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NRL REPORT 3654

THE EFFECT OF IRON CORES ON THE PICKUP EFFICIENCY OF VLF LOOP ANTENNAS, IN AIR AND UNDER WATER (U)

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THE EFFECT OF IRON CORES ON THE PICKUP EFFICIENCY OF VLF LOOP ANTENNAS, IN AIR AND UNDER WATER

S. V. Fratianni

May 4, 1950

Approved by:

T. McL. Davis, Head, Radio Techniques Branch
L. A. Gebhard, Superintendent, Radio Division II

NAVAL RESEARCH LABORATORY
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ABSTRACT

Iron cores are known to improve the pickup efficiency of loop antennas in air, with consequent increase in associated receiving-system sensitivity. Investigations show that such improvement is retained with the loops submerged in salt water, so that VLF loops intended for underwater radio reception can profitably employ iron cores, provided that the loop dimensions are sufficiently small. Data obtained in laboratory and field measurements indicate that approximately 5 decibels improvement in sensitivity was due to the iron core, for the given value of inductance and the particular loop structures employed in the investigation.

PROBLEM STATUS

This is an interim report. Work on other phases of the problem is continuing.

AUTHORIZATION

R10-43R
NE 120-201 (BuShips Problem S1083.1)

THE EFFECT OF IRON CORES ON THE PICKUP EFFICIENCY OF VLF LOOP ANTENNAS, IN AIR AND UNDER WATER

INTRODUCTION

The increase in pickup efficiency of a loop antenna in air, obtainable by the use of a suitable, powdered-iron core, has been reported by several investigators.[1,2] A limited investigation with miniature VLF loops conducted at NRL in 1941 left some doubt as to whether the improvement obtained in air extended to underwater operation in simulated seawater.[3] A more thorough investigation of the underwater operation of iron-cored loops was undertaken in September 1946. While not constituting a complete study, the results of the investigation as reported herein indicate that a gain in over-all receiving system sensitivity on the order of 5 decibels or more is possible by the use of iron in submerged loop antennas.

SUMMARY OF IRON-CORED LOOP-ANTENNA THEORY

The available analyses[4,5] of iron-cored loop behavior generally assume that the magnetomotive force (mmf) in the radio wave generates a magnetic flux in the iron core which is proportional to the effective permeability (μ_e) of the core. Since this effective permeability is usually greater than one, there is an increase in flux linkages over that obtained with an air core. Thus, for a value of $\mu_e = 4$, the voltage initially generated by the radio wave in a given loop winding is four times that for an air core. The counter-mmf established by the flow of current in the loop winding reduces the initially generated voltage but this effect can be minimized by using an iron core which is long, compared to its cross-section.

Since higher permeability results in a decrease in the number of turns required for a given value of inductance, it is advantageous to spread the turns along the length of the core.

---

[1] *Burgess, R. E., "The Iron-Cored Loop Receiving Aerial." Paper RRB/CR, Radio Research Board, Great Britian, 15 November 1941.*
Ibid: Wireless Engineer, Vol. XXIII, p. 172-178 June 1946.

[2] *Kihn, H., "Loop Antennas with Ferromagnetic Cores." TR [illegible], RCA Labs, November 1940.*

[3] *Isely, F. C., "Submerged Reception of Low Frequency Signals - Design of Compact Loops in Connection With." NRL ltr report C-SS/7, FI:ib (Confidential), 5 January 1942.*

[4] *Burgess, R. E., op. cit.*

[5] *Kihn, H., op. cit.*

This allows the use of more turns for the given inductance because the magnetic coupling between turns is thereby reduced. It may be desirable to use two or more spaced windings, side by side and in parallel, rather than to wind a few turns of coarse pitch when very low loop-inductance values are needed.

With the windings thus distributed, it is possible to obtain an increase in loop terminal voltage, as compared to an air-core coil of the same inductance and Q, which is close to the square root of the effective permeability of the iron-cored coil. This effective permeability can be approximated from the ratio of the air-core to the iron-core coil turns, provided that the absolute dimensions and the length-to-diameter ratio are nearly the same and that the inductance values of the two coils are not far from being identical. Thus:

$$n \doteq \sqrt{\mu_e} \doteq \sqrt{\frac{N_A}{N_I}}$$

when n is the ratio of iron-core to air-core coil pickup voltage, μ_e is the effective permeability of the iron-cored coil as determined from the ratio of air-core to iron-core turns for the same inductance, N_A is the number of air-core coil turns, and N_I is the number of iron-core coil turns.

The magnetomotive force of an underwater radio wave can be considered as affecting an iron-cored submerged loop in a manner similar to that experienced in air. It can then be expected that the improvement in pickup afforded by a properly designed iron-cored loop in air will also be obtained in submerged operation.

FIELD IN VICINITY OF AIR- AND IRON-CORED LOOPS

Figure 1 illustrates magnetic-field configurations around air-cored and iron-cored loop antennas in air. If sea water were the medium, this sketch would have to be slightly modified to include the signal-attenuation effects of sea water.[6] That is, the sketch would show a progressive decrease in the number of magnetic lines from top to bottom of each loop. The radio wave is assumed to be horizontally polarized and advancing vertically downward.

Figure 1(A) shows the magnetic lines of force equally distributed about the air-cored loop. The lines of force directly over the loop and progressing downward will induce equal voltages in the upper and lower conductors, (2) and (4), and the terminal voltage of the winding will be the algebraic summation of these voltages. With an iron core (Figure 1(B)), the magnetic lines on either side of the core can be considered as being deflected toward the core by virtue of the higher permeability of the iron as compared to air. This results in more magnetic lines threading the core (and coil) and a distortion of the field in the vicinity of the core. The net terminal voltage of the loop winding will be greater than that obtained with an air-core coil of the same inductance and Q.

