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DNA 3778T

(12)

AN OVERVIEW DISCUSSION OF PROPAGATION EFFECTS OF NUCLEAR ENVIRONMENTS ON VLF-LF COMMUNICATION SYSTEMS

The Rand Corporation
1700 Main Street
Santa Monica, California 90406

31 August 1975

Topical Report for Period 4 September 1974—31 August 1975

CONTRACT No. DNA 001-74-C-0019

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UNDER SUBTASK S99QAXHE043-26.

Prepared for

Director
DEFENSE NUCLEAR AGENCY
Washington, D. C. 20305

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

19 REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER 18 DNA 3778T

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER 9

4. TITLE (and Subtitle) 6 AN OVERVIEW DISCUSSION OF PROPAGATION EFFECTS OF NUCLEAR ENVIRONMENTS ON VLF-LF COMMUNICATION SYSTEMS.

5. TYPE OF REPORT & PERIOD COVERED Topical Report for Period 4 Sep 74—31 Aug 75,

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s) 10 C. M. Crain

8. CONTRACT OR GRANT NUMBER(s) 15 DNA 001-74-C-0019

9. PERFORMING ORGANIZATION NAME AND ADDRESS
The Rand Corporation
1700 Main Street
Santa Monica, California 90406

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 16 DNA- NWED Subtask S99QAXHE043-26 17 EØ43

11. CONTROLLING OFFICE NAME AND ADDRESS
Director
Defense Nuclear Agency
Washington, D.C. 20305

12. REPORT DATE 11 31 Aug [redacted] 75

13. NUMBER OF PAGES 28

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) 12 21p.

15. SECURITY CLASS (of this report) UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

This work sponsored by the Defense Nuclear Agency under Subtask S99QAXHE043-26.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

VLF-LF Systems
Nuclear Effects

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

It is the purpose of this brief overview to bring out the general features of long-wavelength propagation at VLF and LF frequencies, how nuclear environments can degrade the normal communications capability which these systems provide, the consequences of remaining uncertainties in predicting the degree of degradation expected under worst-case conditions. More detailed technical understanding of the overall problem is available in DNA literature.

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296 600

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I. BACKGROUND AND INTRODUCTION

In recent years much national effort has been directed toward providing assured survivable communications from the NCA and CINCS to the various elements of the strategic forces under conditions of heavy nuclear attack. This effort has included a variety of communication means--satellites, rockets, airborne transmitters, mobile and dispersed surface facilities, and both soft and hard fixed surface facilities. Transmission frequencies of interest cover the radio frequency spectrum from a few hertz to some 10^{11} hertz. For the vital function of providing minimum essential one-way assured communication from the command authorities to the force elements, particular attention has been given to communication systems which use transmission frequencies below about 10^5 hertz. This is because of the attractive propagation characteristics of these so-called long wavelength radio signals. The Navy has actively pursued the development of a system (SANGUINE) employing a buried transmitter(s) which radiate signals at frequencies below 10^2 hertz in the so-called ELF (extremely low frequency) region of the radio spectrum. The Air Force and Navy have developed capabilities to transmit signals from both fixed and airborne transmitters in the range between 10^4 and 10^5 hertz, i.e., in the upper VLF (very low frequency) and lower LF (low frequency) portions of the radio spectrum.

A common feature of communication systems capable of long range communication at frequencies in the VLF and LF portions of the radio spectrum (the frequency region examined in this report) is that the transmitters require physically large radiating elements and high transmitter input power. For this reason it is not practical to attain long range two-way communication capabilities between command authorities and the force elements by use of these frequency bands.

Despite their being limited to one-way communication functions, the potential capability of long wavelength systems--using practical transmitter facilities and radiated powers--to provide communications at global or a sizable portion of global distances for very vital purposes has provided one of the principal bases for development of such systems.

Interest in new and physically survivable long wavelength communication systems was considerably increased in the early 1960s. This occurred because HF (high frequency, 3-30 MHz) radio communication was considered relatively more vulnerable to disruption due to effects produced by nuclear weapon detonations--particularly detonations at high altitude--than communication systems which operated in other portions of the radio spectrum. Following the 1962 high altitude tests a considerable amount of data on VLF transmission effects caused by the various high altitude bursts became available from many sources--to a large extent from groups routinely monitoring the several world-wide VLF transmitters of the United States, the USSR, Japan, etc. These data clearly indicated that the previously prevailing general impression that VLF transmission would not be seriously affected by nuclear burst environments was incorrect. The Defense Nuclear Agency, recognizing the importance of developing an improved understanding of VLF propagation in nuclear environments, organized a working group which met at Stanford Research Institute in October, 1963. The participants included those having relevant data, theoretical experts in nuclear phenomenology and long wave propagation, and those having system application interests and responsibilities. In brief, the working group found that the available data from the 1962 tests indicated generally more severe effects on VLF transmission than previously anticipated, that the understanding of the nuclear phenomenology and VLF propagation was inadequate to explain the observed effects, and that those using and planning systems employing VLF transmission sorely needed better information on expected system performance in various feasible nuclear environments. Shortly after the meeting of the DNA Working Group on VLF it was recognized that positive and negative ions as well as electrons could significantly influence VLF and LF propagation in a nuclear environment and that previous assessments which included only electrons were in general optimistic; the inclusion of ion effects subsequently made possible a much better agreement between observation and predictions and, to a large extent, eliminated the mystery as to why much of the observed propagation degradation in the 1962 tests exceeded previous expectations.

