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ADC025645	
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REPORT NO. NADC-80228-30

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(S) NOTEBOOK ON NONACOUSTIC DETECTION OF SUBMARINES (U)

Paul M. Moser
Sensors and Avionics Technology Directorate
NAVAL AIR DEVELOPMENT CENTER
Warminster, Pennsylvania 18974

12 NOVEMBER 1980

FINAL REPORT

INDEPENDENT RESEARCH PROJECT

Work Unit GC 189

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CLASSIFIED BY: OPNAVINST 8813.5 CH-1
ID: 05,53.1 DTD 25 JAN 1980
REVIEW ON: 12 NOVEMBER 1990

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER NADC-80228-30	2. GOVT ACCESSION NO. AD-C025645	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) NOTEBOOK ON NONACOUSTIC DETECTION OF SUBMARINES (U)	5. TYPE OF REPORT & PERIOD COVERED FINAL 20 MAR 1978-30 SEP 1979	
7. AUTHOR(s) Paul M. Moser	8. CONTRACT OR GRANT NUMBER(s)	
9. PERFORMING ORGANIZATION NAME AND ADDRESS Sensors & Avionics Technology Directorate Naval Air Development Center Warminster, PA 18974	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS P.E. 61152N T.A. ZR01111 W.U. GC189	
11. CONTROLLING OFFICE NAME AND ADDRESS Technical Director Naval Air Development Center Warminster, PA 18974	12. REPORT DATE 12 Nov 1980	
	13. NUMBER OF PAGES 64	
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report) ~~SECRET~~	
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE Review on 12 Nov 1990	
16. DISTRIBUTION STATEMENT (of this Report)		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number)		
Submarine Detection Nonacoustic	Fields Magnetic Electric	Acoustic Kelvin Wave Wake Contaminants Electromagnetic
20. ABSTRACT (Continue on reverse side if necessary and identify by block number)		
(U) The study described in this report was undertaken to seek out, in some organized way, new methods and means for detecting completely submerged submarines with particular emphasis on nonacoustic techniques for achieving search rates in excess of 1500 square nautical miles per hour. An approach was adopted in which scores of possible interactions of the submarine, environment, and potential sensor through "fields" associated with each were examined and subjected to "back-of-the-envelope" feasibility calculations. Many of these calculations are included in this report. The coverage of the subject matter is extensive rather than intensive and phenomenological rather than technological. Several areas are recommended for further detailed study.		

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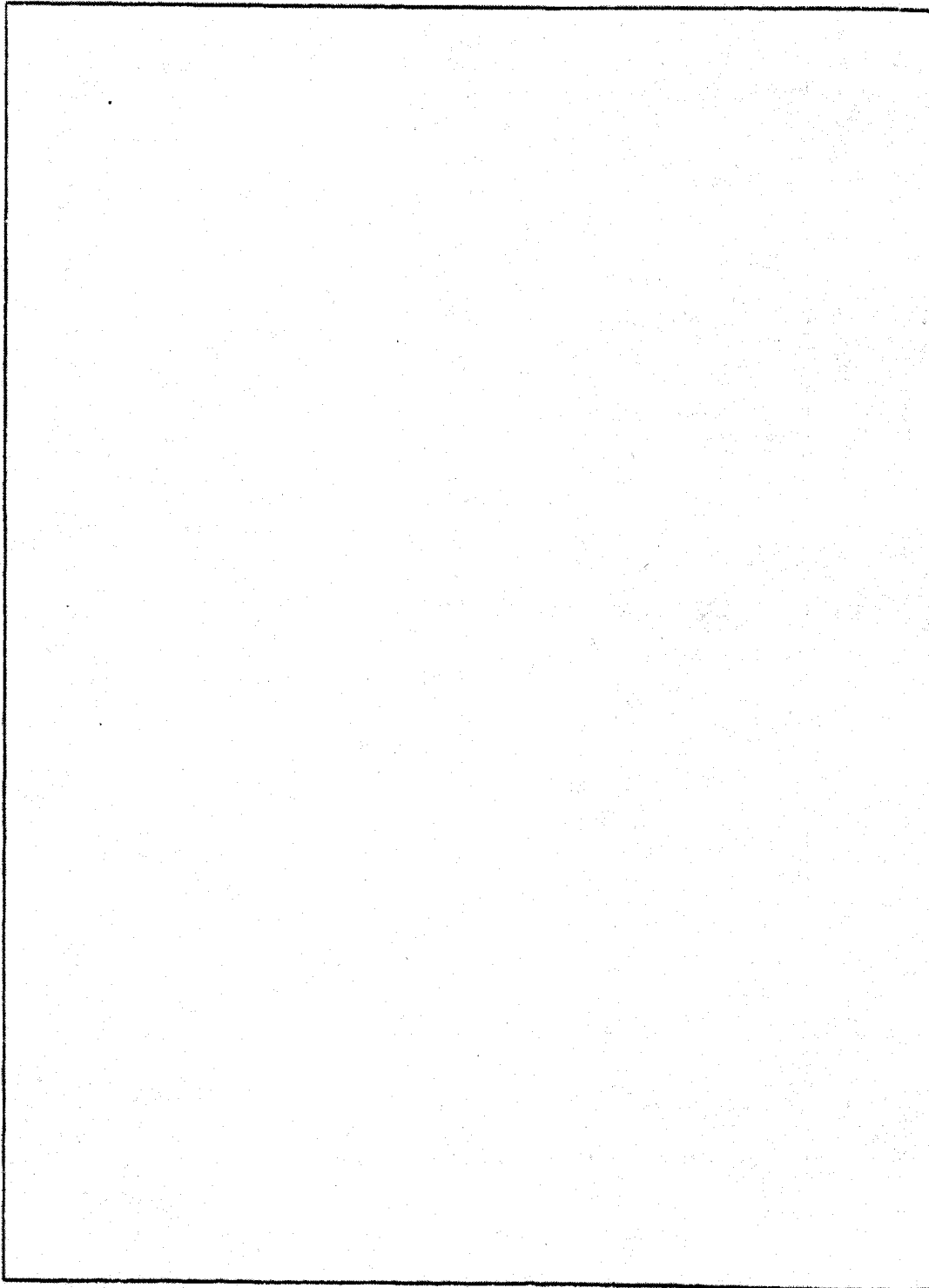
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(S) SUMMARY (U)

(C) INTRODUCTION (U)

(C) The techniques most commonly used today for detecting submarines involve the detection of sound emitted by or reflected from the target. However, it is expected that in the future, the effectiveness of acoustic sensors will decline because of increasingly noisy seas, acoustic countermeasures, and quieter submarines with antireflective coatings. The study described herein was undertaken to seek out, in some organized way, new methods and means for detecting submarines with particular emphasis on nonacoustic techniques for achieving search rates of the order of 1500 to 5000 square nautical miles per hour.

(S) RESULTS (U)

(S) This study started effectively at the bottom line requirement for a high-search-rate sensor and attempted to work upward through the various phenomena and technologies potentially applicable to the nonacoustic detection of submarines. A "field" approach was adopted in which scores of possible interactions of the submarine, environment, and potential sensor through "fields" associated with each were examined and subjected to "back-of-the-envelope" feasibility calculations. The most promising approaches, from the point of view of high search rate, appear to be those in which a submarine-generated field (magnetic, Kelvin wave, gaseous contaminant, acoustic) is probed by a scanning beam of electromagnetic radiation originating from a search aircraft.

(S) CONCLUSION (U)

(S) The quest for new large-area search sensors should concentrate on the remote detection of submarine-generated magnetic, Kelvin wave, gaseous contaminant, and acoustic fields.

(S) RECOMMENDATIONS (U)

(C) A detailed study should be conducted of the various magneto-optical phenomena that are derivatives of the Zeeman and Faraday effects to determine how they might be applied to the remote detection of small variations in a weak magnetic field.

(C) A study should be performed to determine the detection envelope as a function of sea state and submarine size, speed and depth for an ideal Kelvin wake detector. The results of this study should then be used in a systems analysis to determine the operational utility of the hypothetical ideal Kelvin wake detector. If so indicated by the studies, development of equipment (which may be a combination of sensors designed to measure the various characteristics of the Kelvin wake) should proceed.

(S) An investigation into the remote electro-optical detection of gaseous contaminants produced by submarine should be conducted. The study should cover contaminants that exist in the form of bubbles in the water, dissolved in the water, and in the air.

(C) A study should be carried out to determine what ways, if any, are available for sensing, from an airborne platform, pressure variations in a submarine-generated acoustic field without the need for an electromechanical transducer at the air-sea interface.

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1.0 ~~(S)~~ INTRODUCTION (U)

~~(C)~~ At present the most widely exploited techniques for detecting completely submerged submarines involve the detection of sound emitted by or reflected from the submarine. However, it appears that in the future the utility of acoustic sensors will diminish because of (1) the development of quieter submarines, (2) the installation of anechoic coatings on submarines, (3) the increasing acoustic noise levels of the seas from ever increasing numbers of engine-powered water craft and offshore drilling rigs, and (4) the development of acoustic and electromagnetic decoys and jammers. Accordingly, in recent years, there has been renewed interest in the possible development of new types of nonacoustic sensors to supplement or supplant acoustic devices, with particular emphasis on achieving high area search rates.

(U) In the past, the approach to nonacoustic detection has been episodic and sporadic with many arcane second-order effects being investigated which offered little likelihood of success under even controlled and contrived test conditions and an even smaller likelihood of eventual fleet acceptance. Independent Research Project GC 189 (Program Element 61152N, Task Area Number ZR01111) "Systematic Investigation of Potential Nonacoustic Submarine Detection Techniques" was established on 20 March 1978 to seek out, in some organized way, new ways for detecting submarines. This investigation started at the bottom line by asking "What does the fleet need?" and "What classes of phenomena and sensors could possibly satisfy that need?" The bottom line in this case was a sensor capable of yielding effective search rates of 1,500 to 5,000 square nautical miles per hour against submarines of all types, depths and speeds. In most previous investigations, the starting point has been some skill of the principal investigator in a field such as hydrodynamics, infrared radiometry or magnetism that was applied to the problem. In this investigation an attempt was made to proceed without bias toward any particular technology.

(U) The objective of this investigation was to discover and to assess the feasibility of new and/or hitherto unexploited concepts for the detection of submarines with particular emphasis on nonacoustic sensors applicable to airborne platforms, and to identify and propose specific projects for further research and development. The approach taken sought not only to focus attention on phenomena that are likely candidates for exploitation but also to eliminate quickly those phenomena that, even though technically feasible, would not be operationally feasible and to eliminate phenomena that show no promise of yielding high search rates.

(U) Initially, a matrix approach was proposed as a means for identifying techniques to be investigated. This was analogous to the approach taken by Mendeleev in his development of the periodic table of the elements, which served to identify previously undiscovered chemical elements. Along one axis of the proposed matrix there was to be arrayed a "high-resolution spectrum" of the sciences (physics, chemistry, biology, etc.) subdivided into their respective branches (e.g., mechanics, heat, sound, electricity and magnetism) and further subdivided into phenomena (such as the Zeeman effect, the Faraday effect, the Kerr magneto-optic effect, the Voigt effect, etc.). The same spectrum of the sciences was also to be arrayed along a second axis to cover cross-discipline effects (e.g., generation of sound pulses in water by a remote pulsed laser, acoustic modulation of a microwave beam, etc.). Along the third matrix axis, the properties and characteristics of submarines were to be arrayed. Each point of intersection within the matrix would then represent a potential technique for detecting submarines which would be assessed subsequently for feasibility.

(U) The matrix approach was tried but it soon became evident that there was a staggering number of possible effects and that some kind of prefiltering was required to render the task tractable within the constraints of the project. Specifically, means for assigning phenomena associable with submarines into categories were devised that would permit one to (1) eliminate quickly those phenomena that, even though technically feasible, would not be operationally feasible, and (2) eliminate phenomena showing no promise of high search rates.

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2.0 (S) THE FIELD APPROACH (U)

2.1 (U) CATEGORIES OF FIELDS

(U) To bring the problem into focus the question was asked: "How do sensors work in general?" Except for the relatively improbable case of direct mechanical contact between the sensor and the submarine (e.g., contact mines, noisemakers that attach themselves magnetically to the submarine hull, arrays of fine fibers or nets suspended in the water to which radar reflecting balloons or chemical dispensers are attached), all detection techniques can be described in terms of "fields." These fields may be divided into four categories:

1. Generated by the submarine
2. Generated by the sensor
3. Existing independently but affected by the submarine
4. Interactive sensor- and submarine-generated fields.

Each of these categories will be treated in subsequent sections of this report.

2.2 (S) FACTORS AFFECTING SEARCH METHOD AND RATE (U)

(U) The choice of a method for searching for submarines and the rate at which search can be conducted depend upon a number of factors such as (1) initial intensity and falloff rate of the phenomenon associated with the submarine, (2) dimensional aspects of the phenomenon, the sensor, the space to be searched and of the background noise, and (3) media and interface factors.

2.2.1 (U) Initial Intensity and Falloff Rate

(U) It is axiomatic that the sought-for phenomenon associated with the submarine must exhibit an intensity that is initially large relative to background noise and fundamental platform noise in both the temporal and spatial domains. Physically quantifiable effects typically vary with distance from the source as r^{-2} for the case of a point or spherically symmetric source (e.g., acoustic field), as r^{-3} for a dipole field (e.g., magnetic field), as r^{-4} for the gradient of a dipole field (e.g., gradient of the magnetic field) or as e^{-r} (e.g., light traveling through water). The foregoing considerations effectively eliminate phenomena that possess other desirable dimensional, media and interface attributes. An example of the latter is the dipole gravitational field anomaly of a submarine which, at a distance of 500 meters, is so small that a 0.4- μ m vertical displacement of the sensor in the earth's gravitational field would produce a spurious "signal" equivalent to that from the submarine.

2.2.2 (S) Dimensional Aspects (U)

(U) Other important factors related to potential search rates are the dimensional aspects of the fields involved. Fields generated by the submarine may exist and/or propagate in one, two or three dimensions. Examples of one-dimensional effects are the essentially line-like trails of contaminants (e.g., zinc and copper ions) and turbulence produced by a moving submarine which persist at the depth at which they were generated. See figure 2.1.

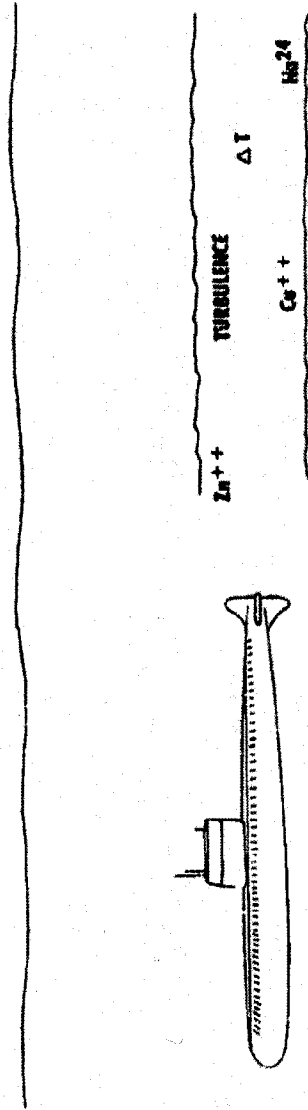
Examples of submarine-generated effects that propagate in two dimensions are the V-shaped pattern of waves (Kelvin wake) that spreads out in a horizontal plane on the ocean surface (figure 2.2) and the array of bubbles that rise at different rates behind a (moving) submarine in the form of a vertical plane in the body of water (figure 2.3).

Examples of three-dimensional effects are the magnetic, gravitational and acoustic fields produced by the submarine. See figures 2.4, 2.5 and 2.6.