VOLTAGE VECTORS FOR AIR- AND IRON-CORED LOOPS

Figure 2 provides an approximate vector representation of the voltages induced in the members of the loop antenna in air and in sea water for the air-cored and iron-cored loop

[6] *Norgorden, O, "The Submerged Reception of Radio Frequency Signals." NRL Report R-1669, December 2, 1940.*

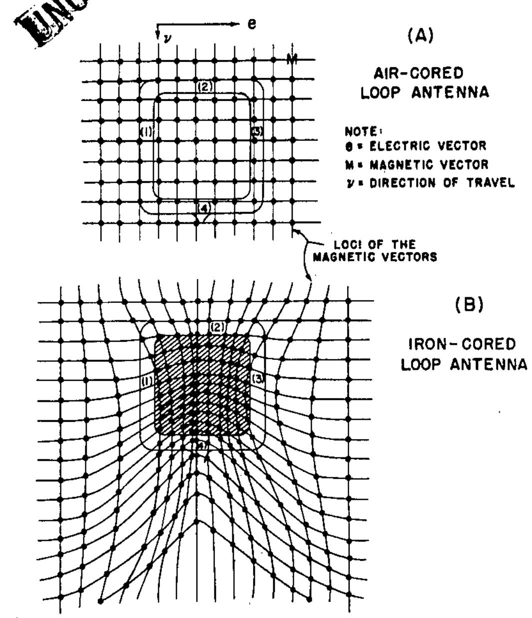

Figure 1 - Schematic magnetic-field configuration with air-cored and iron-cored loop antennas in air

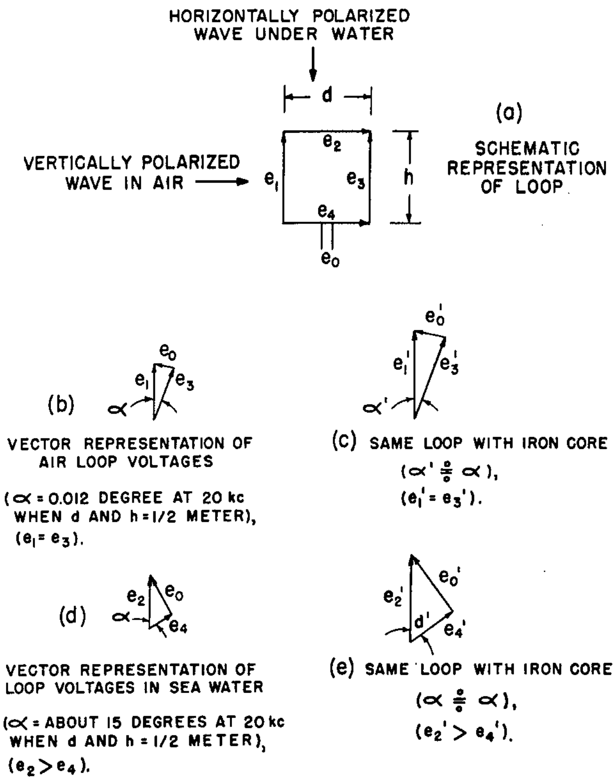

Figure 2 - Loop induced voltages

antennas. It shows that with the normal vertically polarized, horizontally advancing wave front in air, the vertical members of the air-cored loop antenna will have equal voltages (e_1 and e_3) induced, displaced by a small phase angle (α) which is dependent on the relative time of arrival of the wave front at the fore and aft vertical members of the loop winding.

This phase angle will have a maximum value of $\alpha = 360 \frac{d}{\lambda}$, where d is the horizontal distance between the vertical members of the square loop shown and λ is the length of the radio wave. Thus α for a value of d = 1/2 meter (19.7 inches) and a frequency of 20 kc (15,000 meters wavelength) will be $360 \frac{0.5}{15,000} = 0.012$ electrical degrees. A round loop winding can be represented as an equivalent square loop of the same area. The loop-antenna terminal voltage is the vector difference (e_0) of the voltages (e_1 and e_3). If an iron core is introduced in this antenna, the field distortion effect will result in proportionally greater induced equal voltages (e_1' and e_3'), phased by approximately the same angle (α). In this case, the voltage vector difference (e_0') will be greater in the same proportion as the increase in e_1 and e_3.

Figure 2(d) shows the voltage-vector diagram of the air-cored loop submerged. The underwater wave front is horizontal and is advancing vertically downward. The horizontal members then develop unequal induced voltages (e_2 and e_4). Due to the much lower velocity of propagation of the radio wave in sea water (less than one-thousandth of the velocity in air), the phase angle underwater is over one thousand times greater than it is in air. The loop terminal voltage (e_0) is then much greater than it would be in air for the same field strength, mainly because of the difference in amplitude of e_2 and e_4. If an iron core is introduced in the submerged loop antenna, proportionally greater voltages will be induced, with about the same phase angle as obtained without the iron core.

LOOP Q VALUES

In general, the Q of an iron-cored loop will be greater than that of an air-core loop for the same amount or weight of copper in the winding. The difference in Q could be still higher if the iron-cored coil were not deliberately wound so as to utilize the greatest possible number of turns for a given inductance in order to afford as much pickup as possible. Higher Q of the over-all loop circuit will produce an improvement in receiving system sensitivity proportional to approximately the square root of the ratio of the change in over-all Q values.[7] It should be noted, however, that in a transformer-coupled loop system, the transformer primary and secondary Q values also enter into the over-all loop system Q, so that rather large changes in loop Q may produce rather small changes in over-all Q, particularly when the loop and transformer Q values are of the same order.

DESIGN OF THE EXPERIMENTAL LOOP ANTENNAS

The effect of an iron core on loop pickup and receiving system sensitivity is best determined by comparison to an air-core loop with the same inductance, Q, and physical dimensions. The tests described below were made on this basis, within the prevailing limitations of availability of materials, such as size and types of wire for the windings and shapes and dimensions of iron-dust cores.