In November 1963, DNA organized a working group on LF propagation in nuclear environments which met at Rand and spent a major portion of its time studying the question of the newly proposed role of ions in LF propagation. Although important elements of ion chemistry in the relevant 30 - 60 km height region were not adequately known (such as the dominant ion species, ion-neutral collision frequencies, and several reaction rates), analyses using best estimates of uncertain parameters indicated that, at the lower LF frequencies, nuclear produced environments in the 30 - 60 km height range could have disastrous consequences to normal sky-wave propagation. The major conclusion of the working group was that:

> "In any event, it appears basically sound, in order to provide invulnerablility to nuclear burst-produced propagation effects, to design LF systems on the basis of a surviving groundwave signal and normally expected noise backgrounds."

The height region from 30 to 60 km has proved most difficult for experimental work on charged particle chemistry, and important uncertainties remain; however, present understanding supports the above conclusion of the LF working group.

Since it became recognized that long wavelength signal propagation could be upset to an operationally significant degree by nuclear burst environments, DNA has supported theoretical and experimental work directed toward making available to system operators and planners the needed degree of understanding for judicious system development and operational assessments. A sizable amount of information relevant to the problem has been obtained and documented in DNA handbooks and reports. This work includes theoretical work on signal propagation under normal and disturbed conditions; experimental work under natural disturbed conditions such as exi occasionally in polar regions following large solar disturbances; theoretical and experimental work directed toward resolving the major uncertainties concerning the conductivity of the lower ionosphere and, hence, the propagation characteristics of long wavelength signals; simulation of transmission path performance using models which closely resemble the earth-ionosphere transmission waveguide; and calculated transmission effects at VLF and LF frequencies for a wide variety of assumed plausible nuclear burst environments and typical operational path geometries. As a result, a vastly improved understanding, relative to that existing when atmospheric nuclear testing was terminated, has evolved and is available for use by system planners, operational users, war game studies, etc.

II. NUCLEAR EFFECTS ON AVAILABLE RADIO MEANS FOR LONG RANGE COMMUNICATIONS

A. Long Range Radio Communications

Radio transmission of information between terminals well beyond line-of-sight is possible by several techniques which employ a wide range of the radio spectrum from ELF to the millimeter wavelengths. For transmission to distances of more than several hundreds of kilometers, three principal means, namely long wavelength (VLF and LF) propagation, high frequency (HF) propagation, and satellite relay are currently in operational use. All three means are subject to deleterious propagation effects (in addition to physical effects on terminals and terminal equipment not considered in this report) which may be brought about by nuclear detonations. Figure 1 illustrates the more germane features of how signals are propagated from transmitters to receivers by the three methods, and also indicates for each method the important height regions where the signal is subject to the more significant nuclear effects.

B. Satellite Relay

In the case of satellite relay transmission, the signal may be reduced in amplitude and modified in phase by excess ionization produced below about 400 km for nuclear bursts in general. This effect is a straightforward transmission phenomenon though an ionized medium. Under non-nuclear conditions it is negligible at the frequencies normally used [UHF (300-3,000 MHz) and above]. Under nuclear disturbed conditions important amplitude reduction or "black-out" effects can be produced, particularly at the lower frequencies. The more generally significant effect on satellite relay transmission under either normal or nuclear disturbed conditions is caused by large scale striated type structures which exist normally or may be induced by nuclear detonations in a region from perhaps as low as 100 km altitude to perhaps as high as several thousand km. Satellite transmission effects and their understanding is being actively studied by DNA and others (those primarily concerned with natural conditions) and is mentioned here only for purposes of perspective on the three principal long range transmission methods.