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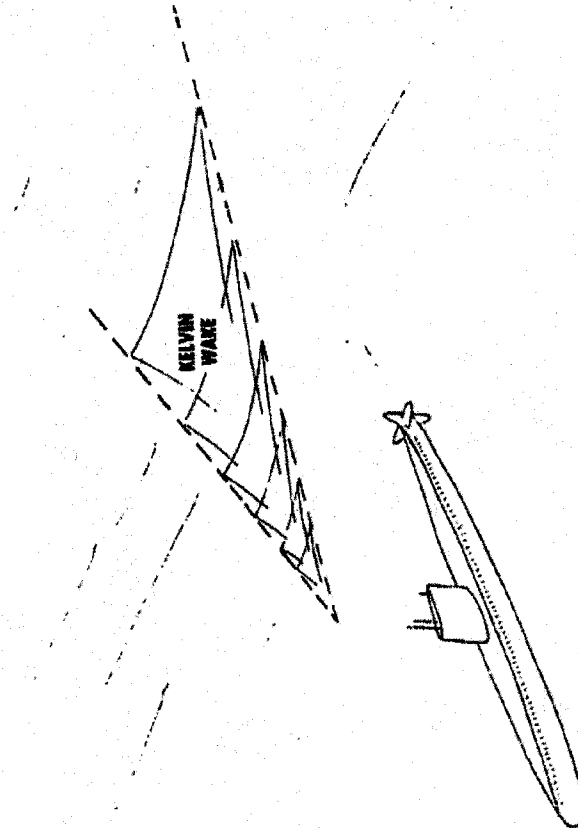


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Figure 2 1 (U) One-Dimensional Fields Of A Submarine In Three-Dimensional Space

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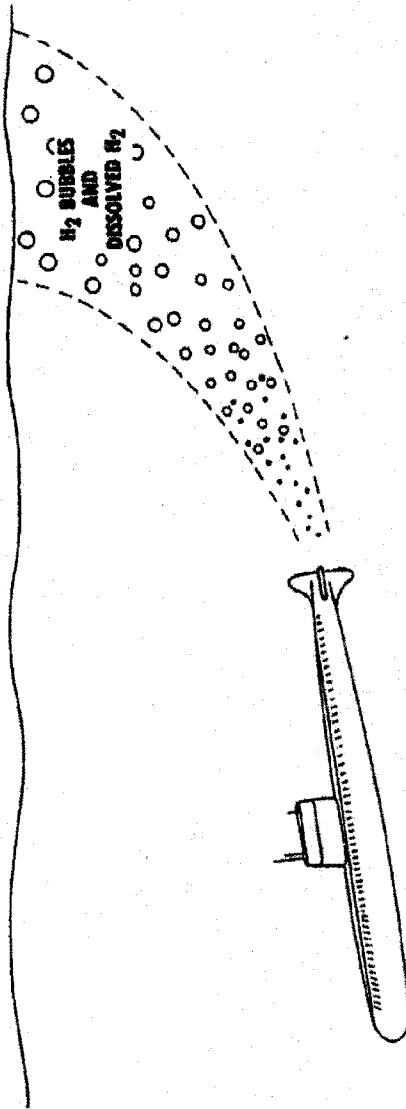


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Figure 2.2 (U) Two-Dimensional (Horizontal) Field Of A Submarine In Two-Dimensional Space

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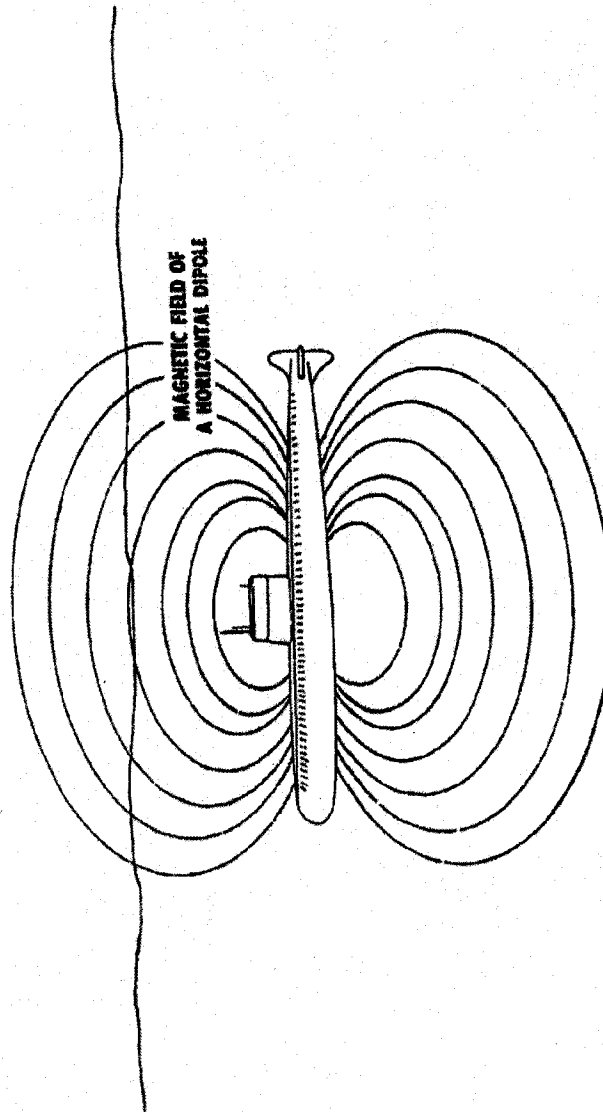


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Figure 2.3 (U) Two-Dimensional (Vertical Curtain) Field Of A Submarine In Three-Dimensional Space

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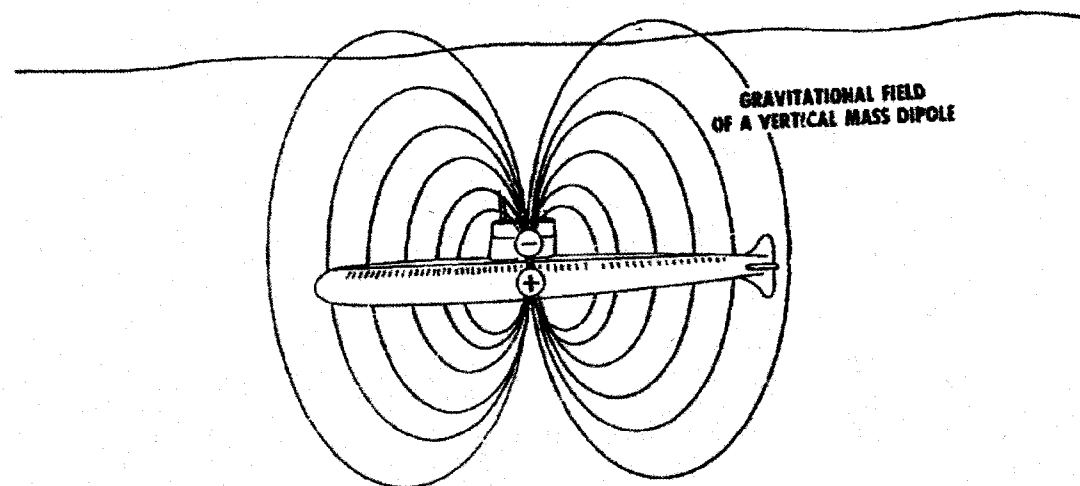


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Figure 2.4 (U), Three-Dimensional (Horizontal Dipole) Field Of A Submarine In Three-Dimensional Space

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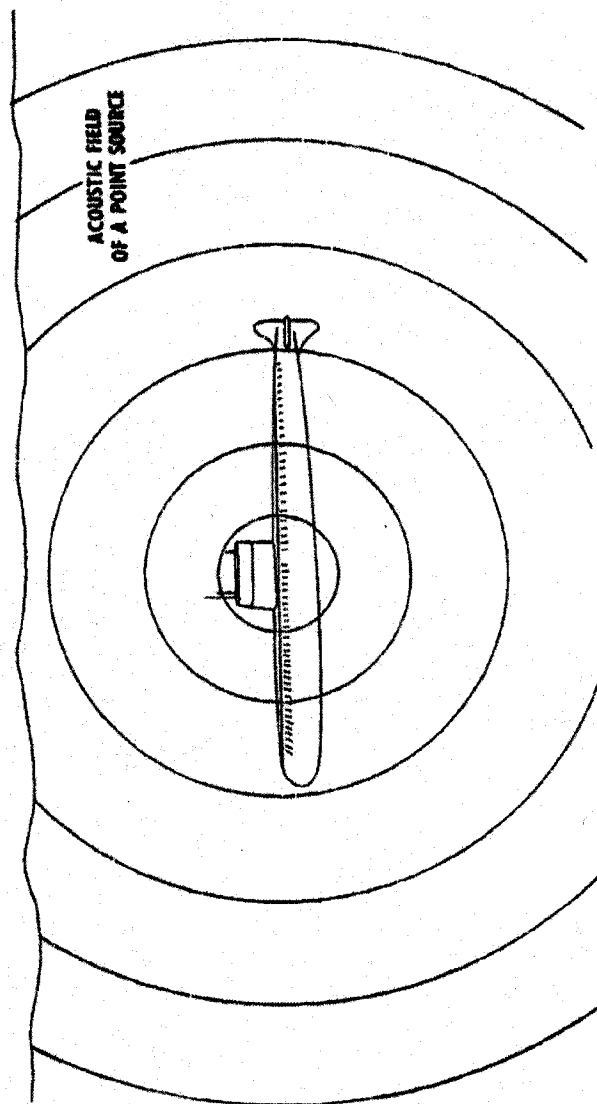
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Figure 2.5 (U) Three-Dimensional (Vertical Dipole) Field Of A Submarine In Three-Dimensional Space

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Figure 2.6 (U) Three-Dimensional (Point Source) Field Of A Submarine In Three-Dimensional Space

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(U) In a related manner, sensors can operate in zero, one, two or three spatial dimensions. A simple (single-hydrophone) sonobuoy and a stationary magnetometer (e.g., in a magnebuoy) are point (zero-dimensional) sensors which, of themselves, have no outreach capability. (The submarine-generated fields must come to them.) A magnetometer in a moving aircraft may be considered as operating in one dimension, with detection by it depending upon whether the line that it describes penetrates the three-dimensional magnetic anomaly of the submarine. Examples of two-dimensional sensors are the passive imaging devices such as conventional television, forward looking infrared (FLIR) and photographic cameras. (Here it may be argued that these sensors interrogate a three-dimensional volume but collapse it to a two-dimensional image.) Examples of three-dimensional sensors are range-gated active television, optical radar and stereoscopic cameras.

(C) Another dimensional aspect involves the space that must be searched to detect a submarine-generated effect. For example, to detect nongaseous contaminants (such as zinc or copper ions), which would remain essentially at the (unknown) depth of the submarine that produced them, would require a search in three dimensions within the body of the water. On the other hand, if a submarine were to produce contaminants that would rise to and remain at/near the air-water interface, a search need be conducted in only two dimensions.

2.2.3 (U) Media And Interface Constraints

(U) Another significant factor affecting search rate is the medium (or media) (air, or water, or both) in which the submarine-generated effect exists. Because the density of water is about 800 times greater than that of air and its viscosity is about 55 times greater, drag forces limit the speed at which it is feasible to move a sensor through water to a small fraction of the speed feasible through air. Accordingly, in the interest of high search rates, primary attention should be given to submarine-generated effects that are detectable by airborne sensors.

(U) Another important consideration is that most fields that exist comfortably in one medium (e.g., sea water) do not couple well into a second medium (e.g., air) because of interface losses, transmission losses, or both. Notable exceptions to this rule are the static magnetic and gravitational fields of a submarine which are essentially indifferent to whether the surrounding medium is air or water. A second exception is the Kelvin wake which exists at (and because of) the interface between air and water. On the other hand, electromagnetic radiation over quite wide frequency bands propagates very well through air but very poorly through sea water except at extremely low frequencies and within a narrow band in the visible part of the spectrum. Sound (particularly at low frequencies) propagates very well through water and fairly well through air but, because of a 4.4 to 1 mismatch in the speeds of propagation in the two media, very little passes from one to the other unless some kind of impedance matching "transformer" bridges the interface.

2.3 (U) DESIRABLE ATTRIBUTES OF SUBMARINE-INDUCED PHENOMENA

(U) The object of the quest for phenomena applicable to submarine detection ideally should possess the following attributes:

1. always occurring
2. direct coupling with the submarine
3. distinctive signature
4. quantitative understanding exists
5. immunity to countermeasures
6. provides a positive indication of the exact present position, heading, speed, depth and class of the submerged submarine
7. can be coupled with a remote sensor
8. no expendables required.

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(U) Some potentially exploitable phenomena occur regardless of the environment and others are critically dependent upon the vagaries of the environment. For example, a moving submarine will always produce acoustic noise and a turbulent wake; on the other hand, certain other phenomena require the submarine to operate in or near a region of large density gradient or in a region where certain biological organisms exist.

(U) Some otherwise desirable phenomena, for example, long-lived wake effects, are only weakly coupled to the submarine that generated them. There is little advantage to detecting a portion of a wake that may be three hours old unless there is some confidence that the wake is essentially continuous and that the other end is still "attached" to the submarine.

(U) Certain types of submarine-generated phenomena differ from natural background phenomena only in degree whereas others differ in spatial configuration or in kind. Obviously, the more distinctive the signature, the better.

(U) Predictability of submarine-generated effects stems from a quantitative understanding of the phenomena involved.

(U) Certain types of submarine-induced phenomena can be turned off quite readily by a submarine threatened by detection. Such simple countermeasures might include changing depth to avoid passing through a field of bioluminescent organisms or to avoid generating internal waves at the pycnocline.

(U) By considering factors such as the foregoing, one should be able to identify and eliminate potential techniques that show little likelihood of developing into operational sensors and to focus attention on those that possess the attributes necessary for fleet acceptance.

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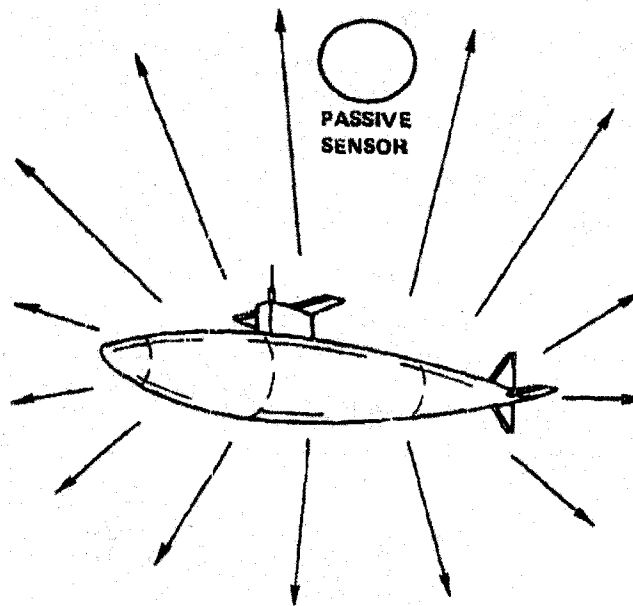
3.0 ~~(S)~~ "FIELDS" GENERATED BY THE SUBMARINE (U)

(U) Figure 3.1 illustrates a generalized situation of a passive point (zero-dimensional) sensor immersed in a field produced by a submarine. In this drawing, the air-water interface is not shown to allow for the possibilities that the submarine may be on the surface or submerged and that the sensor may be above, at, or below the interface. The submarine may be at rest or in motion.

3.1 ~~(S)~~ SUBMARINE AT REST (U)

~~(S)~~ If the submarine is at rest, it may produce the following fields:

1. Steady magnetic field
2. Steady electric field
3. Gravitational field
4. Neutron field
5. Gas bubble field
6. Field of dissolved non-gaseous chemical contaminants.



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Figure 3.1 (U) Passive Point Sensor In A Submarine-Generated Field

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3.1.1 ~~(S)~~ Steady Magnetic Field (U)

~~(S)~~ Steady magnetic fields originate from the "permanent" and induced magnetization of the ferromagnetic material constituting the hull of the submarine and from galvanic corrosion currents flowing through the submarine and the surrounding water. A submarine may develop a "permanent" magnetic moment as a result of long-term alignment with the earth's magnetic field (e.g., in a shipyard during construction or while berthed in a dock). Permanent magnetization is enhanced if, while the submarine is aligned with the earth's field, its hull is heated or is stressed through vibration, mechanical shock or submergence. (From the point of view of reducing their magnetic moments, it may be desirable to construct and berth submarines in an east-west orientation.) The ferromagnetic material of the submarine (even if it is not "permanently" magnetized) also distorts the earth's fairly uniform magnetic field. This distortion can be described as if it originates from a temporary induced magnetic field produced by the submarine. The anomaly in the earth's magnetic field produced by a submarine is a function of its orientation; its magnitude is greatest for a north-south alignment. For purposes of computation, a "standard" submarine is generally considered to behave as a magnetic dipole having a representative moment of about $1.4 \times 10^8 \text{ A} \cdot \text{m}^2 = 1.4 \times 10^8 \text{ gauss} \cdot \text{cm}^3 = 5,000 \text{ gauss} \cdot \text{ft}^3 = 5 \times 10^8 \text{ g} \cdot \text{ft}^3$. Current operational magnetic anomaly detecting equipments exhibit an internal-noise-limited sensitivity of about $10^{-11} \text{ tesla} = 10^{-7} \text{ gauss} = 10^{-2} \text{ nT} = 10^{-2} \text{ g}$. Because the field of a magnetic dipole varies inversely as the cube of distance, this type of sensor must penetrate into the magnetic field of the submarine to a distance of less than about 1,100 meters (3,600 ft) from the submarine in order to detect it. If the sensor could be made to operate at this sensitivity level in a 225-knot, low-altitude aircraft, it would provide an area coverage rate of about 270 square nautical miles per hour, which is an order of magnitude less than that desired for a search sensor. The magnetic anomaly of a submarine can be reduced by passing large current through "degaussing" coils or by constructing it of nonferromagnetic material.

~~(S)~~ Another source of a steady magnetic field from a submarine is that arising from galvanic corrosion currents. The bronze propeller forms the positive terminal and zinc blocks attached to the steel hull (to protect the hull from corrosion) form the negative terminal of a galvanic cell when they are immersed in sea water, producing an electromotive force of about one volt. The positive terminal is short-circuited to the hull through the propeller shaft and its bearings, resulting in currents of 10 to 100 amperes flowing through the low-resistance path of the submarine and the surrounding water. Because of random variations in the degree of polarization of the electrodes as a function of time, these large steady currents are noise modulated. For a shallow submarine the current distribution in the water is unsymmetrical in the vertical plane and produces a horizontal magnetic dipole whose north-seeking pole is on the port side of the submarine and its south-seeking pole is on the starboard side. If a perfectly symmetrical current distribution should exist around the submarine, the magnetic field outside the current distribution would be zero.

3.1.2 ~~(S)~~ Steady Electric Field (U)

~~(S)~~ The electromotive force of galvanic origin described above produces a steady electric field in the vicinity of the submarine. In addition, submarine-generated temperature gradients (section 3.2.6) and chemical concentration gradients (section 3.1.6) in the water produce weak electric fields. These electric fields, which are essentially confined to the water, are detectable by means of electrodes immersed in the water. These phenomena do not lend themselves to a large area rapid search sensor.

3.1.3 (U) Gravitational Field

(U) In accordance with the law of universal gravitation, every mass particle produces a gravitational field that varies inversely as the square of the distance from the particle. Since a

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submarine has mass, it produces a gravitational field. Unfortunately, such gravitational effects are, at best, very small. In addition, a completely submerged, neutrally buoyant submarine displaces a mass of water equal to its own mass and therefore no first order effect is produced. However, because the distribution of mass within the submarine is nonuniform, second order effects may be produced.

