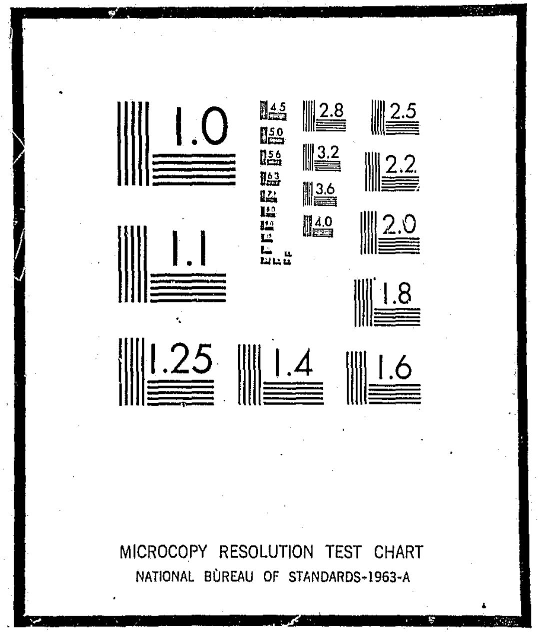

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Aerospace Report No.
TOR-0073(3653-01)-1

ASSESSMENT OF TECHNOLOGY APPLICABLE TO BODY-MOUNTED ANTENNAS

Prepared by

H. E. King and C. O. Yowell
Electronics Research Laboratory
Laboratory Operations

MARCH 1973

This project was supported by Air Force Contract Number F04701-C-0073 through an inter-agency agreement, IAA No. LEAA-J-IAA-035-2, between the Space and Missiles Systems Organization, Air Force Systems Command and the Law Enforcement Assistance Administration, U.S. Department of Justice, under the Omnibus Crime Control and Safe Streets Act of 1968, as amended. Points of view or opinions stated in this document are those of the authors and do not necessarily represent the official position or policies of the U.S. Department of Justice.

Law Enforcement Development Group
THE AEROSPACE CORPORATION
El Segundo, California

Prepared for

LAW ENFORCEMENT ASSISTANCE ADMINISTRATION
U. S. DEPARTMENT OF JUSTICE

Contract No. F04701-72-C-0073

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Prepared by

H E King
H. E. King, Head
Antenna and Propagation Department
Electronics Research Laboratory

C. O. Yowell
C. O. Yowell
Electronics Research Laboratory

Approved by

A H Silver
A. H. Silver, Director
Electronics Research Laboratory

H. W. Nordyke
H. William Nordyke
Director, Law Enforcement and
Adjudication Systems
Law Enforcement Development Group

John O. Eylar, Jr.
Director, Law Enforcement
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AHSilver
A. H. Silver, Director
Electronics Research Laboratory

H.W. Nordyke
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ABSTRACT

An assessment of the technology of body-mounted antennas is presented that includes a survey of the radiators applicable to the Law Enforcement Assistance Administration (LEAA) police personal radio. A discussion of electrically small antennas provides an understanding of the limitations in antenna efficiency, bandwidth, and of the near environment. The antenna technology is drawn from the open literature and from DOD and NASA experiences with their manpack antennas for the foot soldier and Apollo astronauts. The effect of the human body on the antenna radiation patterns is shown. Data are included for the antenna at waist level and in a hand-held position. Other factors, such as biological effects from a transmitting antenna very near to the human body, propagation losses, and RF noise in the VHF-UHF spectrum, are discussed briefly.

A test plan for laboratory measurements of candidate antennas and body effects experiments is outlined. These tests will be performed by the Electronics Research Laboratory of The Aerospace Corporation.

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PREFACE

The Aerospace Corporation, under contract to the Law Enforcement Assistance Administration, is determining the feasibility of a body-mounted antenna for use with police transceivers. Experience with the construction, operation, and testing of electrically small antennas is being utilized by personnel of The Aerospace Corporation's Electronics Research Laboratory, which is also involved in U.S. Air Force Advanced Ballistic Reentry Systems (ABRES) and space system projects. The development work is being done in two phases. The first phase, accomplished during the period 11 September through 31 October 1972, called for an assessment of technology that would be applicable to the development of a body-mounted antenna; that work is documented in this report.

The second phase of the development is now in progress. A set of candidate antennas will be built and tested, and the best of these will be given a more exhaustive performance evaluation. The project calls for a final development report documenting the work. and the construction of prototype units that may be used in development tests.

Police communication systems may be affected by man-made noise. RF noise is prominent in the police frequency band, and a priori knowledge of the sources, and its effect on the communication system may alleviate future problems.

Transmitter and receiver locations should be selected for maximum height and line-of-sight coverage. In downtown city streets, coverage can be reduced by as much as 20 to 25 dB at 150 MHz as the result of shadow losses from high-rise buildings. Additional losses from irregular terrain can be as high as 20 to 40 dB over the free-space loss for distances of 6 mi in the VHF-UHF band. Propagation losses through an eucalyptus grove is higher for vertical polarization than for horizontal polarization.

The studies indicate that, where conditions permit, operation of personal equipment with $\lambda/4$ whips held head high will provide the most effective communication. If it is required that the antenna be small and inconspicuous, antenna losses of 5 to 15 dB will result plus a further loss of another 10 to 30 dB from body effects. Mechanical convenience means a great sacrifice in electrical performance. Along with the losses associated with the antenna, receiver performance is limited by propagation effects and man-made noise. The potential RF hazard, heating or the effect on higher organisms, remains an open question.

