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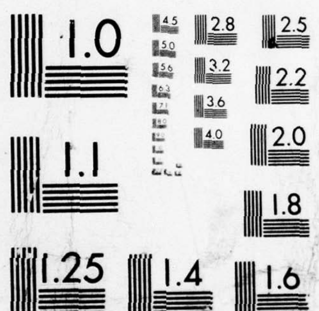

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NAP-OF-THE-EARTH COMMUNICATION PROGRAM FOR U.S. ARMY HELICOPTERS

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June 1978

Final Report for Period 1 March 1976–31 March 1978

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A two-year Army study effort related to a large procurement of VHF/FM and HF/SSB radios for Army helicopters is described. The communication problem, requirements and solutions for helicopters flying nap-of-the-earth (NOE) in the modern battlefield are given. A model for predictions of communication ranges in irregular terrain (terrain, noise environment and radio system parameters as variables) was developed ~~by SRI for the analysis~~. Model inputs are median basic transmission loss (from Longley-Rice), man-made, atmospheric, and galactic noise (CCIR Reports 258 and 322), candidate radio system parameters (Transmitter ERP and required SNR at receiver), and the standard deviations of these parameters. The model output is the probability of successful communication, p_s, at a given range in irregular terrain. The model was used in the European SCORES scenario to predict communication and mission effectiveness in the Fulda region for candidate radio systems. Limited model validation data are given. Quantitative

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20. ABSTRACT (Continued)

test results for the TCATA FM-320 NOE communication test ~~(Fort Hood, Texas, 1976)~~ are given and discussed. These tests compared the AN/ARC-114 Baseline radio with other radio candidates — 40-W VHF, Retransmission, and HF/SSB. In addition, quantitative results are given for VHF/FM, HF/SSB, and satellite NOE systems tests, ~~conducted in Hawaii (August 1976)~~. Technical appendices contain information on OH-58 VHF and HF helicopter antenna gain (dBi), FSK data transmission, speech processing, and HF and VHF field strength measurements made at Fort Hood, Texas.

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ACKNOWLEDGMENTS

This project necessitated the active involvement of the SRI project team with representatives from various Army commands, including the U.S. Army Aviation Research and Development Activity (AVARDA), Fort Monmouth, New Jersey; the U.S. Army Aviation Systems Command (AVSCOM), St. Louis, Missouri; the U.S. Army Materiel Development and Readiness Command (DARCOM) Headquarters, Alexandria, Virginia; the U.S. Army Aviation Center (AAVNC), Fort Rucker, Alabama; the U.S. Army Training and Doctrine Command (TRADOC) Headquarters, Fort Monroe, Virginia; the TRADOC Combined Arms Test Activity (TCATA), Fort Hood, Texas; the U.S. Army Satellite Communication Agency (SATCOMA), Fort Monmouth, New Jersey; the U.S. Army Aviation Flight Test Activity (AFTA), Lakehurst, New Jersey; and the U.S. Army Communications Command, Communications-Electronics Engineering Installation Agency (CEEIA), Fort Huachuca, Arizona. The SRI work on this project could not have been successfully completed without the cooperation and support of each of these commands.

It is the author's pleasure to acknowledge the strong support and encouragement of our technical monitor, Mr. B. V. Ricciardi of AVRADA. It was our pleasure to work with Mr. Ricciardi and his staff: Mr. J. F. Brune, Mr. F. A. Cansler, Mr. T. V. Dentino, and Mr. T. Eller. The encouragement given by Mr. S. Greenspan, Mr. T. J. Sueta, and COL D. A. Peterson was also appreciated.

In the early phases of the SRI work, it was our privilege to work with LTC J. M. Pinson, the TCATA FM-320 test officer. His military judgment and professional approach added greatly to the validity and comprehensiveness of the valuable data acquired during that test. The support of LTC Pinson and his staff during the on-site portion of the SRI participation in the FM-320 test was greatly appreciated. During the planning of the FM-320 test, LTC J. C. Tirre of TRADOC Headquarters and MAJ E. Nichols of AAVNC helped incorporate the user point of view into the effort. Mr. G. Lane of CEEIA provided the HF frequency predictions for the FM-320 test and was most cooperative and responsive in providing interpretations of these predictions. Mr. Lane also kindly shared some of his as yet unpublished results on required signal-to-noise ratios for tactical communications. Dr. Gene Marner of AVSCOM provided some insights for the SRI team regarding the NOE communication problem and further analysis of the FM-320 data.

The SRI team benefited from the pertinent questions and quidance of COL E. V. Kelly of TRADOC Headquarters, Chairman of the NOE COM Study Advisory Group. COL Kelly, being neither a communicator or an aviator, brought the broader Army viewpoint to the study effort.

During the preparation of the NOE COM concept formulation package (CFP), SRI worked closely with the AVRADA and AAVNC staffs. The AVRADA effort was led by LTC R. S. Stebbins, and the first AAVNC NOE COM Action Officer, CPT R. E. Blackmon, conceived the idea of applying the SRI communication system performance model to SCORES Europe I, Sequence 2A, in order to calculate the communication effectiveness and mission effectiveness of the candidate radio systems. The SRI team worked closely with CPT T. C. Mowdy, CPT W. J. Culberson, CPT H. K. Staub, Mr. K. J. Young, Mr. C. G. Songy, and the second action officer, MAJ R. P. Watts, to implement the SCORES analysis. MAJ Watts and MAJ E. C. Black of AAVNC provided useful comments on an early draft of the SRI final report. The numerous discussions with Mr. J. M. Burwell of AAVNC on such technical matters as frequency scanning and selective calling were much appreciated.

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The authors wish to acknowledge the assistance of CPT Thomas S. Allen of AFTA, who flew the OH-58A at Lakehurst, New Jersey during the VHF antenna-gain measurements. The authors would also like to acknowledge the assistance of Mr. John F. Brune, who operated the receiver during these tests, and Mr. Frank A. Cansler, who made most of the thruline wattmeter and VSWR measurements. They also provided the results of other tests they made at Fort Monmouth.

Finally, it is the author's privilege to acknowledge the excellent support received from the SRI Telecommunications Science Center, directed by Dr. D. L. Nielson. Mr. John Leung assisted with the analysis of digital communication techniques and Mr. James Gaddie helped analyze the antenna problems and speech processing for HF systems. Ms. Paula Bell contributed above and beyond the normal level of effort to develop in a timely manner the computer programs used in the SRI communication system performance model and the SCORES communication and mission effectiveness evaluation.

I INTRODUCTION

A. Statement of the Problem

1. General

The U.S. Army faces a serious problem in communicating by radio with and among helicopters on the modern battlefield. The helicopter is an essential vehicle for both defensive and offensive Army combat operations. Its use is integrated into Army doctrine as both a weapons platform and a support vehicle. The mission effectiveness and relative worth of helicopter systems in both roles are closely related to this communication effectiveness. The threat environment forces the helicopters to fly at very low altitudes (viz, treetop level and below)--at what is called nap-of-the-earth (NOE)[1*]--and the communication effectiveness of currently deployed helicopter radios is inadequate during NOE flight.

At present, the Army uses the AH-1 attack helicopter. This vehicle will be replaced in the near future by the advanced attack helicopter (AAH). The attack helicopter operates in a hostile environment in the main battle area near the forward edge of the battle area (FEBA), where its primary mission is to neutralize enemy tanks or other targets in direct support of the ground commander. Present tactics call for the attack and scout (OH-58) helicopters to be used as a team in which the scout helicopter acquires the target and then calls in the attack helicopter, which neutralizes the target. These aircraft must have reliable communication with each other, the supported ground commander, the forward staging area--the Forward Area Rearm and Refuel Point (FARRP)--and the holding area where attack aircraft hide while awaiting their turn to move into firing positions.

---

*References are listed at the end of the text.

In a support role, other Army helicopters are used as troop delivery or resupply vehicles from the rear areas of a division to the forward area. These missions are currently performed by the UH-1 (utility) and CH-47 (cargo) helicopters; the UTTAS will also be used in the future. Reliable communication is required from these aircraft to the supported forward commanders. In addition, communication is required with controlling units in the rear--aviation company operations. The UH-1 and OH-58 are also used as command and control aircraft, and for various other special missions. Command and control aircraft require communications to subordinate elements and to redirect assets to critical locations. There are approximately 7700 helicopters in the Army inventory (1978), most of which could be required to fly NOE at one time or another.

Army helicopters now are equipped with 10-W VHF/FM radios operating in the 30- to 76-MHz band. These radios are the AN/ARC-131, and the newer AN/ARC-114, and -114(A). The present family of aircraft radios are inadequate for communication at the required ranges to the supported ground commander (less than 17 km as stated by the Armor Center) and to other helicopters, and to rear echelons nominally out to 50 km). (Actual required ranges will depend upon the tactical situation.) These radios were designed to operate under line-of-sight (LOS) conditions from the helicopter flying at high altitudes to both rear and forward units, where intervisibility usually existed. Under present doctrine, the helicopter must fly at extremely low altitudes, or NOE, to take maximum advantage of terrain and thereby reduce its vulnerability to physical and electronic warfare (EW) threats and increase its survivability. Because line-of-sight conditions rarely exist at these altitudes, the terrain masking reduces communication range substantially.

2. Impact of the Communication Problem

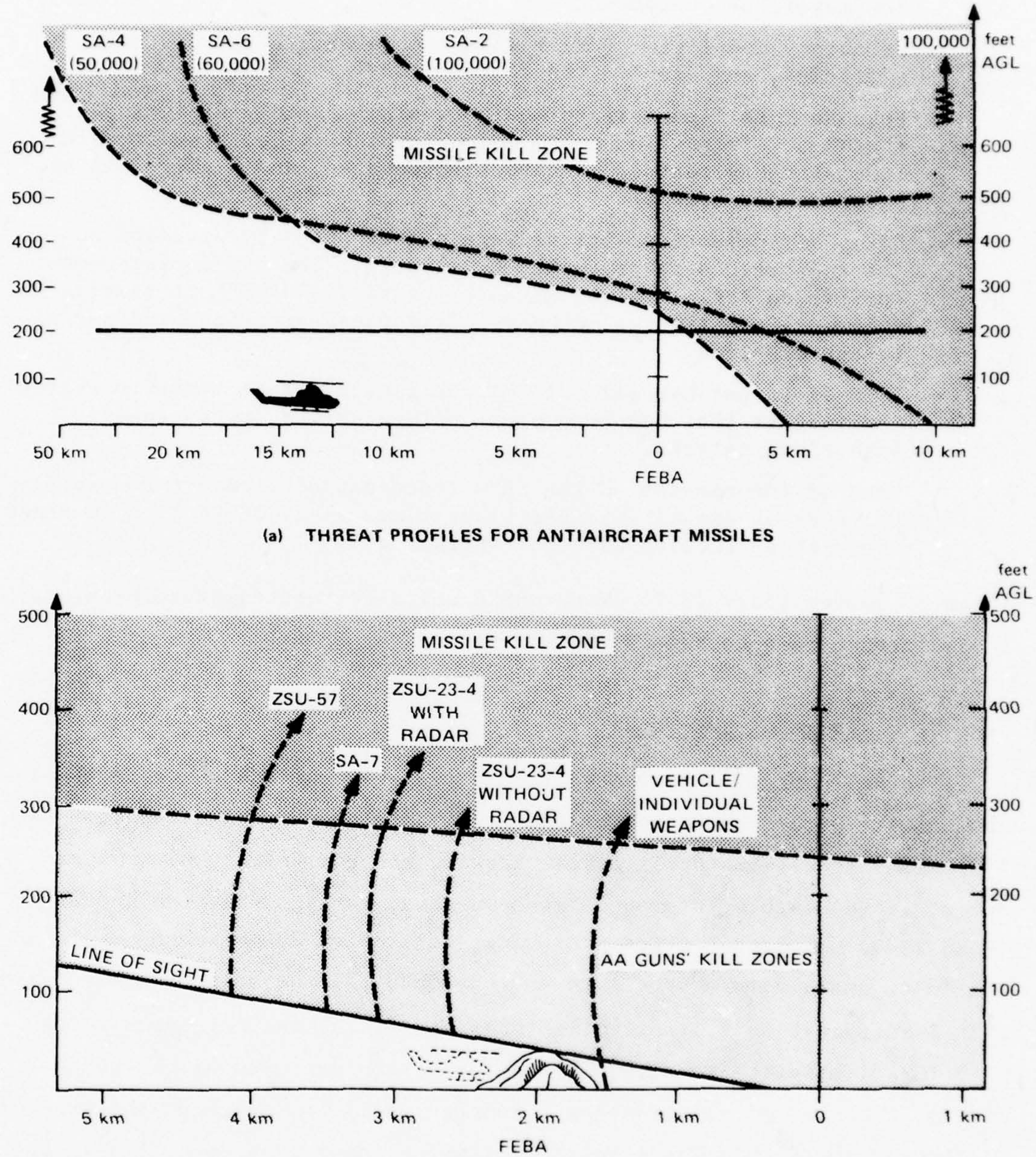
Examples of the command and control problems resulting from lack of liable helicopter communications are cited from a division-size exercise (REFORGER-76), conducted in Europe (near Fulda, Federal Republic of Germany) in 1976 by the 101st Airborne Division (Air Assault);[2]

- The present family of aircraft radios are not sufficient for aircraft-to-ground communication when the aircraft is flying NOE, low level, or contour.
- Frequency modulation (FM) radios are restricted by distance, obstacles, and are limited to LOS.
- Because intelligence information was not rapidly disseminated, the OH-58 aircraft expended valuable blade time, resulting in fewer targets that could have been engaged, and higher loss of aircraft and crews.
- Enemy air defense positions were not reported by division and the supported brigade to the helicopter. The helicopter cannot survive on the mid/high intensity battlefield without timely, accurate intelligence on enemy air defense artillery and surface-to-air missiles.
- Lack of target handoff information caused attack teams to search for targets that had been previously acquired, or to engage suboptimum targets.
- Lack of information on the FEBA trace caused aircraft to overfly the FEBA or expend valuable blade time using NOE tactics in areas where these tactics were not warranted.

A recent survey (July 1977) of European units reiterated these problems[3] and an urgent need to remedy them was stated by USAREUR.[3]

3. Nature of the Threat

The helicopter is prevented from climbing to altitudes where it can communicate with other units by the formidable enemy ground threat: An aircraft that climbs to altitudes where it can communicate with other units, is vulnerable to ground-based weapons, particularly the ZSU-23/4 (Quad 23--a multitube optical- or radar-controlled 23-mm weapon). In addition to small arms ground fire and the Quad 23, the helicopter is faced with a surface-to-air missile (SAM) threat. These weapons include the SA-7 (Grail missile--passive, IR-seeking weapon deployed at the company level), the SA-8 missile (having a substantially longer range than the SA-7), and the SA-9. The threat profile for these weapons begins in the vicinity of the FEBA and forms a destructive ground-to-air umbrella within line-of-sight to 5000 meters; it extends into the rear areas at slightly higher altitudes (see Figure 1).[4] The effective ranges of these and other weapons are given in Reference 6.

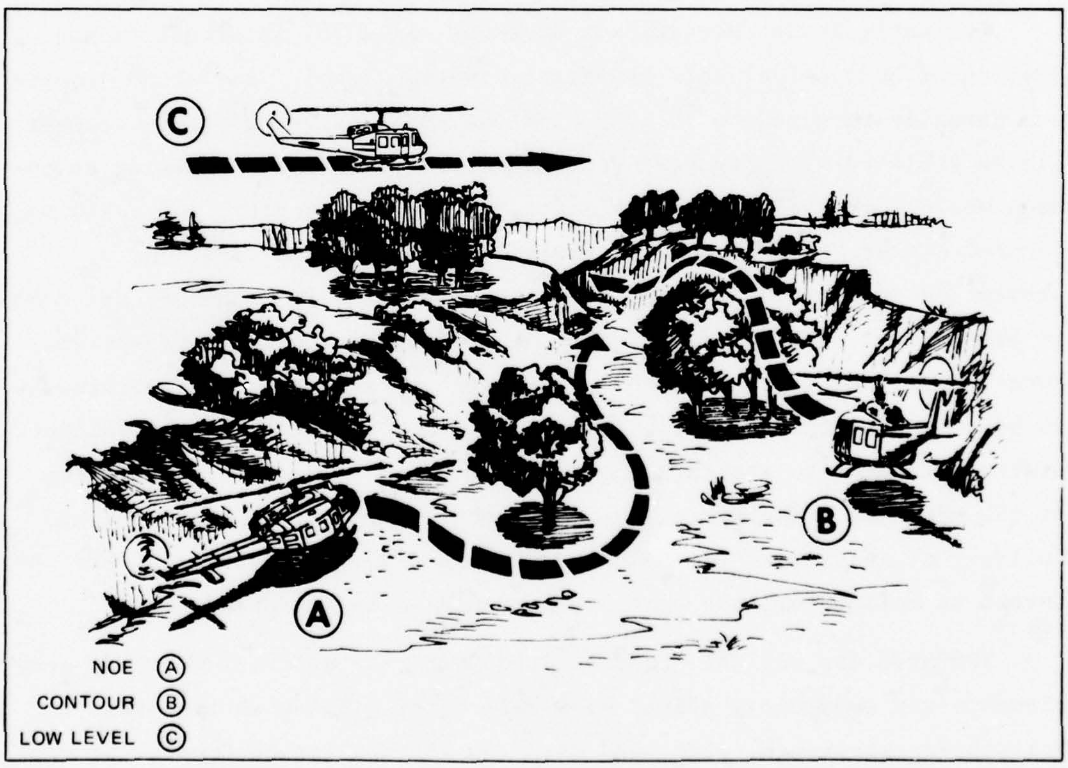


(a) THREAT PROFILES FOR ANTIAIRCRAFT MISSILES

(b) THREAT PROFILES FOR AIR DEFENSE ARTILLERY

FIGURE 1 THREAT PROFILES FOR ANTIAIRCRAFT MISSILES AND AIR DEFENSE ARTILLERY

To defeat these weapons, the aircraft flys in three flight regimes (see Figure 2), depending upon the range from the threat.[1] The highest altitudes are in the low-level flight regime, defined as flight conducted at a select altitude at which detection or observation of aircraft is avoided or minimized. This tactic is used in rear areas. Contour flight is defined as low-altitude flight in close proximity to the contours of the earth and its vegetation to take advantage of available cover and concealment to avoid observation or detection from points of departure or landing. It is characterized by varying airspeed and altitude as vegetation and other obstacles dictate. Finally, nap-of-earth (NOE) flight is defined as flight as close to the earth's surface as obstacles and vegetation will permit, generally following the contours of the earth. Air speed and altitude are varied as influenced by terrain, weather,



SOURCE: Reference 1

FIGURE 2 NOE, CONTOUR, AND LOW-LEVEL FLIGHT visibility and enemy situation. NOE flight is used in the forward areas of the battlefield in the areas of greatest threat. NOE flight represents the most difficult altitudes for tactical communication.

In addition to the weapons threat, it is anticipated that electronic warfare (EW) will be used on the modern battlefield. These techniques will be used in both the HF and VHF portion of the spectrum to intercept, direction find, monitor for intelligence, and jam U.S. Army communication. Soviet/Warsaw Pact Doctrine emphasizes EW and has provided numerous EW assets to the operational commander.[6-7] Their techniques call for VHF/FM jammers to be located 1 to 2 km behind the FEBA having an estimated range of 15 and 25 km; also, this doctrine calls for the massing of EW equipment on the enemy flanks to inhibit communication at the intended point of breakthrough. EW equipment assets exist capable of jamming almost half of the Army's VHF/FM nets.

Currently Soviet/Warsaw Pact doctrine calls for interception and jamming of HF tactical nets above the division level. Soviet HF jammers are normally targeted to 30 km behind the FEBA. However, longer ranges can be achieved with higher-powered equipment. Soviet HF jamming equipment while relatively unsophisticated, exists in quantity, and could be located closer to the FEBA were the doctrine to be modified. Also, present doctrine calls for deployment of direction finding (DF) stations in proximity to the FEBA; these are netted to weapons-delivery systems. Location of the target with these DF stations permits target coordinates to be passed to the weapons systems, and a capability exists to deliver destructive fire to the target promptly (within the range capabilities of the weapons). Therefore, the time between detection, location, and delivery of destructive fire can be very short. In summary, the EW threat to helicopters and other Army ground units is formidable.

The need for reliable communication from the aircraft to other Army elements was succinctly stated by a helicopter pilot with ten years of helicopter experience, stationed with the 155th Aviation Company at Fort Ord, California. This pilot had approximately 2400 hours of flight experience, including a combat tour in Vietnam during which time he served as mission commander.

As a mission commander in a modern combat environment flying at the altitude we used in Vietnam would be fatal. This has been demonstrated. Further, as a mission commander, no matter what the combat mission is, if you can't communicate with the personnel associated with that mission, you're not going to complete that mission. You've got to have communication with ground elements, the people in charge, and have intercommunications between the elements of the fire team or attack helicopter team. This means communication from air-to-ground, ground-to-air, and air-to-air. All three of these must be present, unless the mission is so thoroughly prebriefed that communications during the mission are not necessary. Such a prebriefing to eliminate communications is generally infeasible.

4. Summary

In summary, the present VHF/FM radios employed in Army helicopters do not provide adequate communication over the required operational ranges when the aircraft is flying at NOE altitudes. As a result, the potential of helicopters (and their weapons systems) is not fully realized. For example, reliable NOE communication ranges in even gently rolling terrain are now limited to an estimated range of 10 km or less.[8,9] As the roughness of the terrain increases, the effective communication range decreases. The choice faced by the pilot in the absence of a NOE communication system is to do without communication or to climb to altitudes where he can reestablish communication; however (as noted) climbing increases his vulnerability to ground-based weapons and EW. Alternatively, he can attempt to locate a favorable communication point by changing location slightly while at NOE altitude, or he can fly closer to his intended receiver and try again. This, however, detracts from his primary mission objective and also decreases remaining flight time. Furthermore, multiple transmissions of tactical voice messages increase the aircraft's susceptibility to intercept, jamming, direction finding, and attack by ground-based weapons. For these reasons, the Army has identified a requirement[10] for and embarked upon the procurement of a helicopter NOE radio system capable of providing reliable communication in various types of terrain at the required operational ranges.

B. Organization of This Report

The NOE communication problem was addressed in a joint letter of agreement (LOA) signed by TRADOC and DARCOM (see Appendix I). The objectives of the study, scope of SRI work, and technical limitations and constraints, are given in Section II.

An engineering analysis of the major NOE communication system test conducted at Fort Hood, Texas (FM-320) is given in Section III.

The Critical Issues and Unknowns identified in the LOA are addressed in Section IV.

The general method of approach, participating organizations, and summary of findings are given in Section V.

The appendices contain supplementary material which were documented during the NOE study.

Appendix A contains a description and results of a communication performance model for predicting operational range (OR) in irregular terrain. This model was used both for OR estimates of candidate radio systems and for the SCORES scenario used to quantify communication and mission effectiveness.

Appendix B contains the results of an NOE communication test run in Hawaii using three systems: VHF/FM, HF/SSB, and UHF/satellite.

Appendices C and I further document the requirement for an improved NOE communication system for helicopters flying NOE.

Appendices D, E, F, G, and I contain analyses of important technical characteristics of the NOE radio system--speech processing for HF/SSB transmitters, FSK data transmission, and VHF and HF antenna gain of selected helicopter antennas.

II OBJECTIVES, SCOPE, AND LIMITATIONS

A. NOE Communication Program Objectives

The primary program objective for the Army was to select an NOE communication system(s) from currently available technology to provide a near-term solution to the NOE communication problem. The statement of the problem was formally promulgated in a joint letter signed by the Commanding General of the U.S. Army Training and Doctrine Command (TRADOC) and the Commanding General of the Army Materiel and Readiness Command (DARCOM). This Letter of Agreement (LOA) for Nap-of-the-Earth (NOE) Communication System (1 December 1975),[11*] contained a statement of the need, a system concept, a set of engineering and operational unknowns, and critical issues to be resolved from a full-scale test program:

> There is a need for an improved single-channel aircraft voice communication system which will provide reliable securable communications from zero to fifty kilometers range for Army aircraft operating at Nap-of-the-Earth (NOE) altitudes, down to and including ground level. The time frame for this system shall be from FY79 to FY85. The successful mission accomplishment and aircraft survivability are dependent on reliable communications necessary encountering an enemy threat as depicted in TRADOC European and Mid-East scenarios which will have a strong air defense and electronic warfare environment that will be active in the vicinity of the FEBA.

The second objective contained in the LOA was to determine the communication and mission effectiveness for available candidate radio systems with respect to the existing helicopter radio system, which was to be used as a baseline reference.

The third objective contained in the LOA (not explicitly stated) was to determine the performance of candidate NOE radio systems in different types of terrain and as a function of range.

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*The letter is reproduced in Appendix I.

The fourth objective of the LOA was to determine the human factors impact of an NOE communication system installed in the helicopter.

The LOA represented the most recent jointly approved (proponent and materiel developer) document, and it initiated the present NOE communication system study.* Under its direction, the following tests and analyses have been performed and the following actions taken:

- A full-scale operational test of candidate NOE communication systems was conducted at Fort Hood from October to December 1976. This operational test, the FM-320 NOE communication test,[9] also included some engineering tests.
- Supplemental (small-scale) engineering tests were conducted by the U.S. Army Avionics Research and Development Activity (AVRADA)† to investigate various aspects of the NOE problem. These included flight tests run in New Hampshire (July 1976), Hawaii (August 1976), and in the Fort Monmouth areas (August 1977).
- After completion of the FM-320 tests, a formal Study Advisory Group (SAG) was established to develop a concept formulation package (CFP) and required operational capability (ROC) which would lead to the procurement of the most cost-effective candidate system for NOE communication.[10,13]

B. Scope of SRI Work

SRI International was under contract to the U.S. Army Avionics Laboratory (now AVRADA) from the period 1 March 1976 to 31 March 1978 to provide technical support during the coordinated U.S. Army NOE Communication (NOE COM) Program. During this contract, SRI provided technical assistance in the following areas:

- Design of the TCATA FM-320 test, on-site assistance, and data analysis.
- Development of Measures of Effectiveness and Alphanumeric (A-N) Test Material for the FM-320 tests.
- Design of the two-system comparison tests conducted in Hawaii, and analysis of these data (see Appendix B).

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*The problem has been recognized for some time (ROC for AN/ARC-98).[12]

†Formerly Avionics Laboratory, U.S. Army Electronics Command.

- Measurement of absolute gain (dBi) of the VHF/FM antennas installed on helicopters, assistance in measurement of antenna gain for the HF/SSB shorted-loop aircraft antenna (see Appendix F).
- Development of the Communication Effectiveness and Sub-Mission Effectiveness models used with the SCORES (Europe I, Sequence 2A) scenario to evaluate NOE COMM candidate system performance in the non-EW and EW tactical context.
- Development of a Radio System Performance and Communication Range model for helicopters flying Nap-of-the-Earth. This model was used to predict the operational communication range estimates in irregular terrain used in the NOE COMM CFP (TOD, TOA, BTA and COEA) (see Appendix A).
- Providing answers to the technical critical issues and unknowns contained in the LOA (see Section IV).
- Participation in a Study Advisory Group (SAG) on-site survey of aviation commands in Germany to develop user requirements (see Reference 3).
- Providing technical assistance to AVRADA regarding its role in the SAG between January 1977 and March 1978. This included preparing technical briefings, assisting in preparation of Concept Formulation Package documents and participating in all SAG meetings.
- Explore selected new technology with application to current and longer term solutions to the NOE COM problem (e.g., speech processing (see Appendix D and Ref. 14), data systems (see Appendix E).

C. Technical Limitations

A number of technical limitations and constraints affected this project; these arose principally from the number of organizations participating in the NOE communications program, their charters, time limitations, and fund limitations available to conduct the test programs. The technical limitations and constraints are:

- The candidate communication systems were operationally tested in one type of terrain--Fort Hood, Texas. Large-scale communication tests were originally planned for two additional terrain types (the mountains of Fort Carson, Colorado, and Fort Huachuca, Arizona), but the tests were only run in the Fort Hood area.
- It was necessary to determine the effects of terrain--particularly on the VHF/FM systems--analytically using a communication system performance model incorporating a propagation model (the Longley-Rice model)[15] to evaluate VHF/FM system performance in different

terrain types. Such a model was developed to predict the probability of successful communication as a function of range (see Appendix A). The operational range of the combat radio was then defined as the range at which a required probability of successfully establishing a usable channel was met or exceeded.

- The maximum range requirements changed during the course of the study. The LOA specified a range interval of 0 to 50 km. During meetings of the SAG, both short-range and long-range (0 to 50 km) requirements were identified. Data were taken during the FM-320 test primarily to address the long-range requirements.

- Not all of the engineering tests requested by AVRADA were accomplished during the operational FM-320 tests conducted at Fort Hood. This test was directed toward three objectives:

  - An operational comparison of the candidate systems
  - A determination of the human factors aspects of the candidate systems
  - Supplementary engineering tests of interest to the materiel developer.

  Resources were scarce during this test and the major effort was directed toward the first objective.

- The relationship of the primary measure of effectiveness used at Fort Hood, percent correct random alphanumeric (A-N) test messages, was not related by the pilots to the required A-N score for tactical helicopter missions. This required the subsequent use of a pilot listener panel and their military and communication judgement in interpreting similar alphanumeric test messages and scores in an operational context. The FM-320 test officer made such an interpretation,[16] which was also used for the operational context.

- The FM-320 tests were structured and analyzed by the TRADOC Combined Arms Test Activity (TCATA) as a comparison between candidate communication modes; e.g., VHF/FM groundwave versus HF/SSB near-vertical incidence skywave (NVIS). While specific radios (e.g., AN/PRC-70 and AN/ARC-102) were used to vary the HF transmitter power (e.g., 40-W and 400-W HF/SSB, respectively), there was no test of specific radios per se. TCATA did not address the critical issues and unknowns contained in the LOA, because of insufficient test resources.

- Not all candidate modes/systems (hereafter called systems) tested at Fort Hood were evaluated by SRI. The AN/PRC-70 VHF/SSB radio was not evaluated because of suspected equipment problems with this radio set as installed in the test aircraft. This radio, built for ground forces, was especially modified for aircraft use during the FM-320 tests.

- Not all measures of effectiveness suggested by SRI were used during the TCATA test. Specifically, SRI requested squelch-break-height measurements for the VHF/FM, VHF/SSB and HF/SSB systems operating in the groundwave mode to determine the relative vulnerability of the aircraft during an attempt to reestablish communication with a remote base station by climbing to an altitude at which the squelch "broke" on both aircraft and ground receivers. Squelch-break-height measurements (expressed in feet above ground level, for two-way communication) were performed for the baseline VHF/FM system and Improved FM System only. The squelch-break altitude for other candidate systems was not measured.

This final report provides a supplementary analysis of the FM-320 test results and also addresses the technical aspects of the critical issues and unknowns contained in the LOA. These issues will be addressed using the available data from the FM-320 tests, supplementary engineering tests, the results of the SCORES Europe I Sequence 2a scenario, operational information provided by the aircraft proponents, the Study Advisory Group meetings, and the SRI-developed communication performance and operational range prediction model.

III ANALYSIS OF THE FORT HOOD (FM-320) DATA

A. The Test Design

1. Measures of Effectiveness

To compare the performance of the candidate modes/systems, three measures of effectiveness (MOEs) were developed:[17,8] alphanumeric test messages, height to break squelch, and probability of successful communication. These are discussed in the following subsections.

a. Alphanumeric Test Messages

The first MOE was a measure of communication effectiveness using randomly selected alphanumeric (A-N) characters sent through the radio channel. Communication effectiveness was defined as the percentage of A-N characters correctly received, sent one way without repeats through the communication channel. This measure provided a quantitative comparison of each of the candidate radio systems as a function of the range and other test variables.

A 30-character test message containing an equal number of randomly selected letters and numbers was developed;[18,19] this was called an A-N Test Message. The A-N Test Messages were formatted and transmitted as tactical spot reports by the tester (TCATA). The tester determined that messages sent in this spot report format operationally resemble grid or target coordinates that helicopters routinely transmit over radio systems. Alphanumeric messages in this format can be practically recorded in the helicopter by a test observer and graded at the end of the simulated mission. Figure 3 shows a typical data recording sheet. A "word" consists of six randomly selected A-N characters. Both characters and numbers are sent using the phonetic alphabet (i.e., 9 = niner, B = bravo). These messages were copied down on answer sheets, graded, and used as the primary measure of effectiveness for the tests by TCATA.[9]

DATE/TIME 1010/0930Z PAGE 3 OF 10

SYSTEM TEST CODE IFM1

RANGE (Km) 10 ALT NOE LEG: (IN) OUT

A/C NO 090 TAPE NO 7 HDG N

SPOT REPORT NO 201 RUN NO. 9

LINE	WORD					
A	9	7	~~8~~	A	C	Ξ
B	B	E	I	3	5	9
C	O	L	~~X~~	X	Y	F
D	6	4	D	L	5	2
E	1	A	T	F	~~X~~	O

RATE: TOO FAST TOO SLOW (OK)

READABILITY: 0 1 2 3 (4) 5

5 Perfectly Readable/No Perceptible Noise
4 Readable w/NOTICEABLE NOISE
3 Readable w/DIFFICULTY
2 Readable w/EXTREME DIFFICULTY
1 Unreadable/UNUSABLE
0 No Signal Heard

PERCENT CORRECT 27/30 A-N 90%

COMMO CKT COMMENTS

ATMOSPHERIC NOISE NOTED

DATA TAKER BT TALKER BR

FIGURE 3 SAMPLE DATA SHEET

b. Height to Break Squelch

The second MOE was the altitude required to establish two-way communication from the aircraft to the base station. In this test, the aircraft climbed to whatever altitude was required to establish two-way communication to the base station. The measure was to be the height, in feet, above ground level (AGL) required to communicate above an NOE-situated site. Because of testing time limitations, this measure was made only with the baseline (AN/ARC-114) and Improved FM (AN/ARC-114 with 40-W amplifier driving the tailfin antenna) systems.

Aircraft altitude can be related to aircraft vulnerability for a given terrain and threat scenario. Lower communication altitudes indirectly indicate the degree of protection against a ground weapons threat.

The minimum two-way communication altitude was used as a secondary MOE for the Baseline and Improved VHF/FM systems. The decrease in the minimum two-way communication altitude achieved with the Improved VHF/FM system provided a measure of the benefit of the improved system.

c. Probability of Successful Communications

The primary measure of effectiveness used by SRI to analyze the Fort Hood data was the probability (of occurrence) of successful communication, p_s. For this measure, "success" was defined as occurrence of an A-N score ≥ X percent. A threshold of X = 90 percent was used, based on user recommendation.* An A-N score of 90 percent corresponds to an acceptable communication channel for which first time attempts will be completed with occasional repeats of words or phrases. Hence

$$p_s = \text{probability of occurrence of successful communication}$$

---

*For the FM-320 tests, the FM-320 test officer estimated that a mean A-N score of > 85 percent would correspond to an acceptable communication channel over which conversational two-way communication would be received with first-time reliability by a trained (military) listener. Channels of lower quality would require frequent repeats.[16]

In addition, a three-member pilot listener panel from the 155th Aviation Company, Fort Ord, California, related the A-N test material to radio channel quality. These pilots were asked to 1) score the A-N test messages from sample tape recordings which ranged from good to bad channels, 2) subjectively rate the quality of the channel using a five-point standard circuit merit (CM) definition for voice channel quality, and 3) state what channel quality would be the minimum acceptable quality for NOE communication. The three-member panel agreed that circuit merit ratings of 3 (readable with difficulty) correspond to the minimum acceptable channel for NOE communication. Their A-N scores for this channel quality (listened to in the laboratory and not in a helicopter) were greater than 90 percent correct.

The user (U.S. Army Aviation Center, Fort Rucker) surveyed the TRADOC schools regarding the tactically required A-N score and then specified that an A-N score of 90 percent be established as the quantitative description of a minimum acceptable channel for their two-way tactical voice communication. For these reasons, an A-N score of 90 percent (or greater) was selected as the standard for an acceptable channel for NOE communication.

where

Success = (A-N) ≥ 90 percent on a random, 30-character message. The relationship between A-N score and channel acceptability is given in Table 1.

2. Test Variables

Many variables affect two-way helicopter communication (Table 2). The principal FM-320 test variables were range, altitude, terrain, the communication mode/system used, and aircraft transmitter power. Finally, the link tested is an important variable. Links are defined as air-to-ground (A-G), ground-to-air (G-A), and air-to-air (A-A).* Performance over these links differs when all other variables are held constant.

a. Range

The range intervals at which the communication systems tests were planned were spaced approximately logarithmically at operationally significant distances of 1, 2.5, 5, 10, 25, and 50 km. Actual ranges (1, 2.5, 5, 9, 24, 40 km) for the test differed slightly from these because of terrain and military reservation boundary limitations. Selection of ranges spaced at octave (two-to-one) multiples of distance resulted in incremental basic transmission loss for a groundwave signal between each site of 10 dB or more. Figure 4 is a map of the Fort Hood test sites.

The test ranges were selected to identify the capabilities and limitations of two different modes of propagation--groundwave and near-vertical-incidence skywave (NVIS). VHF/FM radio systems operate in the groundwave mode, in which the launched signal generally follows the surface of the earth and is either diffracted along the path profile between the transmitter and the receiver or reflected by terrain irregularities. Signals in the VHF tactical band (30 to 76 MHz) are attenuated by both range and terrain irregularities. The test ranges of 1 to 10 km were

*Hereinafter referred to, respectively, as air-to-ground, ground-to-air, and air-to-air.

Table 1

RELATIONSHIP BETWEEN ALPHANUMERIC SCORE (FM-320 TESTS)
AND OPERATIONAL SUITABILITY OF CHANNEL FOR NOE COMMUNICATION

Mean A-N Score (% Correct)	FM-320 Test Conditions Resulting in Mean	Voice Channel Quality for Two-Way Communication	Operational Suitability of Channel for Two-Way Communication
100	Highest test score achievable in field. Scores of 100% correct frequently occurred during FM-320.	Perfectly readable; no noise (Circuit Merit: 5).	Excellent. First-time reliability. High-quality circuit. Excellent channel.
95–90	Indicates reliable high-quality circuit. Results when 95-100% test scores averaged with mid-range scores (70-90%). Few or no zeros persent	Perfectly readable but with noticeable noise (Circuit Merit: 4).	Good. Good-quality circuit; small number of repeats. Good channel. 90% specified by user as Minimum Acceptable Value (MAV).†
80–70	Results when high (90-100%) scores averaged with low scores (0%).	Readable with difficulty. Requires frequent repetition. Lowest commercial grade (Circuit Merit: 3).	Marginal. Poor-quality circuits; frequent repeats. Between A-N = 70-80, a marginal channel exists, which is barely adequate for NOE communication.
70		Readable with extreme difficulty. Loud background noise. Noncommercial (Circuit Merit: 2).	Unacceptable. Poor-quality circuit; many repeats required. Background-noise limited.
60–10	Scores in this range infrequently appeared. Scores occurred with averaging 70-100% scores with zeros.	Unreadable/unusable. (Circuit Merit: 1).	Unacceptable.
0	Indicated no communication existed in FM-320 tests. Scores of 0% frequently occurred during the FM-320 tests.	No communication* (Circuit Merit: 0).	Unacceptable.

*A sixth channel quality level was defined in addition to the five standard CM qualities to indicate that no signal was heard. This provided a useful distinction between a weak (but unusable) signal and no signal at all.

†Based on laboratory tests (and not Fort Hood averaged A-N scores) an A-N score of ≥ 90% is achieved by pilots for a Circuit Merit 3 channel. An r4 channel in the laboratory probably degrades to an r3 channel for a pilot flying NOE.

Table 2

FM-320 TEST VARIABLES

Variable	Condition
Spatial:	Range Terrain Altitude Siting
Time of Day:	Day Night Dawn
Frequency Band/Modulation:	HF/SSB (2 to 8 MHz, below MUF)* HF/SSB (8 to 30 MHz, above MUF) VHF/FM (30 to 76 MHz)
Power Output:	HF (40, 100, 200, 400 W PEP) VHF (10, 40 W)
Link:	Air-to-Ground (A-G) Ground-to-Air (G-A) Air-to-Air (A-A)

*MUF is the maximum usable frequency for ionospheric skywave propagation. In the context of the FM-320 tests, this is the maximum frequency returned to earth by the ionosphere out to ranges from 1 to 40 km. These paths are termed near-vertical-incidence-skywave (NVIS) paths.

selected before the tests to bracket the expected failure range of the VHF systems (excluding retransmission). The HF/SSB signals also propagate in groundwave mode, but to longer ranges than their VHF/FM counterparts.

HF/SSB radios have the capability of operating in groundwave and in NVIS mode. For the NVIS mode, the energy is directed vertically to the ionosphere and returned to the surface of the earth. Because of NVIS propagation, HF/SSB systems with appropriate antennas have the capability of operating at extended ranges independent of terrain effects. The 25 and "50" km points were selected to investigate the communication performance of HF/SSB radios in the NVIS mode, and to check all systems for their ability to support communication to the range specified in the LOA.

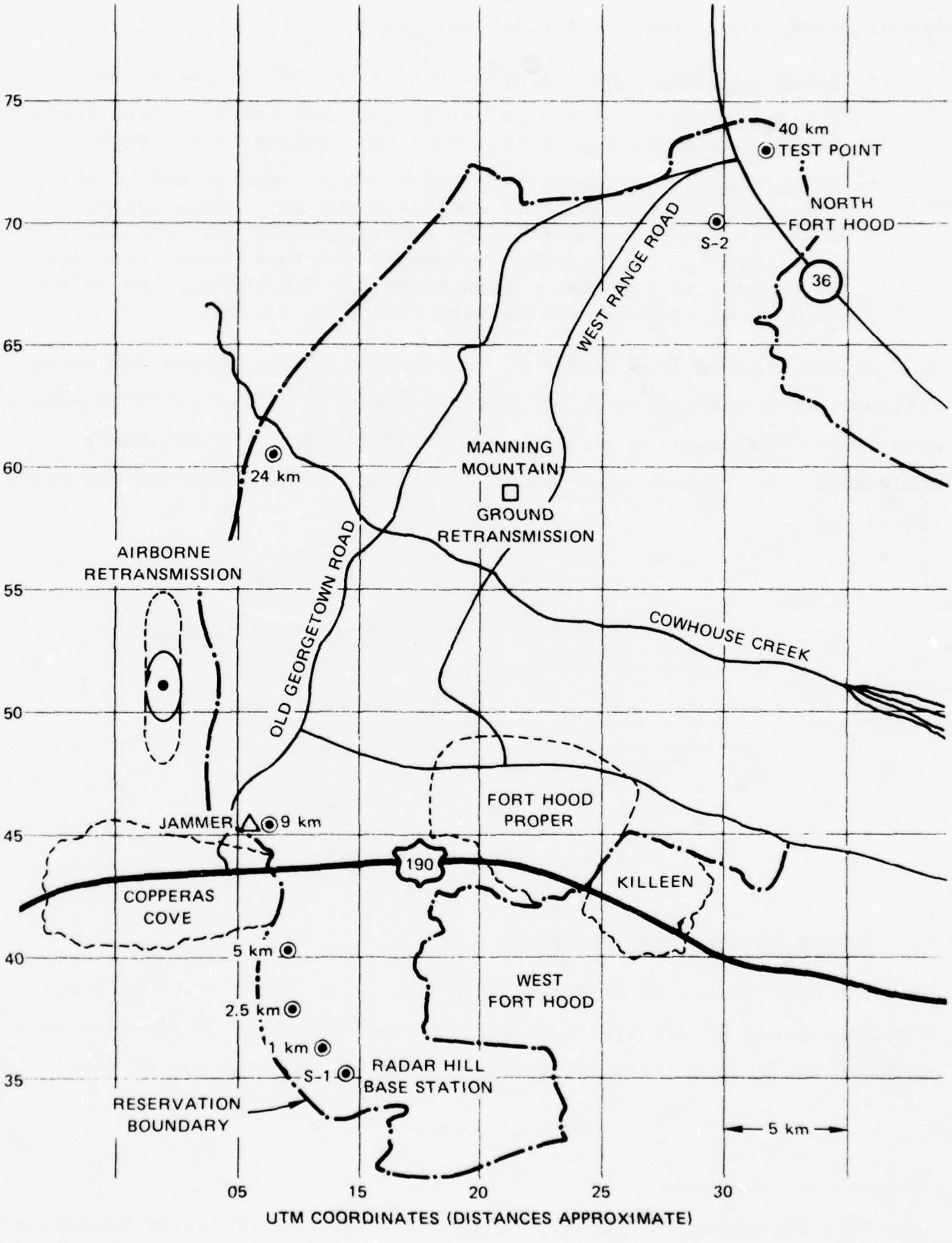

FIGURE 4 SITE MAP — FORT HOOD

b. Altitudes

The altitude intervals for the test were selected from an operational standpoint. Three altitudes were used:

- Skids on Ground (SOG)--The bottom of the NOE flight regime.
- NOE Altitude--Skids approximately 3-ft AGL for Fort Hood terrain, representing the top of the NOE flight regime in the test.
- Height-to-Break-Squelch Altitude--Height above ground to which the aircraft must climb to establish two-way communication. This altitude is operationally significant in that the aircraft must climb to it in order to communicate to a remote base station. As the aircraft climbs above the NOE regime, its vulnerability to ground-based weapons and EW increases.

As can be seen from Figure 5, the choices of six ranges and three altitudes resulted in a grid or matrix containing 18 cells. This matrix constituted the sampling grid for the FM-320 tests. The following analysis in this report used data from the NOE region (SOG and NOE altitudes) only.

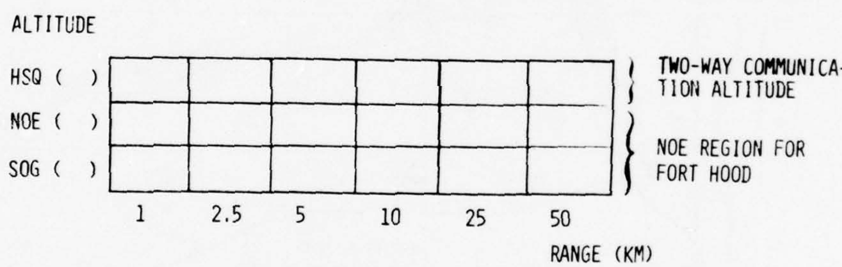

FIGURE 5 RANGE/HEIGHT CELLS

B. System Performance Comparison

The performance of eight candidate radio systems tested at Fort Hood during the FM-320 test was analyzed, and the 400-W HF/SSB system produced the best results (Figure 6).* The characteristics of these

*The VHF/SSB system (AN/PRC-70) performance was not evaluated because of equipment problems.

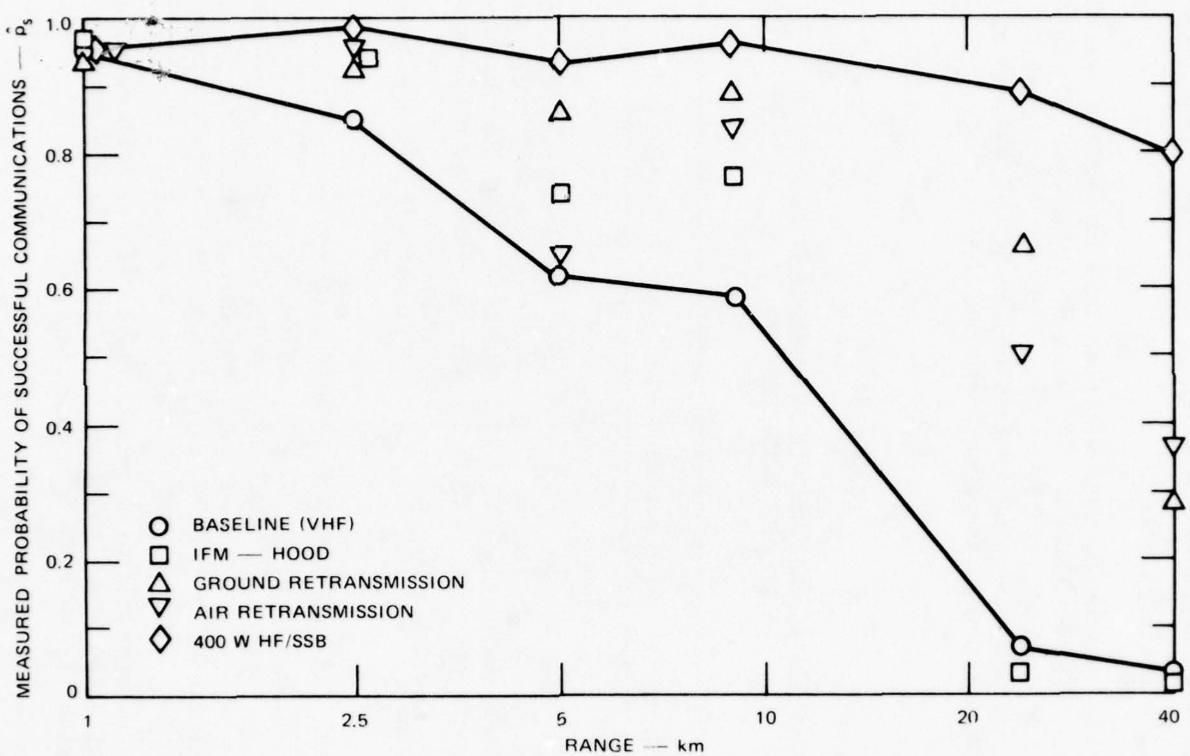

FIGURE 6 MEASURED PROBABILITY OF COMMUNICATION SUCCESS, $\hat{p}_s$, AS A FUNCTION OF RANGE, ALL LINKS, SOG AND NOE ALTITUDES — SUCCESS DEFINED AS A-N SCORE ⩾ 90 PERCENT (FM-320, FORT HOOD, TEXAS; 1976)

systems are summarized in Table 3. For this analysis, a point estimate of the probability of successful communication ($\hat{p}_s$) was computed from multiple observations at each range by determining the fraction of the attempts when A-N ≥ 90 percent. Only skids-on-ground (SOG) and NOE altitudes were considered for data taken during all times of day (dawn, day, and night). SRI's findings were:

- The HF/SSB systems performed better than the VHF/FM systems at the 24- and 40-km ranges. The best HF system was the AN/ARC-102 (400-W PEP), closely followed by the AN/ARC-174 (100-W PEP, with speech processing). Performance of the HF/SSB systems at the 24- to 40-km range was power-dependent.

Table 3

CANDIDATE NOE COMMUNICATION SYSTEMS TESTED AT FORT HOOD (FM-320)

Band and System*	Power (watts)	Comments
VHF		
AN/ARC-114	10	Baseline (VHF), tailfin antenna
Improved FM (Hood)	40	AN/ARC-114 w/40-W amplifier
Ground Retransmission	40	AN/VRC-49 w/RC-292 antenna
Air Retransmission	10	Air Retransmission Console
VHF/SSB†	40	Modified AN/PRC-70
Ground Terminal	40	AN/VRC-46 w/RC-292 antenna
HF		
HF/SSB 1	400‡	AN/ARC-102
HF/SSB 2	200‡	AN/ARC-98
HF/SSB 3	100‡	AN/ARC-174 w/speech processing
HF/SSB 4	40‡	Modified AN/PRC-70§
Ground Terminal	400‡	AN/GRC-106 w/dipole antenna

*All aircraft systems measured on the OH-58. All VHF/FM measurements made with the FM-1 (tailfin) antenna; all HF/SSB measurements made with the shorted loop antenna.

†Not evaluated by SRI because of equipment problems.

‡Peak-envelope power (PEP).

§Tested at low power only (also operates at 200 W PEP).

- The HF/SSB systems performed well and similarly at ranges of 9 km and less. These systems varied in power from 40-W to 400-W PEP. Communication at these ranges was achieved primarily via the groundwave mode.

- Performance of all VHF/FM systems at 9 km and less was highly influenced by the selection of the test site, and terrain. At 24 km and beyond, the Baseline and Improved FM (IFM--Hood) systems were unsatisfactory for NOE communication. The exact failure range for these systems was not measured during FM-320, but lies between 9 and 24 km.

- Retransmission (either airborne or ground-based platforms) did not perform well at the 40-km site, and was marginal at the 24-km site. Any VHF/FM retransmission system's performance is highly dependent on the siting chosen for the retransmission platform. The EW vulnerability of retransmission was not tested.

- The VHF/FM base station was sited behind Radar Hill for these tests. A foreground obstacle attenuation cause by Radar Hill of about 15 dB was measured at the primary test frequency (65 MHz). Furthermore, the 5-km site was adversely located with respect to surrounding terrain.

C. System Performance by Link

Three NOE communication links were tested: aircraft-to-aircraft, aircraft-to-ground, and ground-to-aircraft. Link performance is affected by transmitter power, antenna gain and height, the receiver noise environment, and mode of propagation (NVIS or groundwave).

The FM-320 data were sorted by link and $\hat{p}_s$ was computed at each range for A-N scores ≥ 90 percent (Figures 7 through 9). Skids-on-ground and NOE altitudes only were considered for the aircraft. The following findings were made:

- The 400-W HF/SSB (AN/ARC-102) radio had the best link performance at all of the test ranges. Propagation was primarily via groundwave mode to 9 km, combined groundwave and skywave at 24 km, and skywave at 40 km. Performance of the other HF sets (40 to 200 W) was generally inferior to the 400-W set at 24 and 40 km.

