplied at a very low impedance, feeds the series resonant circuit. The inductance of the series resonant circuit is the detector coil which inductively couples to the coil of the transponder.

The frequency determining circuits, for both the oscillator and series circuits have ten bands two kcs wide, covering a frequency range 80 to 100 kcs. A two section ganged variable air capacitor adjusts the frequencies of the oscillator and of the series circuit with a single control. A small variable air capacitor in parallel with the capacitors of the series circuit permits fine tuning and takes care of tracking errors which result from use of different portions of the bands. Trimmers and padders are provided for adjusting the frequency limits of each band.

The voltage developed across the capacitor of the series circuit is applied to the amplifier. This circuit is similar in operation to the receiver circuit of the first model of detector (see Figure 3.3.1 (b) except that it has been modified to use filament type tubes. The use of amplitude modulation in the oscillator permits the use of RC coupled amplifiers operating at audio instead of RF frequencies. Only the peaks of the input signal pass through the first stage of the amplifier. The RF component of the signal is filtered out after an additional stage of amplification and after further amplification and clipping the audio component is fed to the ear phones.

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Proper adjustment of the detector involves setting the main tuning control to the desired frequency and adjusting the fine tuning and amplitude control, whereupon a constant audio tone will be heard in the ear phones. This tone is caused by the peaks of the signal in the series circuit. When the detector is carried within the presence of the transponder the amplitude of the audio tone decreases until a null is produced, indicating the presence of the transponder.

Tracking of the frequency of the oscillator and the series resonant circuits of the receiver is obtained by using a dual ganged variable air capacitor whose sections are closely matched, by providing adjustable trimmers and padders, and by an adjustable inductance for the oscillator. In theory, if the oscillator and receiver inductances are made equal tracking will result if the same value of capacitance is provided for each circuit. In practice the effective inductance of the oscillator coil and of the receiver coil depend on frequency but not in exactly the same manner because of different amounts of distributed capacity. The trimmers and padders permit matching the frequency of the oscillator and of the receiver at the end points of the bands. The bands are made only 2 kcs wide so that the tracking errors at points in between are necessarily small. The inductance of the oscillator is adjusted to minimize the tracking error at midband. It has been found that if the inductance is so adjusted for the lowest frequency band, the other bands will track. The fine frequency control permits exact tracking of the frequency of the two circuits on each of the bands for any position of the main tuning control.

3.3.2.2. Circuitry

The circuit for the detector is shown in Figure 3.3.2.2 (a). The

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diagram has been simplified by showing the capacitors of only one band. Figure (3.3.2.2 (b)) shows the schematic of the band switch with the capacitors for the ten bands. The oscillator uses a type 3V4 vacuum tube in a Hartley type oscillator. The primary winding of T20 is the adjustable inductance of the oscillator whose secondary winding supplies the output of the oscillator. C20 and R20 develop the operating bias for the oscillator. The screen is used as the plate of the oscillator and it is connected to ground for RF through C21 and C22. R21 is the screen dropping resistor supplying the screen voltage. Plate voltage is supplied through R23 and L20. L20, C24 and C25 form a filter circuit which keeps the RF out of the B-battery supply and thus out of the amplifier, which obtains its B voltages from the same batteries. Amplitude modulation at audio frequency is obtained by screen modulation from the relaxation oscillater R22, C22 and V21.

The output of the oscillator is obtained from the secondary of T20. This winding has across it R17 which is a 0.42 ohm resistor which is small enough to prevent any variation in impedance of the series circuit from cuasing changes in the oscillator's amplitude or frequency. The oscillator output is fed to the series circuit which is made up of the detector coil L1 and the capacity combination of C13A, C16, C17, and C112, C132, C119, C139 selected by the band switch. This series circuit is resonant to the same frequency as the operating frequency of the oscillator. L1, the detector coil, is a rectangular coil measuring 14 by 16 inches by 3 inches thick. A Faraday shield is provided between this coil and the operator to minimize the effects of changes in distributed capacity.

The amplifier uses four type 1U4 vacuum tubes. The first stage is a cathode follower with the filament placed at a sufficiently positive

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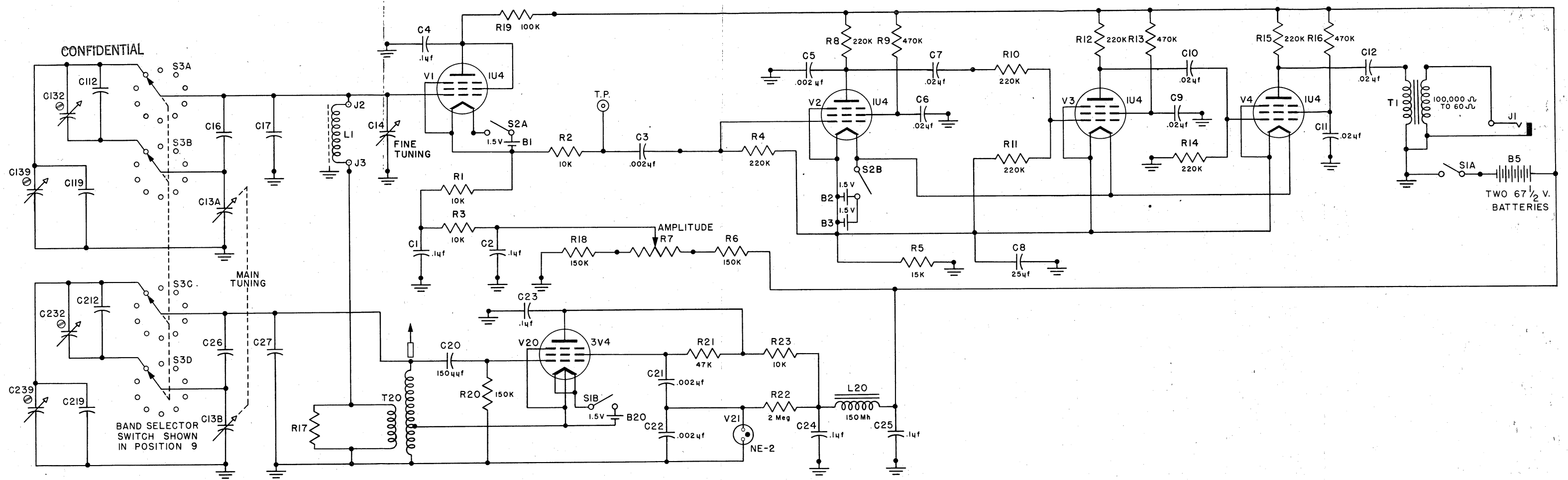

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CIRCUIT DIAGRAM OF DELTA-Q SYSTEM DETECTOR
FIGURE 3.3.2.2(a)

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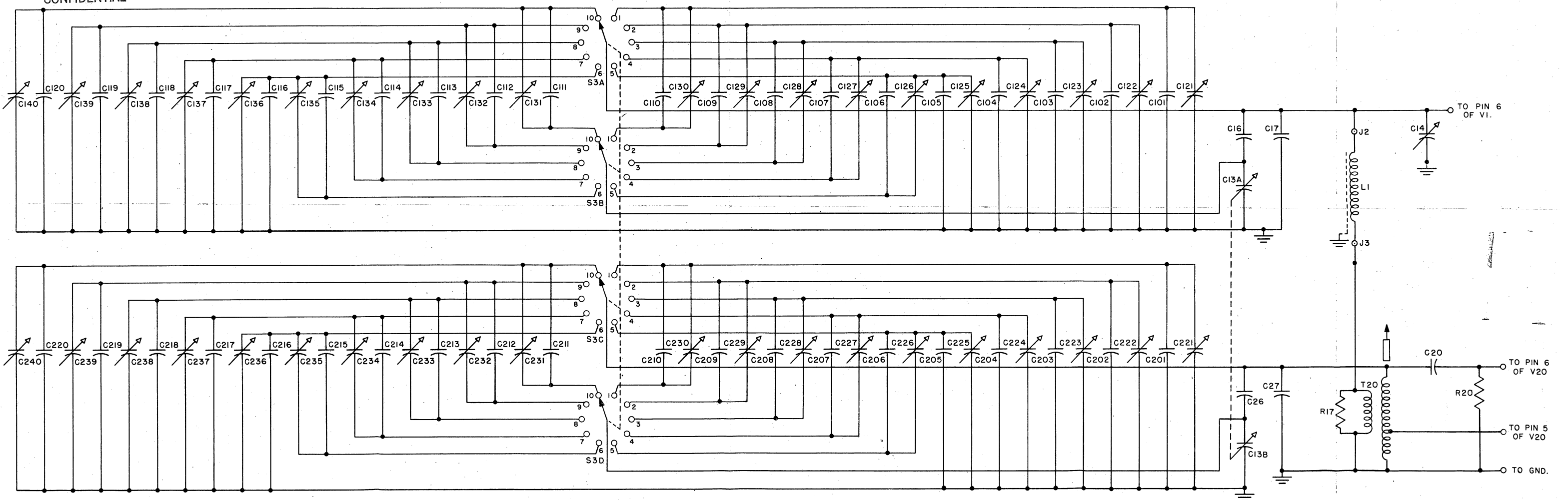

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FIGURE 3.3.2.2(b) BAND SWITCHING CIRCUITS bias through R1, R3 and the voltage divider R6, R7, R18, so that with no signal on the grid the tube is cut off. This positive bias is adjustable by means of R1. This is the amplitude control, and it determines what amplitude of input will produce an output across R1. With sufficient signal developed across the capacitance of the series circuit, i.e., a signal whose peak value exceeds the positive bias, the peaks of the amplitude modulated signal appear across R1. Plate voltage for this stage is supplied through R19 which prevent any plate voltage variations of the common battery supply from causing instability. C4 bypasses the plate to ground and with R19 decouples the plate from the common battery supply. C_1 and C_2 decouple the batteries, which supply the bias for this stage, from the cathode circuit. The output of the cathode follower is fed to the next stage through R2 and C3 which serve to isolate the cathode of the cathode follower from the Test Point, which is used in aligning and testing the operation of the detector.

The second stage of the amplifier serves to amplify the signal and also to filter out the RF portion of the signal so that its output is an audio signal. The drive for this stage is developed across R4. R8 is the load resister across which the output is developed and C5 bypasses the RF component of the signal. R9 and C6 supply and bypass the voltage for the screen grid.

The third stage of the amplifier serves as an audio amplifier with the input voltage being developed across R11. The bias for this stage is only the contact potential of the tube, the grid being connected to the filament through R11. The output of this stage is developed across R12. There is a voltage divider in the input of this stage which reduces the drive. This is required in order to obtain the necessary clipping action of the last stage and still use a large enough portion of the signal in the first stage.

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If too small a portion of the signal is used in this stage, the audio component of the signal will be of the same amplitude as the hash that remains after filtering out the RF.

The last stage of the amplifier is used as a clipper amplifier. Only the peak portions of the signal are amplified in this stage. This clipping is accomplished by the bias which is developed across R5 through which all the plate and screen current for last three stages flow. This voltage, which is positive with respect to ground, supplies bias only for the last stage because only in this stage is the grid connected through a resistor (R14) to ground instead of back to the filament. The output is developed across R15 and is fed to the audio transformer. This is "sub-ouncer" and is extremely small and light. This transformer is used to impedance match the ear phones to the high impedance output.

The use of filament type tubes necessitates the use of separate filament batteries: one for the oscillator, one for the first stage of the amplifier, and one for the last three stages of the amplifier. The batteries for the oscillator and for the first stage of the amplifier operate at RF potentials with respect to ground and consequently are located with respect to other components in a manner which minimizes interaction.

The plate voltage for the oscillator, amplifier, and the bias for the first stage of the amplifier are supplied by two 67½ volt batteries.

The double pole switches are used to open the three separate filament circuits and disconnect the ground connections of the B batteries.

3.3.2.3 Configuration

The design of the configuration of the detector has been motivated by two objectives: The detector when in the non-operating carrying position should be as small and convenient a package as possible; when in the operating

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position or when it is being used in the search process for locating the position of the transponder, it should have a configuration which is most convenient for the operator and which gives optimum results in locating the transponder.

The detector is made up of two major components: the detector coil, and the metal box which contains the electronic circuits. The detector coil is rectangular in shape, and is a three pie spider web type coil similar to coils used for the transponder. Its outside dimensions are 14 by 16 inches by 3 inches thick. The coil fits into a plastic box which forms the outside of the detector and serves to protect the coil. A Faraday shield is built in to the bottom of the plastic box. The inside dimensions of the coil are 10 by 12 inches by 2 3/4 inches. The metal box containing the electronic circuits folds into this space when the detector is in the non-operating position.

A rectangular shape was chosen for the detector coil so as to give the largest area and thus the greatest mutual inductance with respect to the transponder coil. The electrical characteristics of this coil are very similar to that of the transponder coil.

The metal box containing the circuits of the detector is fastened to the lid of the plastic box in which the detector coil is contained. The controls for operating the detector are located on the top and side of this metal box. The control on the top is the main tuning control. There are two switches which turn on the detector. These switches are automatically turned off when the detector is closed up. The amplitude control, fine tuning control and band switch are located on the side.