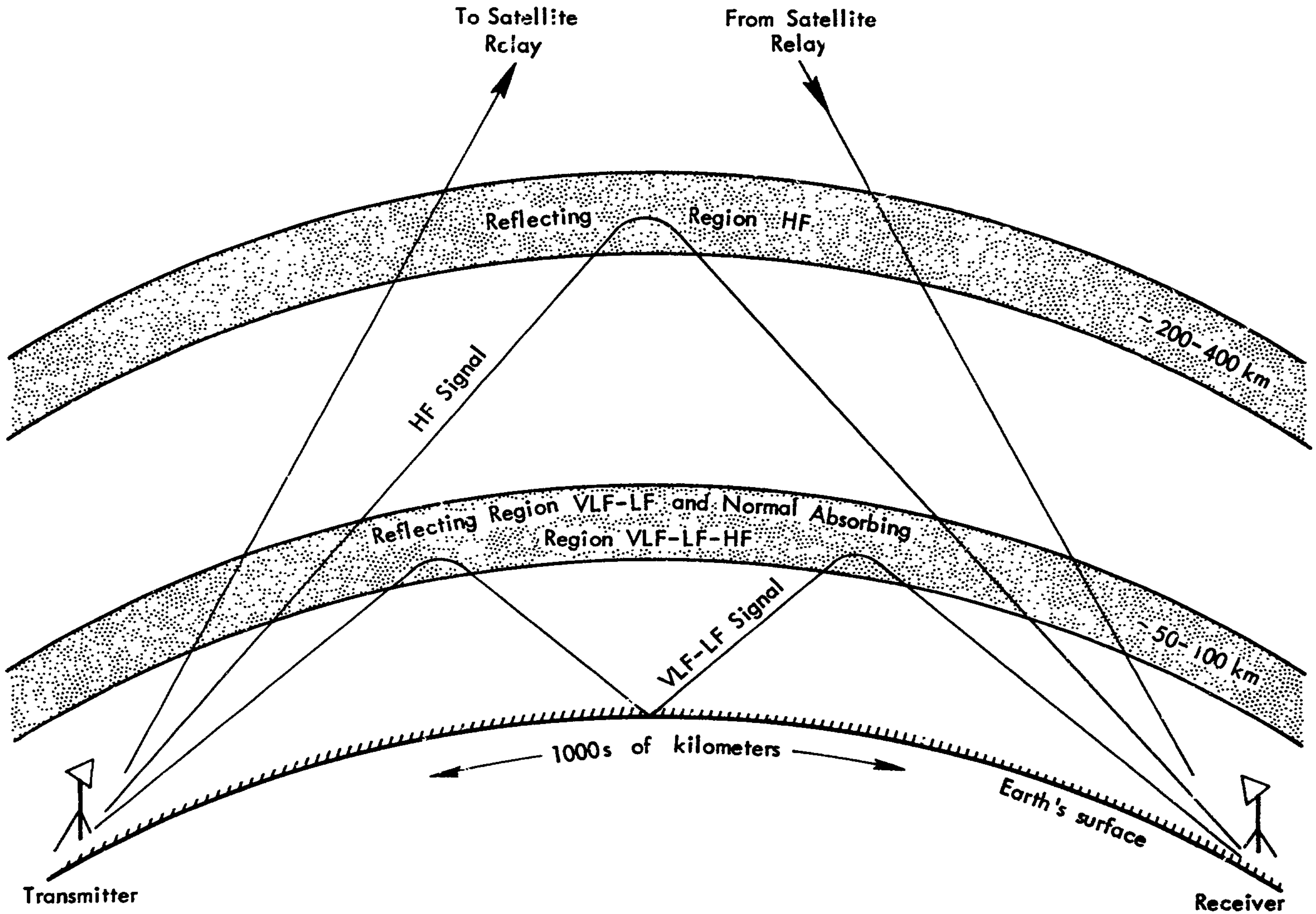


Fig. 1 — Illustration of long-range signal transmission means (not to scale)

C. High Frequency Radio Communications

For the same reason it is worthwhile to briefly discuss HF transmission. High frequency signals propagate to large distances due to "reflection" from the upper regions of the ionosphere, typically at altitudes from 200 to 400 km depending on frequency, time of day, and geographical location. For a ionosphere reflection height of, say, 300 km transmitted signals can reach receivers up to distances of about 4000 km by means of a single ionospheric reflection. Transmission by multiple reflections between the ionosphere and earth can be efficient enough to occasionally permit useful signals to be propagated globally; however, the reliability of normal HF transmission is well under 100 percent for single ionospheric reflection and degrades appreciably with each subsequent reflection. As shown in Fig. 1, the propagated signal has to pass through the absorbing lower ionosphere before reflection by the more intensely ionized and "reflecting" upper ionosphere. Under normal daytime conditions absorption of the signal by the lower ionosphere (D region) is high enough to prevent useful long-range signal transmission at the lower HF frequencies but low enough at the higher HF frequencies (which can be reflected by the upper ionosphere) to permit useful communication. At night the upper ionosphere is less highly ionized; hence lower frequencies must be used than in the daytime in order to secure reflection. At night, ionization in the lower ionosphere (the height region of daytime absorption) almost completely disappears, and consequently the lower frequencies in the HF band can then be employed for the long-range transmission. By judicious choice of frequency for a given path and time of day, satisfactory communication can be achieved in the HF band to very long ranges both by day and by night.