- The best performance for HF/SSB was recorded on the ground-to-air link, because of the 400-W base station and dipole antenna used. The air-to-ground link was slightly worse. The air-to-air link was definitely the weakest at 40 km where performance was limited by the low gain of the aircraft antenna at the test frequencies. Two-thirds of the HF data were taken in the 2- to 3-MHz band (chosen from predictions to ensure NVIS propagation), where

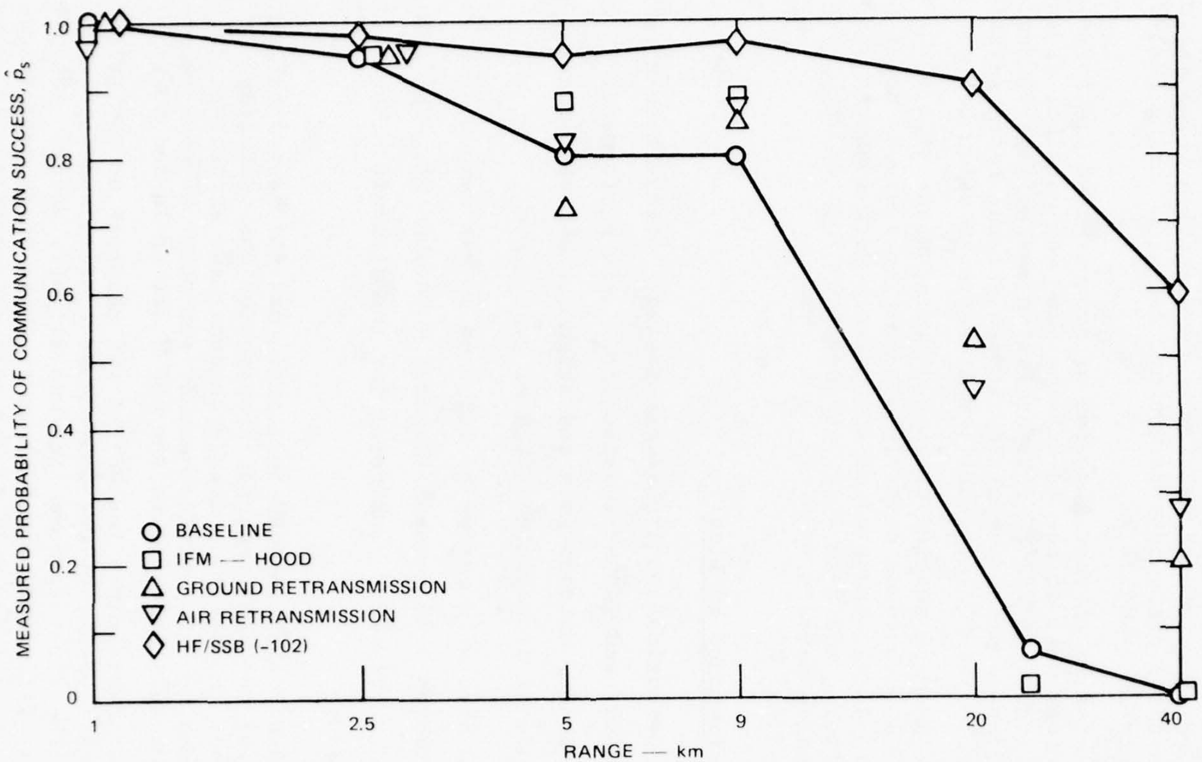

FIGURE 7 MEASURED PROBABILITY OF COMMUNICATION SUCCESS, $\hat{p}_s$, AS A FUNCTION OF RANGE, AIR-TO-AIR LINK, SOG AND NOE ALTITUDES — SUCCESS DEFINED AS A-N SCORE $\geq$ 90 PERCENT (FM-320, FORT HOOD, TEXAS; 1976)

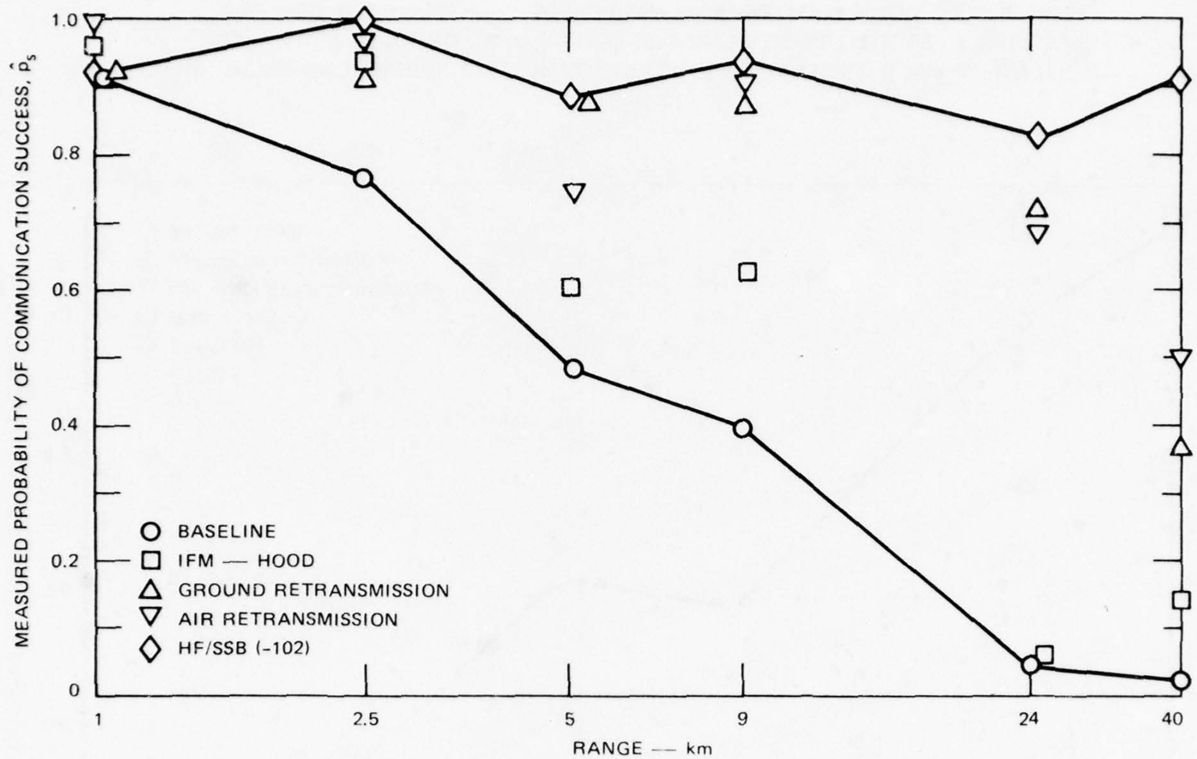

FIGURE 8 MEASURED PROBABILITY OF COMMUNICATION SUCCESS, $\hat{p}_s$, AS A FUNCTION OF RANGE, AIR-TO-GROUND LINK, SOG AND NOE ALTITUDES — SUCCESS DEFINED AS A-N SCORE $\geqslant$ 90 PERCENT (FM-320, FORT HOOD, TEXAS; 1976)

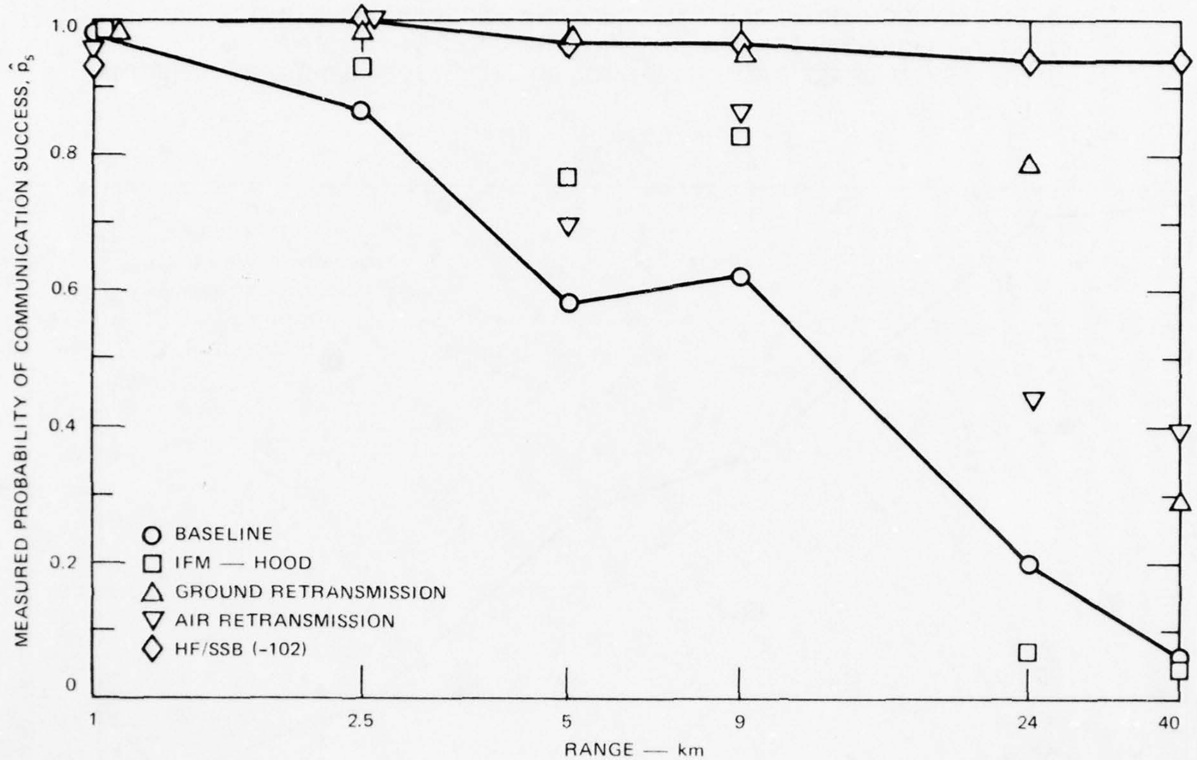

FIGURE 9 MEASURED PROBABILITY OF COMMUNICATION SUCCESS, $\hat{p}_s$, AS A FUNCTION OF RANGE, GROUND-TO-AIR LINK, SOG AND NOE ALTITUDES — SUCCESS DEFINED AS A-N SCORE ⩾ 90 PERCENT (FM-320, FORT HOOD, TEXAS; 1976)

the aircraft antenna had a gain of -16 dBi or less. The gain of the aircraft antenna improves at frequencies greater than 3 MHz, with a commensurate increase in performance (see Appendix F).

- All HF/SSB radios (40 to 400 W) performed equally for all links at ranges out to 9 km. At these ranges, propagation was via the groundwave mode, and high predetection signal-to-noise-ratios (SNR) existed (Figure 10).
- The VHF/FM retransmission systems performed well for all links at 9 km and less. However, link performance was degraded at 24 and 40 km. The retransmission results were highly dependent on the siting of the retransmission platforms.
- The air-to-ground and ground-to-air links for Baseline and Improved FM systems were both marginal at the 5- and 9-km sites; however, the Improved FM system was measurably better. Performance was affected by terrain and site selection and the base station foreground obstacle. Performance was unsatisfactory at the 24- and 40-km sites.
- The air-to-air link performance for Baseline and Improved FM system was satisfactory at 9 km and less. The path profiles for the air-to-air link were less severe than for air-to-ground, and no foreground obstacle was present.
- Performance of Improved FM was significantly better than for the Baseline for the air-to-air and air-to-ground links to 9 km. This is attributed to the improvement achieved by using a 40-W power amplifier, instead of the 10-W amplifier.
- Performance of the Improved FM system was significantly better than that of the Baseline system for the ground-to-air link. Since the receivers in the aircraft were identical, and a common AN/VRC-46 base station was used, the results should have been the same. The difference in results is attributed to learning curve effects (and possibly ground radio transmitter [RC-524] problems) present when the baseline data were collected during the first three days of the FM-320 tests (see also Appendix A).

Values of the probability for successful communications, $\hat{p}_s$, measured for A-N thresholds of 90, 80, and 70 percent are given in Tables 4, 5, and 6 respectively.*

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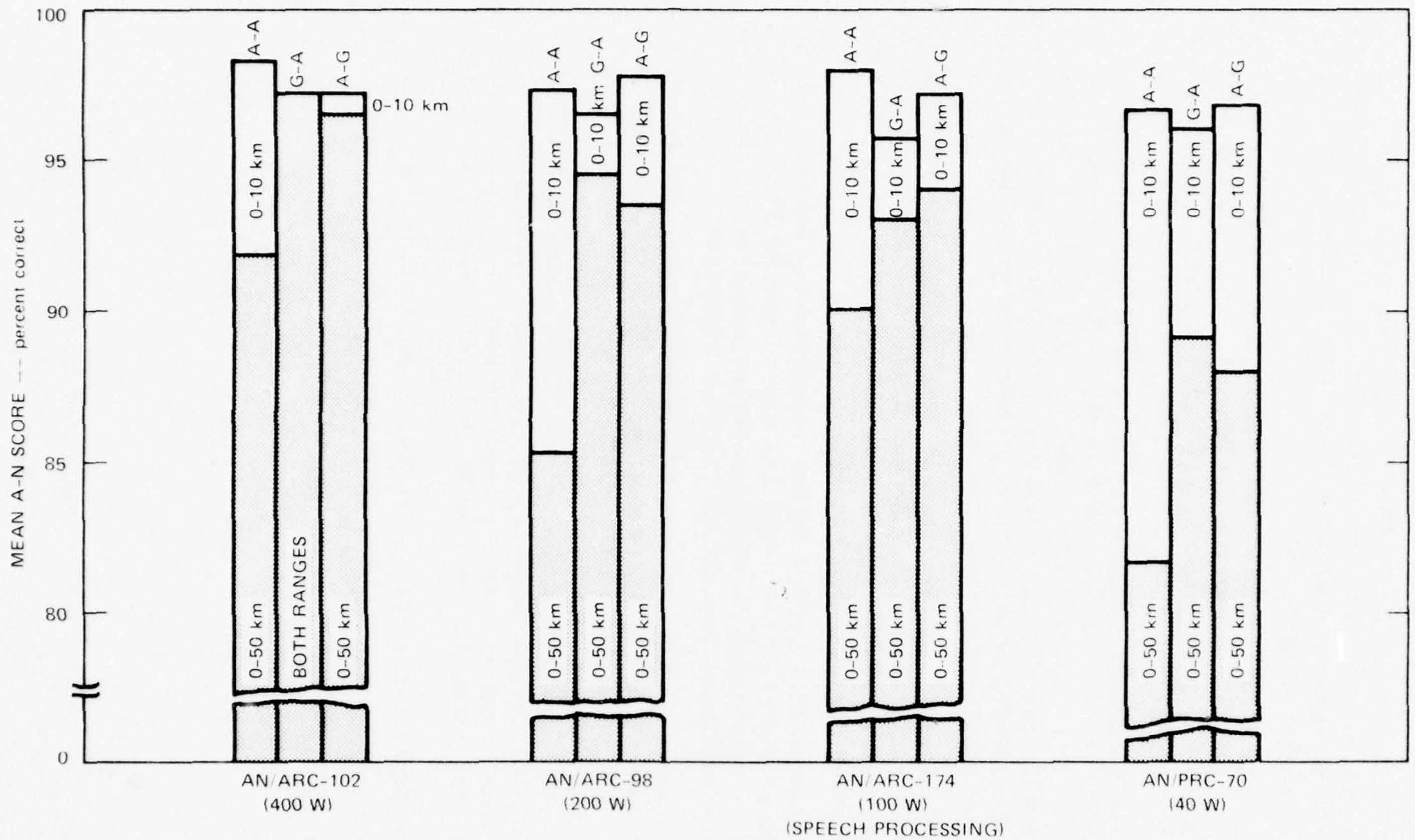
*The calculation of $\hat{p}_s$ was first suggested by Dr. G. R. Marner of AVRADCOM, St. Louis, and the plotted version of $\hat{p}_s$ as a function of range has been termed "Marner curves" by the NOE COM SAG.



SOURCE: FM-320 DATA (EDITED)
SRI LISTING OF 5-13-77

FIGURE 10 HF/SSB SYSTEM PERFORMANCE COMPARISON, BY LINK, FOR SOG AND NOE ALTITUDES — ALL TODs, TWO RANGE INTERVALS, DIPOLE ANTENNA USED AT BASE STATION

Table 4

MEASURED PROBABILITY OF COMMUNICATION SUCCESS, $\hat{p}_s$, AS A FUNCTION OF RANGE AT SOG AND NOE ALTITUDES--SUCCESS DEFINED AS A-N SCORE ≥ 90 PERCENT (FM-320 Test, Fort Hood, Texas; 1976)

System and Link	Measured Probability of Communication Success, $\hat{p}_s$, at Indicated Range (km)					
	1	2.5	5	9	24	40
VHF/FM Systems (65 MHz)						
Baseline (AN/ARC-114)						
Air-to-Air	1.00	0.95	0.80	0.80	0.07	0.00
Air-to-Ground	0.89	0.77	0.49	0.40	0.04	0.02
Ground-to-Air	0.98	0.86	0.58	0.62	0.10	0.06
Improved FM (40 W)						
Air-to-Air	0.98	0.94	0.88	0.88	0.02	0.00
Air-to-Ground	0.96	0.94	0.60	0.62	0.04	0.14
Ground-to-Air	0.98	0.94	0.77	0.83	0.07	0.04
Ground Retransmission (AN/VRC-49)						
Air-to-Air	1.00	0.94	0.74	0.85	0.53	0.21
Air-to-Ground	0.90	0.90	0.89	0.89	0.71	0.37
Ground-to-Air	0.94	0.94	0.92	0.92	0.69	0.26
Air Retransmission						
Air-to-Air	0.97	0.94	0.81	0.86	0.44	0.28
Air-to-Ground	1.00	0.97	0.75	0.92	0.69	0.50
Ground-to-Air	0.89	0.94	0.39	0.75	0.36	0.33
HF/SSB Systems (2.2-4.4 MHz)						
400 W (AN/ARC-102)						
Air-to-Air	1.00	0.98	0.95	0.98	0.91	0.59
Air-to-Ground	0.91	1.00	0.89	0.94	0.83	0.92
Ground-to-Air	0.94	1.00	0.97	0.97	0.94	0.94
100 W (AN/ADC-174 with speech processing)						
Air-to-Air	0.98	1.00	0.98	0.95	0.69	0.63
Air-to-Ground	0.97	1.00	0.97	0.90	0.90	0.73
Ground-to-Air	0.97	0.93	0.93	0.87	0.83	0.73
40 W (AN/PRC-70)						
Air-to-Air	0.97	0.91	0.94	0.94	0.65	0.18
Air-to-Ground	0.95	0.95	0.95	0.82	0.55	0.55
Ground-to-Air	0.92	0.96	0.88	0.96	0.83	0.71

Table 5

MEASURED PROBABILITY OF COMMUNICATION SUCCESS, $\hat{p}_s$, AS A FUNCTION OF RANGE AT SOG AND NOE ALTITUDES--SUCCESS DEFINED AS A-N SCORE ≥ 80 PERCENT (FM-320 Test, Fort Hood, Texas; 1976)

System and Link	Measured Probability of Communication Success, $\hat{p}_s$, at Indicated Range (km)					
	1	2.5	5	9	24	40
VHF/FM Systems (65 MHz)						
Baseline (AN/ARC-114)						
Air-to-Air	1.00	0.96	0.87	0.82	0.07	0.00
Air-to-Ground	0.96	0.85	0.49	0.54	0.04	0.02
Ground-to-Air	0.98	0.92	0.64	0.68	0.10	0.06
Improved FM (40 W)						
Air-to-Air	0.98	1.00	0.94	0.90	0.04	0.00
Air-to-Ground	1.00	1.00	0.64	0.72	0.06	0.14
Ground-to-Air	0.98	0.98	0.83	0.90	0.08	0.04
Ground Retransmission (AN/VRC-49)						
Air-to-Air	1.00	1.00	0.74	0.85	0.53	0.27
Air-to-Ground	0.96	0.94	0.94	0.90	0.71	0.39
Ground-to-Air	0.96	0.98	0.98	0.96	0.73	0.28
Air Retransmission						
Air-to-Air	1.00	1.00	0.83	0.92	0.47	0.33
Air-to-Ground	1.00	1.00	0.81	0.94	0.81	0.50
Ground-to-Air	0.94	0.97	0.44	0.83	0.42	0.36
HF/SSB Systems (2.2-4.4 MHz)						
400 W (AN/ARC-102)						
Air-to-Air	1.00	0.97	0.97	0.97	0.91	0.66
Air-to-Ground	0.97	1.00	0.97	1.00	0.92	1.00
Ground-to-Air	0.97	1.00	1.00	0.97	1.00	1.00
100 W (AN/ADC-174 with speech processing)						
Air-to-Air	0.98	1.00	1.00	0.97	0.77	0.69
Air-to-Ground	0.97	1.00	0.97	0.97	0.93	0.80
Ground-to-Air	0.97	0.97	0.93	0.97	0.90	0.83
40 W (AN/PRC-70)						
Air-to-Air	1.00	0.94	0.97	0.97	0.65	0.27
Air-to-Ground	1.00	1.00	1.00	1.00	0.80	0.65
Ground-to-Air	1.00	0.96	0.96	0.96	0.96	0.71

Table 6

MEASURED PROBABILITY OF COMMUNICATION SUCCESS, $\hat{p}_s$, AS A FUNCTION OF RANGE AT SOG AND NOE ALTITUDES--SUCCESS DEFINED AS A-N SCORE ≥ 70 PERCENT (FM-320 Test, Fort Hood, Texas; 1976)

System and Link	Measured Probability of Communication Success, $\hat{p}_s$, at Indicated Range (km)					
	1	2.5	5	9	24	40
VHF/FM Systems (65 MHz)						
Baseline (AN/ARC-114)						
Air-to-Air	1.00	0.98	0.95	0.86	0.06	0.00
Air-to-Ground	0.98	0.94	0.58	0.40	0.04	0.02
Ground-to-Air	0.98	0.96	0.66	0.70	0.10	0.06
Improved FM (40 W)						
Air-to-Air	1.00	1.00	0.94	0.98	0.04	0.00
Air-to-Ground	1.00	1.00	0.74	0.78	0.08	0.14
Ground-to-Air	1.00	1.00	0.87	0.90	0.07	0.04
Ground Retransmission (AN/VRC-49)						
Air-to-Air	1.00	1.00	0.74	0.85	0.56	0.26
Air-to-Ground	1.00	0.96	0.94	0.96	0.77	0.39
Ground-to-Air	0.98	0.98	0.98	0.96	0.79	0.29
Air Retransmission						
Air-to-Air	1.00	1.00	0.89	0.97	0.47	0.33
Air-to-Ground	1.00	1.00	0.89	0.97	0.83	0.53
Ground-to-Air	0.97	1.00	0.50	0.86	0.44	0.39
HF/SSB Systems (2.2-4.4 MHz)						
400 W (AN/ARC-102)						
Air-to-Air	1.00	0.97	1.00	0.97	0.91	0.66
Air-to-Ground	1.00	1.00	1.00	1.00	0.94	1.00
Ground-to-Air	0.97	1.00	1.00	0.97	1.00	1.00
100 W (AN/ADC-174 with speech processing)						
Air-to-Air	0.98	1.00	1.00	0.97	0.81	0.71
Air-to-Ground	0.97	1.00	0.97	1.00	0.97	0.83
Ground-to-Air	0.97	1.00	0.93	0.97	0.93	0.83
40 W (AN/PRC-70)						
Air-to-Air	1.00	0.94	0.97	0.97	0.71	0.29
Air-to-Ground	1.00	1.00	1.00	1.00	0.85	0.70
Ground-to-Air	1.00	0.96	0.96	0.96	1.00	0.71

D. Channel Reliability

An estimate of channel reliability can be derived from the A-N test data. Channel reliability is defined here as the probability that a communication channel (of any quality) existed. Specifically, reliability is the percentage of occurrences that a communication channel existed having a A-N score > 0 percent. During the FM-320 tests, the A-N score was computed for each test message. If communication between the transmitter and receiver did not exist, an A-N test score of 0 percent was logged. Furthermore (because of the relatively sharp performance degradation of the receivers in the vicinity of the sensitivity threshold), if the predetection SNR exceeded the threshold, at least a marginal communication channel generally existed and high (> 50 percent) A-N test scores resulted, especially for the VHF/FM systems. If a usable channel was not obtained, the aircraft flew to the next site. Channel reliability (as defined here) represents a crude approximation to the percentage of the time that the receiver sensitivity threshold was exceeded.

The FM-320 test data were sorted to determine $\hat{p}_s$ for an A-N score > 0 percent, and used as an estimate of channel reliability. The results are given in Table 7 for the candidate systems:

The following findings are made from the FM-320 data:

- The channel reliability on fixed frequencies with the HF/SSB systems was high for ranges out to 24 km. Propagation at these ranges was primarily via groundwave or combined groundwave and NVIS mode.
- The channel reliability for fixed-frequency operation of the HF/SSB systems at 40 km was substantially lower than at the closer ranges. Propagation was via the NVIS mode. Reliability was generally power-dependent at this range. The low-reliability results were caused by low antenna gain for the air-to-air links at the lowest test frequencies. SRI believes that narrowband interference on the HF channels, particularly during the nighttime and dawn test periods, combined with low transmitter antenna gain in the 2- to 3-MHz region, contributed to these lower channel reliability results.

Table 7

MEASURED PROBABILITY OF ESTABLISHING A COMMUNICATION CHANNEL AS A FUNCTION OF RANGE AT SOG AND NOE ALTITUDES-- SUCCESS DEFINED AS A-N SCORE > 0
(FM-320 Test, Fort Hood, Texas; 1976; All Links and Times of Day)

System and Frequency*	Probability of Establishing a Channel at Indicated Range, d (km)					
	1	2.5	5	9	24	40
VHF/FM Systems						
Baseline (AN/ARC-114; 65 MHz)	1.00	0.99	0.81	0.81	0.08	0.04
Improved FM (40 W; 65 MHz)	1.00	1.00	0.93	0.94	0.06	0.04
Ground Retransmission (AN/VRC-49; 70 and 30 MHz)	1.00	1.00	0.93	0.97	0.78	0.40
Air Retransmission (70 and 30 MHz)	1.00	1.00	0.88	0.99	0.64	0.54
HF/SSB Systems (2.2-4.3 MHz)						
400 W (AN/ARC-102)	1.00	1.00	1.00	1.00	0.98	0.91
100 W (AN/ARC-174 with speech processing)	1.00	1.00	1.00	1.00	0.94	0.81
40 W (AN/PRC-70)	1.00	1.00	1.00	1.00	0.91	0.66

*All data taken on a single frequency; frequency changes not permitted during a test run.

- A significantly higher channel reliability would have been achieved for the HF/SSB systems if frequencies higher in the HF band had been used and if frequency changes had been permitted during a given test period (e.g., dawn).*
- High channel reliabilities existed for the VHF/FM systems, including retransmission, out to 9 km; however, reliability at the 5-km site was adversely affected by site selection.
- Low reliability existed for the Baseline and Improved FM systems at the 24- and 40-km sites. Performance at these sites was terrain and site-selection dependent. Although better results occurred for retransmission, this mode of communication is also limited by terrain, retransmission platform location, and aircraft location.

E. Altitude Dependence of the Baseline and Improved FM Systems

The height to establish two-way communication for air-to-ground and air-to-air links was measured at each of the test sites for Baseline and Improved FM systems. In general, the altitude at which communication can be established is a measure of the exposure to the ground-based weapons threat.

Reference 4 cites two threat envelopes (see Figure 1). Helicopters at all altitudes over the range from 0 to 4 km from the forward edge of the battle area (FEBA) face a threat from anti-aircraft artillery.

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*Assume that performance on single HF/SSB frequency is interference-limited, that interference is narrowband, that two frequencies are available, and that interference on A and B is uncorrelated. Then

$$p_s(A,B) = \text{probability of successful communication on either A or B.}$$

$$\begin{aligned} p_s(A,B) &= 1 - p\ (\text{failure}) \\ &= 1 - p\ (\text{both channels fail}) \\ &= 1 - p\ (\text{channel A fails}) \times p\ (\text{channel B fails}). \end{aligned}$$

For example, let $p_s(A) = 0.59$ (assumed)

$p_s(B) = 0.80$ (assumed)

$$\begin{aligned} p_s(A,B) &= 1 - [1 - 0.59][1 - 0.8] \\ &= 1 - [0.41][0.2] \\ &= 0.92. \end{aligned}$$

In summary, two-frequency operation increases reliability of HF/SSB in the presence of narrowband interference, for the assumptions given.

The threat from missiles exists at all altitudes greater than 350 ft from 0 to approximately 15 km from the FEBA. The surface-to-air missile kill zone varies with distance, target altitude, and weapons siting. Helicopters generally fly at 200 ft altitude (or less) forward of the division rear boundary to be under the SAM threat envelope. The higher the aircraft is required to fly to establish (or maintain) communication, the greater the exposure to antiaircraft weapons.

Table 8 gives the measured altitudes required to establish two-way communication from the aircraft to the base station and from aircraft to aircraft. The VHF/FM results are highly site- and terrain-dependent, and the siting was different for the air-to-air and air-to-ground links. HF/SSB results are given for comparison; they are neither terrain- nor siting-dependent. The parentheses around some heights indicate exposure of the aircraft to an assumed 200-ft threat forward of the division rear boundary. Improved FM--Hood and HF/SSB radio systems could establish two-way communication at 40 km under a 200-ft altitude for the Fort Hood test geometry. Only the HF/SSB systems could communicate at NOE and SOG altitudes at 24 and 40 km.

F. HF/SSB System Performance Comparison--Time of Day Dependency

During the Fort Hood FM-320 tests, three periods were used as representative of night, dawn, and daytime operations. Primary and alternate HF/SSB frequencies were assigned for each test period. Operation during a given flight was specified to be conducted on either the primary or the alternate assigned frequency. Frequency changes during a flight were not allowed (to limit the complexity of the experiment). VHF/FM data were also collected at all times of day (TOD) but were not formally analyzed for TOD dependence. By inspection, there was no apparent TOD dependence.

Primary and alternate HF/SSB test frequencies were selected from NVIS frequency predictions for the Fort Hood area for the months of interest by the U.S. Army Communications Electronics Engineering Installation Agency (CEEIA), U.S. Army Communications Command, Fort Huachuca, Arizona. Selections were conservatively made from these predictions to

Table 8

HEIGHT REQUIRED TO ESTABLISH TWO-WAY COMMUNICATION
TO THE BASE STATION OR TO ANOTHER AIRCRAFT
(FM-320 Test, Fort Hood, Texas; 1976)

Numbers in parentheses indicate altitudes greater than permitted by threat profile defined in Reference 1

Link and Range (km)	Height Required to Establish Communication for Indicated System (ft AGL)		
	Baseline	Improved FM	HF/SSB (AN/ARC-102)
Air-to-Air			
1	0	0	0
2.5	0	0	0
5	0	0	0
9	0	0	0
24	(260)	120	0
40	(450)	40	0
Air-to-Ground			
1	0	No data	0
2.5	0	No data	0
5	75	No data	0
9	5	No data	0
24	(270)	No data	0
40	(380)	No data	0

ensure the existence of NVIS propagation. The primary and alternate frequencies were selected to fall below the predicted frequency of optimum transmission (FOT). A sample prediction chart is shown in Figure 11. Frequencies thus selected had a predicted reliability (of propagating) greater than 90 percent--e.g., for 90 percent of the days in the month, the given frequency would propagate with a reliability of 90 percent or greater.

U.S.ARMY COMMUNICATIONS-ELECTRONICS ENGINEERING INSTALLATION AGENCY

FREQUENCY RELIABILITY TABLE

PROJECT 341   RPA 75101.0   DCA   SSN 12.1   NOVEMBER 1976
FORT HOOD, TX   TO GROUND STATION 2   AZIMUTHS   MILES   KM.
31.03N - 97.37W   31.48N - 97.37W   .00 180.00   31.1   50.0
TYPE OF SERVICE 3A3A   MINIMUM ANGLE = .0 DEGREES
XMTR 2 30 HORZ HW DIPOLE [H 9.14] [L -.50] [A -0] OFF AZ = 0
RCVR 2 30 HORZ HW DIPOLE [H 9.14] [L -.50] [A -0] OFF AZ = 0
POWER = .200KW   3MHZ MAN-MADE NOISE = -166DBW   REQD.S/N = 50DB
=

FREQUENCIES IN MHZ

	f_p*	f_s		f_s	f_p†							
UT	2.2	2.5	3.3	4.1	4.4	5.1	5.8	6.1	6.5	7.4	7.7	
02	.92	.90	.62	.21	.12	-	-	-	-	-	-	REL.
04	.90	.89	.53	.22	.13	-	-	-	-	-	-	REL.
06	.86	.88	.75	.33	.23	.07	-	-	-	-	-	REL.
08	.85	.87	.86	.59	.44	.18	.07	.07	-	-	-	REL.
10	.85	.84	.59	.34	.24	.07	-	-	-	-	-	REL.
12	.92	.90	.58	.30	.21	.06	-	-	-	-	-	REL.
14	.98	.98	.99	.99	.99	.93	.69	.49	.28	.04	-	REL.
16	.99	.99	.99	.99	.99	.99	.96	.95	.88	.54	.42	REL.
18	.99	.99	.99	.99	.99	.98	.95	.92	.85	.59	.49	REL.
20	.99	.99	.99	.99	.99	.98	.95	.92	.86	.60	.51	REL.
22	.99	.99	.99	.99	.99	.98	.92	.85	.71	.29	.20	REL.
24	.96	.96	.95	.89	.79	.33	.05	-	-	-	-	REL.

UT	00	02	04	06	08	10	12	14	16	18	20	22
MUF	4.8	3.5	3.5	3.8	4.3	3.8	3.7	6.1	7.5	7.6	7.7	6.9
FOT	4.1	2.7	2.8	3.1	3.5	2.5	2.7	5.2	6.4	6.3	6.3	5.9

DASHES IN RELIABILITY LINES SIGNIFY RELIABILITIES OF 00 PERCENT

PROVIDE UPDATE INFORMATION TO THIS AGENCY ATTN: CCC-EED-PED

FORT HUACHUCA, ARIZONA 85613
AUTOVON 879-6779

*PRIMARY FREQUENCY, f_p, NIGHT (08-10 UT) AND DAWN (1130-1330 UT) 2.5 MHz SECONDARY FREQUENCY.

†PRIMARY FREQUENCY, f_p, DAY (15-17 UT). 4.1 MHz SECONDARY

FIGURE 11 IONOSPHERIC FREQUENCY PREDICTIONS FOR FORT HOOD, TEXAS (October-December 1976)

The frequencies selected for the three time periods were:

Period	Hours (LT)	Primary (MHz)	Secondary (MHz)
Night	0200-0400	2.240	2.489
Dawn	0530-0730	2.240	2.489
Day	0900-1100	4.370	4.089

Diurnal effects on system performance were evaluated at 40 km using the ground-to-air data. The ground transmitter was an AN/GRC-106 (400 W) operating into a half-wavelength dipole antenna elevated 40 ft. Four different aircraft radio receivers were used with the shorted-loop antenna. Propagation was via the NVIS mode. The results in terms of mean A-N score are given in Table 9. At least four 30-character A-N messages were sent during each time period. Performance was best during the daytime period, followed by night and the dawn period.

Table 9

PERFORMANCE OF HF/SSB GROUND-TO-AIR LINK (NVIS MODE) FOR THREE TIME PERIODS AT SOG AND NOE ALTITUDES-- 40-km RANGE (FM-320 Test, Fort Hood, Texas; 1976)

Receiver	Mean A-N Score (Percent Correct) at Indicated Time of Day		
	Night	Dawn	Day
AN/ARC-102	95	97	98
AN/ARC-174	83	70	97
AN/PRC-98	99.5	79.5	86.5
AN/PRC-70*	(77)	(60)	(83.5)
Average	92.5	82.2	93.8
Ranking	2	3	1

*The test scores for the AN/PRC-70 should have been equivalent to other sets used in ground-to-air links. While the reason for the lower performance is not known with certainty, equipment problems (e.g., cabling) are suspected. The AN/PRC-70 data were not included in the average A-N score.

Diurnal effects on system performance were also evaluated at 24 and 40 km using the air-to-ground data. Propagation at 24 km was via NVIS and groundwave modes, whereas at 40 km it was via the NVIS mode. The ground receiver was an AN/GRC-106 with a dipole antenna. The results are given in Table 10. Performance was best during the day test period followed by dawn and night.

Table 10

PERFORMANCE OF HF/SSB AIR-TO-GROUND LINKS
FOR THREE TIME PERIODS AT SOG AND NOE ALTITUDES--
24- AND 40-km RANGES
(FM-320 Test, Fort Hood, Texas; 1976)

Transmitter	Mean A-N Score (Percent Correct) at Indicated Time of Day		
	Night	Dawn	Day
400 W (AN/ARC-102)	97	94	98
200 W (AN/ARC-98)	66	74	100
100 W (AN/ARC-174)	71	85	98
40 W (AN/PRC-70)*	(64)	(45)	(93)
Average	78.0	84.3	98.6
Ranking	3	2	1

*Not included in averages because of suspected equipment problems.

The test data for the ground-to-air link at 40 km was inspected for A-N score = 0 percent. An A-N score of 0 percent indicates that the HF/SSB channel (on a fixed frequency) could not be established. The results are shown in Table 11. No occurrences of communication outage occurred during the day. Several occurred during the night or dawn periods.

Table 11

OCCURRENCE OF ZERO A-N TEST SCORES
FOR FOUR HF/SSB RADIO SYSTEMS
ON GROUND-TO-AIR LINK,
SOG AND NOE ALTITUDES
(40-km Range)

Factor	Time of Day		
	Night	Dawn	Day
Outages	3	4	0
Trials	48	36	34
Percent outage	6%	11%	0%
Rank order	2	3	1

From the above analysis, SRI concludes that the preferred times to communicate using HF/SSB in NVIS mode is the daytime period. Communication during the dawn period and nighttime hours is more difficult than daytime. This is probably a result of the presence of more severe levels of atmospheric noise and narrowband interference on the radio channels during dawn and night. This observation is consistent with the findings of Hagn and Vincent in Thailand while using low power HF sets on NVIS paths.[20] It is also consistent with the results of the Hawaii NOE COM tests (see Appendix B).

The test data at 24 and 40 km were taken on fixed HF frequencies, with no frequency changes permitted. If frequency changes were permitted to avoid narrowband interference, the night and dawn A-N test scores would increase dramatically. SRI recommends that at least two frequencies be assigned to tactical nets for any given time of day to improve performance in the presence of narrowband frequency-selective interference in the HF band.

IV CRITICAL ISSUES AND UNKNOWNS

A. Introduction

The Department of the Army's Letter of Agreement (LOA) for Nap-of-the-Earth (NOE) Communication Systems (1 December 1975) contains eight critical issues and five unknowns to be resolved for candidate NOE communication systems.[11] The critical issues contain specific technical and operational questions to be resolved by testing. The unknowns contain broader issues and are related to the critical issues. Information on the operational capabilities and limitations of the candidate systems can be found in the communication effectiveness (CE) results, and mission effectiveness (ME) results of the SCORES (Europe I, Sequence 2A) scenario described below.[21] Operational range data for the candidate systems in irregular terrain can be obtained from the communication performance range predictions (see Appendix A). Test information can be found in the results of the TCATA NOE communication test (FM-320) conducted at Fort Hood, Texas.[9]

B. SCORES Scenario

1. Description

SCORES gaming techniques were used by the Director of Combat Development (DCD-Studies), U.S. Army Aviation School, Fort Rucker, Alabama to simulate tactical operations involving Army helicopters of an armored division. The scenario was run for aviation assets of a heavy division with medium lift (CH-47) and medical (UH-1) helicopters from Corps assets, operating in the region of Fulda in the Federal Republic of Germany. TRADOC centers and schools supervised and approved the employment of the helicopters for which they then were propments (had operational control). All radio communications required to accomplish the aircraft missions were listed. Military judgment was used by the propment centers and schools to determine which communications were critical to successful completion of the aircraft missions, and all noncritical messages were discarded. This resulted in 412 critical communication events during the six-hour period considered. Each major aircraft mission was divided into tactically significant sub-missions resulting in 134 sub-missions.

Radio systems were modeled, and the candidate systems evaluated at the communication event ranges using the SRI communication system performance model (Appendix A). For each transmission (and reception) the aircraft (or ground unit) location (position and altitude) was determined from the scenario. Any communication events not completed were assumed (for analysis purposes) to cause the aircraft sub-mission to be degraded.

2. Measures of Effectiveness

Two measures of effectiveness were used:

- Communication Effectiveness (CE)--The percentage of mission-critical two-way communication events completed in the scenario.
- Sub-Mission Effectiveness (ME)--The percentage of sub-missions completed in the scenario without communication-caused degradation.

For a communication event to be defined as successful, successful transmission of the message and receipt of acknowledgment was required. Each sub-mission consisted of at least one communication event. All communication events had to be completed for a sub-mission to be considered undegraded.

VHF aircraft radio systems used in the scenario were run at two VHF frequencies, 45 and 65 MHz. The HF radios were run at 25 MHz (groundwave). The technical characteristics of these radios are summarized in Appendix A.

3. Deployment of Radios

The deployment (issue of radios to Army units) affects interoperability and hence the scenario results. The individual Baseline, IFM--BTA* and HF/SSB--BTA radio systems were issued to all Army units in the scenario; however, the combined radio system--HF/SSB and IFM--BTA radios--

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*BTA $\triangleq$ Best Technical Approach (see Reference 22).

were deployed to only selected units. The following deployments of radios were used:

(1) Baseline. The AN/ARC-114(A) was installed in all scenario aircraft. Ground stations used the AN/VRC-12 family of radios.

(2) IFM--BTA. IFM--BTA was installed in all aircraft. Ground stations used the AN/VRC-12 family and RC-292 antenna at 10 m.

(3) HF/SSB--BTA. An HF/SSB--BTA transceiver was installed in all aircraft. Selected ground stations were equipped with a comparable system. These were all aviation ground units, maneuver and field artillery units down to the company/battery level, Brigade Forward Area Support Coordinating Officer, and medical regulating units (for casualty routing.)

(4) HF/SSB and IFM--BTA. HF/SSB and IFM--BTA radios were installed in all scenario aircraft. All ground stations were equipped with the AN/VRC-12 family of radios. HF ground radios were given to aviation ground units down to the company level, and to medical regulating units.

(5) SAG Solution. IFM radios given to all aircraft. HF/SSB radios given to selected aircraft. HF ground radios deployed as in (4) above.

Evaluation of Deployment (1) in the scenario represents the present (Baseline) case. Deployment (2) evaluates the effectiveness of an IFM radio installed in the aircraft. Deployment (3) evaluates the effectiveness of deployment of HF radio to all aircraft and to a large number of ground units. This complete "fill" of HF radios was not recommended by the SAG at its meeting 9-10 March 1978. Deployment (4) evaluates the effect of IFM--BTA and HF/SSB radios in all aircraft, and only a partial fill of ground units. Deployment (5) evaluates the effect of IFM in all aircraft, HF/SSB in selected aircraft (AH-1 and some OH-58 aircraft excluded), HF/SSB radios in aviation ground units and medical regulating units. This deployment is the SAG recommendation. The SAG recommendation was evaluated by the U.S. Army Aviation School (DCD-Studies) Fort Rucker, Alabama, and is not contained in this report.

C. Unknowns to be Resolved

1. Increase Communication of Improved VHF/FM

Quantitative data as to the degree of increased communication effectiveness of improved VHF/FM (Unknown 7a).

The improvement in communication effectiveness is defined as percentage improvement of IFM--BTA[22] with respect to baseline (AN/ARC-114). The results are given in Table 12 for the non-EW environment. The IFM--BTA radio achieved a higher communication effectiveness than baseline in the SCORES scenario.

Table 12

COMMUNICATION EFFECTIVENESS (CE) AND IMPROVEMENT (CEI) OF IFM--BTA AND BASELINE--NON-EW ENVIRONMENT

Frequency (MHz)	Baseline CE (%) (1)	IFM--BTA CE (%) (2)	Improvement* CEI (%)
45	17	68	~300
65	55	82	~50

*Improvement = {[(2) - (1)]/(1)} x 100, in percent.

2. Capabilities/Limitations of HF/SSB

Capabilities and limitations of HF/SSB for NOE communication (Unknown 7b).

The capabilities and limitations of HF/SSB are given in Table 13. The major capabilities are:

- Ability to reach all the required ranges independent of terrain and siting of the ground and air units when using the NVIS mode.
- Ability to communicate using the groundwave mode over ranges greater than those achievable by IFM--BTA.

The main limitations of HF/SSB are:

- The HF/SSB radio is not interoperable with the current AN/VRC-12 family of VHF/FM radios or with SINCGARS.
- Channel noise is greater than for VHF/FM radios, resulting in lower channel quality.
- Frequency management of HF assets will require more effort than for VHF/FM.

Table 13

CAPABILITIES AND LIMITATIONS OF HIGH-FREQUENCY SINGLE-SIDEBAND (HF/SSB) RADIO

Capabilities	Limitations
Can achieve required range (50 km) and beyond	Not interoperable with AN/VRC-12 family (VHF/FM)
NVIS mode is terrain-independent and provides complete coverage at all ranges in all terrains	Noisier channel than VHF or UHF
Performance is generally independent of site location of ground and air units	HF/SSB channels are subject to interference, particularly at night
Operates in groundwave mode with better signal than VHF because of higher power and narrower bandwidth	Radios heavier than VHF/FM
Can operate with reduced EW threat vulnerability in groundwave mode using variable power	Additional operator training and communication planning may be required
Difficult to DF NVIS skywave from short range	Fewer operating frequencies are available than for VHF band because of frequency-assignment process.
Skywave jamming requires large multifrequency EW antenna	Frequency changes are required over 24-hour day
Groundwave ranges are independent of ionospheric effects, but dependent on transmitter power, antenna gain and terrain	skywave subject to infrequent propagation outage
Groundwave mode operates in EW environment better than VHF/FM because of higher power and narrower bandwidth	Easy to DF on groundwave operating at high transmitter power
	Susceptibility to jamming

- HF/SSB is susceptible to intercept and direction finding from greater ranges than VHF/FM, because of longer propagation ranges. It can also be jammed from a greater range by ground-based jammers.

3. Increased Communication Planning and Training

Quantitative data as to the degree of increased operator training and communication planning required for utilization of HF/SSB systems (Unknown 7c).

The only information bearing on this unknown is from a survey of nine pilots who participated in the TCATA FM-320 test at Fort Hood.[9] In this test four HF/SSB systems and two VHF/FM systems were evaluated.

The following findings are contained in the FM-320 report in response to the question, "What was the time required to learn to operate the systems?,"

> The AN/ARC-114 radio required the shortest time to learn to operate. The improved FM radio required only slightly more time. The control head was the same for both of these systems. Since all of the pilots had used it extensively prior to the test, no learning time was required. All pilots stated that none of the systems required more than a few minutes to learn to operate, and this was accomplished with minimum instruction. The AN/PRC-70 required the longest time to learn to operate.

In response to the question: "Which radio system was the easiest to operate?," the following findings were reported:

> The AN/ARC-98, VHF/SSB (AN/PRC-70) and the AN/PRC-70 (HF/SSB) received relatively equal scores for ease of operation. The AN/ARC-114 was rated the most difficult to operate.

In response to the question: "Which radio system did the pilots like best?," the following findings were reported:

> The AN/PRC-70 was rated as the most preferred radio primarily because of its functional versatility: i.e., pushbutton FM and HF band operation, multipower, and multimode (HF/SSB, VHF/SSB, and VHF/FM) operation. The AN/ARC-102 was rated the least preferred primarily because of the inability of the aviator to squelch the irritating channel noise.

The communication planning aspects of HF/SSB were not addressed by TCATA during the FM-320 test. A communication plan for HF/SSB Near

Vertical Incidence Skywave (NVIS) operation was prepared by SRI International; this plan was followed during the test. The communication plan made use of ionospheric predictions for the Fort Hood test area (October through December 1976) supplied by the U.S. Army CEEIA, Fort Huachuca, Arizona. From these predictions, a primary and secondary operating frequency was selected for each of three test periods (night, dawn, and day). The operating frequencies were chosen at or below the frequency of optimum transmission (FOT). The predictions appeared to be accurate based on three months of testing. The communication planning was relatively easy, because of the small scale and controlled nature of the FM-320 test; HF/SSB communication planning for a large divisional (or corp) military exercise would be more difficult.

4. VHF/FM Retransmission

Quantitative data as to the increase in communication system effectiveness and area coverage obtained through the use of VHF/FM retransmission equipment for special applications (Unknown 7d).

No communication effectiveness data (SCORES) were computed for retransmission because of the difficulty in siting a retransmission station(s) in the scenario environment. However, quantitative data exist for retransmission ranges from model predictions in the Fulda area. In addition, measured retransmission ranges exist for both ground and airborne retransmission from the FM-320 test.

A ground retransmission system in the Fulda terrain can successfully communicate in the non-EW environment at longer ranges than the Baseline or IFM--BTA systems. Ground retransmission ranges for an air-to-ground-to-air link are given in Table 14. In this table, the AN/VRC-49 was used as the retransmission station (RC-292 antenna with 10-m mast sited on hilltop), operating with the candidate VHF/FM radio installed in the aircraft. The operation ranges for the air-to-ground-to-air link for Baseline, IFM--Hood, and IFM--BTA working with the retransmission station are given for comparison. The required probability of success was $P_{sr} = 0.9$ (see Appendix A).

Table 14

OPERATING RANGE USING RETRANSMISSION IN FULDA TERRAIN
(p_{sr} = 0.9 for Total Air-to-Ground-to-Air Link)

Frequency (MHz)	Operating Range (km) for Indicated System*		
	Baseline (Present System)	IFM--Hood	IFM--BTA
35	6.5	10	18
45	10	14	19
65	14	16	20

*Assume both aircraft antennas at 3-meter heights with random siting, ground antenna at 10 meters with excellent siting; terrain interdecile range Δh = 300 meters; medium vegetation.

The probability of successful communication, p_s, for retransmission can be estimated from the Fort Hood data. These data were taken at six locations only, and are based on the A-N test scores of ≥ 90 percent recorded during FM-320. These data are single-point estimates ($\hat{p}_s$) at each of six ranges.

Air and ground retransmission systems tested at Fort Hood (65 MHz) had longer communication ranges (higher $\hat{p}_s$) than either the Baseline or IFM--Hood systems (Table 15). Conversely, both retransmission systems had shorter communication ranges (lower $\hat{p}_s$) than the HF/SSB system (AN/ARC-102).

5. Combined VHF/FM and HF/SSB Radio

Performance of a combined VHF/FM and HF/SSB radio in an NOE environment (Unknown 5e).

The combination of the IFM--BTA and HF/SSB--BTA systems,[22] both installed in the aircraft, achieved a higher communication effectiveness than either the Baseline system or the IFM-BTA in the European SCORES scenario. The communication effectiveness results were highly influenced by the presence of an HF/SSB--BTA subsystem installed in the

Table 15

MEASURED PROBABILITY OF SUCCESSFUL COMMUNICATION, $\hat{p}_s$, ON AIR-TO-AIR LINKS WITH AND WITHOUT RETRANSMISSION--SUCCESS DEFINED AS A-N SCORE ≥ 90 PERCENT (FM-320, Fort Hood, Texas; 1976)

System	$\hat{p}_s$ at Indicated Range (km)					
	1	2.5	5	9	24	40
Baseline						
Direct	1.00	0.95	0.80	0.80	0.07	0.00
w/Air Retransmission	0.97	0.94	0.81	0.86	0.44	0.28
w/Ground Retransmission	1.00	0.94	0.74	0.85	0.53	0.21
IFM--Hood (direct)	0.98	0.94	0.88	0.88	0.02	0.00

aircraft. For this analysis, HF ground radios are assumed to be assigned to aviation and medical regulating units only.* The combined VHF/FM and HF/SSB subsystem in a single aircraft could be in two configurations--both capabilities integrated into a single package (such as the AN/PRC-70) or each as a separate subsystem. Simultaneous communications in each band could be achieved only for the latter configuration. The communication effectiveness results are given in Table 16.

D. Critical Issues to be Resolved

1. HF/SSB Mission Effectiveness

Will an HF/SSB system provide an acceptable level of communications reliability under NOE flight conditions, and how does it relate to NOE mission effectiveness? (Critical Issue 10a).

The results for mission effectiveness for HF/SSB are given for the non-EW environment in Table 17. The HF/SSB systems operated in ground-

*The assumed deployment (TBOI) of HF/SSB ground transceivers affects both the communication effectiveness and mission effectiveness results. If all ground units (in the scenario) were equipped with HF transceivers, the results would be higher.

Table 16

COMMUNICATION EFFECTIVENESS OF COMBINED IFM--BTA AND HF/SSB--BTA IN EW AND NON-EW ENVIRONMENTS

System	Communication Effectiveness, CE (Percent), at Indicated Frequency and Environment			
	45 MHz		65 MHz	
	Non-EW	EW	Non-EW	EW
Baseline only	17	12	55	28
IFM--BTA only	68	41	82	45
Combined IFM--BTA and HF/SSB--BTA [Deployment option (4)]	82	72	88	75

Table 17

MISSION EFFECTIVENESS OF CANDIDATE RADIO SYSTEMS IN SCORES SCENARIO (Based on 134 Sub-Missions)

System	Percentage of Sub-Missions Completed	
	45 MHz	65 MHz
Baseline	4	33
IFM--BTA	46	63
HF/SSB [Deployment Option (3)]	82	82
Combined HF/SSB and IFM--BTA [Deployment Option (4)]	68	75

wave mode at 25 MHz; baseline and IFM--BTA are given for comparison. These VHF systems were evaluated at 45 and 65 MHz.