(U) To provide stability, a submarine is designed such that its center of mass lies below its center of buoyancy. Because of the greater concentration of mass below and lesser concentration above, a submarine behaves gravitationally as a vertical mass dipole. The magnitude of the gravitational anomaly Δg at a distance r directly above the submarine is given by

$$\Delta g = \frac{2 G \mu}{r^3}$$

In which G is the universal gravitational constant and μ is the gravitational dipole moment. If the submarine is approximated as a neutrally buoyant cylinder of 8.4-m diameter and mass 7.12×10^6 kg (7,950 tons), and 55% of its mass is distributed uniformly throughout its lower half and 45% is in its upper half, its gravitational dipole moment $\mu = 1.19 \times 10^8$ kg·m and, at distance $r = 100$ m,

$$\Delta g = - \frac{2 \times 6.67 \times 10^{-11} \text{ N} \cdot \text{m}^2/\text{kg}^2 \times 1.19 \times 10^8 \text{ kg} \cdot \text{m}}{100^3 \text{ m}^3} = -1.59 \times 10^{-10} \text{ m/s}^2$$

(U) If the gravitational sensor is to be employed on an aircraft, attention must be directed toward the "noise" generated by movement of the sensor. The variation in the acceleration due to gravity g with distance from the center of the earth r_E is

$$\frac{dg}{dr_E} = - \frac{2g}{r_E} = - \frac{2 \times 9.81 \text{ m/s}^2}{6.37 \times 10^6 \text{ m}} = -3.08 \times 10^{-6} \text{ s}^{-2}$$

The change in sensor altitude dr_E that would produce a spurious "signal" equal to the signal from a submarine at a range of 100 m is therefore

$$dr_E = \frac{-1.59 \times 10^{-10} \text{ m/s}^2}{-3.08 \times 10^{-6} \text{ s}^{-2}} = 5.16 \times 10^{-5} \text{ m} = 51.6 \text{ } \mu\text{m}$$

That is, the sensor must be stable or compensated to less than 51.6 μm in altitude if a detection range of only 100 m is to be achieved. This subject is treated in greater detail in reference (a). It does not appear worthwhile to pursue the concept of gravitational detection of submarines.

3.1.4 ~~(S)~~ Neutron Field (U)

~~(S)~~ The leakage of neutrons from the reactor of a nuclear submarine can be detected beneath its hull either directly or by means of radioactivity induced in the sea water. Radioactive isotopes of sodium and chlorine are produced which have half lives of the order of an hour. Detection can be accomplished either by towing a gamma ray counter through the water or by taking water samples.

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concentrating them by boiling, and counting the gamma ray emissions. The probability of intercepting a small region of induced radioactivity by a zero-dimensional (point) sensor or sampler is very low; this approach does not lend itself to search.

3.1.5 (S) Gas Bubble Field (U)

(S) A submarine may introduce into the surrounding seawater a variety of gases which will rise in the form of small bubbles having diameters of the order of a centimeter or less. The size of any given bubble as it rises depends upon a number of competing effects: decreasing pressure and increasing temperature tend to increase its size and the dissolving of the gas tends to reduce its size. If the net effect is an increase in size as the bubbles rise, they may grow so large as to become unstable and thus subdivide repeatedly into smaller bubbles. The larger bubbles rise at greater rates and have a smaller ratio of surface area to volume relative to the smaller bubbles; therefore a larger portion of the gas contained in the larger bubbles will arrive at the surface. The gases introduced into the water may include air that attached itself to the exterior of the hull while the submarine was on the surface, or air leaking from the interior of the submarine. If the submarine generates breathing oxygen for the crew by the electrolytic decomposition of water, hydrogen gas is produced as a waste product, which must be eliminated continuously or intermittently. The oxygen consumption of a man at rest is about 0.5 liter/minute. Because in the electrolysis of water two molecules of hydrogen are produced for each molecule of oxygen, one liter of hydrogen is produced per man per minute. If the crew consists of 120 men (all at rest), hydrogen will be produced and vented at an average rate of 120 liters/minute (4.24 cu ft/min) referred to standard temperature and pressure. Another source of hydrogen and oxygen is the electrolysis of water by the galvanic corrosion currents described previously. If a current of 10 amperes is flowing, the rate of liberation of hydrogen gas is no greater than

$$\frac{10 \text{ C/s}}{2 \times 1.6 \times 10^{-19} \text{ C/molecule}} = 3.1 \times 10^{19} \text{ molecules/s} = 0.07 \text{ liter/min.}$$

Oxygen is liberated at half the hydrogen rate. Even if the corrosion current is 100 amperes, the rate of evolution of gas (hydrogen and oxygen) by this mechanism is less than one percent of that from the oxygen generator.

(S) Another gas that is produced on the submarine and which may be vented to the ocean is carbon dioxide. Through respiration, the crew will produce this gas (along with water vapor) at a lower volume rate than it consumes oxygen (about 60 liters per minute). Because carbon dioxide is about 50 times more soluble than hydrogen in water and because natural sea background concentrations of carbon dioxide are much greater and much more variable than concentrations of hydrogen, its importance to submarine detection appears to be less than that of hydrogen.

(S) Gases in the ocean may be detected either as a column of rising bubbles (i.e., by physical means) or as a dissolved contaminant (i.e., by chemical means) in the water. Under certain conditions of relatively shallow source depth, a major portion of the emitted gas will enter the atmosphere and form an elongated trail under the influence of the wind. For the particular case being considered here (a passive sensor and a submarine at rest), the gas will exist in the form of an essentially one-dimensional column that may extend beyond the surface for which search with a zero-dimensional sensor would provide a low probability of success.

3.1.6 (S) Nongaseous Contaminant Field (U)

(S) A submarine also introduces into the water nongaseous contaminants such as zinc ions from the electrolytic corrosion processes discussed earlier and copper ions from the antifouling

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paints. Because the same electrochemical processes are involved with zinc as for the hydrogen produced through galvanic corrosion described earlier, it can be expected that the number of Zn^{++} ions going into solution will not exceed the number calculated previously for the maximum number of hydrogen (H_2) molecules liberated from the water. For a current of 10 amperes, therefore, Zn^{++} ions will be produced at a maximum rate of

$$3.1 \times 10^{13} \text{ ions/s} = 5.2 \times 10^{-3} \text{ moles/s} = 3.4 \times 10^{-3} \text{ gram/s} = 0.20 \text{ gram/min.}$$

The natural background concentration of Zn^{++} in sea water is about 0.01 mg/liter. For a submarine at rest to produce an increase in Zn^{++} concentration equal to the background level in a volume of water equal to its own volume would require it to remain in the same location for 5.7 hours. The natural background concentration of Cu^{++} of about 0.003 mg/liter is somewhat more favorable for the detection of small increments but still unpromising.

3.2 (S) SUBMARINE IN MOTION (U)

(C) If the submarine is in motion it will produce not only the "fields" discussed previously but also the following additional "fields":

1. Time-varying electric field (corrosion, motional)
2. Time-varying magnetic field (corrosion, motional)
3. Stray 50/60/400-Hz electromagnetic field
4. Kelvin wake
5. Turbulent wake
6. Thermal wake
7. Gaseous contaminant wake
8. Nongaseous contaminant wake
9. Hydrodynamic pressure field
10. Acoustic (pressure, displacement, velocity) field
11. Electromagnetic radiation (radio, radar, infrared, light, gamma rays)

3.2.1 (S) Time-Varying Electric Field (U)

(S) Time-varying electric fields can be produced by modulation of the galvanic corrosion currents described previously and by motion in the earth's magnetic field of the submarine and the water in its wake. Corrosion currents may be modulated at the propellor rotation frequency because of small variations in electrical resistance between the propellor shaft and its bearings as a function of the shaft's angular position. Because these variations are "spikey," the modulation is rich in harmonics.

(S) Modulation may also occur at the "blade rate" (propellor rotation frequency times the number of blades on the propellor) owing to periodic variations in the length of the path between the blades and portions of the submarine hull. The modulated currents themselves may also be modulated at the swell and wave encounter frequencies.

(S) Because large electric currents pass through the hull, small changes in resistance of the hull may produce time-varying electric fields. Such resistance changes could be caused by vibration from on-board machinery, rattling hatch covers and perhaps even loud sounds within the submarine.

(C) Time-varying electric fields from a submarine can be measured by measuring the potential differences between pairs of electrodes placed in the water.

(C) Because submarines and sea water are electrical conductors, their motions through the

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earth's magnetic field will give rise to local electric field anomalies. If the vertical component of the earth's magnetic induction is B , the width of the submarine is w and its speed is v , then, from Faraday's law, the emf $\mathcal{E}$ generated across the submarine is

$$\mathcal{E} = B w v.$$

For a 10-knot, 10-meter wide submarine in a field of 0.5×10^{-4} tesla, $\mathcal{E} = 2.6$ mV, which is less than one percent of the emf from galvanic corrosion and therefore not of great significance.

(c) The motion imparted to the water by the submarine may take a number of forms such as turbulence, vortices, surface waves and internal waves which may persist for significant times. To get some idea of the magnitudes of the fields involved, consider the submarine-generated surface wave case. To a first approximation, the magnitude of the electric field strength E along the transverse waves of the Kelvin wake is given by

$$E = B v.$$

(These waves propagate at the speed of the submarine.) Therefore, for a 10-knot submarine, $E = 2.6 \times 10^{-4}$ V/m. Fields of this magnitude should be readily measurable with electrodes immersed in the water. However, distinguishing submarine-generated effects from natural background noise would be challenging. Furthermore, there appear to be better ways for detecting moving water.

3.2.2 (b) Time-Varying Magnetic Field (U)

(c) Time-varying magnetic fields are produced by the motional emf currents and the modulated corrosion currents discussed above. Consider first the magnetic field from a single Kelvin wave. For sea water of resistivity $\rho = 0.25$ ohm·m, the current density along the wave is

$$j = E/\rho = \frac{2.6 \times 10^{-4} \text{ V/m}}{0.25 \text{ ohm} \cdot \text{m}} = 1.03 \times 10^{-3} \text{ A/m}^2.$$

If the wave is assumed to have a cross-sectional area of 1 m^2 , then the current it will carry will be 1.03 mA. The magnetic induction B that it will produce at a range of $r = 10 \text{ m}$ is

$$\begin{aligned} B &= \frac{\mu_0 I}{2\pi r} = \frac{2 \times 10^{-7} \text{ Wb/A} \cdot \text{m} \times 1.03 \times 10^{-3} \text{ A}}{10 \text{ m}} = 2.1 \times 10^{-11} \text{ Wb/m}^2 \\ &= 2.1 \times 10^{-7} \text{ gauss} = 0.021 \gamma. \end{aligned}$$

This would be barely detectable by a current fleet operational airborne magnetometer operated at a very low altitude of 10 m under conditions of very low sea state. There are better ways for detecting waves (e.g., visually).

(c) Consideration has been given to the possibility of detecting submarine-generated internal waves by use of magnetic sensors. This appears futile for a number of reasons: (1) There is a low joint probability that a large density gradient will exist and that the submarine will be operating

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in, near it; (2) The internal wave generating efficiency of a normally operating submarine is very low; and (3) The very slow movement of the water in an internal wave field interacting with the weak magnetic field of the earth will yield very small currents and correspondingly weak magnetic effects.

✓ From the point of view of time-varying magnetic effects produced by modulated corrosion currents, a submarine may be considered as a horizontal alternating electric current dipole. Assume that the total galvanic corrosion current is 25 A and that most of this is confined to the aft half of a 100-m long submarine. Assume further that propellor shaft rotation produces a 1% modulation of this total current. Thus, the alternating current moment of the submarine will be

$$i dl = 0.01 \times 25 \text{ A} \times 0.5 \times 100 \text{ m} = 12.5 \text{ A} \cdot \text{m}.$$

From the Biot-Savart law, the contribution to the magnetic induction along the perpendicular bisector of the dipole at a range $r = 1 \text{ km}$ is

$$dB = \frac{\mu_0 i dl}{4\pi r^2} = \frac{10^{-7} \text{ Wb/A} \cdot \text{m} \times 12.5 \text{ A} \cdot \text{m}}{10^6 \text{ m}^2} = 1.25 \times 10^{-12} \text{ tesla} = 1.25 \times 10^{-8} \text{ gauss} = 1.25 \times 10^{-3} \gamma.$$

This is small compared to the magnetic induction at the same range from the ferromagnetic material of the "standard" submarine discussed previously. However, there may be advantages to this detection approach because the signals may be more readily distinguishable from noise because their fundamental frequency will equal the submarine's propellor shaft rotational rate and because the magnitude of this effect varies inversely as the square of distance whereas the effects of ferromagnetic origin vary inversely as the cube of distance.

3.2.3 (U) Stray 50/60/400-Hz Electromagnetic Field (U)

(U) Alternating current at frequencies such as 50, 60 and 400 Hz is used typically aboard submarines for ship's service motors of less than 25 horsepower. Some of these currents may leak into the hull of the submarine and give rise to time-varying external magnetic fields. It appears, however, that in a properly maintained submarine, such hull currents do not normally exist and therefore a method of detection based upon this effect would yield a low probability of detection.

3.2.4 (U) Kelvin Wake (U)

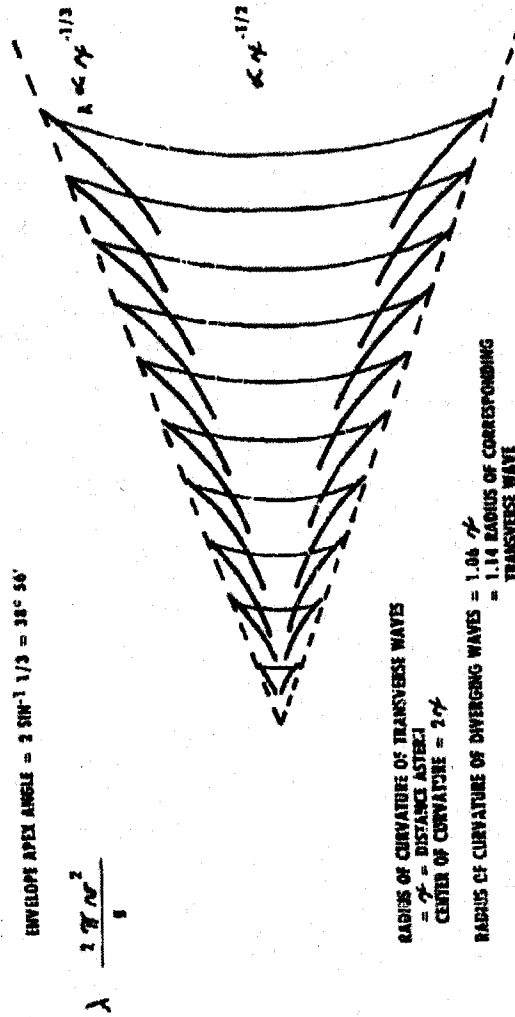
(U) A submarine passing through a body of water produces a pattern of waves on the surface that is called a Kelvin wake. See figure 3.2. The wavelength of these waves and, to a first approximation, their amplitude are proportional to the square of the speed of the submarine. The amplitude increases with increasing submarine size and decreases exponentially with increasing submarine depth. For a submarine travelling at constant velocity, the wave pattern is contained within a triangular envelope whose vertex is over the submarine and which forms an angle of approximately 39°. The amplitudes of the waves along the center line of the wake vary inversely as the square root of the distance from the submarine. An example of a class of passive sensors that could be inserted into the Kelvin wave field is a wave buoy that could measure water surface displacements by any one of a variety of methods. An array of such buoys could be used to obtain directional wave spectra. The buoy approach does not lend itself to large area search; the detection of Kelvin waves by more practicable means is covered in section 6.2.

(U) In this calculation the magnetic effects of the return path currents through the sea water have been ignored. These effects will tend to act in the opposite direction and to reduce the overall effect relative to that calculated here.

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RADIUS OF CURVATURE OF TRANSVERSE WAVES

$= \lambda =$ DISTANCE ASTER

CENTER OF CURVATURE $= 2 \lambda$

RADIUS OF CURVATURE OF DIVERGING WAVES $= 1.06 \lambda$
 $= 1.14$ RADIUS OF CORRESPONDING TRANSVERSE WAVE

OVER THE STEER

$$A_{\text{ECKART}} = \frac{1}{2} \frac{v^2}{g} \left(\frac{d}{h} \right)^3$$

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Figure 3.2 (U) Kelvin Wake

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3.2.5 (C) Turbulent Wake (U)

(C) A significant portion of the energy developed by a submarine's power plant is dissipated in the form of water turbulence which tends to be confined to a cylindrical tube of about 20-m radius at the depth of the submarine. This turbulence may continue to exist, at levels exceeding normal background values, for periods of several hours after passage of a submarine. This type of wake may be considered as a one-dimensional field in three-dimensional space. Searching for such a phenomenon with a zero-dimensional (point) sensor would yield a low search rate and a low probability of detection. If the submarine's depth is about 20 m or less, the turbulent wake may intersect the surface. In this special case the probability of detection is enhanced insofar as one need search in only two dimensions (vice three) for this one-dimensional field. Passive point sensors of many types can be used to detect wake turbulence. These include sensors that are moved mechanically through the water to detect microfluctuations in its temperature, pressure, index of refraction, sound propagation velocity, or heat absorption rate. Because such sensors must be inserted into the wake, they do not yield high search rates. However, for detecting the surface expression of turbulent wakes generated by shallow submarines, indirect methods such as passive infrared (thermal) imaging can be used to enhance search rates. In this case, an imaging device that can scan (the sea surface) in two dimensions is used to search for a one-dimensional wake in two-dimensional space. Infrared line scanners can detect both temperature changes in the wake (e.g., from the movement of cool subsurface water to the surface and the reordering of naturally existing sea surface thermal patterns) and emissivity changes (e.g., from a smoothing of the water surface in the wake). The persistence of turbulent wakes generated by shallow depth submarines and detectable by infrared line scanners is given in reference (b) by the empirical relation $T = 120 e^{-1.05 S}$ in which T is the mean persistence time in minutes and S is the sea state according to the Naval Oceanographic Office Code. The detectable wake length L is the product of the submarine speed v_s and the persistence time. For L in nautical miles and v_s in the knots, $L = 2.0 v_s e^{-1.05 S}$. Thus for a submarine speed of 10 knots and sea state 1 the mean detectable wake length would be 7.4 nmi. If all wake orientations are equally probable, the average component of wake length perpendicular to the direction of travel of the search sensor would be $2/\pi$ times this length or 4.7 nmi. If it is assumed that the infrared scanner provides a sweep width of 1 nmi and that interception of a 0.4-nmi portion of the wake is adequate for detection, the sensor would provide an effective sweep width of 9.9 nmi. An aircraft speed of 250 kn would therefore provide an effective search rate of about 2,500 nmi² per hour. A more general expression for the effective area search rate A_n in nmi²/hr is

$$A_n = \left[\frac{8 v_s}{\pi e^S} + \frac{h}{3,040} \tan \frac{\theta}{2} - 0.51 \right] v_a$$

in which v_a is the search aircraft's speed in knots, h is its altitude in feet and θ is the total lateral angular field of view of the infrared scanner. For a typical value of $\theta = 120^\circ$ and an assumed aircraft altitude of 2,000 feet (to remain below the cloud base) the minimum area search rate goal of 1,500 nmi²/hr can be achieved or exceeded, for sea state 1, if the condition

$$v_a (v_s + 0.68) \geq 1,630$$

is met. Thus the 1,500 nmi²/hr search rate goal could be achieved for shallow depth submarines under conditions of low sea state for various combinations of reasonable aircraft and submarine speeds.