When in the non-operating position, the detector has been made so as to resemble a briefcase or small piece of luggage. A handle fastened to the plastic box is provided for carrying the detector in this manner. For certain applications where the detector will be carried in a rucksack, this handle can be left off. A handle fastened to the metal box containing the circuits for the detector is used to carry the detector when it is in operation. This handle slides out to the proper position for a balance so that the detector will hang naturally in the proper position. The toggle switches which turn on the voltage to operate the detector are so located so that when the handle slides back in position to close the detector the switches are turned off.

When in the operating position the detector coil hangs so as to form about a twenty degree angle with the vertical. Experiments indicate that the greatest range is obtained with the coil in a vertical position rather than in a horizontal position. This is not true when the transponder is submerged in sea water in which case the horizontal coil gives the greatest range. The patterns of detectability are shown in Appendix 4.2.

3.3.2.4 Method of Operation

The operation of the detector for locating the position of the transponder and thus the cache requires a knowledge of the resonant frequency of the transponder when buried in its particular medium. Tests have indicated (see section 3.3.4.3) that the resonant frequency of the transponder that is measured in air is slightly higher than that measured with the transponder in some other medium. The first step in the use of the Delta-Q cache marker system is to measure and record the frequency of the transponder after it has been buried (or submerged) to mark the location of a cache. The detector has ten bands and a main tuning dial and the designation of the frequency will

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be, for example, band 5, dial reading 34. In addition to this information, the user of the detector will know the approximate area within which the cache is located.

Prior to actually using the detector for the search the operator should make certain that the batteries in the detector are in good condition. This can be determined by turning on the detector with the detector coil in the operating position with the amplitude control set at its maximum position. The fine tuning control is adjusted until the audio tone is heard in the ear phones. The amplitude control is then adjusted to reduce amplitude of the audio tone to a comfortable level. The fine tuning control should then be rocked back and forth; this bringing the series circuit in and out of resonance and the audio tone which is absent on either side of resonance should be a maximum at resonance. The amplitude control should also be retotated from its minimum to its maximum position and this should change the audio tone from a minimum to a maximum value. If all these results are observed the detector and its batteries are in good operating condition. This test should all be made with the detector held in the operating position.

Upon arrival at the area in which the cache and transponder is located, the detector is placed in the operating position. The two toggle switches are switched to the "on" position and the band switch and main tuning control are adjusted to the values obtained when the transponder was initially buried (submerged). The amplitude control is adjusted in conjunction with the fine tuning control until the audio tone is heard. The fine tuning control is then adjusted so that the audio tone is present for about 20 degrees of rotation of the main tuning control on either side of the dial setting at which the transponder is reportedly located. This adjustment assures tracking

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over the portion of the dial containing the frequency of the transponder and permits rotating the main tuning control through resonance. A null in the audio tone will be obtained when the main tuning control goes through the frequency of the transponder.

The manner in which the operator holds the detector with relation to his body and ground and with respect to the direction he walks is important in obtaining successful use of the detector in locating the transponder since the resonant frequency of the series circuit in the detector is affected by changes in the distributed capacity of the detector with respect to the operator and ground. The detector must be carried in a manner which keeps these changes to a minimum. If these changes in distributed capacity are too great, the audio tone will disappear. This can cause a false indication of the presence of a transponder. With a little practice the operator will learn how to carry the detector without these changes affecting the operation. The detector should be kept about six to eight inches away from the operator's body and the same distance above the ground.

The orientation of the detector with respect to the direction the operator is walking is important because of the directional properties of the vertical detector coil. If the detector coil is lined up with the direction that the operator is walking there will be a band or region parallel to this path and about a foot wide in which a transponder will not be detected. This blind region is eliminated by rotating the plane of the detector coil and thus the detector so that it forms about a thirty degree angle with the direction of walking. A discussion of this directional property is given in Section 3.3.4.6.

As the operator walks along with the detector in the manner

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described above, he will continually hear the audio tone. The region covered by the detector will be a twelve foot strip. If the transponder is located in this strip a null in the audio tone will occur when the operator passes within six feet of the transponder. The operator can positively identify the presence of the transponder by rocking the main tuning control. A null should be found each time the resonant frequency of the transponder is passed. Once the approximate location of the transponder is found, its exact location can then be determined as follows. The detector coil is brought up to a horizontal position by changing the length of the supporting lines. The detector must now be retuned because there has been a change of distributed capacity of the detector coil with respect to its surroundings. This retuning is accomplished by adjusting the fine tuning control, until the audio tone is again heard. This adjustment must be made with the detector out of range of the transponder. The region of the null will now be a circle. After the region of the null has been located the exact location of the transponder may be determined by turning up the amplitude control, or raising the detector higher above the ground. This decreases the sensitivity and reduces the diameter of the null circle. The position of the center of the transponder can now be located to within a few inches.

The actual search process can cover any series of paths which will give coverage of the area in which the cache is known to be located, each path being twelve feet wide. A straight forward approach would be to patrol parallel paths starting at one edge of the field and ending at the other end. This is probably not the quickest way. A better way would be to cover the area by concentric rings using a stake and a string with knots or some other kind of marker every twelve feet. The stake is placed in the center of the area. The

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operator holds the string taut and increases the radius of his circular path by twelve feet after completing each circle. This system would enable the operator to make a systematic search in the dark. If the stake is driven at the most probable location of the cache this last method will locate the cache in the shortest time. These two methods are suggested as possible approaches to the problem.

3.3.3 Transponder

3.3.3.1 Coil Form

The final configuration of the coil form has largely been by experimental investigations. Tests were made of honeycomb solenoid and spider-web type windings and it was found that the spider-web winding gave the highest Q. This is attributed to the low distributed capacity that is attained with this kind of winding. In order to increase the mutual inductance between the transponder and the detector coil, a three pie section winding was used.

Experiments showed that the Q of the coil was greatly improved with the use of a good insulating material for the coil form. Styrene was finally chosen because of its good electrical properties, ease of molding, and low cost.

To simplify the manufacture of the three pie coil form for the spider-web type winding, it was decided to make the coil out of three identical pieces. Figure 3.3.3.1 shows one section of the coil form. By making the coil form in three sections, the mold that is needed for the manufacture is simplified in that there are no under cuts in the molded piece. The individual pieces of the coil form are provided with dowel extensions and holes which permit easy alignment when cementing the sections together.

Inquiries were made of a number of plastic molding manufacturers

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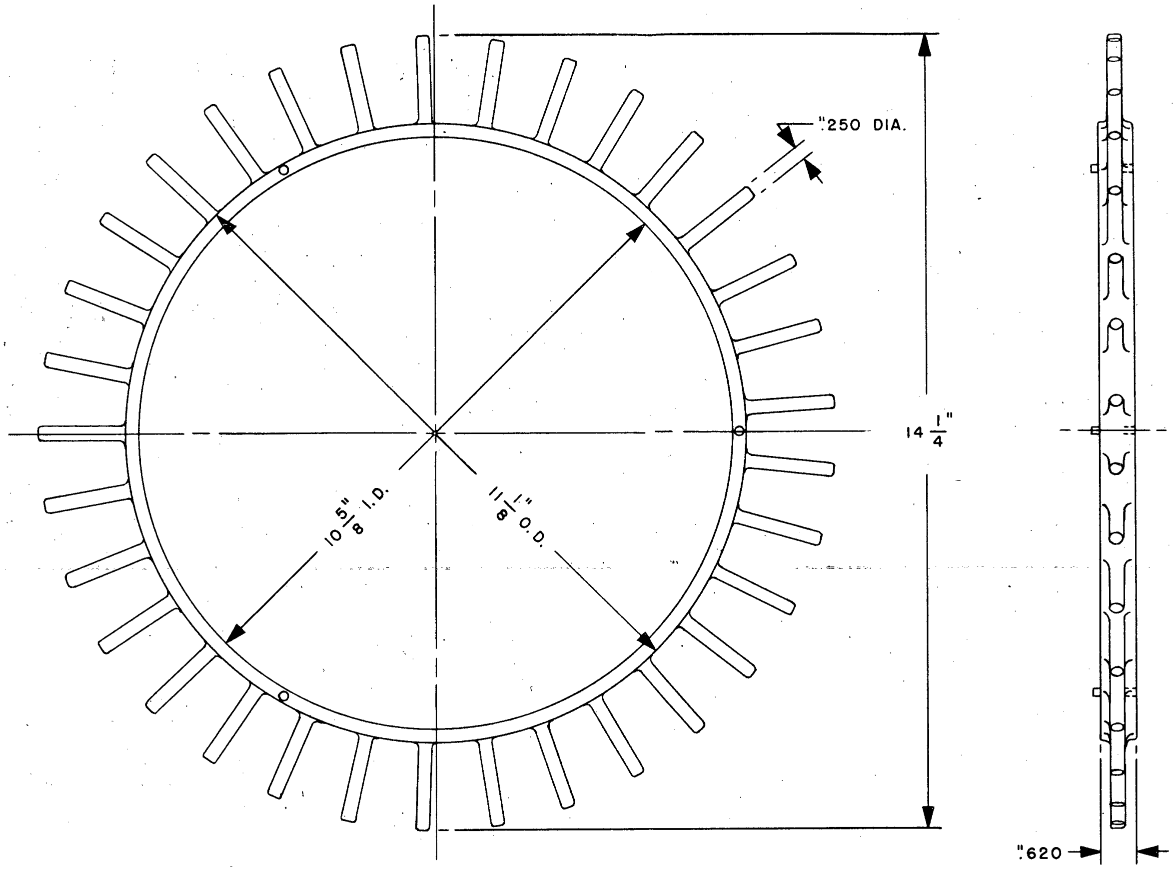

FIGURE 3.3.3.1 COIL FORM

to determine the prices for the metal molds and for the coil form sections. The price for the metal molds for injection molding ranged from $990 to $4625 with an estimated time for completion of 12 to 14 weeks. The prices per molding for quantities of 1000 varied from $0.359 to $0.75, and in quantities of 10,000 from #0.287 to $0.65. Three such moldings are required for each transponder.

3.3.3.2 Wire

The wire that is used to wind the transponder plays an important role in determining the Q. While the dc resistance of the coil is determined by the cross section and the length of the wire used to wind the coil, the ac resistance depends on how the copper is distributed within the cross section. During Phase I it was determined that Litz wire, which is a stranded wire where the individual strands are insulated from each other, gave the highest Q. There are however a number of kinds of Litz wire that can be obtained and the problem was to determine which kind to use.

There are basically two kinds of Litz wire. One kind consists of individual strands, insulated from each other, bundled together, and wrapped with an insulating material such as cotton or silk. For this kind of Litz wire there can be any number of strands of any wire size for the individual strands. The second kind of Litz wire has the individual strands woven together in some specified manner. For this kind of Litz wire not only must the number and size of the strands be specified, but in addition, the manner in which the strands are woven.

The requirement imposed on the resistance of the wire by wanting to have a high Q coil is that the ratio of the ac to dc resistance of the wire be as close to unity as possible. The ac resistance of the wire will always be greater than the dc resistance of the wire. For an individual

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strand the resistance ratio approaches unity as the diameter decreases. The decrease in the ratio is rapid for relatively large diameters, and then decreases more slowly. The particular diameter at which this assymptotic approach of the resistance ratio to unity begins depends on the operating frequency. As the number of strands is increased, the resistance ratio increases. This is because of the effect of the magnetic field, produced by the current flowing in the strands on the outside of the wire, on the current flowing in the inner strands. This effect is greatly reduced by transposing the strands in a manner which gives each strand all possible positions in the wire. Another manner by which this effect can be reduced is by weaving the strands so as to form a hollow tube. In fact, this method is more effective in keeping the resistance ratio close to unity.

One of the difficulties that was encountered was in finding a manufacturer who would make small quantities of special Litz wire. Some manufacturers had machines that could not handle small wire sizes. For example, one manufacturer furnished woven Litz wire using No. 38 strands. Tests of the coils wound with this wire showed a much lower Q than experience indicated and further tests showed that as many as 75 per cent of the strands were discontinuous. Another manufacturer, which proved to be the best and cheapest source of Litz wire, recommended that woven Litz wire should not be made with wire lighter than a No. 30.

Measurements were made of transponders wound with different wire to determine the effect of wire size on the Q and detectability of the transponder. The number of turns used in winding the transponder was determined by the wire diameter; the maximum number of turns was used in each case. The different wires used are as follows:

No. 1 - 105 turns of Litz wire consisting of 50 strands of No. 38 [redacted] merely bunched together.

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No. 2 - 60 turns of Litz wire consisting of 24 strands of No. 30 where the individual strands are braided on a glass fiber core.

No. 3 - 90 turns Litz wire consisting of 64 strands of No. 38 where 8 strands are braided together to form a cable and then 8 such cables are braided together.

No. 4 - 99 turns of No. 18 solid wire formvar insulated.

The Q's of the four coils as a function of frequency are shown in Figure 3.3.3.2(a)

The detectability was measured using the Boonton Q-Meter and the detector coil of the detector. The Q-Meter was adjusted to measure the Q of the detector coil; the transponder was tuned through the operating frequency of the Q-Meter, and the change in Q was observed. The transponder coil and the detector coil were maintained parallel with their axes of symmetry collinear. Readings were taken of the change in Q for frequencies 10 kcs apart from 50 to 150 kcs. The results are shown in Figure 3.3.3.2(b) which indicate that over the frequency range of 80 to 100 kcs, the transponder using 24 strands of No. 30 braided over a glass fiber core gives the best results. This is the wire that has been chosen for the final model of the transponder.