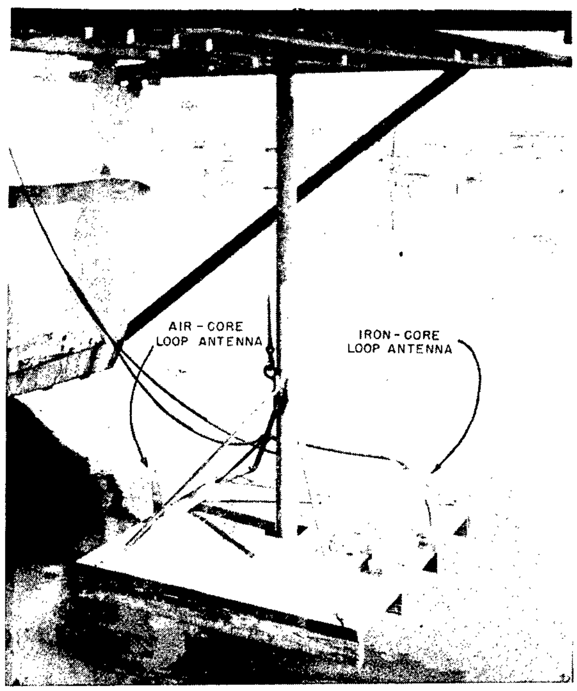

Figure 3 - The set No. 1 wax-covered loop antennas

Four loop antennas (Figures 3 and 4) were designed and constructed to allow investigation of loops with two different shape factors. The two, set No. 1 loops (Figure 3,) were bank wound on rectangular phenolic forms, each approximately 13 x 6 x $2\frac{1}{2}$ inches. In one of these forms, powdered-iron core elements were placed as shown in Figure 5(A). These bar-type elements were obtained from a German Model LN-28067 airborne direction-finding loop. Tests indicated that these cores probably had a permeability (μ) of 51.[8] For the No. 1 iron-cored loop, approximately 250 turns of 30/40/40 "Litz" wire was required for an inductance of approximately 7 millihenries. To obtain nearly equivalent inductance and Q for the air-cored loop of this No. 1 set, the second antenna

[7] Fratianni, S. V. "Theory and Design of Resonant Transformer-Coupled Loop-Antenna Input Systems for VLF Reception." NRL Report R-3281 (Restricted), April 28, 1948.

[8] Lutz, S. G., "Survey of Features of German Powdered-Iron Components." NRL Report R-3029, p. 21, September 1, 1946.

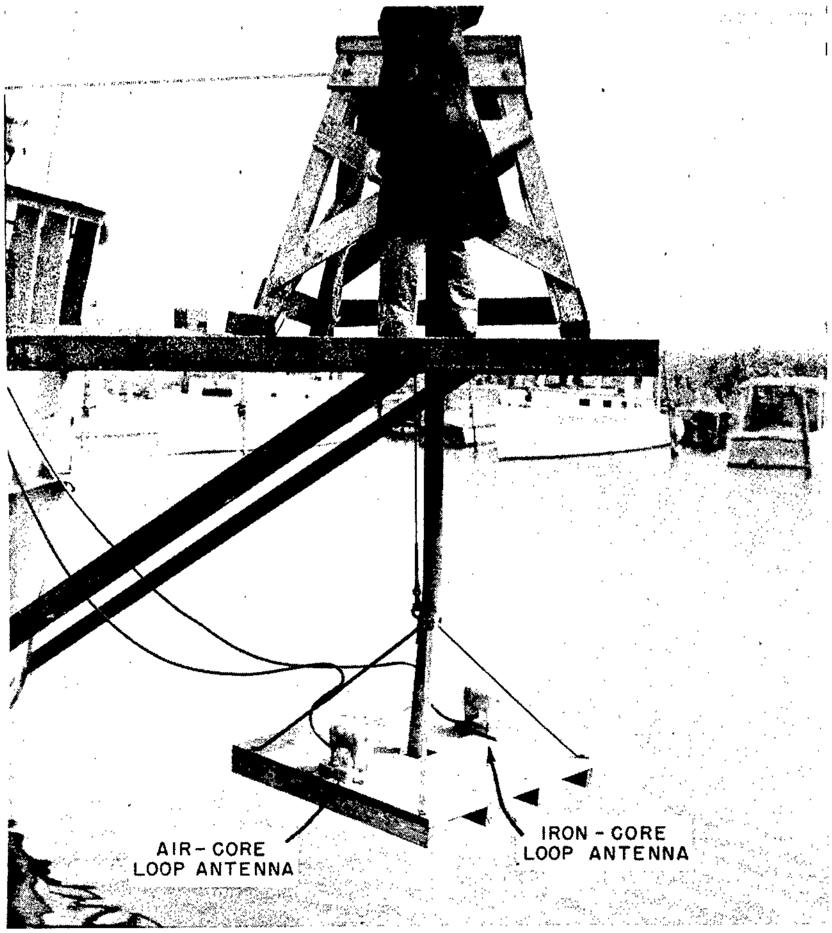

Figure 4 - The set No. 2 wax-covered loop antennas

required about 500 turns of 90/38 "Litz" wire. Both of these coils covered a winding length on the forms of approximately 11 inches, so that the shape factors of the two loops were approximately alike. For the iron-cored antenna, the core was allowed to extend beyond the ends of the winding, as shown in Figure 5(A), thus allowing a somewhat greater field-distortion effect to be obtained.

The set No. 2 loops, shown in Figure 4, were bank wound on 4-1/8 inch diameter phenolic tubes. The iron-cored antenna of this set contained six, 4-inch diameter, powdered-iron toroids, having a permeability of approximately 14. Both antennas of this set had coils wound on a 3-inch section of the forms, so that the shape factors were alike. The core assembly extended slightly beyond the ends of the windings, as shown in Figure 5(B). For approximately equal inductances and Q's, the air-cored antenna required 155 turns of 30/40/40 "Litz" wire. These sets, No. 1 and No. 2 loops, were initially coated with 1/2 inch of yellow "Superla" wax for the submerged measurements. Due to water leakage through the wax coatings, it was subsequently found necessary to recoat the loops with 1/4 inch of "Thiokol" (3M Sealer EC754 and 3M Accelerator EC807), a synthetic rubber manufactured by the Minnesota Mining Company. This insulation thickness was used to keep the sea water far enough away from the windings so that the Q of the loops would not be seriously reduced when they were submerged. Figures 6 and 7 also show that the loop antennas employed structural members (wood) to support the forms as required. The loop terminal leads were passed through Vinylite sleeving and connected to one end of a 50-foot cable in a suitable junction box.