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3.2.6 (C) Thermal Wake (U)

(C) All of the energy developed by a submarine's power plant is degraded eventually into heat. A submarine developing 25,000 shaft horsepower imparts mechanical energy to the water at the rate of 18.6 MW. If the power plant is 25% efficient, an additional amount of power $P = 55.8$ MW is imparted to the water directly in the form of heat. If only the latter heat is assumed to raise uniformly the temperature of an 8.4-m diameter (d) cylinder of water astern a 20-kn (speed $v = 10.3$ m/s) submarine, the increase ΔT in water temperature will be

$$\Delta T = \frac{4P}{\pi d^2 \rho v c} = \frac{4 \times 55.8 \times 10^6 \text{ W}}{\pi \times 8.4^2 \text{ m}^2 \times 1030 \text{ kg/m}^3 \times 10.3 \text{ m/s} \times 4186 \text{ J/kg} \cdot \text{K}} = 0.023 \text{ K}.$$

In the above expression, ρ is the density of sea water and c is its specific heat capacity.

(C) Despite the large rate of heat influx, the rise in water temperature is surprisingly low; so low, in fact, that little upward movement of the heated water can be expected. (That is, in ocean waters having a typical vertical temperature gradient, the heated water may rise less than a meter before it comes into thermal equilibrium with its surroundings. In isothermal water, viscous drag forces would inhibit vertical motion of the heated water.) Thus, if heated water from a submarine is to be detected, it must be done at/near the depth of the submarine itself. Because the expected temperature rise is comparable to the natural variations in sea water temperature and because dragging a sensor through the water would yield low search rates, this approach to detection does not appear promising.

(C) Because sea water is an ionic solution, an electric potential difference will develop across the thermal gradient between the warm wake and the cooler adjacent water. Electric currents will be produced and a weak magnetic field will result. It is expected that the magnetic field resulting from the warm wake will be unusably small.

3.2.7 (S) Gaseous Contaminant Wake (C)

(C) The evolution of gaseous contaminants by a stationary submarine was considered previously. The effect of forward motion of the submarine is to extend the one-dimensional vertical column of rising gases to a two-dimensional vertical curtain of bubbles and dissolved gases, provided that there is a significantly wide distribution of bubble sizes and therefore rise rates. The trail of dissolved gases could be detected by towing a zero-dimensional (point) electrochemical sensor through the water at any convenient shallow depth. The curtain of bubbles could be detected by active physical means such as the scattering of sound or light. The remote detection of bubbles by the latter means will be considered later under field-field interactions.

(S) It follows from the earlier discussion of contaminants that the most likely candidate for detection is hydrogen. For present purposes of calculation, assume that a 200-foot deep, 10-knot submarine is releasing hydrogen continuously at a rate of 120 liters/minute (reckoned under conditions of standard temperature and pressure) and that all of the gas dissolves in the water as it rises. Assume further that the hydrogen is distributed uniformly in a vertical slab of water one submarine diameter wide (taken here as 8.4 meters) and 200 feet (61 meters) thick. Since the submarine travels 309 meters in one minute, the concentration of hydrogen in this slab will be

$$\frac{120 \text{ liters/min}}{8.4 \text{ m} \times 61 \text{ m} \times 309 \text{ m/min}} = 7.6 \times 10^{-4} \text{ liters/m}^3 = 7.6 \times 10^{-4} \text{ ml/l}$$

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which, in calm seas, could remain quite constant and coherent for periods of several hours because of the low diffusion rates in liquids. This concentration is about 50 times greater than the normal ambient concentration of hydrogen in sea water and well within the range of sensitivity of electrochemical sensors using polarographic techniques or operating on the principle of a hydrogen fuel cell. It appears that the principal erasure mechanism tending to destroy the coherence of the trail of dissolved hydrogen would be current shear in the water whose magnitude and frequency of occurrence are not well known at present. For a sample calculation, if it is assumed that the trail of a 10-knot submarine remains detectable and recognizable for three hours, the average effective projected length of the trail would be $2/\pi \times 3 \text{ hrs} \times 10 \text{ nmi/hr} = 19.1 \text{ nmi}$. If the sensor can be towed through the water at a speed of 30 knots, an area search rate of 573 nmi²/hr could be achieved. If the sensor is towed from a ship, care must be exercised to avoid the molecular hydrogen introduced into the water from the galvanic corrosion of the towing vessel.

3.2.8 (C) NONGASEOUS CONTAMINANT WAKE (C)

(C) Nongaseous contaminants such as zinc and copper discussed earlier will form a one-dimensional line-like trail behind a submarine that will tend to remain at the constant depth of the submarine. An earlier calculation yielded a representative rate of Zn⁺⁺ production of 0.20 gram/min. If this is distributed uniformly within a cylindrical volume having a cross-sectional area equal to that of a submarine (taken as 55 m²) traveling at 10 knots, the concentration of Zn⁺⁺ would be

$$\frac{0.20 \text{ g/min}}{55 \text{ m}^2 \times 309 \text{ m/min}} = 1.2 \times 10^{-5} \text{ g/m}^3 = 12 \text{ ng/liter}$$

which is only about 0.1% of the natural background level.

(U) The detection of contaminants in a wake that remains at the depth of the submarine does not lend itself to large area rapid search because it involves moving a zero-dimensional sensor or sampler through a three-dimensional space in the search for an essentially one-dimensional target.

3.2.9 (C) Hydrodynamic Pressure Field (U)

(C) The movement of a ship or submarine through the water can produce local time-dependent variations in pressure. In shallow waters such as ship channels and harbors, bottom-mounted pressure sensors can detect the passage of a vessel and have been used to actuate explosive mines. This phenomenon does not appear to be of value in a search mission.

3.2.10 (C) Acoustic Field (U)

(U) An extremely small fraction of the total power developed in a submarine is radiated as sound; that is, even though the power developed by a submarine's engines may be of the order of 10 megawatts, only about 10⁻⁷ of this is emitted as sound. To a first approximation, a submarine may be considered as a point source of sound whose power output ranges within a few orders of magnitude of one watt depending upon the speed, depth, type and mode of operation of the submarine. The noise spectrum consists of a continuum of propeller (cavitation) noise and flow noise upon which lines corresponding to harmonics of the rotational rates of the various pieces of machinery are superimposed. The power radiated per unit bandwidth in the continuum varies inversely as frequency such that more than 95% of the radiated power is emitted at frequencies of less than 1 kHz. Because water is extremely transparent to sound and because sound sensors of except al

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sensitivity (including the human ear, with its sensitivity of about 10^{-16} W/cm²) are available, a moving submarine generates an acoustic field which may be detectable at ranges of many tens of miles.

(U) Sound may be detected by sensing variations in the macroscopic properties of pressure, density, temperature or index of refraction of the medium, or the microscopic properties of displacement, velocity or acceleration of the molecules. If it is assumed that a submarine radiates sound as a simple omnidirectional point source in a homogeneous, isotropic, nonlossy, unbounded medium, the intensity I at a range r is

$$I = \frac{P}{4\pi r^2}$$

where P is the radiated power.

The rms acoustic pressure p is given by

$$p = (\rho_0 c I)^{1/2}$$

In which ρ_0 is the mean density of the propagating medium and c is the speed of propagation.

The rms displacement x of the molecules is

$$x = \frac{p}{2\pi \rho_0 c f}$$

In which f is the frequency.

The rms velocity v of the molecules is given by

$$v = \frac{p}{\rho_0 c}$$

and the rms acceleration a is

$$a = \frac{2\pi f p}{\rho_0 c}$$

The rms density variation ρ is

$$\rho = \frac{\rho_0 p}{B} = \frac{p}{c^2}$$

in which B is the bulk modulus of elasticity of the medium.

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(C) Insofar as this study is concerned with the nonacoustic detection of submarines, a detailed discussion of present acoustic detection techniques would be beyond the scope of this report. The foregoing discussion has been provided to set the stage for subsequent discussions of "nonacoustic" detection of acoustic fields. Such "nonacoustic" techniques would include optical detection of index of refraction fluctuations associated with periodic changes in the density of the medium through which sound waves are passing, and microwave detection of the periodic displacement of its surface by use of Doppler radar techniques. It is unlikely that a "nonacoustic" point (zero-dimensional) sensor could be developed that could compete on performance and cost bases with conventional acoustic sensors that employ electromechanical transducers to sense pressure variations associated the acoustic field. A possible advantage of "nonacoustic" approaches would be the ability to detect the acoustic field remotely without the need for placing transducers in the water. Such approaches will be discussed under the heading of interactive sensor- and submarine-generated fields.

3.2.11 (C) Electromagnetic Radiation (U)

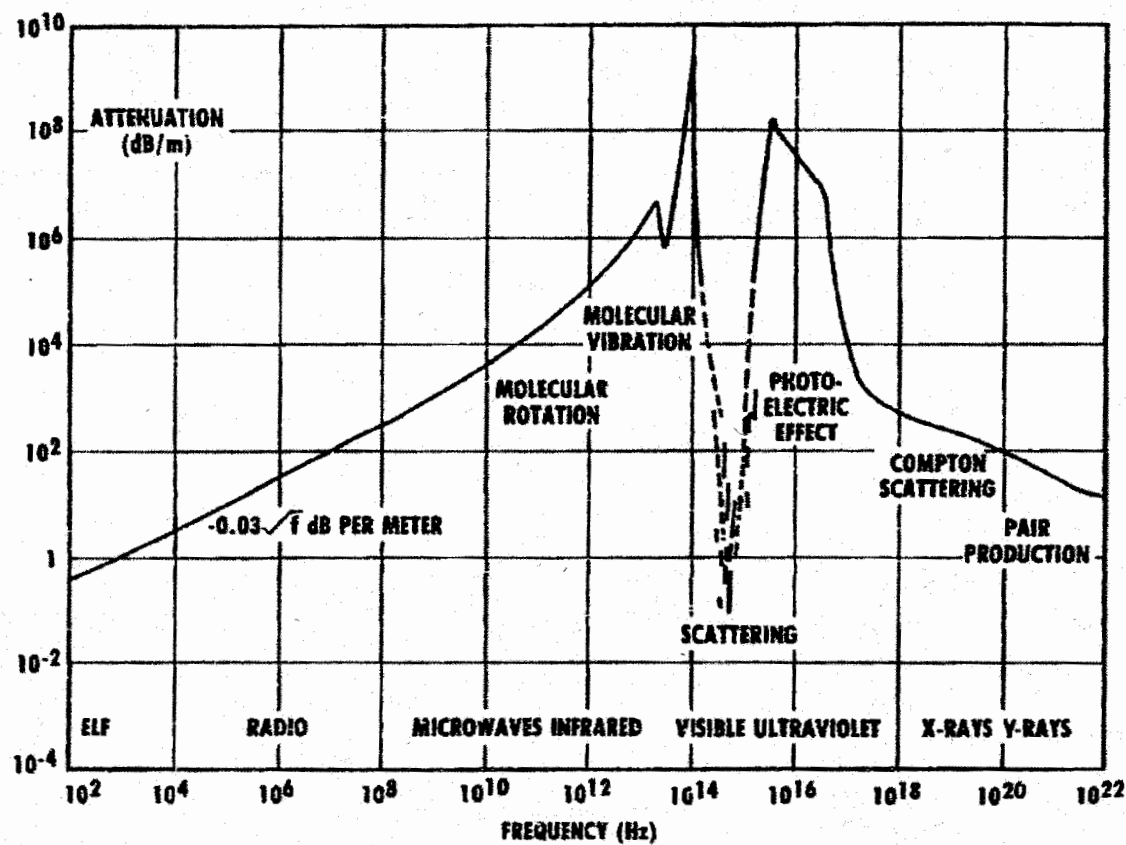
(C) A submarine may emit radiation in discrete intervals over most of the electromagnetic spectrum ranging from the extremely low frequency (ELF) radiation resulting from the modulation of corrosion currents discussed previously to gamma rays emitted from a nuclear reactor. At intermediate frequencies are radio waves from communication and navigation devices and electrical machinery, microwave radiation emitted by radars, infrared radiation emitted by the hull by virtue of its finite temperature, and visible light from deliberate light sources and from bioluminescent organisms that may be clinging to the hull. Unfortunately (from the submarine detection point of view), sea water is a rather hostile environment for electromagnetic radiation. Figure 3.3, which was adapted from reference (c), is a plot of the attenuation of electromagnetic radiation in sea water as a function of frequency from 10^2 to 10^{22} Hz.

Note that in only two portions of the spectrum, namely, in a narrow region about 6×10^{14} Hz (the visible light band) and at frequencies less than 10^2 Hz, does the attenuation drop to less than 1 dB per meter. At wavelengths near the center of the visible band, the attenuation by sea water ranges from about 0.1 to 1.0 dB/m. As indicated in figure 3.3, at the low frequencies the attenuation decreases as the square root of frequency. In this section of the report we are concerned only with the passive detection of submarine-generated fields. In normal operation a completely submerged submarine cannot be expected to be a significant source of light. The possibility of detecting submarine-generated extremely low frequency radiation has been discussed in conjunction with time-varying electric and magnetic fields arising from modulated corrosion currents.

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Figure 3.3 (U) Attenuation Of Electromagnetic Energy In Sea Water
(Conductivity of 3 siemens/meter was assumed)

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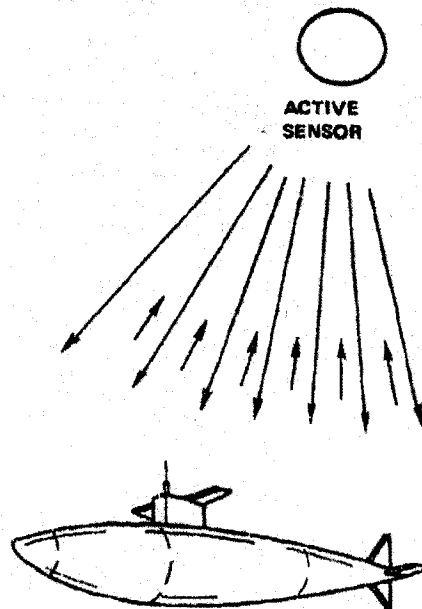
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4.0 (U) "FIELDS" GENERATED BY SENSORS (U)

(U) In this section are considered the various types of fields that can be generated by an active sensor which can, in principle, interact with a remote submarine and produce a detectable effect at the sensor as shown schematically in figure 4.1.

These fields include:

1. Electromagnetic radiation
 - a. ELF (extremely low frequency)
 - b. Radio frequency
 - c. Microwave
 - d. Infrared
 - e. Visible light
 - f. X-rays
2. Sound
3. Surface gravity waves
4. Internal gravity waves
5. Steady electric field
6. Steady magnetic field
7. Field of magnetic particles
8. Field of surface (water) current indicators



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Figure 4.1 (U) Submarine In A Sensor-Generated Field

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4.1 (C) VISIBLE LIGHT (U)

(U) As discussed in section 3.2.11, electromagnetic radiation does not propagate well through sea water except in the visible part of the spectrum and at frequencies less than about 1 kHz.

(C) Within the visible spectrum, sea water is most transparent in the wavelength range of about 450 to 510 nm depending upon the concentration, type, and size distribution of particulates suspended in the water. Light suffers an attenuation in water as a result of scattering and absorption that can be expressed in the form

$$I = I_0 e^{-kr}$$

in which I is the intensity of a beam of monochromatic light of initial intensity I_0 after having traversed a distance r . For ocean waters, the values of the attenuation coefficient k near the wavelength of maximum transmission range from about 0.03 m^{-1} to 0.30 m^{-1} . The reflectivity of the paints used on submarines is about 6%. For angles of incidence of less than 45° with respect to the normal, about 97% of the light striking the water surface penetrates the air-water interface; however, as the angle of incidence increases beyond about 60° , the surface reflectivity increases greatly, the water surface becomes more mirror-like and, as an incidence angle of 90° is approached, very little light penetrates the interface. A sensor operating in the visible portion of the spectrum would be constrained to operate below the cloud base, the altitude of which is quite variable with geographical location and season.

