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AIR FORCE SURVEYS IN GEOPHYSICS, NO. 312

On the Feasibility/Desirability of an Air Force ELF/VLF Satellite-to-Ground Communications Link

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12 June 1975

IONOSPHERIC PHYSICS LABORATORY PROJECT 4603

AIR FORCE CAMBRIDGE RESEARCH LABORATORIES

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Preface

Impetus for this study was provided by a request from Hq. Air Force Systems Command. Numerous organizations and individuals provided the information which forms the basis for the discussions herein. We have tried to acknowledge these groups and individuals throughout the report, but unfortunately, the format does not always properly convey the magnitude and nature of their generous support. We specifically thank Mr. David Anderson, Air Force Systems Command, and Mr. Loren Bearce, Naval Research Laboratory, for their many comments and pertinent suggestions throughout the course of this investigation.

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On the Feasibility/Desirability of an Air Force ELF/VLF Satellite-to-Ground Communications Link

1. INTRODUCTION

It is known that Extremely Low- and Very Low-Frequency (ELF/VLF) waves propagate to great distances in the earth-ionosphere waveguide, can be received beneath the surface of the earth, are relatively unaffected by natural ionospheric disturbances, and, in a nuclear environment, suffer less degradation than do higher frequencies. Thus, the development of an ELF/VLF satellite communications system, if feasible, could result in an increase in the overall emergency communications capability of the United States. Accordingly, initial exploratory studies of the feasibility of extending ELF/VLF communications links to include satellite-to-satellite, ground-to-satellite (uplink) and satellite-to-ground (downlink) have been conducted by the Air Force Cambridge Research Laboratory (AFCRL), the Naval Research Laboratory (NRL), and other organizations over the past decade.

Many years of observations of natural phenomena, such as 'whistlers', and uplink satellite receiver experiments, such as LOFTI,[1] have shown that long radio waves can penetrate the F-max region of the ionosphere, where the electron density is 100,000 times larger than that which would produce complete opacity if the

(Received for publication 12 June 1975)

1. Leiphart, J.P., Zeek, R.W., Bearce, L.S., and Toth, E. (1962) Penetration of the ionosphere by very-low-frequency radio signals-interim results of the LOFTI I experiment, Proc. IRE 50(No. 1):6-17.

ionosphere were a simple plasma. This transmission window is due to the geomagnetic field of the earth, which constrains the electron motion produced by incident electromagnetic waves. In the early 1960's, AFCRL began a small program to explore the uplink VLF transmission window to obtain data of potential interest for engineering applications.[2] For this, signals from terrestrial VLF radio stations were monitored by use of rocket-borne receiving and telemetry systems.

At a mid-geomagnetic latitude (Eglin, Florida), signals from three VLF stations were recorded up to an altitude of 500 km at night. At the high altitudes, the recorded signals were 6 to 16 dB below the values on the surface of the earth. In a daytime probe, only the relatively strong signal from NAA (17.8 kHz) was received well to 500 km, where it was 20 dB down. Day flights at low- and high-latitudes (Natal, Brazil and Ft. Churchill, Canada) showed that the fields above 100 km were at least 30 dB and 40 dB, respectively, below the surface values. Field strength profiles in the 0-70 km waveguide region showed a variety of forms, but in general the signals decreased with increasing altitude.

The flight data for Eglin suggested a coherent penetration model, several outputs of which, including polarization, group delay, and Doppler shift, were quantitatively cross-checked and compared with other data. The observations at Natal were consistent with the expected failure of waves to penetrate perpendicularly to the earth's geomagnetic field lines, but at Ft. Churchill the penetrating fields were much weaker than anticipated, being at least 20 dB down from those observed at Eglin.

Full-wave computer calculations based on the model were used to obtain wave-field profiles at various latitudes. These were generally in good agreement with the observations, except at Ft. Churchill, where further study of the appropriate ionospheric parameters is required.

Results of the studies suggest that the penetration of VLF waves up-through the ionosphere may be appreciably dependent on the propagation direction relative to the earth's geomagnetic field. Reciprocal relationships suggest then that there should be strong directional effects for waves penetrating down-through the ionosphere, and into the earth-ionosphere waveguide. This would have an important influence on the expected coverage and field strengths available from an ELF/VLF radiator in space.

To date no ELF/VLF transmitting antenna experiments have been conducted in space, and although much important information has been obtained by uplink studies such as those conducted at AFCRL, much additional experimental and theoretical data are required before the feasibility of downlink ELF/VLF

2. Harvey, R.B., Harrison, R.P., Fields, V.C., Hirst, G.C., Kossey, P.A., and Lewis, E.A. (1973) Rocket Penetration of the VLF Ionospheric Transmission Window, AFCRL-TR-73-0293.

communications can be ascertained. The major technical problem areas to be resolved are: (1) the efficiency of launching ELF/VLF waves from a satellite in or above the ionosphere (antenna problem), (2) the losses that these signals will suffer in penetrating through the ionosphere under both normal and disturbed ionospheric conditions (penetration problem), and (3) the nature of the waves excited in the earth-ionosphere waveguide, and their propagation losses (coverage problem). In addition to these technical problem areas, there are, of course, major engineering problems to be resolved before the ELF/VLF transmissions from space can be attempted.

The Naval Research Laboratory[3] has sponsored and closely followed many studies in these major downlink problem areas. Many significant theoretical and conceptual results have been obtained from these efforts, and some theoretical models from which reasonable predictions can be made have evolved, but even these cannot be adequately tested because of the absence of downlink propagation data. Various satellite experiments have been proposed to obtain downlink data but because of their complexity and relatively high costs (tens of millions of dollars), none have ever been attempted. Thus, the feasibility/desirability of an ELF/VLF satellite communications system has remained largely unanswered. The Navy's efforts and interest in this technical area were sharply reduced when the SANQUINE concept was officially adopted for implementation to provide long range communications to the fleet.