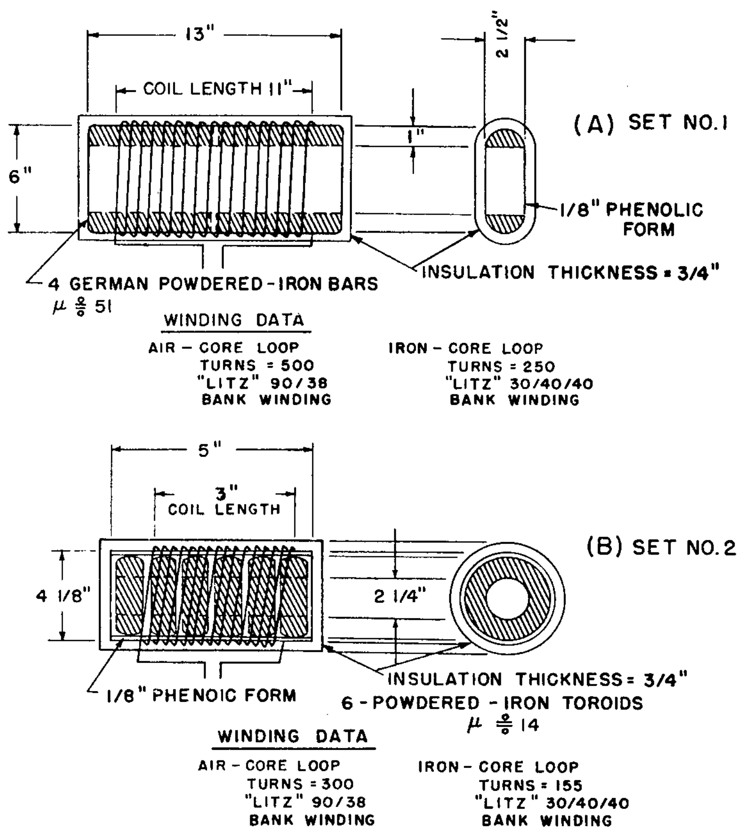

Figure 5 - Schematic structural diagram of experimental iron-core loop antennas

LABORATORY MEASUREMENTS - EQUIPMENT AND PROCEDURES

In the laboratory investigations, comparative sensitivity measurements of the antennas in conjunction with an appropriate receiver were obtained in shielded rooms. The equipment was arranged as shown in Figure 8(A). Two separate rooms, (A) and (B), were used, with the pickup equipment in room (A) and the measuring equipment in room (B), thus avoiding possible loop pickup from equipment spurious radiations and/or interference from external signals. The set No. 1 and No. 2 loop antennas were placed, one at a time, in the same physical position relative to a transmission line which radiated the signal for the measurements first for the "in-air" measurements and then for the "in-tank" or "submerged" measurements. As indicated in Figure 8(A), the tank was a radome (of plastic insulating material) which contained simulated Chesapeake Bay water (approximately six pounds of table salt (NaCl) to fifty gallons of tap water).

