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CONTROLLED ARTIFICIAL GENERATION OF ULTRA-LOW-FREQUENCY HYDROMAGNETIC WAVES IN THE IONOSPHERE AND MAGNETOSPHERE

by

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This report summarizes theoretical and experimental work sponsored by the Defense Advanced Projects Agency at Stanford University through the Office of Naval Research Contract No. N00014-75-C-1095. The primary purpose of this work, which was conducted during the interval 1 January 1975 through 28 February 1977, was to investigate the possibility of obtaining a relatively inexpensive method for the controlled artificial generation of ultra-low-frequency (ULF; frequencies less than 5 Hz) geomagnetic pulsations. Because of the great

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20 ABSTRACT (Continued)

penetration of these signals in sea water, the controlled artificial source could conceivably be used as a transmitter to communicate with deeply submerged receivers at a low data rate. A second purpose of the work was to investigate the feasibility of using airborne loop antennas for air/undersea communication at ULF.

The following are the major conclusions of this work:

(1) The controlled artificial generation of ULF geomagnetic pulsations by the "peninsula method," i.e., by the passage of a ULF-modulated electric current around a relatively nonconducting peninsula in the sea or in a large saline lake, is feasible and that further experiments, in particular, a full-scale ULF wave generation experiment, appear desirable.

(2) The controlled artificial generation of ULF geomagnetic pulsations by the "VLF method," i.e., by the injection of ULF-modulated VLF signals into the magnetosphere from a large ground-based VLF transmitter, appears possible, but further theoretical and experimental studies are required to clarify the generation mechanism.

(3) Air/undersea communication at ULF using airborne loop antennas is possible under the following illustrative conditions: For a horizontal plane loop antenna at 3 km altitude and a ULF receiver at a 0.1 km depth, communication is possible for horizontal distances out to a maximum distance in the range 10 to 33 km; the corresponding maximum distance for a vertical plane loop antenna is in the range 13 to 64 km. It is also possible, if desired, to limit communication to a comparatively small circular area directly beneath the aircraft.

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CONTROLLED ARTIFICIAL GENERATION OF ULTRA-LOW-FREQUENCY HYDROMAGNETIC WAVES IN THE IONOSPHERE AND MAGNETOSPHERE

by

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Note: In this report we use the abbreviation ULF (ultra-low-frequencies) for frequencies less than 5 Hz. Pc 1 geomagnetic pulsations are observed in the upper part of this frequency range (0.2 to 5 Hz). ELF (extremely-low-frequencies) is used to designate frequencies in the range 5 Hz to 3 kHz, and VLF (very-low-frequencies) is used for frequencies in the range 3 to 30 kHz.

ABSTRACT

This report summarizes theoretical and experimental work sponsored by the Defense Advanced Research Projects Agency at Stanford University through the Office of Naval Research Contract No. N00014-75-C-1095. The primary purpose of this work, which was conducted during the interval 1 January 1975 through 28 February 1977, was to investigate the possibility of obtaining a relatively inexpensive method for the controlled artificial generation of ultra-low-frequency (ULF; frequencies less than 5 Hz) geomagnetic pulsations. Because of the great penetration of these signals in sea water, the controlled artificial source could conceivably be used as a transmitter to communicate with deeply submerged receivers at a low data rate. A second purpose of the work was to investigate the feasibility of using airborne loop antennas for air/undersea communication at ULF.

The following are the major conclusions of this work:

(1) The controlled artificial generation of ULF geomagnetic pulsations by the "peninsula method," i.e., by the passage of a ULF-modulated electric current around a relatively nonconducting peninsula in the sea or in a large saline lake, is feasible and that further experiments, in particular, a full-scale ULF wave generation experiment, appear desirable.

(2) The controlled artificial generation of ULF geomagnetic pulsations by the "VLF method," i.e., by the injection of ULF-modulated VLF signals into the magnetosphere from a large ground-based VLF transmitter, appears possible, but further theoretical and experimental studies are required to clarify the generation mechanism.