(C) The foregoing factors serve to impose the limits of performance on any active device to be used for the direct optical detection of submarines. That is, because the lateral scan angle is limited to about $\pm 60^\circ$ relative to the normal, the sensor swath width is limited to about 3.5 times the sensor altitude, which, in turn, is limited by the cloud base, which, for the North Atlantic, has a median altitude of about 1,500 feet for coverage of 50% or more. If one takes 2,000 feet as a nominal operating altitude, the swath width would be about 1.14 nmi and the area search rate would be about 14% greater numerically than the search aircraft speed or about $285 \text{ nmi}^2/\text{hr}$ for a 250-kn aircraft. The sensor's depth capability is governed largely by the sea water attenuation coefficient. For representative ocean waters, it appears that the law of diminishing returns limits detection depths to about 100 meters. A simple rule of thumb is that a ten-fold increase in illuminator power yields an increase in depth capability of about one attenuation length (the reciprocal of the attenuation coefficient k). Thus, to improve the depth capability in sea water of medium clarity (e.g., $k = 0.067 \text{ m}^{-1}$) from 100 meters to 115 meters (15%) would require a ten-fold increase in illuminator power. A number of equipment possibilities exist, including

1. Active line scanner
2. Active range-gated television
3. Optical radar.

4.1.1 (C) Active Line Scanner (U)

(C) In the case of the active line scanner, the conjugate image of a small intense light source is scanned repeatedly, by means of a rotating mirror, across the ocean surface perpendicular to the direction of aircraft travel; forward scan is produced by the forward motion of the aircraft. A receiver, consisting essentially of a multiplier phototube at the focus of an optical system, is scanned in synchronism with the transmitter. The output of the phototube is then used to intensity-modulate a cathode-ray tube to produce a picture-type display. To reduce the effect of glare from the ocean surface, the equipment can be angled to scan about 20° ahead of the aircraft. With a significant increase in complexity, a form of range gating can be achieved by having the receiver's instantaneous field of view trail behind the transmitter spot on the surface.

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4.1.2 (U) Active Range-Gated Television

(U) Active range-gated television systems have been employed on Navy patrol aircraft for nighttime ship classification. Such devices typically provide narrow fields of view and therefore do not yield high search rates. In addition, because each pulse of light from the illuminator must illuminate the entire sensor field of view (rather than a single picture element at a time), a much larger laser peak power is required compared to that for an optical radar.

4.1.3 (S) Optical Radar (U)

(S) Optical radars have been developed and investigated for submarine detection since 1962. In controlled experiments involving an optical radar installed in a helicopter, signals reflected from submarines at keel depths as great as about 60 meters have been detected in state five seas off Key West, Florida. See reference (d).

4.1.4 (S) "BLEACHING" (U)

(S) One might speculate on the possibility of using a brute force technique involving a high-energy laser that could "bleach" the sea water by driving all potential absorbers to higher energy levels. Unfortunately, in all but the clearest ocean waters, the major contributor to the attenuation is scattering rather than absorption. Thus, in general, the improvement to be gained would be small.

(S) If sea water can be assumed to be a saturable absorber, the power densities that would be involved could be prodigious. Suppose one wanted to bleach water at a wavelength of 450 nm. The energy of each photon would be 4.42×10^{-19} J. If it is assumed that one photon must be absorbed by one electron per molecule to saturate a one-milliliter sample of water, the energy of the pulse of photons must be 1.48×10^6 J. The sample would remain transparent for a period equal to a relaxation time which might be of the order of 10^{-12} to 10^{-8} s. During this brief interval a second pulse could be transmitted along the path of the first to seek out the target. The task is fraught with difficulties, however; for example, for such short relaxation times the path would become absorbing again before the reflected pulse could return. The approach doesn't appear too feasible.

4.2 (S) EXTREMELY LOW FREQUENCY RADIATION (U)

(S) Active electromagnetic sensors operating at frequencies of less than about 1 kHz are used in prospecting for minerals and have been proposed for detecting submarines. The choice of an optimum frequency is dependent upon a number of competing factors: (1) the attenuation coefficient in sea water is proportional to the square root of frequency; (2) the wavelength of the electromagnetic radiation in sea water should be small in comparison with the size of a submarine if significant backscattering from the target is to occur; and (3) the method and relative ease of generating the radiation are dependent upon frequency.

(S) For sea water of conductivity 4 siemens/meter, the speed of propagation v of a plane electromagnetic wave of frequency f is given by $v = 1.6 \times 10^3 f^{-1/2}$ m/s. The corresponding wavelength $\lambda = 1.6 \times 10^3 f^{-1/2}$ m and the attenuation coefficient $k = 0.004 f^{1/2}$ m⁻¹. For the underwater wavelength to be less than one-fourth the length of a 125-m long submarine would require a frequency greater than 2.6 kHz. If one can tolerate a power loss no greater than 99% on the one-way trip of the radiation down to a 300-meter deep submarine, a frequency of 15 Hz or less is dictated. It appears that the choice of a compromise frequency would be governed by the method of generation of the radiation.

(U) Two general methods of generating extremely low frequency (ELF) fields are considered: rotating electromagnets carrying steady currents and nonrotating coils carrying time-varying currents.

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(U) The magnetic induction B produced at a distance z along the axis of a magnetic dipole of moment μ is given by

$$B = \frac{\mu_0 \mu}{2\pi z^3}$$

in which μ_0 is the permeability constant. The magnetic moment of an air core coil of N closely spaced turns and area A carrying a current i is $\mu = N i A$. For a magnetic dipole to produce a magnetic field at a distance of 100 m equal to that of the earth (i.e., approximately 0.5 gauss = 0.5×10^{-4} tesla) would require a dipole having a moment

$$\mu = \frac{2\pi B z^3}{\mu_0} = \frac{0.5 \times 10^{-4} \times 10^6}{2 \times 10^{-7}} = 2.5 \times 10^8 \text{ A} \cdot \text{m}^2.$$

4.2.1 (C) Rotating Superconducting Electromagnet (U)

(C) For purposes of reference, in 1972 a superconducting magnet of moment $10^8 \text{ A} \cdot \text{m}^2$ was developed and flight tested in a CH-53 helicopter for use in a Navy minesweeping program. See reference (e). From an extrapolation of data given in reference (f), it appears that a superconducting electromagnet could be constructed that would produce a magnetic moment of about 10^8 ampere-meter² but which would weigh about 400 lb and have a diameter of about 6 meters. One might first consider the possibility of installing such a device in an aircraft and passing a time-varying current through it to produce a time-varying magnetic field. However, when one considers that the inductive time constant L/R would be of the order of tens of minutes for such a device, one is discouraged from trying to energize it with an alternating current.

(U) If a superconducting magnet is energized with a direct current, a remote time-varying magnetic field can be produced by rotating the coil. However, the task of installing and rotating a liquid-helium-cooled coil of 6-meter diameter on an aircraft is not to be taken lightly. Smaller diameter coils could be designed but at the expense of greater weight; for example, to achieve the same magnetic moment of $10^8 \text{ A} \cdot \text{m}^2$ with 5-m and 4-m diameter coils would involve weights of about 800 and 1500 lb respectively. These weights would include provisions for dissipating the considerable amount of energy stored in the magnetic field in the event the coil windings unexpectedly go out of the superconducting mode.

(C) In practice, the rotating magnet might be attached beneath the search aircraft but preferably separated and shielded from it to reduce the adverse effects on aircraft instruments and occupants. The receiver could be a magnetometer or magnetic gradiometer installed in a second aircraft or towed behind the transmitting aircraft.

4.2.2 (C) Nonrotating Large Coil (U)

(C) A second approach toward generating ELF fields from an aircraft is to construct a coil of very large area by winding a conventional electrical conductor around the aircraft from wingtip to wingtip to tail. For a P-3 aircraft, the wing span is 30.4 m and the overall length is 35.6 m. The length of each turn of wire would be about 87.2 m and the area of the coil that would result would be approximately 364 m². To achieve a magnetic dipole moment having a root-mean-square value of $10^8 \text{ A} \cdot \text{m}^2$ (two orders of magnitude smaller than that discussed above) would require a total circulating rms current of 2747 ampere turns. If the coil is constructed of bare solid copper wire of

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size A.W.G. 0000, which is rated at 325 amperes, an 8.45-turn coil could be used. Its electrical resistance, at an assumed temperature of 50°C, would be 0.133 ohm and the power dissipated in it would be 14 kW. The weight of the copper wire would be 705 kg (1550 lb). To provide some idea of the rate of falloff of the field with distance, it should be noted that the amplitude of the magnetic induction produced along the axis of this coil would be equal to the earth's field at a distance of only 17.8 m from the aircraft.

(P) It is expected that an active ELF sensor could be developed that would yield detection ranges comparable to that achievable with a passive magnetometer or magnetic gradiometer. Insofar as detection by this method does not require the submarine to have a magnetic moment nor even to be constructed of ferromagnetic material but only to have an electrical conductivity significantly different from that of sea water, it could provide a capability against degaussed steel and titanium hull submarines that conventional magnetic anomaly detectors do not afford. In any case, however, it would not provide the sought-for search rates of 1,500 to 5,000 nmi²/hr.

4.3 (P) SOUND (U)

(P) One of the most widely exploited techniques for detecting and localizing submarines involves the generation of sound by a transducer immersed in the water and the subsequent detection of the echo of that sound reflected off the submarine. As pointed out previously, sound propagates well through both water and air but does not penetrate well from one to the other. Accordingly, if one wishes to generate underwater sound from a high speed platform such as an airplane or a helicopter, one usually bridges the air-water interface with dipping sonars or with sonobuoys. Consider for the present, however, the possibility of projecting sound directly into the water from an overflying aircraft. The reflectance R of sound at the air-sea interface at normal incidence is given by

$$R = \frac{\rho_w v_w - \rho_a v_a}{\rho_w v_w + \rho_a v_a}$$

in which ρ_w and ρ_a are the densities of water and air, respectively, and v_w and v_a are the velocities of sound in water and air, respectively. Inserting representative MKS values into this equation yields

$$R = \frac{1.03 \times 10^3 \times 1.5 \times 10^3 - 1.2 \times 335}{1.03 \times 10^3 \times 1.5 \times 10^3 + 1.2 \times 335} = 0.99948.$$

That is, only 0.052% of the normally incident sound passes through the interface. Because sound travels in sea water at a speed about 4.4 times greater than in air, the index of refraction of water n_2 (for sound) relative to that of air n_1 is $n_2 = 1/4.4 = 0.227$. For sound in air incident on the water surface at an angle θ_1 relative to the normal, the angle of refraction θ_2 of the sound in water is given by Snell's law

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

or

$$\sin \theta_2 = 4.4 \sin \theta_1.$$

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Because $\sin \theta_2$ cannot exceed unity, the maximum value of θ_1 (i.e., the critical angle θ_c) for which sound can enter the water is

$$\theta_c = (\theta_1)_{\max} = \arcsin \frac{1}{4.4} = 13.1^\circ.$$

Sound in air is "totally internally reflected" back into the air for angles of incidence greater than 13.1° . Thus only that sound that falls within a cone of half-angle 13.1° (that is, within a solid angle $\Omega = \pi \tan^2 13.1^\circ \approx 0.171$ ster) has some possibility of entering the water, and, from the foregoing, no more than 0.052% of that can penetrate. If an overwater sound source, such as an aircraft, radiates acoustic power at a rate of P watts uniformly in all directions (i.e., over 4π ster), the power P' incident on the surface within this solid angle and passing into the water will be

$$P' < \frac{0.171 \times 5.2 \times 10^{-4}}{4\pi} P = 7.1 \times 10^{-6} P \text{ watt.}$$

Note that the total amount of acoustic power entering the water is independent of source altitude. The sound intensity I in the water directly below a 1-W source at an assumed altitude of 1000 m is

$$I = 5.2 \times 10^{-4} \times \frac{1}{4\pi \times 1000^2} \frac{\text{W}}{\text{m}^2} \times \frac{\text{m}^2}{10^4 \text{ cm}^2} = 4.1 \times 10^{-15} \text{ W/cm}^2$$

which is above the threshold of hearing (10^{-16} W/cm^2) of the unaided human ear. If all of the sound from an aircraft thus incident upon a shallow depth submarine were reflected back to the surface without further loss or spreading, the intensity above the surface would be

$$5.2 \times 10^{-4} \times 4.1 \times 10^{-15} = 2.1 \times 10^{-18} \text{ W/cm}^2.$$

Detection of this low intensity sound against a background of direct path sound of intensity at least 3.7×10^6 times greater (i.e., $(5.2 \times 10^{-4})^{-2}$) does not appear promising for detecting submarines. An easier, but less desirable, alternative would be to penetrate the interface only once by using an airborne source to produce a rapid succession of sound pulses having known points of incidence on the sea surface and using a passive listening sonobuoy to receive the returns from the submarine.

(C) The question seems to reduce to this: How can one overcome the acoustic mismatch at the air-sea interface without mechanically bridging that interface? Perhaps the answer is the acoustical analog of quarter-wavelength thick coatings of intermediate index of refraction used so successfully in optics to render surfaces nonreflective. Another possible answer is to produce the sound indirectly by zapping the surface by a pulsed source of electromagnetic radiation such as an airborne laser. Water is quite opaque to 10.6-micrometer radiation from a CO_2 laser; that is, it absorbs essentially all the energy within the first 100 micrometers of depth. A 1-joule laser pulse has sufficient energy to boil explosively 383 micrograms of water initially at 15°C , thereby producing a "bubble" of vapor having a volume of 0.62 cm^3 . A "click" of sound is produced at the surface which can be used in an active sonar system in conjunction with a passive listening sonobuoy. This

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approach suffers several limitations: first, the efficiency of converting infrared energy to acoustic energy by this method is only about 10^{-6} ; second, the sound is produced at the very surface and thus does not propagate well in water exhibiting typical vertical temperature gradients.

4.4 (U) SURFACE GRAVITY WAVES

(U) Another type of field that could be produced artificially and which could interact with a submarine is a surface gravity wave field which could be generated by the harmonic motion of a large piston in the water. The motion would not be confined to the surface but, for the deep water case, would consist of the movement of individual fluid particles in vertical circular orbits. The radii R of the particle orbits decrease exponentially with depth z as given by

$$R = A e^{-2\pi z/\lambda}$$

in which A is the amplitude of a wave of wavelength λ . Thus surface waves of 1-m amplitude and 100-m wavelength will be accompanied by particle orbital motion of 8.6-cm diameter at a depth of 50 m. Since the period T of ocean waves is related to λ by the formula $T = (2\pi\lambda/g)^{1/2}$, where g is the acceleration of gravity, the period of orbital motion of the particles in the above example would be 8.0 seconds and their orbital speeds would be about 3.4 cm/s. The presence of a submarine and/or its turbulent wake at a depth where these orbital motions are significant will cause a small amount of scattering the surface waves. A stationary submarine would produce a series of waves expanding in the form of rings over the position of the submarine. These small amplitude waves would have to be detected against a background of naturally occurring waves and the artificially generated wave field. The energy investment in a 10 km $\times$ 10 km field of waves of 100-m wavelength and 1-m amplitude would be of the order of 10^{11} joules. To maintain a 10-km wide field of such waves would a power expenditure of the order of 10^6 watts. This approach does not appear feasible, especially for the large area search mission.

4.5 (U) INTERNAL GRAVITY WAVES

(U) The problems associated with the generation and utilization of an internal gravity wave field would be analogous to those discussed above. Coupling the generator to the medium and detecting the scattered internal waves would probably be more difficult in this case.

4.6 (U) STEADY ELECTRIC FIELD

(U) A steady electric field could be produced by applying a potential difference between electrodes placed in the water. An intrusion into the field by a metallic submarine would reduce the resistance of the path between the electrodes. Consider the specific illustrative example of two large vertical plane parallel electrodes, each 100 m by 100 m, separated by a distance of 1 km in sea water of conductivity 4 siemens/m. If a submarine, approximated as a right circular cylinder of infinite conductivity, length 125 m and diameter 8.4 m, is placed between the electrodes, the resistance between the electrodes will be reduced by about 0.07%, a value which is fairly independent of the orientation of the submarine relative to the field. If the size of the electrodes, and/or the distance between them were to be reduced, larger signals would result but the probability of the submarine's entering the field would be reduced. Perhaps the limiting noise in such a detecting system would arise from random variations in temperature and salinity of the intervening sea water. The conductivity of sea water varies with temperature by 2 to 3% per kelvin, the actual amount depending upon the salinity and the location of the temperature interval. Thus, for the case assumed above,

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variations of the order of 0.02 to 0.03 K in the temperature of the water between the electrodes would produce noise comparable to the signal from a submarine. This approach may be marginally feasible from a technical point of view but it hardly appears attractive from the operational viewpoint, particularly as a large area search sensor.

4.7 (U) STEADY MAGNETIC FIELD

(U) A steady magnetic field could be produced over limited regions of space such as harbors, channels and estuaries by means of large current-carrying loops laid on the bottom, circulating electric currents in the water, permanent magnets, and conventional and superconducting electromagnets. Effects produced by the submarine may be of two types: a distortion of the magnetic field if the submarine is constructed of ferromagnetic material, and motional electric fields produced by the movement of the submarine (assumed to be an electrical conductor) and/or of the water in the applied magnetic field. Effects of both types may be detected by magnetometers, magnetic gradiometers, or by simply monitoring the electric currents in loops of wire. Once again, these approaches do not lend themselves to large area search.

4.8 (U) FIELD OF MAGNETIC PARTICLES (U)

(U) If a large number of magnetic particles (either magnetized or magnetizable) could be sown over large areas of the ocean they would tend to align their magnetic moments (permanent or induced) in the direction of the local magnetic field. If the presence of a submarine alters significantly the direction of the earth's magnetic field and if the orientation of the magnetic particles can be detected remotely, a potential technique for detecting submarines would result. If the magnetic moments and moments of inertia of the particles are known, then the magnitude of the local magnetic field could be determined by measuring the frequency of oscillation of the particles.