CHAPTER I. INTRODUCTION

The user of a personal radio generally regards the antenna as a simple wire or telescoping rod that protudes from the apparatus; at first glance it appears that no particular engineering is involved in its design. However, even a simple antenna, and especially a body-mounted antenna, for a personal radio involves a number of tradeoffs with other factors. Some of the basic antenna requirements are compactness, ruggedness, inconspicuousness, location, convenience, and radiation efficiency. In addition, other factors, such as body effects on the antenna, biological effects from RF radiation, man-made noise, and propagation phenomena in the city, wooded areas, and rough terrain, must all be considered in an integrated, well-designed communication system.

This report documents an assessment of the state of the art of radiator technology applicable to the body-mounted antenna. The problems associated with making compact or inconspicuous (hidden) antennas are outlined. Chapter II presents a discussion of electrically small antennas to provide the reader with an understanding of the limitations in antenna efficiency, bandwidth, and the effects of the changing surrounding environment. The antenna technology is drawn primarily from DOD and NASA experiences with manpack antennas for the foot soldier and Apollo astronauts; e.g., the problems associated with the body-mounted antenna for the police officer are similar to those of the foot soldier. Other factors, such as body effects, biological effects from a transmitting antenna very near to the human body, propagation losses, and RF noise

in the VHF-UHF spectrum, are briefly discussed. A test plan for laboratory measurements of candidate antennas and body effects experiments is outlined in Chapter VI. This experimental effort is to be performed by the Electronics Research Laboratory of The Aerospace Corporation.

Throughout the report, losses attributed to the small antenna, the effects of the body on the antenna, and propagation are discussed. These losses must be factored into the systems analysis to ensure proper communication effectiveness; this report however, does not suggest means of compensating for these losses. The reader should recognize that a 3-dB loss represents a reduction in area coverage by a factor of 2; that is the communication distance is reduced by a factor of $\sqrt{2}$ in a line-of-sight propagation environment. The relative reduction in communication coverage for system losses is presented in Table 1.

Table 1. Communication Coverage vs System Losses

Loss (dB)	Area Coverage	Range (Distance)
0	1.0	1.0
3	0.5	0.707
6	0.25	0.5
10	0.1	0.316
20	0.01	0.1
30	0.001	0.0316

CHAPTER II. ELECTRICALLY SMALL ANTENNAS

It is preferable that the antenna for a police officer's personal radio be invisible, noninterfering with the officer's motions, rugged, convenient to use, unattainable by grabbing to an assailant, and yet be an efficient radiator. All of the foregoing physical requirements indicate a need for a very small, compact antenna. However, one cannot have both an efficient radiator and a small antenna; that is, there is a fundamental limitation as to what can be expected from an electrically small antenna.[1] A compact antenna for a radio that has a reasonably good radiation efficiency has not been designed. In many cases, as a tradeoff, the system designer has made the decision to employ a relatively large, efficient antenna rather than to build a communication system employing higher transmitter power. On the other hand, a great deal of effort is being devoted to improvement of the electrically small antenna. The problem, however, is a difficult one. It should not be expected that some radically new principle will soon be discovered through further research, but the solution to the problem will require careful analysis as the various systems have different mechanical and electrical requirements.

An electrically small antenna is defined as one whose dimensions are small compared with the usual resonant length ($\lambda/2$ long) antenna. Practically speaking, dipoles less than 0.2λ long are considered short; e.g., at 150 MHz, a resonant $\lambda/2$ dipole is 39 in. long while a dipole 15.5 in. long (or a monopole or whip antenna of 7.8 in.) may be considered a short antenna.

Any small antenna in a free-space environment, whether it be a dipole or a loop (magnetic dipole), will have identical radiation patterns, i.e., a doughnut-shaped pattern being omnidirectional in the equatorial plane and the elevation field pattern given by $\sin\theta$. A resonant antenna will have a pattern slightly more directional than the pattern of a short dipole. The beamwidth between half-power points of the $\lambda/2$ antenna is 78 deg as compared with 90 deg for the short dipole (see Figure 1). It is interesting to note that the directivity (gain of a lossless antenna) between the $\lambda/2$ and short dipoles is only 0.4 dB. In theory, it means that there is no advantage in using the longer dipole, but because the radiation resistances are very much different the practical situation must be considered. The radiation resistance of the $\lambda/2$ dipole is 73 ohms. For the short dipole, the radiation resistance is represented by $R_{rad} \approx 200(\ell/\lambda)^2$, where ℓ indicates the total length of the short dipole (a short dipole of length 0.2λ will have a radiation resistance of 8 ohms).

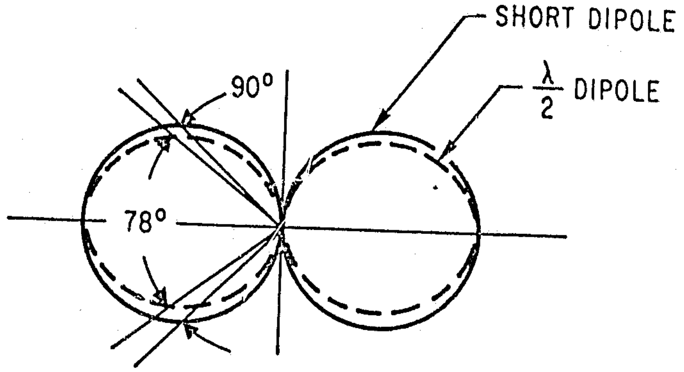

Figure 1. Comparison of radiation patterns for a resonant and a short dipole

Small antennas have intense electric and magnetic fields that extend into the near-field region of the dipole. If the antenna is located near objects, the user, and the ground, these strong fields may be dissipated in ohmic resistance. Then antenna efficiency can be reduced because these small losses may be large compared with the power radiated. Furthermore, losses in the tuning circuit to match the low radiation resistance to the transmitter provide an additional reduction in efficiency.