Nuclear detonations can deleteriously disturb or completely disrupt HF transmission by producing added ionization at lower levels. This causes absorption in the lower ionosphere (say from 50 to 150 km). Nuclear detonations of sufficient altitude also create large mechanical disturbances which destroy the mirror-like reflecting properties of the normal ionosphere. HF frequencies are the ones most subject to deleterious propagation effects in nuclear-produced environments. Their relative vulnerability was anticipated and was demonstrated in the high altitude test programs of 1958 and

1962. Assessment of the degree of degradation of HF communication systems by nuclear bursts is highly dependent on scenarios and other assumptions. DNA has available several documents, handbooks, and reports on expected system performance in a variety of plausible nuclear environments. In general, disruption is least for nighttime conditions and for single bursts. It is greatest for multiple-burst environments and daytime conditions. Also, as suggested by Fig. 1, degradation due to absorption of the signal is only significant if the HF transmission passes through the lower ionosphere (D region) at a location where the ambient ionization has been appreciably enhanced by nuclear radiations. For single bursts, depending on height, it is possible to have situations where paths whose terminals are close to the burst-region are less upset than the paths with more remote terminals. Attempts to assess test data in terms of the proximity of the great-circle path to the burst have led to difficulty, and have caused some confusion about the degree of understanding of the HF blackout problem. It is necessary to treat the problem as three dimensional, to consider explicitly the geometry of the transmission path, and to allow for the height at which absorption is introduced. When this is done, the test data (single bursts in all cases) are in reasonable agreement with current theory.

D. Long-Wavelength Radio Communications

Propagation of long-wavelength signals to distances of the order of 1000s of kilometers is basically different from HF propagation and to propagation between satellite and earth stations. For HF and satellite communications one can reasonably consider the propagation paths to be rays that pass through nuclear-disturbed regions of the ionosphere. For long-wave transmission, on the other hand, one can consider the signal to be guided in the waveguide formed by the conducting earth (lower boundary) and the lower conducting ionosphere between about 60 and 90 km altitude under normal conditions. Nuclear radiations change the physical height of the upper waveguide boundary and its vertical and horizontal conductivity structures. This causes phase and amplitude changes of the signal propagated in the waveguide. Instead of thinking in terms of integrated effects along rays (illustrated in Fig. 1), which pass through regions whose ionization content has been increased by nuclear radiations one can think of long-wavelength propagation effects as arising from distributed effects along the waveguide path. For a burst at very high altitude (say, an earth radius), the upper waveguide boundary is uniformly changed both in height and conductivity gradient along much of the propagation path. The expected change in signal phase and amplitude can then be evaluated using waveguide propagation theory by calculating the attenuation and phase shift per unit distance along the waveguide and applying these parameters to the appropriate length of path. In most plausible nuclear-detonation scenarios the upper boundary of the waveguide is not uniformly modified and the problem of confidently estimating the propagation effects caused by burst(s) is much more difficult. Theoretical techniques have been developed in DNA studies for solving long-wave propagation problems for an arbitrarily non-uniform waveguide boundary such as would be produced by either single bursts at high altitude or by a number of bursts with a detonation distribution in space and time such as would be expected in real nuclear engagements. Also experimental work using scaled models has permitted checking the VLF-LF theoretical work concerning irregular waveguides. Comparisons of theory and simulator experiments have proved quite satisfactory. Figure 2 illustrates the general features of the irregular waveguide concept. The normal or undisturbed waveguide boundary is shown at constant height and can be considered to have a reasonably uniform vertical gradient of conductivity, whereas the waveguide boundary produced by the three illustrated nuclear bursts is quite variable in height and in vertical conductivity gradient along the path between transmitter and receiver. During the transition periods from night to day and day to night, the normal waveguide boundary undergoes a slow change in height and conductivity gradient in the regions of sunset and sunrise. Studies of transmission effects along paths traversing these transitional regions thus provides an additional opportunity to assess the theoretical propagation models; however as suggested by Fig. 2 the problem is much more complex for many feasible nuclear environment situations than for the single natural change of the waveguide height produced in the day-night transition region.