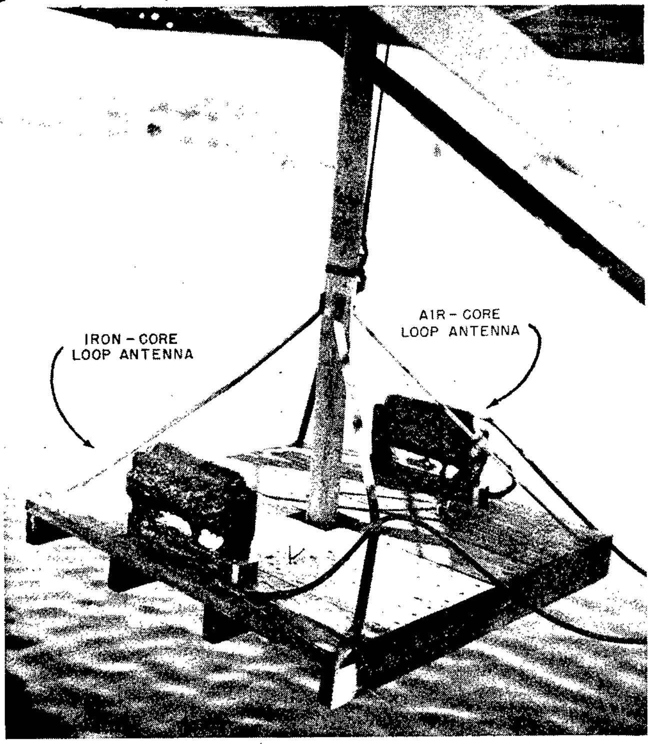

Figure 6 - The set No. 1 rubber-covered loop antennas

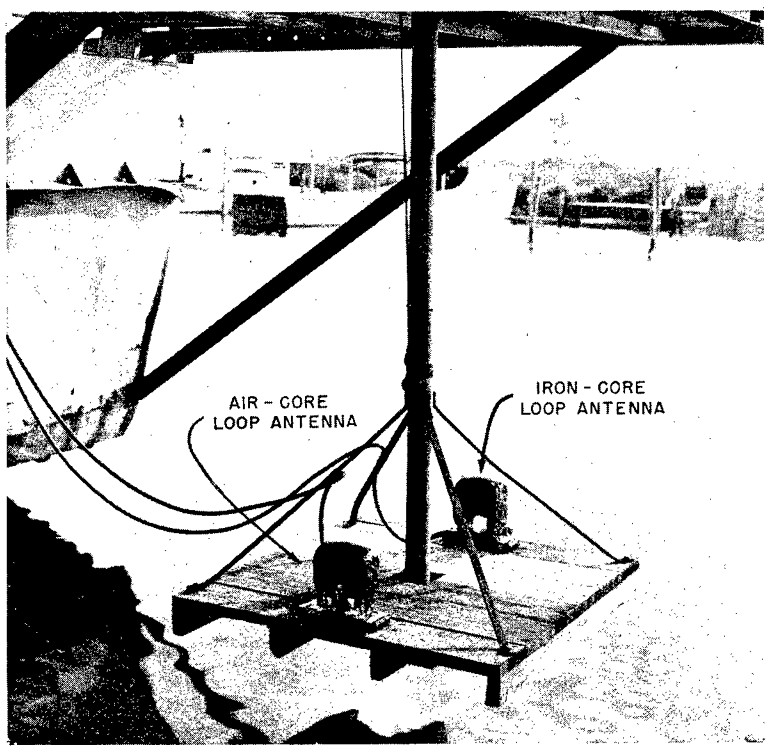

Figure 7 - The set No. 2 rubber-covered loop antennas

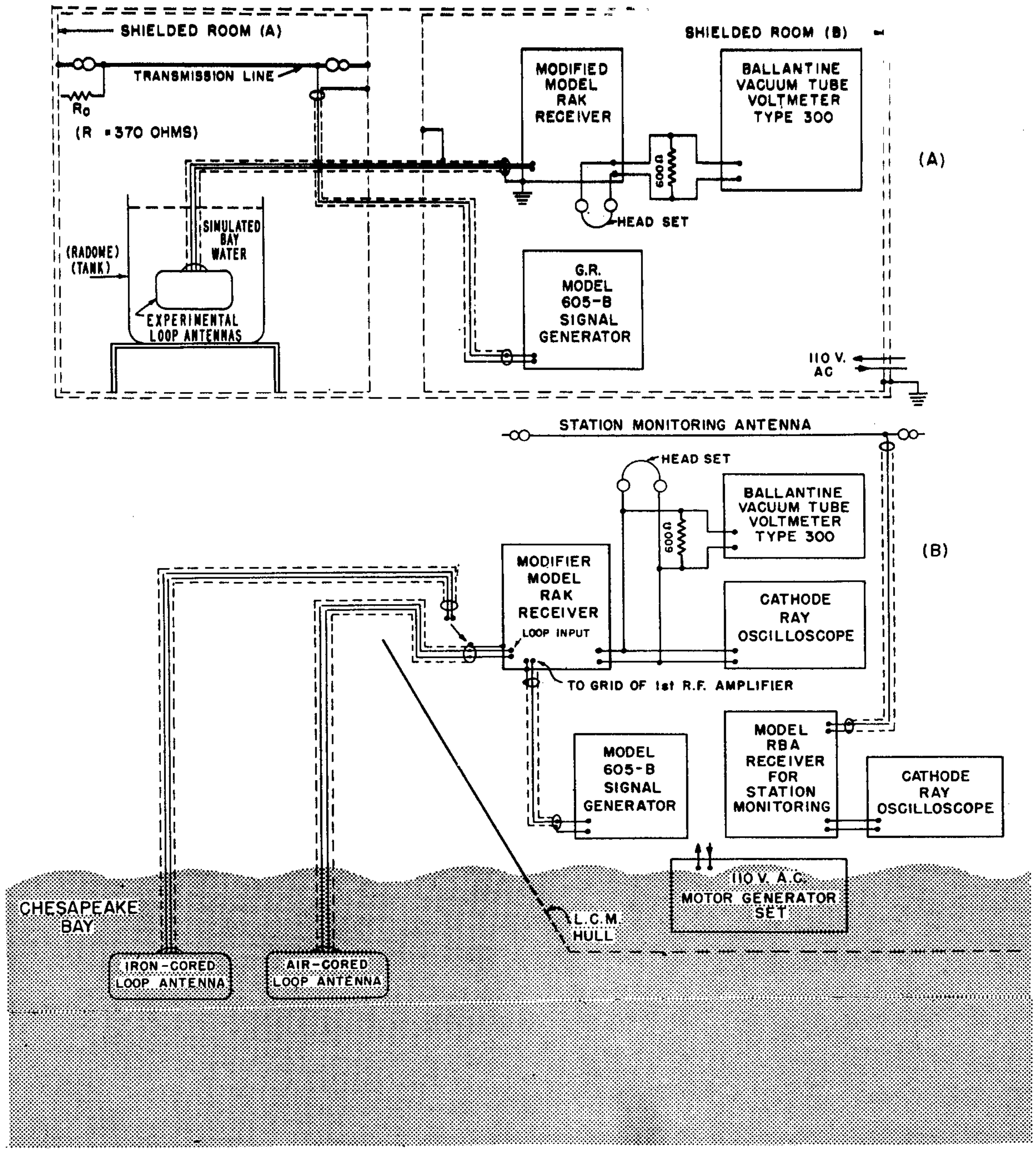

Figure 8 - Equipment arrangement for laboratory and Chesapeake Bay measurements of submerged loop performance

A model 605-B General Radio Signal Generator was used to energize the transmission line, the latter being terminated in its characteristic impedance (about 370-ohms resistance). A Model RAK-7 receiver, modified for loop-antenna reception with an appropriate coupling transformer, was used to resonate the loop antenna to the signals radiated by the transmission line.[9]

For each loop-antenna condition, "in-tank" or "in-air," the signal-generator input microvolts to the transmission line for receiver standard output were determined for a series of signals in the 15- to 25-kilocycle range. A standard output of 6 milliwatts into a 600-ohm load, at 20-db signal-to-noise ratio was maintained.

The Q of each loop antenna was measured in air, submerged in the tank, and then again in air after submergence to check for water penetration. All Q measurements were obtained with measuring equipment arranged as shown in Figure 9. A Model OH-1 Radio-Frequency Bridge was used to measure r-f resistance and resonating capacitance, from which the Q values were derived—no suitable direct-reading Q meter being available for the 15- to 25-kilocycle band. The bridge was initially balanced without the loop, and the value of resistance R, which provided balance, was recorded. With the loop antenna switched into the circuit, the bridge was rebalanced by adjusting series capacitor C and series resistance R. The difference between the first and second reading of R was the radio-frequency resistance of the loop antenna (assuming that the losses of the tuning capacitor were negligible). The Q of the loop antenna was then computed from the usual formula

($Q_0 = \frac{1}{2\pi fCR}$, where R is in ohms, C is in farads, and f is in cycles per second).