(3) Air/undersea communication at ULF using airborne loop antennas is possible under the following illustrative conditions: For a horizontal plane loop antenna at 3 km altitude and a ULF receiver at a 0.1 km depth, communication is possible for horizontal distances out to a maximum distance in the range 10 to 33 km; the corresponding maximum distance for a vertical plane loop antenna is in the range 13 to 64 km. It is also possible, if desired, to limit communication to a comparatively small circular area directly beneath the aircraft.

I. INTRODUCTION

During 1975 and 1976, scientists from the Radioscience Laboratory at Stanford University undertook a series of experimental and theoretical studies to investigate the possibility of generating ultra-low-frequency (ULF; frequencies less than 5 Hz) and possibly also extremely-low-frequency (ELF; frequencies in the range 5 Hz to 3 kHz) hydromagnetic waves in the ionosphere and magnetosphere. This work was sponsored by the Advanced Research Projects Agency of the Department of Defense (ARPA Order No. 1733) through the Office of Naval Research Contract No. N00014-75-C-1095, and the period covered by this contract was January 1, 1975 through February 28, 1977. The experimental and theoretical studies were divided into two classes, covering two possible methods of ULF wave generation: (1) excitation of ULF waves in the lower ionosphere by passage of a large ULF-modulated electric current around a relatively nonconducting peninsula in the sea, and (2) excitation of ULF waves in the magnetosphere or ionosphere by VLF waves from a large ground-based VLF transmitter.

The studies were motivated by the possibility of obtaining a relatively inexpensive method for the controlled artificial generation of ULF geomagnetic pulsations. With the exception of the extremely noisy pulsations produced by high-altitude nuclear explosions (e.g., Green et al., 1962; Crook et al., 1963; Bomke et al., 1964; Bowman and Mainstone, 1964; Kovach and Ben-Menahem, 1966), ULF measurements have been confined to naturally-occurring pulsations. These measurements have given much useful and interesting information about the ionosphere and magnetosphere (e.g., Jacobs, 1970), and, through magnetotelluric studies, about the structure of the earth (e.g., Cantwell and Madden, 1960; Green et al., 1962; Bostick and Smith, 1962). However, difficulties with the separation of source and propagation effects have prevented the full exploitation of the information present in the pulsation data. A controlled artificial source of pulsations would not only provide useful ULF signals for probing the ionosphere, magnetosphere, and the earth, but would enhance the usefulness of the naturally occurring pulsations for these studies by providing new information about their modes of propagation. Because of the great penetration of ULF electromagnetic fields into sea water, the controlled artificial source of pulsations could also conceivably be used for communication at a low data rate with deeply submerged receivers.

Given the possibility of having deeply submerged ULF receivers (to receive the signals generated over large areas of the world by methods 1 and 2 above, for example), the question arises whether these receivers could also be used as part of an air/undersea communication system. Such a system would require an airborne source of ULF electromagnetic fields. A preliminary study indicated that airborne loop antennas (i.e., magnetic dipoles) might be capable of producing measurable undersea ULF electromagnetic fields for receiver depths and source-receiver separations that were likely to occur in practice. It appeared therefore that a more thorough study of this mode of ULF communication could give useful results. Thus, as a third part of the research conducted under ONR Contract No. N00014-75-C-1095, a theoretical study was made of (3) the possibility of using ULF signals from airborne loop antennas for air/undersea communication.

The results of the 1975 and 1976 series of experimental and theoretical studies of ULF wave generation and air/undersea communication at frequencies in the ULF range were encouraging. These results have been detailed in three recent technical reports. Thus in this final report we only summarize the results by listing the report titles and their abstracts. A list is also given of published articles, and the report ends with a brief overall conclusion and a list of references.

II. SUMMARIES OF TECHNICAL REPORTS ISSUED ON CONTRACT NO. N00014-75-C-1095

1. Technical Report No. 4207-6 (SEL 77-013), "Air/Undersea Communication at Ultra-Low-Frequencies Using Airborne Loop Antennas," by A. C. Fraser-Smith, D. M. Bubenik, and O. G. Villard, Jr., June 1977.