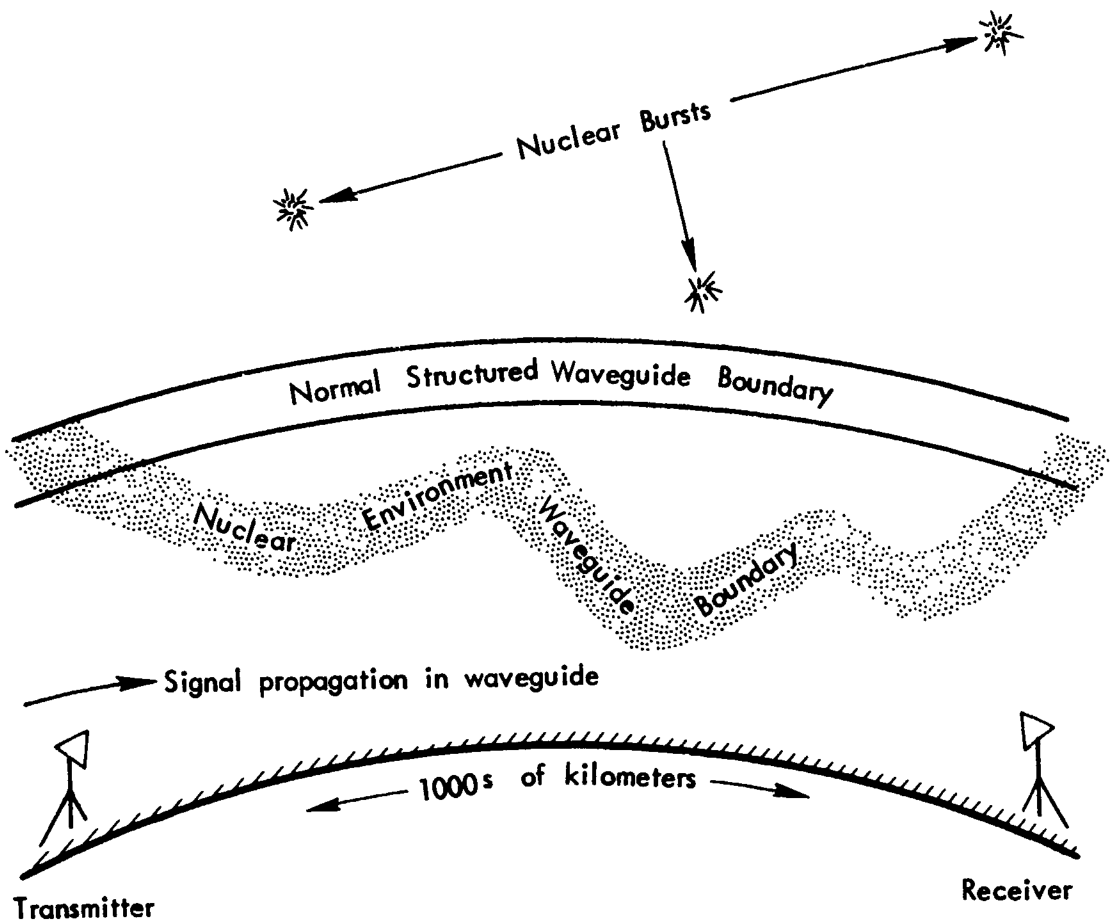


Fig. 2 — Illustration of hypothetical three burst modification of transmission waveguide (not to scale)

III. OPERATIONAL DEGRADATION OF VLF-LF SYSTEMS IN NUCLEAR ENVIRONMENTS

As discussed in Sections I and II-D, long-wavelength radio-signal transmission can be seriously degraded by changes in the structure of the lower ionosphere (below 90 km) produced by the ionizing radiation from nuclear detonations. Both the amplitude and phase of the propagated signal can be suddenly and significantly altered by one or more bursts to such a degree that useful transmission is lost. The duration and magnitude of the amplitude and phase perturbations are directly dependent on the nuclear burst conditions (yields, heights of burst, etc.), and on the geographical relationship of the bursts to the radio transmission paths. In DNA studies a sizable number of plausible nuclear environments and path geometries have been analyzed; they are documented in available DNA literature (handbooks and reports). One should refer to this material for detailed understanding of specific situations. Current and proposed VLF-LF systems are not immune to degradation or disruption as was generally assumed prior to the in-depth investigations in recent years. While such systems may be considered relatively "survivable" compared to long-range HF communication systems for plausible nuclear environments, they are unquestionably subject to difficulties that should be known and considered by those concerned with system planning, development, and operations.

For purposes of this report the degree to which VLF-LF system performance can be affected by nuclear environments is presented in a relative way, i.e., the upper limit or worst-case degradation from possible and plausible nuclear scenarios and relevant transmission paths is referenced to the normally experienced transmission levels. In this way one can relate the current peacetime performance of VLF-LF systems as obtained from day-to-day experience to possible performance of the same systems under nuclear environment conditions. This approach illustrates how serious the degradation may be but does not provide the detailed understanding for specific links and for prescribed nuclear burst scenarios which may be obtained from the available DNA literature and computational capability. In general the performance of a VLF-LF link can lie between the normal peacetime performance and the upper limit values of signal disturbance presented, depending on the nuclear-burst scenario postulated.