Because of the success of its uplink studies AFCRL was tasked by Hq. Air Force Systems Command to prepare a development plan for an ELF/VLF demonstration transmission experiment from a satellite to ground. Further, AFCRL was asked to evaluate the operational need and potential payoff to the Air Force of developing such a communications capability. This report describes AFCRL's findings and response to that AFSC request.

2. COORDINATION BETWEEN PARTICIPATING AIR FORCE AGENCIES

A meeting of representatives from the Air Force organizations tasked in the program directive was held at AFCRL on 1 November 1973 to coordinate efforts for the preparation of the development plan for an ELF/VLF space-to-ground radio wave propagation experiment. All organizations tasked in the PD were represented at the meeting (see Table 1) which was called so that areas of responsibility could be further defined, and to establish schedules for the completion of various tasks outlined in the program directive.

3. Bearce, L.S. (1972) Antennas and Transionospheric Propagation as Related to ELF/VLF Downlink Satellite Communications, NRL Report 7462, Naval Research Laboratory, Washington, D.C.

After a brief outline of the general nature and history of the subject area, AFCRL described results of a number of its rocket experiments which were conducted to investigate the transmissivity of the ionosphere at VLF. This presentation served to introduce a number of problem areas related to the PD development plan which were later discussed in detail at the meeting. Specific problem areas related to a satellite demonstration experiment were identified and discussed. The appropriate Air Force organizations in attendance investigated and provided specific information on a number of these for incorporation in this report.

Table 1. List of Attendees at Air Force Coordination Meeting

Attendee	Organization
Col. D.L. Evans	AFCRL/LI
E.A. Lewis	AFCRL/LIE
J.E. Rasmussen	AFCRL/LIE
P.A. Kossey	AFCRL/LIE
Lt. Col. F.J. Belmonte	SAMSO/XRLC
G.C. McKoy	SAMSO/Aerospace Corp.
H.C. Koons	SAMSO/Aerospace Corp.
D.P. Kauffman	SAMSO/Aerospace Corp.
Lt. Col. C.E. Gingrich	ESD/XRP
D.A. Kocyba	RADC/OCCL
H.M. Bartman	AFAL/AAI
W.P. Conrardy	AFML/MX
R.L. Kerr	AFAPL/POE

3. PARTICIPATION OF OTHER ORGANIZATIONS

In order to focus national interest in the program, a wide variety of governmental agencies and organizations in the private sector were invited to contribute to any of the pertinent subject areas. These included space payload design, antenna deployment, ground test environment, and such factors as power source, transmitter, antenna (or other radiator), satellite orbit, type of transmission, frequency, ELV/VLF transmissivity under both normal and disturbed ionospheric conditions, noise, field strength prediction, expected ground coverage, location of ground receiving sites, and possible operational uses of an ELF/VLF satellite communications system. Among the organizations which provided information relative to these subject areas were: Hqs. Strategic Air Command (SAC), Air Force Weapons Laboratory (AFWL), Air Force Foreign Technology Division (AFFTD), Naval Research Laboratory (NRL), Naval Electronics Laboratory Center (NELC), Office of Naval Research (ONR), U.S. Army Electronics Command National Aeronautics and Space Administration (NASA), Institute for Telecommunication Sciences (ITS), RAND Corporation, Mitre Corporation, Aerospace Corporation, Stanford Research Institute (SRI), Develco Corporation, Radio Corporation of America (RCA), Pacific Sierra Research Corporation, Raytheon Corporation, and the Sylvania subsidiary of General Telephone and Electronics. The comments and formal inputs obtained from these organizations have been employed in the discussions which follow.

4. MAJOR TECHNICAL PROBLEM AREAS

The discussions below sketch out the major problem areas associated with assessing the feasibility/desirability of implementing an ELF/VLF satellite communications system, and show that their solutions remain largely unknown at this time. Further discussions of these problems are given in the excellent surveys by Dybdal,[4] Develco Corp., Radio Corporation of America, and Stanford Research Institute.[5]

4.1 The Antenna-in-Space Problem

Efficient (resonant) ELF/VLF antennas must be very long because of the long wavelengths involved. Even allowing for a possible high index of refraction for an antenna in the F-max region of the ionosphere, the required lengths may still be in the order of thousands of feet.

To date no ELF/VLF transmitting antenna experiments have been conducted in space, so that engineering data on which to base or predict antenna performance in a magneto-ionic environment are not available. However, extensive theoretical studies have been undertaken in recent years to investigate a wide variety of topics in this area, such as radiation patterns, impedance characteristics, dependence of characteristics with antenna orientation with respect to the earth's magnetic field, effects of electron depletion sheaths that surround space vehicles, etc. In the mathematical formulation of such studies, simplifying assumptions are required in order to achieve tractable solutions, but without adequate experimental

4. Dybdal, R.B. (1971) Feasibility Study of Whistler Mode Satellite-to-Ground Communication Link, Aerospace Report TR-0172 (2320)-1, The Aerospace Corp., El Segundo, Calif.

5. Blair, W.D. (1968) ELF-VLF Transmitter-Receiver Rocket Program, SRI Proposal for Research No. ELU 68-172, Standard Research Institute, Menlo Park, Calif.

data the validity of such assumptions remains unknown.[4] Furthermore, to design a remotely controlled satellite experiment sufficiently sophisticated to cope with the unknowns may be prohibitively expensive at this time.