A short antenna used in a small communications set strapped to a man's body can be a whip or monopole type. The antenna configuration is basically a short, asymmetrical dipole with the whip forming one half of the dipole and the radio set case the other half. Major losses are the result of the man's body absorption, and insulator, dielectric, ground, and matching circuit losses. The ohmic losses in the inductive reactance required to match a short whip generally represent a significant portion of the total losses.

A small loop has an inductive impedance that requires a capacitor matching network. Capacitors can be made with very low loss, however, and loop antennas have been found to be more efficient than the whip type. For a given radiation efficiency, it is possible to tolerate a much higher conductivity dielectric in the near-field region of a small loop antenna than with a whip.[2] In other words, the efficiency of a loop antenna is affected less by ground losses than that of a whip. Of course, some losses occur with all types of antennas operating close to a nonfree-space environment.

Small, low-efficiency antennas are frequently used for reception without performance degradation whenever cosmic and atmospheric noise and man-made noise are greater than the internal receiver noise. In cities, the peak noise is often higher than the thermal noise.[3] Under these high-noise conditions, it is possible that a separate, hidden antenna could be used that would provide a continuous receiving capability. A complete analysis and tradeoff should be made to determine the system effectiveness of using separate antennas for the transmit and receive modes.

High antenna efficiency is needed primarily for the transmit mode; otherwise, the transmitter power is dissipated in the various loss mechanisms. A waste of the high-level RF power also represents a bigger battery drain, especially when a given radiated power requirement must be met.

An additional reduction in signal strength is caused by radiation pattern distortion of a body-mounted antenna. Appreciable nulls exist in the antenna-man radiation pattern such that the direction the user is facing with respect to the point of communication is important. As compensation for the null, it is necessary to add another 10 to 30 dB in the power budget of the communication system. The pattern distortion exists for both small and large resonant antennas. The body effects on the antenna are discussed further in Chapter IV-A.

The general properties of small antennas can be summarized as follows:

- Relative intense reactive fields exist in the near-field region of the antenna. Coupling of these fields to nearby objects and ground reduces the antenna efficiency.

- Q is large for a lossless antenna, which means narrow bandwidth. The Q can be reduced, which results in lower efficiency and more bandwidth.
- The free-space radiation patterns of a small dipole or a loop have the same shape.
- The loop incorporates a capacitor tuning network that has lower losses as compared with the inductive matching network of a dipole.
- The loop has less ground losses than a monopole and therefore is less affected by the changing environment.
- High antenna efficiency is primarily of concern in transmitting. While receiving, a lower efficiency antenna can be used without degradation if the local noise level is greater than the receiver noise.

CHAPTER III. ANTENNA TYPES

A. General

The personal police transceiver must be designed to satisfy numerous law enforcement functions. It must be convenient and capable of operation in a "hands free" mode. The transceiver must be designed for use by a uniformed officer, in a tropical or arctic environment, on a normal, routine assignment or when quelling a civil disturbance, with or without a protective helmet or gas mask. The transceiver antenna must satisfy all the transceiver requirements and must be compact, capable of concealment, able to radiate efficiently, and difficult to damage during a deliberate attack. In addition, it should not present a "grab handle" for an assailant. Although the transceiver and antenna should meet all the operational requirements, a single configuration may not satisfy the requirements of all the different law enforcement functions. Therefore, a compromise must be made, or special antennas must be designed for operation in a routine mode and under stress conditions.

Many antenna configurations are candidates for application as a body-mounted antenna. Although the various antennas look different, they are basically a loop or a dipole. The various configurations resulted from the novel and effective methods the designers have employed to impedance match the antenna. Regardless of the antenna configuration, two small antennas with identical volumes will yield the same maximum radiation efficiency.[1] However, because of the various communication system, mechanical, and environmental requirements, the various configurations must be analyzed to determine the ones best suited for the proposed application. A description of the various loop and dipole configurations applicable for body-mounted antennas is presented in Chapter III-B. In Chapter IV is a description of the body effects on antennas and the results of actual measurements that ultimately are a major consideration in antenna selection.

B. Antenna Configurations

A review of the open literature was made for assessment of body-mounted antenna technology. A substantial amount of information was derived from the documentation prepared at the Antenna Workshop,[4] which was held at the U.S. Army Electronics Command (ECOM), Ft. Monmouth, New Jersey, in February 1968, and was devoted solely to the packset antennas for the foot soldier. The NASA Apollo astronaut backpack antenna system was also reviewed.[5]

1. Whip antennas. The most common and probably the simplest antenna is the monopole or whip. The ECOM has devoted substantial technical effort toward development of this type antenna for the foot soldier.[4] Although their work was devoted primarily to the 30- to 76-MHz range, the technology is applicable to police transceiver frequencies of 150 and 450 MHz.

A monopole is generally excited by a signal source against a metal sheet (or ground plane) or with the ground plane replaced with a number of radial wires orthogonal to the monopole. For the personal radio set, the radio case is considered the ground plane and is usually ineffective. A

counterpoise — additional wires or wire shields above ground and serving as a "ground" terminal — would have to be added to acquire an effective ground system. A counterpoise differs from the ground plane in that it is essentially RF-isolated from ground (i.e., the counterpoise has a relatively high impedance to ground). The counterpoise must be properly designed, e.g., by incorporation of RF chokes, to minimize additional power loss to the ground. The ECOM has perfected the electrical design of these chokes, which consist of coax, e.g., RG-188, wound on a toroidal ferrite core, to provide effective isolation over a wide frequency range.[6] (p. 50), [7] (p. 244).