4.8.1 (U) Orientation (Field Direction Changes) (U)

(U) Consider first the change in the direction of the earth's magnetic field that could be produced by a "standard" submarine of magnetic moment $\mu = 1.4 \times 10^5 \text{ A} \cdot \text{m}^2$ as a function of range. Assume that the submarine can be represented magnetically as consisting of N and S poles lying along the submarine's longitudinal axis and separated by a distance $2a = 80 \text{ m}$. The magnetic induction B_s from the submarine along the perpendicular bisector of the line joining the N and S poles and at a distance s from it is given by

$$B_s = \frac{\mu_0}{4\pi} \frac{\mu}{(s^2 + a^2)^{3/2}} = \frac{0.014}{(s^2 + 1600)^{3/2}} \text{ tesla}$$

Consider the best case situation in which the submarine is aligned in an east-west direction. Assume the horizontal component of earth's magnetic induction to be $B_E = 0.2 \times 10^{-4} \text{ T}$. Then the maximum angle $\Delta\theta$ through which a magnetic compass needle would be deflected by the presence of a

submarine would be $\Delta\theta = \arctan B_s/B_E = \arctan \frac{700}{(s^2 + 1600)^{3/2}}$. If it is assumed that deflections of

as small as 0.1 degree could be sensed, detection could be accomplished at a submarine-to-compass-needle range of $s = 62 \text{ m}$. In principle, large numbers of magnetized needles would be scattered over a wide expanse of ocean surface and their orientations sensed remotely, perhaps by a high-resolution radar of variable polarization. Only under perfectly calm sea conditions could one expect all of the needles to be properly aligned. In a sea that is not calm, the orientation of

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any particular compass needle will be determined mostly by chance and only slightly by the magnetic torque between the earth's magnetic field and the magnetic moment. Suppose that there is a scattering of the orientations of compass needles over a range of $\pm 0.5^\circ$. If 0.5° is then taken as the smallest angular displacement that can be sensed for an ensemble of needles, the maximum range to the submarine would then be only 16 m. The prospects for detecting submarines by this method do not appear encouraging.

4.8.2 (D) Oscillation (Field Magnitude Changes) (U)

(D) A somewhat more promising approach might be to sow the ocean surface with magnetic particles that would respond to submarine-produced changes in the magnitude of the magnetic field rather than its direction. The frequency f of small oscillations of a compass needle about its center of mass in the absence of friction is

$$f = \frac{1}{2\pi} \sqrt{\frac{\mu B_E}{I}}$$

If $B_E = 0.5 \times 10^{-4}$ T, $\mu = 7.8 \times 10^{-3}$ A·m² and the moment of inertia $I = 4.8 \times 10^{-12}$ kg·m², then $f = 4.8$ Hz. The change in frequency df accompanying a change in the magnitude of the magnetic field dB_E would be

$$df = \frac{1}{4\pi} \sqrt{\frac{\mu}{I B_E}} dB_E = \frac{f}{2 B_E} dB_E$$

For the condition assumed above and a change $dB_E = 1$ nT (from, for example a "standard" submarine at a range of 303 m) $df = 4.6 \times 10^{-5}$ Hz. Measurement of such a small frequency change would require an observation time of the order of $(df)^{-1}$, that is, a rather discouraging 6.1 hours.

(D) To make this approach feasible it would be necessary to use magnetic particles exhibiting a much higher ratio of μ/I than that discussed above (i.e., 1.6×10^7 A/kg) as a means of increasing f and df to values that are measurable in reasonable times (i.e., of the order of one second). Electrons and the nuclei of many species of atoms possess magnetic moments; representative values are 9.27×10^{-24} A·m² for a free electron and 1.41×10^{-26} A·m² for a hydrogen nucleus (proton). If one assumes that a proton can be considered as a solid sphere of uniform density of radius 1.4×10^{-15} m and mass 1.67×10^{-27} kg, its moment of inertia I_p would be

$$I_p = \frac{2}{5} \times 1.67 \times 10^{-27} \times (1.4 \times 10^{-15})^2 = 1.31 \times 10^{-57} \text{ kg·m}^2$$

and its ratio of magnetic moment to moment of inertia would be 1.08×10^{31} A/kg. Its frequency of oscillation in the earth's field would be 3.7×10^{12} Hz from the formula applied above to the case of the compass needle. Actually, however, the situation is not quite so simple. Because the magnetic moments arise from the spinning of the charged particles about their axes, the particles also possess mechanical angular momentum. Accordingly, the particles do not simply vibrate (as would a

(U) Here it was assumed that the needles are 1.0 cm long and 0.10 mm in diameter and made of Alnico 5 having a density of 7.3 grams/cm³ and a remanent magnetization of 12,500 gauss.

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compass needle) but rather precess at the Larmor frequency about the direction of the external magnetic field in a manner analogous to a rotating top in a gravitational field. The frequency of precession f is given by

$$f = \frac{g e B}{4 \pi M}$$

in which e is the electronic charge, M is the mass of the particle, B is the external magnetic induction and g is a gudge factor whose value depends upon the species of particle. For a proton in a magnetic field of 0.5×10^{-4} tesla

$$f = \frac{5.585 \times 1.6 \times 10^{-19} \times 0.5 \times 10^{-4}}{4 \pi \times 1.67 \times 10^{-27}} = 2129 \text{ Hz.}$$

For a free electron in the same field,

$$f = \frac{2.000 \times 1.6 \times 10^{-19} \times 0.5 \times 10^{-4}}{4 \pi \times 9.11 \times 10^{-31}} = 1.40 \times 10^8 \text{ Hz.}$$

The change in frequency df accompanying a change dB in the external magnetic field is

$$df = \frac{f}{B} dB.$$

For $dB = 1 \text{ nT}$, $df = 0.043 \text{ Hz}$ for a proton in the earth's field and $df = 28 \text{ Hz}$ for a free electron. Observation times required to measure these frequency changes would be of the order of $(df)^{-1}$ or about 24 s and 0.04 s, respectively. Hydrogen nuclei are present in sea water in great abundance; unpaired electrons are present in oxygen molecules in the atmosphere and in paramagnetic salts dissolved in sea water. Accordingly it is not necessary for the sensor to generate a field of these particles. Further discussion of this topic is deferred to section 6.1.

4.9 (P) FIELD OF SURFACE (WATER) CURRENT INDICATORS (U)

(P) Under certain oceanographic and submarine operating conditions, a moving submarine can effect and/or affect local water surface currents. If the water surface could be tagged, perhaps by markers dispensed from an aircraft, it would be possible to detect very small changes in surface current produced by a submarine. Surface currents could arise in a number of ways such as displacement of water by the submarine, generation of vortices by control surfaces, turbulence, changes in convection patterns, surface gravity waves, turbulent wake collapse, internal waves, streams of rising bubbles or hot water, and a vertical component of propeller wash. Techniques such as using a crop duster aircraft to lay a grid of sulfur or aluminum powder or simply throwing reams of mimeograph paper from an airplane have been tried. Calculations of local surface currents from the displacement of water by the hull of a 6-kn submarine yield values of about 3 cm/s for a keel depth of

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100 ft and 0.03 cm/s for a keel depth of 300 ft. Surface currents of up to 1.4 cm/s have been calculated as resulting from vortices from the negative "lift" of control surfaces for a 5.5-kn submarine operating at a keel depth of 130 feet with a net hydrostatic buoyancy of 24 long tons. Such local surface current anomalies move with the submarine and therefore act for only a short time on a given region of water. Accordingly, seeding techniques such as those mentioned above, which reveal displacements of the surface water over a period of time, do not provide a sensitive indication of motion. It appears that another mechanism, the effect of surface currents on the slopes of short surface waves, could provide a much more sensitive indicator (and one which does not require the use of expendables). This approach is considered in section 5.3.

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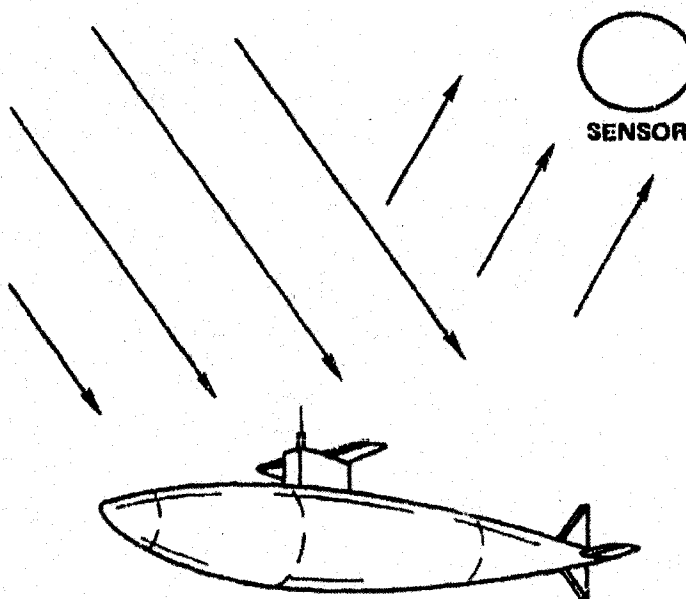
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5.0 (U) "FIELDS" EXISTING INDEPENDENTLY BUT AFFECTED BY THE SUBMARINE (U)

(U) In this section are considered the various types of fields of natural origin and of human cultural origin which can, in principle, interact with a submarine and produce a detectable effect at a remote sensor as illustrated schematically in figure 5.1. In some cases, the effect may be simply a redistribution of the "energy" of the field. In other cases, the "field" may represent stored energy whose release is triggered by the presence or passage of a submarine. The "fields" considered here include:

1. Electromagnetic radiation
 - a. ELF (extremely low frequency)
 - b. Sunlight
2. Sound
3. Surface gravity waves
4. Steady magnetic field
5. Bioluminescent organisms
6. Sea animals
7. Ocean stratification
8. Internal wave fields
9. Water convection cells
10. Thermal microstructure
11. Surface films.



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Figure 5.1 (U) Scattering Of An Independently Existing Field By A Submarine

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5.1 (C) ELECTROMAGNETIC RADIATION (U)

5.1.1 (C) Extremely Low Frequency (U)

(C) As discussed in section 4.2, extremely low frequency (ELF) radiation can penetrate sea water to considerable depths. The amplitude of a plane electromagnetic wave as it penetrates into a conductor decreases to a value of $1/e$ (37%) of its initial value in a distance d (the "skin depth") given by the equation

$$d = \sqrt{\frac{2}{\omega \mu \sigma}}$$

In which ω is the angular frequency of the radiation, and σ and μ are the conductivity and magnetic permeability of the conductor, respectively. For sea water, the skin depths corresponding to frequencies of 1.0, 10, 100, and 1000 Hz are 252 m, 80 m, 25 m, and 8.0 m, respectively. As discussed in section 4.2, another factor influencing the choice of frequency is the length of the submarine compared with the undersea wavelength of the radiation. If the submarine is equipped with a low frequency antenna (such as a floating wire or a trailing buoy ferrite-loaded loop) for receiving long-range communications, the tuned, deployed antenna system will reradiate 50% of the electromagnetic radiation that it intercepts. Thus, the submarine will act as a very low level source of radiation when it is irradiated at the frequency to which its antenna system is tuned. The incident radiation may be either man-made or of natural origin. The frequencies selected for the SANGUINE/SEAFARER communication system are 45 and 75 Hz. Commercial electric power transmission lines serve as vast antenna systems emitting radiation at frequencies of 50 and 60 Hz. Radio broadcast stations are another source of "free" electromagnetic radiation.

5.1.1.1 (C) Sferics/Whistlers (U)

(C) Electromagnetic radiations originating from atmospheric electrical discharges, such as those accompanying thunderstorms, are known as sferics. Sferics emitted by lightning discharges exhibit a frequency distribution ranging from a few hertz to a few gigahertz with the peak occurring at about 10 kHz and are detectable at ranges of thousands of miles. Sferics in the audio frequency range may propagate along the lines of the earth's magnetic field to the conjugate point in the opposite hemisphere. Sferics which propagate in this manner are called "whistlers." The characteristic drawn-out descending pitch of the whistler is a dispersion effect owing to the greater velocity of the higher frequency components of the disturbance. Whistlers can be detected at considerable depths in the ocean. Sferics in general and whistlers in particular represent electromagnetic radiation that could possibly be used in a detection scheme involving their reradiation or scattering by the submarine.

5.1.2 (C) Sunlight (U)

(C) Radiation in the visible part of the spectrum is supplied by the sun at a rate of several hundred watts per square meter. By a happy coincidence the radiation from the sun peaks near the wavelength of greatest transparency of water (except for frequencies lower than about one kilohertz.) A portion of the sunlight that enters the water is absorbed and is degraded eventually to heat; another portion is scattered and some of this light comes back out of the water. The presence of a submarine can affect the magnitude, the spectral distribution and the polarization of the back-scattered light. If a given submarine is in clear deep water of low particulate content, it may

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appear light relative to the dark water; if it is in water of high particulate content, it may appear dark relative to a light background. If the submarine is viewed from an angle that is different from the angle from which it is illuminated, the shadow cast by the submarine may be detectable as a shaft of relative darkness in the body of the water regardless of how well the spectral reflectivity of the submarine matches that of the water.

5.1.2.1 (S) Color Differences (U)

(S) Because sea water acts as a filter whose spectral pass band becomes narrower as the path length through it increases, the spectral distribution of light reflected from the submarine will differ from that scattered by the water beyond the submarine. Small differences in color over a submarine can be enhanced by differential spectral filtering and/or by the use of false-color techniques to expand a small portion of the spectrum (i.e., the blue-green portion) to cover the entire visible spectrum. Electro-optical viewing devices which are now undergoing development show promise of detecting the very small contrasts that would be associated with a submarine shadow while possessing adequate dynamic range.

5.2 (S) ACOUSTIC (U)

(S) The sound (acoustic noise) background of the sea originates from many sources: seismic disturbances, ocean turbulence, breaking crests of wind driven waves, surface waves, storms, ships, off-shore oil drilling rigs, ocean bottom mining, industrial establishments on shore, marine animals, falling rain and cracking ice. This quite variable sound field is usually regarded as a hindrance in submarine detection. However, the intrusion of a submarine into a region of ensounded sea space can produce spatial and spectral changes in the ambient sound distribution in the form of reflections and shadows.

5.3 (S) SURFACE GRAVITY WAVES (U)

(S) The oceans possess a tremendous amount of energy in the form of surface gravity waves. This energy is not limited to the surface but is present also in the form of orbital motion of the fluid particles at depth as discussed in section 4.4. A submerged submarine can cause a potentially detectable redistribution of a small amount of this natural surface wave energy.

5.4 (U) MAGNETIC FIELD

(U) A large ferromagnetic body such as a submarine can distort the earth's magnetic field such that the resulting anomaly appears as the field of a magnetic dipole superimposed on the (relatively) uniform field of the earth. The considerations of section 3.1.1 apply.

5.5 (S) BIOLUMINESCENCE (U)

(S) Bioluminescent organisms are reported to inhabit all parts of the oceans at number densities varying from several to several thousand per cubic meter as a function of depth, time of day, geographical location and season. Many of the thousands of different species of marine bioluminescent organisms emit flashes of light when they are disturbed mechanically. The energy of a representative flash is of the order of 10^{-10} joule and its spectral peak corresponds to the wavelength of maximum transmission through sea water or about $0.48 \mu\text{m}$. The passage of a submarine through a field of such creatures can stimulate them to emit light which can be detected by the human eye with the possible aid of a telescope, low light level television or image intensifier. The luminescent wake from a submarine at a keel depth of 130 feet has been detected by the unaided

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eye of an airborne observer. (Reference (g)) It has been reported that, in some cases, light from one organism can excite others to radiate. In this manner, sheets of luminescence can propagate at high speed across the water. (Reference (h)) Thus it is conceivable that a submarine, at a depth far greater than that from which the feeble light from bioluminescent organisms could be detectable above the surface, could produce local effects that would propagate to the surface from organism to organism. Because of competing "noise" from the reflection of sunlight and moonlight from the ocean surface, this approach seems limited to use on dark nights.

5.6 (C) FORAGE FISH (U)

(C) In certain geographical locations at certain times of the year, types of sea animals such as anchovies, herring and menhaden exist in such large populations that they may be considered as constituting a field. It has been observed that the passage of a submerged submarine through a field of forage fish frightens the fish such that they flee toward the surface and, in so doing, discharge a considerable amount of gas from their air bladders. (Reference (i)) These streams of bubbles have been detected by active sonar (actually a recording fathometer) and, presumably, could also be detected by nonacoustic means. There are a number of limitations to this general approach, however. First, the existence of sufficiently large numbers of forage fish is probably limited to the continental shelves. Second, these species feed near the surface at night and rest in deeper waters during hours of daylight. (Actually, these limitations may not be too serious insofar as submarines tend to remain over the continental shelves and to operate nearer the surface at night.) Third, if the submarine is traveling at high speed, the fish receive a greater advance warning from the greater amount of noise produced by the submarine and move casually out of its way without releasing air.

5.7 (C) STRATIFICATION (U)

(C) The oceans typically are stratified in layers characterized by differences in temperature, salinity, density, index of refraction, color, flora and fauna. The passage of a submarine through such stratified water can cause local displacements of the layers from their equilibrium positions and subsequent oscillations about those positions.

5.7.1 (C) Particulate Layers (U)

(C) The turbulence generated by a submarine can produce a redistribution of small plants and animals in the wake. These effects are detectable by a variety of methods but perhaps optical means offer the greatest flexibility. Changes in chlorophyll concentration can be monitored by means of a fluorometer immersed in the water or by color changes observable from above the surface. An optical radar could be used to detect abrupt differences in index of refraction and local changes in population of suspended particles. This general approach seems limited to small volume search rates; i.e., if an airborne optical sensor is used, its depth capability will be small; if an immersed sensor is used, its area coverage will be small.

5.8 (C) INTERNAL WAVE FIELD (U)

(C) Density stratified water is capable of supporting internal waves. The simplest case to consider is one in which a thick layer of density ρ' is resting upon a second thick layer of greater density ρ . If water near the interface of the two layers is vertically displaced periodically from its rest position at a frequency f , a train of interfacial waves is produced of wavelength

$$\lambda = \frac{g}{2\pi f^2} \frac{\rho - \rho'}{\rho + \rho'}$$

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in which g is the acceleration due to gravity. The celerity c of the waves is given by

$$c = \lambda f = \left[\frac{g \lambda (\rho - \rho')}{2\pi(\rho + \rho')} \right]^{1/2}$$

(Note that for the special case of an air-water interface, $\rho' \ll \rho$, and the above equations reduce to those describing surface gravity waves.) Because the density of one layer may differ from that of the second by only about 1%, the wavelengths and speeds of propagation of internal waves are only about 1% and 10%, respectively, of their surface counterparts. An internal wave field may exist wherever/whenever density stratified water exists. A submarine can cause a scattering of internal waves similar to that produced on surface gravity waves. Generally, the frequency of naturally occurring internal waves is very low and the coupling between them and a submarine is rather weak. In addition, the detection of a field of internal waves from an aircraft poses problems much more severe than does the detection of surface waves; the difficulty is heightened by the need to detect small submarine-caused changes in the naturally occurring internal wave field. This approach does not appear promising.