4.2 The ELF/VLF Ionospheric Penetration Problem

The absorption losses suffered by ELF/VLF waves as they penetrate through the ionosphere is another major area requiring further investigation, particularly for propagation during disturbed ionospheric conditions. At mid-latitudes, uplink studies[2] indicate that under normal nighttime conditions, 15-20 kHz signals suffer between 10-15 dB attenuations as they penetrate up-through the ionosphere (grazing incidence). The attenuations are about 8-12 dB larger under normal daytime conditions. At the geomagnetic equator and at polar latitudes the signals are at least 20 dB less than those observed at mid-latitudes. Full-wave computer studies, using theoretical penetration models evolved from the experimental data, are generally in good agreement with these results, except for the polar latitudes where the theory does not predict the poor penetrations observed experimentally. Predicted downlink penetration losses are comparable to those expected for uplink penetration, with the losses decreasing with decreasing frequency. This has an important bearing on the question of which frequencies should be used if penetration is to be achieved under disturbed ionospheric conditions, such as would be encountered in a nuclear scenario.

4.3 The Coverage Problem

Experimental studies[2] and theoretical predictions based on penetration models which evolved out of them, suggest that the coverage on the earch which can be expected from an ELF/VLF satellite will be confined to mid-geomagnetic latitudes. The extent of the blackout regions about the geomagnetic equator and at the poles is still undefined. Further, the theory of the coupling of the downcoming ELF/VLF waves into the earth-ionosphere waveguide is not sufficiently developed to predict the extent of the coverage, even in the mid-latitude regions. Observations of whistlers suggest however that the signal energy will enter the earth-ionosphere waveguide over an area defined roughly by a circle of about 500-800 km radius. Information on how these fields couple in the waveguide modes and to what distances they may propagate with sufficient strength for communications purposes is lacking.

5. THE CRITICAL QUESTION OF FREQUENCY

There is a critical question to be considered, relative to a space-to-ground communications, which relates to questions of propagation survivability. It must be assumed that a sub-LF system would have to perform in emergency situations; that is, under disturbed ionospheric conditions, such as those associated with Polar Cap Absorption (PCA) events, or with nuclear scenarios. For propagation inside the earth-ionospheric waveguide, reflectivity is the dominant consideration, and it is expected that under disturbed ionospheric conditions, long waves will suffer less degradation than do higher frequency waves. Indeed, the TACAMO and Air Force Trailing Wire Systems have been predicated on this assumption, and are relied upon to provide some communications capabilities even during nuclear disturbances. The question of propagation survivability under disturbed conditions for a satellite-to-ground link is a different and more critical question because it requires the ionosphere to have a degree of transparency.

The downlink blackout problem was addressed in a report by the RAND Corporation,[6] and, as shown in Figure 1, it was concluded that under normal daytime conditions, the ionosphere is relatively transparent to waves having frequencies below about 10 kHz (or above about 10^7 Hz) but if downlink transmission is to be undertaken directly* through even an only moderately nuclear-disturbed ionosphere, frequencies as low as a few tens of Hz (or greater than about 10^8 Hz) must be utilized if less than 30 dB transmission loss is to be suffered. Other theoretical calculations, both at AFCRL and NELC, have reached similar conclusions. Much of the more detailed assessment of the question of propagation survivability which follows was provided to AFCRL by SAMSO/Aerospace Corp. (Dr. H. C. Koons); other comments, provided by the RAND Corporation (Dr. Cullen Crain) and by Pacific Sierra Research Corp. (Dr. Edward Field) have also been incorporated in this discussion.

5.1 Ionospheric Penetration in Nuclear-Disturbed Environments

It is emphasized that in the discussion which follows all the estimates presented are from theoretical analyses, and are not the result of any experimental measurements. Further, only losses associated with the penetration of the waves through the ionosphere are discussed since it is expected that those will be the most significant ones affecting ELF/VLF propagation from space to ground.

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*That is, neglecting the possibility that the waves might somehow find their way around a local region of impenetrability.

6. Booker, H.G., Crain, C.M. and Field, E.C. (1970) Transmission of electro magnetic waves through normal and disturbed ionospheres, RAND Report R-558-PR, Santa Monica, Calif.

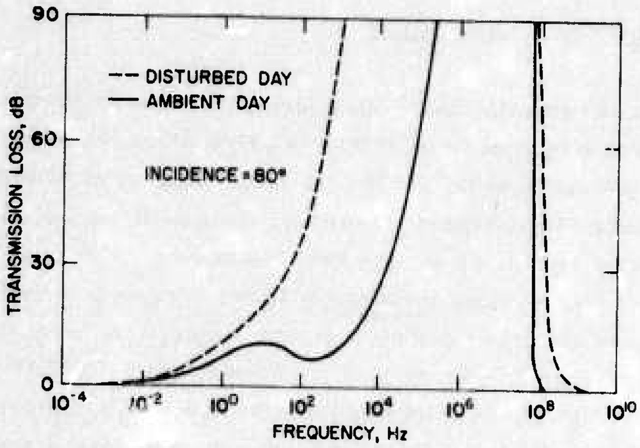

Figure 1. One-Way Transmission Loss Through the Ionosphere as a Function of Frequency (See Reference 6)

A nuclear detonation will create a highly localized disturbance where the time lapse and the distance from the detonation will have considerable impact on the level of attenuation to be experienced. In terms of an operational application, the relative positions of the localized detonation, satellite transmitter, and surface or subsurface receivers must be considered.

The results of a theoretical analysis that considered the effects of an ionospheric nuclear detonation on ELF propagation are presented in Figure 2 for daytime conditions. The analysis assumes a 6 megaton detonation at 91 km, and a propagation frequency of 3 kHz. The region from ground level to 100 km is divided into layers and, using appropriate values of electron densities, the absorption loss is determined for waves travelling normal to the earth's surface using the Appleton-Hartree formulas. Twenty dB increases in absorption exist 15 min after detonation even as far as 1200 km from ground-zero for both day and night conditions.