3.3.3.3 Packaging

The packaging of the transponder must provide protection for the transponder from its environs. In addition the material used for the packaging must have sufficiently good electrical properties so as not to seriously alter the detectability of the transponder. An additional requirement is that the material used for the packaging must be of low cost.

Two approaches to this problem were considered. One was to cast the transponder in a material having the necessary physical properties, the second was to place the transponder in a shell type structure.

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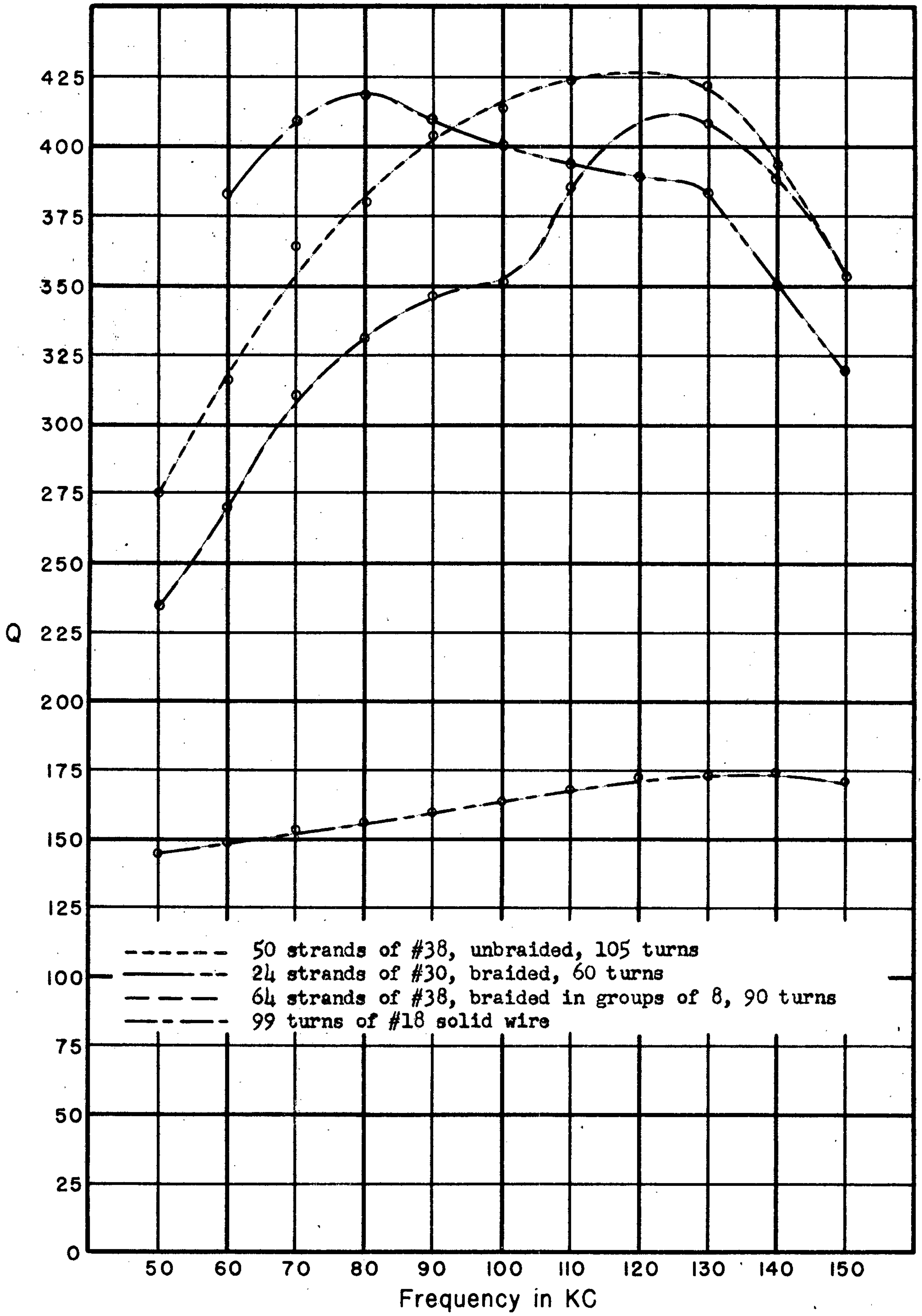

FIG. 3.3.3.2(a) Q AS A FUNCTION OF FREQUENCY

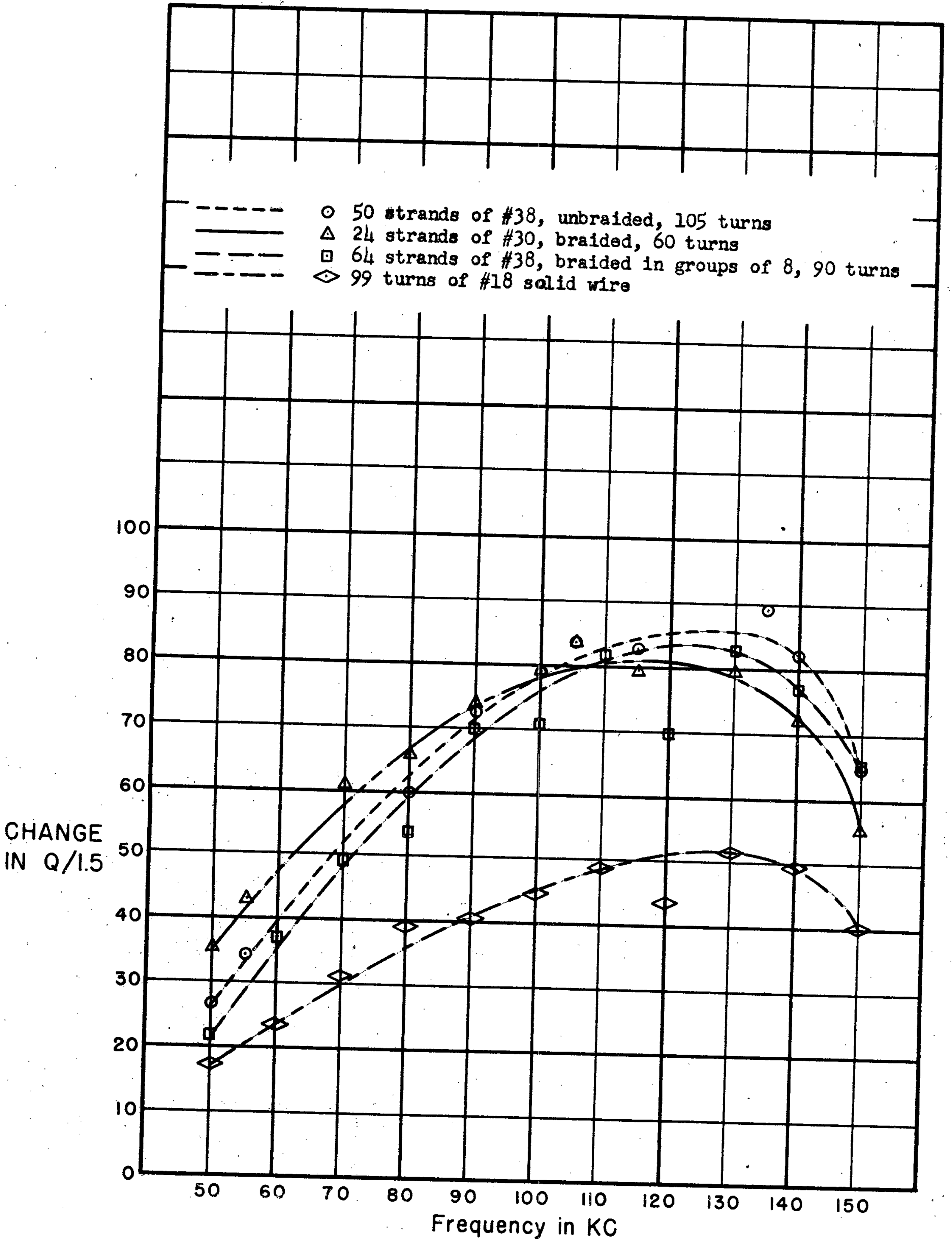

FIG. 3.3.3.2(b) TRANSPONDER RESPONSE CHARACTERISTICS

The size of the transponder was one of the limiting factors in the casting method of packaging. Most of the plastics that are available for casting undergo shrinkage and experience showed that cracks and voids are formed when casting an object the size of the transponder. The available plastics which have very little shrinkage are too expensive. Another difficulty encountered with casting is that the temperatures at which the thermoplastic materials can be poured are excessive for the material out of which the coil forms are made. This results in distortion of the transponder coil.

The method that was chosen for the final form of the transponder consists of telescoping half-shells of the form shown in Figure 3.3.3.3. These half-shells are made of a polyester resin reinforced with glass fiber clothe or mat. This material has excellent mechanical and electrical properties, giving the necessary protection to the transponder and still preserving the high Q. In production these half-shells can be made for about $1.50 each with a mold cost of about $3000.00.

The transponders are put together by placing the coil and the capacitor inside of the inner half-shell. As an extra precaution against failure of the transponder due to moisture, Cerese wax is poured in over the coil and capacitor filling the remaining space. The electrical properties of this wax have been tested and have been found to be very excellent. The surfaces of the half-shells which come in contact are coated with an epoxy resin and the transponder is finally assembled. A small hole is provided in the outer half-shell to permit the escape of air when assembling the two halves of the shell. Otherwise the air would force its way through the glue joints and destroy the seal. This hole is filled later with the epoxy resin.

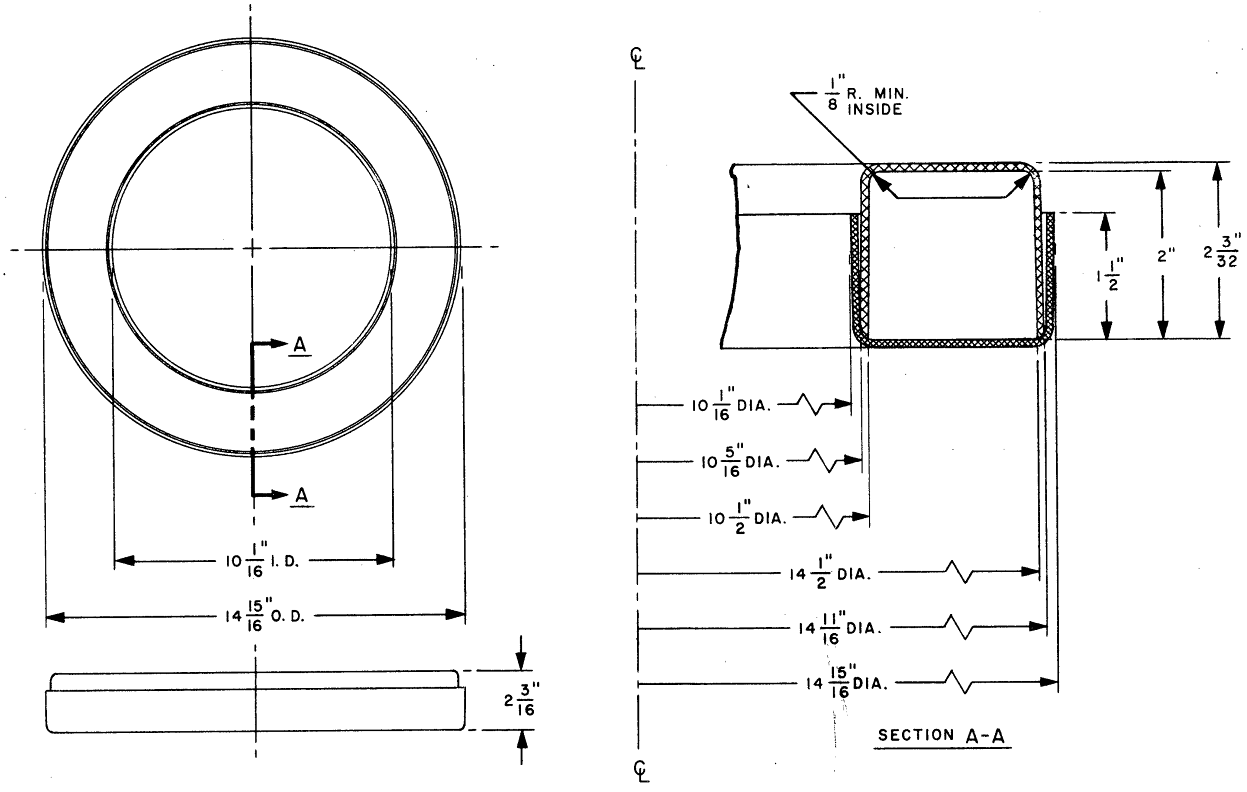

FIGURE 3.3.3.3 COIL CASE

3.3.3.4 Coil Winder

In order to determine whether the transponder coil could be wound using production techniques, a coil winder was designed and a wooden model was built and tested. The coil winder is discussed in detail in Interim Report No. 5. The design of the coil winder was found satisfactory for the production winding of the transponder coils and no further work was performed in perfecting the operating model.

3.3.4 Performance

Tests have been made to determine the performance of the cache marker system under actual field conditions, and to determine the effects of temperature, the effects of different soils and sea water on its operation. The methods of testing and the results are given in the sections which follow. A word of caution is necessary about extrapolating these results in predicting the operation of the transponder after it has been buried or submerged for five or more years. The transponder has been designed of materials which should make its life indefinite but additional testing is required in which the transponder is left buried for many months and periodically checked.