The communication reliability for HF/SSB at given range, d, can be computed for different terrains using the SRI radio system performance model for irregular terrain. Communication reliability is defined as the probability of successful communication on the first attempt, p_s.

A user-specified required value for the probability of successful communications is denoted by p_{sr}. Operational range is thus defined as that range for the computed $p_s = p_{sr}$ (also see Appendix A).

Table 18 gives the predicted operational range for three radios for $p_{sr} = 0.9$. Ninety percent of the communications will be completed on the first attempt at range, d. Data are given for three terrains: Fort Hood (hilly), Fulda (low mountains), and Korea (rugged mountains). The frequency for the VHF/FM candidates was 45 MHz. The frequency for HF/SSB was 25 MHz (groundwave). The HF/SSB--BTA candidate can communicate over the longest ranges.

Table 18

PREDICTED OPERATIONAL RANGE FOR CANDIDATE RADIO SYSTEMS
OPERATING IN AIR-TO-AIR AND AIR-TO-GROUND LINKS
IN THREE TERRAINS--$p_{sr} = 0.9$

Terrain	Operational Range (km) on Indicated Link					
	Baseline		IFM--BTA (45 MHz)		HF/SSB (25 MHz)	
	A-A	A-G	A-A	A-G	A-A	A-G
Fort Hood	3.4	6.2	8.3	13.8	34	40
Fulda Region, FRG	2.0	4.7	5.9	11.0	19	26
Korea (38°N,127°E)	1.6	3.8	4.5	9.3	16	20

2. Operator Training and Communication Planning

To what extent will operator training and communication planning for missions need to be modified to take advantage of the increased communications provided by NOE communication systems? (Critical Issue 10b).

Communication planning for missions will have to be accomplished at all levels (Corps and below) to support HF/SSB communications successfully. Both operational (e.g., netting) and technical planning will be required; these are clearly interrelated. Factors to be considered are frequency allocations, frequency selection and assignments to radio nets, selection of mode (groundwave or skywave) and appropriate ground antenna systems, communication protocols (e.g., for lost communications), EW- or interference-avoidance protocols, and special provisions for appliques incorporated within the radio (e.g., addresses for selective calling). Frequency-dependent coverage areas for VHF/FM systems will dictate care in assignment of VHF frequencies to support radio nets in their required areas while minimizing coverage beyond the required areas.

Operator training was briefly addressed in the FM-320 report. Provisions for operator training have been addressed in the NOE COM Required Operational Capability (ROC).[10]

3. AN/GRC-106 Suitability

Are the present generation ground HF/SSB radio set (AN/GRC-106) and its antenna system suitable to terminate the air-ground link of an NOE communication system? (Critical Issue 10c).

The AN/GRC-106 is the current HF/SSB ground radio in the Army inventory. This radio, designed in the late 1950's and introduced in the early 1960's, was designed to provide reliable ground-to-ground single-channel voice and single-channel radio teletype (RATT) between higher echelons (Corps and Division). It is currently deployed down to the battalion level, but is used down to the company level. There are approximately 5000 units in inventory, including spares.

The AN/GRC-106 is not a suitable ground link terminal for NOE COM Air-to-Ground communications. The projected HF/SSB radio for aircraft is a modern HF/SSB radio, which has features not available in the AN/GRC-106: multiple preset frequencies, rapid tuning, frequency scanning, and selective call (SELCAL) addressing. The operational concept for use of these features is rapid frequency change in the face of interference (or jammed channels), and SELCAL-actuated audio squelch and selective calling (addressing) of the called unit.

Because the AN/GRC-106 will not meet the technical or operational requirements specified, it does not meet the operational concept for employment of HF/SSB for the NOE problem. Furthermore, the existing horizontal dipole and vertical (vehicular) whip and coupler will not meet the employment concept. The AN/GRC-106 radio requires a minimum of 10 to 15 seconds to tune into an antenna and approximately the same time for an existing dipole. If the dipole length has to be changed, at least five minutes are required to establish operation on a new frequency.

SRI recommends that a ground version of the modern HF/SSB radio recommended for the aircraft be procured in sufficient quantities to terminate the ground link. This radio would be essentially the aircraft radio modified for ground operation in vehicles or command posts. It will be interoperable with the AN/GRC-106 when used in a reduced-capability mode. Developmental effort will be required for broadband (or multifrequency) HF/SSB ground antenna (2 to 10 MHz) suitable for the NVIS mode. Vertical whip antennas and couplers (for the groundwave mode) are currently available.

4. Size, Weight, and Power

Will the size, weight, power, and antenna requirements of an HF/SSB system be compatible with the airframe of attack, utility, cargo and observation helicopters? (Critical Issue 10d).

This question was answered by the materiel developer. Liaison with the AVRADCOM aircraft project managers was provided by AVRADA and size and weight and power requirements for HF/SSB radios have been estimated. The HF/SSB shorted-loop has been installed on two aircraft (OH-58 and UH-1) and installation of this antenna on other aircraft types should not be a problem. The AH-1 helicopter will require restructuring of the fusalage compartment to accommodate a HF/SSB radio (if installed in that aircraft). Some weight trade-off may have to be made in the AH-1 and OH-58A aircraft to accommodate HF/SSB. The Aviation Center addressed the size, weight and power question in the CFP.

5. Mission Effectiveness of VHF/FM

To what degree can the airborne VHF/FM system be improved and how does it relate to NOE mission effectiveness? (Critical Issue 10e).

The effective radiated power (ERP) for IFM--BTA system represents a 10- to 15-dB increase over the current Baseline radio installed in the aircraft. ERP is given by

$$ERP = P_T - L_T + G_T \quad \text{, in dBm,}$$

where

P_T = transmitter power, in dBm

L_T = transmission line and mismatch loss, in dB, and

G_T = transmitter antenna gain, in dBi.

After a thorough review of engineering alternatives and technical constraints by the materiel developer, improvements have been recommended for the IFM--BTA system (Appendix A). The resultant ERP for the IFM--BTA system and for the Baseline system are given in Table 19.

The NOE mission effectiveness for the Baseline and IFM--BTA systems is given in Table 17.

6. Retransmission

Is retransmission a viable alternative? (Critical Issue 10f).

This is primarily an operational question. It has been addressed in the Executive Summary of the Concept Formulation Package.[21]

The conclusion of the users (Study Advisory Group, 9-10 March 1978) is that retransmission is not a workable solution. Retransmission has the following deficiencies: range limitations, EW vulnerability, threat vulnerability, more personnel required, more frequencies required, longer set-up time, and added planning burden on siting the retransmission station in the right place at the right times in the potentially

Table 19

EFFECTIVE RADIATED POWER FOR IFM--BTA AND BASELINE SYSTEMS

System	Effective Radiated Power (dB) at Indicated Operating Frequency		
	35 MHz	45 MHz	65 MHz
Baseline			
Transmitter power, P_T (dBm)	40	40	40
Transmission line loss, L_T (dB)	1.0	1.1	1.4
Transmitter antenna gain, G_T (dBi)	-16	-10	-4
ERP (dBm)	23	28.9	34.6
IFM--BTA			
Transmitter power, P_T (dBm)	49	46	46
Transmission line loss, L_T (dB)	1.0	1.1	1.4
Transmitter antenna gain, G_T (dBi)	-10	-3	-0
ERP (dBm)	38	41.9	44.6
Improvement over Baseline (dB)	15	13	10

fluid modern battlefield. In addition, airborne retransmission requires a minimum of two dedicated aircraft and crews--one on-station and one in a standby status.

7. Combined VHF/FM and HF/SSB Radio

What benefits accrue to the use of a combined airborne VHF/FM, and HF/SSB radio? (Critical Issue 10g).

The principal benefits that accrue from the use of a VHF/FM and HF/SSB radio combined in one unit (as compared to separate VHF/FM and HF/SSB subsystems) are reduced size, reduced panel space in the cockpit of the aircraft, and increased pilot efficiency because of human factors--specifically having a single multifunction control head for two radio systems. Table 20 compares engineering estimates for size and weight.[22]

Table 20

SIZE AND WEIGHT FOR A COMBINATION (VHF/FM AND HF/SSB) RADIO AND FOR SEPARATE SUBSYSTEMS

System	Size		Weight		Comment
	(cm^3)	(in^3)	(kg)	(lb)	
Combination Radio	22,198	1,355	18	40	AN/PRC-70[23]
Separate Radios:					
FM (AN/ARC-114)	2,393	146	3.18	7	IFM--BTA*
40-W Amplifier	2,300	140	3.0	6.6	IFM--BTA*
HF/SSB (200 W)	19,822	1,210	18	40	
Subtotal	24,515	1,496	24.18	53.6	

*Does not include applique unit for digital signaling.

The size and weight reduction benefits are especially important for the smaller helicopters (especially the AH-1). The nine pilots assigned to the FM-320 Test rated the AN/PRC-70 as the preferred radio because of its functional versatility: FM and HF band operation, multipower capabilities, and multimode operation. This system also permits VHF/SSB as an option with potential EW and frequency management (more channels) benefits.

8. Enemy Electronic Countermeasures

To what degree will enemy electronic countermeasures affect NOE Communications? (Critical Issue 10h).

The electronic warfare (EW) environment was overlayed on the SCORES scenario by the threat section of the DCD, USAAVNC, Fort Rucker, Alabama to determine the effect of jamming on the communication and mission effectiveness of the candidate systems. Soviet and Warsaw Pact doctrine was used.[7] Equipment deployment and EW tactical employment of ground-based jamming equipment followed this doctrine; however, no airborne EW assets were considered. Each communication event was analyzed to see if it could be intercepted by the opposing force. If intercepted, the event was analyzed to determine whether assets to jam were available, and whether the communication event was of sufficient importance to jam. Jamming was not attempted if the friendly communication was not successful. The model described in Appendix A was used with the appropriate system parameters for the EW receivers and transmitters to determine the success of the intercepts and jams.

Communication effectiveness for 412 mission critical two-way messages was determined with and without jamming. VHF/FM candidate radios were assumed to be operated at 45 and 65 MHz. HF operation was assumed to be at 25 MHz, groundwave mode, and is given in Table 21.

Table 21

COMMUNICATION EFFECTIVENESS OF CANDIDATE RADIO SYSTEMS
IN EW AND NON-EW ENVIRONMENTS (SCORES SCENARIO)
(Based on 412 Communication Events)

	Communication Events Completed (Percent)	
System and Operating Frequencies	Non-EW	EW
Baseline		
45 MHz	17	12
65 MHz	55	28
IFM--BTA		
45 MHz	68	41
65 MHz	82	45
HF/SSB [Deployment Option (3)], 25 MHz	92	82
Combined HF/SSB and IFM--BTA [Deployment Option (4)]		
25 and 45 MHz	82	72
25 and 65 MHz	88	75

Mission effectiveness for 134 sub-missions with and without EW are given in Table 22. A mission effectiveness of 66 percent in the EW environment occurred for HF/SSB installed in all aircraft and ground units. Similar effectiveness occurred for a partial fill of HF radios in ground units (Table 22). The high effectiveness for HF/SSB (compared to IFM--BTA resulted from having HF radios in all aircraft [Deployment Option (3)], and the relatively large number of short air-to-air communication links in the scenario. The higher-power HF system was able to override the jamming signal for many of these short links.

Table 22

MISSION EFFECTIVENESS OF CANDIDATE RADIO SYSTEMS
IN EW AND NON-EW ENVIRONMENTS (SCORES SCENARIO)
(Based on 134 Sub-Missions)

	Sub-Missions Completed (Percent)	
System and Operating Frequencies	Non-EW	EW
Baseline		
45 MHz	4	3
65 MHz	33	19
IFM--BTA		
45 MHz	46	28
65 MHz	63	37
HF/SSB [Deployment Option (3)], 25 MHz	82	66
Combined HF/SSB and IFM--BTA [Deployment Option (4)]		
25 and 45 MHz	68	53
25 and 65 MHz	75	56

E. TCATA (FM-320) EW Tests

Limited HF/SSB EW tests were conducted at Fort Hood, Texas during FM-320. An AN/TLQ-17 jammer with an omnidirectional whip antenna was sited 10 km downrange from the friendly HF/SSB base station. As the aircraft flew downrange on the NOE course, distance from the base station increased and distance to the jammer decreased. HF/SSB propagation was groundwave mode at 4.3 MHz. Test messages (A-N messages) were transmitted to and received by the aircraft in the presence and absence of jamming. Aircraft transmitter powers of 40, 100, 200, and 400 W PEP were used. The ground station was an AN/GRC-106 (400 W PEP) with a halfwave dipole antenna elevated 40 ft AGL.

The following findings were given in the FM-320 report:*[13]

(1) Electronic jamming is effective against all HF radio systems (all powers) at ranges of 5 to 40 km from the base station. [Ranges to the jammer were shorter than the ranges to the base station for these cases.]

(2) Electronic jamming is ineffective against all of the HF radios at ranges of 1 and 2.5 km (from the base station). [Corresponding ranges to the jammer were 9 and 7.5 km respectively for this geometry.]

At the 1 and 2.5 ranges mean A-N score (for all HF/SSB radios) was 97 percent correct in the presence of EW. At 5 km to 40 km ranges [from the base station] mean A-N score was zero percent correct.

(3) The effectiveness of electronic jamming is the same [under the observed FM-320 test conditions] against aircraft powers of 40, 100, 200, and 400 W PEP.

(4) It was recommended that further testing of electronic jamming devices be conducted at various distances, and that both omnidirectional [used for the FM-320 test] and directional jammer antennas be used.

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*Material in brackets added for clarity by SRI.

V SUMMARY OF RESULTS

A. Objectives

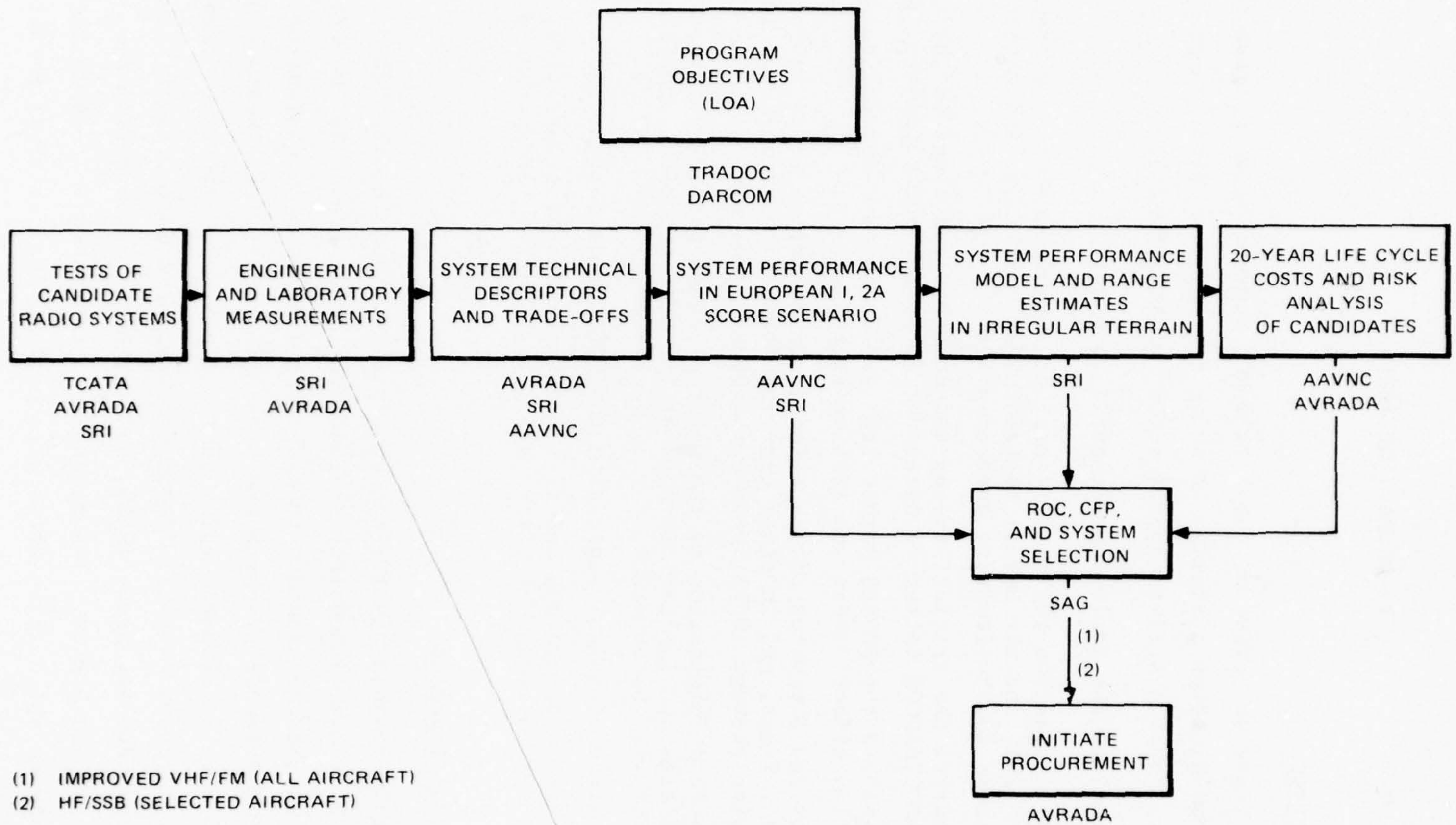
The primary objective of the Army's NOE Communication program is to select a communication system(s) to solve the NOE communication problem for the Army for the near-term period (IOC of FY 1980-81).

SRI provided the following technical support:

- Helped plan the TCATA field test of NOE communication systems (FM-320), and the Hawaii tests of VHF/FM, HF/SSB, and satellite systems for helicopters operating NOE.
- Answered the critical issues and unknowns contained in the TRADOC/DARCOM Letter of Agreement (LOA) for the candidate systems.
- Developed the SCORES methodology and computer codes for communication effectiveness and mission effectiveness.
- Provided estimates of operational communication range in Fort Hood, Texas, and in other terrains for use in the concept formulation package (CFP), and in the SCORES analysis.
- Provided information to the materiel developer on systems capabilities and limitations so that the best technical approach (BTA) will be obtained.
- Provided technical support to the NOE Communications SAG.
- Performed laboratory and field measurements of propagation, noise, and system technical parameters (e.g., helicopter antenna gain).

B. Method of Approach

The study methodology for the analysis is shown in simplified form in Figure 12. This methodology includes the major events of the program and indicates the contributors to each. Participating organizations were the U.S. Army Avionics Research and Development Activity (AVRADA); Directorate of Combat Development (DCD-Studies); U.S. Army Aviation Command, Fort Rucker, Alabama (AAVNC); TRADOC Combined Arms Test Activity (TCATA); and the Study Advisory Group (SAG), consisting of members from the TRADOC schools and DARCOM. The sequence of the tasks is roughly the time sequence in which these steps were performed. The final result was



(1) IMPROVED VHF/FM (ALL AIRCRAFT)
(2) HF/SSB (SELECTED AIRCRAFT)

FIGURE 12 METHODOLOGY AND PARTICIPATING ORGANIZATIONS FOR THE NOE COMMUNICATION PROGRAM the selection of a candidate system to meet the technical and operational needs of the Army for an NOE communication system for the near time frame (IOC date of FY 1980/81).

The communication effectiveness for eight candidate radio systems was measured during a full-scale helicopter communication test (FM-320) conducted by TCATA at Fort Hood, Texas (October-December 1976).[9] Four VHF/FM systems were tested, including the present AN/ARC-114 (baseline) radio, improved FM--Hood, and airborne and ground retransmission. Four HF radios were tested with powers varying from 40 to 400 W PEP.

Two measures of effectiveness (MOEs) were used during the FM-320 tests. The primary MOE used to measure communication effectiveness was the percent correct of alphanumeric (A-N) messages sent one-way through the channel without repeats. The second measure used was the aircraft height to break squelch, defined as the height to establish two-way communication between an aircraft and base station, or between an aircraft and another aircraft constrained to fly NOE. This measurement was performed by TCATA for the baseline and IFM-Hood systems only operating in two modes: air-to-air (A-A) and air-to-ground (A-G). As the aircraft climbs in order to communicate, it becomes more vulnerable to enemy antiaircraft weapons; therefore, this MOE pertains to relative aircraft vulnerability. The actual vulnerability of the aircraft as a function of altitude depends upon the specific scenario being considered.

SRI and AVRADA performed additional engineering tests. These include flight tests of HF/SSB and VHF/FM systems in Hawaii, and a comparison of each of these systems with a satellite system. Flight tests of HF/SSB were conducted in New Hampshire (White Mountains) and the Fort Monmouth, New Jersey area by AVRADA. Screen room tests to determine radio system performance and channel quality in terms of predetection SNR also were conducted by AVRADA. Gains (in dBi) of VHF antennas on the OH-58 aircraft were measured by SRI and AVRADA. The gains of the HF/SSB (shorted loop) antenna on the OH-58 and the UH-1 aircraft were also measured by AVRADA.

The radio system technical performance parameters were determined from the engineering and laboratory tests. These parameters are frequency-dependent. Technical parameters are transmitter power, transmission line and mismatch loss, and helicopter antenna gain. The required pre-detection SNR for a given channel quality was determined in the laboratory for the special case of Gaussian background noise.

A communication system performance model was developed by SRI and used by AAVNC (DCD-Studies) to evaluate candidate radio system performance using the SCORES Europe I Sequence 2A scenario for an attack helicopter company in the region of Fulda, in the Federal Republic of Germany. Communication effectiveness (number of two-way communication links completed), and sub-mission effectiveness (completion of a series of critical communications related to mission outcome) were computed using a methodology worked out by SRI and AAVNC. This was done for both the non-EW and EW environments. Soviet/Warsaw Pact EW equipment and doctrine were modeled and independently played by an opposing team in the scenario. Performance of the candidate systems (both communication and sub-mission effectiveness) was determined for both the non-EW and EW environments. These results were used to compute the relative effectiveness of each candidate system in determining their relative worth in the cost and operational effectiveness analysis (COEA).

The SRI-developed radio system performance model was also used to provide communication range estimates for helicopters operating in irregular terrain. This model was run for three different terrains--Fort Hood, Texas (hilly), the Fulda region, Federal Republic of Germany (low mountains), and Korea (rugged mountains). Operational range (OR) was predicted for a user-specified required probability of successful communication (p_{sr} = 0.9) at all locations and times in the terrain of interest. Ranges for lesser required probability values were also computed (p_{sr} = 0.5, 0.7, and 0.8). The predictions were checked against limited observations for the Fort Hood and Fulda regions and good agreement between the predicted and observed values was found. The OR estimates were included in the NOE COM Trade-Off Determination (TOD).

Communication system costs were developed by AVRADA and provided to AAVNC (DCD-Studies), where a 20-year life cycle cost (LCC) analysis was performed for each of the candidate systems. AVRADA also provided a technical, cost, and schedule risk assessment for the candidate systems.

The results of this work were presented to the NOE COM Study Advisory Group (SAG) over the period from March 1977 to March 1978. The SAG consisted of members from TRADOC, each of the Army schools (communication users and aircraft proponents), FORSCOM, and members of the DARCOM community. The SAG members reviewed and refined the operational range requirements for each type of aircraft. Two different range requirements were identified. A short-range requirement (approximately 0 to 17 km) was identified by the Armor school as necessary to support the ground maneuver force commander operating in the vicinity of the forward edge of the battle area (FEBA).

A long-range requirement (0 to 50 km) was identified (actually reconfirmed)* for command and control of helicopter assets under the control of the aviation company commander.

After a thorough review of the technical, operational, and cost characteristics of the candidate radio system, along with the user requirements, the SAG selected two radio systems to meet these requirements:

(1) An improved VHF/FM radio system to be installed in all helicopter assets. This system must be able to communicate at the shorter ranges at nominal parity with the ground commander's radio.

(2) A modern HF/SSB radio system for selected helicopters suitable to communicate at extended ranges (out to 50 km) for command and control of other aviation units. Furthermore, the commander of the aviation unit must be equipped with an HF/SSB ground radio at the company operations center in order to control his aircraft.

These recommendations were formalized as a Required Operational Capability (ROC) and given to the DARCOM materiel developer (AVRADCOM) to initial

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*The LOA which initiated the study (see Appendix I) specified a required range out to 50 km.

procurement action. The target date for the initial operating capability (IOC) for the NOE Communication Radio Systems is FY 1981.

C. SRI Findings

These findings are based on the SRI communication performance model, which computes the probability of successful communications, p_s, as a function of range. Operational range (OR) estimates from the model are obtained for each required probability of success (p_{sr}). Field tests (FM-320 and others) and laboratory measurements also contributed to the following findings:

1. VHF/FM Radio Systems

- The current VHF/FM aircraft radio (AN/ARC-114) will not meet the short range requirement (0 to 17 km) in the non-EW environment. Predicted communication ranges for Fort Hood (Texas), Fulda, and Korea (30°N, 127°E) are 5, 3.4, and 2.2 km, respectively, when $p_{sr} = 0.9$ for air-to-air links, operated in a low hover (antenna at 3 m) on 65 MHz.
- The AN/ARC-114 used at NOE altitudes is range-limited by its 10-W transmitter power and antenna gain, which results in inadequate *effective radiated power (ERP)*. The longest ORs are achieved at frequencies of about 65 MHz, where the aircraft tailfin antenna (FM-1 antenna on OH-58 aircraft) is most efficient. Shorter ranges result at 35 and 45 MHz because of the lower aircraft antenna gain and the lower resultant ERP.
- The improved VHF/FM (BTA) radio, which has a 40-W transmitter power and improved antenna, will not meet the 0 to 17-km range requirements in Fulda terrain, but it has significantly larger ranges (and lower height for two-way communication at a given range) than the AN/ARC-114. Predicted communication ranges for Fort Hood, Fulda, and Korea are 9.8, 6.9, and 4.8 km, respectively, for f = 65 MHz, $p_{sr} = 0.9$, air-to-air links, with an antenna height of 3 m.
- For VHF/FM systems, the shortest ranges occur for the air-to-air link. Longer communication ranges occur on the air-to-ground and ground-to-air links. The ground-to-air link has a longer operational range than the air-to-ground link, because of higher effective radiated power, ERP, and increased antenna height (10 m).
- The VHF/FM ground antenna can be improved over the current antenna (RC-292) by using a new field-expedient broadband omnidirectional antenna. The RC-292 cannot operate efficiently across the 30- to 76-MHz VHF/FM band without physical changes to

the antenna and ground plane elements. Broadband directional antennas offer additional improvements for certain applications. A directional VHF ground antenna (the OE-254/GRC) has recently been developed to replace the RC-292 antenna.[24] This new antenna will be coming into the inventory in FY 1980.

- Ground or airborne retransmission is not a satisfactory solution for the long-range (0 to 50 km) requirement. Communication ranges achieved with this system depend critically on antenna siting, but they are generally less than 50 km. Operational deficiencies are position preplanning requirement for fluid tactical situations, frequency supportability when twice as many frequencies are needed, ground station set-up times, EW and ground fire vulnerability, and additional personnel requirements.

- Improved FM Best Technical Approach (IFM--BTA) is the best candidate of the VHF/FM candidate studies. IFM--BTA is susceptible to EW; however, IFM--BTA will perform significantly better than the AN/ARC-114 radio in the EW environment.

- Aircraft equipped with IFM--BTA will be able to communicate at lower altitudes to significantly longer ranges than the present system. Communication at lower altitudes will reduce the vulnerability of the aircraft to groundfire and surface-to-air missiles (SAMs).

- The VHF/SSB radio tested at Fort Hood (FM-320) was not operating correctly during that test, and the data were not analyzed by SRI. Theoretically, a 40-W (ERP) VHF/SSB system offers an improvement over the IFM--BTA system for channels of marginal quality operating in an EW environment. A large number of 3-kHz VHF channels exist in the 30- to 76-MHz portion of the spectrum and this is an attractive feature. VHF/SSB is not interoperable with the AN/VRC-12 family (or SINCGARS), however, and the channel quality is generally inferior to FM in both the clear and secured modes. The same appliques apply as for HF/SSB.

2. HF/SSB Radio Systems

- The proposed 200-W PEP (speech processing) HF/SSB aircraft radio system will meet the long range requirement (0 to 50 km) in the non-EW environment. HF/SSB operates in two modes: groundwave and near vertical incidence skywave (NVIS). Predicted communication ranges for 25-MHz groundwave mode for air-to-air links operating at 3 m antenna height for Fort Hood, Texas, Fulda, and Korea, are 34, 19, and 16, respectively (p_{sr} = 0.9). Longer ranges (50 km and beyond) can be achieved using the NVIS skywave mode.

- The HF/SSB radio (BTA) can successfully communicate using the NVIS mode at lower power (40 W PEP) over 50-km ranges (or greater) by proper frequency selection, with the best results being obtained during daytime. At nighttime and during dawn, high power is frequently required because of the presence of noise and interference in the channel.

- The channel quality of HF/SSB is inferior to VHF/FM, but it is operationally acceptable for NOE missions. The proposed modern HF/SSB radio for NOE communication will be equipped with a selection signalling-actuated squelch to ensure positive communication contact and to reduce pilot fatigue caused by continuous background noise and interference (such as that experienced with the current AN/ARC-102).
- The reliability of HF/SSB can be increased by assigning two (or more) frequencies to support a communication net for a given time of day. This improvement gives additional capability to avoid narrowband frequency-selective interference. A frequency-scanning feature (combined with selective signaling) was recommended for the modern HF/SSB radio.
- HF/SSB operating in the groundwave mode performs better than VHF/FM in the EW environment (spot jamming). This is because of its higher power and narrower bandwidth. A manual-keyed continuous wave (MCW) capability was recommended for the aircraft radio for pilot acknowledgment of messages and brevity code (shorthand) signaling in an adverse electromagnetic environment (EW, or over extremely marginal channels, such as those encountered on very long groundwave paths).
- An initial investigation of frequency supportability for HF/SSB in the FRG indicates that sufficient HF/SSB frequencies exist for aviation nets. This information was provided prior to formal approval of the frequency-assignment request (Form DD-1494), and additional investigation of this aspect is needed.
- HF/SSB operated satisfactorily in the NVIS skywave mode at four test sites during the NOE Communication Program. Propagation via the NVIS skywave mode is independent of terrain. The test sites used were Fort Hood, Texas (October-December 1976), Hawaii (August 1976), New Hampshire (August 1976--limited flight tests during daytime), and Fort Monmouth, New Jersey (August 1977). The frequency of operation for the NVIS skywave mode was 10 MHz or lower. Ionospheric predictions of the lowest usable frequency (LUF), maximum usable frequency (MUF), and frequency of optimum transmission (FOT) were provided for the test sites by U.S. Army CEEIA, Fort Huachuca, Arizona. Primary and secondary frequencies were selected at or below the FOT. Although the predictions were not explicitly validated as part of this program, they were accurate enough. No outage attributed to lack of NVIS propagation on the properly chosen test frequencies was noted during any of the tests conducted.
- The HF/SSB shorted-loop antenna tested on the OH-58 and UH-1 aircraft is near-optimum for all Army aircraft that will use the NVIS mode. This antenna radiates both a horizontally polarized skywave component toward the zenith, and also a vertically polarized groundwave component off the aircraft nose and tail. The pattern toward the zenith is essentially omnidirectional for ranges out to 50 km, whereas the groundwave pattern has maxima

off the nose and tail of the aircraft, and nulls off the sides of the aircraft (but not a figure-eight pattern).[25] The vertical component is of sufficient magnitude for groundwave communication when the 200-W PEP transmitter is used. The gain of the shorted-loop antenna is marginal in the 2- to 3-MHz region of the spectrum, because of poor antenna efficiency. A gain of -16 dBi or lower for the NVIS mode was measured in this part of the band. As frequency is increased above 3 MHz, antenna efficiency (and resultant gain) improves dramatically. A separate antenna optimized for groundwave formance may be needed in the 20- to 30-MHz band.

- The A-G and A-A HF links during the FM-320 (Fort Hood) were supported primarily by groundwave mode at distances up to 24 km. Operating frequencies were 2.4 and 4.1 MHz. High A-N test scores resulted for 400W PEP HF transcievers installed in the aircraft and ground station. The ECOM loop in the aircraft (and dipole ground antenna) were used. No pattern variability problems in the aircraft were reported by the pilots. Also the test frequencies were located in the most inefficient range for the aircraft antenna. If longer groundwave communication ranges are required (or reduced HF power operation, or groundwave operation in rugged terrain), it is recommended that an HF aircraft antenna having an omnidirectional azimuthal pattern optimized for the groundwave mode of communication be investigated.

- A half-wavelength dipole antenna (H = 40 ft) was used as the ground antenna for the Fort Hood and Hawaii tests. This antenna has a theoretical maximum gain toward the zenith of about 6 dBi. This antenna is limited to single-frequency operation and is not frequency-agile. SRI recommends that a broadband (or frequency-agile) horizontally polarized antenna be developed for use with the ground terminal of an air-to-ground NOE COM system using the NVIS mode. Half-wave horizontal dipoles (or equivalent) located ≥ 1/10 wavelength above ground should be used in the interim. Alternatively, a slant wire antenna such as used at Fort Hood could be used for frequency agility, but with lower performance compared to a dipole.[26]

- A 30-ft vertical whip antenna was used for engineering measurements at Fort Hood, Texas. This antenna produced a usable groundwave signal at 2.2 and 4.1 MHz at a distance of 39 km from the base station when driven by a 400-W PEP transmitter. It is recommended that the existing 15-ft vehicular whip (with an improved rapid-tuning coupler) or a new longer whip be used for groundwave communication where required operational ranges so dictate.

- A modern HF/SSB radio with variable power will be required for terminating the ground end of the NOE COM link. This radio should include a rapid tuning feature and be compatible with the frequency scanning and selective calling features of the recommended aircraft radio. The AN/GRC-106 can be used on an interim basis with single-frequency capability until the more frequency-agile ground radio is available.

REFERENCES

1. Terrain Flying, FM 1-1 (Headquarters, Department of the Army, Washington, D.C., 1 October 1975).

2. "Reforger-76--After-Action Report," 101st Aviation Group, 101st Airborne Division, Fort Campbell, Kentucky (26 October 1976).

3. Ronald S. Stebbins, A. Winkenhofer, T. V. Corbett, and G. H. Hagn, "Trip Report USAREUR (6-21 July 1977)," Internal Memorandum, U.S. Army Aviation School, Directorate of Combat Development--(Studies), Fort Rucker, Alabama (1 August 1977).

4. Gunnery Training for Attack Helicopters, TC 17-17 (Commandant, U.S. Army Armor School, Fort Knox, Kentucky, 31 December 1975). [See also Aviator's Recognition Manual, TC1-88 (29 March 1977).]

5. "Soviet Doctrine and Planning Factors for Ground Operations (U)," Defense Intelligence Agency, Washington, D.C. (October 1976), (SECRET).

6. "HYDRA: A Handbook of Soviet Ground Based Air Defense (AD) Systems (U)," Army Training and Doctrine Command/Tactical Air Command (October 1977) (SECRET)

7. "The Warsaw Pact Electronic Warfare and Signal Intelligence Threat Workbook (U)", Department of the Army (ASCI), Washington, D.C. (May 1977) (SECRET).

8. B.V. Ricciardi, B. C. Tupper, and H. G. Hagn, "Design of a Full-Scale Test for U.S. Army Helicopter Nap-of-the-Earth (NOE) Communication Systems," Proc. 23rd Conf. Design of Experiments in Army Research, Development and Testing [in preparation].

9. John M. Pinson, John Mellor, William P. Leach, Robert J. Cleland, "Nap of the Earth Communications (NOE COMMO) System," TCATA Test Report FM-320, RCS ATCD-8, Headquarters, TRADOC Combined Arms Test Activity, Fort Hood, Texas (March 1977).

10. "Nap-of-the-Earth Communications (NOE-COMM) Required Operational Capability (ROC)," NOE-COMM Study Advisory Group, U.S. Army Aviation School, Fort Rucker, Alabama (April 1978).

11. "Letter of Agreement for Nap-of-the-Earth (NOE) Communications System, Headquarters, United States Army Training and Doctrine Command, Fort Monroe, Virginia (1 December 1975). [Reproduced in Appendix I of this volume.]

12. "Proposed Required Operational Capability (ROC) for a Nap-of-the-Earth Communications System," Letter from Headquarters, U.S. Army Material Command (DARCOM) to Commander, U.S. Army TRADOC (5 November 1974).

13 "Nap-of-the-Earth Communication (NOE-COMM) Study Plan," NOE Comm Study Advisory Group, U.S. Army Aviation Center, Fort Rucker, Alabama (March 1977).

14. D. T. Magill and D. J. Fylstra, "Speech Intelligibility Enhancement--Nap-of-the-Earth (NOE) Communication Program," Task Letter Report, Contract DAAB07-76-C-0868, SRI Project 4979, SRI International, Menlo Park, California (7 March 1978).

15. A. G. Longley and P. L. Rice, "Prediction of Tropospheric Radio Transmission Loss Over Irregular Terrain," U.S. Department of Commerce (ESSA) (July 1968), AD-676 874.

16. LTC J. M. Pinson, Test Officer, TCATA FM-320, Fort Hood, Texas, private correspondence (7 October 1977).

17. "Measures of Effectiveness (MOEs) for Nap-of-the-Earth Communication Systems Tests," Appendix A to FM-320 Test Design Plan Inputs, Working Paper, Stanford Research Institute, Menlo Park, California (15 April 1976).

18. "Alpha-Numeric Test Messages," Appendix C to FM-320 Test Design Plan Inputs, Working Paper, Stanford Research Institute, Menlo Park, California (15 April 1976).

19. "Training Material for NOE Communication Systems Test," Appendix E to FM-320 Design Plan Inputs, Working Paper, Stanford Research Institute, Menlo Park, California (5 October 1976).

20. G. H. Hagn and W. R. Vincent, "Comments on the Performance of Selected Low-Power HF Radio Sets in the Tropics," IEEE Trans. Vehicular Technology, Vol. VT-23, No. 2, pp. 55-58 (March 1974).

21. Figure 19 and 20 in "Nap-of-the-Earth Communications (NOE-COMM), Part 1, Volume 1, Executive Summary," Concept Formulation Package, ACN 38309, U.S. Army Aviation Center, Fort Rucker, Alabama (April 1978).

22. "Nap-of-the-Earth Communications (NOE-COM), Best Technical Approach," Concept Formulation Package, U.S. Army Aviation Center, Fort Rucker, Alabama, 1978.

23. Operation and Instruction Manual, Communication System AN/PRC-70 (ABN), Technical Manual (Cincinnati Electronics).

24. C. R. Brewer, G. O. Dykes and B. R. Schulze, "VHF (FM) Tactical Antennas," MASSTER Test Report No. FM 312, Headquarters, Modern Army Selected Systems Test, Evaluation and Review, Fort Hood, Texas, 1976.

25. J. F. Brune and J. E. Reilly, "Compact HF Antenna (with Propagation Studies)," Research and Development Technical Report, ECOM-4366, U.S. Army Electronics Command, Avionics Laboratory, Fort Monmouth, New Jersey (November 1975).

26. G. H. Hagn, "On the Relative Response and Absolute Gain Toward the Zenith of HF Field-Expedient Antennas--Measured with an Ionospheric Sounder," IEEE Trans. Ant. and Prop., Vol. AP-21, No. 4, pp. 571-574 (July 1973).

Appendix A

RADIO SYSTEM PERFORMANCE MODEL AND COMMUNICATION RANGE ESTIMATES FOR HELICOPTERS FLYING NAP-OF-THE EARTH (NOE)

Appendix A

RADIO SYSTEM PERFORMANCE MODEL AND COMMUNICATION RANGE ESTIMATES FOR HELICOPTERS FLYING NAP-OF-THE EARTH (NOE)*

1. Introduction

a. The Concept of Communication Operational Range

One important measure of the tactical utility of a military radio is the operating range that can be achieved in the tactical environment. The current (10 W) airborne transceivers (AN/ARC-114) which were designed for line-of-sight (LOS) operation, do not achieve sufficient range while helicopters are flying nap-of-the-earth (NOE).[1†] Helicopters are driven to NOE altitudes (generally lower than 20 m and frequently as low as 3 m) to survive the physical[2] and electromagnetic[3] threats of the modern battlefield. This problem led to the current letter of agreement requesting a study of improved NOE communications.[4] The range a radio can achieve depends upon the radio system parameters (e.g., transmitter power), the loss of signal power resulting from propagation from the transmitter to the receiver, and the ambient radio noise and interference (or electronic warfare) environment in which the receiving antenna must operate. The operational requirements[5] and usage also influence the range. The loss attributable to propagation is not a deterministic quantity, nor is the ambient radio noise level. Therefore, the range of a radio is best treated as a random variable.[6-10] Also, the propagation, noise, and system performance models each have uncertainties that are best dealt with as random variables. We must consider the odds of achieving a given range with a given radio system operating in a given terrain and noise environment. This approach permits statistical combination of the uncertainties of the many parameters that enter into

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*By G. H. Hagn, contributions by B. C. Tupper.

†References are listed at the end of the Appendix.

prediction of system performance, including the statistical uncertainty in the model itself. One can compute the probability of successful communication, p_s, as a function of range for a given scenario (radio system, terrain, noise environment, operational usage), and, by specifying a required probability of successful communication (p_{sr}), then define the operational range (OR)[9] of the radio as that range at which $p_s = p_{sr}$. This approach is illustrated in the example of Figure A-1.

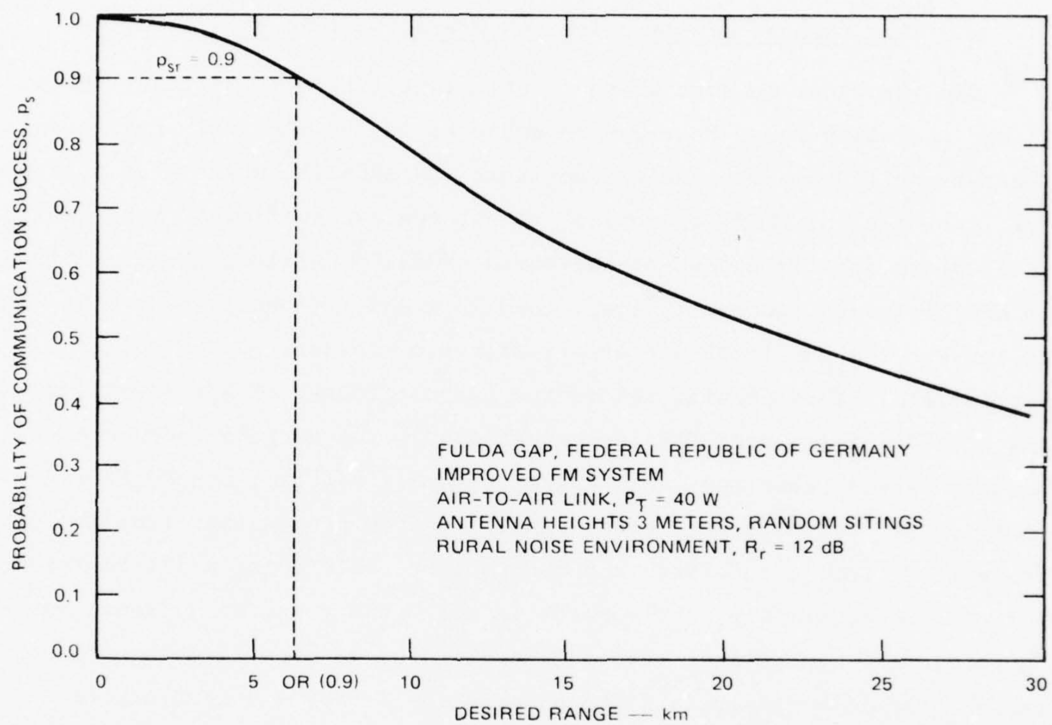

FIGURE A-1 EXAMPLE OF PROBABILITY OF SUCCESSFUL COMMUNICATION AS A FUNCTION OF RANGE AND OPERATIONAL RANGE

Let us now define our terms more precisely and then compute the range for the baseline (AN/ARC-114) and candidate NOE communication radio systems in selected example terrains of interest.

b. Definition of a Successful Communication

Simply stated, a communication success consists of achieving an adequate communication channel on an acceptable number of tries (i.e., an adequate percentage of the time) in the operational environment. The definition of adequate for each situation of interest must be specified by the user. For example, certain missions may require a first-try success probability of 0.9 (a communications channel established for 90 percent of the tries) with no repeats, whereas other missions may have lower operational reliability requirements. We can describe channel quality with a subjective rating scale (e.g., r3 = marginally acceptable, r4 = good, r5 = excellent, see Chapter III) or with an objective measure such as the minimum acceptable score (in percent correct) on a random character alphanumeric (A-N) test message of a specified duration. In each case, the rating or scoring should be done by listeners as representative as possible of the users for whom a system is being designed, and a representative vocabulary should be used.

c. General Method of Computing Probability of Successful Communication

We must begin by considering the required channel quality and relating it to something that we can measure (or compute). The degradation of both AM (SSB) and FM systems caused by band-limited Gaussian noise has received much attention and analytical solutions have been derived to relate the output signal-to-noise ratio (SNR) to the input (predetection) SNR.[11*] We can estimate the output SNR required to achieve the necessary channel quality and use a model of the receiver to relate this to a required input (predetection) SNR (R_r, in dB). Therefore, for the purposes of this study, a communication success is defined as achieving a predetection SNR $\geq R_r$ (and hence producing a communication channel of acceptable quality for a brief portion of an hour on any given communication attempt without moving).

Once R_r has been determined by consideration of user requirements and equipment characteristics, we must compute the probability that the

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*The degradation caused to such a system by random impulsive (or quasi-impulsive) noise is complex and difficult to treat analytically. It is a function of both the channel quality grade of interest and the noise statistics as well as the system parameters (e.g., modulation index).[12]

actual predetection SNR ≥ R_r in the operational environment of interest. Such a computation requires estimates of the expected values and variabilities of the received signal and noise. Models are needed for the propagation, the noise environment, and the radio system performance. Also needed are the expected values of the radio system parameters and their variabilities. There is uncertainty in both the propagation model accuracy, the noise model accuracy, the receiver system performance model accuracy, and in our knowledge of the radio system and environmental variables. These uncertainties must be quantified, combined in the correct manner, and used in our prediction of p_s.

In summary, we can compute, as a function of distance (d), the probability of a given candidate radio system achieving a given channel quality (r_i). This calculation is made for a given link (e.g., aircraft-to-aircraft), which includes specification of antenna heights. The result is a probability, $p_s(d, r_i)$, which can be compared to a required probability (p_{sr}) to estimate an operational range, OR, for a given link and for a required channel quality, r_i. This methodology is illustrated in Figure A-2.

2. User Requirements

a. General Comments

To predict operational range, the radio system user must specify his communication channel quality and reliability requirements. The geo-political environment (and the resulting military requirements it generates) leads to the specification of a geographical area of interest (latitude and longitude). Estimates are needed of the earth's electrical properties (dielectric constant and conductivity), the terrain roughness (interdecile range of elevations), and the height and type (density) of any vegetation. The season of the year and, in some cases, the time of day are needed. Also, the degree of urbanization (if any) should be specified. Certain operational information is required: antenna physical heights and type of siting (random, good site, excellent site), and whether the radio system must operate while in motion. Finally, the

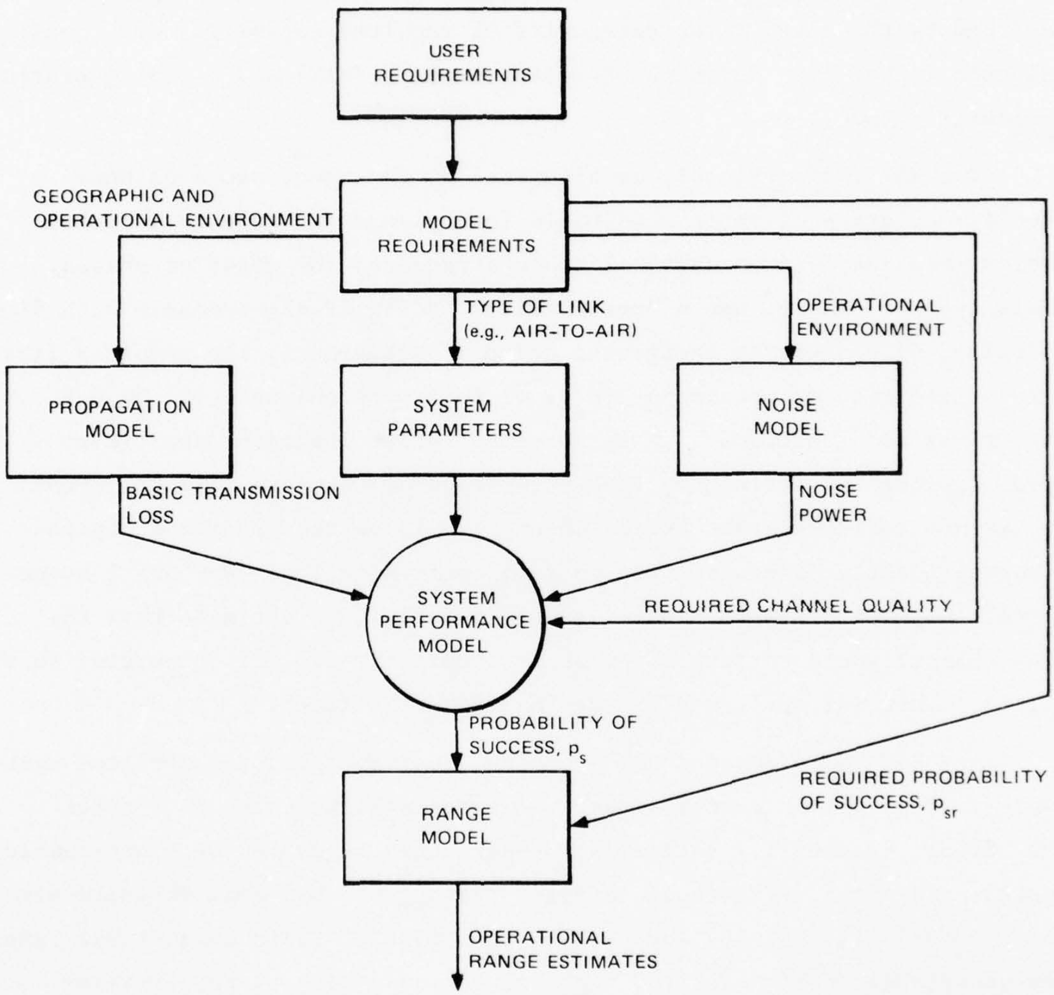


FIGURE A-2 METHODOLOGY FOR ESTIMATING OPERATIONAL RANGE (OR) user must specify the required channel quality (r_i) and the required probability of successful communication (p_{sr}).

b. Required Operational Capability

The required operational capability for NOE communication has been defined by the user.[5] Two categories of required capability were considered in Ref. 5: a minimum acceptable value (MAV) and a best operating capability (BOC).

The MAV radio channel, as specified by the user, has a channel quality or grade of service suitable for two-way interactive tactical voice messages, with occasional repeats required for words or phases. This type of channel has a "readability" rating of r3--readable with difficulty, with annoying background noise. Furthermore, the required first-try probability of occurrence (p_{sr}) of this type channel will be 0.9 for all times and locations.[5] A three-member pilot listener panel (Fort Ord, California) evaluating tape recordings of channels with different r_i values indicated that the r3 channel would be the minimum acceptable channel quality (adequate) for tactical communication. For our listener panel test results with sample message material, we estimate that the MAV channel would correspond to an A-N score (FM-320) of 90 percent in the field. This was confirmed by the FM-320 Test Officer.[13]

The BOC radio channel has a channel quality (grade of service) suitable for two-way interactive tactical voice messages with no repeats required. Readability rating is r4--perfectly readable, with noticeable background noise. The required first-try p_{sr} of this channel would also be 0.9 for all times and locations. This type of radio channel was rated as acceptable (desirable) for tactical communication by the listener panel. We estimate that the BOC channel would correspond to A-N scores of greater than 90 percent in the field. Table A-1 summarizes the MAV and BOC channel qualities.

The required antenna siting is assumed to be random for the helicopters and good (hillsides) for the ground stations.[14] Ground-based retransmission sites are assumed to be excellent (hilltops).

Table A-1

REQUIRED OPERATIONAL CAPABILITY

Level of Requirement	r_i	p_{sr}	Repeats	A-N Score
Minimum Acceptable Value, MAV	r3	0.9	yes	≈90%
Best Operating Capability, BOC	r4	0.9	no	>90%

A rural environment is assumed for environmental radio noise (see Section 5).

3. Radio System Performance Model

Consider first the flow of the RF power of the desired signal from the transmitter to the receiver depicted in Figure A-3. We can write the following equation for P_R:

$$P_R(d) = P_T - L_T + G_T - L_b(d) + G_R - L_R$$

where

P_R = received power (dBm)

P_T = transmitter power (dBm)

$L_{T,R}$ = insertion loss of transmission line and antenna coupler (including mismatch loss, if any) for transmitter and receiver, respectively (dB)

$G_{T,R}$ = antenna gain for the transmitting and receiving antennas, respectively (dB relative to an isotropic radiator, or dBi)

L_b = basic transmission loss (dB).