It is interesting to compare the information contained in Figures 1 and 2 for the specific frequency of 3 kHz. Extrapolation of Figure 1 for daytime conditions, would reveal a 3 kHz transmission loss of approximately 150 dB. This corresponds to the losses in Figure 2 at 1 sec and 50 sec for distances from the burst of 1200 km and 0 km respectively. If it can be assumed that, although the magnitude of attenuation for any arbitrary time will change, the shape of the curves of Figure 2 will remain essentially the same as a function of frequency; quantitative estimates of attenuation for any frequency can be determined by adjusting the ordinate in accordance with Figure 1. The results of this exercise are shown in Figure 3.

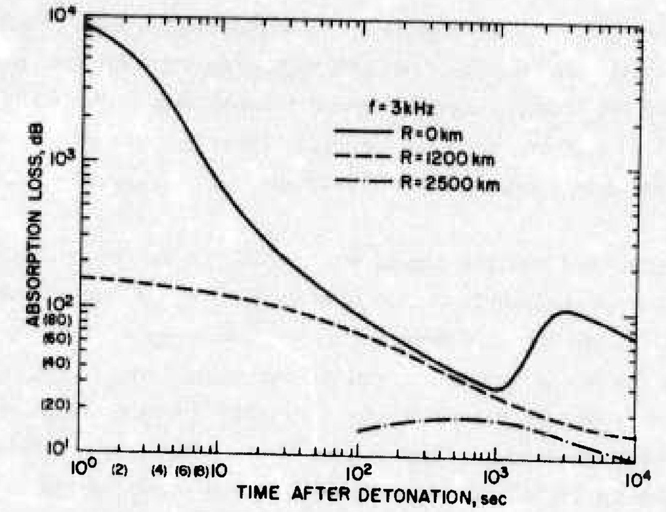

Figure 2. Effects of Ionospheric Nuclear Detonation on ELF Propagation, Daytime Conditions. R denotes the distance from the detonation point. (SAMSO/Aerospace)

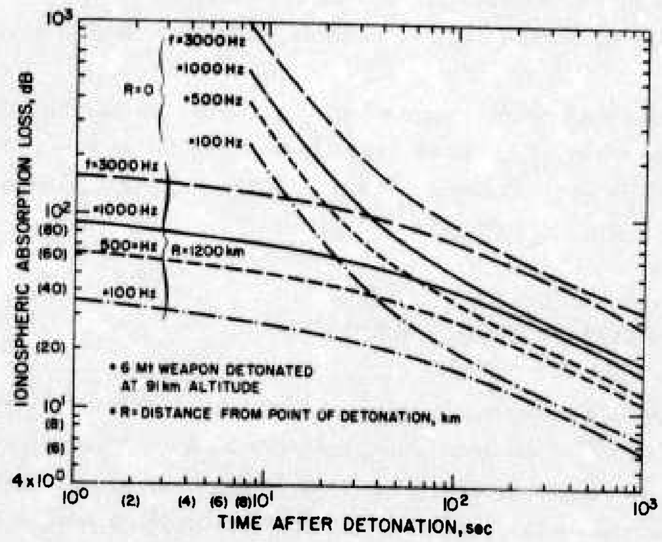

Figure 3. Absorption in Nuclear-Disturbed Daytime Atmosphere (SAMSO/Aerospace)

Several general conclusions may be made with reference to Figure 3. The most obvious conclusion is that the attenuation decreases with decreasing frequency. Furthermore, it would appear that the level of attenuation is relatively uniform for $0 \leq R \leq 1200$ km for times greater than 100 sec after detonation. This latter conclusion must be qualified by the unusual jump in the $R = 0$ curve of Figure 2.

It has been estimated that the signal energy will enter the earth-ionosphere waveguide over an area defined by a circle of about 500-800 km radius. For the maximum range from the point of detonation, it would appear that the attenuation will be too severe for successful communications immediately after the detonation, even with a frequency of 100 Hz. Therefore, a blackout interval in the order of minutes during which communications will be impossible appears inevitable for the geometry requiring signal propagation near the point of detonation. Satellite motion with respect to the point of detonation together with some finite degree of propagation within the earth-ionosphere waveguide may tend to shorten the duration of the blackout. A possible scheme for a working system would be to use several satellites in a manner to maximize the probability that at least one satellite is transmitting under undisturbed ionospheric conditions. In this case, the signal might reach the receiver by propagating over the earth in a waveguide mode, but as noted earlier there are currently no reliable estimates for the magnitude of such a signal.

Thus, it appears that requirements for survivable communications may dictate the use of ELF rather than VLF in an operational downlink system. In this case the costs of a satellite experiment may be prohibitive in view of competing systems, and the current economic environment.

6. DESIRABILITY OF AN ELF/VLF SATELLITE SYSTEM

Because of the high costs and high risks associated with even a relatively simple satellite ELF/VLF demonstration transmission experiment, the question of the desirability of such a system must be considered as well as the question of feasibility. Comments on the desirability question from ESD, SAC, RAND Corporation, Pacific Sierra Research Corporation, and Develco Corporation, are included in the discussion which follows.