3.3.4.1 Field Tests of the System

The field tests which are described below were performed with an early model of the detector which used the motor-driven rotating capacitor for frequency modulating the oscillator. This was used as a means for solving the tracking problem in this early model. The final model of the detector does not use a frequency modulated oscillator. The horizontal ranges of detectability which are stated below are for this early model. The final model has been improved to give greater horizontal range not only for the discovery of the transponder but also for more positive indication of the transponder's presence.

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The field test consisted of burying three transponders, locating the positions of the transponders with the detector, and digging up the transponder at the indicated positions to determine how accurately their positions had been located. The horizontal ranges at which the transponders were detectable were measured. The frequency shifts of the resonant frequencies of the transponders were measured with the detector.

The transponders used for this test were resonant at 83, 98.5 and 106.3 KC in air. Their construction consisted of a plexiglass coil form wound with 60 turns of Litz wire made of 24 strands of No. 30 wire woven on a glass fiber core. The coil and its tuning capacitor were impregnated with a heavy coating of cerese wax and incased in fibre glass reinforced polyester resin shell.

The site was prepared by digging holes five feet deep with a trench digger. The transponders were placed in these holes and the holes were filled with dirt with the use of a bulldozer. Two of the transponders were buried five feet below the level of the ground and the third was buried at four feet below the ground. After the holes had been filled the bulldozer leveled off the ground so that the locations of the holes were not discernible. Markers which had been left to locate the positions of the transponders had been shifted by the bulldozer.

The representative of the sponsor who was present at the tests was briefly instructed on how the detector was used and then he proceeded to locate the first transponder. He encountered some difficulty at first for two reasons. The rotating capacitor operated intermittently and he mixed up the use of the amplitude control and the fine tuning control. He had much less difficulty in locating the other two transponders.

The transponders buried at a depth of five feet had a horizontal range of detectability of about four feet. The transponder buried at a depth of four feet had a horizontal range of detectability of five feet. Measurements were made to determine how close the transponder would have to be approached when walking rapidly along a straight path to obtain a positive indication of the presence of the transponder. This information was obtained with the detector tuned to the resonant frequency of the transponder in the ground without any further adjustment as the detector was carried along. This distance was found to be about two to two and one-half feet. This determines that where the detector is tuned to the proper frequency before the search is started, detection should be accomplished by walking parallel paths four to five feet apart.

The positions of the transponders as located with the detector were marked and the ditch digger dug holes at these positions. It was found that the positions had been located to within one or two inches of the centers of the transponders.

The ground consisted primarily of clay and was wet due to two preceding days of rain. The resonant frequency was lowered by the following amounts due to the increase in distributed capacity caused by having a greater dielectric constant for the surrounding medium. For the 83 KC transponder 0.28 KC, for the 98.5 KC transponder 0.30 KC, and for the 106.3 KC transponder 0.48 KC.

3.3.4.2 Temperature Tests of Transponder and Detector

Temperature tests on the transponders in the form of cycling from one extreme temperature to another were performed to determine the effects on frequency and detectability. Temperature tests on the detector

[redacted]

were used to determine the life of the batteries, i.e., whether they have sufficient capacity to operate the detector continuously for four hours at zero degrees Fahrenheit.

The temperature cycling test was performed on two encased transponders. The test consisted of cycling the transponders from -78°C in dry ice to +80°C in an oven. The detectability and frequency of the transponders were measured at the high and low temperatures for each cycle. No change in the range of detectability was observed during the temperature cycling process. The resonant frequencies of the transponders, which were measured before and after each of the two temperatures, are given in Table 3.3.4.2. The transponders were at each temperature for one hour before cycled. Frequency shifts occurred only for the second and third cycle, this being attributed to inaccuracies in the measuring system. One transponder remained in the dry ice for fifteen hours with no resulting change in range of detectability.

Table 3.3.4.2. Results of Temperature Cycling of Transponders

	Transponder	Frequency (kcs) at -78°C	Frequency (kcs) at +80°C
1	2	98.48	98.48
	3	82.48	82.48
2	2	98.45	98.43
	3	82.69	82.58
3	2	98.36	98.36
	3	82.65	82.58
4	2	98.48	98.48
	3	82.42	82.42
5	2	98.48	98.48
	3	82.48	82.48

The temperature tests of the detector consisted of putting the detector in a deep freeze and monitoring the output of the oscillator both for

[redacted]

amplitude and frequency. The temperature of the deep freeze was between -9 and -15°F, these being the two temperatures read on two different therometers. The amplitude was measured with a Dumont 'scope and the frequency was measured by comparison with the frequency of a Hewlett Packard signal generator. The detector was set on a frequency of 80 kcs and the generator operated on half this frequency since its maximum frequency is about 70 kcs. Before putting the detector in the deep freeze the amplitude and frequency were measured at room temperature, 70°F. as 50 and 80.1 kcs respectively. The amplitude was measured in arbitrary units on the scope and the settings of the controls for vertical gain were left untouched during the course of the experiment. Readings of the amplitude and frequency were taken immediately after the detector was placed in the deep freeze. After that readings were taken every fifteen minutes. The measurements are presented in Figure 3.3.4.2.

The output voltage of the oscillator was measured with a Ballantine voltmeter in order to compare it with the voltage output that is necessary to maintain proper operation of the detector. After correction for the loading effect of the voltmeter the voltage output of the oscillator proved to be ample for the operation of the detector.

After the four hours in the deep freeze, the detector was tested to determine if it would still detect the transponder. Moisture condensed on the detector and made the detector inoperative until the moisture evaporated. This condition of having the detector at a very low temperature and the placing it at room temperature is probably very unlikely. The more likely case is where the detector will be at room temperature and then placed under conditions where the temperature will be lowered. This condition should not result in the condensing of moisture on the detector.

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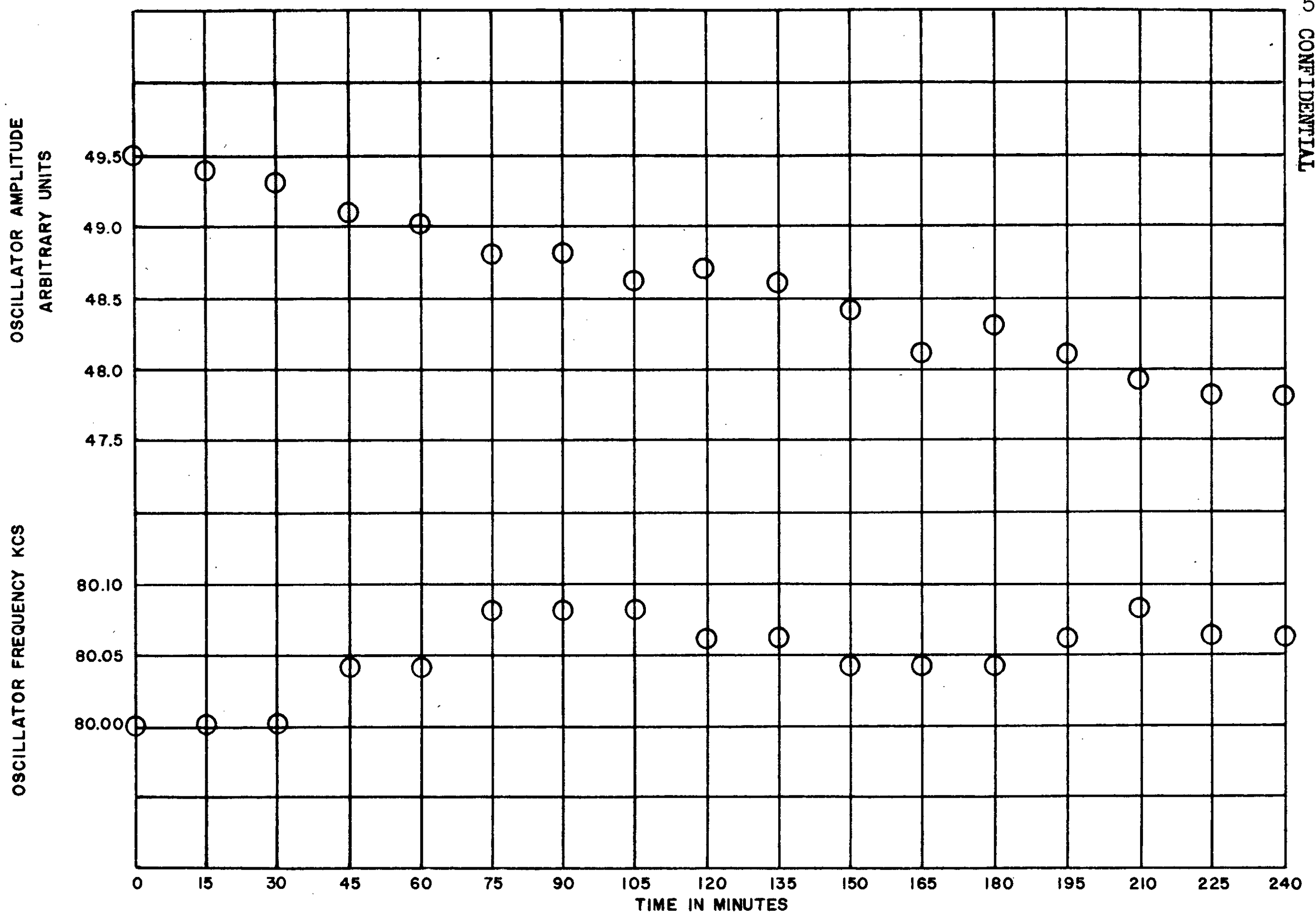

FIG. 3.3.4.2 TEMPERATURE CHARACTERISTICS OF DETECTOR AT −10° F

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3.3.4.3 Effects of Soils

The change in the ability to detect the transponder when buried, as compared to the ability to detect the transponder in air, depends on the electrical properties of the medium in which it is buried. The electrical properities of the medium change the electrical properties of the transponder, and they may also affect the attenuation of the signal through the medium. Experiments and calculations indicate that the reduction in signal due to these propagation losses can be neglected. However, the changes in the electrical properties of the transponder cannot be neglected since they cause a change in the resonant frequency of the transponder. They also may cause a change in the Q of the transponder; but, with the exception of salt water, this has not been observed in any of the media that we have tested. The changes in frequency are caused by the change in distributed capacity due to the dielectric constant of the surrounding medium in which the transponder is buried, and by the change in inductance caused by the magnetic susceptibility of the surrounding medium, being different than that of air.

Measurements were made to determine the frequency shifts of two transponders tuned to 98 and 82 kcs, for the following materials: pave, sand, fine gravel, coarse gravel and magnetite. Both pave and magnetite have magnetic susceptibilities which are considerably greater than that of air, this especially being true for the magnetite which was of a very pure form. These experiments were performed outside of the laboratory and the frequency measurements are based on the calibration of the detector. Magnetite gave frequency shifts which were greater than that which could be covered by the bands provided by the detector. A sample of magnetite was obtained and the measurements of the frequency shifts occurring for this material were made at

[redacted]

the laboratory. The results of measurements are given in Table 3.3.4.3.

Table 3.3.4.3
Transponder Frequency Shifts in Various Materials

Material	Frequency in Air in kcs	Frequency in the Soil in kcs	Frequency shift in cps
Pave	98.420	97.810	610
Pave	82.460	82.100	360
Sand	98.450	98.170	280
Sand	82.510	82.340	170
Fine Gravel	98.450	98.110	340
Fine Gravel	82.540	82.300	240
Coarse Gravel	98.450	98.300	150
Coarse Gravel	82.540	82.400	140
Magnetite	96.4	76.0	20,400
Magnetite	81.2	63.7	17,500

The frequency shifts measured 0.61 kcs or less with the exception of that obtained for pure magnetite. The detector has been designed to accomodate frequency shifts which are less than 1 kcs providing the resonant frequency in air is close to the upper end of the channel. The frequency shifts are always in the direction that decreases the resonant frequency of the transponder. In general the detector will not be capable of taking care of the frequency shifts that would result due to pure magnetite. No information is available as to the occurance of pure magnetite. However, if the procedure is followed in using the cache marker system outlined in Method of Operation this should not be a great hinderance to its use.

3.3.4.4 Seat Water Tests

Field tests of the cache marker system were carried out in the Atlantic Ocean to determine the effect of sea water on the operation of the system. The tests were carried out at Fort Miles, which is located at Cape Henlopen on the eastern shore of Delaware. The actual tests were made at the mine dock.

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The horizontal range of detectability was measured with the transponder submerged at various depths below the surface of the water. This range was determined for the detector coil held parallel to the surface of the water as well as perpendicular to the surface of the water. In each case the transponder washeld parallel to the surface of the water.

For the case where the detector coil was perpendicular to the surface of the water the edge of the detector coil was located about eight inches above the surface of the water. The maximum horizontal range was measured for the transponder just submerged and at various distances below the surface of the water.

Distance below Water's surface	Maximum horizontal range
at the surface	38 inches
1 foot	38 inches
2 feet	36 inches
3 feet	30 inches
3½ feet	24 inches

For the case where the detector coil was parallel to the surface of the water, the bottom of the detector coil was located about one and a half feet above the surface of the water. The maximum horizontal range was measured for the transponder submerged at the same depths below the surface of the water.