FIELD MEASUREMENTS - EQUIPMENT AND PROCEDURES

As a check on the laboratory measurements, the performance of the two types of loops was also measured with the loops submerged in Chesapeake Bay. The signals used were keyed cw emissions from NSS (Annapolis, Maryland). A few checks were also made on signals from Long Island, New Jersey, and Panama.

The equipment for the comparative tests at the Bay was arranged aboard an LCM Landing Craft, as shown in Figures 8(B) and 10. Each set of loop antennas was mounted on an outboard platform, which could be lowered into the water by means of a steel cable controlled by a winch fastened to the bulkhead of the landing craft. The construction of the rigging allowed platform rotation of approximately 360 degrees, thus providing a means by which the loop antennas could be rotated for maximum signal pickup at any depth attained. This provision was necessary since loop antennas under water, as in air, have a "figure-8" or cosine-law reception pattern.[10,11] Fifty-foot, shielded, twin-lead rubber cables were brought up from the loops and over the bulkhead to the receiver. While each set of antennas was in air, the loop Q's and the over-all sensitivity values were recorded at signal frequencies determined by the VLF transmissions of NSS and other high-power stations. This procedure was repeated with the loop antennas submerged at 3- and 6-foot depths at various bay locations, and repeated again when the antennas were pulled out of the water.

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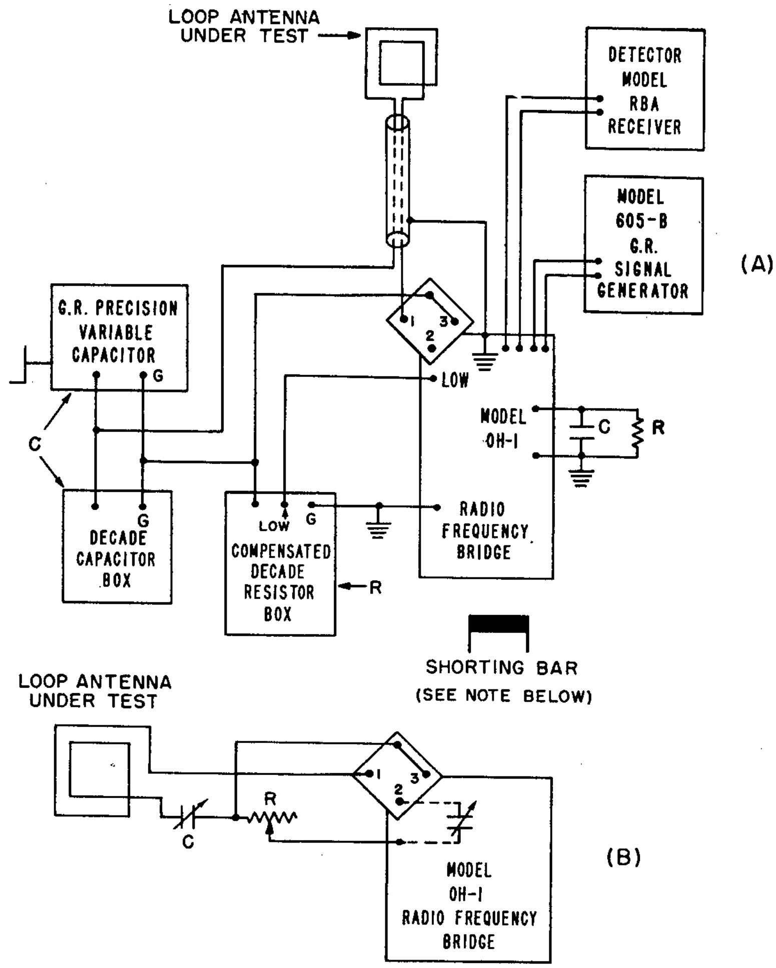
[9] *"Modifications and Developments of the RAK Receiver Units." NRL Interim Report C-SS/7 (1223:SVF) C-1220-38/46, March 11, 1946.*

[10] *Isely, F. C., "Test of Underwater Reception of Low-Frequency Radio Signals." NRL Report R-1717 (Confidential), April 1, 1941.*

[11] *Bureau of Ships: Radio and Sound Bulletin No. 6., April 1, 1942.*



(A) Block Diagram of Equipment for Measurement of Loop Antenna R-F Resistance and Resonating Capacitance.

(B) Schematic Diagram of the Circuit.

NOTE: (1) The bridge alone is balanced first with a shorting bar across terminals 2 and 3.
(2) The loop antenna circuit and bridge is then balanced with the shorting bar across terminals 1 and 2.

Figure 9 - Radio-frequency bridge system for determination of loop antenna Q

Since the field strength of the signals from the VLF transmitters was determined by geographical location relative to each station, the over-all sensitivity measurements were made with a procedure somewhat different from that used in the laboratory checks. The desired signal was first tuned in. The loop was then rotated to one of its two null positions so that no signal could be heard or seen on the meters. The gain of the receiver was adjusted to produce a noise level definitely observable on the output meter and oscilloscope. The loop was then rotated to a bearing which produced maximum signal output on the meter