The basic whip antenna should be $\lambda/4$ long for optimum performance; however, physical limitations often prevent using a long antenna (e.g., $\lambda/4$ = 17.5 in. at 150 MHz). Loading techniques (see Figure 2, page 12), which generally lead to lower efficiency antennas with narrower bandwidths, are used to reduce the antenna length. The physical appearance is different, but it is basically a whip antenna. This efficiency loss is important for the police radio, but the bandwidth is generally sufficient for the application. It has been demonstrated by ECOM that a more optimum loading configuration for whip antennas can be obtained by locating the inductor on the antenna element, either in a lumped or distributed manner. The principle has been demonstrated theoretically, and its practical implications have already been used to definite advantage.[8] Shepherd and Chaney have also suggested that a body-mounted antenna be exposed above the shoulder for maximum efficiency.[9]

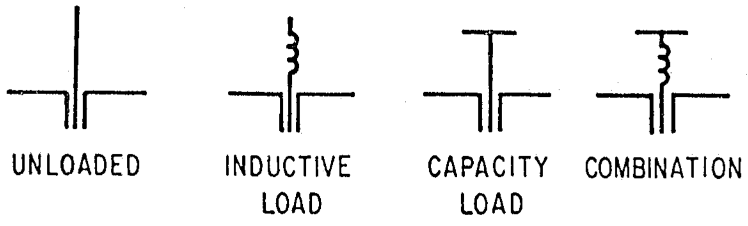

Figure 2. Loading techniques for whip antenna

In addition to the inductive loading of whips, capacity loading can also be used (see Figure 2). Capacitive top loading increases the effective height of the monopole and reduces the tuning losses. However, there is a point of diminishing return in terms of effective height when the top-loading capacity becomes appreciable to the capacitance of the vertical antenna portion. Inductive and capacitive loading are frequently combined.

Extra-thin whip antennas that are not easily detected by the unaided eye have been developed by ECOM.[10] Although their interest is in the 30- to 76-MHz range, the techniques should be applicable to the police transceiver frequencies. If a good conductor is used, a wire of a few mils in diameter suffices for good efficiency; thus, the primary limitations are mechanical. Carpenter, et al.,[10] proposed that the antenna consist of a matrix of boron filaments and a single conducting wire bonded together by plastic. However, Mr. E. Berman of ECOM stated in a recent conversation that a boron strand surrounded by stainless steel filaments embedded in magnesium (see Figure 3, page 13) was found to be strong and flexible. The magnesium is the electrical conductor.

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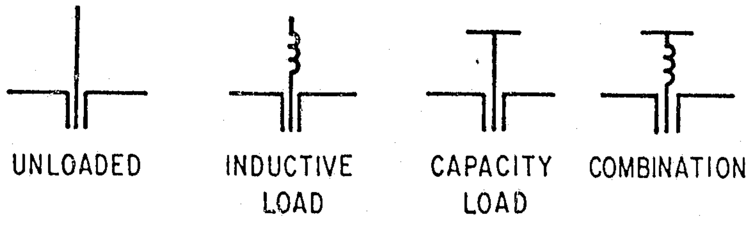
UNLOADED
INDUCTIVE LOAD
CAPACITY LOAD
COMBINATION

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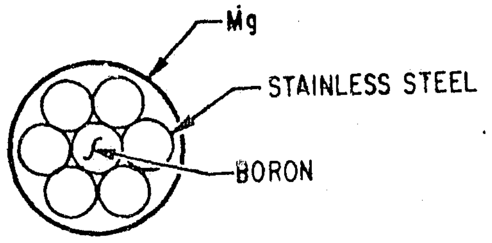

Figure 3. Thin antenna construction

The principle of inductive loading on the antenna element has been demonstrated in practice as a means of shortening the whip antenna and yet maintaining a suitable efficient operation. Because of the added weight and increased visibility of external loading inductors, it may be advantageous to keep the tuning adjustment inside the radio set itself. By the adoption of a sleeve monopole type of whip configuration, the inductive loading on the antenna element itself can be introduced. This type of antenna has been in existence for many years.[11, 12] A sketch of an electrically short version of such a sleeve monopole is shown in Figure 4.[7] Research has been conducted by ECOM on the short-sleeve monopole to tune over the frequency range of 30 to 76 MHz[13] and the VHF range, as discussed with Mr. Robert Whitman of ECOM.

A folded monopole is another commonly used antenna (see Figure 5a, page 14). The two conductors make the antenna more visible but the second conductor, which is attached mechanically to ground, makes

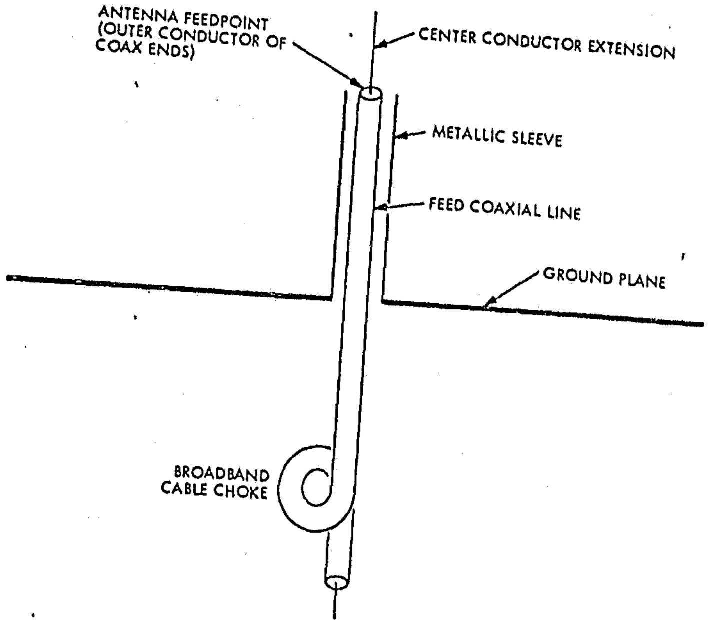

Figure 4. Sleeve monopole antenna configuration [7]