ABSTRACT

In this report we investigate the possibility of using ultra-low-frequency (ULF) signals from airborne loop antennas (i.e., magnetic dipoles) for air/undersea communication. Because of the low data rate at ULF, communication is here understood to mean the transfer of short messages of high information content.

We use numerical integration to calculate the 1 Hz total magnetic field amplitudes in the sea at depths from 0 m to 200 m due to airborne unit moment vertical and horizontal magnetic dipoles at altitudes from 100 m to 10 km. Considering the magnetic moments m attainable with present aircraft power and payload capability ($m = 10^7\ Am^2 - 10^9\ Am^2$) and the minimum detectable amplitude for a 1 Hz signal beneath the sea (~1 mγ), we conclude that air/undersea communication at 1 Hz signal is possible under the following illustrative conditions: For a horizontal plane loop antenna at 3000 m altitude and a ULF receiver at a 100 m depth, communication is possible for horizontal distances to 10 km for $m = 10^7\ Am^2$ and to 33 km for $m = 10^9\ Am^2$. The corresponding limits for a vertical plane loop antenna are 13 km to 64 km. It is also possible, if desired, to limit communication to a comparatively small circular area directly beneath the aircraft. Sea floor effects can alter these values significantly, particularly if the receiver is near the floor.

2. Technical Report No. 4207-7 (SEL 77-041), "A Study of the 'Peninsula Method' for the Controlled Artificial Generation of ULF Waves in the Ionosphere and Magnetosphere," by A. C. Fraser-Smith, O. G. Villard, Jr., and D. M. Bubenik, December 1977.

ABSTRACT

This report presents the results of an investigation of a proposed method for the controlled artificial generation of ultra-low-frequency (ULF) hydromagnetic waves, primarily of class Pc 1 (0.2 to 5 Hz), in the ionosphere and magnetosphere. The basis of this method, which is called the "peninsula method" (a second possible method, the "VLF method," is discussed in a companion report), is the passage of a ULF-modulated electric current around a relatively nonconducting peninsula in the sea or in a large saline lake to form a ULF current loop that produces a ULF magnetic field in the lower ionosphere. Provided the amplitude of the ULF magnetic field fluctuations is sufficiently large, i.e., provided the maximum magnetic moment of the peninsula current loop is greater than about 10^{13} Am^2, it is predicted theoretically that ULF hydromagnetic waves can be generated in a disturbed region of the lower ionosphere above the peninsula. These waves can then propagate away to large distances in the ionosphere and magnetosphere.

The peninsula method is a version of a particular class of ULF wave generation methods based on the use of large ground-based ULF current systems. Compared with other possible methods of generation, these methods appear to have advantage of reliability and versatility. However, both the construction costs and the power requirements for these systems are large. The peninsula method is particularly attractive because it would minimize these latter disadvantages.

Experiments conducted in 1975 and 1976 with a small peninsula on Chappaquiddick Island, Massachusetts, show that the sea

(or salt) water surrounding a peninsula can indeed function as a conducting loop and that this loop can be used to produce ULF magnetic fields above the peninsula. A modeling study based on the results of these experiments indicates that the peninsula method is very efficient: the magnetic field produced at E region height by an electric current flowing through the sea water surrounding the peninsula can be up to 49 times larger than the magnetic field that would be generated by the same current flowing through a wire loop laid along the shoreline of the peninsula. In addition, because of the low resistance of the sea water path, the power required to drive the current through the sea water around the peninsula can be more than an order of magnitude smaller than the power required to drive the same current through the wire loop. Thus the magnetic field produced per unit of input power is substantially higher for the peninsula current loop than it is for a large horizontal wire loop on the ground. The estimated cost of constructing a peninsula ULF generator is found to be over an order of magnitude less than the estimated cost of a horizontal wire loop system of similar capability. We conclude that the peninsula method of ULF wave generation is feasible and that further experiments, particularly a full-scale ULF generation experiment, are desirable.

3. Technical Report No. 4207-8 (SEL 77-042), "Stimulation of ULF Geomagnetic Pulsations by Controlled VLF Transmissions into the Magnetosphere," by A. C. Fraser-Smith, R. A. Helliwell, T. F. Bell, T. L. Crystal, and B. Dingle, December 1977.