The need of the Navy to communicate with its submerged submarines is immediately obvious, so that any system which would enhance or augment this capability would be important. In this regard the Navy has devoted considerable effort in assessing the desirability/feasibility of a space-to-submerged submarine communications capability at sub-LF frequencies. Many of the problem areas that have made it difficult for the Navy to fully assess such a system, are still relatively unsolved, so that similar assessments, even if directly related to Air Force requirements must necessarily suffer from the same lack of information. These question areas include space antenna size and deployment, antenna characteristics in an ionized medium, ionospheric penetration, earth-ionosphere waveguide coupling, expected coverage in the earth-ionosphere waveguide, etc. With these problem areas in mind, it is still possible to discuss, in a somewhat general nature, the pros and cons of such a system's capability from an Air Force point of view; particularly if emphasis is put on how, or if such a system would, offer any special advantages over alternative methods.

It is reasonable to assume that a sub-LF space-to-ground link would be used primarily for emergency communications purposes, that is, communications under disturbed ionospheric conditions. At frequencies in the ELF band and lower, one obvious advantage would be that satellite-based systems would be more acceptable politically than huge ground-based SANQUINE-type installations. However, such satellite systems might not be entirely survivable, could suffer serious blackouts, and would have a relatively limited user access time. The rationale behind the use of VLF for communication purposes is its long range capabilities, even under disturbed ionospheric conditions. For this reason the DoD, AF, and Navy have developed such systems as TACAMO and MEECN which make use of airborne transmitters. These systems, although somewhat encumbered by the use of long trailing wire antennas, are highly mobile, and can transmit at relatively high power levels. It is not readily apparent that the ability to transmit VLF from a satellite would significantly add to these already existing capabilities. Furthermore, it appears that because of the relatively low power levels that would be available to such satellite systems, and because of the large absorption affects on VLF waves as they propagate down through the ionosphere, the coverage available to a user near the surface of the earth may be very limited in extent. Such coverage may only be a few hundred km in extent by many present estimates. Certainly, a satellite could not be competetive with TACAMO or the AF trailing wire systems in this regard. To alleviate this satellite power limitation, it might be that instabilities could amplify signals traversing the magnetosphere; but reliance on such a technique appears to be a highly tenuous proposition however, due to the fact that magnetospheric conditions are often not conducive to amplification or whistler duct guidance, that is, system performance could be highly erratic. Whether such a condition could be tolerated in any sense, in a system which would be used for emergency situations, is highly unlikely.

One possible solution to the range problem discussed above is to proliferate. If enough satellites are in the system, it should be possible to provide the required coverage. In this case, the question immediately arises whether such a system would provide any more capability than the already existing, or proposed 'line-of-sight' systems, that would operate at extremely short wavelengths.

A simple geometrical calculation shows that a UHF satellite at a height of 1000 km would provide line-of-sight coverage on the earth over an area approximately described by a circle with a radius of 3400 km, the 'hot-spot' radius of coverage expected from an ELF/VLF satellite is only about 500-800 km. Also, the ELF/VLF coverage is expected to be limited to mid-latitudes, with dark zones about the geomagnetic equator and in the polar regions. No such coverage limitations exist at UHF. The transmitter power required for the extensive UHF coverage is minimal (milliwatts), while the engineering and power requirements for a space-to-ground ELF system appear to be well beyond the present state-of-the-art. Furthermore, UHF satellites can transmit much more 'information' than would be possible with ELF/VLF, and would not be encumbered with large antennas, thus mitigating appreciably attendant deployment, weight, and physical survivability problems, that can be expected to be major problem areas for an ELF/VLF satellite system.

7. SAMSO/AEROSPACE 'STRAW-MAN' SATELLITE VLF TRANSMISSION EXPERIMENT

In Appendix A, a 'straw-man' satellite experiment is described that has been culled from consideration of a number of proposals that have been made from time-to-time over the past few years to the Air Force and the Navy. Proposals from Develco Corporation, and from RCA, which were originally sponsored by studies conducted by the Naval ResearchLaboratory, have provided most of the data and estimates given therein. The outline given in Appendix A was drawn up specifically for Project 2067, by SAMSO/Aerospace. Briefly, an experiment consisting of a transmitting satellite, a receiving satellite, and associated ground receiving and monitoring sites is described. The estimated cost shown in the proposal is roughly 2 million dollars (1974) which assumes that contributions to the program from the Satellite-Test-Program (STP) Office would be very substantial, but at no cost to the experiment. Deletion of the receive satellite would not lower the 2 million dollar figure since it has already been assumed that this satellite and its associated instrumentation would be 'donated' by STP. If the program cannot receive certain sensors at no cost from STP, as is assumed in the estimated costs, another 0.6 million dollars should be added to the estimate, making the total cost approximately 2.6 million dollars. Further, if the requirements of the VLF satellite experiment are such as to allow no room for payloads for other experimenters, the program could be required to fund the entire spacecraft. In such a case, another 12 to 15 million dollars would be required. In either case, the total cost to the taxpayers would be in excess of 10 million dollars.

8. PRESENT STATUS OF DOWNLINK STUDIES AT AFCRL

The contents of this report constituted a final report to Hq. AFSC under Project 2067. In forwarding these results AFCRL specifically noted the following:

(1) The engineering parameters, attenuation losses, coverage areas, etc., are not well enough known at this time to permit the design of a specific ELF/VLF communications system, and accordingly, it is unclear just how the Air Force might exploit the ELF/VLF ionospheric penetration phenomena.

(2) It remains unclear what the characteristics of a useful Air Force satellite-to-air ELF/VLF system ought to be.

(3) Because of the high costs involved in such a satellite experiment, a high risk satellite experiment is difficult to justify, particularly in these days of tightening economies.

(4) Since no clear and compelling Air Force requirement for an ELF/VLF satellite communications system was discovered, it appears prudent to seek some less expensive approach for determining the unknown parameters mentioned in (1) above.