The basic transmission loss (L_b) is defined as the loss between isotropic antennas located at the same physical locations as the actual antennas. This loss is a function of several variables including range d between the antennas, antenna heights, electrical properties of the ground,

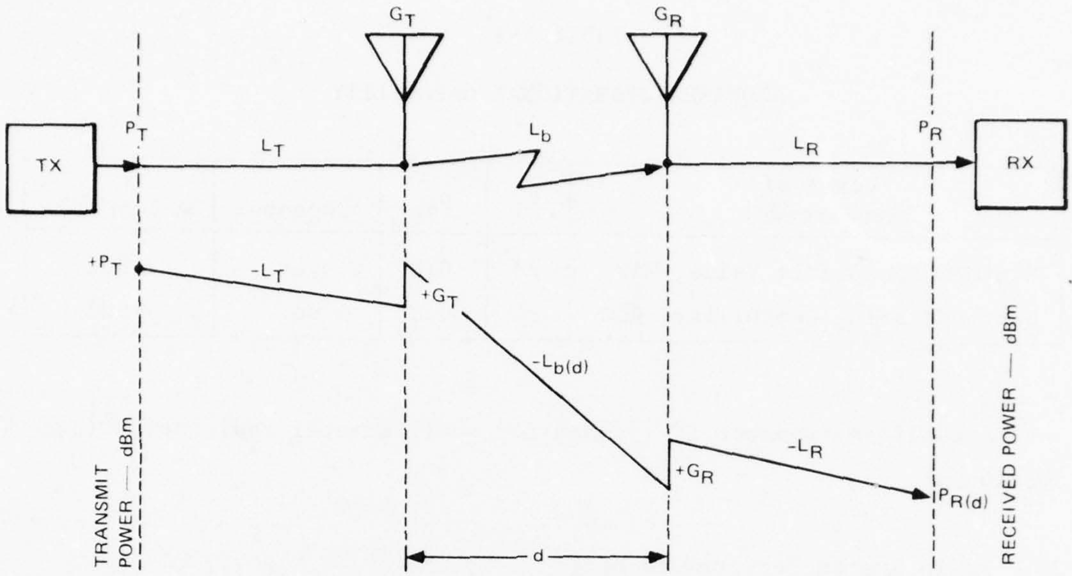


FIGURE A-3 POWER FLOW DIAGRAM FROM TRANSMITTER TO RECEIVER

terrain roughness, degree of vegetation, presence of buildings, and the refractive index of the air.

The expected value of L_b and its variabilities are predicted by the propagation model.[14] The radio system properties are represented in Eq. (A-1) by P_T, L_T, G_T, G_R, and L_R. For a given system, they can be considered to be random variables with expected values (written $\langle\ \rangle$) and variances (σ^2).

It is possible to define a system margin, M (in dB), that is a function of range, d, for a given system, environment and operational deployment:

$$M(d) = SNR(d) - R_r = S(d) - N - R_r \quad ,$$

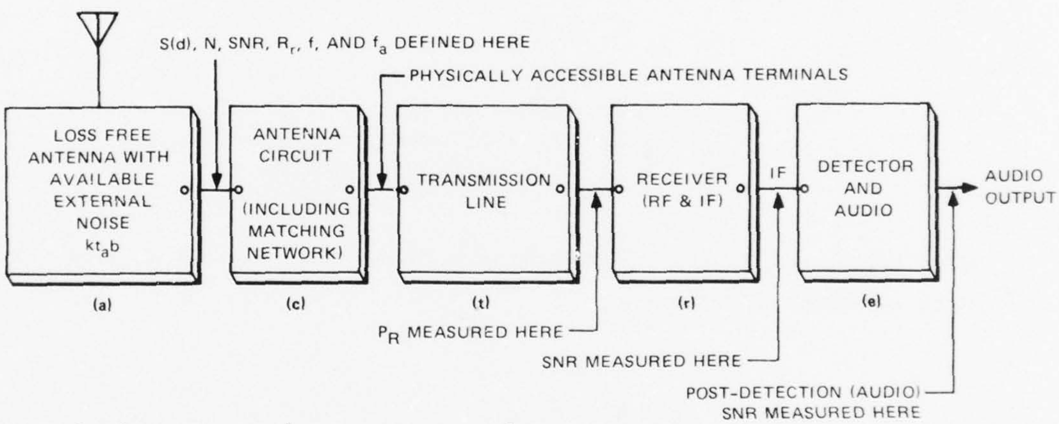
where

SNR(d) = predetection signal-to-noise ratio at distance d.

S(d) = signal power (in dBm) available from the terminals of a receiving antenna, identical to the actual antenna except that it has no losses (see Figure A-4), located at d km from the transmitting antenna.

N = available system overall noise power (in dBm) referred to the same point in the system as S(d).

R_r = required predetection SNR (dB).



$\ell_a = 1$ $\quad \ell_c$ $\quad \ell_t$

t_a $\quad t_c$ $\quad t_t$ $\quad f_r$

$f_a = t_a/t_o$ $\quad f_c = 1 + (\ell_c - 1)(t_c/t_o)$ $\quad f_t = 1 + (\ell_t - 1)(t_t/t_o)$

$f = f_a + (\ell_c - 1)(t_c/t_o) + \ell_c(\ell_t - 1)(t_t/t_o) + \ell_c\ell_t(f_r - 1) =$ system overall operating noise factor

$f = f_a - 1 + \ell_c\ell_t f_r$, when $t_c = t_t = t_o$

FIGURE A-4 RECEIVER BLOCK DIAGRAM AND OVERALL SYSTEM OPERATING NOISE FIGURE

We can assume that an adequate channel for the desired signal is achieved in the absence of undesired signals (including jammers) when $S(d) - N \geq R_r$. We want to compute p_s: the probability that $M(d) \geq 0$ dB.

The expected value of the margin can be computed from the expected values of S(d), N and R_r:

$$\langle M(d)\rangle = \langle S(d)\rangle - \langle N\rangle - \langle R_r\rangle \quad .$$

Let us assume that S(d), N, and R_r can each be described as independent Gaussian random variables with expected values (means, equal to medians for this distribution) as stated above and standard deviations σ_S, σ_N, and σ_{R_r}, respectively. We can now define a new zero-mean Gaussian random variable, which we can use to compute p_s:

$$Z_o(p_s) = \frac{M(d) - \langle M(d)\rangle}{\sigma_M} \quad ,$$

where

$$\sigma_M = \sqrt{\sigma_S^2 + \sigma_N^2 + \sigma_{R_r}^2 + \sigma_Q^2} \quad .$$

The model uncertainty can be treated as a zero-mean Gaussian random variable with standard deviation σ_Q:

$$\sigma_Q = \sqrt{\sigma_c^2 + \sigma_n^2 + \sigma_r^2} \quad ,$$

where σ_c is the standard deviation of the uncertainty of the propagation model, σ_n is the analogous value for the noise model, and σ_r is the uncertainty in the model for the required channel quality (r_i). Now, we can compute $p_s(d, r_i) = \text{prob}[M(d, r_i) \geq 0] = 0.5 + 0.5\ \text{erfc}(Z_o/\sqrt{2})$, where erfc = error function complement.[15] $Z_o(p_{sr})$ for selected p_{sr} values of interest are summarized:

p_{sr}	0.5	0.7	0.75	0.8	0.85	0.9	0.95	0.99
$Z_o(p_{sr})$	0.000	0.526	0.675	0.842	1.037	1.282	1.645	2.326

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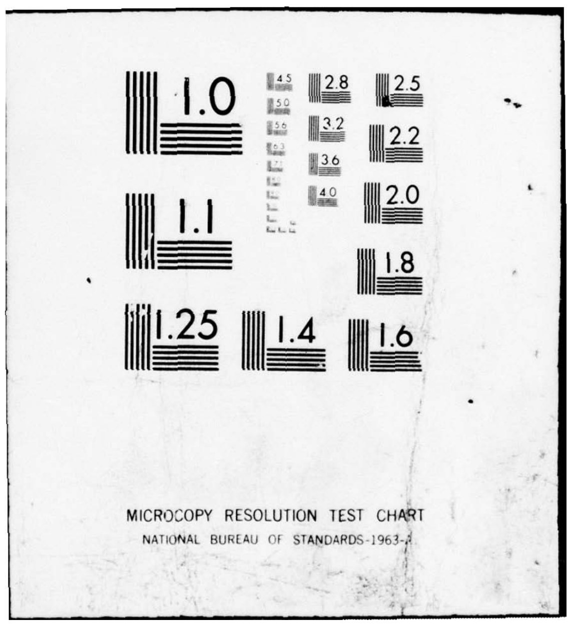
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We must now derive the components of σ_M. The standard deviation of the signal, σ_s, is:

$$\sigma_S = \sqrt{\sigma_{P_T}^2 + \sigma_{L_T}^2 + \sigma_{G_T}^2 + \sigma_p^2 + \sigma_{G_R}^2 + \sigma_{L_C}^2} \quad \text{(dB)},$$

where

σ_{P_T} = standard deviation of the transmitter power (dB).

σ_{L_T} = standard deviation of the transmission line loss (including mismatch loss variability) (dB).

$\sigma_{G_{T,R}}$ = standard deviation of the antenna gain for the transmitter (T) and receiver (R) (dB).

σ_p = standard deviation of the basic transmission loss (dB).

σ_{L_C} = standard deviation of the antenna circuit loss (dB).

The standard deviation of the propagation, σ_p is given by:

$$\sigma_p = \sqrt{\sigma_T^2 + \sigma_L^2 + \sigma_V^2} \quad \text{(dB)},$$

where

σ_T = standard deviation of the time variability of the desired signal (long-term fading) (dB).

σ_L = standard deviation of the location variability (dB).

σ_V = standard deviation of vegetation loss, when present (dB).

The Longley-Rice propagation model[14] provides estimates of σ_L and σ_T. A value of 2.4 dB is assumed for σ_V.[16]

When the external (environmental) noise from the antenna greatly exceeds internal radio set noise, the standard deviation of the overall system noise referred to the equivalent lossless antenna terminals can be estimated by assuming independent time and location variabilities:

$$\sigma_N = \sqrt{\sigma_{NL}^2 + \sigma_{NT}^2} \quad \text{(dB)},$$

where

σ_{NL} = standard deviation of the location variability of the noise (dB).

σ_{NT} = standard deviation of the time variability of the noise (dB).

The noise model provides estimates of σ_N for selected environments.

There is variability in R_r because of the difficulty in estimating exactly the required predetection SNR. First, there is variability in R_r because of the spread of channel quality values obtained from a listener panel hearing the same vocabulary at the same audio SNR. Second, there is variability at the same audio SNR for different vocabularies that may be of interest. These effects are accounted for by a zero-mean Gaussian distribution of R_r with a standard deviation σ_{R_r} = 1.5 dB. There is also an uncertainty in the model itself regarding relating the proper value of R_r to the required channel quality, r_i; this is described in a similar manner with σ_r = 1.5 dB.

Next, let us consider the receiving system in greater detail (see Figure A-4). We can define an overall receiving system operating noise factor f, such that the average noise power of the system, n, referred to the terminals of the equivalent loss-free antenna is given by:[17]

$n = fkt_o b$, average noise power (in W) of system referred to the output of block (a). $N = 30 + 10 \log_{10} n$ is the operating system noise power (dBm).

f = system overall operating noise factor.

k = Boltzmann's constant = 1.38×10^{-23} J/K.

t_o = the reference temperature in K, taken as 288 K.

b = the noise power bandwidth of the receiving system (Hz).

The other terms used in Figure A-4 are defined:

ℓ_a = the "loss-free" antenna loss factor ($\ell_a \triangleq 1$).

t_a = the effective antenna temperature (K).

f_a = the antenna external noise factor ($F_a = 10 \log_{10} f_a$ = the antenna external noise figure).

ℓ_c = the antenna circuit loss factor (power available from lossless antenna/power available from actual antenna).

t_c = the actual temperature (K) of the antenna and nearby ground.

f_c = the antenna circuit noise factor.

ℓ_t = the transmission line loss factor (available input power/ available output power).

t_t = the actual temperature (K) of the transmission line.

f_t = the transmission line noise factor.

f_r = the noise factor of the receiver ($F_r = 10 \log f_r$ = noise figure in dB).

$B = 10 \log_{10} b$ = effective receiver noise power bandwidth, in dB(1 Hz) = power available in a 1-Hz band from a resistor at temperature t_o.

The noise power must be expressed at the same point in the receiving system as the signal power and R_r for use in the margin equation. It is necessary to refer N to the terminals of an equivalent lossless antenna.[17] From Figure A-4 let us now define:

$$L_C = 10 \log_{10} \ell_c$$

$$L_R = 10 \log_{10} \ell_t \quad .$$

For electrically short, lossless dipole antennas in free space, the maximum antenna gain is +1.76 dB relative to an isotropic radiator (dBi). For a halfwave dipole this value is +2.15 dBi. The maximum gain for a VHF helicopter antenna with no losses or significant pattern perturbations is approximately +2 dBi. Therefore, we can estimate the antenna circuit loss for our helicopter antennas as

$$L_C \cong 2.0 - G_R \quad ,$$

where G_R is an estimate of the actual antenna gain relative to an isotropic antenna at the input to the matching circuit (i.e., the physically accessible antenna terminals).*

It is now possible to solve for margin, M(d), in terms of the system, noise, and propagation variables. Let us now combine the equations for S(d), L_C, N, and R_r to specify M(d):

$$M(d) = P_T - L_T + G_T - L_b(d) + G_R + L_C - F - B + 174 - R_r \quad ,$$

$$M(d) \cong P_T - L_T + G_T - L_b(d) - F - B - R_r + 176 \quad .$$

The expected value of M(d) is the algebraic sum of the expected values of the random variables P_T, L_T, and so on. The propagation, environmental radio noise, and receiver models are described in the following section.

4. Propagation Considerations

The basic transmission loss, L_b, is the loss term that is a function of range. The Longley-Rice model[14] predicts the "local median" value of L_b in the band 20 MHz to 10 GHz for the case where there are no buildings

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*In Figure A-4 we have defined the antenna circuit block to include the matching circuit losses as well as any losses in the antenna itself. This corresponds to the case of the tailfin (FM-1) antenna on an OH-58, where the matching circuit is inaccessible (embedded in the vertical stabilizer).

or significant vegetation in the immediate vicinity of the antennas. The model also provides a prediction of the variability of this local median with time (σ_T) and with location (σ_L). An estimate of the model prediction uncertainty (σ_c) is also given. Propagation data indicate that the statistical distribution of the local median (in dB) at a given range in irregular terrain can be presented by a Gaussian distribution.[18-20]

For small changes in range of several wavelengths, $\lambda(\lambda = 10$ m at 30 MHz and 3.95 m at 76 MHz) in irregular terrain, the received signal can vary about the local medial value because of multipath.[20-22] The received signal fading (in μV) below the local median owing to multipath propagation has been described by the Rayleigh distribution (see Figure A-5 for a plot of this distribution).[15,18-25] This rapid fading (for a mobile system moving over relatively short distances through irregular terrain) is not included in the L_b values predicted by the Longley-Rice model.

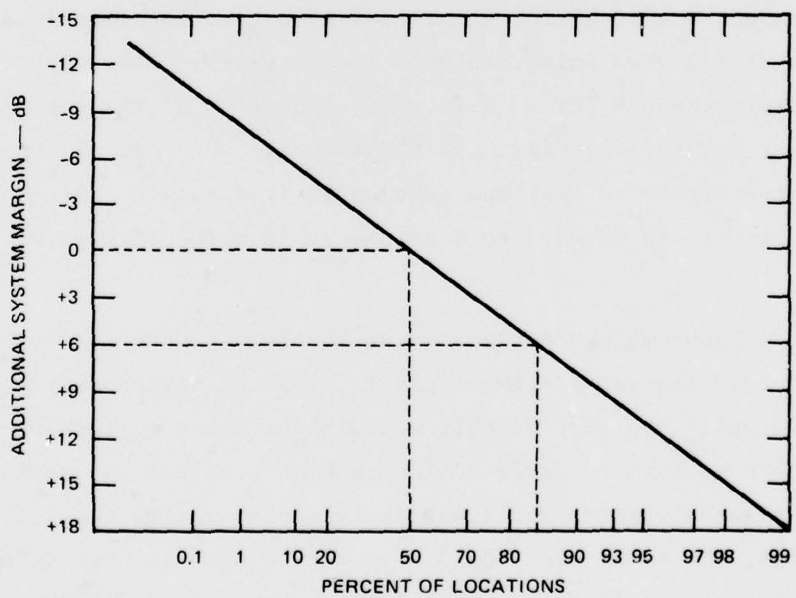

FIGURE A-5 RAYLEIGH DISTRIBUTION: ADDITIONAL SYSTEM MARGIN AS A FUNCTION OF PERCENTAGE OF LOCATIONS COVERED

Increasing system margin 6 dB picks up about 85 percent of the locations when performance is marginal for median L_b; 8.2 dB picks up 90 percent.

Some authors have considered superimposing the log-normal and Rayleigh distributions to account for the variation of the local median basic transmission loss and short-distance variations about the local median.[26] However, it is more convenient to use the Gaussian distribution for the variation of the local median L_b and to compensate for the Rayleigh fading by increasing R_r sufficiently to account for the percentage of nearby locations for which fading protection is required. Commercial designers of land mobile systems in the U.S. use this latter approach and typically allow 6 to 10 dB more system margin to account for this effect,[26,27] depending on the frequency band (6 dB in the band of interest to us) and quality of the channel required (also see p. 308 of Ref. 22).

The effect of this fading on FM communication depends on the fade rate and duration statistics, as well as on the fade amplitude statistics. Since fading results from the motion of the helicopter(s) through the multipath-caused spatial wave-interference pattern, both fade rate and fade duration depend upon the velocity of the helicopter(s). As the helicopter(s) moves, the resulting signal fading causes interruptions of the voice transmission when noise captures the receiver. These interruptions produce a different subjective effect as a function of helicopter speed. At low speeds (typical of difficult NOE flight), the rate of the interruptions generally is not as important as their duration. At high speeds, the interruptions can be hard to distinguish from the effects of impulsive noise.

The only known method of decreasing the high probability of deep fades without increasing system margin is by using diversity reception. For the helicopter application this would require use of two (or more) antennas and some form of predetection combiner, unless two receivers are used. The simplest system would select the antenna with the best SNR; alternatively, the helicopter could move around over an area of several helicopter lengths while listening to the desired signal and pause to communicate in the location of highest received signal strength. This may not be operationally desirable or even possible.

Let us now return to our consideration of L_b, and consider the effects of foliage and buildings. Median basic transmission loss, $L_b(d)$, must also be increased for the effects of foliage and buildings in the vicinity of the transmitting or receiving antennas. Although these effects are small compared to $L_b(d)$, they can affect operational range. The median vegetation loss factor is a function of frequency and polarization.[22] The median urban area loss (i.e., the loss that results from operation in a built-up area) is also a function of frequency and distance.[22,28,37] It is possible to modify the predicted median basic transmission loss with additive terms (in dB) to account for these effects (when present):

$$\langle L_b(d) \rangle = [L_{bLR}(d)] + V_v \cdot [V(f,p)] + V_u \cdot [U(f,d)], \text{ in dB},$$

where

$\langle L_{bLR}(d) \rangle$ = the Longley-Rice median value at distance d, in dB;

$\langle V(f,p) \rangle$ = vegetation loss factor as a function of frequency, f in MHz, and polarization, p(v or h), in dB; and

$$\langle U(f,d) \rangle = 16.5 + 15 \log_{10} \left[\frac{f_{MHz}}{100} - 0.12\, d_{(km)} \right],$$

= urban area loss factor, in dB.[37]

The variable V_v is equal to 1 if both terminals are in vegetation. The variable V_u is equal to 0 if both terminals are in open areas, 0.5 if one antenna is in an urban area, and 1 if both antennas are in urban areas. Only one of these factors (V_v, V_u) can apply to any given terminal.

For our case it was assumed that $V_u = 0$. Foliage was considered (e.g., $V_v > 0$) for antenna heights of 5 m or less. Relatively small values were used for foliage loss. The assumed foliage loss for vertical polarization V(f,v) was 1.1 dB at 35 MHz, 1.3 dB at 45 MHz, and 2.3 dB at 65 MHz. A σ_f = 2.4 dB was used as the estimate of standard deviation.[16]

5. Environmental Radio Noise Model (20-100 MHz)

To compute the predetection SNR and its variability, it is necessary to assume a model for the environmental radio noise. One practical approach to this problem is to assume that the military environment of interest is identical with one of the civilian environments for which the appropriate noise parameters have been measured. To predict the median SNR, we need the median antenna environmental noise figure, F_{am}. Data are available in the literature for the parameter F_{am} for rural, residential and business areas in the United States for the frequency band 250 kHz to 250 MHz.[29,30] The measured data were obtained using electrically short, vertically polarized antennas located near ground, and a least-squares fit was made to obtain an equation for F_{am} as a function of frequency. Data were obtained in 23 business areas, 38 residential areas, and 31 rural areas. The location variability of the median antenna noise for environments of the same category was expressed as a standard deviation, σ_{NL}, and the time variations during a one-hour period at a given location were given as upper and lower deciles (D_u and D_ℓ, in dB) referenced to the median. We would like to estimate an overall σ_N for the frequency band of interest, and assume the noise is described by a Gaussian distribution with mean = median = F_{am} and standard deviation σ_N. Let us assume independence of the time and location variability and define:

$$\sigma_N = \sqrt{\sigma_{NL}^2 + \sigma_{NT}^2} \quad \text{(dB)},$$

where

$$\sigma_{NT} \cong \frac{1}{1.28}\left(\frac{D_u^2 + D_\ell^2}{2}\right)^{1/2} \quad \text{(dB)}.$$

The measured data on variability (in dB) are summarized in Table A-2.

Table A-2

SUMMARY OF VARIABILITIES OF MAN-MADE NOISE

Frequency, $f_{(MHz)}$	Business					Residential					Rural				
	D_u	D_ℓ	σ_{NT}	σ_{NL}	σ_N	D_u	D_ℓ	σ_{NT}	σ_{NL}	σ_N	D_u	D_ℓ	σ_{NT}	σ_{NL}	σ_N
20	10.5	7.6	7.2	4.9	8.7	10.6	6.5	6.9	4.7	8.3	7.8	5.5	5.3	4.53	7.0
48	13.1	8.1	8.5	7.1	11.1	12.3	7.1	7.9	4.0	8.8	5.3	1.8	3.1	3.23	4.5
102	11.9	5.7	7.3	8.8	11.4	12.5	4.8	7.4	2.7	7.9	10.5	3.1	5.9	3.82	7.0

For the purposes of this analysis, we assumed that the noise environment of a helicopter or jeep deployed in the field would be best approximated by the rural noise environment, with $F_{am} = -27.7 \log_{10} f_{MHz} + 67.2$ dB, and $\sigma_N = 7.0$ dB, where the standard deviation is assumed to be independent of frequency in the band 20 to 100 MHz.*

It is possible to define an additional uncertainty to the noise model to describe the uncertainty in model accuracy (from the standpoint of our assumption of the match between our military antenna/environment and the civilian antenna/environment for which we have data). We can describe this uncertainty as a zero-mean Gaussian random variable with standard deviation σ_n. For the purposes of this study, we assumed $\sigma_n = 2.5$ dB.

For completeness, it is noted that the SINCGARS TOD assumed the following environmental noise values: $F_{am} = 25$ dB at 30 MHz, 17 dB at 50 MHz, and 12 dB at 80 MHz.[32] These values, based upon measurements at a rural field site at Wayside, New Jersey (near Fort Monmouth), agree reasonably well (within 3 dB) with our values of 26.3 dB, 20.1 dB, and 14.5 dB, respectively (see Figure A-6). Also shown for comparison in

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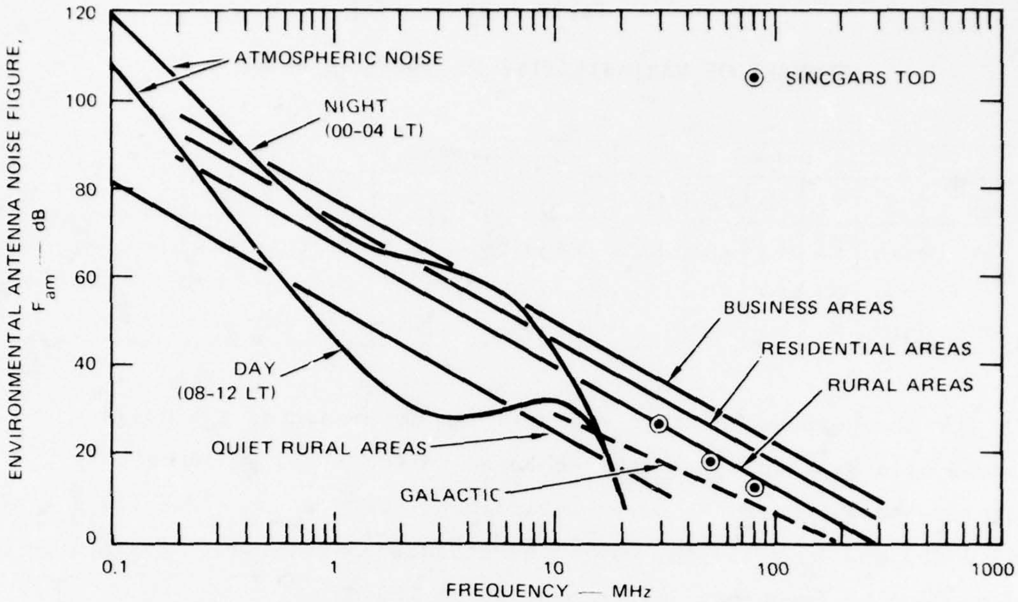
*The base station noise environment can be approximated by the rural case for small bases and by the residential case for larger bases, with $F_{am} = -27.7 \log_{10} f_{MHz} + 72.5$ dB and $\sigma_N = 8.3$ dB. For analysis purposes, a best-case noise environment is established by the presence of galactic noise, with $F_{am} = -23.0 \log_{10} f_{MHz} + 52.0$ dB and $\sigma_N = 1.5$ dB.[31] For a worst-case analysis, we can use the business portion of an urban area, where we can assume $F_{am} = -27.7 \log_{10} f_{MHz} + 76.8$ dB and $\sigma_N = 10.4$ dB.



SOURCE: CCIR Reports 258 and 322, SINCGARS TOD

FIGURE A-6 ESTIMATES OF MEDIAN VALUES OF MAN-MADE, ATMOSPHERIC, AND GALACTIC NOISE EXPECTED NEAR FULDA, FEDERAL REPUBLIC OF GERMANY, SUMMER

Figure A-6 are day and night values of atmospheric noise during summer for the Fulda Gap area of the Federal Republic of Germany.[31] Rural noise exceeds atmospheric noise during day and night for frequencies above 20 MHz, and for this reason it was used in the analysis.

It should be noted that cochannel (other user) interference also limits the performance of tactical radios, in the field, and intentional interference (jamming) can have catastrophic effects. Both of these effects are outside the scope of this appendix, and not considered here. The effects of jamming were considered in the SCORES effectiveness analysis (e.g., see Table 16).

6. Description of the Radio System

Three candidate VHF/FM aircraft systems were modeled using the prediction program. These were Baseline (AN/ARC-114), Improved FM tested at Fort Hood (IFM--Hood), and Improved FM Best Technical Approach (IFM--BTA).[39] The ground system used for each of these candidates was the AN/VRC-46

(RT-524), with a RC-292 vertical antenna mounted on a 10-m mast and fed by 30.5 m of RG-8 coaxial cable. A ground retransmission system was also considered (the AN/VRC-49). Three modern HF radios with transmitter powers of 40, 100, and 200 W (PEP) were analyzed for groundwave transmission at 25 MHz. These systems are described in greater detail in the remainder of this section.

a. AN/ARC-114 System (FM Baseline--Aircraft)

The AN/ARC-114 technical characteristics are summarized in Table A-3.

Table A-3

AN/ARC-114 TECHNICAL CHARACTERISTICS

Parameter	Value
Receiver sensitivity (for audio (S+N)/N = 10 dB)	0.6 μV open circuit--117.4 dBm (see also screen room data in Figure A-7)
Peak deviations, Δf	8 kHz, but adjustable 4 to 12 kHz
Modulating frequency, f_m	3.6 kHz
Modulation index, m	2.2
IF bandwidth	3 dB ≅ 20 kHz, 6 dB = 30 kHz, 60 dB = 60 kHz
Noise power bandwidth, b	25 kHz (estimated)
Noise figure	7 dB ± 1 dB
Transmitter power	+40 dBm (nominal)

We have measured the alphanumeric (A-N) score for the AN/ARC-114 in the screen room as a function of P_R in dBm. The results are given as Figure A-7. We can select a required A-N score and determine P_{rmin} (screen room) from Figure A-7. Had we had a relationship between A-N score and audio SNR, then we would have needed the relationship between

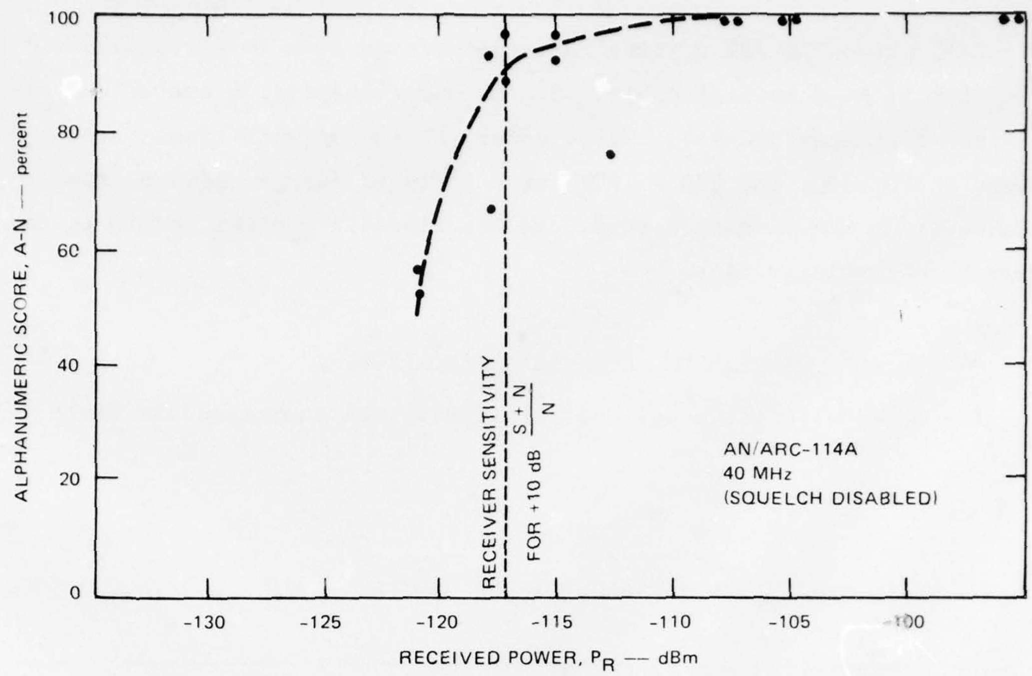


FIGURE A-7 ALPHANUMERIC SCORE AS A FUNCTION OF RECEIVED POWER IN SCREEN ROOM

postdetection SNR and predetection SNR given in Figure A-8. Note that a 10-dB audio SNR corresponds to a predetection SNR of about 6 dB. If we allow another 6 dB to account for multipath effects (see Section 4), then $R_r \cong 12$ dB for a marginal (r3) channel for the AN/ARC-114. We will consider this our minimum acceptable value (MAV). This would correspond to an A-N score of about 90 percent. Our best operating capability (BOC) of >90 percent A-N score for a good (r4) channel would require an $R_r \cong 16$ dB for mobile operation. Here we have assumed that the environmental noise affects the receiver to the same degree as Gaussian noise with the same average power. The assumption is exactly correct for galactic noise. This assumption is the best one we can make for channel qualities similar to those achieved just above squelch break (10 dB audio SNR), but it is not valid for high-quality channels (r4 or r5) affected by impulsive noise.

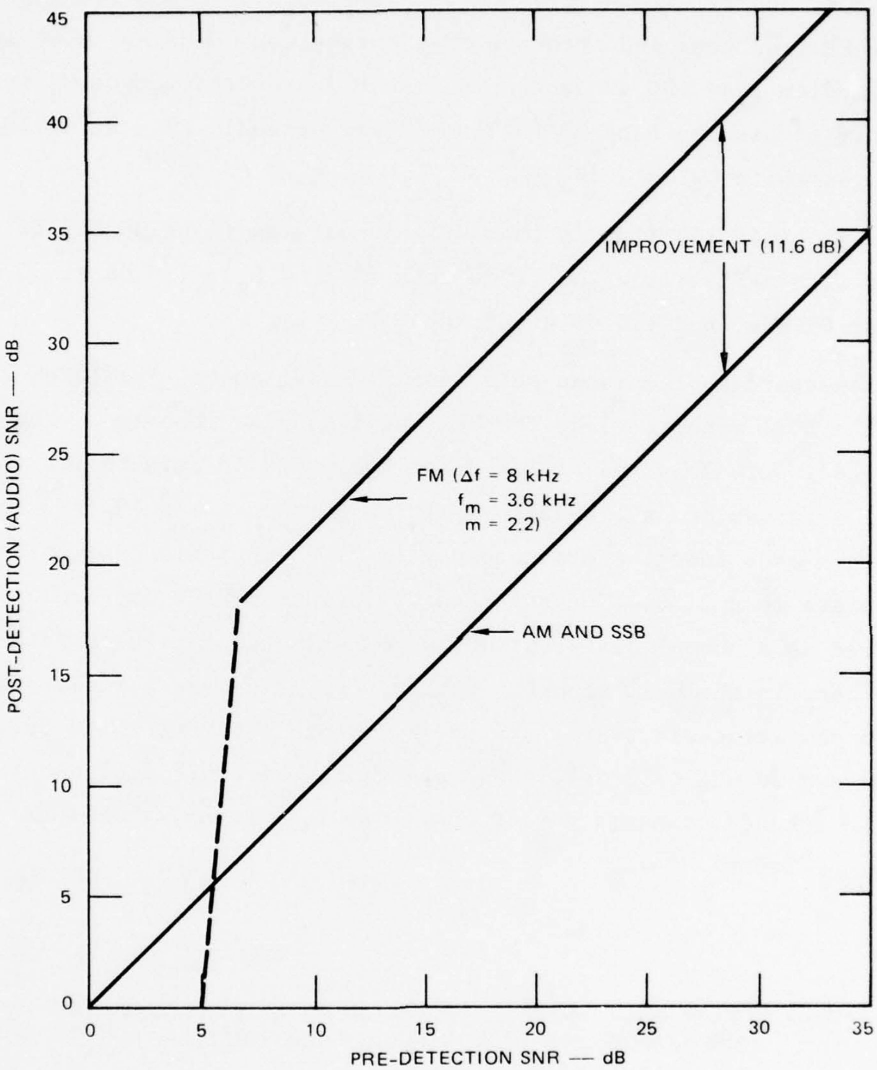


FIGURE A-8 PREDETECTION VERSUS POSTDETECTION SIGNAL-TO-NOISE RATIOS FOR AN/ARC-114 AND AM/SSB AIRCRAFT RADIO SYSTEMS (WITH GAUSSIAN NOISE)

Let us now consider the median values and distributions of P_T, L_T, G_T, G_R, and L_R for the baseline system consisting of the AN/ARC-114 and the FM-1 (tailfin) antenna for the OH-58 helicopter.

Measurements made at NAS Lakehurst, New Jersey by G. H. Hagn, J. V. Brune, and F. M. Cansler in April 1977 on two AN/ARC-114s operating into the FM-1 antenna and into the FM-2 antenna on OH-58 No. 6806 indicated a median P_T = +39 dBm and a σ_{P_T} = 1.8 dB resulting from P_T variations only across the band 30 to 75 MHz (see Appendix F). We will assume P_T = +40 dBm with σ_{P_T} = 2 dB.

The transmission line in the OH-58 is assumed to be 30 ft (9.1 m) of RG-58 with a flat-line insertion loss of $L_T = L_R$ = 1.0 dB at 35 MHz, 1.1 dB at 45 MHz, and 1.4 dB at 65 MHz.

Three sources of antenna gain data are available: The Lakehurst tests, the Bell report,[33] and the McDonnell-Douglas report.[34] The antenna gains in dBi were measured at Lakehurst every 30° in azimuth for the FM-1 and FM-2 antennas on the OH-58 for skid heights of 1 and 10 ft. The median gain as a function of frequency is given in Table A-4; these values are accurate to ± 2 dB. The standard deviations of the pattern nulls, considered as a normal distribution, were estimated for these data and for the data in the Bell report. The average value was 1.9 dB. The standard deviation was typically 1.5 dB except in the vicinity of 30 MHz (2.5 dB) and 60 MHz (3.5 dB), where presumably aircraft resonances provided the greater standard deviations. For this study we will assume $\sigma_{GT} = \sigma_{GR}$ = 2.0 dB.

Table A-4

MEASURED MEDIAN GAIN (IN dBi) OF OH-58 TAILFIN ANTENNA (FM-1) AND COMPARISON WITH SINCGARS ASSUMPTIONS

Measurement	Frequency (MHz)					
	30	40	50	60	70	80
FM-1	-19.4	-14.3	-7.9	-1.7	-7.4	n.d.
SINCGARS TOD (AS-1703/AR)	-4.0	n.d.	0.0	n.d.	n.d.	-4.0

n.d. = no data.

Table A-5 gives the median values and standard deviation for transmitter power (P_T), antenna gain (G_T, G_R), and transmission line and mismatch loss (L_T, L_R) at three frequencies for the AN/ARC-114 baseline radio. Effective radiated power (ERP) for this system is given from:

$$ERP = P_T - L_T + G_T \quad \text{(dBm)}.$$

These equipment values were used to predict the probability of successful communications, p_s, at range d using the model.

Table A-5

AN/ARC-114 SYSTEM PARAMETERS

Frequency (MHz)	P_T		σ_{PT} (dB)	L_T, L_R (dB)	σ_{L_T} (dB)	G_T, G_R (dBi)	$\sigma_{G_{T,R}}$ (dB)	ERP (dBm)
	(W)	(dBm)						
35	10	40	2	1.0	1.5	-16	2	23.0
45	10	40	2	1.1	1.5	-10	2	26.9
65	10	40	2	1.4	1.5	-4	2	34.6

b. AN/VRC-46 System (FM Baseline--Ground)

The standard Army AN/VRC-46 radio was used as the ground radio for all FM systems evaluated. This system consists of an RT-524 receiver/transmitter operating into an RC-292 elevated, vertically polarized monopole antenna with three ground radials. A 10-m ($\approx$ 30 ft) mast was used. An antenna gain of 0 dBi was assumed, and the antenna also was assumed to have an omnidirectional pattern (σ_{GT} = 1 dB). For the ground radio it was assumed that 100 ft of RG-8 (or equivalent) coaxial cable connected the transceiver to the antenna. RT-524 operation was assumed to operate in the high-power (40 W) mode. Table A-6 summarizes this system's median values and assumed standard deviations.

Table A-6

AN/VRC-46 SYSTEM PARAMETERS

Frequency (MHz)	P_T (W)	P_T (dBm)	σ_{PT} (dB)	L_T, L_R (dB)	$\sigma_{L_{T,R}}$ (dB)	G_T, G_R (dBi)	$\sigma_{G_{T,R}}$ (dB)	ERP (dBm)
35	40	46	1.3	1.2	1.5	0	1	44.8
45	40	46	1.3	1.3	1.5	0	1	44.7
65	40	46	1.3	1.7	1.5	0	1	44.3

c. Fort Hood Improved FM (IFM--Hood)

The Fort Hood Improved FM (IFM--Hood) was tested at Fort Hood, Texas during the TCATA FM-320 NOE Communication test (October-December 1976).[38] The system consisted of the AN/ARC-114 transceiver and 40-W broadband amplifier. The amplifier was connected to the tail fin (FM-1) antenna of the OH-58 aircraft. The aircraft antenna is a broadband, folded radiator enclosed as an integral part of the vertical stabilizer.[33] Table A-7 summarizes this system's median values and assumed standard deviations.

Table A-7

IFM--HOOD SYSTEM PARAMETERS

Frequency (MHz)	P_T (W)	P_T (dBm)	σ_{PT} (dB)	L_T, L_R (dB)	$\sigma_{L_{T,R}}$ (dB)	G_T, G_R (dBi)	$\sigma_{G_{T,R}}$ (dB)	ERP (dBm)
35	40	46	2	1.0	1.5	-16	2	29.0
45	40	46	2	1.1	1.5	-10	2	34.9
65	40	46	2	1.4	1.5	-4	2	40.6

d. Improved FM--Best Technical Approach (IFM--BTA)

The Improved FM--Best Technical Approach (IFM--BTA) system was designed by the U.S. Army Avionics R&D Activity, Fort Monmouth, New Jersey after review of laboratory and field test results, study of VHF/FM system components, and limited discussions with industry.[39] The system design parameters are engineering estimates for a VHF/FM system achievable within technical constraints. Major technical constraints are transmitter power limitations and aircraft antenna gain.

This system uses an AN/ARC-114 transceiver operating into a nominal 40-W broadband amplifier. Amplification is selective by frequency band with greater than 40 W of power provided in the 30 to 40 MHz portion of the spectrum to compensate for antenna inefficiency. The amplifier would be matched to an optimum low-impedance feed point of a Contractor-Furnished Equipment (CFE) aircraft antenna (or, alternatively, a new antenna). The design goal for the amplifier and antenna system was to achieve 40-W effective radiated power (ERP) to establish communication parity with the ground VHF/FM radio. For the prediction analysis, the tailfin (FM-1) antenna on the OH-58 aircraft (modified to provide better impedance matching) was assumed. Table A-8 summarizes this system's median values and assumed standard deviation.

Table A-8

IFM--BTA SYSTEM PARAMETERS

Frequency (MHz)	P_T (W)	P_T (dBm)	σ_{PT} (dB)	L_T, L_R (dB)	$\sigma_{L_{T,R}}$ (dB)	G_T, G_R (dBi)	$\sigma_{G_{T,R}}$ (dB)	ERP (dBm)
35	80	49	2	1.0	1.5	-10	2	38.0
45	40	46	2	1.1	1.5	-3	2	41.9
65	40	46	2	1.4	1.5	0	2	44.6

e. Retransmission (Ground)

The ground retransmission system was assumed to be an AN/VRC-49 equipped with a RC-292 antenna. The system characteristics are the same as those for the AN/VRC-46 (Table A-6). In the model, the ground antenna was sited under "excellent" conditions--on a hilltop or mountaintop, thereby increasing the effective height of the antenna. The effective height (h_{eff}) is determined by the structural height of the antenna (h), and the elevation of the intermediate foreground (h_{IF}), which is determined statistically for a given terrain.[14] For excellent siting,

$$h_{eff} = h + h_{IF} \quad .$$

The retransmission case was analyzed in the model for Fulda Gap terrain, having an interdecile range of 300 m. Three siting codes were used in the model--random siting (used for all aircraft), good siting (used for the ground stations), and excellent siting (used for the retransmission ground station). For Fulda terrain, these heights are given in Table A-9, for an RC-292 antenna (structural height of 10 m).

Table A-9

EFFECTIVE ANTENNA HEIGHTS FOR AIRCRAFT ANTENNAS AND RC-292 (10 m) GROUND ANTENNAS--FULDA TERRAIN

Siting	Code	Type of Station Used in Model	Antenna Effective Height (m)
Random	(0)	Aircraft	3.0
Good	(1)	Ground	14.7
Excellent	(2)	Retransmission	19.4

f. HF/SSB Radio Systems (Groundwave)

The performance of a modern, multipower HF/SSB aircraft radio operating in groundwave mode was analyzed using the model. HF/SSB radio specifications from a modern commercial design are given in Table A-10.

Table A-10

HF/SSB TECHNICAL CHARACTERISTICS

Parameter	Value
Receiver sensitivity for audio (S+N)/N = 10 dB	0.7 μV open circuit (-116.1 dBm--50 Ω)
IF bandwidth--6 dB point (kHz)	3.0
Noise power bandwidth, b (kHz)	2.8
Noise figure (dB)	7
Transmitter power, P_T (W PEP)	40, 100, 200
Transmitter speech processing gain (dB)	3-4

Groundwave performance at 25 MHz was analyzed using the model for three aircraft powers:

- System 1-- 40 W PEP with speech processing. This power could be used at intermediate ranges to minimize EW detection. This case was treated in the TOD.[35]
- System 2--100 W PEP with speech processing. This case corresponds to the AN/ARC-174 tested at Fort Hood (FM-320).[38]
- System 3--200 W PEP with speech processing. This case corresponds to the highest power output contained in the BTA. If a 3-dB improvement in power is assumed by virtue of speech processing, this case would correspond to the AN/ARC-102 (400 W, no speech processing) aircraft radio. This case was also treated in the TOD.[35]

The aircraft system consisted of the candidate HF/SSB system (System 1, 2, or 3) operating into the shorted-loop antenna (ECOM loop), on an OH-58 aircraft. Table A-11 summarizes the median values and assumed standard deviations, at 25 MHz. A large value of σ_{G_T} was assumed for the aircraft antenna because of azimuthal antenna pattern variations.[40]

The ground station used for the analysis was the AN/GRC-106 HF/SSB transceiver operating into a vehicular-mounted 15-ft whip antenna. The ground vehicle and antenna were assumed to have "good" siting. An effective antenna height of 3 m was used for the 15-ft whip. The ground station median values are also listed in Table A-11.

Table A-11

HF/SSB AIRCRAFT AND GROUND STATION SYSTEM PARAMETERS FOR GROUNDWAVE MODEL AT 25 MHz

System	P_T		σ_{P_T}	L_T, L_R	$\sigma_{L_{T,R}}$	G_T, G_R	$\sigma_{G_{T,R}}$	ERP
	(W)	(dBm)	(dB)	(dB)	(dB)	(dBi)	(dB)	(dBm)
1	40	46	2	1	1.5	-3	5	42
2	100	50	2	1	1.5	-3	5	46
3	200	53	2	1	1.5	-3	5	49
AN/GRC-106	400	56	2	1	1.5	0	1	55

7. Terrain Descriptions

Since the U.S. Army requires contingency plans for operation under differing geographic and climatic conditions, different locations were selected to evaluate candidate system radio performance. Locations were chosen for both operational and technical reasons. Technical performance of the radio systems will vary for terrain having different physical, electrophysical, and electromagnetic environments.[41] Five different terrain types originally were selected; however, only three were used in the analysis--Fort Hood, Fulda Region (Federal Republic of Germany), and Korea. These general locations were evaluated over an area occupied by a typical division to estimate the physical terrain characteristics. Ground constant estimates were obtained from the USA Mobility Equipment

R&D Center (MERDC), Fort Belvoir, Virginia.[42] The earth's surface refractive index, N_S, was obtained from Bean et al.[36] (N_S does not significantly affect propagation at frequencies below 100 MHz for low antenna heights and ranges less than 50 km.) A constant of N_S = 301 (typical of the continental temperate climate) was used for all test case terrains.

a. Fort Hood, Texas

Th Fort Hood site was chosen because it was the FM-320 test site and is hilly terrain. The Fort Hood operational area consists of 100- to 300-ft plateaus (estimated) rising from the surrounding terrain. The interdecile range is 90 m. The sparse vegetation is dominated by grasses, shrubs, and scrubby trees. Ground conductivity is good. The longest communication ranges (relative to the other terrains) were predicted for Fort Hood; the physical constants used are given in Table A-12.

Table A-12

ENVIRONMENTAL CONSTANTS FOR THREE TERRAINS

Location/Parameter	Frequency (MHz)			
	25	35	45	65
Fort Hood				
Interdecile range, Δh (m)	90	90	90	90
Conductivity, σ (mhos/m)	0.03	0.04	0.045	0.0595
Dielectric constant, ϵ_r	15.5	15.5	15.5	15.5
Fulda Gap				
Interdecile range, Δh (m)	300	300	300	300
Conductivity, σ (mhos/m)	0.01	0.012	0.013	0.0229
Dielectric constant, ϵ_r	9.5	9	8.8	8.2
Korea				
Interdecile range, Δh (m)	430	430	430	430
Conductivity, σ (mhos/m)	0.002	0.0028	0.0032	0.0044
Dielectric constant, ϵ_r	7	7	7	7

b. Fulda Gap, Federal Republic of Germany

The Fulda Gap site, in the general vicinity of the city of Fulda, was chosen because of its operational significance, and because the detailed SCORES scenario (Europe I Sequence 2A) was also run in this terrain. Fulda Gap is low, mountainous country consisting of ridges and valleys. The interdecile range is 300 m. The area is moderately foliated by both deciduous and evergreen trees, low undergrowth, and grasses. Ground conductivity is good. Communication ranges shorter than those for Fort Hood were predicted for Fulda; the physical constants are given in Table A-12.

c. Korea

An area in Korea (38°N, 127°E) was chosen for operational reasons; it is representative of moderately rugged mountains. The interdecile range is 430 m. The vegetation varies from wetland rice paddies to woods (brush wood). Earth conductivity varies, but is generally poor over most of the mountainous terrain. Communication ranges shorter than Fulda Gap were predicted for this terrain; the physical constants are given in Table A-12.

d. General Environmental Descriptors

Table A-13 gives a generalized terrain description for comparison with the test cases and relates ground descriptors to interdecile ranges.

8. Operational Range Estimates

a. Probability of successful communications, p_s, as a function of range was calculated from the model for three terrains--Fulda Gap, Fort Hood, and Korea. Example results are shown graphically in Figure A-9 for Fulda Gap, at 45 MHz, for air-to-air, air-to-ground, and ground-to-air links. Three VHF/FM systems are plotted in each graph--Baseline (AN/ARC-114), IFM--Hood, and IFM--BTA. The ordinate of each plate is the probability of successful communications, p_s for a 45-MHz link. For example, consider the IFM--BTA system operating in an air-to-air link,

Table A-13

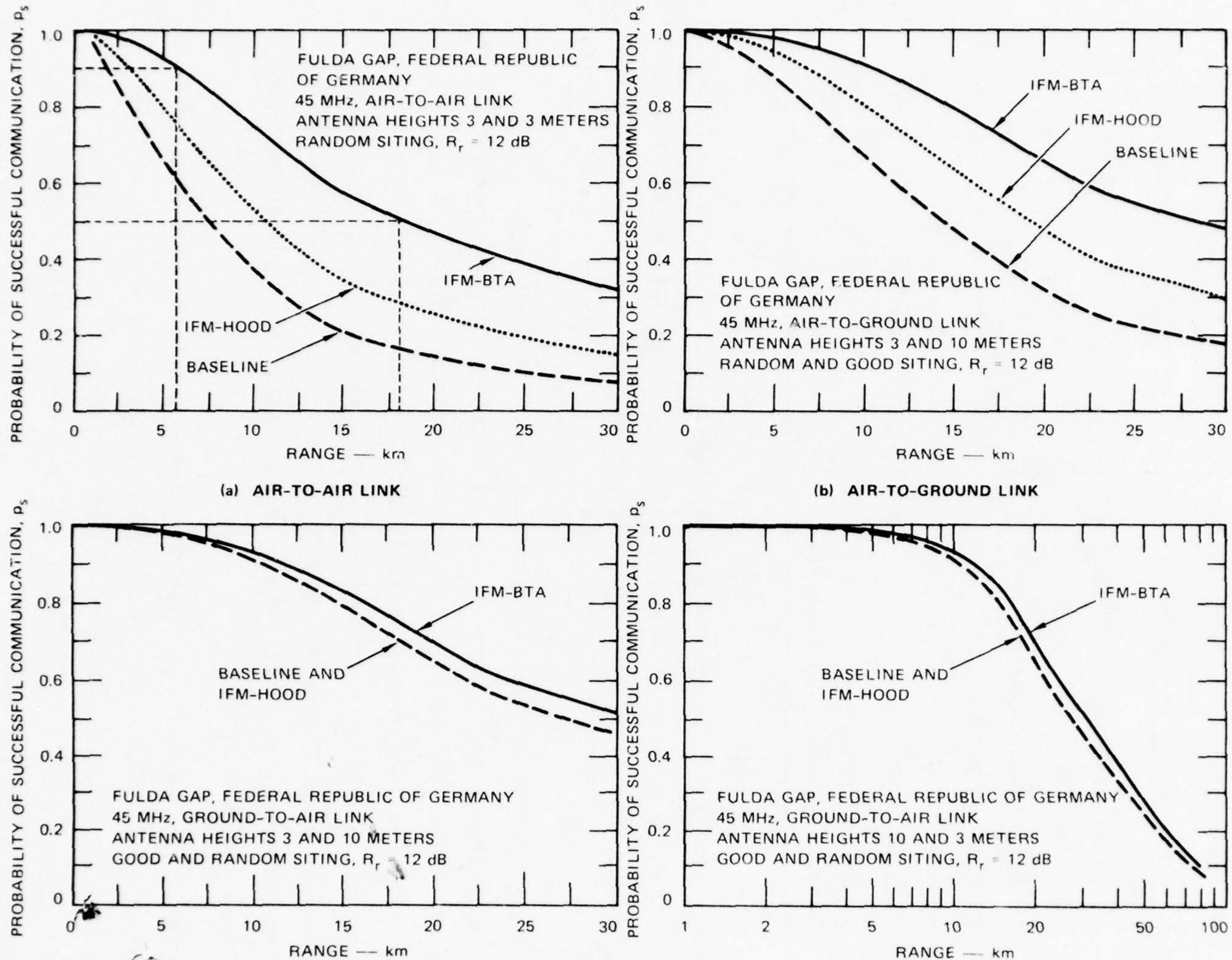
TERRAIN TYPE AND INTERDECILE RANGE

Type of Terrain	Interdecile Range, Δh (m)
Water or very smooth plains	0-5
Smooth plains	5-20
Slightly rolling plains	20-40
Rolling plains	40-80
Hills	80-150
Mountains	150-300
Rugged mountains	300-700
Extremely rugged mountains	>700

for which successful communication is predicted to occur with probability $p_s \geq 0.9$ out to a range of 6 km; at $p_s = 0.5$ the range is approximately 17 km [Figure A-9(a)]. Random siting was used for the aircraft-aircraft links.