Distance below Water's surface	Maximum horizontal range
1 foot	42 inches
2 feet	40 inches
3 feet	36 inches
3½ feet	24 inches

The values that are given for the maximum horizontal range are measured from the center of the detector coil to the center of the transponder.

Better results were obtained with the detector coil parallel to the surface of the water than perpendicular.

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3.3.4.5 Analysis of Coupled Circuits

An examination of the equations which describe the mutual inductance between two parallel coils has resulted in the determination of an optimum size for the detector coil for a given transponder diameter and depth of burial. This study has also revealed the relation between range of detectability and stability in terms of the fractional change in amplitude that must be measured in order to detect the transponder for any distance. The details of this study are given in Appendix 4.3.

The conclusions of this study are that the size of the detector coil that is used for the Delta-Q system gives an efficiency of operation which is about five per cent of optimum. The fractional change in Q or amplitude that must be measured is about 1 part in 400 for 9 feet between the detector and transponder and 1 part in 40,000 for 20 feet between the detector and transponder.

3.3.4.6 Effect of Orientation of Detector Coil

The greatest mutual inductance and corresponding ability to detect the transponder occurs when the detector coil is oriented parallel to the earth's surface and the detector is closest to the transponder. However, this is not true when the detector is not directly over the transponder. It was discovered that orienting the detector coil perpendicular to the earth's surface increased the horizontal range at which the transponder could be detected. This increase in horizontal range is the result of changing the pattern of detectability from a circle to a figure resembling a lemniscate. The patterns of the range of detectability corresponding to different depths of burial are given in Appendix 4.2.

In addition to increasing the range of detectability of the detector this change in orientation of the detector coil with respect to ground also alters the manner in which the null appears in the audio tone of the detector as the transponder is approached. As the transponder is approached with the detector coil parallel to the ground a gradual change in the amplitude of the audio tone occurs. Out of range of the transponder a steady tone is heard and as the transponder is approached with the detector the amplitude gradually decreases until a null is obtained which is present until the detector is carried beyond the transponder and outside of range where the audio tone gradually comes back again. For the case where the detector coil is perpendicular to the earth's surface, the transition from audio tone to null as the detector is brought towards the position of the transponder is much more rapid and occurs at a greater range from the transponder.

Using the detector with the detector coil oriented perpendicular instead of parallel to the ground offers two advantages. The horizontal range at which the transponder can be discovered is increased and a positive indication of the transponder is obtained at greater distances.

3.3.5 Operating Instructions

1. To place the detector in the operating condition:
   a. Open the carrying case and lower the detecter coil to the vertical position.
   b. Pull out the operating handle which is located on the top of the metal box.
   c. Hold the detector by the operating handle in such a way that the carrying case opens away from the operator.
   d. Rotate the band switch to the proper band and set the main turning control to the proper setting. These settings will be known before starting the search.

e. Turn on the detector by pushing the two toggle switches which are located near the handle.

f. Plug in the phones.

2. Make the following initial adjustments:

a. Hold the detector about 8 inches from the operator's body and the same distance above the ground.

b. Rotate the amplitude control to approximately half way between its maximum and minimum settings.

c. Rotate the fine tuning control until an audio tone is heard. The presence of the audio tone is an indication that the detector is operating properly. If not heard, increase the setting of the amplitude control slightly and re-adjust the fine tuning control.

d. Now adjust the fine tuning control to a position so that the main tuning control can be rocked through about five divisions on either side of its prescribed setting without the audio tone dropping out.

e. Now back off the amplitude control until the audio tone can just be heard. This is the condition for maximum sensitivity. Make sure the main tuning control can still be rocked without the audio tone dropping out.

3. Make the search:

a. Listen for a null in the audio signal. This is an indication of the presence of the transponder. A null can also occur if the detector becomes mis-tuned due to bringing it too close to the ground or to the operator. A true indication is determined by rocking the main tuning control through the known transponder

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setting and verifying that the null occurs only when this control is on the proper setting.

b. During the search carry the detector so that it forms about a 30 degree angle with the direction in which the operator is walking.

c. Cover the area in which the transponder is believed to be located by marching along paths not over 12 feet apart. Decrease this distance by about two feet for each foot the detector is raised above the ground due to deep snow or other causes.

4. Determine the exact location of the transponder:

a. Place the detector coil in the horizontal position.

b. Repeat the initial adjustments, paragraph 2 above.

c. Approach the position of the transponder and while doing so reduce the sensitivity of the detector by turning up the amplitude control. This will reduce the area in which a null can be heard and thus more accurately locate the transponder.

5. To place the detector in the carrying condition:

a. Push in the operating handle. This will push the toggle switches to the off position.

b. Unplug the phones and place in carrying case.

c. Close the carrying case.

6. To place a transponder with a cache:

a. Cover the cache with not less than one foot of earth.

b. Place transponder in the hole so that it is parallel to the surface of the ground (or water).

c. Cover transponder with at least one foot of earth.

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d. Bring the detector near the transponder and find the exact setting of the band switch and main tuning control for the null. Record this setting for future use.

e. Finish filling the hole.

The frequency of each transponder will be marked on it. This frequency will change when it is buried. The change will always lower the frequency from 0.2 to 0.5 kilocycles depending upon conditions. Thus a future search can be expedited if the frequency is carefully measured when the cache is made. A calibration curve is furnished with each detector by means of which it is possible to set it to any frequency within its range.

If it were not possible to measure the frequency of the transponder after burial with the cache, it is still possible to locate it provided its original frequency in air was known:

a. At the suspected location of the transponder bury another transponder of about the same frequency to a depth of at least one foot. Measure the amount that the frequency has changed. Use this as a correction to the frequency of the transponder whose location is yet to be determined.

b. If the above is not feasible then it will be difficult to find the transponder. This difficulty is one of the security features of this system. The best course to follow is to lay out the area in 10 foot squares and at the center of each square stop and tune around the center frequency obtained from the table below:

If Transponder Frequency in air is:	Tune Detector to:
80 to 85 kcs	0.2 kcs lower
85 - 90 kcs	0.3 kcs lower
90 - 95 kcs	0.4 kcs lower
95 - 100 kcs	0.5 kcs lower

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3.3.6 Maintenance

3.3.6.1 Trouble Shooting

If equipment fails to operate:

1. Check terminal voltages of batteries with equipment turned on.
2. Check oscillator output.
3. Check receiver input.
4. Check audio amplifiers.
5. Check output transformer and phones.

1. To check terminal voltages, remove the battery cover and turn equipment on. (The large coil does not need to be in the operating position to check the voltages.) Measure the voltages at the battery terminals with a voltmeter and replace weak batteries as follows: plate batteries, 100 V., filament batteries 1.0 V. New batteries should be inserted and then tested also before replacing battery cover. New battery voltage should change very little between equipment off and on conditions.

2. To check oscillator output, remove lead from J2 and connect a scope from J2 to the chassis. Waveform (a), Figure 3.3.6.1, should be seen, after adjusting the scope, for proper operation. Amplitude of the signal should be approximately 0.45 V peak to peak. If no signal is observed check the oscillator tube V20 and its circuits if necessary. Resistance from grid to ground should be about 70 ohms and cathode to ground about 25ohms. (Chassis is ground). If waveform (b) is observed, check the neon tube V21 and its circuits.

3. To check receiver input the equipment must be in its

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Waveform (a) Waveform (b) Waveform (c)

Waveform (d) Waveform (e)

Figure 3.3.6.1

[redacted]

operating position with both coil leads connected. The coil must be away from all metal objects or persons. Remove the trimmer cover and connect the scope between T.P. and chassis. (Since there is a positive voltage of about 70 volts on T.P., it is necessary to use a capacitor input to scope). Adjust the scope sweep for several cycles and then the amplitude and fine tuning to get waveform (c). The fine tuning should be very sharp and the amplitude control should vary the amplitude of the spike. If no signal at all can be found check the coil L1 and the tuning section. Try several bands to be sure it is out on all bands. Resistance of L1 should be about 5.5 ohms. If no spike can be found with the adjustment of the controls check tube V1 and check to see if it has the proper operating voltages. If still no spike can be found, follow the alignment procedure.

4. Audio should be heard in the phones as the spike amplitude passes a minimum amplitude, as shown in wavefore (d). If no audio is heard check tubes V1, V2, and V3, and then if necessary the receiver can be signal-traced with an audio oscillator through V2, V3, and V4. (Be careful to use a capacitor in the audio lead in order to keep from destroying the operating bias voltages. Bias for V4 is developed across R5 and C8 and should be about 17 volts. V2 and V3 have their grids returned to the cathode so they have no bias.) V4 is held below cutoff by the cathode bias and will not conduct until the positive peaks exceed the bias. Waveform on plate of V4 should look like waveform (e).

5. If amplifiers work well then check the output transformer and phones if you still have no audio out.

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3.3.6.2 Battery and Tube Replacement

The batteries and tubes of the detector are made accessible by removing the aluminum cover which is next to the plastic lid of the carrying case. When replacing the filament batteries, the polarity marked on the clips which hold the batteries should be observed and the batteries put in accordingly. Make certain that the ends of the clips press firmly against the batteries. The B batteries will only go in one way. Care should be taken to make sure that the smaps are closed tight.

To replace the tubes of the receiver circuit, the B batteries must be removed. The tube for the oscillator circuit is readily replaceable. The neon tube is soldered into the circuit but it should seldom need replacement.

3.3.6.3 Alignment Procedure

An oscilloscope, frequency meter (or signal generator) and insulated tuning wand are required.

1) General procedure

Remove the trimmer cover and set up the detector in operating position, making sure the detector coil is well clear of metallic objects. Set the fine tuning control to its mid-point and leave it there during the entire alignment. At all times when using the Test Point maintain the amplitude control at a setting which will keep the spike slightly higher than the peak of the sine wave, as shown in Figure 3.3.6.1 (d), or keep the audio level in the phones at a comfortable operating level. Use fresh batteries and keep them off except while actually performing the alignment.

2) Procedure for adjusting the oscillator inductance

a. Set the band switch on step No. 1. This is the lowest frequency band.

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b. Carefully set Band #1 trimmers and padders to half capacity for both the oscillator and receiver.

c. Set the main tuning control to 0 (lowest frequency).

d. Connect oscilloscope to Test Point and turn on the equipment.

e. With an insulated tool tune the slug in the oscillator transformer, while maintaining the amplitude adjustment described in paragraph 1., until the pattern of Figure 3.3.6.1 (d) is obtained. When this is properly done, any movement of the tuning slug in either direction should cause the spike to disappear.

f. The inductance of the oscillator coil is now the same as that of the receiver coil.

3) <u>Procedure for setting the oscillator to proper frequency coverage.</u>

a. Set the band switch to Band #1.

b. Remove the coil lead from the oscillator output terminal J2 by pulling out the banana plug. Plug the oscilloscope test lead into its place.

c. If a frequency standard is available with a zero beat output circuit, connect it across the test lead and the chassis (this is across the oscillator output) and tune for a zero beat.

Note: The audio modulation will also be heard.

If the frequency standard (or calibrated signal generator) has sufficient output to drive the horizontal input of the oscilloscope connect it to the horizontal input and connect the vertical between the test lead and chassis. This will give a lissajous pattern. This procedure is preferred because the audio signal

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will not obscure the results.

d. Now set the main tuning control to 95 and the signal generator to 82 kcs.

e. Tune the oscillator trimmer for a zero beat.

f. Set the main tuning control to 5 and the signal generator to 80 kcs.

g. Tune the oscillator padder for zero beat.

h. Repeat d, e, and f until no further adjustment is necessary.

i. Repeat the above procedure on each of the bands, working from #1 up to #10. Set high ends on 95 and low ends on 5 on the main tuning control. This will allow some overlap. Band #2 will cover 82-84 kcs, Band #3 will cover 84-86 kcs, etc. (Some bands may cover slightly more or less than 2 kcs but there should be no breaks in the coverage.)

j. Repeat the entire procedure to be certain that distributed capacity effects have not been reflected into bands previously adjusted.

4) <u>Procedure for setting receiver trimmers and padders</u>

This should not be done until the oscillator adjustment has been completed.

a. Replace coil lead in oscillator output. Remove and TURN OFF the signal generator. Connect oscilloscope to Test Point and adjust the sweep to get Figure 3.3.6.1 (d).

b. Set band switch to Band #1. Set main tuning control to 95.

c. Adjust receiver trimmer on Band #1 for maximum peak amplitude of the spike, turning down the amplitude as may be necessary (paragraph1)

d. Set main tuning control to 5.

e. Adjust receiver padder on Band #1 for maximum peak amplitude of the spike as in c.

f. Repeat c, d, and e until no further adjustment is necessary.

g. Repeat above procedure for all bands and then repeat entire procedure until no further adjustment is necessary.

3.3.7 Construction Details

Drawings of those components for the detector which are either modified standard parts, or of ERA design, are in Appendix 4.4. Since a model is being supplied no drawings of the detector case or of its assembly have been made. A parts list for the detector is furnished.

[redacted]

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Appendix 4.1 The Attenuation of Electromagnetic Waves upon Penetration into the Earth

The attenuation of the electromagnetic wave upon entering the earth is given (in Terman's Radio Engineer's Handbook, First Edition, McGaw-Hill Book Company, New York (1943) p. 698) in terms of

$$\frac{\text{Current density at depth d}}{\text{Current density at surface}} = \epsilon^{-pd}$$

where

$$p = \left[\frac{XB}{2}\left(\sqrt{1 + \frac{(\sigma \times 10^9)^2}{B^2}} - 1\right)\right]^{\frac{1}{2}}$$

d = depth (cm.)