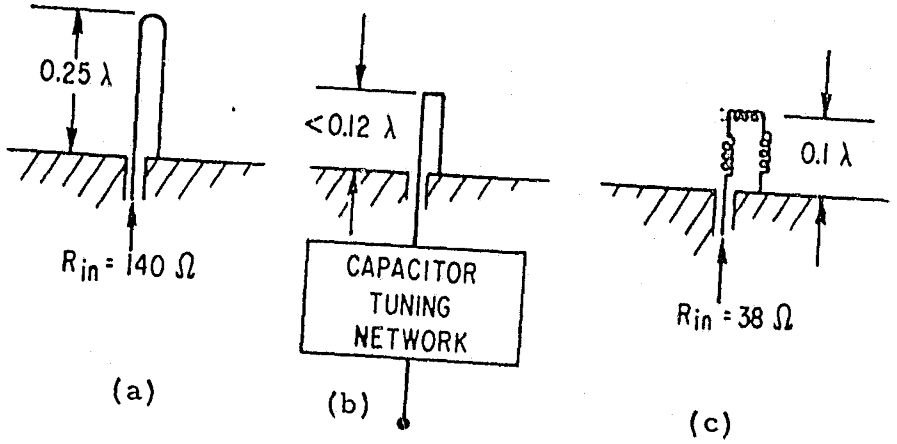

Figure 5. Folded monopole configurations

the monopole less susceptible to destruction. A monopole less than approximately 0.12λ high can be tuned by a low-loss capacitor tuning network as shown in Figure 5b, page 14. A resonance occurs at 0.12λ, which simplifies impedance matching. The geometry of the short, multiple-loaded, folded monopole is indicated in Figure 5c, page 14. For a loaded height of 0.1λ, it has been shown theoretically that the input resistance is equivalent to the resistance of a 0.25λ monopole.[15 (p. 230)]

2. Loop antennas. Loops, which consist of a radiating conductor coiled into one or more turns, are used successfully as miniaturized antennas for rockets and radio receivers. The relationship between loop dimensions and the theoretical radiation efficiency is discussed by G.S. Smith.[16] The loop is advantageous because it is relatively insensitive to external capacity changes and it utilizes low-loss capacitor tuning networks. In contrast, the whip is very sensitive to external capacity changes, such as body and earth proximity changes, because it is by nature a very low-capacity, high impedance antenna. The efficiency of a loop antenna is affected less by ground losses than that of a whip.[2] In addition, loops can be externally loaded with capacitors and fed either in a balanced or an unbalanced condition. A balanced loop has a high immunity to local electrical interference pickup.

The ECOM has found that a half-loop on a small mounting plate, which is the back of the communication set, is suitable for a backpack radio for the 30- to 76-MHz band.[17]

The diameter of the loops must be small in terms of wavelength to be attractive for use in a personal radio; thus, the efficiency is

low and several turns are added to enhance the performance. The Ohio State University (OSU) antenna laboratory has found that a multiturn loop, where the total wire length approaches λ/2, can be designed to radiate with good efficiency,[18] and they have performed theoretical and experimental analyses on this type of loop.[19, 20] OSU proposed that, for a man-pack loop antenna system, the multiturn loop be configured around the torso in a vest or a jacket and attached to the radio pack in a piggyback mode. The ECOM workshop discussion group indicated that a loop placed around a man's body will not work well because an electromagnetic field inside the loop will cause a large loss due to the associated currents in the man's body.[21]

The Harry Diamond Laboratory (HDL) and OSU have built several multiturn loops for high-impact use. The 170-MHz antenna is 3 in. in diameter by 1.5 in. in height, and the three-turn loop is foamed (54 lb/cu ft density, $\epsilon_r = 2.4$) for ruggedness. The bandwidth is 1 MHz, but the loop can be tuned over a 20-MHz band.* For the police transceiver antenna, the HDL loop can be made much smaller than the present HDL design, which has a large volume that was dictated by the need for high-impact (1000 g) use. The actual loop dimensions are approximately 0.5 in. high by 1.5 in. long; the loop circuit is shown in Figure 6, page 17. Such a loop can be readily mounted on the transceiver or on a shoulder mount, and possibly on top of a helmet. For 450- and 920-MHz operation, the multiturn loop would be fairly small in size.

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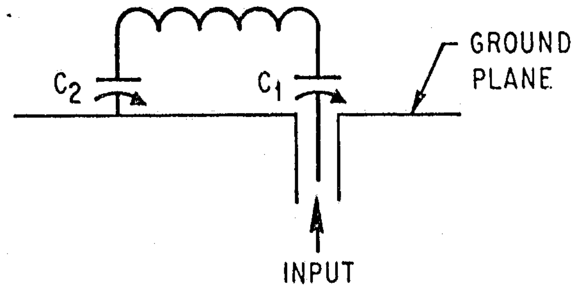
*Frank Reggia of the Harry Diamond Laboratory is preparing a technical report on multiturn loop antennas.