Figure A-9(b) contains predictions for the air-to-ground link. Communication ranges are larger because of increased ground antenna height and good (hillside) siting of the ground antenna. Figure A-9(c) contains predictions for the ground-to-air link. Communication ranges are still greater, owing to higher transmitted power, antenna gain, and siting. The Baseline and IFM-Hood systems for ground-to-air communication have the same performance, since they have identical receiving antennas and receivers (see Section 6).

Predictions were calculated for ranges out to 80 km by the program, and plotted on two scales: 0 to 30 km (linear) and 0 to 80 km (semilogrithmic). Figures A-9(a) to A-9(c) are examples of the linear plots, whereas Figure A-9(d) is an example of the semilogrithmic plot of the ground-to-air predictions.



(a) **AIR-TO-AIR LINK**

(b) **AIR-TO-GROUND LINK**

(c) **GROUND-TO-AIR LINK**

(d) **GROUND-TO-AIR LINK**

FIGURE A-9 SAMPLE PLOTS OF PROBABILITY OF SUCCESSFUL COMMUNICATION AS A FUNCTION OF RANGE

b. Tabular Results

The probability of successful communication, p_s, and corresponding ranges is given in Tables A-14 through A-19 for a required probability, p_{sr} = 0.9, 0.8, 0.7, and 0.5. The ranges for three VHF/FM systems are given. These are:

- Baseline (AN/ARC-114)
- Improved FM (Fort Hood)
- Improved FM (Best Technical Approach)

Three HF/SSB system ranges (all for systems with speech processing) are given for groundwave mode at 25 MHz. These are:

- HF/SSB 40 W PEP
- HF/SSB 100 W PEP
- HF/SSB 200 W PEP

The results are given for three terrains--Fort Hood, Fulda Gap, and Korea (mountains). Communication range decreases as terrain irregularity (interdecile range) increases.

Antenna heights (m, AGL) and sitings are given in the tables. The required SNR (R_r) for minimum acceptable quality (MAV) for VHF/FM systems is 12 dB, including a 6-dB protection term for Rayleigh fading (85 percent of the locations). For HF/SSB system, the minimum required SNR to produce a channel quality having the MAV is 10 dB. No protection term was included for Rayleigh fading for the HF case; however, a 4-dB credit was assumed for speech processing and included in R_r = 10 dB.[43] A greater value of R_r would be needed for operation in the secure mode using the PARKHILL applique.[44]

c. Retransmission

Communication range between two aircraft (A_1,A_2) via a ground retransmission station (G) was estimated from the model for Fulda Gap. The aircraft were assumed to be randomly sited at 3-m altitudes and equipped with IFM--BTA radios. The ground station was assumed to be sited under excellent conditions (hilltop or mountaintop), and be equipped with a VRC-49 radio operating into a 10-m RC-292 antenna.

Table A-14

OPERATIONAL RANGES FOR STATED REQUIRED PROBABILITY OF COMMUNICATION: HF/SSB, FORT HOOD TERRAIN
(R_r = 10 dB)

Required Probability of Successful Communication, p_{sr}, at Indicated Frequency and Link*	Operational Range (km)		
	40 W PEP†	100 W PEP†	200 W PEP†
p_{sr} = 0.9			
25 MHz, air to air	20	25	34
25 MHz, air to ground	25	32	40
25 MHz, ground to air	48	48	48
p_{sr} = 0.8			
25 MHz, air to air	33	37	50
25 MHz, air to ground	38	45	57
25 MHz, ground to air	64	64	64
p_{sr} = 0.7			
25 MHz, air to air	43	50	62
25 MHz, air to ground	50	60	71
25 MHz, ground to air	79	79	79
p_{sr} = 0.5			
25 MHz, air to air	65	73	>80
25 MHz, air to ground	72	>80	>80
25 MHz, ground to air	>80	>80	>80

*For air-to-air links, assumes both antennas at 3-meter heights, both random sitings. For air-to-ground links, assumes aircraft antenna at 3 meters with random siting, ground antenna at 10 meters with good siting.

†Operational Range estimates based on aircraft transmitter being equipped with speech processing circuitry (Processing Gain ≈ 4 dB) and operating in the clear (unsecured) mode.

Table A-15

OPERATIONAL RANGES FOR STATED REQUIRED PROBABILITY OF COMMUNICATION:
HF/SSB, FULDA GAP TERRAIN
(R_r = 10 dB)

Required Probability of Successful Communication, p_{sr}, at Indicated Frequency and Link*	Operational Range (km)		
	40 W PEP†	100 W PEP†	200 W PEP†
p_{sr} = 0.9			
25 MHz, air to air	12	15	19
25 MHz, air to ground	16	19	26
25 MHz, ground to air	28	28	28
p_{sr} = 0.8			
25 MHz, air to air	19	23	31
25 MHz, air to ground	24	30	39
25 MHz, ground to air	43	43	43
p_{sr} = 0.7			
25 MHz, air to air	28	32	42
25 MHz, air to ground	35	40	52
25 MHz, ground to air	57	57	57
p_{sr} = 0.5			
25 MHz, air to air	48	52	55
25 MHz, air to ground	55	62	77
25 MHz, ground to air	>80	>80	>80

*For air-to-air links, assumes both antennas at 3-meter heights, both random sitings. For air-to-ground links, assumes aircraft antenna at 3 meters with random siting, ground antenna at 10 meters with good siting.

†Operational Range estimates based on aircraft transmitter being equipped with speech processing circuitry (Processing Gain ≈ 4 dB) and operating in the clear (unsecured) mode.

Table A-16

OPERATIONAL RANGES FOR STATED REQUIRED PROBABILITY OF COMMUNICATION: HF/SSB, KOREA TERRAIN
(R_r = 10 dB)

Required Probability of Successful Communication, p_{sr}, at Indicated Frequency and Link*	Operational Range (km)		
	40 W PEP†	100 W PEP†	200 W PEP†
p_{sr} = 0.9			
25 MHz, air to air	10	12	16
25 MHz, air to ground	15	17	20
25 MHz, ground to air	22	22	22
p_{sr} = 0.8			
25 MHz, air to air	15	18	24
25 MHz, air to ground	20	23	32
25 MHz, ground to air	37	37	37
p_{sr} = 0.7			
25 MHz, air to air	22	27	34
25 MHz, air to ground	28	32	42
25 MHz, ground to air	47	47	47
p_{sr} = 0.5			
25 MHz, air to air	39	43	56
25 MHz, air to ground	47	52	65
25 MHz, ground to air	70	70	70

*For air-to-air links, assumes both antennas at 3-meter heights, both random sitings. For air-to-ground links, assumes aircraft antenna at 3 meters with random siting, ground antenna at 10 meters with good siting.

†Operational Range estimates based on aircraft transmitter being equipped with speech processing circuitry (Processing Gain ≈ 4 dB) and operating in the clear (unsecured) mode.

Table A-17

OPERATIONAL RANGES FOR STATED REQUIRED PROBABILITY OF SUCCESSFUL COMMUNICATION: VHF/FM, FORT HOOD TERRAIN
(R_r = 12 dB)

Required Probability of Successful Communication, p_{sr}, at Indicated Frequency and Link*	Operational Range (km)		
	AN/ARC-114	IFM--Hood	IFM--BTA
p_{sr} = 0.9			
35 MHz, air to air	1.9	2.5	6
35 MHz, air to ground	4.2	6.2	12.8
35 MHz, ground to air	11.8	11.8	14
45 MHz, air to air	3.4	4.6	8.3
45 MHz, air to ground	6.2	9.2	13.8
45 MHz, ground to air	13.8	13.8	15.5
65 MHz, air to air	5	7.6	9.8
65 MHz, air to ground	9.5	13.7	16.8
65 MHz, ground to air	15.5	15.5	16.5
p_{sr} = 0.8			
35 MHz, air to air	2.7	4	8.7
35 MHz, air to ground	6.0	8.7	17.8
35 MHz, ground to air	16.7	16.7	19.3
45 MHz, air to air	4.5	6.8	11.9
45 MHz, air to ground	9.2	12.8	18.7
45 MHz, ground to air	19.1	19.1	21.5
65 MHz, air to air	7.5	10.8	14
65 MHz, air to ground	13.5	19	23
65 MHz, ground to air	21.5	21.5	22.5
p_{sr} = 0.7			
35 MHz, air to air	3.6	5.4	11.2
35 MHz, air to ground	7.6	11	22
35 MHz, ground to air	21	21	24.5
45 MHz, air to air	6.2	9	15
45 MHz, air to ground	11.5	16	22.8
45 MHz, ground to air	24.2	24.2	27.8
65 MHz, air to air	10	14	19.5
65 MHz, air to ground	17.5	24	30.5
65 MHz, ground to air	28	28	30
p_{sr} = 0.5			
35 MHz, air to air	5.7	8.3	18
35 MHz, air to ground	11.5	16	33
35 MHz, ground to air	33	33	39
45 MHz, air to air	9.5	13.5	26
45 MHz, air to ground	16.8	23	36
45 MHz, ground to air	37	37	42
65 MHz, air to air	14.5	22.8	31
65 MHz, air to ground	26	37	48
65 MHz, ground to air	42	42	45

*For air-to-air links, assumes both antennas at 3-meter heights, both random sitings. For air-to-ground links, assumes aircraft antenna at 3 meters with random siting, ground antenna at 10 meters with good siting.

Table A-18

OPERATIONAL RANGES FOR STATED REQUIRED PROBABILITY OF SUCCESSFUL COMMUNICATION: VHF/FM, FULDA GAP TERRAIN
(R_r = 12 dB)

Required Probability of Successful Communication, p_{sr}, at Indicated Frequency and Link*	Operational Range (km)		
	AN/ARC-114	IFM--Hood	IFM--BTA
p_{sr} = 0.9			
35 MHz, air to air	1.0	1.5	4.0
35 MHz, air to ground	2.8	4.3	10.2
35 MHz, ground to air	9.7	9.7	11.5
45 MHz, air to air	2.0	3.1	5.9
45 MHz, air to ground	4.7	7.1	11
45 MHz, ground to air	10.5	10.5	11.9
65 MHz, air to air	3.4	5	6.9
65 MHz, air to ground	5.5	9.5	12
65 MHz, ground to air	11.2	11.2	12.2
p_{sr} = 0.8			
35 MHz, air to air	2.5	4	8.2
35 MHz, air to ground	6.4	9.2	18
35 MHz, ground to air	17.2	17.2	19.2
45 MHz, air to air	4.5	6.6	11.3
45 MHz, air to ground	9.5	13.3	19
45 MHz, ground to air	17.3	17.3	20.2
65 MHz, air to air	7	10	13
65 MHz, air to ground	13	17.6	21.3
65 MHz, ground to air	20	20	21.2
p_{sr} = 0.7			
35 MHz, air to air	2	3	6.5
35 MHz, air to ground	4.5	6.8	14.2
35 MHz, ground to air	13.7	13.7	15.5
45 MHz, air to air	3.2	5	8.5
45 MHz, air to ground	7	10.2	15
45 MHz, ground to air	15	15	16.3
65 MHz, air to air	5	7.7	10
65 MHz, air to ground	10	14	17
65 MHz, ground to air	16	16	17
p_{sr} = 0.5			
35 MHz, air to air	4.5	6.5	12.8
35 MHz, air to ground	10	13.9	21.8
35 MHz, ground to air	24.5	24.5	30
45 MHz, air to air	7.4	10.5	18.2
45 MHz, air to ground	14.2	19	28
45 MHz, ground to air	27	27	31
65 MHz, air to air	11	15.2	22.2
65 MHz, air to ground	19.2	26.2	29
65 MHz, ground to air	31	31	33

*For air-to-air links, assumes both antennas at 3-meter heights, both random sitings. For air-to-ground links, assumes aircraft antenna at 3 meters with random siting, ground antenna at 10 meters with good siting.

Table A-19

OPERATIONAL RANGES FOR STATED REQUIRED PROBABILITY OF SUCCESSFUL COMMUNICATION: VHF/FM, KOREA TERRAIN
(R_r = 12 dB)

Required Probability of Successful Communication, p_{sr}, at Indicated Frequency and Link*	Operational Range (km)		
	AN/ARC-114	IFM--Hood	IFM--BTA
p_{sr} = 0.9			
35 MHz, air to air	0.5	1.4	3.2
35 MHz, air to ground	2.3	3.9	9.2
35 MHz, ground to air	8.5	8.5	9.7
45 MHz, air to air	1.6	2.3	4.5
45 MHz, air to ground	3.8	6	9.3
45 MHz, ground to air	9	9	10
65 MHz, air to air	2.2	3.7	4.8
65 MHz, air to ground	5	7.8	10
65 MHz, ground to air	9.2	9.2	10
p_{sr} = 0.8			
35 MHz, air to air	1.5	2.3	5.1
35 MHz, air to ground	4.2	6.1	12.5
35 MHz, ground to air	12.2	12.2	14
45 MHz, air to air	2.5	4.1	7.2
45 MHz, air to ground	6.1	9	13.1
45 MHz, ground to air	12.9	12.9	14.1
65 MHz, air to air	3.9	5.9	7.7
65 MHz, air to ground	8	11.5	14
65 MHz, ground to air	13.1	13.1	14
p_{sr} = 0.7			
35 MHz, air to air	2.2	3.2	7
35 MHz, air to ground	5.5	8	16
35 MHz, ground to air	15.3	15.3	17.2
45 MHz, air to air	3.8	5.6	9.6
45 MHz, air to ground	8.2	11.8	16.4
45 MHz, ground to air	16	16	17.5
65 MHz, air to air	5.2	7.7	10.1
65 MHz, air to ground	10.8	14.7	17.7
65 MHz, ground to air	16.5	16.5	17.5
p_{sr} = 0.5			
35 MHz, air to air	4.6	5.5	10.9
35 MHz, air to ground	9	12.2	22.2
35 MHz, ground to air	21.3	21.3	24.3
45 MHz, air to air	6.3	9	14
45 MHz, air to ground	12.5	16.8	22.5
45 MHz, ground to air	22.2	22.2	24.6
65 MHz, air to air	8.5	12.1	16
65 MHz, air to ground	16.1	21.1	26.1
65 MHz, ground to air	23.5	23.5	26

*For air-to-air links, assumes both antennas at 3-meter heights, both random sitings. For air-to-ground links, assumes aircraft antenna at 3 meters with random siting, ground antenna at 10 meters with good siting.

The communication range for the $A_1/G/A_2$ link was desired for a $p_{sr} = 0.9$. The retransmission line consisted of two independent links, A_1/G and G/A_2. Values for $p_s(A_1/G)$ and $p_s(G/A_2)$ were calculated and the range that corresponded to a product of 0.9 for the two-link probability determined. This range was used as an estimate of the retransmission range for Fulda Gap (Table A-20).

Table A-20

OPERATING RANGE OF RETRANSMISSION
FOR FULDA TERRAIN FOR $p_{sr} = 0.9$

Frequency (MHz)	Operational Range (km)		
	System 1	System 2	System 3
35	6.5	10	18
45	10	14	19
65	14	16	20

p_{sr} is shown for total air-to-ground-to-air link. Assumes aircraft antennas at 3 meters, randomly sited; ground antenna at 10 meters with excellent siting.

The one-way (A/G and G/A) p_s values from the curves of p_s as a function of d, from which the values in Table A-20 were computed, are summarized for p_{sr} = 0.9, 0.8, 0.7, and 0.5 in Table A-21.

d. <u>Communication Range for Aircraft above the NOE Flight Regime</u>

To investigate the possible retransmission ranges achievable in Fulda terrain a test case was run with the aircraft at higher altitudes. Aircraft could operate at altitudes above the NOE regime if they were far enough behind the forward edge of the battle area (FEBA). For this case

Table A-21

COMMUNICATION RANGES BETWEEN TWO AIRCRAFT WITH GROUND RETRANSMISSION FOR STATED PROBABILITY OF SUCCESSFUL COMMUNICATION: FULDA TERRAIN (R_r = 12 dB)

Required Probability of Successful Communication, p_{sr}, at Indicated Frequency and Link*	Operational Range (km)†		
	AN/ARC-114	IFM--Hood	IFM--BTA
p_{sr} = 0.9			
35 MHz, air to ground	3.1	5.0	11.5
35 MHz, ground to air	11	11	12.7
45 MHz, air to ground	5.1	7.9	12.1
45 MHz, ground to air	12.1	12.1	13.5
65 MHz, air to ground	7.2	11	13.5
65 MHz, ground to air	12.2	12.2	13.3
p_{sr} = 0.8			
35 MHz, air to ground	5.2	7.8	16.2
35 MHz, ground to air	15.4	15.4	17.6
45 MHz, air to ground	8	11.7	17
45 MHz, ground to air	15.6	15.6	18.3
65 MHz, air to ground	11.2	15.5	19
65 MHz, ground to air	17.5	17.5	18.7
p_{sr} = 0.7			
35 MHz, air to ground	7	10.4	20
35 MHz, ground to air	19.2	19.2	21.5
45 MHz, air to ground	11	15	21
45 MHz, ground to air	20.5	20.5	22.2
65 MHz, air to ground	14.5	19.5	23.5
65 MHz, ground to air	22	22	23
p_{sr} = 0.5			
35 MHz, air to ground	11.3	15.7	30
35 MHz, ground to air	27.5	27.5	32.5
45 MHz, air to ground	16.2	21.4	31
45 MHz, ground to air	30	30	33.5
65 MHz, air to ground	21.3	29	36
65 MHz, ground to air	32	32	36

*Assumes aircraft antennas at 3-meter heights with random sitings; ground antenna at 10-meter height with excellent siting.

†Operational Ranges are one-way ranges.

the aircraft was assumed to be randomly sited, and equipped with three radio systems:

- Baseline (AN/ARC-114)
- IFM (Fort Hood)
- IFM (Best Technical Approach)

The ground retransmission station was assumed to be a AN/VRC-46 equipped with a RC-292 antenna with 10-m mast. The ground station was sited under excellent conditions (hilltop). Values of p_s versus range for A/G and G/A were calculated. Aircraft altitudes were increased as the helicopter moved farther away from the FEBA. Altitudes were:

Location of Aircraft	Aircraft Antenna Height m(AGL)
NOE flight	3
NOE flight	10
Brigade rear	30
Division rear	50
Corps rear	100

The communication ranges for A/G and G/A (to and from a mountaintop retransmission site) are given for $p_{sr} = 0.9$ in Table A-22.

9. Model Assumptions, Accuracy, and Agreement with Observations

a. Model Assumptions

The two key model assumptions, both of which are reasonable, are:

- The basic transmission loss, environmental noise level, and radio system parameters can be described as independent Gaussian random variables when expressed in dB.
- The model uncertainties can be described as zero-mean, independent Gaussian random variables when expressed in dB.

Note that the central limit theorem of statistics tends to make the overall composite distribution of margin M (in dB) to be Gaussian, even though all the component terms are not precisely Gaussian. The environmental radio noise model given in CCIR Report 258-3 for "rural" noise is

Table A-22

COMMUNICATION RANGE BETWEEN AN AIRCRAFT AND A GROUND STATION
WITH 0.9 PROBABILITY OF SUCCESSFUL COMMUNICATION,
AIRCRAFT OPERATING AT AND ABOVE NOE ALTITUDES; GROUND ANTENNA 10 METERS
ABOVE GROUND, EXCELLENT SITING: FULDA TERRAIN
(R_r = 12 dB)

Aircraft Antenna Height* at Indicated Frequency and Link	Operational Range (km)		
	AN/ARC-114	IFM--Hood	IFM--BTA
3 meters			
35 MHz, air to ground	3.7	5.1	12
35 MHz, ground to air	11	11	12.8
45 MHz, air to ground	5.2	8	12
45 MHz, ground to air	12.8	12	13.5
65 MHz, air to ground	7.3	11	14
65 MHz, ground to air	13	13	14
10 meters			
35 MHz, air to ground	4.8	7.2	16.3
35 MHz, ground to air	15.3	15.3	18
45 MHz, air to ground	7.8	12	18
45 MHz, ground to air	18.5	18.5	21
65 MHz, air to ground	12.5	18	23
65 MHz, ground to air	20.6	20.6	23
30 meters			
35 MHz, air to ground	7.5	11	23
35 MHz, ground to air	22.5	22.5	25.5
45 MHz, air to ground	12.3	17.8	26
45 MHz, ground to air	26	26	30
65 MHz, air to ground	19	25	31
65 MHz, ground to air	30	30	31
50 meters			
35 MHz, air to ground	9.3	13.5	28
35 MHz, ground to air	26	26	30
45 MHz, air to ground	15	22	30
45 MHz, ground to air	32	32	35
65 MHz, air to ground	23.5	30	37
65 MHz, ground to air	35	35	37
100 meters			
35 MHz, air to ground	12.5	19	36
35 MHz, ground to air	34	34	40
45 MHz, air to ground	21	28	39
45 MHz, ground to air	40	40	43
65 MHz, air to ground	30	39	45
65 MHz, ground to air	42	42	45

*Random siting

used for the frequency band 20 to 76 MHz. This model is almost identical to that assumed for the SINCGARS Trade-Off Determination (TOD) (see Figure A-6).

The model is useful for predicting operational range for $0.1 \le p_{sr} \le 0.9$; the Gaussian assumption becomes less valid when p_{sr} falls outside this interval. The model tends to predict too low a probability of success at very short ranges (where $p_s > 0.9$) and too high a probability at very long ranges ($p_s < 0.1$). The interval of primary interest is $0.5 \le p_{sr} \le 0.9$. The range for which $p_{sr} = 0.5$ is sometimes called the expected range (or the probable range). This range is used by some as a communication planning range.[32] A higher value of p_{sr} is necessary for the NOE communication case because of the operational requirement for the radio system to provide a satisfactory channel for more than half the attempts. Also, a higher p_{sr} is needed because of the bias toward the NOE helicopter being in the most "difficult" part of any given terrain.

b. Model Accuracy

The overall model accuracy can be assessed from a consideration of the uncertainties in each individual input. It can also be assessed by comparing predictions of p_s with measurements. The model uncertainties have been estimated and described as the σ terms associated with each variable; hence, their effect is included in the p_s predictions. Note that the model used for propagation is the same model approved by the Army for SINCGARS (see Table A-23), and it is the most accurate model currently available. This table also summarizes the results of the NOE COM model predictions for median basic transmission loss when it was run for the conditions assumed in the SINCGARS TOD (which are given in Table A-24).[16] The agreement between the two different computer code versions of the Longley-Rice model is excellent, generally within roundoff accuracy of ± 1 dB. Therefore, it is safe to assume that the VHF propagation models used for NOE COM and SINCGARS are identical. The accuracies inferred from the comparisons of predictions of p_s with observations ($\hat{p}_s$) are discussed in Section 9-c, below.

Table A-23

COMPARISON OF MEDIAN BASIC TRANSMISSION LOSS (IN dB) COMPUTED
USING THE LONGLEY-RICE MODEL (SINCGARS AND NOE COM VERSIONS)

Path Length (km)	Propagation Model Version	Frequency/Antenna Height Combination											
		30 MHz				50 MHz				80 MHz			
		2m,2m*	5m,5m	2m,15m	15m,15m	2m,2m	5m,5m	2m,15m	15m,15m	2m,2m	5m,5m	2m,15m	15m,15m
25	SINCGARS†	139	137	134	128	144	141	137	129	149	143	139	130
	NOE COM‡	139	136	134	128	145	141	137	129	149	143	139	129
35	SINCGARS	144	142	139	132§	150	146	143	136	155	148	145	137
	NOE COM	144	141	139	135	150	146	142	135	154	149	145	136
50	SINCGARS	150	148	145	141	157	153	149	142	162	156	153	143
	NOE COM	150	148	145	141	156	153	149	142	161	156	152	143
80	SINCGARS	160	158	156	151	168	164	160	153	174	168	164	156
	NOE COM	160	158	155	151	169	163	160	153	172	167	163	155

*Antenna structural heights above ground.

†SINCGARS CFP, Appendix II, Trade-Off Analyses, p. II-23 (October 1975).

‡SRI International computer run using NOE COM Propagation Model (1977 version of Longley-Rice).

§Should be approximately 134 dB. Value given in Ref. 32 is a typographic error. (see Reference 16).

Table A-24

ENVIRONMENTAL AND SYSTEM PARAMETERS USED FOR PREDICTION OF MEDIAN BASIC TRANSMISSION LOSS (L_b) FOR SINCGARS

Parameter	Value
Environmental	
Terrain interdecile range, Δh (meters)	60
Ground conductivity, σ (mhos/m)	0.005
Dielectric constant, ϵ_r	15
Surface refractive index, N_s (N units)	301
System	
Frequencies (MHz)	30, 50, 80
Antenna polarization	Vertical
Antenna heights (meters above ground level)	2,2 5,5 2,15 15,15
Antenna siting	Random
Model	Longley-Rice (circa 1973)

Source: F. J. Triolo, Chief, Special Items Team, Net Radio Technical Area, COMM/ADP Laboratory, U.S. Army ECOM, Fort Monmouth, New Jersey, Internal Memorandum dated 12 September 1973. The Longley-Rice model computer runs were made by P. A. Major of ECOM.

c. Comparison of Model Predictions with Observations

Data are not available to provide a true statistical validation of the operational range predictions; however, some data exist that can be used to compare the model predictions with observations.

During the FM-320 tests conducted in 1976 at Fort Hood, the baseline system (AN/ARC-114) and a version of Improved FM (IFM--Hood) (consisting of an AN/ARC-114 with a 40-W amplifier) were used to pass 30-character alphanumeric (A-N) test messages.[38] A usable channel can be defined as one yielding an A-N score ≥ X percent, where X is a user-specified term. The FM-320 data can be processed to yield the percent of the 30-character test messages with an A-N score ≥ X percent for a given system and link. The result at a given range can be taken as a point estimator $\hat{p}_s$ of the actual probability of successful communication, p_s. While we can plot observed values of $\hat{p}_s$ at various ranges (see Figures A-10 to A-13 for X = 90 percent), we cannot compare the results directly with predicted p_s as a function of range because the number of locations sampled is so small--only one at each of six ranges. The air-to-air predictions for the baseline and IFM--Hood systems seem plausible when compared with the FM-320 data; however, the air-to-ground and ground-to-air predictions are too optimistic for both systems. This is primarily because of the foreground obstacle (Radar Hill) at the Fort Hood ground site and because of learning-curve effects; neither effect was included in the model. The baseline air-to-ground and ground-to-air data were taken first. The ground-to-air results for baseline and IFM--Hood systems should have been identical, since the aircraft receiving systems were identical and the same transmitter was used. The observed difference in performance is shown in Figure A-13. The IFM--Hood results are in much better agreement with the model predictions, indicating that the learning curve effects were significant.

The limited data available from the Fulda Gap area were obtained during a field test of coverage for potential mountaintop retransmission sites.[45] For these tests, a communication link was established from a randomly sited jeep (with AN/VRC-46 operated in the high-power mode into an AS-1729 whip antenna) to a mountaintop (with AN/VRC-46 and RC-292 antenna on a 10-m mast). Dead spots were noted from three different mountaintop locations beginning at ranges of 6.0, 9.2, and 11.5 km. Although the operating frequencies for this test were not known, the results are consistent with the ranges predicted for p_{sr} = 0.9 (a good choice for estimating the range to the nearest <u>observed</u> dead spot) for a 40-W VHF/FM mobile system operating near Fulda with random siting for the mobile terminal with its 3-m antenna and excellent siting for the mountaintop 40-W terminal with its 10-m antenna.

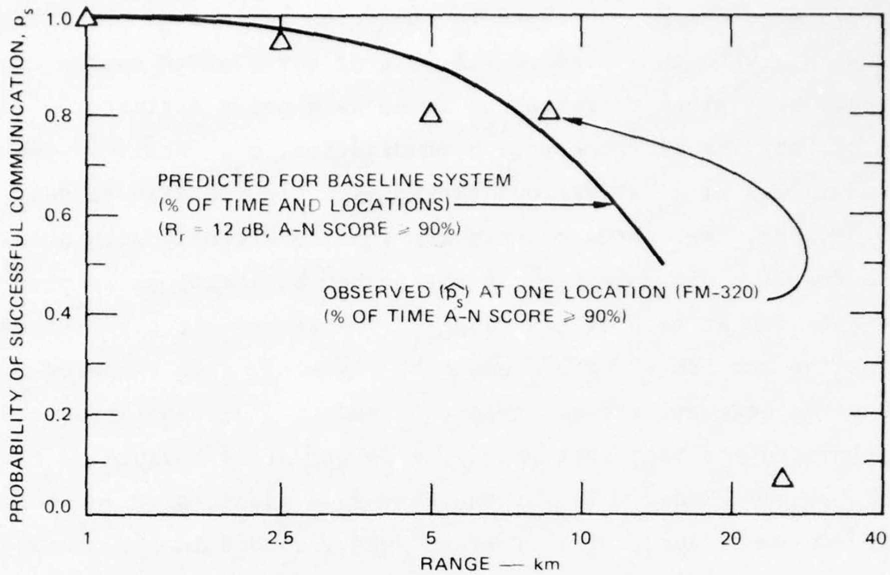


FIGURE A-10 PROBABILITY OF SUCCESSFUL COMMUNICATION (p_s), 65 MHz, AIR/AIR LINK, BASELINE RADIO (AN/ARC-114) — FORT HOOD, TEXAS — R_r = 12 dB

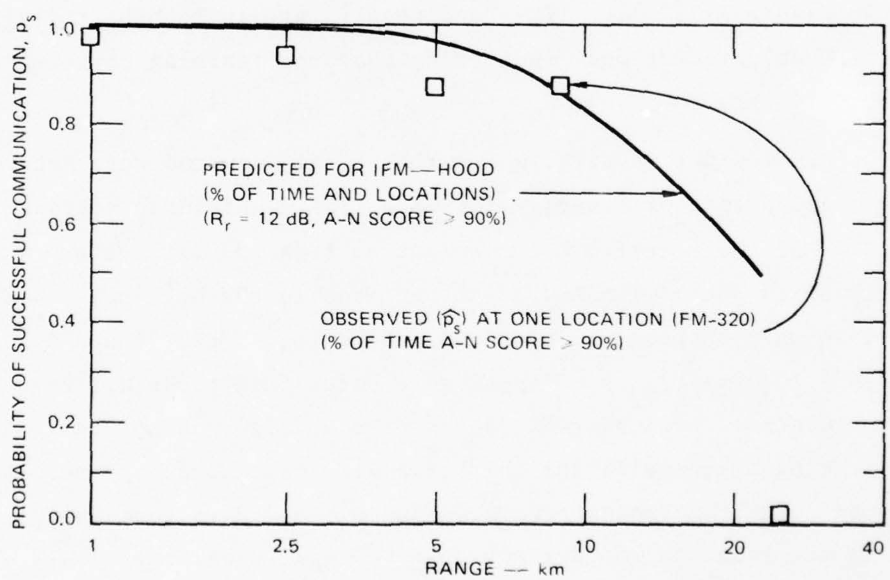


FIGURE A-11 PROBABILITY OF SUCCESSFUL COMMUNICATION (p_s), 65 MHz, AIR/AIR LINK, IMPROVED FM–HOOD — FORT HOOD, TEXAS — R_r = 12 dB

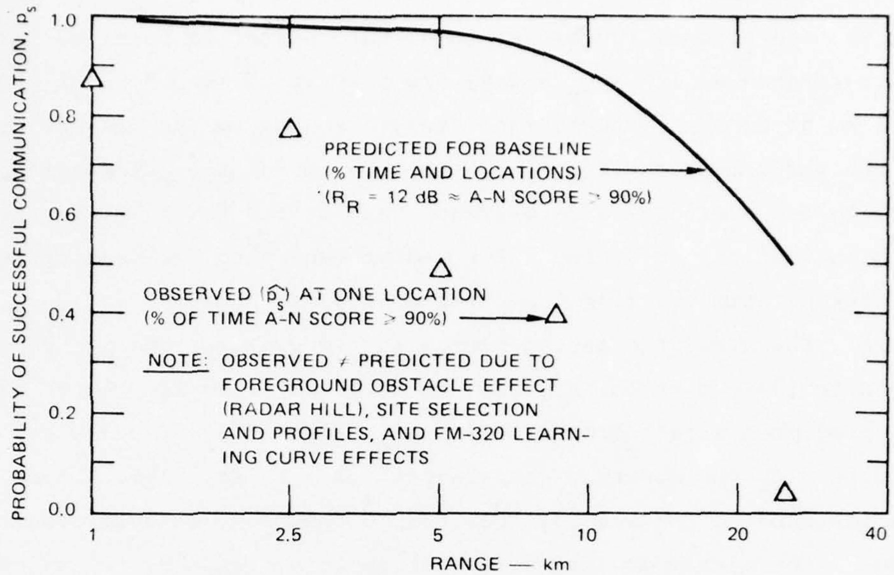


FIGURE A-12 PROBABILITY OF SUCCESSFUL COMMUNICATION (p_s), 65 MHz AIR/GROUND LINK, BASELINE RADIO (AN/ARC-114) — FORT HOOD, TEXAS — R_r = 12 dB

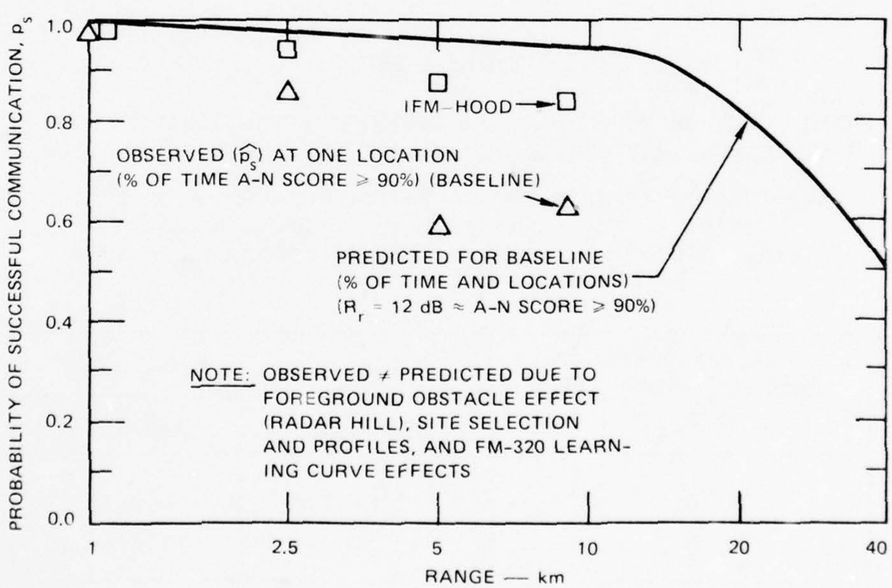


FIGURE A-13 PROBABILITY OF SUCCESSFUL COMMUNICATION (p_s), 65 MHz GROUND/AIR LINK, BASELINE RADIO (AN/ARC-114), AND IMPROVED FM–HOOD — FORT HOOD, TEXAS — R_r = 12 dB

The 40-W VHF/FM mobile terminal used near Fulda has equipment characteristics similar to the IFM helicopter radio used at Fort Hood. The predicted operational ranges for this radio system in Fulda terrain for the air-to-ground link (p_{sr} = 0.9) are 5 km at 35 MHz, 8 km at 45 MHz, and 11 km at 65 MHz. Hence, the observed ranges to the nearest dead spot from the three mountaintops of 6.0 to 11.5 km for the jeep system agree well with the predicted air-to-ground ranges, 5.0 to 11 km, for the corresponding helicopter system. The median ranges to the dead spots observed on different azimuths from the three mountaintops were 12.5, 20.0, and 28.1 km. The predicted median ranges (p_{sr} = 0.5) for the air-to-ground links were 15.7 km at 35 MHz, 21.4 km at 45 MHz, and 29.0 km at 65 MHz. These predicted air-to-ground helicopter ranges (15.7 to 29.0 km) agree very well with the observed jeep ranges (12.5 to 28.1 km). These results are summarized in Table A-25. For this comparison, we have assumed that the 40-W jeep system and the 40-W helicopter system had similar equipment characteristics. The ground station and antenna heights and siting used for the Fulda measurements were identical to those used in the model calculations.[46]

Table A-25

COMPARISON OF PREDICTED AND OBSERVED OPERATIONAL RANGES BASED ON ONE-WAY GROUND RETRANSMISSION RANGES--FULDA GAP

Interdecile range = 300 m; Vehicular antenna height, siting = 3 m, random; Ground antenna height, siting = 10 m, mountaintop; Transmitter power = 40 W

User-Specified Required Probability p_{sr}	Retransmission Range (km)	
	SRI Model*	Measured†
0.9	5.0-11.0	6.0-11.5
0.5	15.7-29.0	12.5-28.1

*Frequency 35-65 MHz

†Frequency 30 < f_{MHz} < 76 MHz

The model predicts reasonable operational ranges for $0.5 \le p_{sr} \le 0.9$, based upon these limited checks in two types of terrain. The measured operational range data available for this comparison are very limited. However, the model's range estimates appear accurate to approximately ± 25 percent when compared with the Fort Hood and Fulda observations. Additional data for model validations are highly desirable.

REFERENCES

1. FM 1-1 Terrain Flying, Headquarters, Department of the Army, Washington, D.C. (1 October 1975).

2. TRADOC, "HYDRA: A Handbook of Soviet Ground Based AD Systems," U.S. Army Training and Doctrine Command, Fort Monroe, Virginia (October 1977). (SECRET).

3. ACSI, "The Warsaw Pact Electronic Warfare and Signal Intelligence Threat Workbook," Asst. Chief of Staff (Intelligence), U.S. Department of Army Headquarters, Washington, D.C. (May 1977). (SECRET).

4. TRADOC/AMC, "Nap-of-the-Earth Communication System," Letter of Agreement for Nap-of-the-Earth Communication System, U.S. Army Training and Doctrine Command, and U.S. Army Materiel Command, Alexandria, Virginia (1 December 1975).

5. TRADOC, "Nap-of-the-Earth Communications (NOE COMM) Required Operational Capability (ROC)" (draft), U.S. Army Training and Doctrine Command, Fort Monroe, Virginia (May 1978).

6. W. R. Vincent and G. H. Hagn, "Comments on the Performance of VHF Vehicular Radio Sets in Tropical Forests," IEEE Trans. Vehicular Technology, Vol. VT-18, No. 2, pp. 61-65 (August 1969).

7. G. H. Hagn and G. E. Barker, "Research Engineering and Support for Tropical Communications," Final Report Covering the Period 1 September 1962 through 15 February 1970, Contract DA 36-039 AMC-00040(E), SRI Project 4240, Stanford Research Institute, Menlo Park, California (February 1970). AD 889 169.

8. T. W. Doeppner, G. H. Hagn, and L. G. Sturgill, "Electromagnetic Propagation in a Tropical Environment," J. Defense Research, Series B: Tactical Warfare, Vol. 4B, No. 4, pp. 353-404 (Winter 1972). (CONFIDENTIAL). Declassified by DARPA letter, 4 June 1973.

9. L. A. Berry, "Probabilistic Tradeoffs for Efficient Spectrum Use with a 'CB' Example," U.S. Department of Commerce, OT/ITS, Boulder Colorado Report OTR 77-177 (April 1977).

10. R. D. Jennings and S. J. Paulson, "Communication System Performance Model for VHF and Higher Frequencies," OT Report 77-128, Office of Telecommunications, U.S. Department of Commerce, Boulder, Colorado (October 1977).

11. E. W. Pappenfus, W. R. Bruene, E. O. Schoenike, Single Sideband Principles and Circuits (McGraw-Hill Book Company, New York, New York, 1964).

12. W. L. Firestone, "A Review of Communication Interference Problems," IEEE Trans. Vehicular Communications, Vol. VT-14, No. 1, pp. 57-66 (March 1965).

13. LTC J. M. Pinson, U.S. Army Combined Arms Test Activity, Fort Hood, Texas, private communication, 1977.

14. A. G. Longley and P. L. Rice, "Prediction of Tropospheric Radio Transmission Loss over Irregular Terrain, A Computer Method--1968," ESSA Tech. Report ERL-79-ITS 67, U.S. Department of Commerce, Boulder, Colorado (1968), NTIS No. 676-874.

15. Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables, U.S. Department of Commerce, NBS, Applied Mathematical Series (1955).

16. F. J. Triolo, "Median Transmission Loss Calculations," Memorandum for Record, Net Radio Technical Area, Comm/ADP Laboratory, U.S. Army Electronics Command, Fort Monmouth, New Jersey (12 September 1973).

17. CCIR, "Operating Noise-Threshold of a Radio Receiving System," Report 413, International Radio Consultative Committee, International Telecommunication Union, Geneva (1966).

18. J. J. Egli, "Radio Propagation above 40 Mc over Irregular Terrain," Proc. IRE, Vol. 45, pp. 1383-1391 (October 1957).

19. W. C. Y. Lee and Y. S. Yeh, "On the Estimation of the Second-Order Statistics of Log-Normal Fading in Mobile Environment," IEEE Trans. Com., Vol. COM-22, No. 6, p. 869 (June 1974).

20. F. I. Meno, "Mobile Radio Fading in Scandinaviana Terrain," IEEE Trans. Vehic. Tech., Vol. VT-26, No. 4, pp. 335-340 (November 1977).

21. W. R. Young, Jr., "Comparison of Mobile Radio Transmission at 150, 450, 900 and 3700 MHz," Bell Sys. Tech. J., Vol. 31, pp. 1068-1085 (November 1952).

22. K. Bullington, "Radio Propagation for Vehicular Communications," IEEE Trans. Vehic. Tech., Vol. VT-26, No. 4, p. 306 (November 1977).

23. R. M. Clark, "A Statistical Theory of Mobile Radio Reception," Bell Sys. Tech. J., Vol. 47, pp. 957-1000 (July-August 1968).

24. M. C. Gans, "A Power-Spectral Theory of Propagation in the Mobile Radio Environment," IEEE Trans. Vehic. Tech., Vol. VT-21, No. 1, pp. 27-38 (February 1972).

25. F. Hansen and F. I. Meno, "Mobile Fading--Rayleigh and Lognormal Superimposed," IEEE Trans. Vehic. Tech., Vol. VT-26, No. 4, pp. 332-335 (November 1977).

26. Private communication, W. Borman, Motorola, 16 December 1977.

27. Private communication, T. Lusk, General Electric, 30 December 1977; N. Shepherd, General Electric, 4 January 1978.

28. Keith Allsebrook and J. D. Parsons, "Mobile Radio Propagation in British Cities at Frequencies in the VHF and UHF Bands," IEEE Trans. Vehic. Tech., Vol. VT-26, No. 4, pp. 313-326 (November 1977).

29. A. D. Spaulding and R. T. Disney, "Man-Made Radio Noise, Part I: Estimates for Business, Residential, and Rural Areas," OT Report 74-38, Office of Telecommunications, U.S. Department of Commerce, Boulder, Colorado (June 1974).

30. CCIR, "Man-Made Noise," Report 258-2, International Radio Consultative Committee, International Telecommunication Union, Geneva (1976).

31. CCIR, "Worldwide Distribution and Characteristics of Atmospheric Radio Noise," Report 322, International Radio Consultative Committee, International Telecommunication Union, Geneva (1964).

32. SINCGARS, Concept Formulation Package, Appendix II, Tradeoff Analysis (U), p. II-16, Headquarters, Department of the Army, Washington, D.C. (October 1975) (C).

33. J. G. Mast and R. C. Henschel, "Antenna Development for OH-58A Helicopter," Report No. 206-099-212B, Final Report, Contract DAAJ01-68-1699, Bell Helicopter Company, Fort Worth, Texas (July 1969).

34. L. N. Medgyesi-Mitschang and J. M. Putnam, "Prediction of VHF/FM Antenna Radiation Patterns," Final Report for Period 15 March 1977-14 August 1977, Contract DAAB07-77-C-3036, McDonnell Douglas Research Laboratories, St. Louis, Missouri (September 1977).

35. "Nap-of-the-Earth Communications System Tradeoff Determination, Draft," U.S. Army AVRADA and AAVNC (DCD--Studies), Fort Rucker, Alabama (April 1978).

36. B. R. Bean, J. D. Horn, and A. M. Ozanich, Jr., Climatic Charts and Data of the Radio Refractive Index for the United States and the World, National Bureau of Standards Monograph 22 (1960).

37. Anita G. Longley, "Radio Propagation in Urban Areas," Conference Record of 28th IEEE Vehicular Technology Conference, IEEE Catalog No. 78CH1297-1VT, pp. 503-511 (March 1978).

38. J. M. Pinson, J. Mellor, W. P. Leach, R. J. Cleland, "Nap-of-the Earth Communications (NOE COMMO) System," TCATA Test Report FM-320, RCS ATCD-8, Headquarters, TRADOC Combined Arms Test Activity, Fort Hood, Texas (March 1977).

39. "Nap-of-the Earth Communications (NOE COMM) Best Technical Approach," Concept Formulation Package, U.S. Army Aviation Center, Fort Rucker, Alabama, 1978.

40. J. F. Brune and J. E. Reilly, "Compact HF Antenna (with Propagation Studies)," Research and Development Technical Report, ECOM-4366, U.S. Army Electronics Command, Avionics Laboratory, Fort Monmouth, New Jersey (November 1975).

41. G. H. Hagn, "Working Group IV: Environmental Descriptions," Technical Report ACC-ACO-1-74, Proceedings of Workshop on Radio Systems in Forested and/or Vegetated Environments, Fort Huachuca, Arizona, edited by J. R. Wait, R. Oh, and T. Telfer, pp. IV-1 to IV-15 (February 1974) Ad 780-712.

42. Robert Falls, U.S. Army Mobility Research and Development Center (MERDC), Fort Belvoir, Virginia, Private Communication (1977).

43. G. Lane, U.S. Army Communications Electronics Engineering Installation Agency, Fort Huachuca, Arizona, Private Communication, 1978.

44. G. Lane, "Performance Criteria for PARKHILL Secure Voice Operation on Tactical HF Radio Circuits (U)," Technical Report EMEO-PED-78-1, U.S. Army CEEIA, U.S. Army Communications Command, Fort Huachuca, Arizona (1978).

45. Message from Commander, 11th Armored Cavalry Regiment, Fulda, FRG, to Commander, U.S. Army Aviation Center, Fort Rucker, Alabama (DTG 261900Z, August 1977).

46. Private Communication.

Appendix B

HAWAII NOE COMMUNICATION SYSTEM TEST RESULTS

Appendix B*

HAWAII NOE COMMUNICATION SYSTEM TEST RESULTS

1. Introduction

Three radio systems were tested on the island of Oahu, Hawaii, under NOE conditions during the period from 2-22 August 1976.† The systems/modes tested were HF/SSB, VHF/FM, and UHF/FM satellite. These tests were run as part of a cooperative effort between the U.S. Army Electronics Command (ECOM) Avionics Laboratory,‡ and the U.S. Army Satellite Communication Agency (SATCOMA). The ECOM portion involved a comparison of the three radio systems on a ground-to-air (G-A) path to a helicopter flying a predesignated NOE course on Oahu (see Figure B-1). Two additional tests were conducted by ECOM: a 24-hour HF/SSB test over a 32-km path and a VHF/FM test over discrete paths extending to 20 km.

The SATCOMA portion of the test consisted of transmitting from a ground satellite station to a helicopter flying both under NOE and terrain-masked conditions. The satellite uplink was from the ground station to a stationary equatorial satellite (GAPFILLER), located at approximately the longitude of the international date line. The elevation angle of the satellite from Oahu was approximately 52 degrees. The results of the SATCOMA portion have been reported in a separate document by that agency.[1§]

The principal finding of the Hawaii tests was that the HF/SSB and satellite systems performed equally and extremely well, both in the NOE course and at all other sites on Oahu. Alphanumeric (A-N) test messages

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*By B. C. Tupper.

†This test was performed by a joint AVRADA/SATCOMA team. The AVRADA project leader was Frank A. Cansler, assisted by Temple Eller (AVRADA). SATCOMA personnel were Olaf Guzmann and Ken Masterman-Smith.

‡Now the Avionics Research and Development Activity (AVRADA) of AVRADCOM.

§References are listed at the end of the appendix.

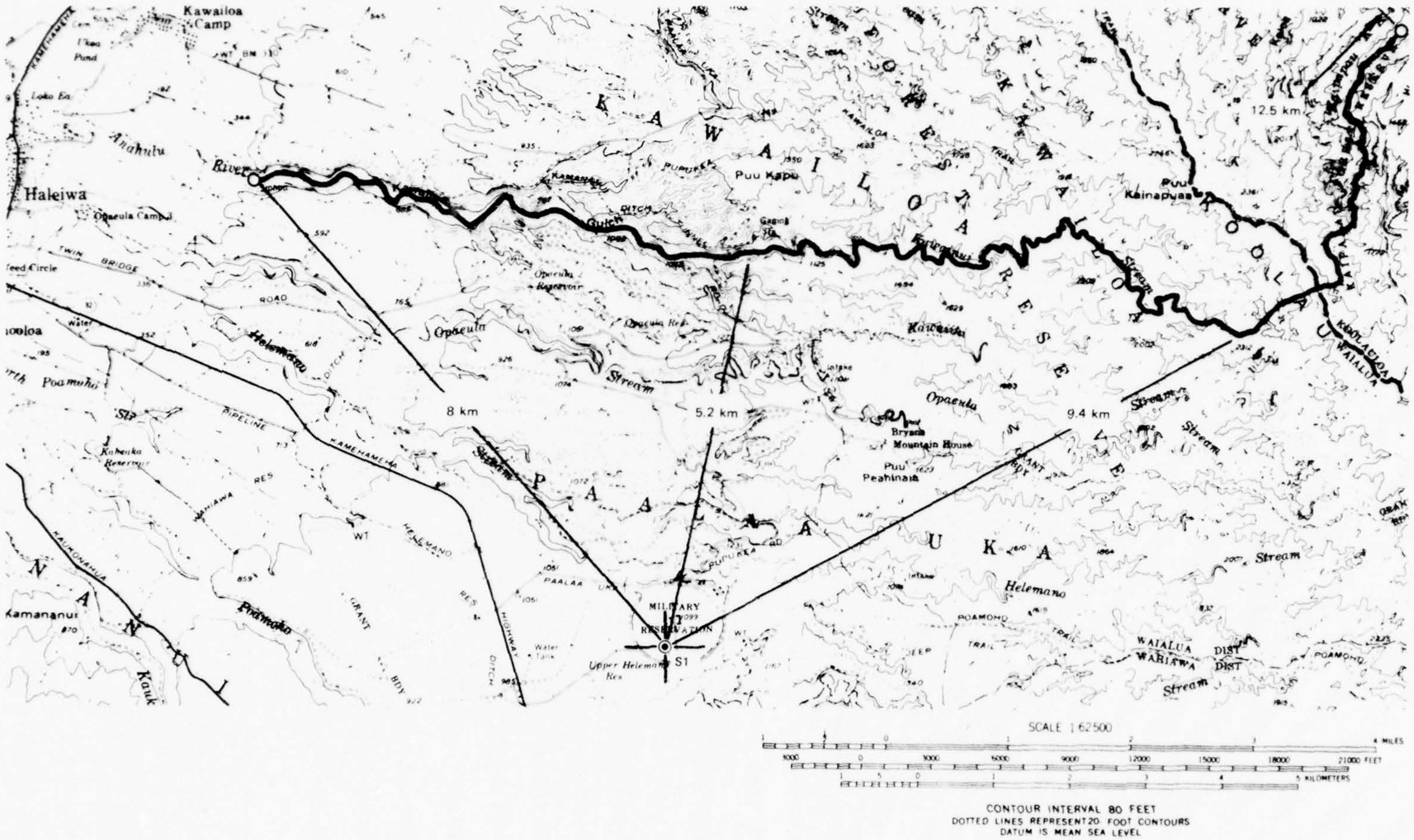


FIGURE B-1 NOE COURSE, OAHU, HAWAII

were used to determine communication effectiveness. HF/SSB had a median A-N score of 97-100 percent over the NOE course, while the median satellite score over this course was 100 percent.

A second finding from the tests was that the 40-W VHF/FM ground-to-air system performed unsatisfactorily over the NOE course. VHF/FM would not operate at all in two of the three course regions, resulting in A-N scores of 0 percent. However, in the third region of the course, under non-line-of-sight conditions, the VHF/FM system did operate satisfactorily and yielded a median alphanumeric test score of 93-100 percent. The overall conclusion was that HF/SSB and UHF/FM (satellite) systems provided a solution to the NOE COM problem for operations over Hawaii terrain or terrain similar thereto, whereas VHF/FM is generally unsatisfactory for conducting an NOE mission over that type of terrain. Communication outages occurred for the VHF/FM system at ranges as close as 5 to 8 km. Findings are reviewed in detail in the results section of this appendix.

2. Objectives

The objectives of the ECOM portion of the Hawaii test were as follows:

- To determine the effectiveness of three communication systems operating under NOE flight conditions in Hawaii terrain;
- To establish the communication range of the 40-W VHF/FM system under NOE flight conditions in Hawaii terrain;
- To ascertain the capabilities and limitations of HF/SSB and VHF/FM in the Hawaii environment;
- To evaluate the viability and accuracy of frequency planning for HF/SSB (NVIS) operation, based on CEEIA-provided ionospheric predictions;
- To obtain information on the suitability of the three systems tested for an NOE mission.

The following assumptions and caveats apply to the Hawaii test results. First, the systems were tested using the ground-to-air link only. Alphanumeric (A-N) messages were not sent over the reciprocal, air-to-ground link. Second, because of safety restrictions, the aircraft flew only during daytime hours. Hence, all HF/SSB data recorded in the aircraft were taken during daytime conditions. It was determined from the 24-hour HF/SSB tests that the interference levels on the HF/SSB frequencies were significantly lower during the daytime period than at night. Third, although there were several NOE courses on Oahu, aircraft flight time limitations made it necessary to restrict flights to a single course. Finally, four runs were made over the NOE course for each system. Multiple A-N messages were sent during each run. Simultaneous runs, made for each pair of radio systems, yielded similar (i.e., repeatable) results.