$X = 0.008\,\pi^2 f_{mc}$

$B = 0.556 \times 10^{-6} f_{mc}$

k = dielectric constant of earth

f_{mc} = frequency, mc

σ = earth conductivity, emu

Type of Terrain	Dielectric Constant	Conductivity (emu)
Fresh water	80	1×10^{-14}
Sea water	81	4.64×10^{-11}
Sandy, dry, flat: typical of coastal country	10	2×10^{-14}
Soil (limits)	20 to 5	3×10^{-13} to 10^{-14}

For $f_{mc} = 0.1$ $\quad X = 8 \times 10^{-4}\pi^2 = 7.89 \times 10^{-3}$

$B = 5.56 \times 10^{-8}\,k$

For sea water $k = 81$, $\sigma = 4.64 \times 10^{-11}$. Calculating p we get 1.35×10^{-2} and $\frac{1}{p} = 74$ cm. This is the depth the fields will penetrate before they drop off to $1/\epsilon$.

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For fresh water $k = 80$ $\sigma = 10^{-14}$

$p = 2.55 \times 10^{-4}$ $\frac{1}{p} = 3.92 \times 10^{3}$ cm or 39.2 meters.

For soil $k = 20$ $o = 10^{-13}$

$p = 6.28 \times 10^{-4}$ $\frac{1}{p}$ 1.59×10^{3}cm or 15.9 meters.

We find that only in the case of sea water should we expect a large departure from the results of our experiments of magnetic coupling in air.

[redacted]

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Appendix 4.2 Range of Detectability Patterns for the Vertical Detector Coil-

Experiments were performed to determine the horizontal ranges at which the transponder could be discovered with the detector coil oriented in an approximately vertical position with respect to the plane of the transponder. These measurements were made for geometries corresponding to depths of burial of three, four, five, six and seven feet.

An outline of the experimental set up is shown in Figure 4.2 (a). The detector was maintained in a fixed position and the transponder was moved. Measurements for each depth of burial were obtained with the transponder's motion confined to the corresponding plane. The plane of the transponder was always maintained parallel to its plane of motion. The output of the detector was monitored and the region of the null in the audio output for each plane was plotted. It will be noted that this geometry corresponds identically to having the transponder buried at a depth equal to the distance of a given plane from the bottom of the detector. The transponder will be discovered whenever it falls into a null region, there being a different pattern for the null region for each depth of burial.

The results of these measurements, the plots of the null regions (or the plots of the regions of detectability) are shown in Figure 4.2 (b). They are presented as they would be viewed when sighting along a line perpendicular to their planes which contain the motion of the transponder for each depth of burial, with the detector between the viewer and these planes.

These patterns can be visualized as attached to the detector and are carried along with it. When the transponder falls into this pattern, a null is produced and the operation becomes aware of the presence of the transponder. If the detector is oriented so that the plane of the detector and detector coil contain the direction in which the operation is walking there will be a strip along the path of the operater which forms a region of no

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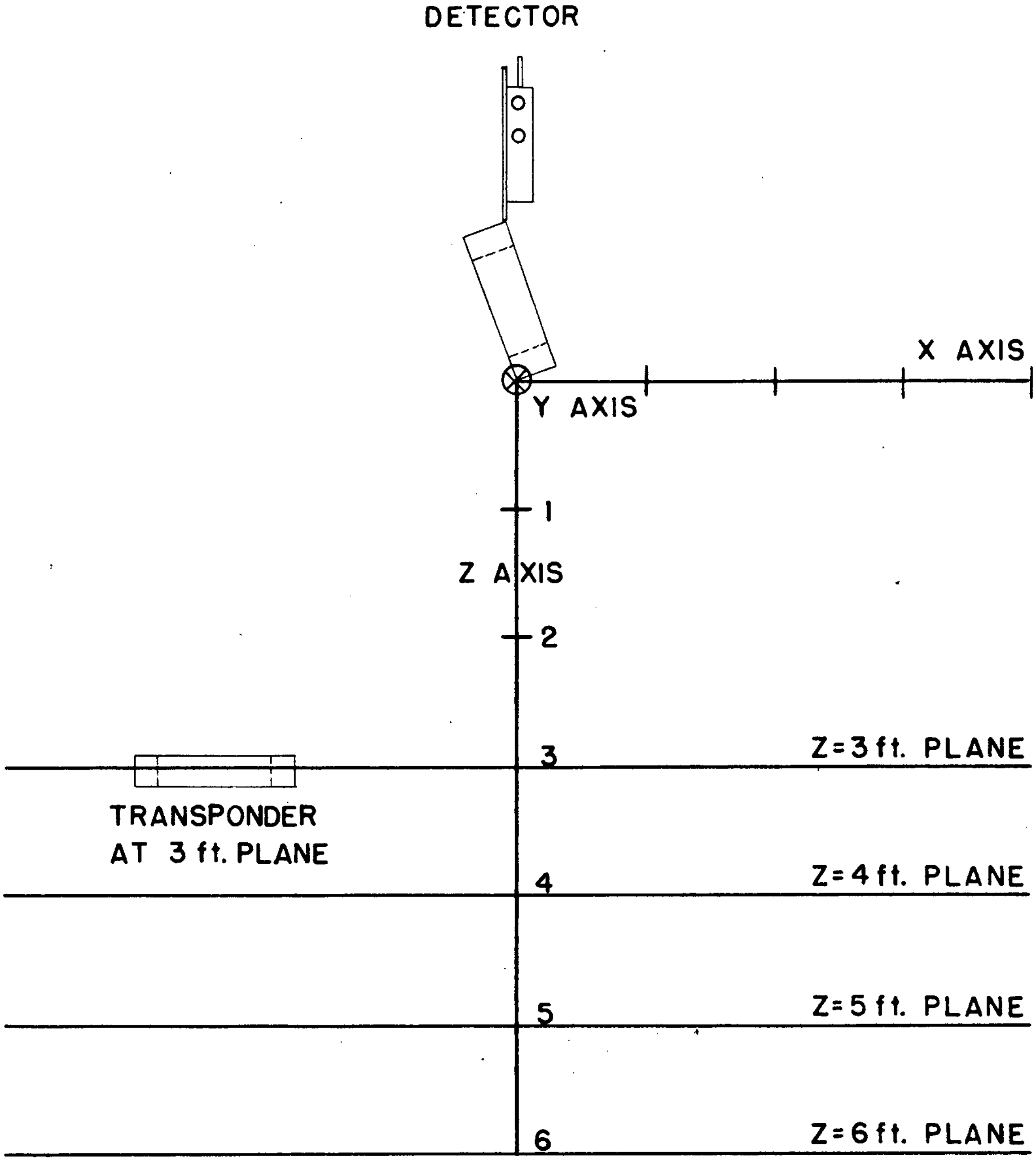

FIGURE 4.2(a)
GEOMETRY FOR MEASURING
RANGE OF DETECTABILITY PATTERNS

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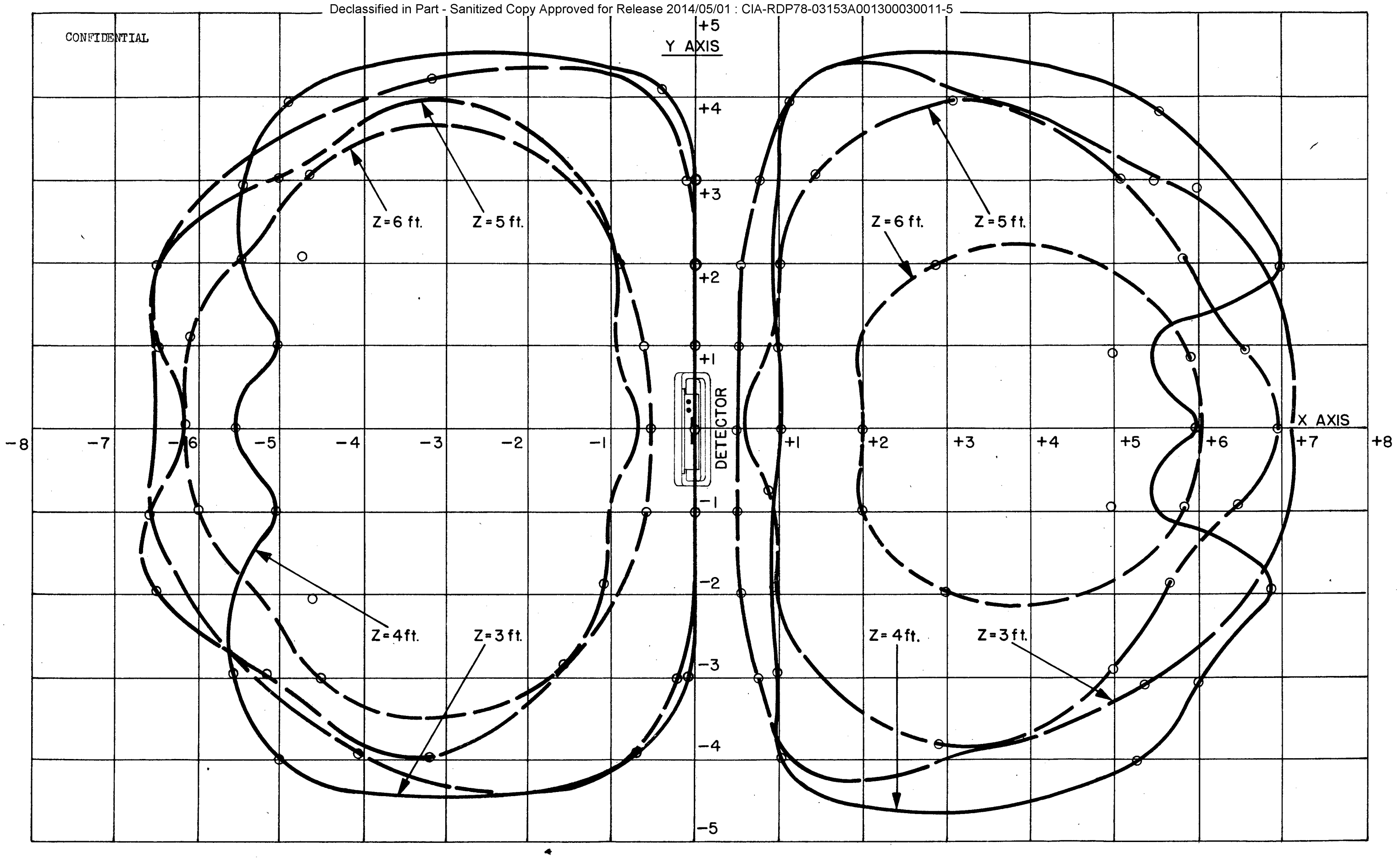

FIGURE 4,2(b) RANGE OF DETECTABILITY PATTERNS FOR THE VERTICAL DETECTOR COIL

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detectability. This blind region can be eliminated by the simple expedient of holding the detector so that its plane forms about a 30° angle with the direction in which the operator is walking.

[redacted]

Appendix 4.3 - Some Basic Theory of Coupled Circuits

An examination of the equations which describe the mutual inductance between two parallel coils has resulted in the determination of an optimum size for the detector coil for a given transponder diameter and depth of burial. This study has also made available the relation between range of detectability and stability in terms of the fractional change in amplitude that must be measured in order to detect the transponder for any distance.

The change in Q caused by a tuned circuit was measured with the Boonton Q meter for a number of distances between the coil connected to the Q meter and the tuned circuit. These measurements were made with the Q meter and the tuned circuit tuned to the same frequency. The results of these measurements are shown in Fig. 4.3(a). In order to determine how the change in Q behaves as a function of distance, these data were plotted on loglog paper. If it is assumed that the change in Q is proportional to 1/c raised to some power, where c is the distance between the coils, then the slope of the curve obtained by plotting the data on loglog graph paper is the value of this power. Fig. 4.3(b) shows the data replotted on loglog graph paper where it can be seen that the slope is not a constant for small values of c. For values of c larger than 4.5 feet the slope remains constant and corresponds to the sixth power. This is the value which is expected from previous consideration of how the mutual inductance varies with distance. The curve has been extrapolated so that values for the change in Q at large values of c could be obtained.