(5) A much less expensive approach might be to experiment with rocket borne transmissions on a R&D basis. A proprietary proposal has been received by AFCRL for rocket deployment of very long antenna wires for short times commensurate with the lifetimes of battery power supplies. This approach could provide important needed data by a series of low risk 'nibbles', rather than by a 'go-for-broke', one time, high risk satellite experiment.

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10. Baker, D., Weil, H., and Bearce, L.S. (1973) Impedance and large signal excitation of satellite-borne antennas in the ionosphere, IEEE Trans. Ant. Prop. AP-21:672.

11. Wang, T.N.C. and Bell, T.F. (1970) on VLF radiation resistance of an electric dipole in a cold magnetoplasma, Radio Sci. 5:605.

12. Chobotov, V.A. (1972) STP Orbital Separation Problem, Aerospace Technical Memorandum ATM-72 (2701-01)-15, The Aerospace Corp., El Segundo, Calif.

Appendix A

SAMSO/AEROSPACE 'Straw-Man' Demonstration Experiment

A1. CONCEPT OF THE SAMSO/AEROSPACE EXPERIMENT

The minimum experiment recommended to prove the concept that signals radiated by a satellite ELF/VLF transmitter can be received on the ground consists of two spacecraft and several inexpensive ground installations as shown in Figure A1. One spacecraft is primarily a transmitter spacecraft, the other a receiver spacecraft. The two are launched by a single launch vehicle and separated with sufficiently small separation velocity (about 1.0 ft/sec) to assure that their maximum range is less than 500 km for the first 60 days of the mission.

It is envisioned that the ELF/VLF transmitter will be submitted to the Satellite Test Program (STP) office in the "experimental only" category and that all of the environmental sensors with the exception of the magnetometers and sun sensors will be chosen from the STP approved list. The STP office would also integrate both spacecraft and provide the launch vehicle.

A2. TRANSMITTER SPACECRAFT (SAMSO/AEROSPACE)

The transmitter spacecraft payload consists of a 1000-ft tip-to-tip electric-dipole antenna, an ELF/VLF transmitter and tuner capable of delivering 1 kW of power to the antenna terminals, and appropriate environmental sensors.

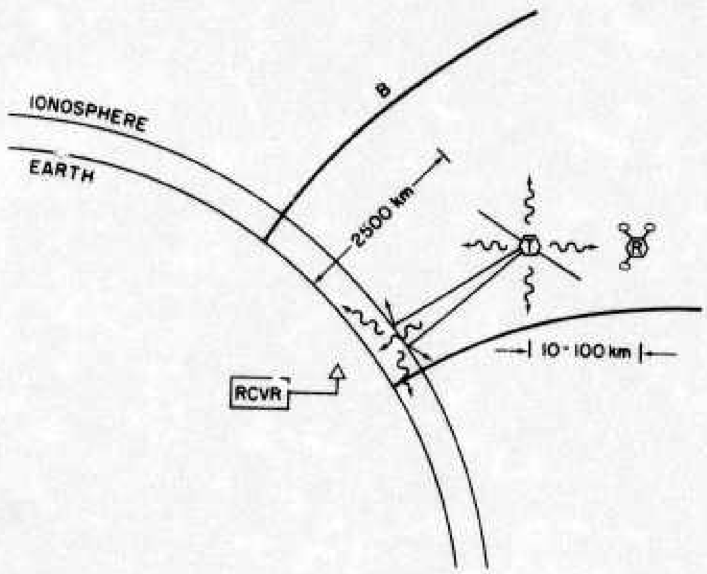

Figure A1. Transmission Experiment Concept

Electric-Dipole Antenna. The electric-dipole antenna is proposed for this demonstration because similar antennas of longer length (1500-ft tip-to-tip) have been flown on the Radio Astronomy Explorer-A satellite. The technology is well developed with at least two vendors available. Calculations by Develco predict signal-to-noise ratios as high as 20 dB at local nighttime.

The alternatives to the electric-dipole antenna are the loop antenna and the particle-beam antenna. Calculations by Develco predict that a 300-ft diam lossy loop will also produce a readily detectable signal on the ground. However, loop deployment technology has not proceeded beyond the study state.[7] The loop is an attractive antenna because the antenna impedance is essentially resistive and hence the antenna tuner is greatly simplified compared with the electric-dipole. The radiation resistance and antenna patterns of a loop are calculated using the same theory as for an electric-dipole antenna. Hence the data from a demonstration utilizing the electric-dipole antenna can be used to validate the theory for a loop antenna as well.

The second alternative, a particle beam, is less well understood. In theory an ion gun can generate a charged particle beam whose current is modulated by neutralizing electrons. Studies are underway to determine the net charge moment

7. Moulds, C. (1972) Deployment Study, Technical Memorandum, Contract No. N00014-72-C-0534, Westinghouse Electric Corporation, Defense and Space Center, Baltimore, Md.

when such a beam is emitted into a plasma. A preliminary spaceflight will be required before this concept can be assessed for a space-to-ground demonstration.

Tuning. The impedance of an electric-dipole antenna is dominated by the conductance and reactance of the plasma sheath which surrounds the antenna elements. Calculations of this sheath impedance, using a quasi-static assumption which allows the ac behavior to be determined from successive dc steps, predict that the sheath is predominantly resistive at low frequencies, low voltages, and high plasma densities, and predominantly capacitive at higher frequencies, high voltages, and low plasma densities.[8,9]

However, the antenna impedance experiment flown on satellite OVI-21 measured an inductive rotation of the phase angle as the voltage increased.[10] These measurements indicate that the dynamic behavior of the sheath is not yet understood. A computer simulation of the dynamic sheath, removing the quasi-static assumption, should be undertaken in parallel with experiment definition. An analysis of the OVI-21 data, scaling to the higher voltages required for the demonstration should be adequate for preliminary experiment planning.