3. Test Description

a. Radio Systems Tested

Three NOE radio systems were tested in Hawaii: the AN/ARC-102 HF/SSB system, the AN/VRC-46 VHF/FM system, and the AN/ARC-171(V) satellite system. The base station for each of these was installed in an instrumented trailer located at the Helemano satellite tracking station of the U.S. Navy Communications Station, Wahiawa, Hawaii. An airborne transceiver for each of the systems was installed in a UH-1H test aircraft. Test transmissions were sent from the ground and recorded in the aircraft. A summary of the equipment parameters for the test radio systems is listed in Table B-1.

The 400-W AN/ARC-102 system was installed at both ends of the HF/SSB link--in the equipment van and in the aircraft. The base station set was connected to a horizontal half-wave dipole (doublet) antenna located 40 feet above the ground on a NW-SE axis. The dipole antenna was marked for operation at each of the assigned test frequencies (see Table B-2). Three primary test frequencies were used:[3] 3.300 MHz, 2.993 MHz, and 2.586 MHz. The frequencies selected for operation were based on ionospheric predictions provided by the U.S. Army CEEIA, Fort Huachuca, Arizona (Figure B-2).

The HF/SSB aircraft installation consisted of an AN/ARC-102 (400 W) transceiver, a Collins 490S-1 coupler, and the ECOM-developed shorted-loop antenna. This loop antenna, slightly longer than the one used on the OH-58 aircraft had been designed specifically for the UH-1.

Table B-1

RADIO SET CHARACTERISTICS FOR HAWAII NOE COMMUNICATION TEST

Radio System	Aircraft (UH-1H)	Ground Station (Helemano, Oahu)
VHF/FM	AN/ARC-131 (10 W), Antenna FM-2 (mounted over cockpit) 40.3 and 38.2 MHz	AN/VRC-46 (40 W) AS-1703/VRC (on van roof) --
HF/SSB	AN/ARC-102 (400 W) Shorted-loop antenna 2.566, 3.300, 5.235 MHz	AN/ARC-102 (400 W) Half-wave dipole (H_A = 40 ft)
Satellite (UHF/FM	AN/ARC-171(V) Yagi antenna (steerable) Uplink: 307.45 MHz (100 W) Downlink: 254.15 MHz Satellite: GAPFILLER Elevation angle: 52°	AN/ARC-171(V) Yagi antenna (steerable) Uplink: 307.45 MHz (100 W) Downlink: 254.15 MHz -- Elevation angle: 52 °

Table B-2

FREQUENCY PLAN FOR HAWAII HF/SSB TESTS

Local Time	Frequency (MHz)	Use
Day (0800-2000)	3.300 2.993 2.586	Primary* Day (morning) Alternate Alternate
	5.235 4.035	Primary Day (afternoon) Alternate
Night (2000-0800)	2.566 2.020	Primary Night Alternate

*Primary operating frequencies selected at or below Frequency of Optimum Transmission (FOT).

```
PROJECT 362   RPA  1001.0  DCA              SSN   8.4        AUGUST  1976
HAWAII              TO 50 KM EAST     2       AZIMUTHS      MILES      KM.
20.50N - 158.00W     20.50N - 157.52W      89.92  270.08      31.1      50.0
TYPE OF SERVICE VOICE                        MINIMUM ANGLE =    .0 DEGREES
XMTR   2   31   HORZ H-W DIPOLE    [H  9.14] [L  -.50] [A -0] OFF AZ =  0
RCVR   2   31   HORZ H-W DIPOLE    [H  9.14] [L  -.50] [A -0] OFF AZ =  0
POWER =    .200KW    3MHZ MAN-MADE NOISE = -166DBW     REQD.S/N = 50DB
```

FREQUENCIES IN MHZ

UT	2.0	2.6	2.9	3.3	4.0	4.5	5.2	6.6	6.8	9.4	10.1	
02	.99	.99	.99	.99	.99	.99	.99	.98	.97	.62	.44	REL.
04	.99	.99	.99	.99	.99	.99	.99	.97	.96	.56	.37	REL.
06	.99	.99	.99	.99	.97	.95	.88	.61	.56	-	-	REL.
08	.99	.98	.96	.92	.78	.62	.31	-	-	-	-	REL.
10	.97	.96	.94	.87	.58	.32	.05	-	-	-	-	REL.
12	.96	.95	.93	.87	.59	.34	.06	-	-	-	-	REL.
14	.95	.96	.90	.75	.39	.23	.08	-	-	-	-	REL.
16	.97	.97	.92	.77	.41	.24	.09	-	-	-	-	REL.
18	.99	.98	.98	.97	.92	.84	.60	-	-	-	-	REL.
20	.98	.99	.99	.97	.92	.85	.63	-	-	-	-	REL.
22	.93	.99	.99	.99	.99	.98	.93	.62	.56	.04	-	REL.
24	.98	.99	.99	.99	.99	.99	.99	.94	.93	.39	-	REL.

UT	00	02	04	06	08	10	12	14	16	18	20	22
MUF	8.9	9.9	7.0	4.8	4.2	4.2	4.2	3.8	3.9	5.4	5.5	7.0
FOT	7.1	7.8	7.6	5.1	3.5	3.2	3.3	3.0	3.0	4.2	4.3	5.5

DASHES IN RELIABILITY LINES SIGNIFY RELIABILITIES OF 00 PERCENT

SOURCE: U.S. Army Communication-Electronics Installation Activity, Fort Huachuca, Arizona.

FIGURE B-2 HF FREQUENCY PREDICTIONS FOR OAHU, HAWAII (August 1976)

The VHF/FM base station was an AN/VRC-46. This system uses a receiver-transmitter RT-524/VRC whose FM transmitter operates at a nominal output power of 40 W. The transceiver was connected to a vertical whip element (AS-1703/VRC) mounted on top of the equipment shelter at 12 ft AGL. An antenna coupler (MX6707/VRC) was used to match the transceiver to the vertical whip. The primary FM frequency used for the test was 40.3 MHz.

The VHF/FM aircraft installation was an AN/ARC-131 (10-W) transceiver, employing an RT-823 receiver-transmitter. This transceiver, with equipment characteristics similar to that of the AN/ARC-114 tested at Fort Hood, (FM-320), was connected to a bent-whip antenna (FM10-30) mounted on the left side of the UH-1 cabin roof. The vertical stabilizer antenna on the UH-1 was not used for any of the VHF/FM tests.

The satellite radio system installed in both the aircraft and the ground station was an AN/ARC-171(V), manufactured by Collins Radio Corp. In addition to the transceiver, the ground satellite system consisted of a satellite frequency control head, a VHF/FM control head, an audio control, a UHF preamplifier, a transmit/receive relay, and a VHF/FM voice modem. The satellite ground station transceiver had a nominal output power of 100 W and was connected to a Yagi antenna array approximately 30 inches in length. Mounted on top of a control servo box for tracking the satellite, this array had a gain of 9 dBi. The uplink frequency used was 307.75 MHz; the downlink frequency (from the satellite to the aircraft) was 254.15 MHz. The elevation angle to the satellite was approximately 52 degrees. The antenna employed had a 60 degree elevation beamwidth. In order to track the satellite, its azimuth was set into the control servo box, after which no further adjustments were required. Because of the relatively broad beamwidth of the satellite system antenna, no tracking in elevation was necessary.

The equipment setup for the satellite transceiver in the aircraft was similar to that for the ground station. The aircraft satellite antenna, specially built by SATCOMA, was mounted on a vertical shaft above the main rotor. The gyro of the aircraft was connected to the tracking device, and the differential signal from the aircraft heading and preset satellite azimuth was used to hold the satellite antenna on the azimuth of the satellite. The downlink power from the satellite at the helicopter receiver input was -143 dBm, producing a system margin at the satellite receiver input of approximately +14 dB.

b. Test Procedures

A NOE communications two-system direct comparison test was developed by SRI for use during the Hawaii NOE flights.[4] A prerecorded audio tape, containing A-N test messages, was used as the source material for the tests. The A-N messages employed were in the same format as those used by TCATA during the FM-320 tests at Fort Hood.

The two-system comparison test was designed to simultaneously test two radio systems over a common transmission path.[4] The A-N test tape was played into two ground radio transceivers (for example, the AN/ARC-102 and AN/VRC-46), and transmitted simultaneously to the aircraft. At the aircraft end of the link, the test message was received on the corresponding aircraft receivers (in this example, the AN/ARC-102 and AN/ARC-131) and recorded on a two-track cassette recorder.

As the aircraft proceeded along the NOE course, the terrain between the base station and the aircraft changed. The simultaneous transmission of A-N messages over two independent radio systems permitted a direct comparison of the two systems as a function of terrain since the path profile between the base station and the aircraft, as well as the altitude of the aircraft, was identical for each system. During intervals between test messages, the pilot would make announcements of the aircraft's position, altitude, and heading, which were recorded. During the analysis, the position of the aircraft was correlated with the A-N scores and quality of the test messages received.

The two-system comparison tests were run for the following system combinations:

- HF/SSB versus UHF/FM (satellite)
- VHF/FM versus UHF/FM (satellite)
- HF/SSB versus VHF/FM.

During subsequent analysis the two-channel tapes containing the alpha-numeric messages were played back in the laboratory and analyzed for the following information:

- Communication effectiveness, defined as percent correct A-N test characters.
- A subjective readability rating of channel quality.
- A noise-annoyance factor for the channel.
- Aircraft position information.

The A-N test scores yielded an objective measure of communication effectiveness. The channel readability rating and noise-annoyance factor constituted subjective ratings of the particular channel over which a message was being sent. The subjective ratings are of interest because they help to identify the capabilities and limitations of the HF/SSB and VHF/FM radio channels.

c. NOE Course Description

A 17-km NOE course running from west to east across the island of Oahu was selected. Figure B-3 is a map showing the course and base station location. The course started approximately 11 km north of Schofield Barracks and followed the Kawailoa Gulch as it approached the mountain range separating the windward side of Oahu from its leeward side. For purposes of analysis, the course was divided into three regions (see Figure B-2).

Region 1 of the course was located in a deep ravine, approximately 7-km long, substantially lower in elevation than the base station. The path profile between the base station and the start of the course for Region 1 indicated that the terrain consists of gently rolling hills intersected by deep ravines. The general elevation falls off from 1100 ft above MSL at the base station to 400 ft above MSL at the start of the course. Vegetation is relatively light over the profiles between the base station and the NOE course in Region 1. The interdecile range for Region 1, scaled from path profiles, is estimated at 170 meters. Interdecile range is the difference between the 10 and 90 percentage points on the terrain elevation distribution.

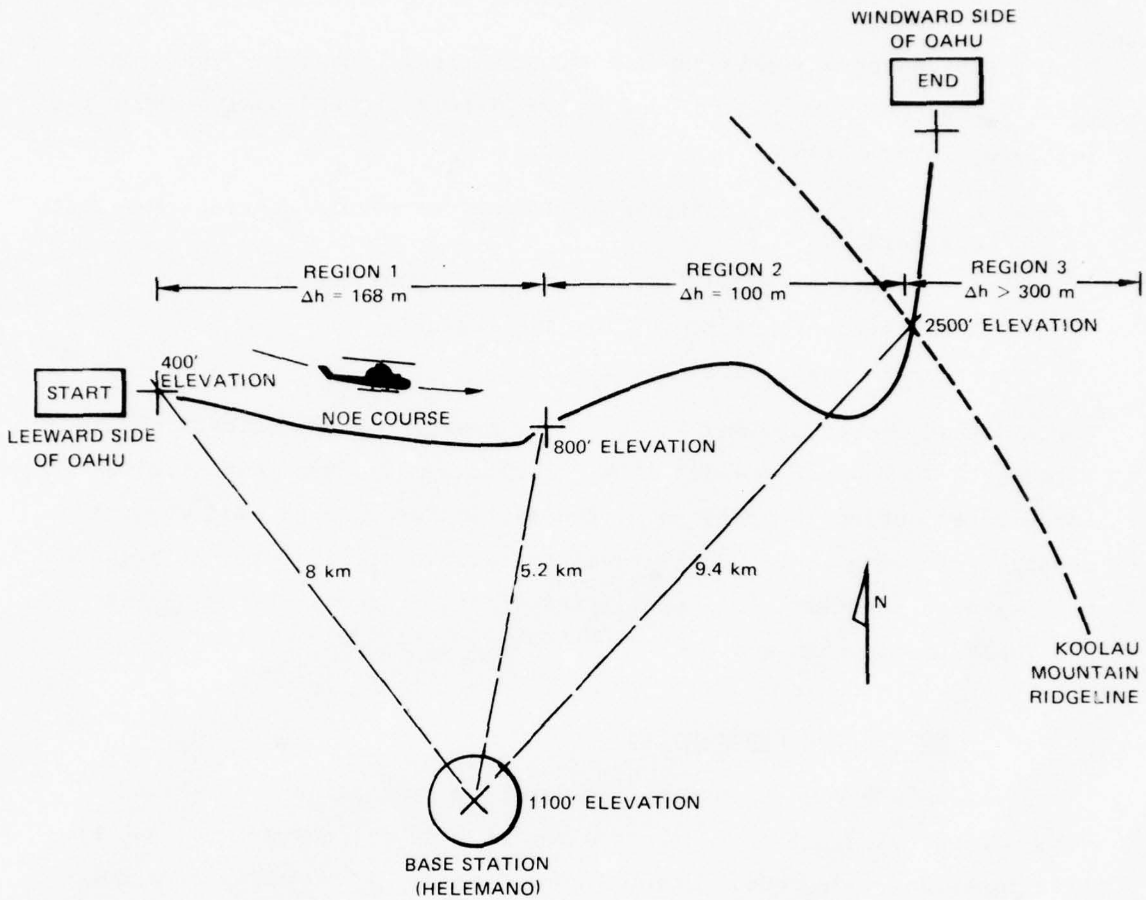


FIGURE B-3 NOE FLIGHT COURSE FOR HAWAII TESTS (Kawailoa Gulch, Oahu)

Region 2 of the NOE course was located approximately 5.2 km north of the base station. At this point, the terrain slopes upward--at first gently and then steeply--as the summit of the Koolau Mountain Range is reached. Ridges extend from the top of this mountain range toward the west and intersect the profiles between the base station and the NOE course. The entire area is heavily vegetated. Region 2 has an interdecile range estimated at 100 meters.

Region 3 of the course extended from the summit of the mountain range to approximately 5 km north. The terrain consists of steep cliffs descending to the ocean. Region 3 is very heavily vegetated (rain forest). The interdecile range from path profiles for Region 3 is approximately 300 meters. All three regions of the course are non-line-of-sight to the base station located at Helemano.

4. Results

a. Two-System Comparison Test Results

Communication Effectiveness--The communication effectiveness of HF/SSB, VHF/FM and UHF/FM satellite radio systems was calculated as the percentage of correct A-N test messages, recorded as the helicopter traversed the NOE course. Data were recorded for the ground-to-air link only. A total of five runs through the NOE course was made. During each run a simultaneous transmission was recorded on each of the two radio systems under test. Two runs were made for the combination of satellite-versus-HF/SSB and also for HF/SSB-versus VHF/FM. Finally, one run was made for satellite-versus-VHF/FM. A total of 134 A-N test messages were received in the aircraft. Of these, 42 messages were received on the VHF/FM system, 57 on HF/SSB, and 35 on the UHF/FM (satellite) system.

The results of the two-system comparison test are summarized in Figure B-4. This figure, broken down by NOE course region, shows the

SYSTEM	REGION 1			REGION 2			REGION 3		
	MEDIAN	MAX	MIN	MEDIAN	MAX	MIN	MEDIAN	MAX	MIN
HF/SSB	100	100	93	100	100	97	97	100	90
VHF/FM	33	80	0	100	100	0	0	0	0
	N = 14 MESSAGES			N = 18 MESSAGES					
SATELLITE	100	100	100	100	100	100	100	100	90
VHF/FM	30-43	80	0	93-100	100	80	0	0	0
	N = 6 MESSAGES			N = 4 MESSAGES					
HF/SSB							97	100	90
SATELLITE							100	100	90
							N = 7 MESSAGES		

FIGURE B-4 COMMUNICATION EFFECTIVENESS FOR THE TWO-SYSTEM COMPARISON TEST OVER NOE COURSE, OAHU, HAWAII (Percentage of correct A-N test messages) median, maximum, and minimum test scores, and the number (N) of 30-character A-N messages analyzed. The characteristics of a given radio system, such as HF/SSB, can be determined for all three NOE course regions by scanning across the figure. A vertical reading compares the performance of HF/SSB with that of VHF/FM.

The HF/SSB system performed extremely well in all regions of the NOE course. The median alphanumeric score in Regions 1 and 2 (see Figure B-4) was 100 percent, but dropped slightly in Region 3. The minimum test score (for HF/SSB) was 90 percent, the maximum 100 percent. All runs were made during daytime.

The HF/SSB system outperformed the VHF/FM system in two of the three regions across the course. For Region 1, in which the scores varied from a minimum of 0 percent to a maximum of 80 percent, the median alphanumeric score for VHF/FM was 33 percent. The HF/SSB and satellite systems performed equivalently over the entire NOE course.

The only system which did not work satisfactorily was 40-W VHF/FM. As discussed previously, it performed poorly in Region 1. VHF/FM would not operate at all in Region 3 because of a large mountain range that separates the base station from the helicopter in this region.

The VHF/FM system, however, did perform well in Region 2, which lies on the western side of the mountain range as the aircraft descends the mountain. This region is non-line-of-sight to the base station. The median VHF/FM test score for the region was 100 percent, with the data ranging from a minimum of 0 percent to a maximum of 100 percent, but clustered predominantly in the 90-100 percent segment. Performance for the air-to-ground link in Region 2 of the course was not measured. However, in view of the lower power (10 W) available in the aircraft, it can be assumed that the air-to-ground link would have been inferior in performance to the 40-W ground-to-air link.

The poor performance of the VHF/FM system in Region 1 of the course is primarily due to terrain effects (path profile). The terrain between the base station and Region 1 is gently rolling, but is intersected by deep ravines that serve as drainage areas for the mountain range. The NOE course was located in the deepest of these ravines at a distance of five to eight kilometers from the base station. It is conjectured that the aircraft, while flying in this ravine, was at elevations (AGL) deep within the "shadow" zone of the ravine rim. In addition, the presence of other ridges between the base station and the aircraft would have caused multiple diffractions to occur.

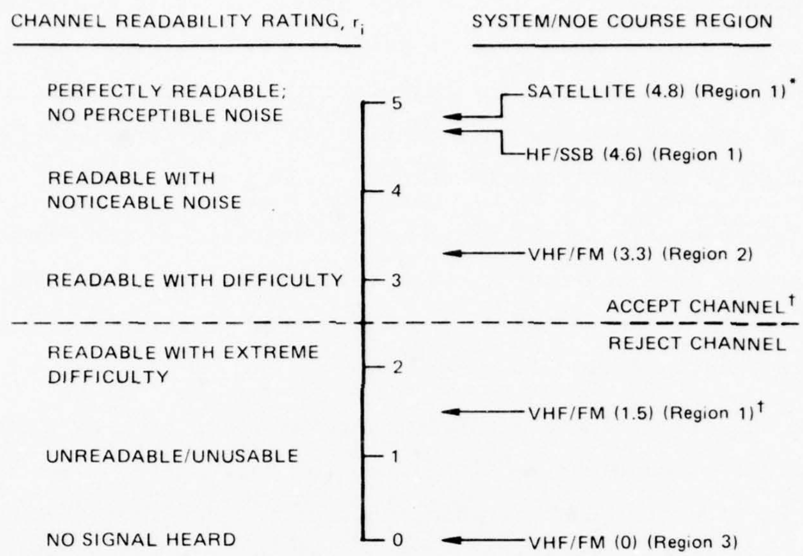
The alphanumeric scores improved dramatically as the aircraft entered Region 2 of the course. The terrain for Region 2 differed from that of Region 1; the ravine of the NOE course, for instance, was less deep there than in Region 1.

Once the crest of the mountain range had been crossed (2500 ft MSL), no transmissions could be received from the base station over the VHF/FM system. In view of the poor performance of the VHF/FM system in two of the three regions for the course, this system was rated unsatisfactory by the pilots for conducting an NOE mission in Hawaii terrain.

Finally, it should be mentioned that SATCOMA used the HF/SSB channel during the satellite experiments as an order wire at numerous locations behind cliffs on Oahu. SATCOMA reported that, even when the satellite was masked by these prominences (which blocked the satellite-to-aircraft downlink, disrupting communication in the satellite system), the HF/SSB order wire continued to function.[1] This suggests the possibility of a combination satellite-HF/SSB system which might be useful for some future applications.

Channel Readability Rating--Each of the test messages taken as the helicopter flew over the NOE course was subjectively rated, using a six-point scale (r_0-r_5), for channel quality. The major attributes included in this rating were message readability, detection of noise, and difficulty in comprehending the text. The results, plotted in Figure B-5 display subjective ratings made by a single listener monitoring the A-N tape recordings in a quiet environment.* This listener was a former Army

*In addition, the Hawaii test pilots subjectively rated the radio systems. These ratings are given in Annex 1 to this appendix.



*Satellite and HF/SSB systems also rated between 4-5 in Regions 2 and 3.

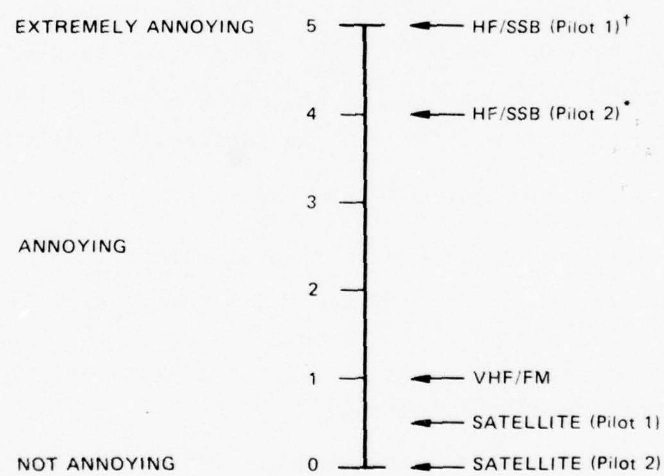
†Channel having subjective ratings of 2 or less were rated unacceptable for NOE missions. Source: Pilot Listener Panel, 115th Aviation Company, Fort Ord, California (3/22/77).

FIGURE B-5 SUBJECTIVE MESSAGE READABILITY RATINGS FOR HAWAII SYSTEMS BY A SINGLE LISTENER IN THE LABORATORY (Based on NOE course audio tape recordings)

officer, with limited military communication experience, but with civilian communication experience as a licensed pilot of private aircraft. He was trained using a sample A-N message tape on which examples of channels possessing different characteristics had been recorded.

Of significance in the attached table is the difference in message readability between the satellite and HF/SSB systems operating in Region 1 of the NOE course, on the one hand, and VHF/FM operating in Region 1, on the other. Satellite and HF/SSB in this region showed essentially identical performance and constituted an acceptable communication link. VHF/FM was readable only with extreme difficulty and provided an unacceptable communication link. In Region 2 the VHF/FM channel readability rating increased to slightly above r_3. In Region 3 it was completely unreadable (r_0).

Channel Noise and Annoyance Factor--For each of the 134 test messages, the annoyance to the pilots of the noise present in the channel was rated. A five-point scale was used, descending from the highest rating (not annoying) to the lowest rating (extremely annoying). The results of this analysis are shown in Figure B-6. The satellite system was rated as having the least bothersome noise. The satellite link operated with a voice frequency-modulated modem. The HF/SSB system operated during the day in the NOE course (and in other areas) was rated slightly more annoying than the satellite system. The VHF/FM system operating in Region 1 had background noise in the channel (radio set and antenna noise) which was extremely annoying to the pilots. The extremely annoying characteristic of the noise in the HF channel was due to an unsquelched receiver, plus the relatively high-volume setting of the receiver output. In Region 2 of the NOE course a better noise rating was assigned to the VHF/FM system falling between annoying and somewhat annoying.



*Pilot 2 rated HF/SSB extremely annoying, because it blocked transmissions from other radios and contributed to pilot fatigue.

†Inability to control loud background noise.

FIGURE B-6 CHANNEL NOISE AND INTERFERENCE ANNOYANCE FACTOR RATING BY PILOTS

The HF/SSB noise ratings were assigned for test messages received in the aircraft during daytime hours. Monitoring of these tapes indicated that almost no local or propagated noise and interference were present on the HF channel during all daytime aircraft flights. However, a test was run during which the operating frequencies were monitored over a 24-hour period. The interference levels present at night were substantially greater than those for daytime. Therefore, if satellite and HF/SSB channels were to be compared over a 24-hour period, the satellite noise factor would remain relatively low (not annoying), whereas the HF noise and annoyance factor (primarily because of interference on the channel at night) would have been significantly higher.

b. HF/SSB 24-Hour Tests

A test was run using HF/SSB radio equipment over a fixed ground-to-ground path for approximately 24 hours. Serving as the transmitting site was the equipment van at the Naval Communications Station, Helemano. The receiving location was a temporary site established at the U.S. Marine Air Corp Station, Kaneohe, on Oahu. The direct path between the transmitter and receiver, a distance of 32 km, was blocked by the Koolau Mountain Range (2700 ft elevation) on the eastern side of Oahu.

The objective of this 24-hour test was to:

- Evaluate the performance of HF/SSB at night.
- Determine the usefulness of the CEEIA ionospheric frequency predictions for a 24-hour period.
- Compare the performance of a dipole (doublet) and whip antenna on the same operating frequency.

The transmitting site at Helemano employed two HF/SSB radio sets. The first set was an AN/ARC-102 (400 W). This set was coupled into a 40-ft-high horizontal dipole antenna (3.300 MHz) and oriented broadside to the transmission path. The second HF/SSB radio set was a vehicle-mounted AN/GRC-106 (400 W) with a 15-ft vertical-whip antenna. The AN/GRC-106 was operated on the following frequencies: 3.300, 2.566, 5.235, 2.020, and 10.130 MHz.

At the receiving site an AN/ARC-102 was connected to a horizontal dipole tuned to 3.300 MHz, thus completing the dipole-to-dipole link. An AN/GRC-106, operating with a jeep-mounted vertical whip in the receive mode, was used to terminate the whip-to-whip link. At 1700 hours (LMT) on 20 August 1976, the 24-hour test was initiated. A-N test messages were sent on preselected frequencies using both the dipole and the whip. The test concluded at 1300 hours on 21 August 1976. Although transmissions were sent both ways, the data were analyzed only from the transmitter at Helemano to the receiver at Kaneohe.

Communication continuity was maintained over this fixed path using several HF frequencies. The results, shown in Table B-3, indicate the presence of a satisfactory communication channel (X) on each of the frequency/antenna combinations utilized. An A-N score of approximately 90 percent or greater was used as an indicater that there was a satisfactory communication channel. A (U) indicates that an unacceptable channel existed.

Table B-3 shows that the 2.566 MHz frequency, which was selected from the CEEIA predictions as the primary nighttime frequency, operated during the entire test interval--1700 through 1300 hours on the following day. However, communication on 3.300 MHz, either on the dipole or whip, was unsatisfactory during the early morning hours (0400 to 0700) because of a strong interfering signal on the test frequency. In general, interference on the channel caused degeneration in the quality of voice intelligibility on all the test frequencies during nighttime hours. Nevertheless, communication was still possible on several of these test frequencies.

An analysis was made of communication effectiveness for the dipole and whip antennas, connected to different radio sets, but which utilized the same nominal rated power. Communication effectiveness, measured as the percentage of correct A-N test messages, was high (100 percent) for each of these two antennas operating at 3.3 MHz. However, other discriminators were used which indicated that the dipole was superior to the whip. During the early morning hours, communication on the test frequency on either antenna was rendered impossible by the strong interference levels

Table B-3

HF/SSB HOURLY COMMUNICATION CONTINUITY
ON GROUND-TO-GROUND PATH (24 HR TEST)
A = Acceptable (A-N Score ≥ 90 percent received)
U = Unacceptable, 0 = No Observation

Local Time	Frequency (MHz)/Antenna				Comments
	3.300		2.566	5.235	
	Dipole	Whip	Whip	Whip	
1700	A	0	0	A	Late afternoon
1800	A	A	A	A	
1900	A	A	A	A	Evening
2000	A	A	A	A	Night
2100	A	A	A	A	Also used 10.13 MHz
--					No data 2200-2400
0100	U	0	A	A	Message quality poor on dipole. Whip not attempted by field personnel. 10.13 MHz unusable.
0200	A	U	A	0	10.13 MHz unusable
0300	A	0	A	0	Whip on 3.3 MHz not tried
0400	U	U	A	0	From 0400-0700, 3.3 MHz unusable because of strong interference
0500	U	U	A	U	Also used 2.02 MHz
0600	U	U	A	0	
0700	U	U	A	U	Morning
0800	A	A	A	A	
0900	A	0	A	0	
1000	A	0	*	*	
1100	*	*	*	*	
1200	A	A	A	A	
1300	0	A	A	A	Also used 10.13 MHz

*Equipment problems, no data

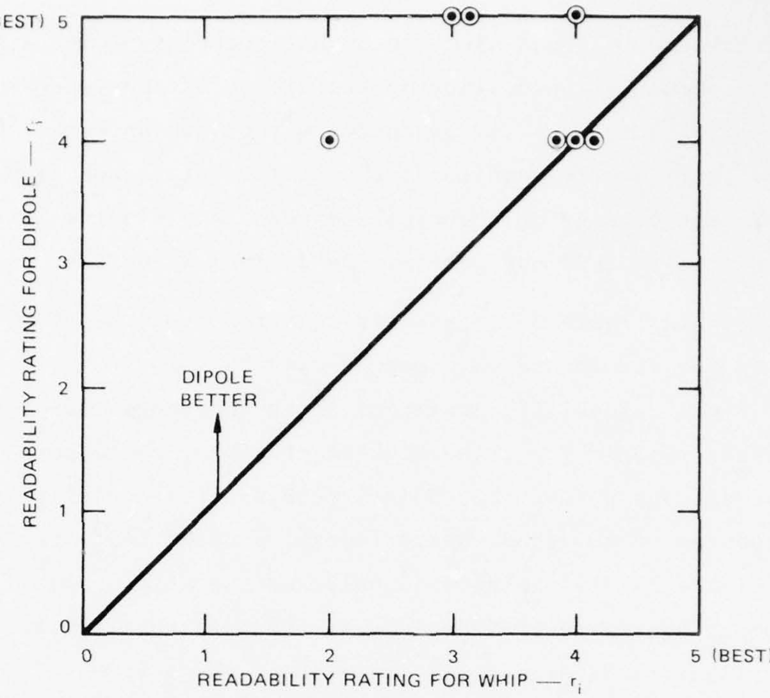
on that frequency. It was also found that coinciding with a marginally acceptable communication quality on the dipole antenna was an unsatisfactory communication quality produced by the whip antenna. During several of their hourly samplings, the field test personnel, after monitoring the test message on the dipole antenna and finding it to be of marginal quality, would not perform the communication test on the whip.

As shown in Figure B-7, a better comparison of the HF/SSB transmissions on the dipole and whip can be made by using the six-point subjective circuit readability scale and noise-annoyance factor ratings. A readability rating of r_5, the highest possible, corresponded to perfectly readable/no perceptible noise. A circuit readability rating of r_0 corresponded to no signal heard (worst). Readability ratings are shown in Figure B-7 for both the dipole and the whip. Data from seven hourly comparisons were considered. As shown in this figure, the readability rating for the dipole was superior to the whip.

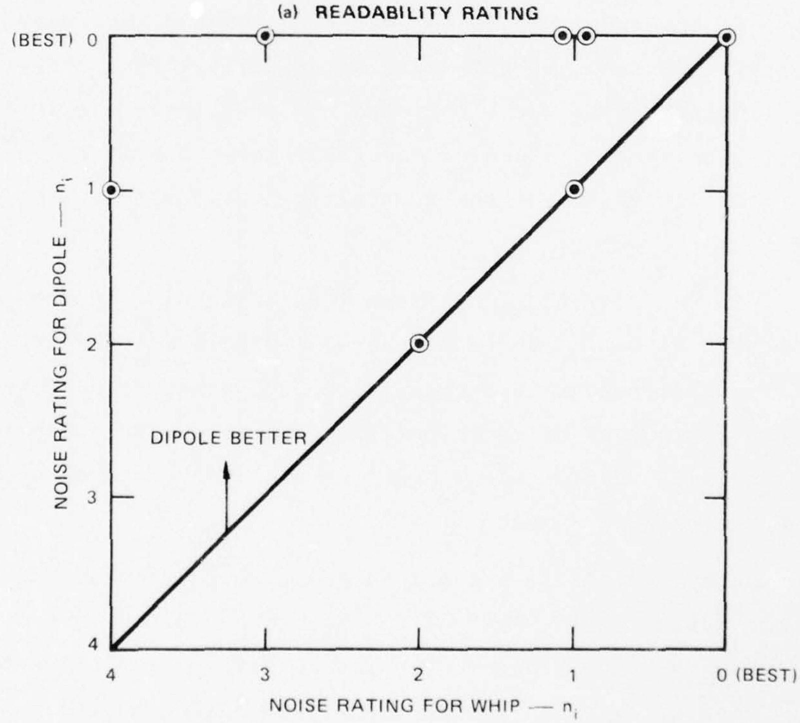
The noise-and-annoyance factor was a second type of comparison between the dipole and whip antennas, using a five-level noise rating. The highest noise rating was a 0 (noise not annoying); the lowest was a 4 (extremely annoying). Based on data from seven hourly comparisons, the results paralleled those for the readability ratings (i.e., dipole equal or superior to the whip).

From this very limited comparison (qualified also by the test geometry employed) it is concluded that the dipole antenna produces a signal having better signal-to-noise ratio characteristics than does the whip antenna. A number of technical factors could cause this result, one of which is the difference in gain toward the zenith between the dipole and the whip on a jeep.[6]

In summary, the dipole and whip antennas appear to produce equivalent results when evaluated in terms of the percentage of correct A-N test messages. However, the dipoles did produce better channel quality. A number of interfering signals were identified during monitoring of the tapes. The authors concluded that the principal factor limiting HF/SSB operation during the 24-hour tests was interference in the channel.



(a) **READABILITY RATING**



(b) **NOISE-AND-ANNOYANCE FACTOR RATING**

FIGURE B-7 COMPARISON OF HF/SSB MESSAGE READABILITY AND NOISE-AND-ANNOYANCE FACTOR USING DIPOLE AND WHIP ANTENNAS (Frequency 3.300 MHz)

c. Other Tests and Observations

Discrete Range Tests--A communication test was run for the VHF/FM system at discrete ranges from the base station. For this test the base station was located at Wheeler Air Force Base, and used an AN/VRC-46 radio set mounted in a jeep with a 12-ft vertical whip. The aircraft flew discrete distances northwest of Wheeler at range intervals 1, 2.5, 5, 10, 15, and 20 km. The 20-km site was located at Dillingham Air Force Base on Oahu. A-N test messages were transmitted from the jeep at Wheeler to the aircraft "skids-on-ground" located at the various ranges. Line-of-sight conditions existed up to the 5-km site. The test frequency employed was 40.3 MHz and the output power of the AN/VRC-46 was measured at 38 W.

Communication from ground to air was maintained at all ranges out to 15 km. At the 20-km location (which was non-LOS to the base station), communication could not be maintained with the aircraft "skids-on-ground." When the aircraft climbed to an altitude of 10 ft (AGL), however, the base station was received in the aircraft. At a distance of 20 km they were separated by mountainous terrain which was vegetated and intersected by ravines. These results indicated a high dependency on communication equipment siting (antenna height) and terrain roughness between the sites.

Two-Way Communication Altitude Tests--Two-way communication altitude measurements from ground to air were made in Region 3 of the NOE course on the eastern side of Oahu. A large mountain range (2500 ft) intersects the path between the base station at Helemano and the aircraft's location. The first measurements were made over a 19-km path from the base station to the aircraft. Squelch-break height for the ground-to-air link for this path was 1600 ft (MSL). The second measurement was over a 16-km path from the base station to the aircraft. Squelch-break height for this path was 800 ft (MSL). Communication altitude was highly dependent on terrain roughness between the sites.

d. Reliability, Availability, and Maintenance (RAM) Information

During the tests, two failures occurred for HF/SSB in the aircraft 400 Hz ac-dc converter and in the power supply of the AN/ARC-102 radio set. These occurred after the aircraft had been operating on the ground for extended periods. In his report, the test engineer hypothesized that the failures had been caused by inadequate ventilation when the aircraft was not in flight. The HF/SSB failures were remedied for the test by substituting other power supply units for the AN/ARC-102.

No failures occurred with the VHF/FM ground and aircraft equipment.

There were three satellite equipment failures during the test. The first involved damage to a UHF preamplifier by a defective RF relay. This failure was rectified by replacing the damaged unit with a spare. The second failure, which occurred in the modulation circuitry of the AN/ARC-171 satellite transceiver, was also corrected by replacing the defective unit with a spare. Finally, a loose satellite antenna cable caused the satellite system to operate intermittently during the early part of the tests. This problem was identified and corrected.

e. Mission Suitability

The candidate radio systems were evaluated by the two test pilots who operated the UH-1 aircraft in Hawaii. Using a specially prepared questionnaire, the pilots were asked to evaluate each of the three radio systems tested on the NOE course with regard to their suitability for supporting a NOE mission. An edited transcript of their comments is attached as Annex 1 to this Appendix. The pilots rated the HF/SSB and satellite systems as equivalent and acceptable for a NOE mission in Hawaii. Both pilots rated the 40-W VHF/FM system as unsuitable for a NOE mission in Hawaii terrain. They complained about the loud rushing noise at the AN/ARC-102 audio output and also about the low audio level present at the output of the satellite receiver in the aircraft. The first complaint could be corrected by a squelch on the HF radio; the second could be remedied by incorporating proper audio drive levels in future satellite installations.

5. Findings and Conclusions

The following conclusions have been drawn from the Hawaii test data:

- The HF/SSB system operated satisfactorily on the NOE course and at all other test locations on Oahu.
- The HF/SSB system operated continuously at 3 and 10 MHz on a flight from Oahu to Molokai (130 km). The satellite system also operated continuously on this flight.
- The satellite system operated satisfactorily everywhere on Oahu, with the exception of deliberate terrain masking of the downlink by SATCOMA during its portion of the tests.
- The satellite and HF/SSB systems had equivalent A-N scores during daytime flights. Subjective message readability ratings also were equivalent (perfectly readable), as was the channel noise degree of annoyance (not annoying).
- The test pilots complained about the noise annoyance (loud rushing sound) of the AN/ARC-102 radio set. This set does not have receiver squelch.
- The limiting factor for the HF/SSB system during the 24-hour tests was the interference encountered at night in the channel. The satellite and HF/SSB systems were not compared for this period. However, it is the opinion of the authors that a satellite channel would have significantly less noise at night than the HF/SSB channel.
- For the 24-hour tests and test geometry the dipole antenna produced a superior signal-to-noise ratio, compared to that produced by the 15-ft jeep-mounted whip.
- For the 24-hour test, circuit continuity was maintained on one of several test frequencies using the AN/GRC-106 whip combination. The AN/GRC-106 and dipole antenna are a satisfactory combination for terminating an air-to-ground or ground-to-ground path when rapid or numerous frequency changes are not required. The AN/ARC-102 was preferred to the AN/GRC-106 because of the relative ease and speed with which it can be tuned.
- The VHF/FM (40-W) set was unsatisfactory on the NOE course. In Region 2 the failure range for the ground-to-air link was 5.5 km.
- The VHF/FM system operating in the unsquelched mode with high audio volume settings produced extremely annoying channel noise.
- The VHF/FM system had the fewest failures (0) during this limited test.
- The test pilots preferred the HF/SSB set (with the audio noise/squelch problem corrected) to the satellite system. Their opinion was based only on daytime comparisons.
- The pilots rated both HF/SSB and UHF satellite channels as acceptable for conducting a NOE mission. In view of its lack of coverage on the NOE course, they rated the VHF/FM system as unsatisfactory.

Annex 1

PILOT COMMENTS ON THE HAWAII TESTS

Introduction

Two pilots participated in the flight tests at Oahu, Hawaii. They were asked for their evaluations of the three radio systems tested, comments as to communication effectiveness for the NOE mission, and their recommendations.

The senior military pilot was a U.S. Army colonel, assigned as the DARCOM aviation officer, Headquarters, Alexandria, Virginia. He has had extensive experience as a communicator and he has logged over 6300 flight hours.*

The senior civilian pilot was a test pilot assigned to the U.S. Army AAD, Lakehurst NAS, Lakehurst, New Jersey. He has had approximately 10 years of experience as a communicator and has logged over 4000 flight hours.†

Their comments on the Hawaii tests, conducted during daytime hours in Oahu, Hawaii, 3-22 August 1976, were dictated in the field. These comments were correlated and organized by the authors to ensure clarity, and to specify the type of mission flown.

Course Description

The first test was flown over a NOE course of approximately 25 km in length, which included cresting a ridge line of over 2500 ft. The course was flown under non-line-of-sight conditions to the base station located at Helemano, commencing 2-1/2 km from the ocean at the entrance to Kawailoa Gulch. In its initial segment the course resembled a 'drain

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*Col. Billy L. Odneal, Project Officer, Flight Simulation, U.S. Army Air Mobility Research and Development Laboratory, Ames Research Center, Moffett Field, California.

†Mr. Jack Morissey, civilian test pilot, U.S. Army AAD, Lakehurst Naval Air Station, Lakehurst, New Jersey.

pipe' starting at the ocean and proceeding toward the eastern mountain ridge. Starting on the northwest corner of Oahu the NOE course continued approximately 20 to 25 km to the east. From an altitude of approximately 150 ft above sea level at the starting point, it increased gradually to approximately 2500 ft and then fell back again to 200 ft.

The maximum bank angle of the aircraft during the NOE course was approximately 60 degrees; air speed varied from zero to 40 knots forward air speed. Flights were conducted during daytime hours only. The aircraft's altitude was approximately 30 ft (AGL) over this course. During the Hawaii tests the VHF/FM and satellite systems were also tested over a 20-km path originating at Wheeler AFB and ending at Dillingham AFB to the northwest. Messages were received in the aircraft at selected range intervals along this path. The aircraft did not fly NOE over this path; however, it was at NOE altitude when receiving the test messages.

Problems in Test Setup

Two problems were created for the pilots by the equipment setup in the aircraft. First, as the receiving equipment was located in the back of the aircraft, they could not control the audio gain of the satellite system. Although the audio level was low, it was easily readable. The control head for the satellite radio was set at maximum volume.

The HF/SSB radio was controlled by the pilots in the front of the aircraft. The major difficulty here was the lack of a squelch and the necessity to turn the RF gain control so high that there was always a loud rushing noise audible. This noise, besides being quite annoying, interfered with other messages that might have to be received during the NOE mission.

Finally, during NOE flight the pilot was unable to switch rapidly from one radio system to the other. Only one radio at a time could be audibly monitored and subjectively evaluated.

Comments on Radio System Capabilities and Limitations

The following capabilities and limitations were observed in the test radios:

(1) The HF/SSB radio was not equipped with squelch. Background noise in the channel produced a loud rushing noise. As it was necessary to run with the RF gain control on a high level, this background rushing noise was extremely annoying.

(2) The comparison tests of VHF/FM and the other systems produced markedly different results in the NOE course, because the aircraft was out of line-of-sight, and VHF/FM came in only intermittently over the entire course. This could have been caused by some bending over hillcrests. The FM was very loud and clear when it did come in. However, it must be emphasized that VHF/FM was not usable in canyons on the NOE course. Some canyons were 300-400 ft deep at places and 500 ft wide. Under these conditions FM was very intermittent. Once we crossed over the eastern 2500-ft ridge line, no FM was received.

(3) The pilot is extremely busy during a NOE flight and is unable to change volume or switch radios for making test comparisons. Therefore, all comparisons are based on the loudest (or the best modulated) frequency that he happens to be listening to at the time. To date the best radio (except for the rushing or squelch noise) has proved to be the high-frequency (HF/SSB) system. It has been reliable in all daytime-flight test situations.

(4) Two external power supplies for the HF/SSB system failed during the tests. Power transformers became overheated and had to be repaired or replaced. This situation was probably caused by the excessive length of the test transmissions, which, it should be noted, were not considered to be typical for tactical applications.

(5) It was remarkable that there was still some FM capability on most places on the island, even below line-of-sight. Nevertheless, the helicopter-to-ground-station link was lost frequently while the aircraft could still hear the ground station. The possibility should be evaluated that some remote ground stations at selected sites (retransmission sites) would suffice for the NOE requirement. However, this might not be possible in fluid combat situations. Use of a remote piloted vehicle (RPV) for radio relay is an alternative solution that should also be investigated.

(6) The FM system is easy to tune, and is relatively free of static and noise. It is readable even when the squelch is disabled.

(7) The UHF satellite radio was clear, but the volume was not as loud as on HF. The volume control, located in the back of the aircraft, was reported to be at maximum for this radio. The UHF satellite radio had no noise or interference, except for a squelch problem which was remedied.

(8) According to the pilots, one reason for the success of the HF/SSB radio was the new shorted-loop antenna provided by ECOM. It works very effectively, probably more effectively than the zig-zag antenna installed on the UH-1.

Pilot Evaluation Questionnaire

The pilots were asked to evaluate each of the three radios tested in the NOE course as to its suitability for an NOE mission. All radios were evaluated on daytime flights only. The pilots rated HF/SSB and satellite as equally suitable to conduct a NOE mission. A questionnaire was completed by the pilots dictating their comments into a tape recorder at the end of the test. The results are shown in Table B-4.

Table B-4

RATING OF CHANNEL SUITABILITY
FOR NOE COMMUNICATION BY HAWAII PILOTS*

Mission Suitability	HF/SSB	Satellite
Better than required	equal†	equal
Communication easily performed	equal	equal
Adequate and acceptable	equal	equal
Extreme difficulty	na	na
Unusable	na	na

*Both pilots rated the VHF/FM system unsuitable for conducting an NOE mission in Hawaii.

†Except that HF/SSB lacked squelch, and that a noise-annoyance condition existed during the intervals between transmissions.

Annex 2

SATCOMA COMMENTS ON THE HAWAII TESTS

The following comments are extracted from the U.S. Army Satellite Communication Agency memorandum on the Hawaii tests.[1]

VHF/FM Performance in NOE Course

Thanks to the high satellite elevation angle, no path shading of the SATCOMA link ever occurred along the NOE course--even at the lowest flight levels. In contrast, the LOS radios (VHF/FM) of the aircraft usually lost contact after their first turn in the NOE valley.

HF/SSB Performance

Except for minor equipment failures, the HF system performed the order-wire function excellently during all SATCOMA tests. HF worked satisfactorily in all situations, including those areas behind cliffs where the SATCOMA link was attenuated or fully blocked. Furthermore, HF never faded on the 90-mile Oahu-Molakai Satellite-versus-HF comparison test, which had been designed to pinpoint the HF skip-zone limits. No skip zone or interference region between skywave and groundwave was detectable. This success is ascribed to the type of polarization achieved with the new airborne shorted-loop antenna (ECOM-loop). All HF tests were performed in the clear voice mode only and, in most instances, used the optimum daytime frequency (3.3 MHz) whenever authorized. Substantial fading occurred during the 24-hour test nighttime experiments. In summary, the HF system proved to be an excellent complementary backup radio for the SATCOMA NOE system.

REFERENCES TO APPENDIX B

1. O. Guzmann and K. Masterman-Smith, "SATCOMA/ECOM NOE Flight Tests," Internal Memorandum, Department of the Army, Headquarters, U.S. Army Satellite Communications Agency, Fort Monmouth, New Jersey (21 January 1977).

2. B. C. Tupper and G. H. Hagn, Test Plan for Hawaii NOE Communication System Tests, Internal Memorandum, Stanford Research Institute, Menlo Park, California (28 June 1976).

3. B. C. Tupper and G. H. Hagn, Frequency Plan for Hawaii NOE Communication System Tests, Internal Memorandum, Stanford Research Institute, Menlo Park, California (9 July 1976).

4. G. H. Hagn, Direct NOE Communication System Comparison Test, Internal Memorandum, Stanford Research Institute, Menlo Park, California (9 June 1976).

5. G. H. Hagn and J. E. van der Laan, "Measured Relative Responses Toward the Zenith of Short-Whip Antennas on Vehicles at High Frequency," IEEE Trans. Vehicular Technology, Vol. VT-19, No. 3, pp. 230-236 (August 1970).

Appendix C

VHF/FM PERFORMANCE DURING EXERCISE REFORGER (1976)

Appendix C

VHF/FM PERFORMANCE DURING EXERCISE REFORGER (1976)*

A division-size exercise, Reforger-76, was conducted in Europe (Fulda Region, West Germany) in 1976 by the 101st Airborne Division (Air Assault). During this exercise both air and ground units encountered a number of communication problems which created difficulties in command and control. Helicopter communications were conducted principally with AN/ARC-114 aircraft radio and AN/VRC-46 ground/vehicular radios. Based on the Reforger exercise after-action report, the problem areas have been identified and summarized below.[1]

Low-Level Communications--The present family of radios is not suitable for aircraft-to-ground communications when the aircraft is flying low-level or contour. Frequency modulation (FM) radio is restricted by line-of-sight transmission, distance, and obstacles. When flying low-level, contour, or NOE, all these restrictions apply.

There is a need for reliable long-range communication between the 159th ASH Battalion and its supported headquarters (DTOC, DISCOM, DIVARTY, Infantry Brigades). Assets of the 159th are deployed throughout the area of operation, often beyond the range of FM.

Tactical Intelligence--Intelligence information was disseminated too slowly, causing UH-1 and OH-58 aircraft to expend valuable blade time. If reliable secure voice (or RATT) had been available, intelligence would have been obtained and disseminated much more rapidly, more targets could have been engaged, and loss of aircraft and crews would have been reduced.

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[1] Reforger-76 After-Action Report, 101st Aviation Group, 101st Airborne Division (Air Assault), Fort Campbell, Kentucky.

*By B. C. Tupper.

Battalion-Attack Team--Clear, reliable, real-time communication from division to battalion and from battalion to attack team is absolutely necessary if the attack battalion is to do its job adequately--namely, to destroy tanks.

Air Defense Threat Reporting--Enemy air defense positions were not reported by the division and its supported brigade. The attack battalion (TOW-COBRA) cannot survive on the mid/high-intensity battlefield without timely, accurate intelligence about enemy air defense artillery (ADA), as well as surface-to-air missile (SAM) locations, troop/vehicle concentrations, and the location of front-line units.

Unnecessary NOE Tactics--The attack battalion lost valuable time using NOE tactics in areas where, given adequate intelligence, faster transit methods could have been used.

Lack of Target Handoff Information--Lack of target handoff information caused the attack teams to search for targets which had been previously acquired.

Lack of Intelligence and Target Information--Lack of intelligence and target information resulted in untimely and suboptimum employment of helicopter units. Five specific problems were emphasized in the REFORGER evaluation:

- Attack teams wasted valuable time by premature initiation of NOE flights.
- Attack teams overflew enemy elements which had moved forward and laterally.
- Enemy elements were misidentified, leading to confusion.
- Employment of attack assets was suboptimum. Attack units directed to large target groupings engaged small enemy units. The ordnance capability of the TOW-COBRA was not matched to appropriate targets.
- Losses to friendly forces occurred because of inadequate ADA and SAM locations.

These examples were cited as deficiencies resulting from communication problems, as well as from problems related to command and control.

Appendix D

SPEECH PROCESSING FOR HF/SSB RADIOS

Appendix D

SPEECH PROCESSING FOR HF/SSB RADIOS*

Speech processing can be used on SSB transmitters which are peak-power-limited,† to improve their performance for voice communications. The ratio of instantaneous peak-to-average power in speech is typically considered to be about 14.5 dB.[1,2] For any given transmitter power, speech processing can decrease the peak-to-average power ratio with a resultant improvement in performance. It also decreases the peak power required to reach the intelligibility threshold of the receiver in the presence of noise.

There are several types of speech processing that can be used to improve the performance of peak-power-limited SSB transmitters; however, some provide better performance than others and they differ in complexity. There are two categories of speech processing commonly used on SSB transmitters: RF clipping or syllabic compression.

For AM double-sideband (DSB) suppressed-carrier signals, the envelope of the RF signal is identical to the envelope of the audio signal modulating the transmitter. For SSB the RF envelope is not identical to

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*By James C. Gaddie, Engineering Associate, Telecommunications Sciences Center, SRI International.

†An investigation of alternative methods for enhancing speech intelligibility through using adaptive filtering of the baseband speech signal was conducted by SRI.[3] The original speech was processed by a linear filter whose transfer function changes with time to match the original speech spectrum. A linear predictive coding technique, such as is under consideration for vocoders, was used. This processing resulted in a sharpening of the formant structure of the processed speech, and was perceived by the listener as producing a penetrating and more intelligible quality than the original speech itself. It is possible that SRI's technique could be usefully combined with the nonlinear processing techniques described in this appendix.

that of the audio signal modulating the transmitter, although they are often somewhat similar. Since the RF envelope of the SSB signal can differ significantly from the audio envelope, there is a potential technical advantage in using the RF-type processor.