In order to indicate the upper limits of possible degradation in a simple way, it is necessary to adopt a simplified but adequate approach for the range of frequencies involved. One can consider the propagation between a given transmitter and receiver to occur by two separate mechanisms, namely a ground wave transmission which is independent of the lower ionosphere, and skywave transmission which is dependent primarily on the height and conductivity-profile of the lower ionosphere. This approach becomes increasingly more approximate as the frequency of transmission is lowered. Likewise, for a given frequency, the approximation gets worse as the severity of the nuclear perturbation of the ionosphere is increased. However, the principal features of expected degradation are obtained with adequate accuracy for an overview of the problem. The results obtained by separating the treatment of the ground and sky waves is likely to *underestimate* amplitude reduction of the propagated signal. This can be verified by comparing the results of this report with those available in the DNA literature using more precise treatments.

Figure 3 shows, as a function of distance between transmitter and receiver, the difference in signal level between the sky-wave and ground-wave components of the signal. The values plotted are for typical conducting earth parameters and for typical normal day and night ionospheric structures and are not significantly dependent, for purposes of this report, on the earth and ionosphere parameters used. To illustrate what one can determine from Fig. 3, consider a transmission path of 3000 statute miles and a transmission frequency of 20 kHz. It is seen that the sky wave exceeds the ground wave by 29 dB during daytime (noon) and by 24 dB at night. Under normal conditions, such as those experienced in day-to-day operations during peacetime, the signal at a receiver 3000 statute miles from a transmitter is that provided by sky-wave propagation. If a severe nuclear environment is created along the path between the transmitter and receiver resulting in complete loss of the sky wave, one would receive a signal due to ground-wave propagation which is 29 dB (day) or 24 dB (night) lower in amplitude.