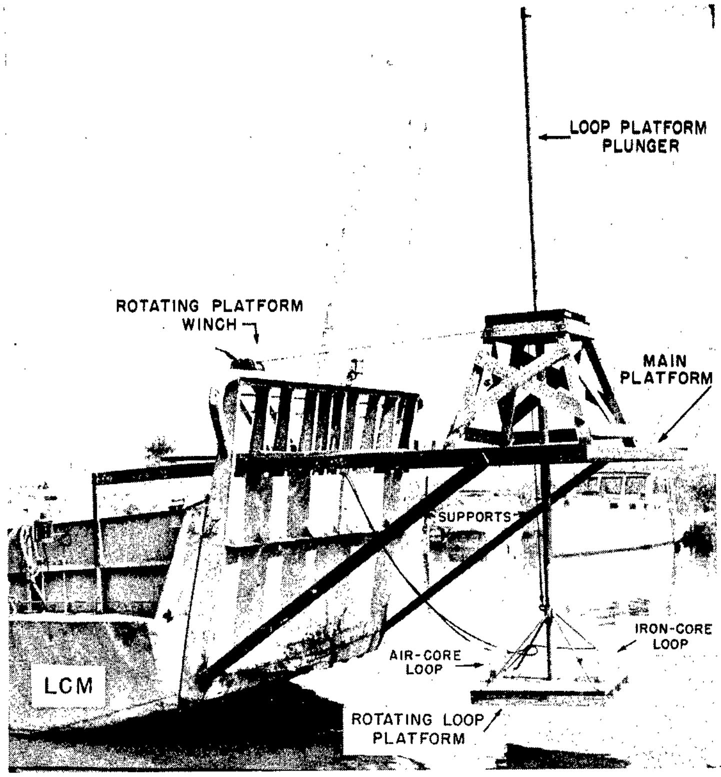


Figure 10 - LCM landing-craft platform and rigging construction

and scope. Great care was taken to insure that this last condition did not result in receiver or oscilloscope amplifier overload.

The loop was again oriented to the null response bearing previously used, and the signal generator was connected to the grid of the first (r-f amplifier) tube in the receiver through a suitable coupling capacitor. The receiver gain control was left as adjusted initially in setting the output noise level. The unmodulated cw input necessary to produce the same output level as previously obtained with the VLF signal was determined for the same frequency. The equivalent signal-generator input to the first-tube control grid was thus determined for both iron- and air-core loops. The improvement in sensitivity resulting from the use of iron was taken as the ratio of the signal-generator input readings for equivalent air- and iron-core loop operating conditions.

RESULTS OF LABORATORY MEASUREMENTS

The graph of Figure 11 shows the initial laboratory values of Q for the set No. 1 waxed loop antennas. Although the loops alone have widely different values of Q (=Qo) the over-all

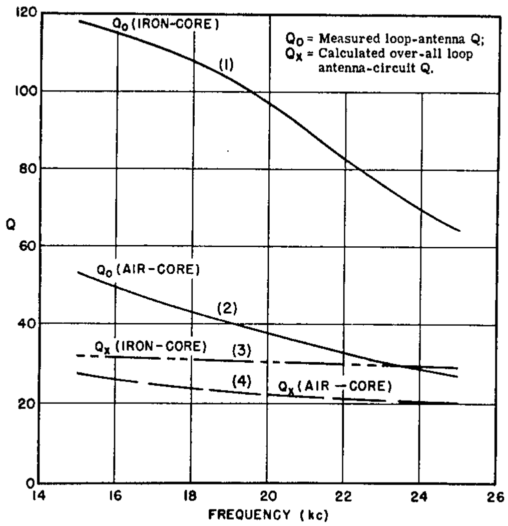


Figure 11 - Laboratory tests-initial Q values of the wax-covered set No. 1 loop antennas in air

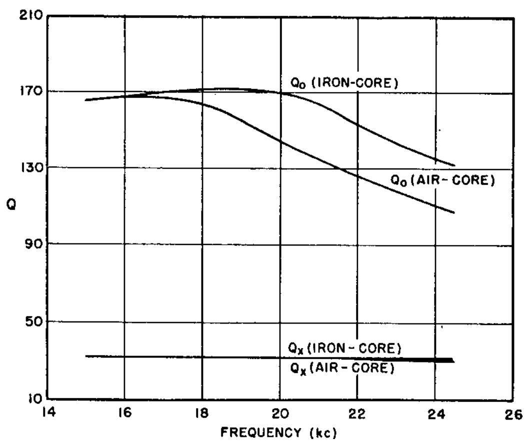


Figure 12 - Laboratory tests-initial Q values of wax-set No. 2 loop antennas in air

loop-circuit Q (=Qx) difference is considerably smaller.[12] The modified Model RAK-7 Receiver used in the investigations employs a loop-coupling transformer whose constants are approximately 50 for transformer primary Q, 90 for transformer secondary Q, and a value of about 0.95 for transformer coupling. The loop-to-transformer, primary-inductance ratio is unity. If these Q values and the "in-air" Q values of 53 for the air-cored loop and 118 for the iron-cored loop at 15 kilocycles are substituted in equation 6 of the reference in footnote 12, the over-all loop system Q's (Qx) will be 27.9 and 31.8, respectively (Figure 11). Since this Qx difference is quite small, any considerable improvement in receiver sensitivity attributable to the presence of the iron core will be due to the field-distortion effects of the iron. Most of the approximately 8-db increase in sensitivity shown by curve (1) Figure 13 can be ascribed to field distortion, the improvement due to the higher iron-cored loop Q being on the order of 1/2 to 2 db. The effective permeability of the iron core, as computed from the air-to-iron core winding ratio (= about 4), would indicate that the field-distortion effect should result in approximately 6-db improvement in sensitivity.

The Q values of the Set No. 2 waxed loops alone as determined by laboratory measurements, in air, are shown in Figure 12. Since the maximum difference in Q of these antennas is on the order of only about 20 percent, the over-all values of Qx are almost identical. The improvement in sensitivity due to use of the iron core was about 3.5 to 4.5 db over the range of 15 to 25 kc (Figure 13), which is somewhat less than the approximate computed value of 5.7 db.

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[12] *Fratianni, S. V., "The Equivalent Selectivity of Transformer-Coupled Loop-Antenna Input Circuits." NRL Report R-3464 (Restricted), May 9, 1949.*

RESULTS OF FIELD MEASUREMENTS

The most reliable of the results obtained at Chesapeake Bay are shown for each set of rubber-coated loop antennas in Table 1. Since only one high-power VLF transmitting station was in operation at the time, these measurements were limited to one frequency (18.4 kilocycles). The data of Table 1 show that the antennas had somewhat different Q values as compared to previous laboratory measurements. The differences are probably due to reprocessing of the loops with a rubber coating over the wax.