5.9 (C) CONVECTION CELLS (U)

(C) Typically, during hours of sunlight, the upper layer of the ocean is warmed and, (for temperatures above 4°C) because of thermal expansion, is less dense than the underlying water. Thus a condition of vertical stability exists. At night, the upper layer may lose heat through convection and conduction to the (cooler) air, through radiation to space and through evaporation. The surface layer cools, becomes more dense than the underlying water and becomes vertically unstable. Viscous forces are overcome and the denser water begins to sink in certain regions while warmer subsurface water rises around it to occupy the vacated regions. That is, vertical convection takes place and continues as long as conditions exist for a net outward flow of heat. Under calm sea conditions, convection may occur in the form of a field of cells which, at the surface, appear to a thermal imaging device as closed irregular polygons having widths of about 100 meters and which may penetrate comparable distances into the depths of the water. A completely submerged submarine can produce local flow fields and turbulence which may not reach the surface directly but which can interact with the vertical convection currents to influence the "appearance" of the surface patterns. If the ocean surface is choppy it is not likely that a well organized array of convection cells will exist. Thus, it appears that this phenomenon is available for exploitation only under very calm (sea state zero) conditions.

5.10 (C) THERMAL MICROSTRUCTURE (U)

(C) The ocean surface exhibits a thermal microstructure characterized by temperature variations of the order of 0.001 to 10 kelvins in the size regime of the order of 1 to 10^2 meters. If the turbulent wake of a submarine intersects the surface (See section 3.2.5.), it can reorganize the thermal microstructure in such a manner that the "thermal texture" is changed in the wake without a net change in average surface temperature. This phenomenon is limited in its ASW applications to shallow depth submarine operations.

5.11 (C) SURFACE FILMS (U)

There is an abundance of fatty acids and esters and fatty alcohols in the ocean which can be adsorbed at the surface. Many of these substances are made up of long chain molecules having one

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end which is soluble in water (hydrophilic or water loving) and another end which is insoluble in water (hydrophobic or water fearing). These substances can accumulate on the water with parts of their molecules beneath the surface and parts above to form a monomolecular film. These molecules form a tangled network which immobilizes a thin layer of surface water. This, in turn, inhibits near-surface convective circulation and permits the affected surface to cool by evaporation by about 0.5 K. In addition, this film can damp capillary waves and form a slick. If conditions are proper for a submarine to produce surface currents (e.g., from turbulence, vortices or rising bubbles), the slick material becomes rearranged, that is, compacted in certain areas and removed from others. The region from which the slick is removed will tend to rise in temperature above that of the adjacent water surface and will therefore be detectable by thermal imaging equipment.

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6.0 (S) INTERACTIVE SENSOR- AND SUBMARINE-GENERATED "FIELDS" (U)

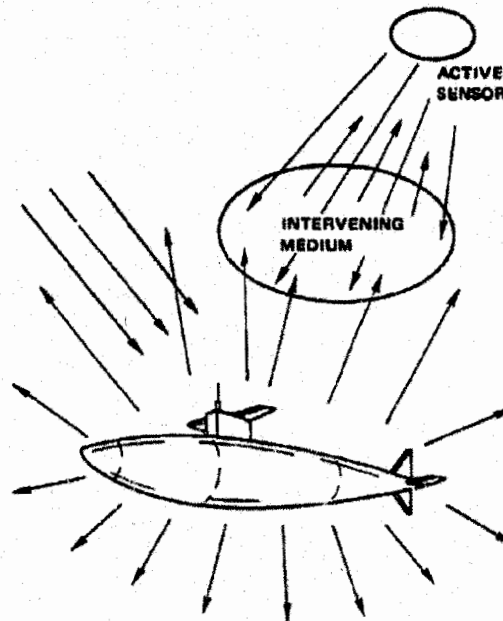
(C) In this section are considered the various types of fields that could be produced by sensors which could interact with the fields produced by submarines to yield detectable effects. See figure 6.1. Fields of the two types are listed in the following two columns.

Sensor-Generated Fields

Electromagnetic
ELF
RF
Microwave
Infrared
Visible
Ultraviolet
X-ray
Steady electric field
Steady magnetic field
Sound
Surface gravity waves
Internal gravity waves
Field of magnetic particles

Submarine-Generated Fields

Steady magnetic
Time-varying magnetic
Steady electric
Time-varying electric
Stray 50/60/400-Hz electromagnetic
Electromagnetic radiation
Gaseous contaminants (bubbles)
Dissolved contaminants
Kelvin wake
Turbulent wake
Thermal wake
Acoustic
Neutron
Hydrodynamic pressure
Gravitational



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Figure 6.1 (U) Interaction Of Sensor- And Submarine-Generated Fields

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The foregoing represents 195 combinations of possible sensor-field/submarine-field interactions. It would be both prolix and nugatory to consider all of these in detail. To render the problem tractable, the only sensor-generated fields that will be discussed here are the electromagnetic. Of the submarine-generated fields, the gravitational, hydrodynamic pressure, and neutron fields will be considered no further. The resulting truncation of the list of combinations appears justified in an investigation whose ultimate goal is a sensor capable of yielding a large area search rate. What is envisaged is an aircraft/satellite-borne sensor that will produce a beam of electromagnetic radiation (of presently unspecified characteristics) that will probe the environment in the vicinity of a completely submerged submarine and interact with one or more of the submarine-generated fields listed to produce detectable effects.

6.1 (C) MAGNETIC FIELD (U)

(U) Steady magnetic fields can be detected and measured remotely by their interactions with electromagnetic radiation itself or with sources of electromagnetic radiation. The first observation of an effect of a magnetic field on electromagnetic radiation was made by Michael Faraday in 1846. Faraday discovered that when plane-polarized light passed through a solid or liquid held between the poles of an electromagnet, the plane of polarization was rotated through an angle that was proportional to the component of the magnetic field in the direction of light propagation. In 1896, Pieter Zeeman established that the wavelength of light emitted by a source was altered when the source was placed in a magnetic field. In broader terms, magneto-optical effects can be divided into two classes: (1) those in which the source of electromagnetic radiation is acted upon by a magnetic field, which effects a change in frequency accompanied by polarization (Zeeman effect) and (2) those in which the speed of propagation of electromagnetic radiation and its state of polarization are modified when the radiation passes through a magnetized medium (Faraday effect).

6.1.1 (C) Faraday Effect (U)

6.1.1.1 (U) Variation In Speed Of Propagation Of Microwaves

(U) The Faraday effect could be exploited in a number of ways. One method that has been proposed utilizes two aircraft traveling at low altitude along parallel paths about ten miles apart. The first aircraft sends out two microwave beams, one having a frequency of 30 GHz and the other 60 GHz, which is derived from the first by frequency doubling. The 60-GHz frequency is selected to correspond to the edge of an oxygen molecular absorption line where the speed of propagation varies as a function of frequency.

(U) The magnetic field of the earth will cause a splitting of the absorption line proportional to the magnitude of the magnetic field; if a submarine is present, its magnetic field will contribute to this line splitting. The net result is that the time required for the 60-GHz radiation to travel between the aircraft is a function of the magnetic field between them whereas for the 30-GHz radiation it is not. If the 30-GHz radiation is frequency-doubled in the second aircraft, variations in the phase of one signal relative to the other can be measured and related to the value of the magnetic field integrated along the line joining the two aircraft. In this manner, submarines can be detected (and localized in one dimension) by two aircraft, providing a search rate of about 2500 nmi²/hr.

(U) It appears that this approach would be bothered by a number of problems. One problem that can be anticipated is that the submarine signal occurs over only a small portion of the path but noise is generated over the entire ten-mile path between the aircraft. In addition to the usual geomagnetic and geological noise, there will be noise from variations in the spacing of the aircraft and from random variations in the temperature, pressure and water vapor concentration in the intervening space. A detailed signal and noise analysis of this proposed method should be made.

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6.1.1.2 (C) Rotation Of Plane Of Polarization Of Light In Water (U)

(C) When a beam of linearly polarized light passes through a medium in which a magnetic field exists, its plane of polarization is rotated through an angle α given by

$$\alpha = V s H \cos \theta$$

In which α is the angle of rotation (in minutes of arc), s is the path length (in cm) through the medium in which a magnetic field H (in gauss) exists, θ is the angle between the direction of H and the path of the light, and V is the Verdet constant (in min/gauss · cm). The value of the Verdet "constant" depends upon the composition of the medium through which the light is passing, the temperature of the medium and the wavelength of the light. For atmospheric air ($T = 20^\circ\text{C}$) and $\lambda = 589.3 \text{ nm}$, $V = 6.83 \times 10^{-6} \text{ min/gauss} \cdot \text{cm}$; for sea water ($T = 20^\circ\text{C}$ and salinity = 3.5%) and $\lambda = 595.6 \text{ nm}$, $V = 0.014 \text{ min/gauss} \cdot \text{cm}$.

(C) A proposed approach relying on the Faraday consists of measuring the rotation of the plane of polarization of a light beam projected from an aircraft into sea water and back-scattered to a receiver in the aircraft. The amount of rotation will be proportional to the component of magnetic field integrated along the path of the light. If the beam of light passes near a submarine, there will be an incremental change in the rotation of the plane of polarization because of the submarine's contribution to the magnetic field.

(C) This approach appears to suffer a number of weaknesses. For example, light becomes depolarized, at least in part, in passing through a scattering medium; this will make more difficult (if not impossible) the task of observing incremental variations of the order of one minute of arc in the amount of rotation. Another problem is that the amount of rotation will be proportional to the length of the path that any given portion of the light travels through the sea water as it is scattered back to the receiver. Inhomogeneities in the magnetic field, particularly in close proximity to the submarine, will produce further depolarization of the beam. This approach does not appear to offer any significant advantages over optical radar but does suffer a number of disadvantages.

6.1.1.3 (U) Rotation Of Plane Of Polarization Of Light In Air

(U) Another approach utilizing the Faraday effect combines features of the preceding two approaches. That is, a beam of plane polarized light is transmitted between two low-altitude aircraft flying along parallel paths, and changes in the angle of rotation are observed. If the spacing between the aircraft is 10 nmi, the amount of rotation from the earth's magnetic field will be of the order of two minutes of arc, and will depend upon factors such as magnetic latitude and direction of propagation of the beam. The "signal" from a submarine's magnetic anomaly would amount to a change in the angle of rotation of about 10^{-3} minute of arc. Stabilization/compensation of two airborne platforms to this degree of precision would be a challenging task.

6.1.2 (C) Zeeman And Related Effects (U)

(C) A number of techniques have been proposed to exploit phenomena related to the Zeeman effect. In this case, the sought-for phenomena involve the remote measurement of the magnetic-field-dependent frequency of emission/absorption of electromagnetic radiation from/by atoms containing unpaired electrons or atomic nuclei having nonzero magnet moments. A number of approaches have been proposed to accomplish this.

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6.1.2.1 (C) Overhauser Effect (U)

(C) One method that might be applied to stimulate atomic nuclei in the vicinity of a submarine to emit electromagnetic radiation at a frequency that is proportional to the local magnetic field is based on the Overhauser effect. In this application a radiofrequency field is applied to the ions of some paramagnetic salt dissolved in the upper layer of the ocean where it is desired to map the earth's magnetic field as a means of locating submarine-induced anomalies in it. The frequency of the incident radiation is selected to equal that of electron spin resonance for the particular paramagnetic ions. Some of the energy absorbed by the ions from the rf field is transferred by collisions to the hydrogen nuclei in the water molecules. These nuclei then emit electromagnetic energy at an audio frequency which is directly proportional to the local magnetic induction. By scanning the rf field (in the spatial domain) one can interrogate a large area in the vicinity of the aircraft while, in principle, detecting the Overhauser resonance on a suitable receiver. Disadvantages of this approach are the weakness of the audio frequency signal emitted and the difficulties in scanning the rf field whose frequency would be in the range of 1 to 100 MHz depending upon which paramagnetic ion is utilized.

6.1.2.2 (C) Two-Photon Interactions (U)

6.1.2.2.1 (C) Intersecting Beams (U)

(C) Another approach that is being investigated involves the use of two intersecting beams of laser radiation whose region of overlap can be made to scan through the space to be interrogated by synchronous steering of the two beams. The wavelengths of the radiation are chosen such that the combined energy of the photons in the two beams corresponds to some atomic transition allowed in one of the constituent gases in the earth's atmosphere near the sea surface. The power density in the beams must be sufficiently high to render two-photon transitions probable. When the affected atoms return to lower energy levels they emit radiation which is "colored" by the magnetic field in that small region of space. A portion of this radiation is intercepted by a receiver and the wavelengths of its Zeeman components are measured as a means of measuring the magnetic field at the remote location where the radiation was emitted. Basically, this technique would permit the remote generation of light that is "tagged" by the magnetic field at the point in space where it originates.

6.1.2.2.2 (C) Common Beam Path (U)

(C) Another possible scanning approach that would eliminate most of the problems of tracking one laser beam with another involves projecting pairs of picosecond pulses of different wavelength from a single optical system. Because the index of refraction of air is a function of wavelength, the second pulse of each pair can be made to overtake and pass through the first pulse. The distance from the source at which the pulses interact can be controlled by adjusting the time interval between the pulses. In this manner "magnetically-tagged" light can be generated wherever desired in a two- or three-dimensional raster and subsequently analyzed to yield an image of the submarine's magnetic anomaly.

6.1.2.2.3 (C) Antiparallel Beam Paths (U)

(C) Another method proposed for magneto-optic scanning involves projecting a beam of continuous wave laser radiation from one aircraft to another flying along a parallel course at a distance of perhaps 10 nmi. The second aircraft transmits laser pulses along the beam back to the first aircraft. Because the position of each pulse is known as a function of time, "magnetically-tagged" radiation resulting from two-photon transitions can be received and

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analyzed to determine the magnetic field strength at all points along the line joining the aircraft. As the aircraft advances, a two-dimensional image of the intervening magnetic field is produced.

6.1.3 (C) Discussion Of Remote Magnetic Detection (U)

(C) All of the foregoing methods for detecting magnetic anomalies remotely are highly speculative; in most cases the principle has not yet been demonstrated for fields as weak as that of the earth, let alone anomalies in that field several orders of magnitude weaker. Once the principles are demonstrated, the nontrivial engineering task of developing a flyable scanning system would remain. On the other hand, because a scanning magnetometer would be able to sense the submarine's magnetic anomaly at/near the surface of the water directly over the submarine, the single-look sensitivity requirement could be eased to perhaps 10 gammas; in addition, the acquisition of many independent looks of the anomaly would permit recognition even if the single-look signal-to-noise ratio were less than unity.

6.2 (C) KELVIN WAKE (U)

(U) A body moving horizontally at constant velocity in deep water produces a highly organized and distinctive train of waves known as the Kelvin wake. The wave pattern produced by a submarine is similar to the familiar ship wake that was studied by Sir William Thomson in the 1880's.

(C) The Kelvin wake consists of two sets of waves: the transverse wave system and the diverging wave system, which are contained within a triangular-envelope of vertex angle $2 \arcsin \frac{1}{2} = 38^\circ 56'$. See figure 3.2. The wavelength λ_T of the transverse waves is

$$\lambda_T = \frac{2\pi v^2}{g}$$

in which v is the speed of the boat and g is the acceleration of gravity.

(C) According to one formulation (Eckart's Rankine-ovoid approximation) given in reference (j) the wave amplitude A over the submarine

$$A \propto \frac{v^2 D^3}{g h^3}$$

in which D is the diameter and h is the depth. According to Reed (reference (k)),

$$A \propto \frac{g h}{v^2}$$

In both cases, a rapid decrease in amplitude with increasing submarine depth is indicated. Along the center line of the Kelvin wake pattern, the wave amplitudes vary inversely as the square root of distance astern; along the cusp lines, where the transverse and diverging wave patterns intersect, the amplitudes vary inversely as the cube root of distance astern. Yim (reference (l)) has developed a computational capability that permits taking into account the hull structure in addition to the hull.

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(C) In contrast with many other nonacoustic phenomena considered for submarine detection, the Kelvin wake is well understood quantitatively. As a potential means for detecting submarines, the Kelvin wake possesses a number of desirable attributes: (1) It is indifferent to water stratification (whereas certain other techniques being investigated are dependent upon stratification); (2) It provides a distinctive geometric pattern covering, perhaps, many hectares; (3) It is relatively immune to countermeasures (Possible countermeasures would be smaller, slower and deeper submarines and/or operation at variable velocity to confuse the wake pattern.); (4) The Kelvin wake is directly coupled with the submarine, and the link from the surface to an airborne sensor can also be quite direct (e.g., radar, optical/photographic, infrared, HF); and (5) It provides a positive surface indication of the exact present position, heading, speed and approximate depth of the submerged submarine.

(C) Previous investigations of the Kelvin wake for submarine detection were oriented largely toward "explaining" the so-called CLINKER effect rather than as a candidate phenomenon in its own right. When it was shown that the characteristics of the Kelvin wake did not match those reported for the CLINKER effect, interest in the former declined. Previous investigations were largely technology- rather than phenomenology-oriented. Empirical limits to detection were established appropriate to the various detection techniques without any assurance, however, that the particular sensing and data processing techniques were optimum. Brief descriptions of various detection techniques are given in the following sections.