It has been found experimentally that 15 dB of audio clipping of more or less constant-level speech reduces the required peak SSB signal power at the intelligibility threshold by 4 dB. Increasing the clipping level to 25 dB gives an additional 1.5 dB improvement.[2] With SSB RF envelope clipping of the same speech followed by a filter to restore the original bandwidth, a clipping threshold set 10 dB below the signal peak reduces the required peak power by 4 dB. A further increase in the clipping level to 20 dB yields an additional 4-dB improvement. This greater magnitude of improvement is due primarily to the lower level of distortion generated. Harmonic distortion generated by clipping the audio signal falls inband whereas the harmonics generated by clipping the SSB envelope fall outside the transmitted bandwidth.

Because of the syllabic character of speech, a syllabic compressor can be used to reduce its peak-to-average ratio. As with clipping, syllabic compressors can work on the audio or RF envelope and, because of lower distortion, better results are obtained for compressors acting on the RF envelope.

Automatic load control (ALC) is used on most modern SSB transmitters to maintain the peak power output of the transmitter under varying input conditions. As a form of RF envelope compression, ALC is also generally used to maintain the syllabic peaks at the maximum peak power output capability of the transmitter. ALC systems generally use fast attack and slow release times and therefore provide compression at the syllabic peak, improving the intelligibility threshold by approximately 1 dB.

A syllabic compressor at the IF stages of the SSB transmitter can be used effectively to decrease the peak-to-average ratio of the SSB speech signal. This type of compressor requires not only a fast attack to follow the rise of the RF envelope, but also a fast decay to track the fall of the envelope. A second SSB IF filter is required at the compressor output to remove those intermodulation products generated by the processes that fall outside the original passband. With 40 dB of peak compression the intelligibility threshold for constant-level speech improves 6 dB for a 6 ms compressor time constant, 5 dB for 11 ms, and 3 dB for 112 ms.

The above figures indicate that clipping of the SSB RF envelope is superior, but that the RF compressor does have one advantage over the clipper: for a given improvement in marginal intelligibility, the compressed RF wave has about 6 dB less third-order IM distortion and about 12 dB less fifth-order IM distortion than the clipped RF wave.

Under nonmarginal conditions, the compressed signal will have somewhat better quality. In the absence of noise, however, either type of processing--RF clipping or syllabic compression--will alter the character of speech. With heavy clipping or fast compression, "breath sounds" and background acoustic noise assume greater significance, making the use of a noise-cancelling microphone very desirable. For operation in the relatively noisy environment of a helicopter, the amount of clipping or fast compression that can be used successfully may be limited by the effects of background acoustic noise (which may also modulate the transmitter). These effects should be considered in selecting the final design parameters, such as the amount of compression or clipping to be used in the speech processing system. The use of speech processing with COMSEC devices must also be carefully considered.[4] Techniques used for unsecured speech processing may not be compatible with the transmission of secured speech. Provisions to deactivate the speech processing circuitry for transmission of secure speech may have to be incorporated in the transmitter. This same argument applies to data transmission.

Four different HF/SSB aircraft radios were used in the NOE test at Fort Hood. The radios were the AN/ARC-70 (operated at 40 W PEP), the AN/ARC-174 (100 W PEP), the AN/ARC-98 (200 W PEP), and the AN/ARC-102 (400 W PEP). All these radios have ALC; in addition, the AN/ARC-174 has a syllabic audio-envelope speech compressor and the AN/PRC-70 has an audio volume compressor.* The AN/ARC-98 and AN/ARC-102 had no speech processing equipment other than ALC.

To evaluate the capability of these speech processing systems to improve communication effectiveness, the 40-km data were analyzed for air-to-ground and air-to-air modes at "skids-on-ground" and NOE altitudes. The data were processed to obtain the percentage of test messages on which the resulting alphanumeric (A-N) scores equalled or exceeded two thresholds: 70% and 90%. Table 1 shows a summary of the transmitting power, type of speech processing, and results for each of four HF/SSB radios tested.

Table D-1

EFFECT OF HF/SSB SPEECH PROCESSING EQUIPMENT UPON A-N SCORE, FM-320, FORT HOOD, TEXAS (1976)†

Radio Type	Power (W PEP)	Speech Processing Equipment	Percentage of Communications Successfully Completed at a 40-km Range	
			A-N Score ≥ 70%	A-N Score ≥ 90%
AN/ARC-102	400	ALC only	81	75
AN/ARC-174	100	ALC plus syllabic audio-envelope compressor	75	67
AN/ARC-98	200	ALC only	51	41
AN/PRC-70	40	Audio compressor plus ALC	46	34

†Data shown are for air-to-ground and air-to-air links, at NOE and skids-on-ground altitudes for dawn, day, and night.

*The characteristics of the AN/PRC-70 speech compression technique were not investigated.

Note that the best performance was obtained with the AN/ARC-102 (400 W) transmitter, followed fairly closely by the AN/ARC-174 (100 W) transmitter. The AN/ARC-98 (200 W) transmitter performance was well below that of the lower-power AN/ARC-174, with which ALC and the syllabic audio-envelope compressor were used.* The performance of the radios was identical at 24 km. Using the AN/ARC-174 transmitter power of 100 W as a reference, the AN/ARC-98 was 3 dB higher in power and the AN/ARC-102 6 dB higher. Thus, the conclusion reached from the data is that the speech processing in the AN/ARC-174 provides at least a 3-dB (but less than a 6-dB) system improvement margin. A conservative estimate based on these data would be that a 4-dB improvement was obtained for unsecured voice with the processor in the AN/ARC-174.

The performance of the AN/PRC-70 speech processor is difficult to evaluate from the data, since no equipment with a power level lower than 40 W was tested.

One of the candidate HF/SSB systems tested, using speech processing, showed an improvement estimated at 4 dB. This system employed ALC and audio-envelope compression. Furthermore, it has been shown in the literature, both theoretically and experimentally, that improvements of up to 8 dB are possible. The feasibility of obtaining improvements greater than 4 dB in any HF/SSB aircraft and ground systems selected for NOE communications should be considered.

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*The AN/ARC-98 tested at Fort Hood was built to specifications provided by ECOM which did not include speech processing. In the voice mode, intermodulation product specification was not less than -30 dB (IMP). This level of intermodulation protection is not compatible with certain types of speech processing circuits. If speech processing circuits had been included in this radio, performance for unsecured voice would have been better.[6] Although SRI did not conduct or observe any HF tests run in the secured mode, we believe that the effect of speech processing on secure voice transmission warrants further investigation.[4]

It is recommended that the HF/SSB transmitter selected for NOE communications be equipped with some type of speech processing to reduce the transmitter power needed to achieve a certain level of performance. The possibly conflicting requirements for a data or secure voice mode (e.g., different AGC time constant) should be further investigated.

REFERENCES

1. E. W. Pappenfus, W. Brune, and E. O. Schoeniki, Single Sideband Principles and Circuitry (McGraw Hill Book Company, New York, 1964).

2. R. L. Craiglow, N. R. Getzin, and R. A. Swanson, "Power Requirements for Speech Communication Systems," IRE Trans. Audio, Vol. AU-9, No. 6, pp. 186-190 (November-December 1961).

3. D. T. Magill and D. J. Fylstra, "Speech Intelligibility Enhancement for the Nap-of-the-Earth (NOE) Communications Program," Task Letter Report, SRI Project 4979, Contract DAAB07-76-C-0868, SRI International, Menlo Park, California (7 March 1978).

4. G. Lane, "Performance Criteria for PARKHILL Secure Voice Operation on Tactical HF Radio Circuits (U)," Technical Report EMEO-PED-78-1, U.S. Army CEEIA, U.S. Army Communications Command, Fort Huachuca, Arizona (1978).

5. W. N. Rousos, Gould Industries (formerly Hoffman NAVCOM Systems), private communication (April 1978).

Appendix E

PERFORMANCE OF FREQUENCY-SHIFT KEYING (FSK)
OVER FM AND HF RADIO

Appendix E

PERFORMANCE OF FREQUENCY-SHIFT KEYING (FSK) OVER FM AND HF RADIO*[1,2]

1. Background

Frequency-shift keying (FSK) modulation has been extensively used by the Army over HF/AM and HF/SSB radio circuits. HF applications have been limited to relatively slow-speed single-channel radio teletype (RATT) for transfer of hard-copy text over tactical links.

FSK is also used for data transfer, as in the TACFIRE artillery fire control system, which uses the AN/VRC-12 family of VHF/FM radio equipment. FSK (binary FM) will be used in SINCGARS when that family of radios becomes operational. FSK modulation is a probable candidate for selective signaling (SELCAL) and frequency scanning for HF/SSB radio used for the NOE program.

Since TACFIRE FSK is to be used with existing and planned VHF/FM radio, any additional data or signaling features used with FM will probably also use FSK. The choice of this type of modulation for FM, although it may not be optimum, is practical, cost-effective, interoperable with digital message devices (DMDs), and performs relatively well when operated above the FM receiver threshold at moderate signaling speeds.

2. FSK over FM Radio

This appendix evaluates two conditions for FSK/FM modulation:

- What is the signaling speed which the FM radio system can support at and above the receiver threshold?

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*This Appendix was prepared by John K. Y. Leung, Research Engineer, Telecommunications Sciences Center, SRI International.

[1]John J. Downing, Modulation Systems and Noise (Prentice-Hall, 1964).

[2]M. Schwartz, W. R. Bennett, and S. Stein, Communication Systems and Techniques, p. 88 (McGraw-Hill, 1966).

- What is the performance of a modified FM radio utilizing FSK modulation?

Certain assumptions are made regarding the noise spectrum:

- The noise spectrum at the FM receiver discriminator output is assumed to be Gaussian. Performance analysis of FSK in Gaussian noise has yielded a very good approximation of the bit error rate (BER) for FSK/FM.
- Because of the complexity of analysis, the actual noise spectrum at the discriminator output (which is of parabolic [weighted] shape) will not be used.

The following assumptions are made for the AN/ARC-114 transceiver:

- The receiver threshold is 0.6 μV open-circuit (0.3 μV across 50 Ω).
- At the threshold a baseband SNR of ~ 10 dB exists.
- The IF bandwidth with a maximum frequency deviation of ± 8 kHz is 16 kHz.
- Baseband width is 3.2 kHz. The deviation ratio (D) for the voice is 8 kHz/3.2 kHz $\approx$ 2.5.
- The deviation ratio for FSK data is estimated at $D \approx 1$.

3. <u>FSK Performance above Receiver Threshold</u>

When the input is a binary sequence of symbol duration T, the power spectrum has the $[(\sin X)/X]^2$ shape, which has a two-sided null-to-null bandwidth of (-1/T, 1/T). Therefore, when the input to the FM is a digital signal, we can consider the message bandwidth to be 1/T.

In FSK, if frequency f_1 stands for "mark" and frequency f_2 stands for "space," the deviation ratio of the FM system is given by

$$D = \frac{(f_2 - f_1)}{T} .$$

Deviation ratio is the same as modulation index and is defined as

$$D = \frac{\text{peak frequency deviation}}{\text{message bandwidth}} .$$

The bit error rate, P_e, of FSK/FM can be approximated in the region above the receiver threshold by

$$P_e = 1/2 \operatorname{erfc}\left(\sqrt{E_b/2N_o}\right) \quad ,$$

where

$$\operatorname{erfc}(z) = \frac{2}{\sqrt{\pi}} \int_z^\infty e^{-t^2} dt \quad .$$

E_b is the energy density per received bit, N_o is the noise spectral density, and erfc is the error function complement. E_b is determined by the transmitter power P_T, and the bit duration T, where

$$E_b = P_T \cdot T \quad ,$$

or

$$E_b = \frac{P_T}{R}$$

where R is the signaling rate. Hence, halving the signaling rate doubles the E_b term.

Bit-error-rate (BER) performance of FSK is determined by E_b/N_o, the ratio of energy-per-bit-to-noise spectral density.

At the receiver, we have

$$(SNR)_{in} = \left(\frac{E_b}{N_o}\right) \frac{R}{B_{IF}} \quad ,$$

where $(SNR)_{in}$ is the SNR at IF of the FM receiver, R is the bit rate, and B_{IF} is the IF bandwidth.

The maximum bit rate, R, for FSK with an IF bandwidth of B_{IF} is

$$R = B_{IF} \quad .$$

Therefore, at the maximum bit rate with D = 1 we have

$$(SNR)_{in} = \frac{E_b}{N_o}$$

and

$$P_e = \frac{1}{2} \operatorname{erfc} (\sqrt{SNR}) \quad .$$

Note that for $P_e = 10^{-5}$, E_b/N_o = 12.6 dB and for $P_e = 10^{-6}$, E_b/N_o = 13.5 dB. Hence, in order to perform with a BER of 10^{-5}, the (E_b/N_o) ratio must be 12.6 dB. It is possible, however, to optimize FSK performance by choosing f_1 and f_2 such that D = 0.7. This value of deviation ratio is used in the SINCGARS-V radio when the input is digital. The corresponding digital performance is[2]

$$P_e = \frac{1}{2} \operatorname{erfc} \left(\sqrt{\frac{1.2\ E_b}{2N_o}} \right) \quad .$$

The gain in E_b/N_o is about 1.2 (0.8 dB) for D = 0.7, as compared to the BER performance when D = 1.

If the deviation ratio is approximately 1, we have f_D = 8 kHz,

$$B_{in} = 8 \text{ kHz} \quad .$$

This is consistent with Section 3.18.5 of the AN/ARC-114 radio specification.[3]

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[3]Military Specification--Radio Set AN/ARC-114( ), MIL-R-55662(EL) Department of the Army, Headquarters, U.S. Army Electronics Command, Fort Monmouth, New Jersey (2 October 1960).

FSK Performance at a Deviation Ratio of 1

Using D = 1, let us estimate the maximum bit rate that the system can support at threshold. We have

$$\frac{E_b}{N_o} = \frac{(SNR)_{in}}{R/B_{IF}} \quad .$$

From Ref. 1, we have

$$(SNR)_{in,\ threshold} \approx 5 + 5 \log_{10} (B/B_m) \quad ,$$

where

$$B/B_m \approx D$$

Therefore, with D = 1, we have at threshold

$$(SNR)_{in,th} = \sqrt{10} = 3.16 = 5 \text{ dB} \quad .$$

At $P_e = 10^{-5}$, we need

$$\frac{E_b}{N_o} = 12.6 \text{ dB} = 18.2$$

and if $B_{IF} = 16$ kHz, the bit rate that the system can support is

$$R = \frac{3.16}{18.2} \times 16 \text{ kHz} = 2.8 \text{ kb/s} \quad .$$

The maximum bit rate with $P_e = 10^{-5}$ at $(SNR)_{in}$ is 2.8 kb/s. This bit rate is for operation at or above the FM receiver threshold $(SNR)_{out}$ of approximately 10 dB; $(SNR)_{in}$ of approximately 5 dB (Figure E-1). If signaling speed were drastically reduced, it would be possible to operate slightly below the $(SNR)_{out}$ threshold of 10 dB.

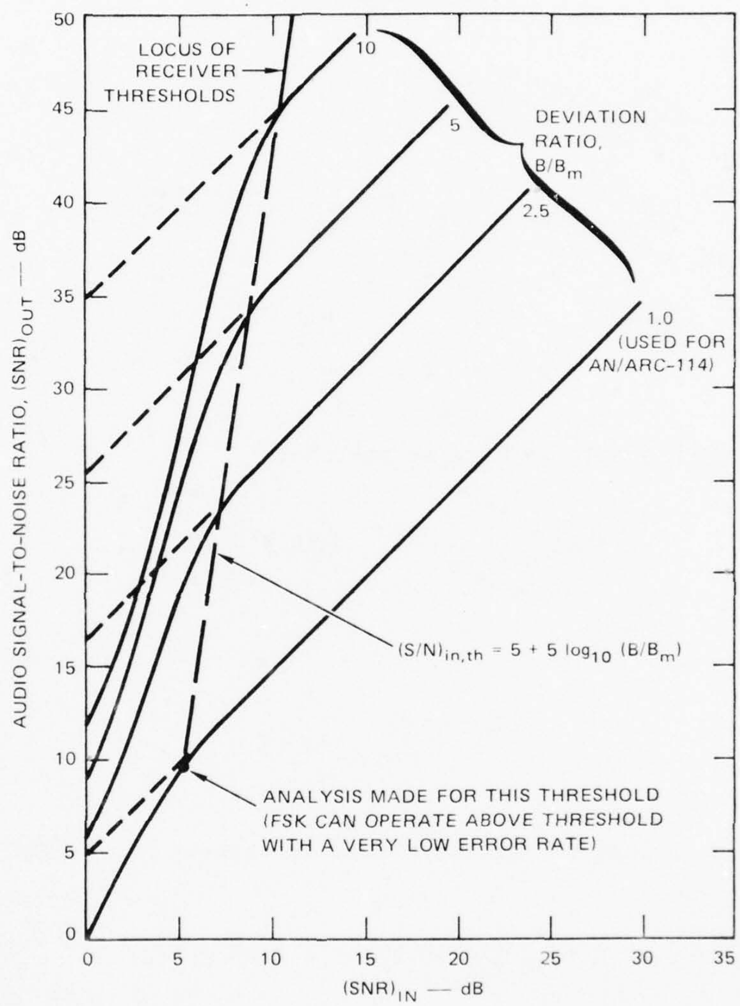

FIGURE E-1 FM THRESHOLD CHARACTERISTICS

If the basic FM receiver were modified by bypassing the discriminator and adding FSK tone-matched filters and a mark-space comparator, the nonlinear portion of the FM receiver curve would be eliminated and substantial improvement achieved for slower-speed digital FSK signaling. With this receiver structure, there would be only a negligible receiver threshold effect or none whatsoever.

An E_b/N_o of 12.6 dB will support a signaling speed of 2.8 kb/s. Halving this signal speed (for a modified receiver) will double the bit duration and increase the E_b/N_o ratio by 3 dB. Hence:

- 1.4 kb/s can be supported at 3 dB below the existing threshold
- 0.7 kb/s can be supported at 6 dB below the existing threshold
- 0.3 kb/s can be supported at 9 dB below the FM receiver threshold.

Hence, if signaling speed is set at 300 b/s for a modified receiver, a 9-dB improvement would be achieved over the existing FM radio.

4. Performance of FSK over HF/SSB Radio

There are three possible future requirements for transmitting data over HF:

- Slow-speed data to implement the selective signaling and frequency-scanning features of the modern HF radio system, recommended as a solution to the NOE communication problem (rate undetermined).
- Slow-speed data to support (or partially support) tactical fire control system (TACFIRE) data links (1200 and 600 b/s, FSK).
- Higher-speed data (2400 b/s) to support future secure voice (vocoder) operation in 3-kHz bandwidth circuits. HF/SSB radio equipment has a nominal 3 kHz baseband width.

Frequency-shift keying (FSK) modulation can be used to transmit data over HF/SSB radios having a nominal 3-kHz bandwidth. Signaling speeds of 1200 b/s are attainable. Assume that two-tone (f_1, f_2) FSK modulation is used within a nominal 3-kHz audio bandwidth and that the tone frequencies are spaced at $0.7 \times 1/T$,* where T is the bit duration

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*The tone spacing of 0.7/T is chosen to optimize FSK performance.[2]

(sec), and R = 1/T = bit rate (b/s). The baseband power spectral density is shown in Figure E-2.

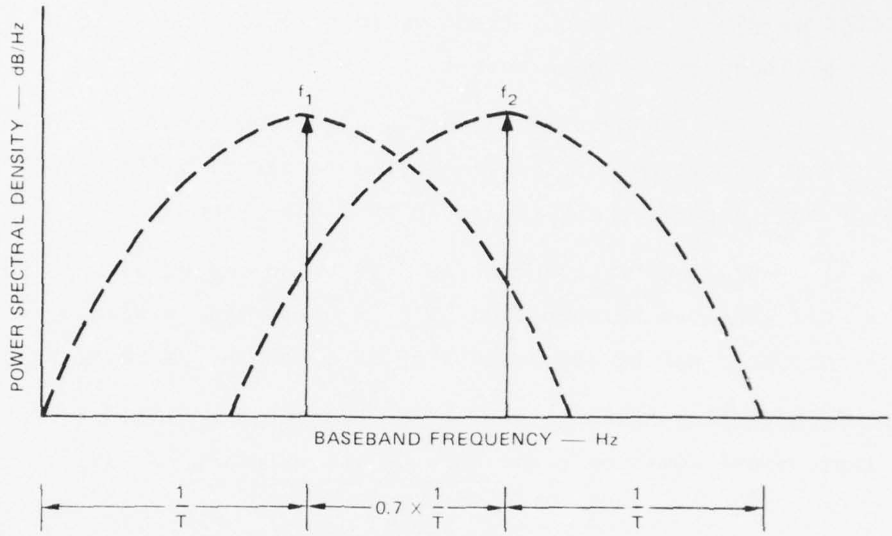

FIGURE E-2 POWER SPECTRAL DENSITY FOR TWO-TONE FSK MODULATION

At the receiver, assume that we filter null-to-null at the edges of the 3-kHz bandwidth. (In practice, the FSK spectrum can be filtered more heavily.) For this case

$$BW = \frac{1}{T} + 0.7 \times \frac{1}{T} + \frac{1}{T} = 3 \text{ kHz} \quad .$$

The bit rate, R, is

$$R = \frac{1}{T} = \frac{3000}{2.7} = 1.11 \text{ kb/s}$$

or, with heavier filtering, $R \approx 1.2$ kb/s. Hence, by using FSK modulation data rates of 1200 b/s (or less) are readily attainable within a nominal 3-kHz bandwidth.

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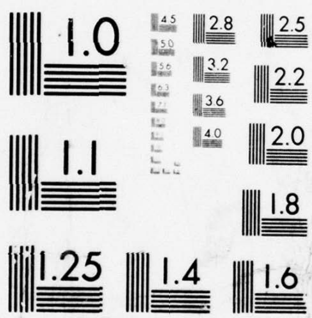

MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

In order to achieve a higher bit rate, such as 2400 b/s, a more complex modulation technique will be required. Multilevel-multiphase modulation is one possibility to be considered in this category.

Appendix F

GAIN AND DIRECTIVITY OF OH-58A HELICOPTER VHF ANTENNAS

Appendix F

GAIN AND DIRECTIVITY OF OH-58A HELICOPTER VHF ANTENNAS*

1. Introduction

The directivity and gain of VHF helicopter antennas strongly influence the performance of VHF/FM radio systems for helicopters flying NOE. However, measured values of the directivity and gain of the VHF antennas on the OH-58A helicopter while flying NOE were not available at the beginning of this study.

Of primary interest are two communication antennas: the FM-1 Tailfin (BHC P/N 206-075-518), and the FM-2 Bent Whip (BHC P/N 206-075-543).[1] The manufacturer's report listed design specifications and presented measured VSWR and field-strength data obtained in flight at 1000 ft altitude at a range of 18 miles.[1] While these data were useful in determining the free-space VSWR and directivity pattern variations, they were not useful for computing antenna gain at NOE altitudes because the transmitter power (P_T) was not specified and the altitude was not NOE. A series of tests was planned by SRI to determine P_T and the directivity and gain for the FM-1 and FM-2 antennas on an OH-58 flying NOE. These tests were conducted concurrently at the Lakehurst, New Jersey Naval Air Station by SRI and the U.S. Army Avionics Research and Development Activity (AVRADA) in April 1977.

The Lakehurst tests included measurements of the forward and reflected power as a function of frequency for the FM-1 and FM-2 antennas. The field strength at 1 km was measured as a function of aircraft altitude and azimuth on selected frequencies. The field-strength data were combined with the net forward power (P_T) data to calculate the antenna gain (G_T) relative to an isotropic radiator (dBi). The Norton model[2]

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*By G. H. Hagn

The FM-2 antenna is located over the cabin roof of the OH-58. It consists of a 22-in. vertical member extending up and forward at an angle of approximately 60 degrees from horizontal, topped by a nearly horizontal 44-in. whip extension aft. The FM-2 antenna, which has a passive matching network, provides vertically polarized radiation with a manufacturer's specified efficiency exceeding 25 percent at 30 MHz and 75 percent at 76 MHz.[1]

The Communications Components Corporation (C^3) of Costa Mesa, California designed a 5-band coupler to improve matching to the FM-2 antenna. The bands are 30-36 MHz, 36-46 MHz, 46-56 MHz, 56-66 MHZ, and 66-76 MHz. The increase in ERP from the FM-2 antenna was measured at the time this coupler was installed.

3. Power Measurements

Forward (P_f) and reflected (P_r) power measurements were made for two AN/ARC-114 transcievers driving the FM-1 and FM-2 antennas of an OH-58A helicopter (Tail No. 68-16806). The OH-58 was stationary on the ground in a large open area, with its rotor parallel to the fuselage. The URM-120 (Serial No. AJD74) power meter was used and the measurements on the FM-2 antenna were repeated several times, but the final measurement was made with a Bird Model 43 wattmeter (Serial No. 204). The results are summarized in Table 1, which also includes the net forward power (P_T). The VSWR was within the design specification of 5:1.

The power measurements were not always consistent. The URM-120 was calibrated on 7 March 1977 and was due for recalibration on 5 July 1977 Therefore the 21 April 1977 measurements were made in the interval between calibrations. As the 50-W element was used, the readings were typically at only 20 percent of the scale; the 10-W element was used whenever possible. Nevertheless, the data are reasonably consistent. A direct comparison between the URM-120 and the Bird Model 43 meter readings was made at 50 to 70 MHz. At 50 MHz, the URM-120 read 10.5W and the Bird 43 read 9.8W for P_T. At 70 MHz, the URM-120 read 3.5W and the Bird 43 read 4.0W.

Table 1

AN/ARC-114 FORWARD AND REFLECTED POWER MEASUREMENTS
OF FM-1 AND FM-2 ANTENNAS ON AN OH-58A HELICOPTER

Frequency (MHz)	FM-1 (Tailfin)			FM-2 (Bent Whip)			FM-2 (Bent Whip)			FM-2 (Bent Whip)			FM-2*
	P_f(W)	P_r(W)	P_T(W)	P_f(W)	P_r(W)	P_T(W)	P_f(W)	P_r(W)	P_T(W)	P_f(W)	P_r(W)	P_T(W)	P_T(W)
30	8.0	2.0	6.0	10.0	2.2	7.8	7.0	1.0	6.0	7.5	2.5	5.0	8.5
35	5.0	1.5	3.5	9.0	0.3	8.7	12.5	1.0	11.5	13.0	1.0	12.0	11.7
40	6.0	1.0	5.0	1.25	0.2	12.3	12.7	1.0	11.7	12.5	1.5	11.0	13.7
45	9.0	1.0	8.0	9.0	1.2	7.8	9.3	0.4	8.9	5.5	1.5	4.5	6.7
50	9.0	0.0	9.0	9.9	1.0	8.9	8.0	0.8	7.2	8.5	0.5	8.0	9.8
55	8.0	0.0	0.0	7.2	0.0	7.2	8.0	0.0	8.0	4.5	0.0	4.5	7.8
60	14.0	0.0	14.0	9.0	0.0	9.0	8.4	0.0	8.4	8.5	0.0	8.5	9.0
65	10.0	0.5	9.5	12.0	0.2	11.8	8.8	1.0	7.8	†	†	†	9.5
70	15.0	0.0	15.0	8.3	2.0	6.3	10.0	2.5	7.5	10.0	1.5	8.5	3.5
75	10.0	1.0	9.0	9.0	0.3	8.7	7.8	0.1	7.7	8.5	0.2	8.3	7.0

*Measured with Bird Model 43 wattmeter

†No data (buzzing noise in headset)

NOTE: One AN/ARC-114 (Serial No. 1599) was connected to the FM-1 (tailfin) antenna, while the other transceiver (Serial No. 425A) was connected to one FM-2 (bent whip over the cockpit) through the C^3 five-band coupler prototype.

The median transmitter power for the AN/ARC-114, operating into the FM-1 antenna, was about 39.3 dBm, the median for the FM-2 antenna's transmitter was about 38.9 dBm. The standard deviations from the median were about 1.8 dB and 1.7 dB for the FM-1 and FM-2 antennas, respectively.

4. Field-Strength Measurements

The field strength from the OH-58A helicopter transmitting system was measured at a distance of 1 km with a Smith Model SM-2S field-strength meter. The Smith receiving antenna was a vertically polarized rod with sloping $\lambda/4$ radial ground-plane elements and with the antenna feed point at 10 ft above ground. The antenna factor for this antenna is given in Table 2.

Table 2

ANTENNA CORRECTION FACTORS FOR ANTENNA OF SMITH FIELD-STRENGTH METER, MODEL SM-2S [dB(m^{-1})]

Frequency (MHz)	30	35	40	50	60	70
Antenna Factor*	-6.0	-3.3	-1.0	+3.0	+6.0	+8.8

*Antenna factor, in dB (m^{-1}), at output of 20 ft-coaxial cable connected to tuned monopole antenna at 10-ft height.

Data were obtained every 30 degrees in azimuth at skid heights of 1 ft and 10 ft. Height-gain measurements were made at skid heights of 0 to 35 ft with the nose of the OH-58A pointing toward the field-strength meter. The measurement at 50 MHz was repeated several times and produced reasonably consistent results. The terrain between the transmitter and receiver was very flat and open. The results of these measurements for the FM-1 and FM-2 antennas are summarized in Table 3. (The C^3 5-band coupler was used with the FM-2 antenna, but without an amplifier.) Table 3 gives the actual measured voltages in dB(1μV). In order to

Table 3

MEASURED VOLTAGE AT 1 km
FROM OH-58A TRANSMITTING ANTENNAS [dB(1 μV)]

Antenna	Frequency (MHz)	Skid Height (ft)	AZIMUTH (degrees)												
			0	30	60	90	120	150	180	210	240	270	300	330	360
FM-1	30	1	39.0	38.0	28.0	35.0	36.0	34.5	33.0	34.0	34.5	32.8	33.6	38.5	39.5
		10	39.5	38.0	31.0	34.5	39.0	39.5	38.0	38.7	38.0	35.0	34.0	40.0	43.0
FM-2	30	0	48.0	46.7	43.2	44.0	44.5	45.8	46.4	46.0	46.2	46.8	46.2	46.5	47.0
		1	46.0	45.5	44.5	45.0	44.5	45.5	46.0	46.0	45.5	45.5	44.5	46.5	46.5
		10	48.0	47.8	46.0	47.0	48.0	48.2	48.7	48.2	49.0	49.0	49.5	50.5	49.5
FM-1	35	1	50.0	47.0	39.0	48.0	46.0	46.5	46.5	45.0	43.0	47.0	44.0	46.5	50.0
		10	50.0	48.0	46.0	50.0	48.5	48.7	49.5	47.5	48.0	49.5	45.0	46.0	50.0
FM-2	35	1	54.0	53.3	50.0	49.0	49.5	53.0	54.5	54.0	52.8	51.5	53.8	53.8	54.0
		10	58.0	57.0	56.0	55.2	55.7	56.0	57.0	56.5	57.0	55.5	57.0	56.0	56.0
FM-1	40	1	47.0	46.4	45.0	45.5	45.0	46.0	45.0	45.0	43.0	44.0	44.5	45.0	46.0
		10	48.5	46.5	45.0	48.3	46.0	47.0	48.0	47.0	47.0	48.0	43.0	46.0	47.0
FM-2	40	1	51.0	50.8	48.0	46.5	45.0	45.5	45.6	46.5	48.0	48.7	50.6	50.7	50.2
		10	53.5	53.5	52.5	51.0	51.5	51.5	52.5	54.5	56.0	56.0	56.2	56.7	58.0
		10	56.0	57.0	56.5	54.0	51.0	55.0	54.5	54.5	55.5	57.0	57.7	59.0	58.0
FM-1	50	1	49.0	48.7	47.5	47.0	49.5	47.8	49.0	48.0	46.0	46.0	44.0	44.0	49.0
		1	53.0	52.0	50.0	48.4	47.5	48.0	49.7	49.0	47.2	46.0	48.0	49.0	50.6
		10	50.0	49.5	51.5	48.0	51.0	51.5	49.0	48.5	47.0	49.0	49.5	49.0	51.0
		10	53.0	48.0	51.0	50.0	49.5	49.0	51.6	53.0	55.0	51.0	54.5	50.0	52.0
FM-2	50	1	48.5	48.4	46.5	43.0	44.0	46.5	46.5	45.0	44.0	44.0	46.5	47.5	47.5
		1	49.0	44.0	46.0	44.0	46.7	48.0	49.0	48.5	47.5	46.0	47.0	47.5	47.5
		10	50.2	48.5	46.5	45.0	48.0	48.0	50.0	49.0	50.0	49.0	50.0	51.0	52.5
		10	56.0	55.7	53.5	51.4	51.5	52.0	53.5	52.5	49.7	46.0	50.7	53.5	56.0
FM-1	60	1	55.0	56.0	57.5	56.4	56.0	55.8	55.3	53.0	49.0	49.0	50.2	50.0	55.0
		10	58.0	58.0	61.0	60.5	63.0	59.0	56.5	52.5	54.5	56.0	58.0	52.0	58.0
FM-2	60	1	54.5	55.0	54.0	52.5	44.0	51.0	52.5	48.5	46.0	52.0	54.0	54.5	54.0
		10	58.6	58.5	60.0	56.0	49.0	54.0	55.6	54.0	50.5	58.0	60.5	60.0	58.0
FM-1	70	1	51.0	50.4	51.0	52.0	50.0	49.2	44.0	44.0	43.0	45.5	44.5	49.2	51.0
		10	52.5	55.0	56.4	55.0	55.5	55.0	53.0	53.0	54.5	52.0	52.0	51.0	55.0
FM-2	70	1	49.0	47.0	45.5	44.5	35.0	31.0	36.5	37.0	45.0	47.2	48.7	49.0	49.0
		10	51.5	50.5	48.0	51.0	47.0	43.0	47.0	48.5	49.5	51.8	52.8	51.0	53.0

obtain the field strength in dB(1μV/m) it was necessary to add the antenna factor in dB(m^{-1}) from Table 2 for the appropriate frequency. The Smith meter had an amplitude-tracking error of up to several dB for small meter deflections. Calibration curves were produced for 50 to 70 MHz (see Figures 2 and 3.) Some of the measured voltages in Table 3 required a meter correction to yield the actual field strength. Additional measurement correction factors for other frequencies are summarized in Table 4.

The antennas on the OH-58A are higher than the skid height reported in Table 3. The actual antenna height depends upon the angle of the fuselage when the aircraft is in flight, although it does not vary to an extreme. To obtain the actual antenna height for the FM-1 and FM-2 antennas, add 5.5 ft and 6.5 ft respectively to the skid height.

The actual measured received voltages with the vertically polarized Smith antenna located 10 ft above ground at 1 km, are summarized in Table 5. The relative height gain in dB can be obtained by computing the difference between these voltages for a given antenna and frequency at the respective heights. For example, there is no height gain for the FM-1 antenna at 30 MHz between skid heights of 0 and 35 ft, whereas the FM-2 antenna exhibited a height gain of +7 dB for the same range.

5. Directivity Patterns

The FM-1 and FM-2 antennas are designed to exhibit a pattern symmetry of generally better than 10 dB.[1] An omnidirectional pattern is required for NOE tactical applications, because the aircraft orientation is then generally random relative to the propagation path direction.

The directivity patterns of the FM-1 and FM-2 antennas at zero degrees elevation angle (skid height = 0 ft) with the OH-58A at NOE altitude can be derived from the measured field-strength data given in Table 3. It should be noted that the FM-2 antenna has better pattern symmetry at the low end of the 30-76 MHz band, whereas the FM-1 antenna has better symmetry at the high end. Both antennas generally exhibit symmetry surpassing the specified value of 10 dB.

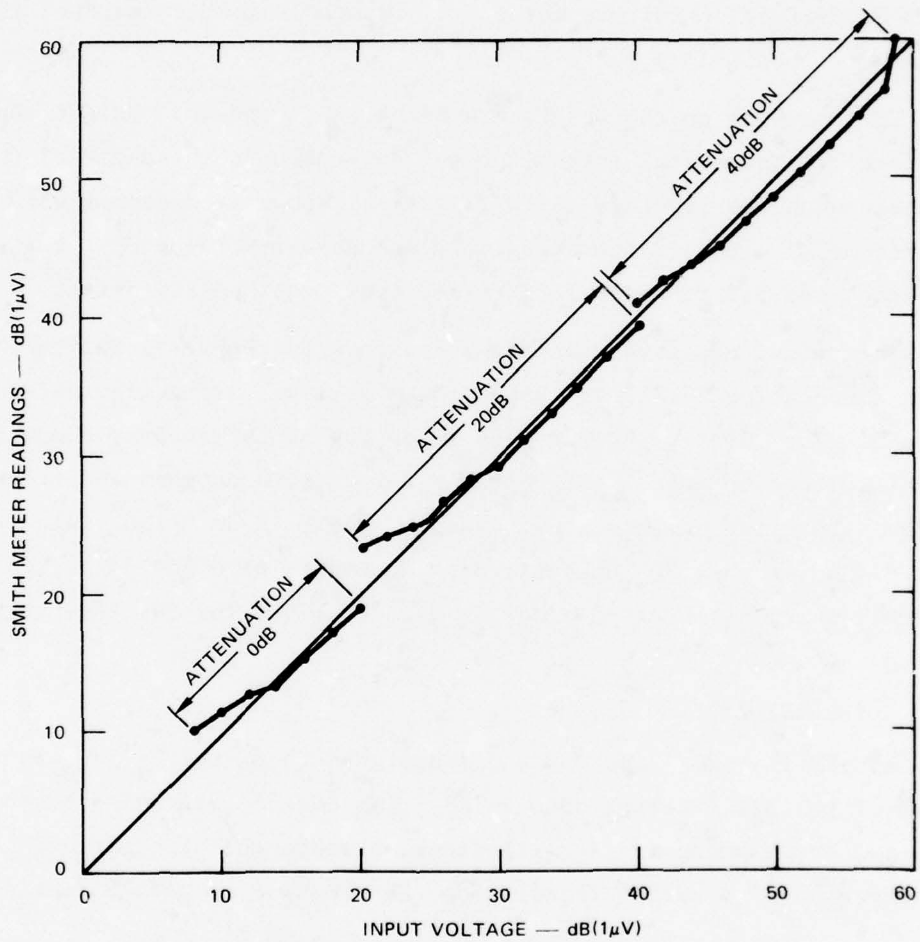

FIGURE F-2 SMITH FIELD-STRENGTH METER (MODEL SM-2S)
AMPLITUDE CALIBRATION — 50 MHz

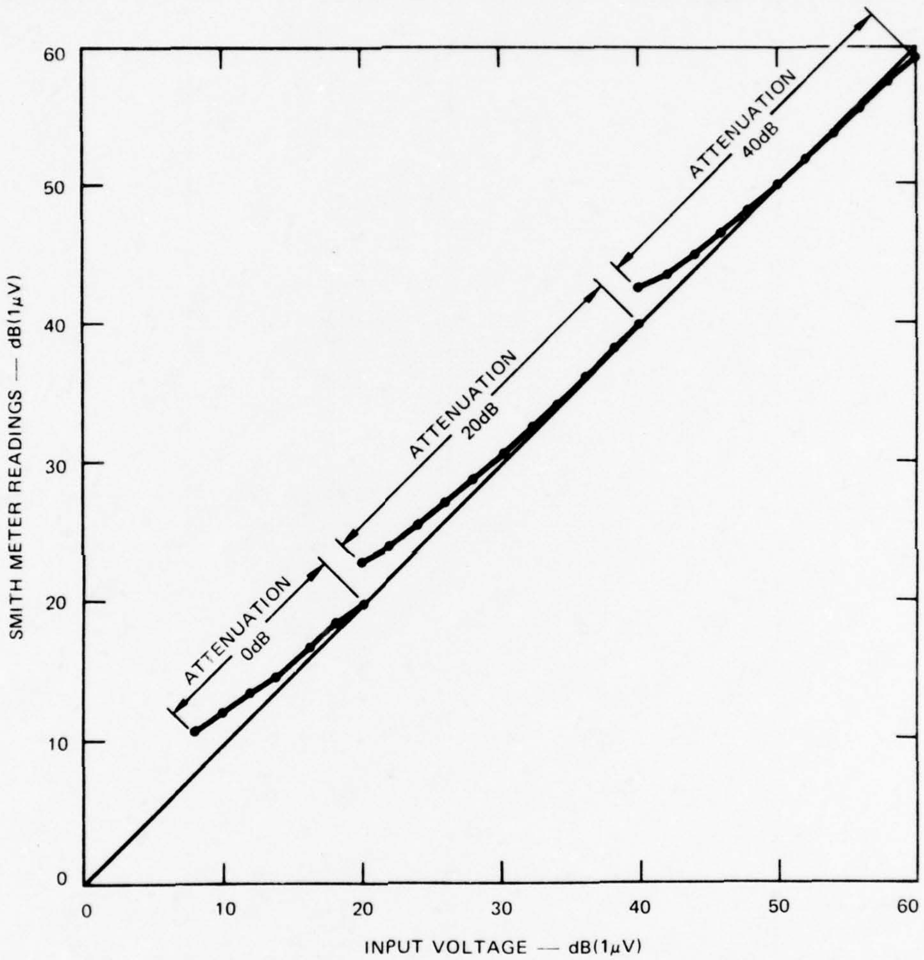

FIGURE F-3 SMITH FIELD-STRENGTH METER (MODEL SM-2S) AMPLITUDE CALIBRATION — 70 MHz

Table 4

MEASURED AMPLITUDE TRACKING ERROR
OF SMI[illegible] SM-2S FIELD-STRENGTH METER

Frequency (MHz)	Attenuation Scale (dB)	Input Voltage dB(1μV)	Meter Reading dB(1μV)
30	0	7.0	7.0
	0	11.0	11.6
	20	30.0	31.7
	40	50.0	50.4
35	0	7.0	7.4
	0	11.0	12.2
	20	30.0	32.0
	40	50.0	50.7
40	0	7.0	8.0
	0	11.0	12.8
	20	30.0	32.6
	40	50.0	51.9
50	0	7.0	7.5
	0	11.0	12.5
	20	30.0	31.5
	40	50.0	50.0
60	0	7.0	7.0
	0	11.0	11.4
	20	30.0	30.2
	40	50.0	49.0
70	0	7.0	7.1
	0	11.0	11.3
	20	30.0	30.2
	40	50.0	48.8

Table 5

RECEIVED VOLTAGE MEASUREMENTS [in dB(1μV)] OH-58A, AT 1 km VERSUS HELICOPTER SKID HEIGHT (IN FEET)

Antenna	Frequency (MHz)	0†	5	10	15	20	25	30	35
FM-1	30	44.0	42.0	43.0	43.0	43.2	43.0	43.0	44.0
FM-2	30	46.5	47.2	48.3	50.0	50.7	51.7	52.5	53.5
FM-1	35	49.0	50.0	50.2	50.4	50.0	49.0	49.0	50.0
FM-2	35	53.3	55.0	56.0	56.5	57.5	58.5	64.0	66.0
FM-1	40	47.0†	46.5	46.0	48.0	51.0	50.0	53.0	54.0
FM-2	40	51.0†	*	56.0	*	*	*	*	*
FM-1	50	46.0	49.0	52.0	54.0	55.0	57.6	58.0	63.0
FM-2	50	50.0	53.0	55.5	58.0	58.2	59.0	59.8	63.0
FM-1	50	46.7	49.6	51.0	52.0	56.0	57.2	60.0	64.0
FM-2	50	50.4	51.8	53.3	56.0	58.0	59.8	61.0	64.0
FM-1	50	49.0	52.0	52.0	54.7	57.0	58.5	59.5	61.0
FM-2	50	48.5†	*	50.2	*	*	*	*	*
FM-1	60	55.0†	59.0	60.5	62.0	64.0	66.0	66.0	67.0
FM-2	60	54.5†	*	58.6	*	*	*	*	*
FM-1	70	46.5	47.5	50.0	55.0	56.0	57.5	60.0	62.0
FM-2	70	45.5	47.5	51.0	53.0	54.0	56.0	57.0	58.0

*No data

†Values with this symbol were taken with the skids at 1 ft.

The directivity of these antennas in free space (at an altitude of 1000 ft and a range of 18 miles) was measured by the manufacturer.[1] These measured field-strength values were converted by SRI to directivity values in dB relative to the gain in the direction of the nose of the aircraft in order to compare the free-space values with those measured at NOE altitude. The free-space directivity values for the FM-1 antenna are summarized in Table 6.

Using the "moment coefficient" technique, Medgyesi-Mitschang and Putnam[3] have modeled the directivity of the FM-1 and FM-2 antennas on the OH-58A as a function of frequency, azimuth, and elevation angle. Matching their results with the data of Table 3, a generally favorable comparison results.

6. Antenna Gains

In the communication system performance model of Appendix A, specification of the median gain of the OH-58A antennas was required for prediction of the operational ranges for the NOE COM candidate radio systems. The Norton[2] model for propagation over a flat earth was used to convert the field-strength values measured at 1 km (for the zero degree heading of the aircraft)* to effective radiated power (ERP) values in dBm at the source for this azimuth. The calculations were made for two sets of ground constants (see Table 7). These values were inferred from Figures III-16 and III-17 of Reference 4. The gain in dB relative to an isotropic radiator (dBi) for the antenna transmitting at zero degrees azimuth G_T (0°) = ERP - P_T. The P_T values were obtained from Table 1. The transmission line losses (L_T) were assumed to be neglible (i.e., $L_T = 0$). Any actual transmission line or matching circuit losses (excluding mismatch losses) were charged against G_T in the system equation of Appendix A.

The field-strength values from all the aircraft skid heights (0-35 ft) were used to estimate G_T (0°) for NOE altitudes, and the results showed good consistency. The median values for the FM-1 antenna for two sets of ground constants are summarized in Table 8. The measured

*Aircraft nose

Table 6

RELATIVE DIRECTIVITY OF FM-1 ANTENNA (in dB)
ON OH-58A AIRCRAFT AT 1000 FT

Frequency (MHz)	Azimuth (degrees relative to nose)												Median Relation to Nose (dB)
	0	30	60	90	120	150	180	210	240	270	300	330	
30.50	0.0	-4.5	-2.3	-2.3	-5.7	-2.3	-2.3	-3.3	-4.8	-0.0	-3.1	-4.2	-2.3
40.10	0.0	-1.0	-9.9	-5.8	-5.8	-7.1	-7.1	-6.6	-3.7	-4.1	-11.8	-1.0	-5.8
46.65	0.0	-2.8	-1.4	-5.6	-2.1	-2.8	-2.6	-2.6	-4.3	-3.7	-0.9	-5.6	-2.8
49.80	0.0	-3.0	+1.4	-1.7	-1.4	-2.6	-2.7	-1.7	+0.5	-2.7	+1.4	-5.5	-1.7
54.50	0.0	-3.5	-0.5	-1.3	-3.3	-2.6	-4.3	-4.6	-0.9	-3.0	+1.4	-2.9	-2.6
60.00	0.0	-2.7	-0.3	-0.7	-2.0	-0.4	-0.5	-0.9	-2.7	+0.5	+1.2	-2.8	-0.6
65.95	0.0	-1.5	-1.1	-2.2	-1.9	-2.6	-1.1	+0.8	-0.5	+0.4	+0.8	-1.2	-1.1
72.05	0.0	-1.8	-1.4	-2.5	-1.1	-3.5	-2.7	-0.6	+1.3	-1.2	-0.6	-1.6	-1.5

Table 7

GROUND CONSTANTS ASSUMED
FOR ANTENNA GAIN CALCULATION

Frequency (MHz)	Conductivity, σ (mho/m)		Relative Dielectric Constant	
	Average Ground	Good Ground	Average Ground	Good Ground
30	2.2×10^{-3}	1.2×10^{-2}	7.5	12
40	2.8×10^{-3}	1.4×10^{-2}	7.5	12
50	3.5×10^{-3}	1.6×10^{-2}	7.5	12
60	4.0×10^{-3}	1.7×10^{-2}	7.5	12
70	4.5×10^{-3}	1.8×10^{-2}	7.5	12

Table 8

MEASURED FM-1 ANTENNA GAINS IN dBi
FOR THE OH-58A AT NOE ALTITUDES

Frequency (MHz)	Average Ground-G_T(0°)	Good Ground-G_T(0°)	Typical Median Values-G_T
30	-18.0 ± 3.0	-20.0 ± 2.0	-19.5
40	-12.7 ± 1.0	-13.5 ± 1.5	-14.5
50	-8.5 ± 1.0	-9.7 ± 1.0	-9.0
60	-3.5 ± 1.0	-5.5 ± 1.1	-4.5
70	-11.9 ± 1.0	-11.9 ± 1.0	-9.9

uncertainties due to different aircraft heights are indicated by ± dB in the table. Typical median values are also given.

The system performance model requires an equivalent standard deviation for the antenna--σ_{G_T} in dB. Estimated standard deviations are summarized in Table 9 for the FM-1 antenna. The data from the FM-2 antenna could also be reduced in this manner, but they were not needed for the modeling in Appendix A, which used only the FM-1 antenna.

Table 9

ESTIMATED STANDARD DEVIATIONS OF FM-1 ANTENNA GAIN, IN dB

Nominal Frequency (MHz)	30	35	40	45	50	55	60	65	70
Bell Report	2	*	3.2	2.2	1.0	1.3	1.6	0.8	0.9
Lakehurst (10 ft)	2.7	1.6	1.6	1.1	1.2	*	4.3	2.1	1.2
Lakehurst (1 ft)	*	*	0.8	*	2.7	*	5.0	3.9	*

*No data

The field-strength values of Table 3 were also analyzed by Mr. J. F. Brune of AVRADA, Fort Monmouth, to estimate the gain at zero degrees in dBi for FM-1, FM-2, and for FM-2 with the 5-band coupler. His results are summarized in Table 10.

7. Acknowledgments

The authors wish to acknowledge the assistance of Capt. Thomas S. Allen, who flew the OH-58A at Lakehurst, New Jersey during the VHF antenna-gain measurements. The authors would also like to acknowledge the assistance of Mr. John F. Brune, who operated the receiver during these tests, and Mr. Frank A. Cansler, who made most of the Thruline wattmeter and VSWR measurements.

Table 10

ESTIMATES OF VHF ANTENNA GAIN (dBi)
AT ZERO DEGREES (NOSE) FOR OH-58 HELICOPTER
AT NOE ALTITUDES

Antenna	Gain at Zero Degrees (dBi)				
	30 MHz	40 MHz	50 MHz	60 MHz	70 MHz
FM-1	-12.50	-10.0	-6.0	-7.5	+1.0
FM-2	-15.0	-8.0	-11.0	-6.5	0.0
FM-2 with coupler	-7.5	-3.0	0.0	-3.5	-2.0

REFERENCES

1. J. G. Mast and R. C. Henschel, "Antenna Development for OH-58A Helicopter (V)," Final Report No. 206-099-212B, Contract DAAJ01-68-1699, Bell Helicopter Co., Fort Worth, Texas (July 1969).

2. K. A. Norton, "The Calculation of Ground Wave Field Intensity over a Finitely Conducting Spherical Earth," Proc. IRE, Vol. 29, No. 12, pp. 623-639 (December 1941).

3. L. N. Medgyesi-Mitschange and J. M. Putnam, "Prediction of VHF/FM Antenna Radiation Patterns," Final Report for Period 15 March 77-14 August 77, Contract DAAB07-77-C-3036, McDonnell Douglas Research Laboratories, St. Louis, Missouri (September 1977).

4. G. H. Hagn and G. E. Barker, "Research Engineering and Support for Tropical Communications," Final Report (covering the period 1 September 1962-15 February 1970), Contract DA 36-039-AMC-00040(E), SRI Project 4240, Stanford Research Institute, Menlo Park, California (February 1970) AD-889 169.

Appendix G

HF ANTENNA GAIN

Appendix G

HF ANTENNA GAIN*

1. Introduction

a. Objective

The gain toward the zenith of the HF antennas used on near-vertical-incidence skywave (NVIS) paths between helicopters or between a helicopter and a ground station is summarized in this appendix.

b. Background

HF near-vertical-incidence sky-wave (NVIS) transmission in the band 2- to 8-MHz was employed successfully during World War II when transmission difficulties were encountered with VHF equipment operating in jungles and mountainous terrain.[1] The NVIS theory was well understood at that time, and half-wave horizontal dipole antennas erected 7 to 30 ft above ground were known to be the best field-expedient NVIS antennas for use with transceivers capable of matching to a low impedance (e.g., 50 ohms).

The use of HF NVIS in the tropics for ground-to-ground links was further studied and improved upon during the Vietnam war.[2,3,4] Helicopters in Vietnam during the final stages of the war were forced to fly at nap-of-the-earth (NOE) altitudes to avoid enemy fire; in this flight mode their low-power VHF communication systems did not perform adequately because of terrain or vegetation blockage of the propagation path. The helicopters, confronted with essentially the same communication problem as the World War II ground forces, could avail themselves of the same general solution (use of the HF NVIS mode). But they also had to cope

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*By G. H. Hagn. Mr. J. C. Gaddie of SRI International and Mr. J. F. Brune of AVRADA contributed to this appendix.

with a new and basic problem: how to equip the helicopter with an HF antenna that would radiate toward the ionosphere as efficiently as possible in the 2- to 8-MHz band. Although some helicopters in Vietnam were equipped with AN/ARC-102s and ZIG-ZAG HF antennas, the NVIS mode was not used to any significant extent. The AN/ARC-102 did not have a squelch, and the continuous background noise of the HF channel was bothersome to the pilots. Besides, the ZIG-ZAG was not a particularly efficient NVIS antenna--for several reasons. Other approaches to the coupling of rf energy to the airframe were sought.