The Q's obtained for the iron- and air-core loops thereby became more nearly equal. The table shows the results of tests at several different locations and loop depths in the

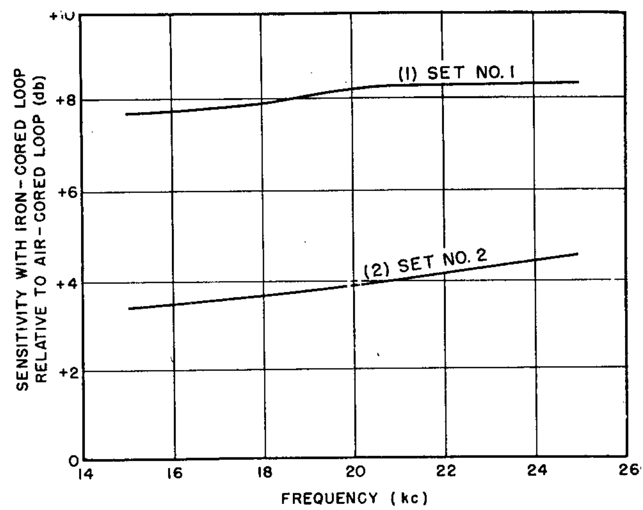


Figure 13 - Laboratory tests-initial over-all receiver-sensitivity comparisons for loop-antenna sets Nos. 1 and 2, wax-covered, in air

TABLE 1
Results of Chesapeake Bay Tests

Each set of measurements made at approximately 18.4 kilocycles, at different locations, and at various loop depths.

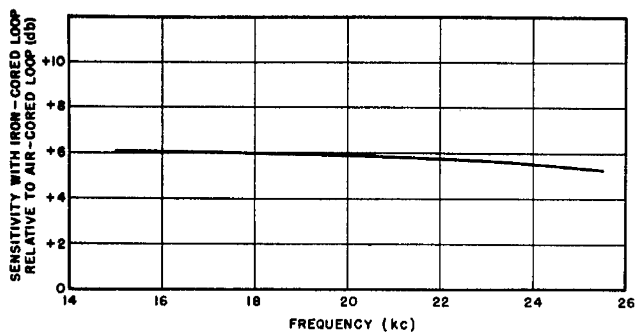
Set No. 1 Loops

Test No.	Loop Antenna Q's				Relative Improvement in Over-all Sensitivity Provided By The Core - DB	
	In Air		Submerged			
	Q Air-Core	Q Iron-Core	Q Air-Core	Q Iron-Core	In Air	Submerged
1	73	76	62	56	6.5	6.0
2	72	75	58	55	4.5	4.5
3	73	75	62	54	6.0	5.0

Set No. 2 Loops

Test No.	Loop Antenna Q's				Relative Improvement in Over-all Sensitivity Provided By The Core - DB	
	In Air		Submerged			
	Q Air-Core	Q Iron-Core	Q Air-Core	Q Iron-Core	In Air	Submerged
1	89	75	76	*Approx.* 35	5.0	4.9
2	89	73	*Approx.* 15*	*Approx.* 34	6.0	9.0*

* *Effect of water leakage in the air-core loop. Measurements were completed before this antenna became totally worthless.*



NOTE: Same result for "in-air" and "in-water" measurements. The loop-Q values are similar to those shown in Table 1.

Figure 14 - Laboratory tests-over-all receiver-sensitivity comparison for rubber-covered, setNo.1 loop antennas

Bay. Variations in the improvement figure for the iron-core case are partly due to the effects of variable salinity or conductivity of the bay water and partly experimental error. Field tests of this nature are difficult to make accurately, because of variations in loop depth and bearing with motion of the vessel in which the equipment is mounted. The results obtained, however, indicate that the improvement in over-all receiver sensitivity provided by use of the iron core is nearly the same for both "in-air" or "in-water" conditions, with an average value of about 5 db.

RESULTS OF LABORATORY RECHECK

The rubber-covered Set No. 1 loops were rechecked in the laboratory following the Chesapeake Bay tests. It was found that the Q values of the loops were substantially identical to those measured at the Bay. Figure 14 shows that use of the iron core resulted in an improvement of 5 to 6 decibels in signal-to-noise ratio of the over-all receiving system, which is close to the values obtained at the Bay.

CONCLUSIONS

It is concluded from the results of this investigation that:

The use of a suitable iron core in a loop antenna results in a substantial improvement in submerged loop pickup, as reflected in increased receiving system sensitivity.

Assuming the same value of inductance, the iron core tends to increase the Q of the loop for a given amount of copper in the winding, thereby producing part of the increase in receiving system sensitivity. The major portion of the increase, however, appears to result from field-distortion effects in the vicinity of the iron core, such distortion providing greater linkage between the radio field and the loop winding. For equal iron- and air-cored loop Q's, the field-distortion effect will, of course, be responsible for all the improvement in loop pickup.

The improvement in sensitivity effected by the use of iron in these studies was on the order of 5 to 6 decibels. With better iron cores and more suitable designs, it should be possible to obtain improvements up to perhaps 10 db and possibly higher. An improvement of 6 db in pickup efficiency makes a circular iron-cored loop equivalent to an air-core loop of almost twice its diameter.

The improvement due to the use of an iron core in air reception is substantially maintained with the loop submerged in sea water.

The negative results of previous laboratory investigations on iron-cored loop pickup appear to be due to lack of proper shielding of the tanks of salt water employed. It is necessary to shield electrically such tanks everywhere except at the top, this being left open to allow entry of the radio waves at the surface of the water. With such a setup, laboratory measurements on submerged loops are comparable to the results of field tests in large bodies of water.

In practice, the use of iron cores will be largely restricted to small loops. For instance, a loop 20 inches in diameter will require a core having weight and volume on the order of 50 to 100 times that required by a 5-inch diameter loop of similar design, for an equivalent improvement in pickup over their respective air-cored loop antennas.

RECOMMENDATIONS

It is recommended that a thorough study of the effect of iron cores on loop-antenna performance be considered. Such a study should include determination of the physical mechanism of the effect, and quantitative information relating improvement in performance to size, weight, antenna pattern, and other factors important in design and operation.

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NAVY-DPPO PRNC. WASH., D.C.