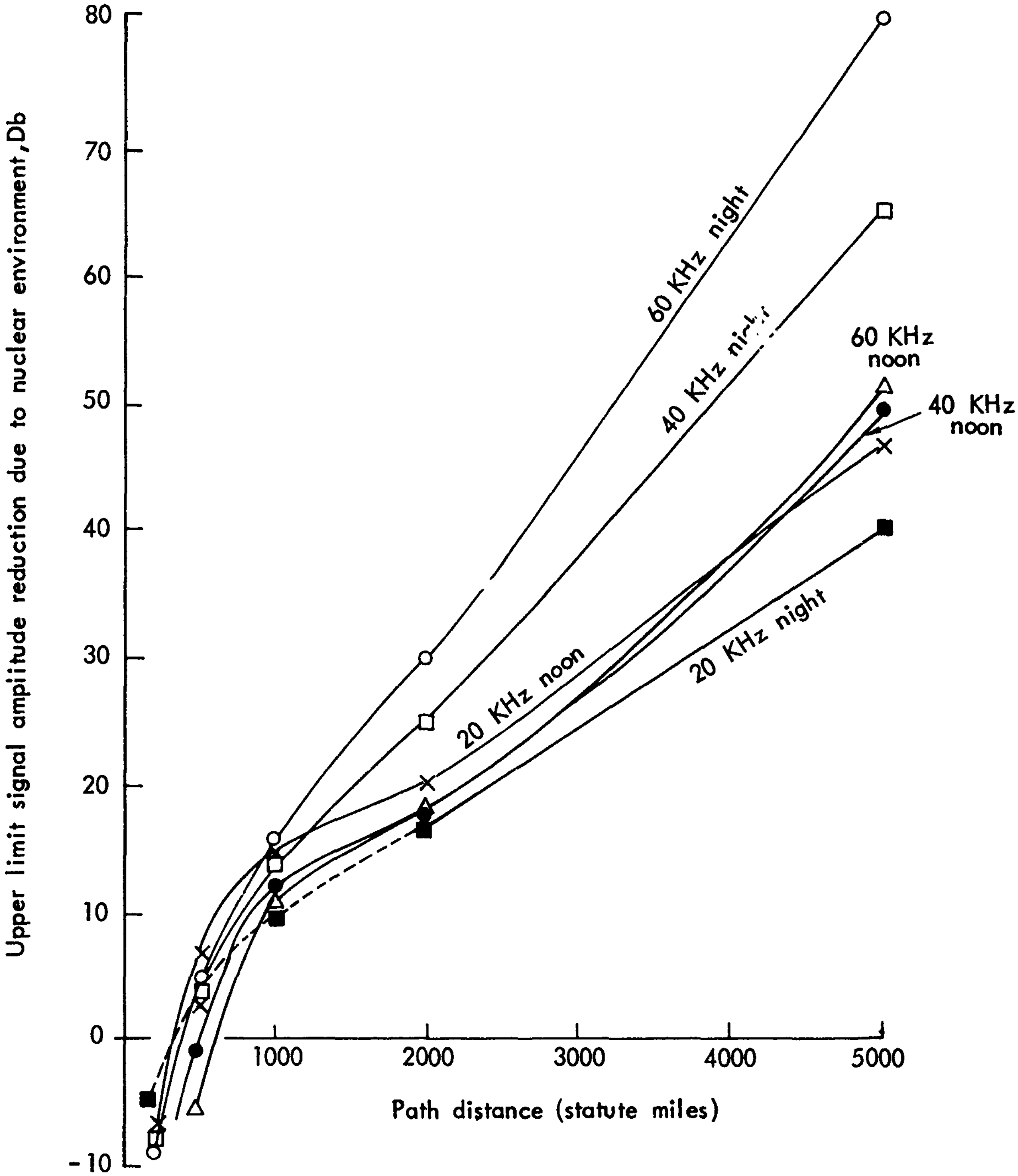
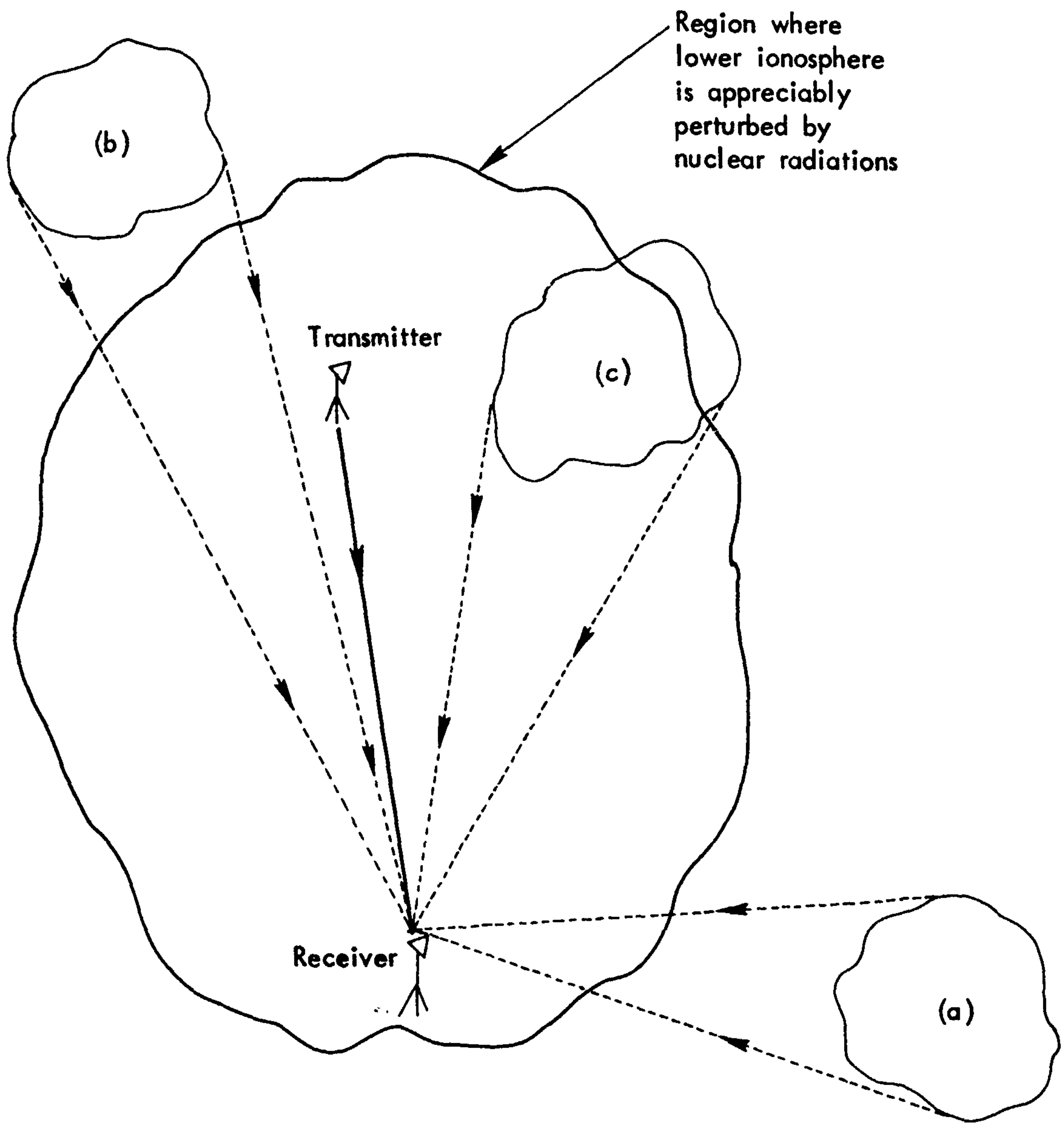


Fig. 3 — Possible signal amplitude reduction due to nuclear environment

Accompanying the amplitude reduction would be a very large change in signal phase, with time characteristics determined by the rate at which the lower ionospheric structure was modified by the nuclear radiations. The fastest rate of change of signal phase would occur for a large single burst at high enough altitude to illuminate the entire path at the same time. Under such conditions, phase changes of the order of a thousand degrees would occur in times of the order of a millisecond. For other burst scenarios, one can expect phase perturbations intermediate between this value and the few degrees per minute which occur naturally.