Cincinnati Electronics developed the shorted Transline, consisting of a 1-in. metal tube approximately 10 ft long and supported 8 in. from the skin of the tail boom. This antenna is fed at the cabin end and grounded to the boom at the tail end. The antenna presents an inductive impedance at frequencies in the 2- to 8-MHz band and can therefore be tuned with a low-loss capacitor. (An open Transline exhibiting a capacitive impedance also was developed.) Further development and testing of this antenna were done in 1975 by the U.S. Army Electronics Command (ECOM),[5] and a modified version called the ECOM loop (see Figure F1), was used during the FM 320 operational tests at Fort Hood in 1976.[6] Analytical model predictions of the performance of this antenna above ground of imperfect conductivity have also been made.[7] These studies all indicated that the shorted Transline or ECOM loop provided the best available NVIS antenna for the helicopter.

Several antennas are candidates for terminating the ground end of an air-to-ground NVIS communication link. There is need for a vehicular antenna which can be used while the vehicle is either stationary or in motion, as well as for a fixed based-station antenna. The best antenna in inventory for a moving vehicle is the 15-ft whip bent over the hood.[8,9] This configuration is about 6-8 dB better than a vertical whip for launching the NVIS mode; however, the gain toward the zenith is very low, only about -25 dBi or less on the shortest NVIS paths in the 2-8 MHZ band.[9] On longer NVIS paths (out to 50 or 100 km) the gain is -15 dBi or less, depending on the frequency. For a parked vehicle, the whip gain for the NVIS mode could be increased by 2-3 dB if the whip is tied or propped up so it extends away from the vehicle rather than over the hood.[9] The possibility should be investigated that a vehicular hoop antenna (similar to the aircraft loop) might provide better NVIS performance.

An ionospheric sounder has been used to measure the gain toward the zenith of several field-expedient HF antennas suitable for ground station utilization:[9,10] a half-wave horizontal dipole (doublet), +8 dBi; inverted L (5:1), +5 dBi; 30°-slant-wire, -4 dBi; 16.5-ft whip, -25 to -35 dBi. These gain values are reduced 1-5 dB when the antenna is located in a forest.[10]

Collins Radio has developed several antennas for tactical (short-range) HF use. Among these is the Collins Model 637K,[11] which was used in the FM-320 tests conducted at Fort Hood. Measured data on this antenna, a vertical 15-ft whip on a jeep, and on the ECOM loop are presented in this appendix.

2. Gain of ECOM Loop on OH-58

The gain of the ECOM loop on an OH-58 toward the zenith was measured by J. F. Brune of AVRADA, Fort Monmouth, New Jersey, on a 33-km sky-wave path between Lakehurst and Wayside, New Jersey, in September 1977. During these tests, the OH-58 was sitting with skids on the ground (SOG). Summarized in Table 1 is the gain of the ECOM loop relative to a half-wave horizontal dipole at a 30-ft height. An estimate by the author of the gain relative to an isotropic radiator is also given. It should be noted that the helicopter antenna gain for SOG is usually the worst possible case. The actual optimum antenna height for maximizing radiation toward the zenith depends upon the wavelength and the electrical ground constants, but it is generally between approximately $\lambda/8$ and $\lambda/4$.[10]

3. Gain of Collins 637K HF Antenna and Vertical 15-ft Whip on Jeep

The Collins 637K K-1 series (AN/AS-2259) antenna is a short, drooping fan dipole with 60-ft element lengths and a 15-ft-high center feed.[11] It covers the 2- to 30-MHz band, is portable, and can be erected in an open area by two men in 5 to 10 minutes. The gain of this antenna and

Table 1

NVIS GAIN OF ECOM LOOP
ON OH-58 AIRCRAFT

Frequency (MHz)	Relative Gain* (dB)	Absolute Gain (dBi)
2.1	-18.5	-15
2.3	-15.5	-12
2.6	-14.0	-11
3.2	-13.6	-8
4.0	-14.5	-10
4.9	-13.4	-8
6.0	-10.2	-4

*With respect to half-wave dipole 30-ft above ground

that of a 15-ft whip on a jeep have been measured by J. F. Brune at Fort Monmouth, New Jersey and at Fort Hood, Texas during the TCATA FM 320 tests.[12] These results are summarized here, along with some relative gain data for ground-wave propagation.

The best set of data was obtained at Fort Hood during 2-5 November 1976, using sites S-1 (Radar Hill) and S-2 (39 km from Site 1) (see Figures 1 and 2).

The procedure was to transmit at S-2 with the Collins Transceiver 718U-2B with a 400-W amplifier into an automatic coupler driving a 60-ft slant-wire ($\approx 40^\circ$) antenna oriented with the elevated wire pointed toward S-1* or to transmit into a half-wave dipole (AN/GRA-50), located 40 ft

*Note that the best NVIS configuration for this path would have been to orient the slant wire away from S-1,[2] since the directivity pattern has a null in the direction along the wire.

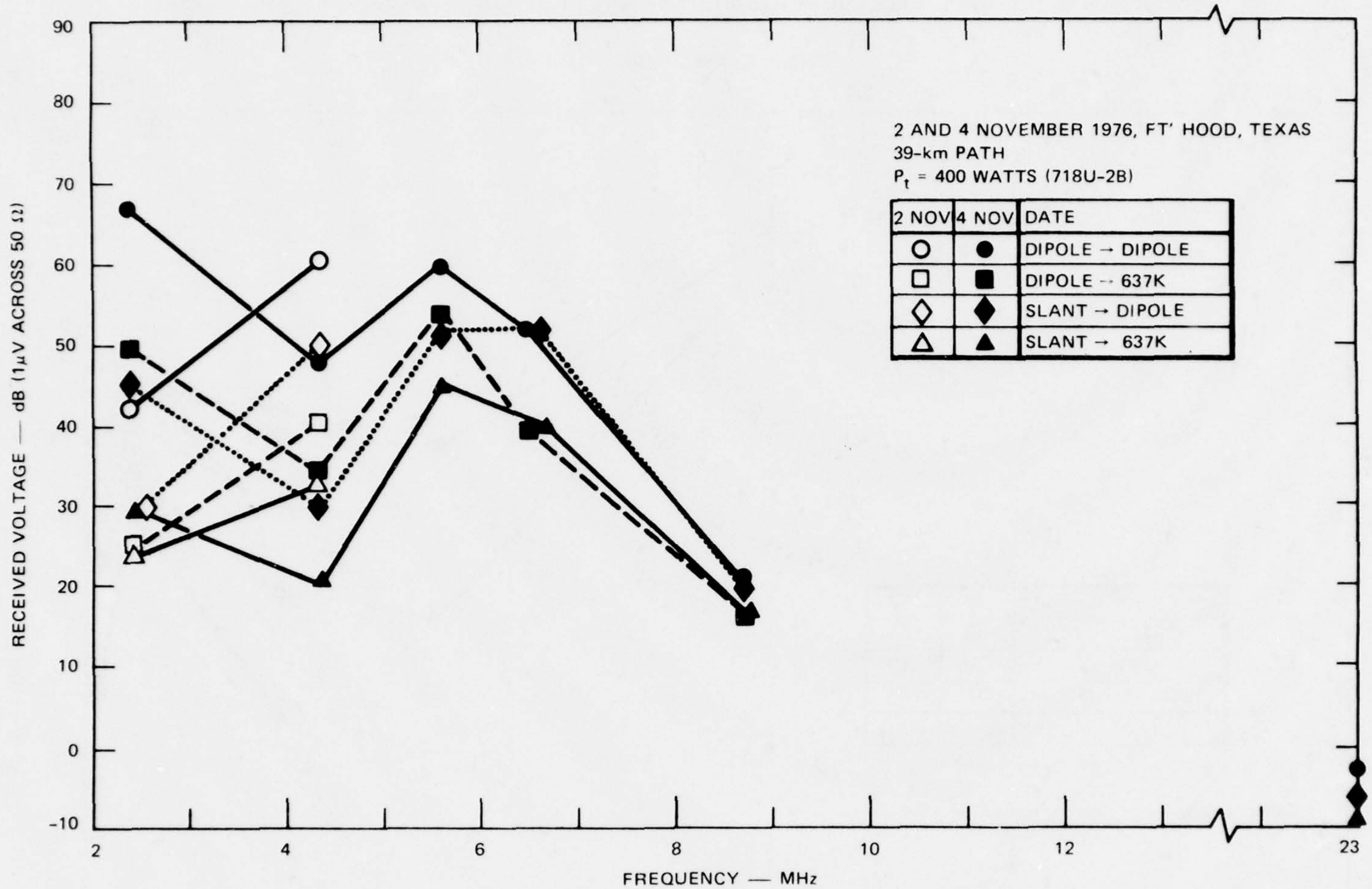

FIGURE G-1 RECEIVED SIGNAL VOLTAGE AS A FUNCTIONAL FREQUENCY, 2 AND 4 NOV. 1976

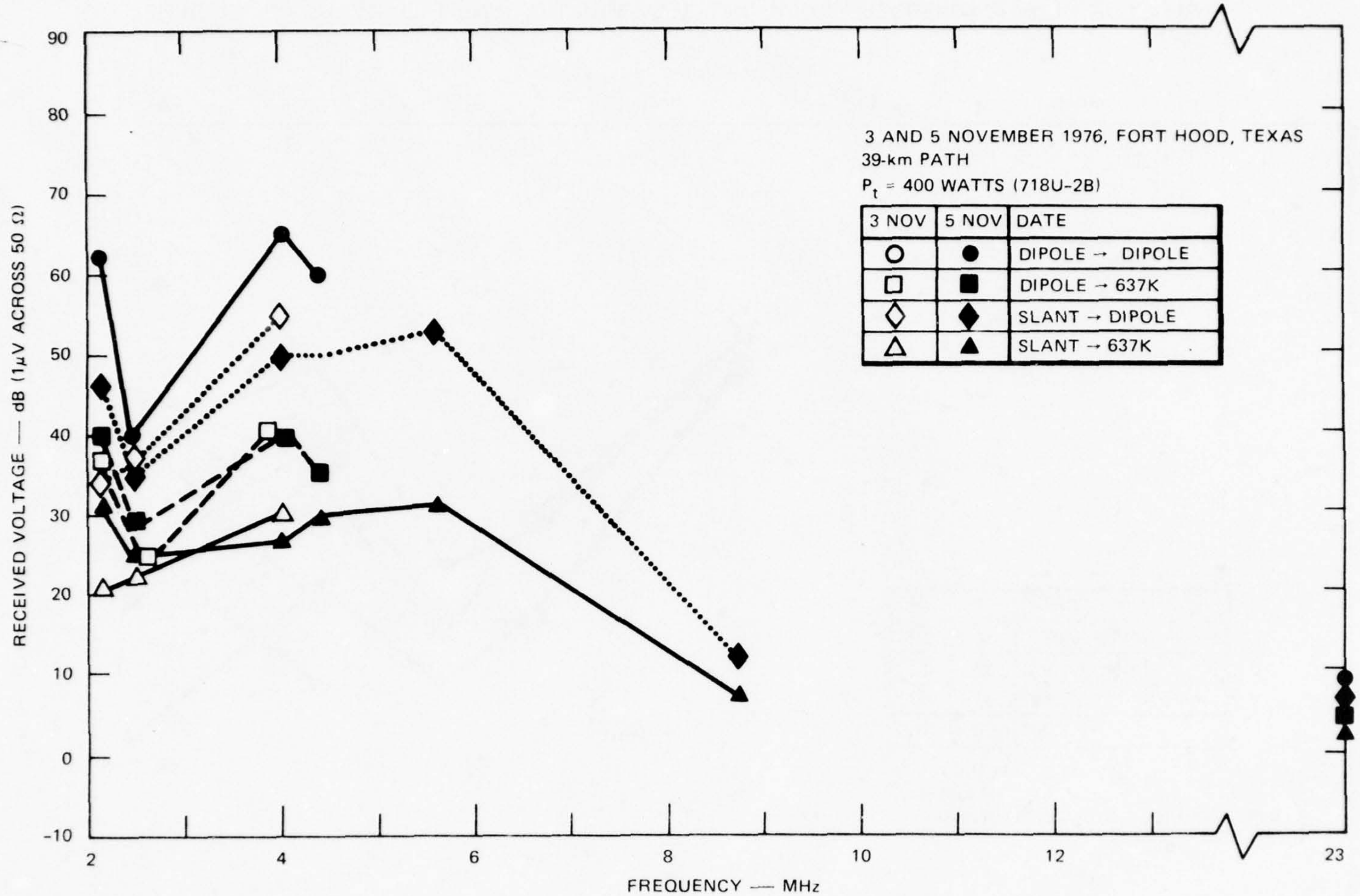

FIGURE G-2 RECEIVED SIGNAL VOLTAGE AS A FUNCTION OF FREQUENCY, 3 AND 5 NOV. 1976

Table 2

GAIN IN (dB) OF THE COLLINS 637K ANTENNA RELATIVE
TO A HORIZONTAL HALF-WAVE DIPOLE AT 40-FEET (39-km PATH)

Frequency (MHz)	Dipole→Dipole / Dipole→637K				Slant→Dipole / Slant→637K				Summary
	2 November	3 November	4 November	5 November	2 November	3 November	4 November	5 November	
2.240	*	-19	*	-22	*	-14	*	-16	-18 ± 4
2.492	-17	-18	-17	-12	-5	-14	-15	-10	-14 ± 4
4.089	*	-20	*	-25	*	-24	*	-23	-23 ± 3
4.370	-20	*	-13	-25	-18	*	-10	-20	-18 ± 8
5.760	*	*	-6	*	*	*	-7	-22	-6.5, -22
6.495	*	*	-12	*	*	*	-12	*	-12
8.715	*	*	-2	-5	*	*	-3	-5	-3.5 ± 1.5
23.485	*	*	-9?	-3	*	*	-4	-3	-3.5 ± 1.5

* = no data

NOTE: Measurements were made during the following intervals:

2 November 76, 1400-1700
3 November 76, 1300-1800
4 November 76, 1300-1730
5 November 76, 1330-1700

above the ground and oriented broadside to the path direction. The receiving antenna at S-1 (39 km away) was either a half-wave horizontal dipole at 40 ft oriented at 45° off broadside or a Collins 637K antenna with its center at 15 ft above ground and the longer elements oriented toward S-2. The measured received voltages are given in Figures 1 and 2.

The gain data for the 637K antenna relative to the dipole on this 39-km path are summarized in Table 2. There were two possible ways to calculate the relative gain of the 637K antenna from the data: 1) take the difference (in dB) between the dipole-dipole and dipole-637K received voltages on a given day and frequency and 2) take the difference between the slant-wire-to-dipole and the slant-wire-to-637K received voltages. The difference in each case is the gain of the 637K relative to the dipole. Relative gain values computed using both methods are shown in Table 2.

Data comparing relative responses of the Collins 637K and a half-wave horizontal dipole at 40 ft were obtained on a 43.7-km path in New Jersey on 4 June and 14 June 1976. The receiving antennas were a half-wave horizontal dipole at 30 ft above ground and the Collins 637K antenna. The gain values are summarized in Tables 3 and 4. On 14 June 1976 data

Table 3

RELATIVE GAIN OF THE COLLINS 637K MEASURED ON A 43.7-km PATH AT FORT MONMOUTH-- 4 JUNE 1976 (1350-1615 hrs)

Frequency (MHz)	Collins 637 Gain Relative to $\lambda/2$ Dipole at 40 Feet (dB)
2.35	-15.2
3.15	-15.2
4.15	-20.2
4.95	-10.1

Table 4

RELATIVE GAIN OF THE COLLINS 637K
AND 15-FOOT VERTICAL WHIP ON A JEEP,
MEASURED ON A 43.7-km PATH
AT FORT MONMOUTH--14 JUNE 1976 (1425-1624 hrs)

Frequency (MHz)	Collins 637 Gain Relative to $\lambda/2$ Dipole at 40-Feet (dB)	15-Foot Vertical Whip on Jeep Gain Relative to $\lambda/2$ Dipole at 40-feet (dB)
2.05	-19.0	no data
2.35	-36.7 (?)	-25.0
3.15	-7.8	-17.8
4.15	-17.0	-14.5
4.95	-13.0	-8.0
5.75	-12.0	-8.5

were also obtained with a 15-ft vertical whip on a jeep transmitting to the dipole. These data are also summarized in Table 4.

There was a general consistency in the results for the Collins 637K antenna; however, several anomalies indicated by a question mark, appeared in these data. The typical NVIS gain of this antenna on a 40-km path, relative to a half-wave horizontal dipole at 40 ft above ground, is summarized in Table 5, which also includes the estimated gain (dBi), based on field measurements, of the 637K antenna. The manufacturer's absolute gain values for this antenna are also presented.[11]

An additional set of data, obtained on 17 December 1976 between 1340 and 1606 hours on a 40-km path, can be used to estimate the relative gain on the 15-ft whip on the jeep. These results are summarized in Table 6.

Table 5

NVIS GAIN OF COLLINS 637K ANTENNA RELATIVE TO HALF-WAVE HORIZONTAL DIPOLE AT 40 FOOT (dB)[12]

Frequency (MHz)	Relative Gain (dB)	Absolute Gain (dBi)	
		Measured	Manufacturer's Estimate
2.0	-19	-15.5	-14.0
2.2	-16	-12.5	-12.0
2.5	-15	-11.5	-9.7
3.0	-15	-9.5	-6.0
4.0	-20	-15	-1.8
5.0	-13	-7	+1.5
6.0	-12	-6	+3.2

Table 6

RELATIVE GAIN OF A 15-FOOT WHIP ON A JEEP MEASURED ON A 40-km PATH AT FORT MONMOUTH, 17 DECEMBER 1975 (1340-1606 HOURS)[13]

Frequency (MHz)	15-Foot Vertical Whip on Jeep Gain Relative to $\lambda/2$ Dipole at 40-Feet (dB)
2.05	-20.0
2.35	-5.0 (?)
3.15	-18.0
4.15	-20.0
5.75	-25.0

The gain values of the 15-ft whip on the jeep relative to a half-wave horizontal dipole at 40 ft above ground for paths of about 40 km are summarized in Table 7. Because of variability in the data, it was not possible to estimate a typical value for each frequency. Some of the anomalous results can be explained by a change in the propagation mode. The orientation of the dipole relative to the path geometry is important for ground-wave paths, but not for NVIS paths. Dipole orientation may have caused some of the inconsistency in the whip antenna results.[2]

Table 7

SUMMARY OF GAIN DATA FOR VERTICAL 15-FOOT WHIP ON JEEP RELATIVE TO HALF-WAVE HORIZONTAL DIPOLE AT 40 FEET (dB)

Frequency (MHz)	14 June 76 43.7 km	17 December 76 40 km
2.05	*	-20.0
2.35	-25.0	-5.0 (?)
3.15	-17.8	-18.0
4.15	-14.5	-20.0
4.95	-8.0	*
5.75	-8.5 (?)	-25.0
6.25	*	*
7.65	*	*
8.95	*	*
10.05	*	*
11.15	*	*
12.05	*	*

* = no data

While the Collins 637K antenna is superior to a vertical jeep-mounted whip for NVIS propagation, the 637K does not appear to be adequate for terminating the ground end of an air-to-ground NOE communications link. Other antennas should be investigated for this purpose.

4. Comments on Ground-Station Antennas for HF NVIS Communications

a. Desired Characterists

(1) The antenna must be frequency-agile with complete coverage of the NVIS spectrum from 2- to 8-MHz (preferably with an upper limit of 10 MHz).

(2) It must have high efficiency and good gain toward the zenith.

(3) It must be simple, easy to install, require a small-to-moderate amount of space and be reasonably portable.

(4) It should have low visibility.

These efficiency and gain requirements are important to ensure that the circuit performance needed will be supported by commensurate transmitting power and to minimize the threat of jamming (EW). High gain toward the zenith is particularly important in the 2- to 4-MHz band, which would include the frequencies most likely to be useful during twilight and nighttime hours, when atmospheric noise is at its maximum level. Frequency agility is essential to compensate for diurnal changes in propagation conditions. The ability to select frequencies for use without antenna restriction is particularly important when one is faced with interference of jamming problems that require a rapid change of operating frequency.

b. Existing Antennas

The half-wave horizontal dipole and the slant-wire are the two antennas currently in use that could terminate the ground end of an HF NVIS link.[8] The dipole is better from the standpoint of NVIS gain,[10] but it requires two towers or other supports, as against only one for the slant-wire. Furthermore, the dipole and slant-wire are both relatively narrow-band antennas. The ideal NVIS antenna would achieve the gain of a half-wave dipole at 30 ft above ground over the entire 2- to 8-MHz band.

One approximation of this is the multifrequency dipole.[3,14,15] This antenna consists of a number of half-wave dipole elements fed by a single coaxial feed line. This type of antenna is also limited by bandwidth restrictions which allow the antenna to operate only in narrow bands clustered around the design frequency of each dipole element. In addition, there is interaction among the individual dipole elements and the antenna is relatively difficult to adjust and moderately difficult to install when more than two dipoles are used. The antenna will not provide the desired frequency agility for spanning the entire 2- to 8-MHz band; however, modifications of this approach may prove to be adequate when used with modern HF radios that have good antenna-matching networks.

Conical doublets (e.g., Telrex TCMD) will operate over a 4-1 frequency range with a dipole-like pattern and over a 8-1 frequency range with a 2-1 VSWR. This antenna, which has three fanned-wire elements, requires two supporting poles 75-85 ft high and 215 ft apart. At frequencies around 6.5 MHz a null will occur toward the zenith because of the high average antenna height. Toward the zenith the gain would be reduced to frequencies as low as 4 MHz. The antenna height could probably be lowered somewhat, but this possibility would be limited by the large fan-out angle required to achieve the wide bandwidth. The relatively large space requirements and support pole height make this type of antenna undesirable from the standpoint of portability and visibility.

The Collins 637K antenna was discussed earlier. A different model may offer better performance at the low end of the band.

Another approach is to use an antenna which is inherently narrowband in terms of impedance, but is easily tuned and has the desired directivity pattern. One such antenna is the small transmitting loop. Such loops have been tested in jungle-type environments, such as Vietnam. Good results have been reported with experimental octagonal loops about

5 ft on each side, mounted 4 ft above ground. Efficiencies of 22 percent at 2.5 MHz and 77 percent at 5 MHz were reported. More efficient loop versions may have been built, and at least one design was commercially available in 1973 from Antenna Research Associates. Their loop was tested in that year by SRI with the Xeledop system.[16,17]

The loop has the following advantages:

- Small and easy to erect.
- Maximum gain toward zenith.
- Can be oriented to null ground-wave interference from one direction.
- Can be tuned to any frequency by an automatic antenna tuner.
- Will launch a vertically polarized ground-wave signal in the plane of the loop.
- Is of relatively low visibility.

The loop has the following disadvantages:

- Efficiency is fair-to-good only when well designed and maintained.
- Construction is very critical, as the loss of signal power at antenna section joints and other structural areas must be kept to a minimum to maintain good efficiency.
- Large conductors with few or no mechanical joints must be used to ensure high efficiency. If mechanical joints are used in loop conductors to improve portability, the loss may increase with age through deterioration of the contact surface during field use.
- Matching components must be very low-loss and must be able to withstand high currents and voltages.
- As the antenna Q is very high, the operating bandwidth about the frequency to which a matching unit is tuned is small.

c. Conclusions

Although the currently existing ground or land-vehicle antennas can be used on NVIS paths with modern HF sets, none of them are truly satisfactory for this application. More work will have to be done in this area.

REFERENCES

1. A. J. Aikens, "HF Sky-Wave Transmission over Short or Moderate Distances Using Half-Wave Horizontal or Sloping Antennas," NDRC Project C-70, Part III, Final Report, National Defense Research Council, Washington, D.C. (15 July 1944).

2. G. H. Hagn and G. E. Barker, "Research Engineering and Support for Tropical Communications," Final Report, Contract DA 36-039 AMC-00040(E), SRI Project 4240, Stanford Research Institute, Menlo Park, California (February 1970) AD-889 169.

3. H. H. Hagn, J. E. van der Laan, D. J. Barnes, D. J. Lyons, J. Chapmen and J. Muro, "Field Tests of AN/GRA-93( ) HF Antenna Kit for Short-Path Sky-Wave Communications in Thailand Forest Environment," Final Report II, SRI Project 6183, Contract DA-28-043 AMC-02201(E), Stanford Research Institute, Menlo Park, California (August 1967) AD 661100.

4. G. H. Hagn and W. R. Vincent, "Comments on the Performance of Selected Low-Power HF Radio Sets in the Tropics," IEEE Trans. Veh. Tech., Vol. VT-23, No. 2, pp. 55-58 (May 1974).

5. J. F. Brune and J. E. Reilly, "Compact HF Antenna (with Propagation Studies)," Research and Development Technical Report, ECOM-4366, U.S. Army Electronics Command, Avionics Laboratory, Fort Monmouth, New Jersey (November 1975).

6. John M. Pinson, John Mellor, William P. Leach, and Robert J. Clelland, "NAP-of-the-Earth Communications (NOE COMMO) System," TCATA Test Report FM-320, RCS ATCD-8, Final Report, TRADOC Combined Arms Test Activity, Fort Hood, Texas (March 1977).

7. L. N. Medgyesi-Mitschang, "Prediction of HF Antenna Radiation Patterns," ECCM Report 75-0907-F, McDonnell-Douglas Research Laboratories, St. Louis, Missouri (July 1976).

8. "Communicating on the Anti-Armor Battlefield," Commandant, U.S. Army Signal School, Fort Gordon, Georgia (7 September 1976).

9. G. H. Hagn and J. E. van der Laan, "Measured Relative Responses toward the Zenith of Short-Whip Antennas on Vehicles at High Frequency," IEEE Trans. Vehic. Tech., Vol. VT-19, No. 3, pp. 230-236 (August 1970).

10. G. H. Hagn, "On the Relative Response and Absolute Gain Toward the Zenith of HF Field-Expedient Antennas--Measured with an Ionospheric Sounder," IEEE Trans. Ant. and Prop., Vol. AP-21, No. 4, pp. 571-574 (July 1973).

11. Instruction Manual for Manpack HF Antennas (637K Series), Collins Radio Group, Rockwell International, Dallas, Texas (1 June 1975).

12. J. F. Brune, memorandum, "Quantitative Field Test Data in Support of FM 320," Fort Hood, Texas (2-19 November 1976).

13. Interim Engineering Report, Airborne Systems and Communications Technical Area, Avionics Laboratory, U.S. Army Electronics Command, Fort Monmouth, New Jersey (10 December 1976).

14. C. W. Bergman and C. Barnes, "An Improved Three-Frequency Dipole," Research Memorandum, SRI Project 6183, Contract DA-28-043 AMC-02201(E), Stanford Research Institute, Menlo Park, California (March 1967).

15. C. Barnes, J. A. Hudick, and M. E. Mills, "A Field Guide to Simple HF Dipoles," SRI Project 6183, Contract DA-28-043 AMC-02201(E), Stanford Research Institute, Menlo Park, California (March 1967-revised June 1968).

16. G. E. Barker, "Measurement of the Radiation Patterns of Full-Scale HF and VHF Antennas," IEEE Trans. Ant. and Prop., Vol. AP-21, No. 4, pp. 538-544 (July 1973).

17. V. D. Cone, SRI International, Private Communication (May 1978).

Appendix H

MEASUREMENTS OF HF AND VHF FIELD STRENGTH VALUES DURING THE FM-320 TESTS

Appendix H

MEASUREMENTS OF HF AND VHF FIELD STRENGTH VALUES DURING THE FM-320 TESTS*

1. Introduction

HF and VHF field-strength measurements were made during the FM-320 tests at Fort Hood, Texas[1] using the actual transmitter and antennas employed during the test. These measurements were made as part of the technical documentation for the Objective 3 (engineering) tests. The HF results were used to help determine when ground-wave and near-vertical-incidence sky-wave (NVIS) modes were involved. The VHF measurements were used to help validate a propagation model used by the DoD Electromagnetic Compatibility Analysis Center (ECAC) in making predictions of VHF coverage for each VHF system involved in the FM-320 tests.[2] The results of these field-strength measurements are summarized in this appendix.

2. HF Measurements

Daytime HF field-strength measurements were made by Mr. B. C. Tupper of SRI International and Mr. J. F. Brune of USAVRADA at Fort Hood 15-19 November 1976 on paths out to 40 km. Two almost identical meters were used: Singer Models NM-25T (Serial No. 413) and NM-26T (Serial No. 04218). Two receiving antennas were used: Singer Model 93049-1 (Serial No. 136) 9-ft rod antenna and Singer Model 92200-3 (Serial Nos. 294 and 353) 15-in. loop antenna. Each system was calibrated for use as a true field-strength meter. The manufacturer's calibration data were used for the loop. The rod was mounted on the hood of a jeep and its antenna factor determined on site in the manner described in Reference 3. While

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*By G. H. Hagn. Contributions by B. C. Tupper (SRI International) and J. F. Brune (AVRADA).

the loop calibration is accurate for both ground-wave and NVIS signals, the rod calibration is accurate only for ground-wave signals.

Two source transmitters located at S-1 (see Figure 4 in the main report) were used at 2.240 MHz and 4.089 MHz: an AN/GRC-106 (AM, 400W) feeding half-wave horizontal dipoles elevated 30 ft, and a Hoffman VCS-801 (AM, 400W) feeding a 30-ft jeep-mounted vertical whip. The AM mode was used to provide a continuous carrier to facilitate data acquisition. During these measurements the loop was oriented for maximum responses, and the maximum, minimum, and average readings were noted during about one minute of observation. Next the loop was reoriented in an attempt to null out the ground-wave signal (if any) and check for the presence of an NVIS signal. Any readings which exhibited fading were noted, and the letter F entered beside the reading. When fading was present it was assumed that the NVIS mode was too. The absence of fading implied ground-wave propagation, although there could also be a ground-wave component mixed into the fading signal which might not always be resolved by the loop orientation check.

The received field strengths were measured at most of FM-320 test points (TPs) indicated on Figure 4. At 2.24 MHz, the Hoffman system (30-ft whip) produced a usable ground-wave signal out to 39 km (at S-2), with no fading observed. The AN/GRC-106 radio (with dipole) system produced a ground-wave out to 23 km, and the level received from the whip and dipole systems was almost identical: +42 dB(1μV/m). At 39 km the dipole produced a fading signal on both the loop and 9-ft rod receiving antennas. At this distance, the ground-wave component from the whip was almost the same as the NVIS component from the dipole measured with the loop: +35 dB(1μV/m). The performance of both transmitters was monitored on the slant-wire antenna at S-2 (described in Appendix G). The whip produced a strong nonfading R-3-quality signal, but the dipole yielded a somewhat weaker, fading signal of R-2 quality. The measured field strengths for 2.24 MHz are summarized in Figures 1 and 2.

At 4 MHz, the Hoffman system produced a ground-wave signal out to 39 km (S-2) without fading as received on the 9-ft whip: +22.5 dB

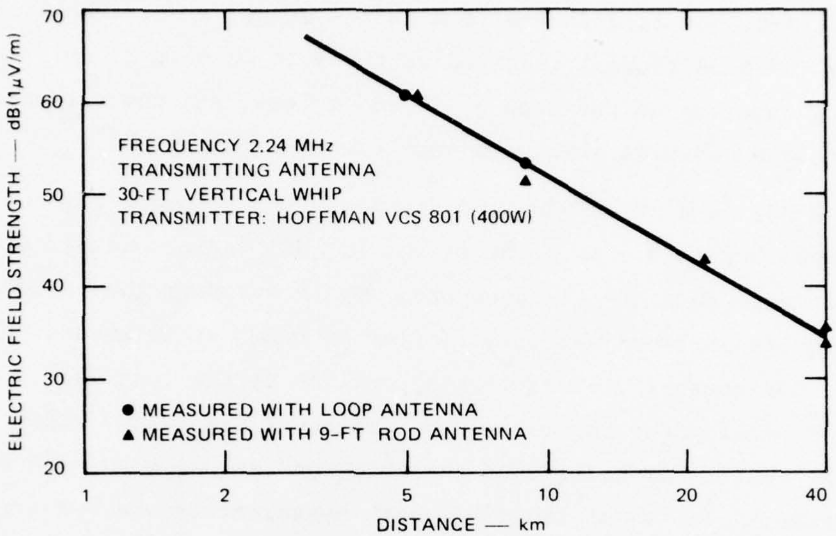

FIGURE H-1 MEASURED ELECTRIC FIELD STRENGTH AS A FUNCTION OF DISTANCE FROM HF BASE STATION, WHIP ANTENNA FM-320 TEST, FT. HOOD, TEXAS (1976)

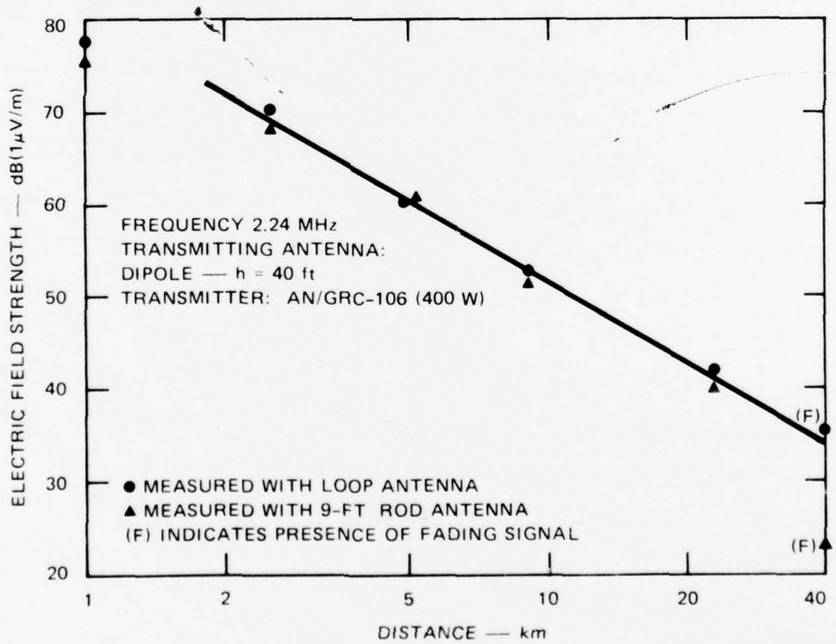

FIGURE H-2 MEASURED ELECTRIC FIELD STRENGTH AS A FUNCTION OF DISTANCE FROM HF BASE STATION, DIPOLE ANTENNA FM-320 TEST, FT. HOOD, TEXAS (1976)

(1μV/m). The loop was not efficient enough to permit reception of this signal at S-2, but it did receive a fading signal about 2 dB stronger than the +33.5 dB (1μV/m) received on the 9-ft whip at 23 km. There was no fading observed on the loop at 10 km or less, and the values measured with the loop and 9-ft whip were very close--within ±2 dB.

At 4 MHz, the AN/GRC-106 and dipole system produced a ground-wave-only signal out to 2.5 km. The slight (±2 dB) fading was perceived on the 9-ft whip antenna at 6 km and beyond. On 19 November the field strength from both transmitters was very similar at 6 km; at 10 km and beyond, however, the average field strength received by the loop was stronger than that received by the 9-ft whip. This was due to the difference between the zenith-directivity of the whip, on the one hand, and the loop, on the other. The 4-MHz field-strength measurements are summarized in Figures 3 and 4.

Reception of the 4-MHz signal from both transmitters on the slant-wire at S-2 produced essentially the same results as the 2.24-MHz check.

One final HF test was performed by transmitting at S-2 with the Collins 718O-2B (400W) and the slant-wire antenna to the 9-ft whip antenna at S-1, 39 km away. The result of this test was that a serviceable circuit was established via ground-wave on 23.485 MHz which (even on a reduced power of 40W) was useful for passing relatively error-free alphanumeric messages. This result was obtained on three separate occasions. At 2.24 MHz a usable nonfading signal was also obtained on two occasions; however, fading was present at 2.492 MHz--indicating a transition from ground-wave to NVIS between these frequencies. Fading was also perceived on the frequencies above 2.492 MHz up to about 9 MHz on this path during daytime. Limited noise measurements indicated that the signal-to-noise ratio was typically about +15 dB.

3. VHF Measurements

Tupper and Brune took some VHF measurements on 17-19 November 1976, using the Smith SM-2S VHF Field-Strength Meter. This meter employs a quarter-wave vertical monopole with a sloping four-element ground plane.

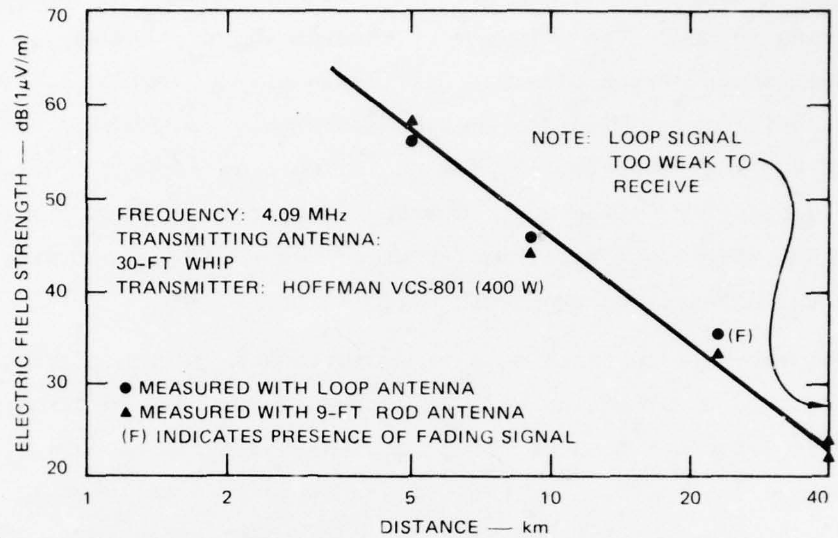

FIGURE H-3 MEASURED ELECTRIC FIELD STRENGTH AS A FUNCTION OF DISTANCE FROM HF BASE STATION, WHIP ANTENNA, FM-320 TEST, FT. HOOD, TEXAS (1976)

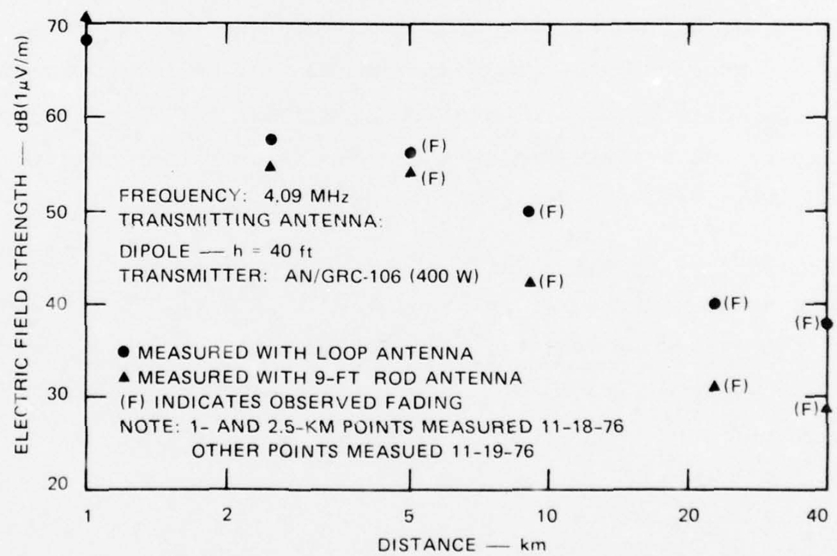

FIGURE H-4 MEASURED ELECTRIC FIELD STRENGTH AS A FUNCTION OF DISTANCE FROM HF BASE STATION, DIPOLE ANTENNA, FM-320 TEST, FT. HOOD, TEXAS (1976)

The antenna feed point is at 10 ft above ground when mounted on the standard tripod. The 65.15 MHz source transmitter at S-1 was the AN/VRC-46 used during the FM-320 test[1]--with a measured output power of 35W driving an RC-292 on a 10-m mast through 100 ft of RG-8. A second identical source on top of Radar Hill was also employed. Because of receiver sensitivity limitation, measurements were confined to ranges of 6 km and 8.7 km, respectively, for these two transmitters locations. On 9-10 December 1976 the authors made additional measurements from the same transmitters, but a calibrated Aiken low-noise preamplifier was used between the antenna and the Smith SM-2S meter.

The procedure for both sets of measurements was to record the field strength at each corner, as well as at the center of a 50-ft-sided square. The median value was then computed, and the variation encompassing all the readings was noted. The results are summarized in Table 1. The measurement locations are the same as the FM-320 test points unless otherwise noted. Radar Hill presented a foreground obstacle for most of the test paths during the FM-320 tests. This obstacle added about 12 dB more loss than would have been experienced had the S-1 site been located on top of Radar Hill where the test coordination transmitter was located for the base station rather than down behind the hill. The optimum hilltop location (siting), would have provided about twice the range for the VHF air-to-ground systems operating on 65 MHz over that inferred from the FM-320 results where "random" siting* was employed.

At several of the test sites it was possible to raise and lower the Smith antenna in order to measure the height-gain effect at 65 MHz. These results, summarized in Table 2, indicate that increasing the antenna height from about 3 m to about 5 m is equivalent to doubling the transmitter power.

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*The base station siting was not truly random, since the site was chosen by the FM-320 test officer to approximate a site he would select in a combat situation (i.e., down behind a hill away from the FEBA). However, this siting would be classified "random" as an input to the Longely-Rice propagation model--for which the hilltop site would be classified as "excellent."[4]

Table 1

SUMMARY OF MEDIAN VHF
FIELD-STRENGTH DATA AT 10 FT

Date (1976)	Distance (km)	Field-Strength dB(1μV/m)		Comments
		Tx atop Radar Hill	Tx at S-1	
12/10	1.0		+37.9 ± 0.5	TP1
11/18	1.0		+44.0 ± 3.0	TP1
12/10	2.5		+23.4 ± 2.3	TP2
11/17	2.5		+28.5 ± 4.0	TP2
11/18	2.5		+25.5 ± 3.0	TP2
11/18	4.5		+23.5 ± 0.5	on top of plateau (elev. 1200 ft) 0.75 km SW of TP3
12/10	5.95		+23.4 ±6.2	UTM 050-401 (1080 ft elev)
12/9	5.95	+57.5 ± 1.1		LOS to top of Radar Hill
11/19	6.0		+22.0 ± 0.5	
12/10	8.66		+8.3 ± 1.8	TP4
12/9	8.66	+32.9 ± 1.1		TP4
12/10	21.7	+10.8 ± 0.0	-1.1 ± 0.5	Cowhouse Creek (elev. 737 ft) UTM 107572
12/10	23.5	+20.3 ± 0.3	+7.8 ± 0.5	ridge coordinate past Cowhouse Creek (elev. 900 ft) UTM 113590
12/10	40.5	+5.8 ± 1.3	no data	TP6 (elev. 720 ft)

Table 2

SUMMARY OF 65 MHz HEIGHT-GAIN MEASUREMENTS

Date (1976)	Distance (km)	Height - Gain (dB)†				
		14 Feet	10 Feet	9.3 Feet	8 Feet	6.5 Feet
12/10	1	*	0.0	-1.2	-1.3	-1.1
	2.5	*	0.0	-0.1	-0.2	-0.8
	5.95	*	0.0	-0.5	-1.9	-2.0
	8.66	*	0.0	-1.3	*	*
	40.5	*	0.0	*	-1.5	*
12/9	5.95	+2.5	0.0	*	*	-2.8
	8.66	*	0.0	*	-1.3	-2.1
"Typical"	all	+2.5	0.0	-0.5	-1.3	-2.0

* = no data

†Gain (dB) referenced to antenna gain measured at 10-ft height

REFERENCES

1. J. M. Pinson, John Mellor, William P. Leach, and Robert J. Clelland, "Nap-of-the-Earth Communications (NOE COMMO) System," TCATA Test Report FM-320, RCS ATCD-D, Headquarters, TRADOC Combined Arms Test Activity, Fort Hood, Texas (March 1977).

2. F. H. Tushoph, "Analysis Support for the U.S. Army Improved VHF Communications Project," Consultative Report ECAC-CR-77-021, Electromagnetic Compatibility Analysis Center, Annapolis, Maryland (May 1977).

3. G. H. Hagn, "Calibration of 9-ft Rod Antenna for MF and HF EMC Measurements," Conference Record, 1978 IEEE International Symposium on EMC, June 20-22, 1978, Atlanta, Georgia, IEEE Catalog No. 78CH1304-5EMC, pp. 160-168 (June 1978).

4. A. G. Longley and P. L. Rice, "Prediction of Tropospheric Radio Transmission Loss over Irregular Terrain," U.S. Dept. of Commerce (ESSA), (July 1968), AD-676 874.

Appendix I

LETTER OF AGREEMENT FOR NAP-OF-THE-EARTH COMMUNICATION SYSTEM

DEPARTMENT OF THE ARMY
Headquarters, United States Army Training and Doctrine Command
Fort Monroe, Virginia 23651
Headquarters, United States Army Materiel Command
5001 Eisenhower Avenue, Alexandria, Virginia 22304

1 DEC 1975

SUBJECT: Letter of Agreement for Nap-of-the-Earth Communication System

1. Title: Nap-of-the-Earth Communication System

2. Statement of Need:

a. There is a need for an improved single-channel aircraft voice communications system which will provide reliable, securable communications from zero to 50 kilometers range, for Army aircraft operating at Nap-of-the-Earth (NOE) altitudes down to and including ground level. The time frame for this system shall be from FY79 to FY85. Successful mission accomplishment and aircraft survivability are dependent on reliable communications necessary in countering an enemy threat, as depicted in TRADOC European and Mid-East Scenarios, which will be a strong air defense and an electronic warfare environment that will be active in the vicinity of the FEBA.

b. CARDS Reference Number: To be determined.

3. System Concept:

a. This system shall provide a means of line-of-sight and/or non-line-of-sight air-to-air, air-to-ground, voice communications at distances of up to 50km to enhance mission performance by aircrews operating in the NOE flight environment. Maximum advantage shall be taken of already existing tactical VHF-FM communications systems by making improvements to increase signal usability where radio line-of-sight conditions are present and to extend communications to non-line-of-sight areas by either airborne High Frequency Single Side Band (HF-SSB) radios, special FM retransmission systems, or a combination of both. The following modes of communications shall be evaluated to determine the capabilities, limitation, and overall effectiveness of an NOE Communication System:

(1) An improved airborne VHF-FM (30-76 MHz) communications system which increases signal reliability and intelligibility, and extends signal penetration in areas of marginal signal reception for maximum line-of-sight tactical communications.

(2) An HF (2-30 MHz) communications system (air and ground) optimized to take

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maximum advantage of the nearly vertical incident skywave (NVIS) mode for short range HF communications coverage where terrain masking obstructs the radio line-of-sight path to include an evaluation of SSB above 12MHz for line-of-sight communications, and a determination of the operational benefits derived from a combination VHF/HF mode.

(3) A VHF-FM non-line-of-sight communications capability using a ground/airborne retransmission as an alternate means of communication.

b. Objectives of this development program are to perform an operational test and analysis of methods/systems that can be used in Army aircraft for NOE communications. This is neither a manufacturer's equipment competition, nor an experimental new technique program, but an operational test and analysis program. Available equipment will be used as required to determine the capabilities and limitations of a suitable concept and method to provide the Army with a viable NOE communications system for the near term. Although it is recognized that this LOA will result in a limited NOE capability with known system limitations, the long term solution using advanced technology as applied to an NOE communications system, should be pursued in such areas as time division multiple access; integrated communications, navigation, and identification; Remotely Piloted Vehicles; Powered, Free Flight and Tethered Balloons; satellite communications; electronic counter counter measures; and small RF repeaters to provide a system that will fully comply with the user needs for the early to mid 1980's time frame.

c. Nuclear survivability is not a potential requirement for this proposed developmental item. Further substantiation and rationale for omitting nuclear survivability will be provided in the ROC in accordance with established USATRADOC procedures.

4. Prospective Relative Effectiveness:

An increase in communications effectiveness of fifty percent over the present day capability is estimated. This in turn should lead to an increase in mission accomplishment of from forty to sixty percent, with the higher increases in the missions of reconnaissance, target acquisition and handoff and aerial firepower. A more refined estimate of the improvement in communications effectiveness and mission accomplishment will be made as the system parameters are more fully explored in the concept formulation phase..

5. Prospective Upper Limit of Unit Cost:

ITEM	MAX. UNIT COST ($K)
HF-SSB Air	25
HF-SSB Ground	28
Improved VHF-FM	4
VHF-FM Retransmission	18

6. Investigation Needed to Develop:

TRADOC, jointly with AMC will prepare a Concept Formulation Package (CFP) for the NOE Communications System to consist of a Trade-Off Determination (TOD), Trade-Off Analysis (TOA), Best Technical Approach (BTA), and Cost and Operational

Effectiveness Analysis (COEA). This will include the results of the following investigations:

a. Operational employment concept:

(1) TRADOC, with AMC support as needed, will develop the doctrine and operational concepts, determine training requirements, and conduct such field tests and experiments as will be required to determine system adequacy.

(2) TRADOC will prepare the test plan, provide test bed aircraft and ground support, install the equipment and prepare a test evaluation report. This report will contain an assessment of which mode or combination of modes best achieves NOE communications.

b. Technical concepts:

(1) AMC will carry out a technical test and evaluation program consisting of experiment design, provide all necessary test hardware, actively participate in and support the test program and assist in preparing the Concept Formulation Package (CFP) by providing technical data, cost information and such other support as required.

(2) The technical results of this effort will be combined with all other experimental data (e.g., previous test results, TACSATCOM, PLRS, etc.) and presented at a scheduled IPR at which time authority and funding approval will be obtained for the acquisition of a viable NOE communications system.

c. Foreign Intelligence will be utilized to provide enemy doctrine, techniques, and capabilities to jam, deceive, detect, and direction find this system.

d. Logistical Support concept: TRADOC will provide necessary information and such support as required to AMC in the development of logistical support concepts for the NOE communications system. AMC, in conjunction with TRADOC, will determine the logistical implications of the system on current and planned logistical doctrine. Research in Human Factors Engineering is required during development, test and analysis of methods/systems that can be used for NOE communications.

e. RAM aspects. AMC, jointly with TRADOC will develop appropriate failure definitions and scoring criteria. In addition, a baseline analysis of all relevant RAM data will be performed to determine the quantitative RAM requirements which will be included in the subsequent ROC or LR.

7. <u>Unknowns to be Resolved:</u>

a. Quantitative data as to the degree of increased communications effectiveness of improved VHF/FM.

b. Capabilities/limitations of HF-SSB for NOE Communications.

c. Quantitative data as to the degree of increased operator training and communications planning required for utilization of HF-SSB systems.

d. Quantitative data as to the increase in communications system effectiveness and area coverage obtained through use of FM retransmission equipment for special applications.

e. Performance of a combined VHF/HF radio in an NOE environment.

8. Technical Risks:

All applicable subsystems technology has been previously demonstrated. program is low risk.

9. Schedules and Milestones:

Program Start	Aug 75
Propagation Analysis Completed	Aug 75
Coordinated Test Design Plan Start	Sep 75
Coordinated Test Design Plan Completed	Feb 76
Program Review	Apr 76
Equipment Available for Test	May 76
Field Tests Started	Jul 76
Concept Formulation Package Initiated (CFP)	Sep 76
Field Test Completed	Oct 76
ROC (LR) Initiation (if appropriate)	Nov 76
MASSTER Test Reports Published	Jan 77
ROC (LR) to TRADOC	Mar 77
IPR	May 77
ROC (LR) to DA	Jun 77
HF IOC	May 79
FM IOC	Sep 79

10. Critical Issues for Test: 1 DEC 1975

a. Will an HF-SSB system provide an acceptable level of communications reliability under NOE flight conditions, and how does it relate to NOE mission effectiveness?

b. To what extent will operator training and communications planning for missions need to be modified to take advantage of the increased communications provided by NOE Communications System?

c. Are the present generation ground HF-SSB radio set (AN/GRC-106) and its antenna system suitable to terminate the air-ground link of NOE communications system?

d. Will the space, weight, power, and antenna requirements of an HF-SSB system be compatible with the airframe of attack, utility, cargo, and observation helicopters?

e. To what degree can the airborne VHF-FM system be improved and how does it relate to NOE mission effectiveness?

f. Is retransmission a viable alternative?

g. What benefits accrue to the use of a combined airborne VHF/HF radio?

h. To what degree will enemy electronic countermeasures effect NOE communications?

11. Funding:

Summary of estimated range of research and development costs as defined in AR 37-18 is expressed in inflated FY-74 dollars ($M-millions). (These costs do not provide for Fast Frequency Hopping or other counter countermeasure capabilities).

a. Advanced Development (6.3)[1,3]

	LOW	HIGH
FY	$1.245	$1.494

FY-75	FY-76	FY-7T	TOTAL
$.440	$.680	$.125	$1.245

NOTE 1: Quantity of Prototypes - 1 Complete System: Defined as all the items required to conduct a successful test program whose objective is to achieve resolution of the critical issues of test.

1 DEC 1975

b. Engineering Development (6.4)[2,3]

		LOW	HIGH
		$0.550	$0.686

FY-77	FY-78	TOTAL
$.300	$.250	$0.550

NOTE 2: Quantity of prototypes - 2 Complete Systems: Includes 2 each of all the necessary airborne and ground equipments required in an ED configuration. These systems will incorporate the necessary modification and/or design changes required as a result of the test program.

NOTE 3: Composite indices have been used in accordance with the guidance provided on 23 Oct 74.

c. Flyaway Cost and Quantity Estimate:

ITEM	UNIT COST ($K)	QTY	LEARNING-SLOPE
HF-SSB Air	$20	5500	85%
HF-SSB Ground	$23	1000	85%
Improv VHF-FM	$ 3	7500	85%
VHF-FM Retrans	$15	500	85%

HARRY A. GRIFFITH
Brigadier General, USA
Director of Research
Development and Engineering

for W.H. VINSON, JR.
Major General, GS
Deputy Chief of Staff
for Combat Developments

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