Transmitter. Calculations by Develco indicate that a successful demonstration requires one kW of ELF/VLF power delivered to the antenna. About 1.8 kW of dc power is required to drive the transmitter envisioned by RCA.

The transmitter must be capable of operating at several frequencies between 1.0 and 10.0 kHz. The direction a signal can propagate away from the vehicle is strongly controlled by the magnetoplasma. Below the local proton gyrofrequency and above the local lower-hybrid-resonance frequency the antenna pattern contains resonances which take most of the available power. However, between these two frequencies the index-of-refraction surface is closed and omni-directional propagation occurs. The proton gyrofrequency is given by:

$$f_{bi} = eB/2\pi M = 1.5 \times 10^3 \text{ B rad/sec}$$

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8. Koons, H.C., Morse, F.A., and McPherson, D.A. (1973) Measurement of the Nonlinear Impedance and Nonlinear Plasma Effects in the Near Field of an Electric-Dipole Antenna, Aerospace Report TOR-0073 (3520)-1, The Aerospace Corp., El Segundo, Calif.

9. Shkarofsky, I.P. (1972) Nonlinear sheath admittance, currents and charges associated with high peak voltage drive on a VLF/ELF dipole antenna moving in the ionosphere, Radio Sci., 7:503.

10. Baker, D., Weil, H., and Bearce, L.S. (1973) Impedance and large signal excitation of satellite-borne antennas in the ionosphere, IEEE Trans. Ant. Prop. AP-21:672.

where B is the magnetic field strength of the earth's magnetic field expressed in gauss. The lower-hybrid-resonance frequency in a low density plasma is approximately

$$f_{LHR} = (f_{bi}\, f_{be})^{1/2} = 6.5 \times 10^4 B$$

where B is again expressed in gauss. The lower-hybrid-resonance frequency is reduced in a moderately high density space plasma.

Ideally the experiment should be performed at frequencies from somewhat below the proton gyrofrequency to above the lower-hybrid-resonance frequency. The latter is achieved within the range 1.0 to 10.0 kHz. A somewhat lower frequency of operation would be required to transmit below the proton gyrofrequency.

Frequency Stability. A frequency accuracy of 0.1 Hz at 10 kHz is required over the life of the mission.

Modulation. Pulse modulation is required. The minimum pulse length will be determined by the tuning system and will be several msec. A desired minimum pulse length is 50 ms corresponding to a Morse Code dot from a conventional VLF transmitter. The maximum pulse length should be as long as possible consistent with the power system. A length of 10 sec should be routinely available and a length of 1 min is desired.

Although more exotic modulation techniques, including phase shift keying, frequency shift keying, frequency sweeps and specific pulse length programs are desirable and inexpensive to implement for wave-particle interaction studies and conjugate wave propagation studies, they are not required for the minimum demonstration.

Environmental Sensors. The space plasma environment surrounding the transmitter will be severely disturbed by the high-voltages on the electric dipole. The sensors are chosen to measure this environment and to determine the potential to which the spacecraft becomes charged. The sensors include a retarding potential analyzer to measure the density, temperature, and relative abundance of thermal ions, and electron and ion spectrometers to measure the distribution functions of energetic particles.

Electric and magnetic field sensors on the transmitter spacecraft will measure the near fields of the electric-dipole antenna as well as the sheath properties and acoustic mode excitation.

A magnetometer is required to determine the magnetic aspect of the electric-dipole antenna. A sun sensor is required to determine the attitude of the antenna. This data is required to determine the antenna pattern.

Telemetry. A SGLS system or two S-band transmitters is required. The current and voltage waveforms driving the electric-dipole-antenna must be telemetered simultaneously with a band width of 30 kHz (third harmonic at 10 kHz is minimum requirement). In addition, a minimum of two broadband channels are required for the data from the electric and magnetic sensors. Most of the data should be acquired in real time operations over KODI, COOK, and NHS. Commutated data is also required.

Orbit. The Develco calculations predict that the ground signal increases as the altitude of the transmitter increases over the range of their calculations; 500 to 2500 km. They state that this increase might continue up to an altitude of 3000 km by which point the index-of-refracture, which is the controlling parameter, goes through a minimum and begins to increase with altitude. A suitable apogee is 2500 km. At this altitude the calculations predict a successful demonstration.

Perigee will most likely be determined by spacecraft stability requirements. Although it is desirable to conduct the experiment down to the higher electron densities at 500 km, it is not required for the demonstration. A circular orbit between 2000 and 2500 km is adequate to demonstrate the concept and validate theoretical models. A polar orbit is required.

Stabilization. A slow spin is desired. The spin vector should be normal to the orbit plane. It is desired that the angle between the antenna axis and the local magnetic field be scanned through maxima and minima several times at each station acquisition.

A3. RECEIVER SPACECRAFT (SAMSO/AEROSPACE)

The primary objectives of the receiver spacecraft are to measure the radiation pattern of the electric-dipole antenna and to determine the plasma wave modes excited by the transmitter. The predicted radiation pattern of an electric-dipole antenna in the magnetoplasma differs drastically from the pattern in free-space. In free-space there is a null in the pattern along the axis of the antenna. However, calculations show a maximum along the axis of the antenna in the magnetoplasma.[11]

Environmental sensors on the received spacecraft will measure ambient plasma conditions outside of the highly disturbed transmitter environment. They will also measure small disturbances in the ambient medium generated by wave-particle interactions.