As another illustration of the use of the results of Fig. 3, consider a system which has the capability to operate in the frequency range 20 to 60 kHz and for which the operator can choose from time-to-time the frequency which provides the best communication capability at a desired distance. Results would depend on propagation conditions, ambient noise levels, and system parameters such as the dependence of effective radiated power on frequency. However, for various distances from 1000 to 5000 statute miles one could expect to use the full range of frequencies at one time or another to achieve most effective communications. At a communication range of 2000 statute miles, for example, it might turn out that 40 kHz is favorable at night and that the received signal is about 10 dB above processed noise under normal conditions. From Fig. 3 one can ascertain that, for worst-case nuclear environment conditions along the path, the signal could drop 25 dB, that is, 15 dB below noise. This assumes that the nuclear environment has no effect on noise level, which depends on whether (1) the dominant noise is from atmospherics at great distance with the propagation paths from the noise sources to the receiver passing through the nuclear perturbed region, or (2) the dominant noise source is nearby atmospheric and/or "man-made" noise. In (2) there would be negligible noise reduction and the signal-to-noise would decrease by the amount of signal reduction. In (1) variation from negligible noise reduction to a noise reduction even greater than the signal reduction is to be expected depending on geographical and geometrical factors. Figure 4 illustrates three geographical situations in which the dominant source of receiver noise is distant atmospherics and in which the nuclear perturbed region has (a) negligible effect on noise level, (b) greater reduction in noise level than signal level, and (c) similar dB



[(a), (b), (c), illustrate three possible regions which contribute dominant noise to receiver as discussed in text]

Fig. 4 — Illustrative situations where nuclear environment has much different effects on received signal-to-noise ratio

reductions in signal and noise, depending on the geometrical relation of the noise propagation path and the region disturbed by nuclear radiation. Clearly any of the three cases, (a), (b), or (c), is possible in general nuclear engagements and for arbitrary transmission paths. Thus, in general, when the receiver noise level is dominated by distant atmospherics, communication service probability can improve or be reduced by an amount determined by the possible signal degradation levels given in Fig. 3. On the other hand, when the receiver noise level is dominated by nearby noise sources, such as is commonly the situation, reduction in signal-to-noise can be expected to be as high as indicated in Fig. 3. Maximum impact on communication service probability so far as signal amplitude is concerned can be determined for a given system and conditions (path length, frequency, etc.) using signal amplitude reduction values illustrated for 20, 40, and 60 kHz in Fig. 3. Again, one must expect large and very rapid phase variations (discussed previously on p. 16) to be associated with the reduction of signal amplitude. Generalization concerning the overall impact of signal reduction and the associated large and rapid phase changes is not possible since such impact is dependent on specific system design. It is quite feasible to provide system test signals for input to system receivers which simulate those expected to be received in nuclear environments. Using such signals for dynamic tests one can realistically assess the degree of vulnerability of the system to propagation degradation created by plausible nuclear environments. DNA can provide technical information on the magnitude and time characteristics of expected perturbations for prescribed bursts and transmission paths for such system proof tests or related user applications.

IV. SUMMARY AND CONCLUSIONS

VLF and LF long-path transmissions are subject to amplitude degradation relative to transmissions experienced in normal operations. These degradations can approximate those illustrated in Fig. 3. In addition, the amplitude reductions will be accompanied by very large (the order of a thousand degrees) and rapid (in the order of milliseconds) phase perturbations relative to those experienced in normal day-to-day operation.

Received signal and noise can be influenced quite differently depending on transmission path geometry relative to the nuclear disturbed region(s) and the location(s) of dominant noise sources and their transmission path(s) to the receiver(s) relative to the nuclear disturbances. It is possible for communication capability to increase if the nuclear perturbed region is located such as to attenuate transmission from the dominant noise sources more than signal transmission.

Capability to determine the expected signal amplitude and phase perturbations for specified nuclear scenarios and transmission paths has been developed and can be provided by DNA. Results for several postulated scenarios have been documented, and results for any other scenarios of particular user interest can be obtained and provided to the user.

System effects of the amplitude and very rapid phase perturbations possible in plausible nuclear environments can be tested by providing simulated signals for these environments to the inputs of system receivers. Such tests appear highly desirable to ascertain the degree of system survivability to be expected and/or to uncover any unexpected vulnerabilities.

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