C_1 = 0.5 TO 1.5 pF
TO ESTABLISH CORRECT
IMPEDANCE LEVEL

C_2 = 1 TO 10 pF
FOR TUNING TO
OPERATING FREQUENCY

Figure 6. Multiturn loop schematic

Another form of loop antenna, called a "halo" or "hula-hoop," has been used in the past (see Figure 7). The vertical height h represents the major radiating portion of the antenna; i.e., it is similar to a top-loaded monopole. Tuning is done by the capacitor, and impedance matching can be accomplished by proper selection of the distance b or by

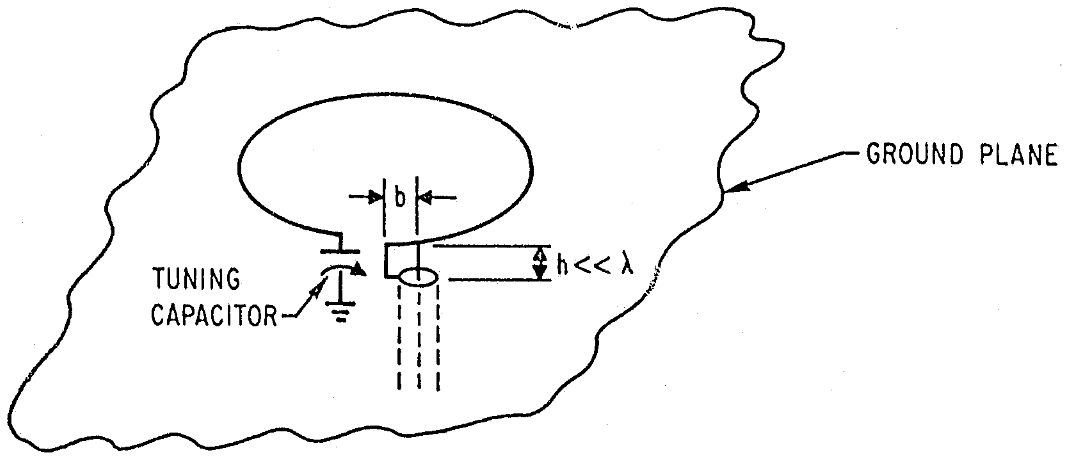


Figure 7. Halo or hula-hoop antenna concept

arranging some means of capacitor matching. Mr. Whitman of ECOM has indicated that this antenna is very critical to tuning and requires four to six reiterations in the tuning process. He is presently developing a dual-winding "electric stove hot burner" loop configuration. The loop is 2.75 in. above the ground plane for 30- to 80-MHz operation. With a 3.5-ft-diam ground plane, the loop's performance is -2 dB with respect to a λ/4 monopole.

A ferrite-loading loop antenna is commonly used for receiving, but it is not extensively used for transmitting. Enhancement of radiation has been found in ferrite antennas; however, large losses are also found in the ferrite, which would result in a change of impedance. The discussion group concluded that very little is known about ferrite antennas as a transmitting element.[22] Therefore, additional analytical and experimental studies should be done on ferrite antennas to determine radiation efficiency, Q, bandwidth, tuning capability, and temperature dependence. The concept of using a ferrite-loaded loop as a separate receiving antenna for a police personal radio set should be evaluated in seeking an optimum communication system.

3. Helmet antennas. For the officer who must wear a protective helmet, consideration should be given to placing the antenna on the helmet. The ECOM investigated helmet antennas (see Figure 8, page 19) for the 30- to 76-MHz frequency band, but did not continue development because of insufficient communication range and interference with the operator's head gear.[23] However, the VHF-UHF band helmet antenna, either the whip or loop type, may be a likely candidate for the police. At 150 MHz, for example, a multiturn loop may be a round knob ~1.5 in. in diameter by 0.6 in. in height.

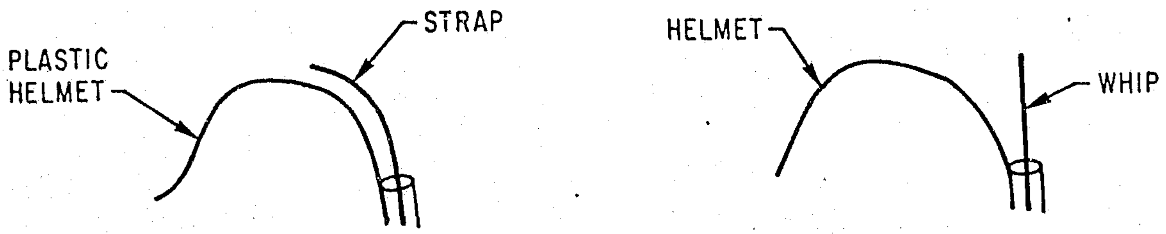


Figure 8. Experimental helmet antennas

At 450 MHz, a multiturn loop is much smaller in size and a 2- or 3-in. loaded whip could be mounted on the helmet. At 950 MHz, a λ/4 whip would be less than 3 in. long. For the best electrical performance, the antenna should be elevated and placed in an unobstructed position that is not affected by the user's body.

4. Clothing antennas. During the 1940s, the first known attempt was made to conceal an antenna within the user's clothing. The antenna consisted of a center-fed, inductively loaded dipole that was surrounded by layers of plastic tubing. The antenna was to be placed in a vertical position under the outer clothing of the operator. The plastic tubing insulated the antenna conductor and prevented direct contact with the operator. With the operator in an upright position, field tests at 50 MHz showed that the communication range of this antenna was only 100 yd as compared with 3 mi for a free-space dipole. With the operator in a prone position, the communication range was virtually nonexistent.[23] Sefton suggested the use of flexible braid,[24] which could be sewn into the standard combat uniform, but provided no experimental data.

Another approach to a dipole concealed in the operator's clothing was proposed by F. Triolo of ECOM, and it was given the name of the Portable or Coverall Antenna.[23] The operator's clothing, either outer or inner, was to be metallized from shoulder to ankles. In effect, the body was to be completely enclosed in a rough approximation of a metallized cylinder. Finding an efficient method of coupling to the antenna proved to be a stumbling block. The investigation was cut short because of higher priority projects; therefore, no conclusive results were obtained.

CHAPTER IV. ANTENNA AND THE BODY

A. Body Effects on the Antenna

A large number of possible antenna configurations for potential police use were discussed in Chapter III. For selection, it is important to determine the effects of the human body on the antenna. The human body can be represented by a complex dielectric constant; therefore, the body behaves as an absorber and as a director or reflector of RF energy. Several experimental investigations of the degradation of the antenna performance in the presence of the human body have been made. In these studies, however, only a vertical whip antenna was considered.