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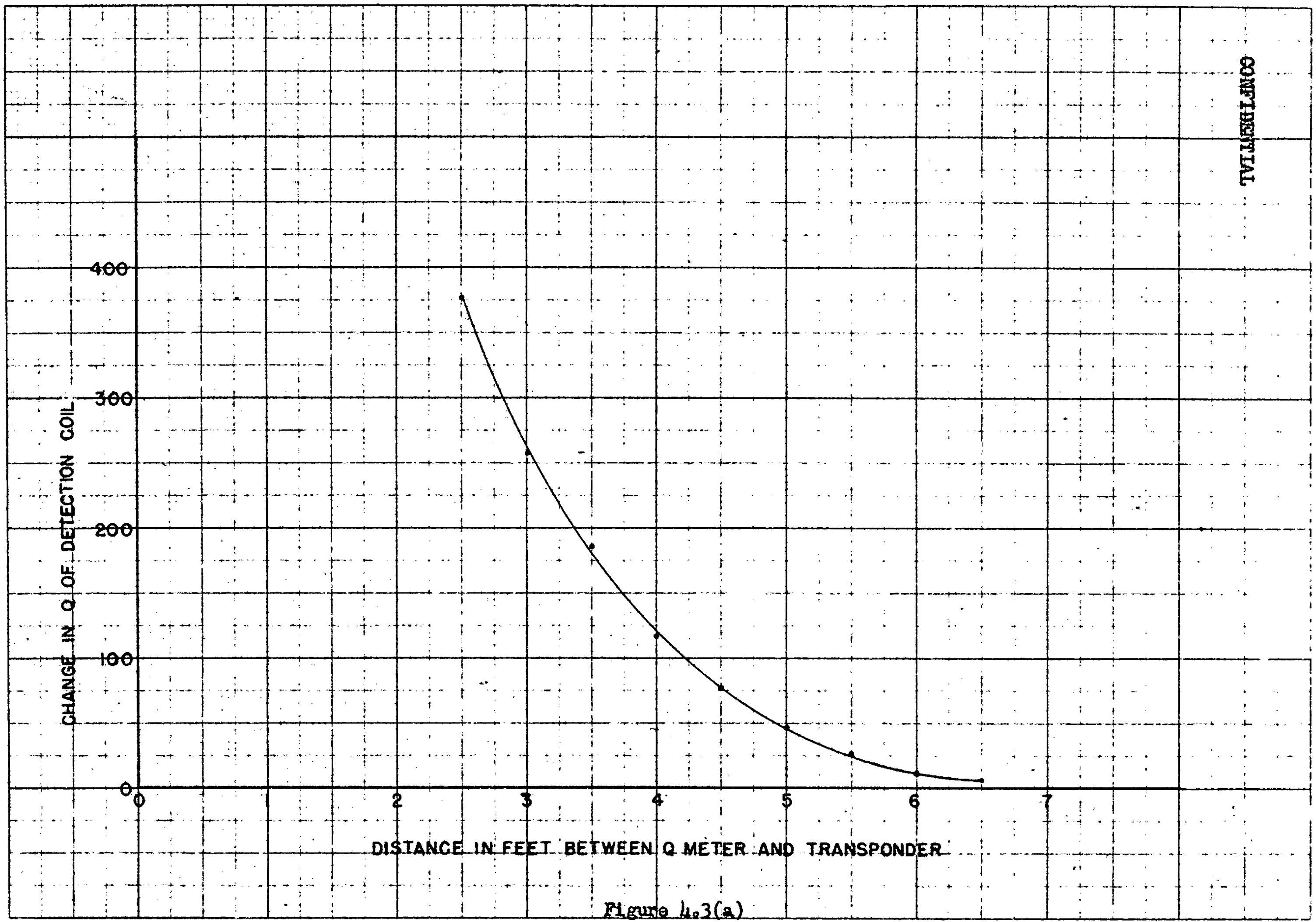

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Figure 4.3(a)

Linear Plot of Change of Q as a Function of Distance Between Transponder and Detector Coil

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MADE IN U.S.A.

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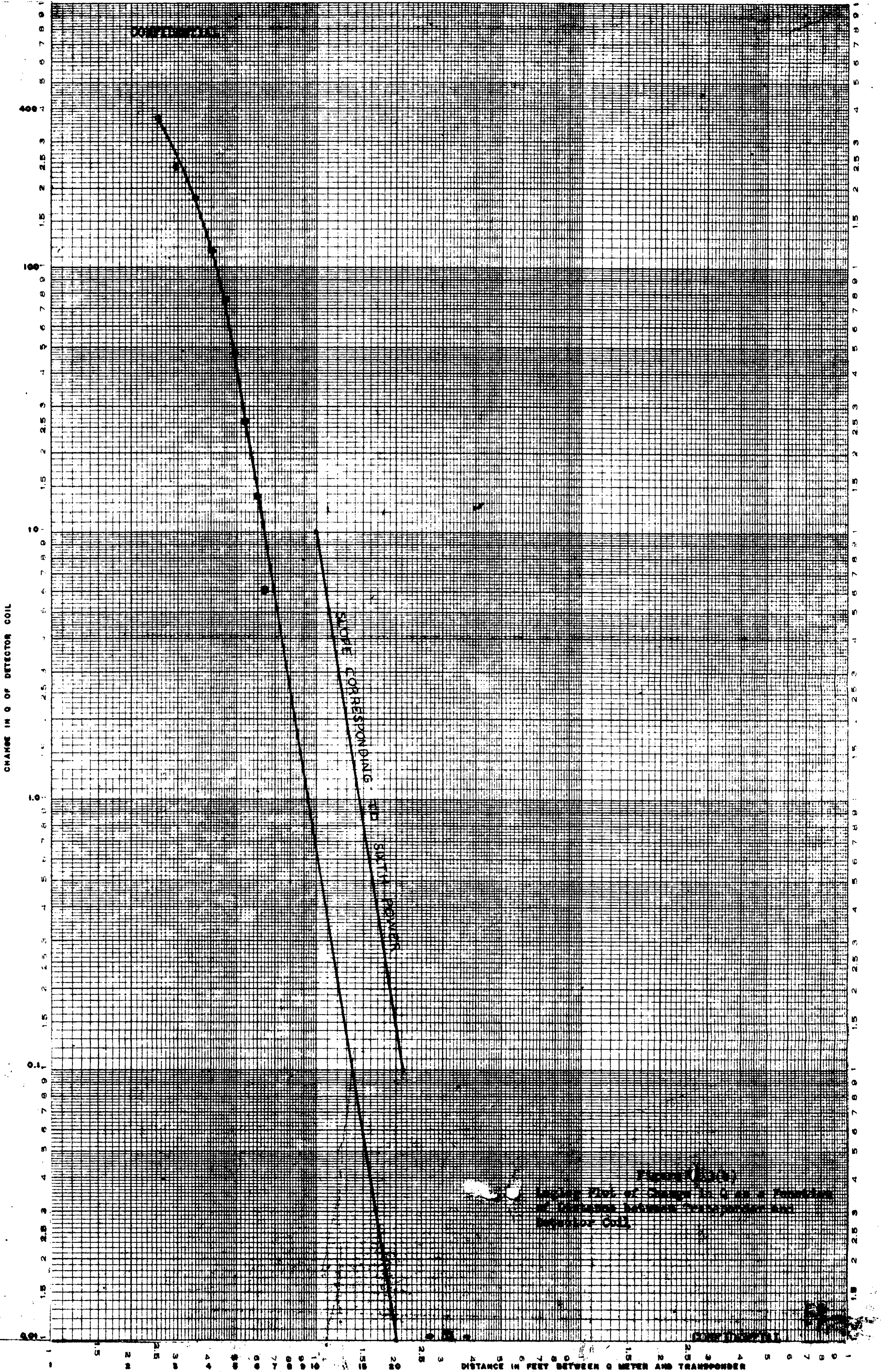

Figure [illegible]
Log-Log Plot of Change in Q as a Function of Distance between Transponder and Detector Coil.

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The equation describing the mutual inductance without any approximations is:

$$L_{ab} = \frac{1}{2} \mu_o \, ab \int_o^{2\pi} \cos \theta \, (c^2 + a^2 + b^2 - 2ab \cos \theta)^{-\frac{1}{2}} \, d\theta \quad *$$

where L_{ab} is the mutual inductance between two coils whose radii are a and b

μ_o is the permeability of the surrounding medium

c is the distance between centers of the two coils

and θ is the best defined by Figure 4.3(c).

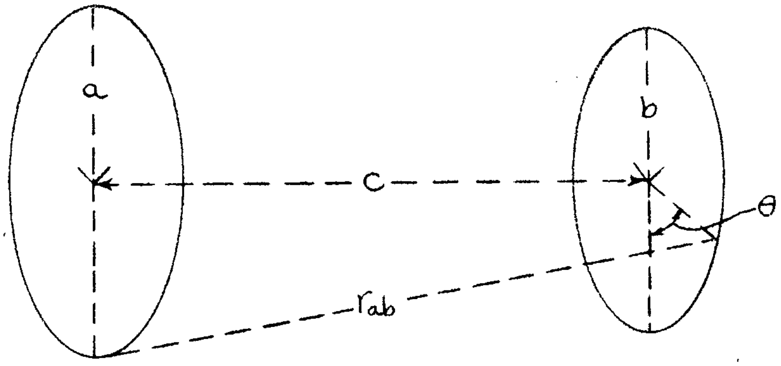

Fig. 4.3(c) Geometry of Coils Used in Calculation of Mutual Inductance.

L_{ab} is an elliptic integral and can be written as:

$$L_{ab} = \mu_o \, (ab)^{\frac{1}{2}} \left[\left(\frac{2}{k} - k\right) K - \frac{2}{k} E \right]$$

where $k^2 = 4ab \left[(a + b)^2 + c^2 \right]^{-1}$ and K and E are the elliptic integrals

$$K = \int_o^{\pi/2} \frac{d\phi}{(1 - k^2 \sin^2 \phi)^{\frac{1}{2}}} \quad \text{and} \quad E = \int_o^{\pi/2} (1 - k^2 \sin^2 \phi) \, d\phi$$

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*G. P. Harnwell, Principles of Electricity and Electromagnetism, McGraw-Hill Book Company, Inc., 1938, p. 304.

which have been evaluated for different values of k in the literature.* For $c > a$ and b

$$L_{ab} \approx \frac{\mu_0 \pi}{16} (ab)^{\frac{1}{2}} k^3 \qquad \text{and}$$

$$k^2 \approx \frac{4ab}{c^2}$$

Then $$L_{ab} \approx \frac{\mu_0 \pi}{16} (ab)^{\frac{1}{2}} \left(\frac{4ab}{c^2}\right)^{3/2}$$

or $$L_{ab} \approx \frac{\mu_0 \pi}{2} \frac{(ab)^2}{c^3}$$

The change in Q due to the tuned circuit is proportional to the mutual inductance squared, $(L_{ab})^2$, and for the conditions $c \gg a$ and b varies as $(1/c)^6$.

The value of $L_{ab}/\sqrt{ab}$ is completely defined by the value of k. Keeping this in mind, consider a graph where $X = \frac{a}{b}$ and $Y = \frac{c}{b}$ and constant k lines are plotted. To see what this gives, we write:

$$\frac{1}{k^2} = \frac{(a + b)^2 + c^2}{4ab} = \frac{a}{4b} + \frac{b}{4a} + \frac{1}{2} + \frac{c^2}{4ab}$$

or $$4\left(\frac{1}{k^2} - \frac{1}{2}\right) = \frac{a}{b} + \frac{b}{a} + \frac{c^2}{ab}$$

In terms of X and Y

$$4\left(\frac{1}{k^2} - \frac{1}{2}\right) = X + \frac{1}{X} + \frac{Y^2}{X}$$

which can be rewritten as

$$\left[X - 2\left(\frac{1}{k^2} - \frac{1}{2}\right)\right]^2 + Y^2 = \frac{4}{k^2}\left(\frac{1}{k^2} - 1\right)$$

which is the equation of a circle of radius $\frac{2}{k}\left(\frac{1}{k^2} - 1\right)^{\frac{1}{2}}$ whose center is on the X axis located at $2\left(\frac{2}{k^2} - \frac{1}{2}\right)$.

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*Charles D. Hodgman, M.S., Handbook of Chemistry and Physics, Chemical Rubber Publishing Company, 34th Edition, 1952-1953, pp. 234-236.

These circles connect points of equal value, $L/\sqrt{ab}$.

Now $$\frac{L}{\sqrt{ab}}\sqrt{\frac{a}{b}} = \frac{L}{b}$$

so that if we multiply $\frac{L}{\sqrt{ab}}$ by $\sqrt{X}$, $\frac{L}{b}$ can be evaluated along each of the circles.

The curves for constant $L/\sqrt{ab}$ and $\frac{L}{b}$ are shown in Figure 4.3(d).

Now consider a line of constant value of Y, tangent to one of the constant $\frac{L}{b}$ curves. This point of tangency gives the value of X for the given value of Y for which L/b is a maximum. In terms of a, b, c this point specifies the values for $\frac{c}{b}$ and $\frac{a}{b}$ for which $\frac{L}{b}$ is a maximum.

Thus, for a transponder of radius b buried at a depth c below the surface of the ground, a detector coil of radius a will give the largest indication of the presence of the transponder.

A curve connecting these points of tangency gives the optimum radius of the detector coil for any given size transponder buried at any depth. If this curve is labeled as 100% to indicate the percentage of signal from the transponder, then curves indicating lesser percentages of maximum signal can be obtained. The curves for 80% and 50% are indicated in Figure 14. They show that the increase in signal is not proportional to the increase in area of the detector coil.