6.2.1 (C) Optical/Photographic (U)

(C) The specular reflection of sunlight has been used for detecting very small changes in wave slope ($\sim 0.2^\circ$) associated with Kelvin wakes. Limits of detectability were inferred for calm sea conditions which could be expressed in terms of the following rule of thumb:

$$\text{Maximum submarine detection depth (ft)} \approx 10 \times \text{submarine speed (kn)}.$$

6.2.2 (C) High-Resolution Radar (U)

(C) A fixed-site, nonscanning radar has been used to observe the ocean surface under which a submarine had passed. The radar wavelength was set to be Bragg-resonant with the capillary waves ($\lambda_{\text{radar}} = 2 \lambda_{\text{capillary}}$) riding on the Kelvin waves.

6.2.3 (C) HF Radar (U)

(C) A fixed-site 2- to 20-MHz radio transmitter was used to illuminate the sea surface at the Bragg-resonant frequency corresponding to the Kelvin waves generated by a submarine (i.e., $\lambda_{\text{HF}} = 2 \lambda_{\text{Kelvin}}$). The Bragg-resonant frequency

$$\nu_{\text{HF}} = \frac{c g}{4 \pi v^2}$$

varies inversely as the square of the submarine's speed, which may not be known a priori. In addition there is an angular dependence. Despite its limitations, this method offers the possibility of providing over-the-horizon detection of favorably oriented wakes.

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6.2.4 (C) Doppler Radar (U)

(C) This is sensitive to the speed of movement of the Kelvin wave pattern which, in turn, is equal to the speed of the submarine generating it.

6.2.5 (C) Passive Infrared Imaging (U)

(C) For large angles relative to the normal, the emissivity of the sea surface is strongly dependent upon the angle at which it is viewed. Therefore, devices such as an infrared line scanner and a FLIR (forward looking infrared) are able to detect Kelvin wakes from high-speed, shallow-depth submarines.

6.2.6 (C) Brewster Angle Imaging (U)

(C) When light is incident at an angle θ_p on a smooth dielectric surface of relative index of refraction n , the reflected light is completely plane polarized perpendicular to the plane of incidence if

$$\theta_p = \arctan n \quad (\text{Brewster's angle}).$$

For water at 20°C and light of wavelength 589.3 nm, $n = 1.33299$ and $\theta_p = 53.123^\circ$. If a perfectly smooth sea surface were illuminated at this angle and the reflected light passed through a crossed polarizer, no light would be transmitted; however, if the slope of the surface were to be modified slightly by the presence of Kelvin waves, the reflected light would be partially unpolarized and a portion would pass through the crossed polarizer. By monitoring the amount of light transmitted, one could infer wave slopes. Alternatively, because the index of refraction of water is a function of wavelength, one could illuminate the surface at/near Brewster's angle with light of several different wavelengths and observe color changes in the light transmitted through the crossed polarizer as a function of wave slope.

6.2.7 (C) Discussion Of Kelvin Wake Detection (U)

(C) From the foregoing, it is seen that Kelvin wakes possess many attributes that could contribute toward their detection and recognition. Yet, it seems that in the work done to date, concentration was limited to one attribute at a time. It is suggested that if all of the information available from observation of a Kelvin wake were to be accepted, processed and utilized in a composite sensor, a useful detecting means would result.

6.3 (S) GASEOUS CONTAMINANTS (U)

(S) In section 3.1.5, the production of gaseous contaminants by a submarine was considered. One extreme case was assumed in which all of the waste hydrogen gas dissolved in the water and detection was achieved by in-situ electrochemical sensors. Now we will consider an opposite extreme case in which all of the gas is assumed to rise in the form of bubbles without dissolving, and detection is achieved remotely by illuminating the upper ocean layer (perhaps 10-m thick) and receiving the light back-scattered from the field of bubbles. (Actually, as a bubble rises, hydrogen dissolves in the water and is partially replaced by nitrogen and oxygen, which come out of solution. A bubble that eventually reaches the surface may be over 90% nitrogen and oxygen.)

(S) Assume that hydrogen gas is produced by a 10-kn submarine at a rate of 2 l/s (STP) and that all of it rises to the surface in the form of bubbles of 1-cm equivalent spherical diameter which are

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spread out laterally by turbulence over one submarine diameter of 8.4 m. The rate at which bubbles reach the surface will be 3820 bubbles/second. If the bubbles are distributed uniformly along the length and width of the submarine's track, there will be 88.3 bubbles per square meter and the mean horizontal component of area occupied per bubble will be 113 cm².

(C) The reflectivity ρ of the hydrogen-water interface can be calculated from Fresnel's formula. For normal incidence and indices of refraction $n_1 = 1.000$ and $n_2 = 1.333$,

$$\rho = \left(\frac{n_2 - n_1}{n_2 + n_1} \right)^2 = \left(\frac{1.333 - 1.000}{1.333 + 1.000} \right)^2 = 0.020.$$

To establish an upper limit for signal strength, assume initially that each bubble can be approximated as a horizontal disc of 1-cm diameter. Then the fraction of the normally incident light that would be reflected from a beam whose cross-section is large in comparison with the space between bubbles would be

$$88.3 \text{ bubbles/m}^2 \times \pi \times (0.5 \times 10^{-2})^2 \text{ m}^2/\text{bubble} \times 0.020 = 1.39 \times 10^{-4}.$$

On the other hand, if the bubbles behave as spheres, the incident light will be reflected and refracted over a wide distribution of angles and only small portions of the area of the bubble (at the top and at the bottom) will be effective in reflecting light into a receiver. The area S of a bubble of radius R which is capable of reflecting parallel rays of light into a receiver of aperture diameter D at a distance r from the bubble is

$$S \approx \frac{D^2 R^2}{(2r - R)^2} \approx \frac{D^2 R^2}{4r^2} \quad \text{for } r \gg R.$$

For $r = 100 \text{ m} = 10^4 \text{ cm}$, $R = 0.5 \text{ cm}$, and $D = 30 \text{ cm}$,

$$S \approx \frac{30^2 \times 0.5^2}{4 \times 10^8} = 5.6 \times 10^{-7} \text{ cm}^2.$$

That is, only a tiny glint of light will be detected from the top of the bubble. In addition, a similar glint will be produced from the bottom of the bubble. Thus, for a representative case, the fraction of the light from a beam whose cross-section is large in comparison with the space between bubbles will be

$$88.3 \text{ bubbles/m}^2 \times 2 \times 5.6 \times 10^{-7} \text{ m}^2/\text{bubble} \times 0.020 = 2.0 \times 10^{-10}.$$

(S) The foregoing two examples represent upper and lower extremes of effective reflectivity of an assumed bubble field. (The possibility of total internal reflection at the water-gas interfaces has been considered; it appears unlikely, however, that this would be a significant factor for the case of

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widely spaced spherical bubbles and a co-located light source and receiver.) An intermediate situation of nonspherical bubbles appears more realistic. In practice, bubbles less than 1 mm in diameter are spherical. Larger bubbles are more ellipsoidal and flattened, assuming the shape of "spherical caps" resembling the top third of a sphere. (See reference (m).) Bubbles having an equivalent spherical diameter of about 1 cm assume a lumpy, raisin shape; bubbles of this type reflect light along their sharply curved ridge lines from areas significantly larger than those of perfect spheres. It appears that, for reasonably clear water, a sufficiently large return should be possible to permit detection of shallow bubble fields at reasonably high search rates. Countermeasures that could be applied by submarines equipped with electrolytic oxygen generators include (1) intermittent, rather than continuous use of the generator and (2) operation at depths great enough that the bubbles dissolve before reaching the upper surface layer of the ocean.

6.4 (C) TURBULENT WAKE (U)

(C) In section 3.2.5, the passive detection of the surface expression of a submarine's turbulent wake was discussed. It was pointed out that the technique was limited to submarine depths of about 20 m. Now we will consider the possibility of detecting turbulent wakes existing in the body of the water by remote optical means. Two cases will be discussed: (1) the redistribution of normally existing populations of light scatterers in the water, and (2) the Doppler shifting/broadening of laser radiation backscattered from the turbulent water in the wake.

6.4.1 (C) Redistribution Of Light Scatterers (U)

(C) In the first case it is assumed that well defined layers of light scatterers exist at depths that can be probed with a laser radar (i.e., about 100 m or less) and that the submarine is traveling at a depth within about 20 m of one of these layers. The action of the submarine-generated turbulence is to raise a trail of "dust" analogous to that produced by a vehicle moving along a dusty road. Because the turbulent motion of the water may persist for several hours, such a trail may be detectable for several tens of miles. This approach is limited to fairly shallow submarine depths.

6.4.2 (C) Turbulence-Induced Doppler Effect (U)

(C) In the second case, it is assumed that spatially and/or temporally coherent laser radiation can be projected down through the body of the water to where a submarine's turbulent wake exists. Some of the incident light will be reflected off scattering particles in the turbulent water and/or off moving water cells of different temperature-related indices of refraction. The reflected light, marked by a mixture of upward and downward shifts in frequency depending upon the velocities of the elementary reflectors, is received and mixed with light taken directly from the laser, and beats, in either the spatial or temporal domain, are produced. An analysis of the distribution of beat frequencies yields the distribution of turbulent velocities in the submarine wake which, in general, would be expected to be different from that of the undisturbed water.

(C) It appears that this method will be limited to very short path lengths in the water (i.e., tens of meters) and therefore shallow detection depths for an airborne sensor because of loss of coherence of the laser beam as it passes through the irregular air-water interface and through the water itself.

6.5 (C) ACOUSTIC FIELD (U)

(U) In section 3.2.10 it was pointed out that a moving submarine is a sound source whose acoustical power output ranges within a few orders of magnitude of one watt. Equations were given to permit calculation of the rms displacement, velocity and acceleration of the water particles in the acoustic field and the rms acoustic pressure and density variations in the medium. At a range of 1 km

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from a 1.0-W point source in a homogeneous, isotropic, lossless, unbounded medium, the sound intensity is 80 nW/m², the rms acoustic pressure is 0.35 Pa, the rms velocity is 230 nm/s, the rms density variation is 160 μg/m³ (or 1 part in 6.6×10^9) and (for an assumed frequency of 6 Hz) the rms displacement is 6.0 nm and the rms acceleration is 8.6 μm/s². In the above, a sea water mean density of 1030 kg/m³ and a sound propagation velocity of 1500 m/s were assumed.

(C) Of all of the foregoing intensive variables associated with a submarine's acoustic field, only one, the acoustic pressure, lends itself readily to measurement. For this reason, most underwater acoustic sensors in use today are pressure sensing devices. The other quantities are discouragingly small; this smallness stems from the large bulk modulus of elasticity B (i.e., low compressibility) and density ρ_0 of sea water. The large product

$$\rho_0 c = \sqrt{B \rho_0} \approx 1.55 \times 10^6 \text{ kg/m}^2 \cdot \text{s}$$

appears in the numerator of the expression for the acoustic pressure but in the denominators of the expressions for displacement, velocity and acceleration of the water particles. It would be very desirable to develop an airborne remote sensor that could sense pressure variations in the water without the need for a mechanical device to bridge the interface. One possibility is to exploit the Debye-Sears effect in which the alternate regions of compression and rarefaction produced in the water by the acoustic field act as a diffraction grating with a grating interval equal to the wavelength of the acoustic waves. Because the grating interval would be very large in comparison with the wavelength of light, diffraction effects would be extremely difficult to measure.

(C) Other methods that have been proposed for sensing acoustic fields remotely are based upon measurement of particle displacement and/or particle velocity. Some of the schemes that have been proposed are: (1) use of a microwave or optical radar to sense the acoustic displacement of the water surface in the vicinity of a submarine; (2) use of a light beam to measure changes in slope of a water surface being displaced periodically by an acoustic field; (3) use of coherent laser radiation in a Doppler velocimeter mode to sense particle motion of light scatterers in the body of the water; (4) use of a beam of monochromatic light to detect, by Bragg diffraction effects, spatially periodic variations in index of refraction of the water associated with the acoustic field; and (5) use of a magnetometer or a magnetic gradiometer to detect magnetic fields produced by electric currents induced from the acoustic wave oscillatory movement of sea water (an electrical conductor) in the earth's magnetic field.

6.5.1 (C) Microwave/Optical Radar (U)

The first of these cases may be considered from two equivalent points of view: i.e., (1) the path between the sensor and the sea surface may be considered as one leg of an interferometer which measures changes in the path length associated with displacement of the sea surface by producing moving interference fringes, or (2) as a Doppler radar which measures the vertical component of velocity of the water surface. In the example considered earlier, the rms displacement of the water is only 6.0 nm (about 30 molecular diameters) which corresponds to about 1/100 of a wavelength of visible light or 1/50 of an interference fringe. To sense such small displacements interferometrically would be a challenging task even under the best of laboratory conditions. (For comparison, the standard meter is defined to only the nearest 1/100 of a wavelength of light.) To attempt measuring such small displacements of a dynamic sea surface from a moving platform such as an airplane would be folly.

(C) One could, in principle, employ a microwave or optical Doppler radar to sense the sinusoidally varying velocity of the water surface. The radar return would be frequency modulated with sidebands spaced at intervals equal to the frequency(ies) of the underwater sound source. For a

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surface rms velocity v_{rms} of 230 nm/s and a radar frequency F of 30 GHz, the frequency swing ΔF of the radar return would be

$$\Delta F = \frac{2\sqrt{2} v_{rms} F}{c} = \frac{2\sqrt{2} \times 230 \times 10^{-9} \times 30 \times 10^9}{3 \times 10^8} = 6.5 \times 10^{-5} \text{ Hz.}$$

If, as before, an acoustic frequency $f = 6 \text{ Hz}$ is of interest, the modulation index

$$\beta = \frac{\Delta F}{f} = \frac{6.5 \times 10^{-5}}{6} = 1.1 \times 10^{-6}.$$

If a laser operating at a wavelength λ of 550 nm were employed, the frequency swing for the same set of conditions would be

$$\Delta F = \frac{2\sqrt{2} v_{rms} F}{c} = \frac{2\sqrt{2} v_{rms}}{\lambda} = \frac{2\sqrt{2} \times 230 \times 10^{-9}}{550 \times 10^{-9}} = 1.2 \text{ Hz}$$

and the modulation index would be

$$\beta = \frac{\Delta F}{f} = \frac{1.2}{6} = 0.2.$$

Under the best of conditions, devices to achieve the foregoing would require a fantastic spectral resolution of the order of 10^{14} . Once again, the successful application of such a device in a moving aircraft over a dynamic ocean surface appears impossible.

6.5.2 (C) Optical Lever (U)

(C) Another approach that has been proposed for detecting an acoustic field in the ocean is to use a light beam reflected off the surface as an optical lever to detect small changes in the slope of the water surface. For points on the surface from which the distance to the submarine is large in comparison with the submarine's depth, the wavelength of the surface disturbance will be equal approximately to the wavelength of the sound waves in water. For waves of assumed frequency 6 Hz and rms displacement 6.0 nm, the maximum change in slope $\tan \theta$ of the water surface will be

$$\tan \theta = \frac{2\pi \times \sqrt{2} \times 6.0 \times 10^{-9} \text{ m} \times 6 \text{ s}^{-1}}{1500 \text{ m/s}} = 2.1 \times 10^{-10} \text{ rad}$$

That is, a change in angle of only 210 prad is expected. If a very narrow light beam were projected straight down to the ocean surface from an aircraft at an altitude of 10,000 m and the position of the

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reflection received at the aircraft were monitored, the displacement Δx that would be observed would be

$$\Delta x = 2 \times 10,000 \text{ m} \times 2.1 \times 10^{-10} = 4.2 \times 10^{-6} \text{ m} = 4.2 \text{ } \mu\text{m}.$$

A beam of visible light of wavelength 550 nm that forms a spot of diameter only 4.2 μm after traveling over a path of 20,000 m would have a divergence angle of 210 prad; to produce such a narrow beam, diffraction effects would require a source aperture diameter d of

$$d = \frac{2.44 \times 550 \times 10^{-9} \text{ m}}{210 \times 10^{-12}} = 6390 \text{ m}.$$

This concept appears unfeasible for airborne application without even considering stabilization requirements and the normal background surface slope variations associated with wind driven waves and swell.

6.6 (C) TIME-VARYING ELECTRIC/MAGNETIC FIELDS (U)

(C) In sections 3.2.1, 3.2.2 and 3.2.3, several means by which a submarine can produce time-varying electric and magnetic fields were discussed. These included modulation of the galvanic corrosion currents at frequencies corresponding to the propeller rotation rate and harmonics thereof and stray fields at the submarine's electric power frequencies of 50, 60 and/or 400 Hz. If sea water bearing such time-varying fields could be irradiated with electromagnetic radiation of sufficiently high power density that the medium behaves nonlinearly, mixing of the submarine-generated and externally applied fields would occur, and sum and difference frequencies would be produced. If some of the radiation is scattered out of the sea it could be detected and demodulated to yield the submarine-generated signals. A highly monochromatic, high-power scanning laser might be used as the radiation source.

(C) Nonlinear effects can also take place in the atmosphere. The Luxemburg effect is a type of atmospheric cross-modulation that could perhaps enable one to detect ELF radiation from a submarine by use of a radio receiver tuned to the frequency of a powerful transmitter.

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26 Aug 2016

MEMORANDUM FOR THE RECORD

FROM: Division Director EO & Special Mission Sensors, Avionics, Sensors and E* Warfare Dept (AIR 4.5.6)

TO: Office of Counsel, Naval Air Warfare Center, Aircraft Division (NAWCAD)

Subj: SECURITY RECOMMENDAION FOR FOIA REQUEST, DON FOIA CASE FILE NUMBER 2025-004095

Ref: (a) SECNAVINST 5720.42F, DON FOIA Program, 06 Jan 99

1. Recommendation. AIR 4.5.6 recommends approval of release of the information found in the following report: NADC-80228-30. Information found in this report was reviewed and found to be unclassified and releasable.
2. Basis of Recommendation. All information was reviewed with current class guides and found to be unclassified and open source.
3. Point of Contact. The point of contact for this security review and recommendation is Mr. Paul W. Reimel, AIR 4.5.6 Division Director, paul.reimel@navy.mil, 301-342-0100.

8/26/2016

X Paul W. Reimel

Paul W. Reimel

Signed by: REIMEL.PAUL.W.1229241016

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