Shepherd and Chaney investigated personal radio antennas and described a series of tests made under laboratory conditions followed by a coverage study made under service conditions in city streets to evaluate the relative performance of small antennas and to accumulate propagation data for system design.[9] The laboratory measurements included a study of the properties of ferrite-loop antennas, coils, whips, and short-wire antennas. It was concluded that λ/4 whips, even when working against the radio set chassis as a poor ground plane, offered the best performance. With operation at 150 MHz, which is a frequency of interest to the police, a 20- to 25-dB shadow loss was found in city streets plus a 10- to 15-dB antenna loss. Where conditions permitted operation of the radio with λ/4 whips held head high, radio performance was found to be comparable to vehicular coverage except for the antenna loss. Where the antenna needs to be inconspicuous, another 5- to 15-dB average system loss may result.

Krupka determined the effect of the human body on the radiation properties of portable and small hand-held transceivers.[25] Impedance, gain, and pattern data from 35 to 152 MHz are shown in his paper. The portable set is 8 × 8 × 2 in. and is strapped to the waist with the antenna either in front or at the side of the body. The pocket-size radio with the whip is held at arms length in front of the body. Pertinent 152-MHz radiation pattern data applicable for police use are presented in Figure 9, with peak gain values shown for the various whip lengths, ℓ_a. When used with the pocket-sized radio, the peak gain is -2 dB for a whip length of 0.27λ. Degradation of the pattern behind the user is unknown, since Krupka did not specify the units. Nevertheless, the patterns do indicate the severity of body effects on the free-space omnidirectional whip pattern.

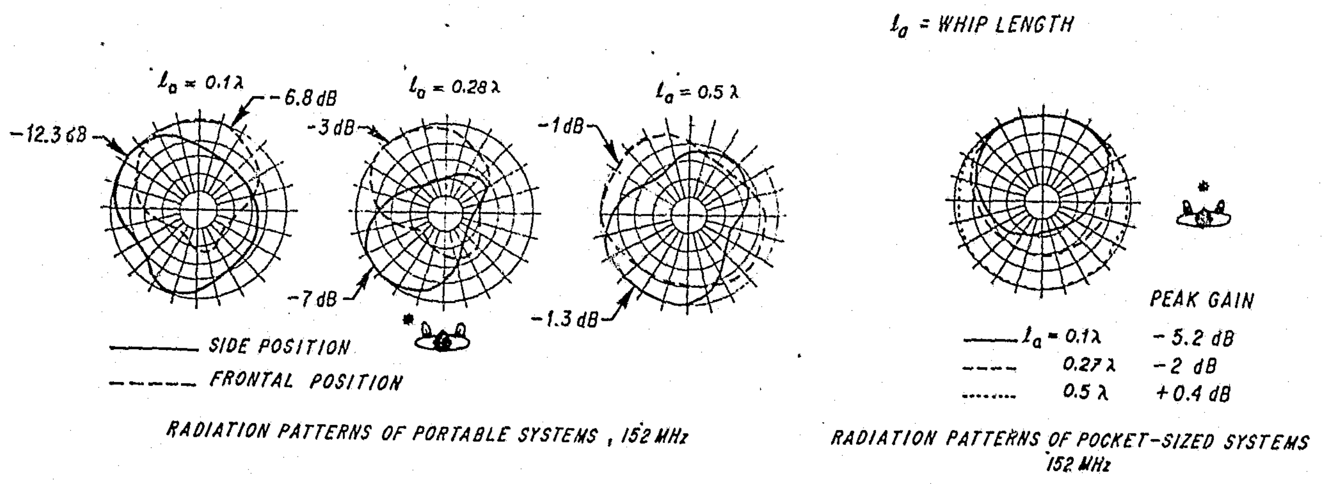


Figure 9. Radiation patterns of the body-antenna system[26]

As one would expect, the shorter whip lengths yielded smaller gain values. A plot of gain vs whip length is shown in Figure 10.

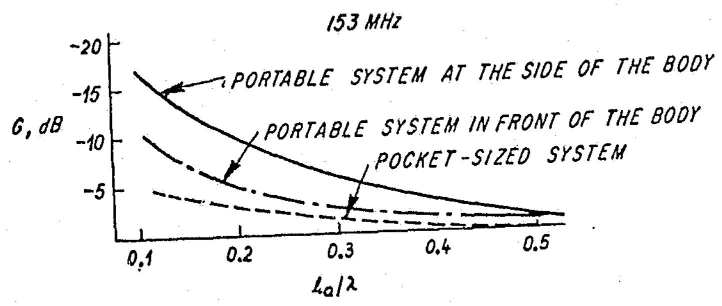


Figure 10. Peak antenna gain vs electrical whip length[25]

Lindsey describes the performance characteristics of the Apollo astronaut backpack antenna.[5] The frequency of operation is 250 to 300 MHz, with the 10.5-in. whip length (λ/4 at 285 MHz) at shoulder height. With the astronaut in a standing position, the azimuth pattern is omnidirectional within ±2.5 dB. With the astronaut in a bending position, the gain varied from -28 dB to +1 dB. As a result of these measurements, the power budget had to be revised to account for the low gain values.