Unfortunately, the region in which we are normally interested is where X is in the neighborhood of one or two, and Y has values of two to five. In this region the curves for constant k and constant L/b converge and additional work would be required to expand this region. In this region the

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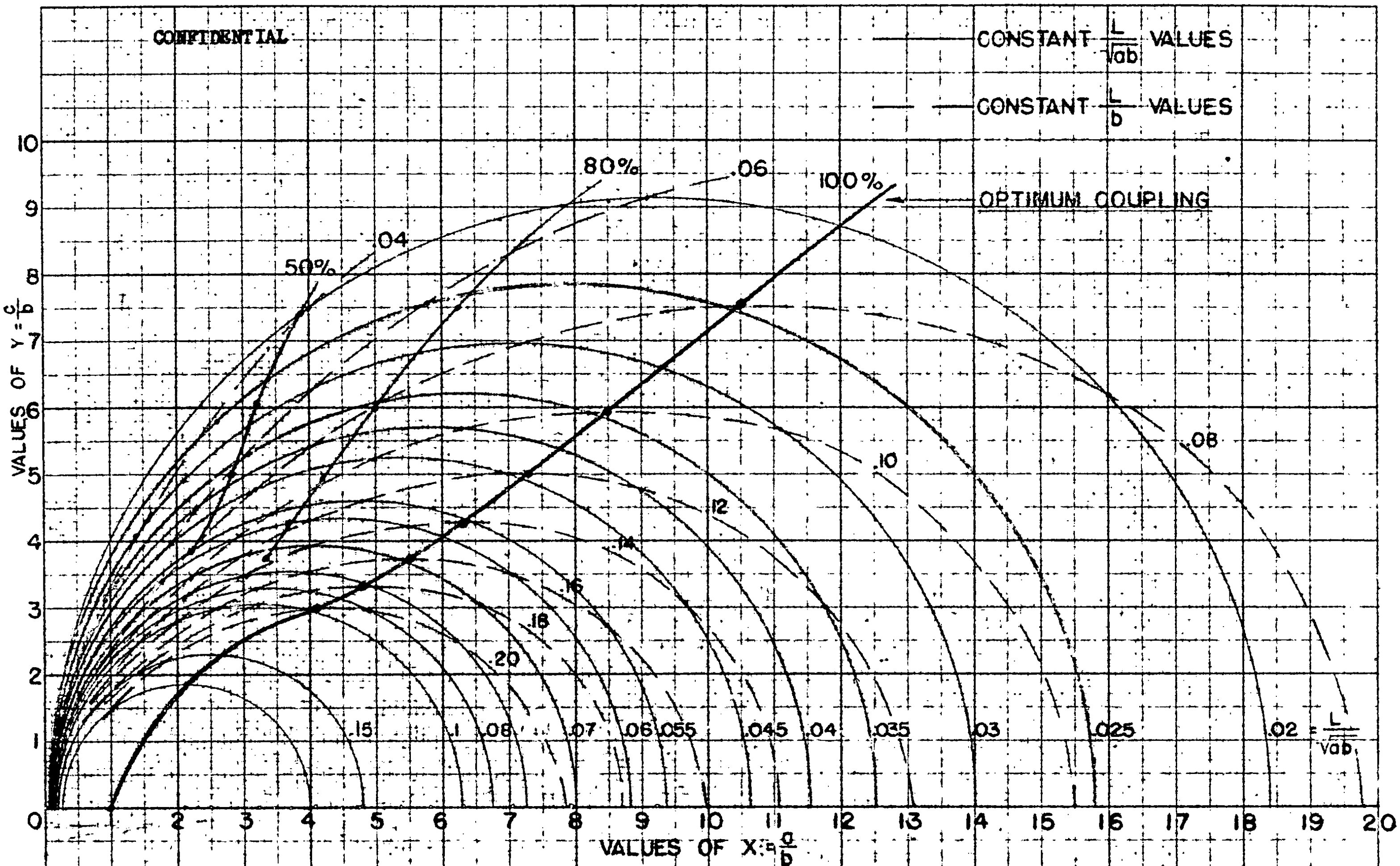

FIG. 4.3(d) FAMILY OF CONSTANT k CURVES SHOWING CURVES OF CONSTANT $\frac{L}{b}$ AND CURVE FOR OPTIMUM COUPLING

percentage of optimum coupling is estimated to be only about five per cent. Improvement in the coupling of the detector can only be accomplished by increasing the size of the detector coil or size of the transponder.

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Appendix 4.4 Construction Details, Delta - Q System

PARTS LIST

Part Number	Description	Manufacturer
R1, R2, R3, R23	Resistor, 10,000 ohm ½ watt composition, ± 10% tolerance	International Resistance Company
R4, R8, R10, R11, R12, R14, R15	Resistor, 220,000 ohm ½ watt composition, ± 10% tolerance	International Resistance Company
R19	Resistor, 100,000 ohm ½ watt composition, ± 10% tolerance	International Resistance Company
R5	Resistor, 15,000 ohm ½ watt composition, ± 10% tolerance	International Resistance Company
R6, R18, R20	Resistor, 150,000 ohm ½ watt composition, ± 10% tolerance	International Resistance Company
R7	Potentiometer, 25,000 ohm 2 watt molded composition, ± 10% tolerance Type AB	Ohmite Resistor Corp.
R9, R13, R16	Resistor, 470,000 ohm ½ watt composition, ± 10% tolerance	International Resistance Company
R17	Resistor, .4 ohm ½ watt composition, ± 5% tolerance	International Resistance Company
R21	Resistor, 47,000 ohm ½ watt composition, ± 10% tolerance	International Resistance Company
R22	Resistor, 2.0 megohm ½ watt composition, ± 10% tolerance	International Resistance Company
J1	Jack, audio output, Type A-1	P.R. Mallory & Co.
J2, J3	Jack, banana, hexed brass nickel plated, with recessed head	Herman H. Smith Inc.
P2	Plug, banana, hexed brass nickel plated, molded plastic handle, red	Herman H. Smith Inc.
P3	Plug, banana, hexed brass nickel plated, molded plastic handle, black	Herman H. Smith Inc.

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Part Number	Description	Manufacturer
B1, B2, B3, B20	Battery, 1½ volt, 2R Radio "A" battery	Burgess Battery Co.
B5, B6	Battery, 67½ volt, XX45 "B" battery	Burgess Battery Co.
C1, C2, C4, C23, C24, C25	Capacitor, .1 mfd, 300 vdc metalized paper	Tobe Deutschmann Corp.
C6, C7, C9, C10, C11, C12	Capacitor, .02 mvd, 500 vdc disc ceramic	Aerovox Corporation
C3, C5, C21, C22	Capacitor, .002 mvd, 500 vdc disc ceramic	Aerovox Corporation
C8	Capacitor, 25 mvd, 25 vdc dry electrolytic	Sprague Products Co.
C13	Capacitor, variable air, 2 section ganged	Variable Condenser Corporation
C14	Capacitor, variable air, single section	James Millen Manufacturing Company
C121 to C140	Capacitor, ceramicon trimmer, 7 to 45 mmfd, Type TS2A-7	Erie Resistor Corp.
C20	Capacitor, 150 mmfd, silver mica, ± 5% tolerance, 500 vdc	Sprague Products Co.
C221 to C240	Capacitor, ceramicon trimmer, 7 to 45 mmfd, Type TS2A-7	Erie Resistor Corp.

Capacitors not included in this list: C16, C17, C101 - C120, C26, C27, C201 - C220

L1	Coil, detection, 100 turns, #50-38, single nylon Litz wire in 3 layers on plexiglas form, with Faraday shield	ERA
L20	Choke, 150 mh, unshielded iron core, 100 ma, DC res., 268 ohm, Type B G535	Merit
T20	Transformer, oscillator, primary constructed with 3 coil sections from 10 mh RF choke (National R100-S) mounted on CTC LS-6 form, secondary consists of 7½ turns of #22 single strand tinned wire wound on composition bakelite coil from 3/4"D x 7/8"	ERA

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Part Number	Description	Manufacturer
T1	Transformer, impedance matching, 100,000 ohm to 60 ohm, primary resistance 4700 ohm, secondary resistance 3.3 ohm, Type SSO-6	United Transformer Company
S1, S2	Switch, toggle, DPST, 3 amp, 125 vac, Type 216	Carling Electric Inc.
S3	Switch, grayhill, Series 24, rotary, six deck, ten position multideck miniature tap switch	Grayhill
X20, X1, X2, X3, X4	Socket, 7 pin miniature mice filled bakelite with tube shield base	Cinch-Jones
V20	Tube, 3V4	CBS-Hytron
V1, V2, V3, V4	Tube, 1U4	CBS-Hytron
V21	Tube, NE-2, neon	General Electric
E7, E8, E9, E10, E11	Shield, tube for miniature 7 pin tube	Cinch-Jones
SP1	Headphones, telex monoset, stethoscope design, 500 ohm impedance	Telex Electro-Acoustic Division

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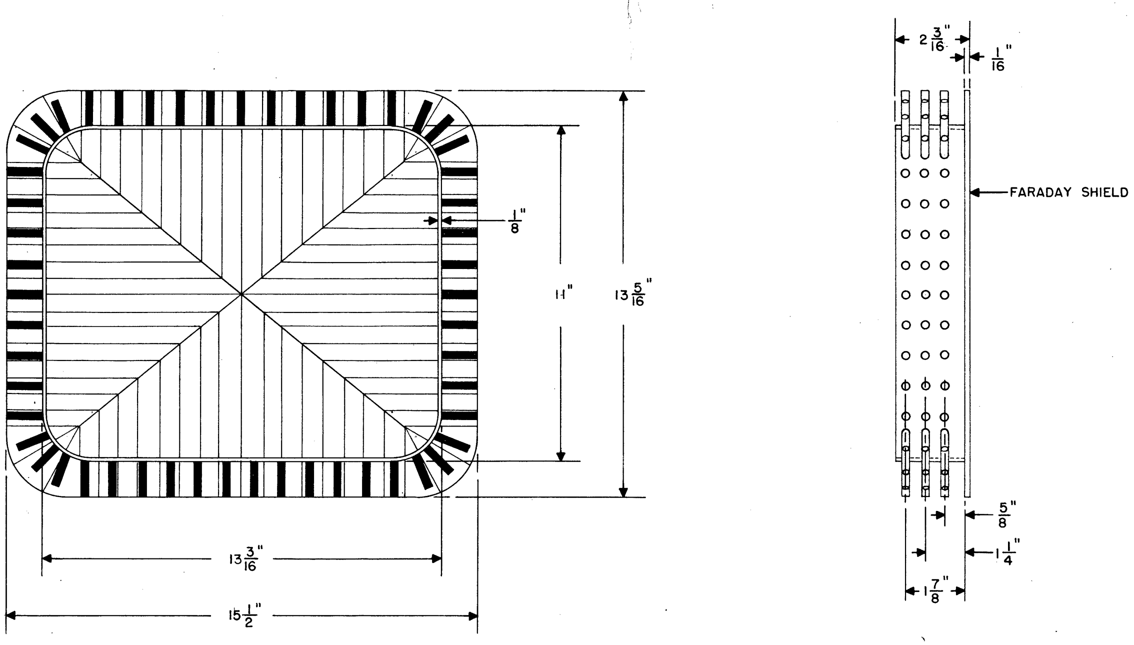

FIG. 4.4(a) DETECTOR COIL FORM AND FARADAY SHIELD

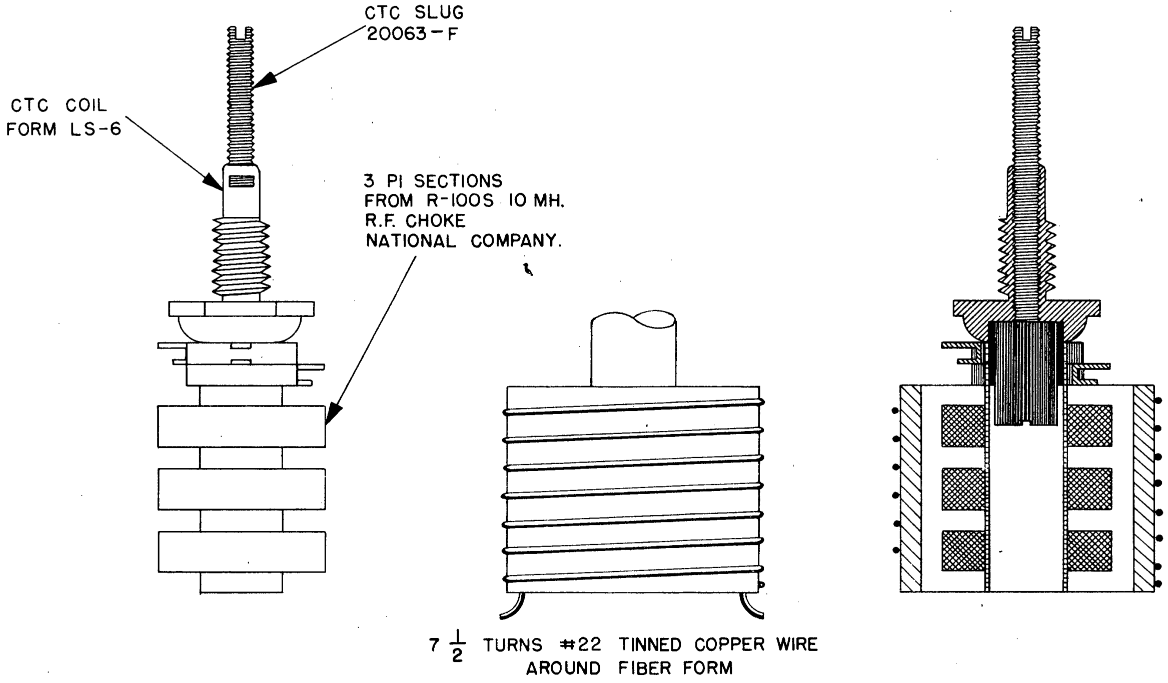

FIGURE **4.4 (b)** OSCILLATOR TRANSFORMER