Instrumentation. The receiver spacecraft payload includes a three-axis electric-field sensor, and a three-axis magnetic-field sensor for field-pattern and

11. Wang, T.N.C. and Bell, T.F. (1970) on VLF radiation resistance of an electric dipole in a cold magnetoplasma, Radio Sci. 5:6?5.

mode-excitation measurements. The environmental sensors are similar to those on the transmitter spacecraft with the addition of an electron density measurement such as a relaxation probe.

A magnetometer is required to determine the magnetic aspect of the field sensors. A sun sensor is required to determine the attitude of the spacecraft.

Telemetry. A SGLS system or two S-band transmitters is required. A minimum of three broadband channels with a bandwidth of 10 kHz is required. The broadband data must be telemetered in real time. Commutation data is also required.

Orbit. The receiver spacecraft should remain within 500 km of the transmitter spacecraft for the first 60 days of the mission. This will require separation velocities of about 1 ft/sec. Computer programs are available for analysis of various separation conditions.[12] It is desirable to have the receiver satellite in the spin plane of the electric-dipole antenna of the transmitter.

Stabilization. Spin stabilization is required. A spin rate between one and three rpm is required to determine the pitch angle distributions of energetic particles.

A4. ESTIMATED COST OF EXPERIMENT (SAMSO/AEROSPACE)

	Develco (1972)	RCA (1969)	Present (1974)
Experiment Plans and Definition	95[1]		95
Payload RFP and Evaluation	120		120
Transmitter S/C Payload			
Antennas	160[3]	981[2]	250[3,6]
VLF Subsystems	430	1,041	1,000[7]
Environ. Sensors	320	805	(300)[4]
Payload Tests	150		150
Receiver S/C Payload			
VLF Receiver			
CRLS-252			
Environ. Sensor			(300)[4,5]
Ground Receivers and Ionosondes	500		200
	1,775	2,827	1,815
			(2,415)

Notes:

1. Cost figures in thousands of dollars.
2. 1-1/8 inch hingelock.
3. 1/2 inch STEM.
4. From STP approved list.
5. Project 649-D Funds
6. Based on Develco estimates with inflation and qualification testing added.
7. 10 MTS man years.

12. Chobotov, V.A. (1972) STP Orbital Separation Problem, Aerospace Technical Memorandum ATM-72 (2701-01)-15, The Aerospace Corp., El Segundo, Calif.

A5. COMMENTS FROM THE STP OFFICE RELATIVE TO THE EXPERIMENT

(1) The approach taken to fly the ELF/VLF payloads requires a dual satellite launch on the same launch vehicle. The orbital altitudes desired put the flight into the Atlas or Thor Delta performance category. For cost reasons STP presently attempts to work with Atlas vehicles when faced with this choice. The second stage would be similar to the Burner II stage used on Flight P72-1. If a circular orbit at or above 1000 nm is required, a third stage or solid rocket apogee motor would also be required. Since three-axis control will probably be necessary to orient and deploy the two satellites on orbit, the two-stage arrangements above the Atlas would be similar to a Burner IIA with slightly smaller TEM 604 or SVM-2 in the upper stages. Launch vehicle capabilities for the various combinations are shown below.

Launch Vehicle		Perigee	Apogee	Weight and Orbit
Atlas F/BII	(P72-1)	250 nm	1500 nm	1900 lbs
Atlas F/BIIA	(TEM-604)	1000 nm	1000 nm	1500 lbs
Atlas F/BIIA	(SVM-2)	1400 nm	1400 nm	1500 lbs

(2) Two satellites are required to support the ELF/VLF payloads. The transmitter satellite would carry the 250 lbs of main experiment. The power, telemetry, ACDS subsystems would be similar to those on STP Flight P72-1 and it appears that the satellite would account for about 650 lbs. This satellite would be capable of supporting more experiments. We would attempt to find up to another 250 lbs of payloads depending on orbit required. The receiver satellite would be a small satellite or the STP S3 variety that would carry the CRLS 252 payload (50 lbs). The satellite without payloads weighs about 250 lbs. Up to 100 lbs of additional payloads might be added here. In addition to the two satellites, approximately 50 to 100 lbs of satellite-to-satellite adapter and structural mounting would be required for holding and deploying the receiver satellite.

ELF/VLF payload	250
Transmitter satellite	650
CRLS 252 payload	50
Receiver satellite	250
Satellite-to-satellite adapter	100
	1300
Margin	160
	1460
Additional STP payloads (incl. margin)	400
	1860

It should be noted that the satellites required to fly the ELF/VLF experiments can be used to support additional experiments if the orbit chosen allows sufficient capability. When the requirements desired by a single experimenter allow no room for additional payloads, the prime experimenter can be required to fund for the spacecraft (AFM 80-2, para. 2-10a).

(3) The orbital inclination and performance would be consistent with a sun-synchronous, noon-midnight orbit at the altitudes selected. The reason for this is to be able to use a spinning spacecraft with the minimum power and attitude requirements.

(4) Finally, the words on costs. Atlas launch costs are strongly dependent on the number launched the year in question. For 1976 and beyond the launch rates are unknown. Assuming that three Atlas F's are launched in the year ELF/VLF is launched, a rough estimate of the uninflated costs would be:

	$M
Atlas launch services	2.7
Atlas hardware	.6
Single upper stage	1.5
LV integration (includes adapter)	1.5
Transmitter satellite	6.0
Receiver satellite	3.2
Shroud, adapters	0.5
	16.0
Third stage & motor (req'd for circular orbits)	.5
	16.5

(5) Caution should be exercised in using the final cost number as "the cost to fly ELF/VLF". It would be the cost to STP to fly a mission that includes other important payloads. STP missions do not usually cost this much but the dual satellite approach required two completely self-sufficient satellites. Herein lies a great deal of the cost.

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