ABSTRACT

This report presents the results of an investigation of a proposed method for the controlled artificial generation of

ultra-low-frequency (ULF) hydromagnetic waves of class Pc 1 (0.2 to 5 Hz) in the ionosphere and magnetosphere. In this method, which is called the "VLF method," a large ground-based very-low-frequency (VLF) transmitter is used to stimulate the ULF waves by injecting pulses of VLF waves into the magnetosphere. A second possible method of ULF wave generation, the "peninsula method," is discussed in a companion report. In the VLF method, the basic stimulation frequency is the pulse repetition (or modulation) frequency, which is chosen to fall in the ULF range. Stimulation of ULF waves may also occur at any of the harmonics of this basic frequency, depending on the magnetospheric and ionospheric conditions at the time, or it may conceivably occur at a nonharmonic frequency if the conditions are particularly favorable and the generation process produces a high level of broadband ULF hydromagnetic noise.

Theoretical and experimental progress with the VLF method has been encouraging. Theoretical progress includes (1) computer simulation of the cyclotron resonance interaction, which is believed to play a key role in both the ULF generation mechanism and the amplification of VLF and ULF waves, (2) completion of a theory for ULF wave generation based on the repetitive precipitation of energetic electrons into the ionosphere by periodic VLF pulses from a ground-based transmitter, and (3) development of a method for computing the fluxes of energetic electrons precipitated by VLF waves in the magnetosphere.

Experimental progress includes the completion of several long-duration VLF transmission experiments using the 100 kW transmitter at Siple Station, Antarctica. Although it does not yet appear possible to stimulate ULF waves on demand using this VLF transmitter, our experiments suggest that VLF transmissions from Siple could alter the occurrences of Pc 1 pulsations at Roberval, Quebec, which is geomagnetically conjugate to Siple Station. Because the Pc 1 pulsation events that occur at Roberval can also probably be observed on many occasions over much of North America (and, by inference, over the equivalent conjugate area in the Southern Hemisphere), our experiments suggest that VLF transmissions into the magnetosphere from a single appropriately-located transmitter can influence ULF activity over a large area of the earth's surface. Thus, further experiments appear to be justified.

Combining the theoretical and experimental results obtained during this research, it is suggested that naturally-occurring repetitive VLF activity can stimulate Pc 1 pulsation events, and it is further suggested that such VLF activity may be a major source of stimulation for Pc 1 pulsations. Thus, future experiments on ULF wave generation with ground-based VLF transmitters would probably benefit greatly if they were combined with a program of simultaneous observations of naturally-occurring VLF and ULF activity.

III. PUBLICATIONS

The following papers have either been published or submitted for publication under contract No. N00014-75-C-1095:

1. Bell, T. F., "ULF wave generation through particle precipitation induced by VLF transmitters," J. Geophys. Res., 81, 3316, 1976.
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13. Fraser-Smith, A. C., "Large amplitude ULF electromagnetic fields from BART," to appear in Radio Science, 1978.

14. Fraser-Smith, A. C., and R. A. Helliwell, "Stimulation of ULF geomagnetic pulsations by naturally-occurring repetitive VLF activity," submitted to Nature, 1978.

IV. CONCLUSION

The primary purpose of the research on ULF wave generation under ONR Contract No. N00014-75-C-1095 was to investigate the feasibility of two relatively inexpensive methods for the controlled artificial generation of ULF geomagnetic pulsations. As described in the preceding summary, it appears probable that these ULF signals can be produced by the "peninsula method." Generation of ULF signals by the "VLF method," i.e., by using VLF transmitters, is less certain, but it is concluded that controlled generation will probably be possible after additional research. These generally encouraging results provide support for the concept of using ULF electromagnetic signals for long-range, low-data-rate communication with deeply submerged receivers.

The second purpose of the research on ULF wave generation was to investigate the possibility of using ULF electromagnetic signals from airborne loop antennas for air/undersea communication. We conclude that this method of communication is feasible and that it may provide a useful low-data-rate communication link between an aircraft and a deeply submerged receiver/transmitter for horizontal distances in the approximate range 0 to 100 km.

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