The Detroit Police Department made an analysis of nearly 5000 portable transmissions, with their officers using a personal radio.[26] The intent of the study was to evaluate the changes that could contribute toward modification or improved operation of future equipment. The 450-MHz study

indicated that the difference between the antenna at face and belt level was 3 dB. They also reported that tests by Motorola Corporation of the 450-MHz λ/4 portable antenna systems showed a cardioid radiation pattern at face level that was -2 dB in the forward direction and -12 dB in the reverse direction when related to the EIA λ/4 mobile antenna standard. Belt-level transmissions when related to the face-level transmissions are about -4 to -5 dB in the forward direction or 6 to 7 dB below a λ/4 EIA mobile standard. The cardioid radiation pattern produced from body shielding has a direct effect on the portable transmission reliability. Depending on the direction and mode of operation (face or belt level), the portable signal level will be from 2 to 17 dB below the λ/4 reference signal. According to the Detroit police, operational tests with the antenna at shoulder level did not cause any interference in the officers' activity.

B. Biological Effects of RF

A substantial amount of research has been done and is continuing on the biological effects of microwaves. There are numerous papers and reports written on this subject; e.g., the February 1971 issue of the IEEE Transactions on Microwave Theory and Techniques is devoted to the biological effects of microwaves. For the body-mounted antenna, RF heating may or may not be a factor. The adopted safe free-space power density of 10mW/cm^2 is measured in the absence of the biological subject for normal environmental conditions.[27] For conditions of moderate to severe heat stress, the power level should be reduced appropriately. Mumford has proposed the reduction of the radiation protection guide to 1 mW/cm^2 for every temperature-humidity-index (THI) point above 70, until 1 mW/cm^2 is reached.[28] The THI is one of the most commonly quoted indexes to express human comfort in terms of temperature, humidity, and air velocity. Most studies have been devoted to the power densities related to the human body in the presence of high-power radars or microwave ovens. Very little has been devoted to the RF radiated from a body-mounted antenna. At the frequencies of interest to the police, the RF heating penetrates deeply, whereas, at the higher microwave frequencies, heating is produced near the surface.

Diverging opinions concerning the RF heating effects have been expressed; e.g., Dr. H. P. Schwan of the University of Pennsylvania, Moore School of Electrical Engineering, who has been working in the field of biomedical electronic engineering for many years, gave the informal opinion that RF heating is "no worry" with the LEAA 4-W transmitter. However, E. Berman of the U.S. Army Electronics Command, who has been working with backpack antennas for the foot soldier for many years, was somewhat more conservative, because of the lack of knowledge of RF effects with the antenna adjacent to the head and body.

The effect of modulated low-power-density RF energy on biological functions is a controversial subject. Schwan has stated that it is not possible to directly stimulate nerve membranes by microwave fields.[29] The field strengths applied by a microwave field to the human body are much smaller than the voltage required to stimulate the nerves; i.e., RF exposure would result in excessive heating before it could evoke stimulation. On the other hand, Frey has suggested several mechanisms whereby low-power RF can

affect neural functions.[30] He argues that, during the nervous system investigation, an X-band transmitter was used as a source. Since one cannot penetrate the skin to a significant extent with X-band energy, the best that could be done were marginal studies on stimulation of peripheral nerve endings. Frey also points out several experiments by others that conclude that significant physiological effects result from low-level electrical fields. There is no doubt a lack in data relevant to the effects on the nervous system by low-power UHF energy that can penetrate the skin. Should RF energy affect the nerves, it does not necessarily mean a hazard exists. Such a conclusion should be made after further investigations.

Frey reports that perception in the auditory system can be induced by a 1-GHz signal frequency that penetrates the head; however, higher signal frequencies, such as 10 GHz, do not penetrate and hence do not induce auditory perception. Auditory system perception cannot be produced unless the carrier is modulated. Brain stem responses have not been observed with an unmodulated carrier.

Mr. Gary Nason of NASA, Manned Spacecraft Center, mentioned that the potential RF hazards with the Apollo astronaut backpack transceiver were not considered to be important. The antenna is located on top of the backpack (shoulder level), and the whip is $\lambda/4$ long, which makes it an efficient radiator. The transmitter output is approximately 0.5 W and operates in the 300-MHz region.

A free-space power density of 10 mW/cm^2 is equivalent to 195 V/m, which is indeed a large signal from a dipole antenna. If it is assumed that a

4-W transmitter is exciting a λ/2 dipole in free space, the maximum induced field a few inches away is 28 V/m at 150 MHz. If it is assumed that the body does not affect the near-field electric intensities, a 4-W RF level appears to be safe. This strong reactive field normally does not represent a flow of energy away from the source but pulses back and forth in the near field of the antenna; however, the body absorbs some of this reactive energy, which changes the antenna characteristics. One should remember that the antenna efficiency is optimistically 25%; thus, the actual power radiated is less than the transmitter power.

Regardless of the arguments of whether or not a certain RF power level is safe, investigations should be made to assure the user that his eyes, brains, nerves, and other organs will not be affected when transmitting 4 W of RF power into a body-mounted antenna. The question of hazard and safety standards remains somewhat open.

CHAPTER V. PROPAGATION

Propagation factors must also be accounted for in an integrated communication system. Man-made noise may affect the receiver and antenna design, while losses in propagation caused by rough terrain, city buildings, and low-height antennas will alter the transmitter power requirements and the communication range. This section summarizes the salient points that should be considered in a system design.

A. Noise

Man-made noise and spurious interferences from radars, and radio, communication, control, and navigational equipment compose the artificial RFI of an urban area. The average noise power at VHF and above decreases with increasing frequency, and, according to Skomal,[3] approaches the minimum detectable signal level of the most sensitive receivers at 500 MHz. Thus, the police communication systems may be affected by man-made noise. Skomal has reviewed the status of current experimental and theoretical understanding of the range and frequency variation of incidental, surface, and man-made radio noise in metropolitan areas. Where possible, the known major sources contributing to the composite metropolitan area noise are examined individually. A plot of the composite source noise is presented in Figure 11, page 30. An a priori knowledge of noise may alleviate major problems after installation of permanent communication equipment.

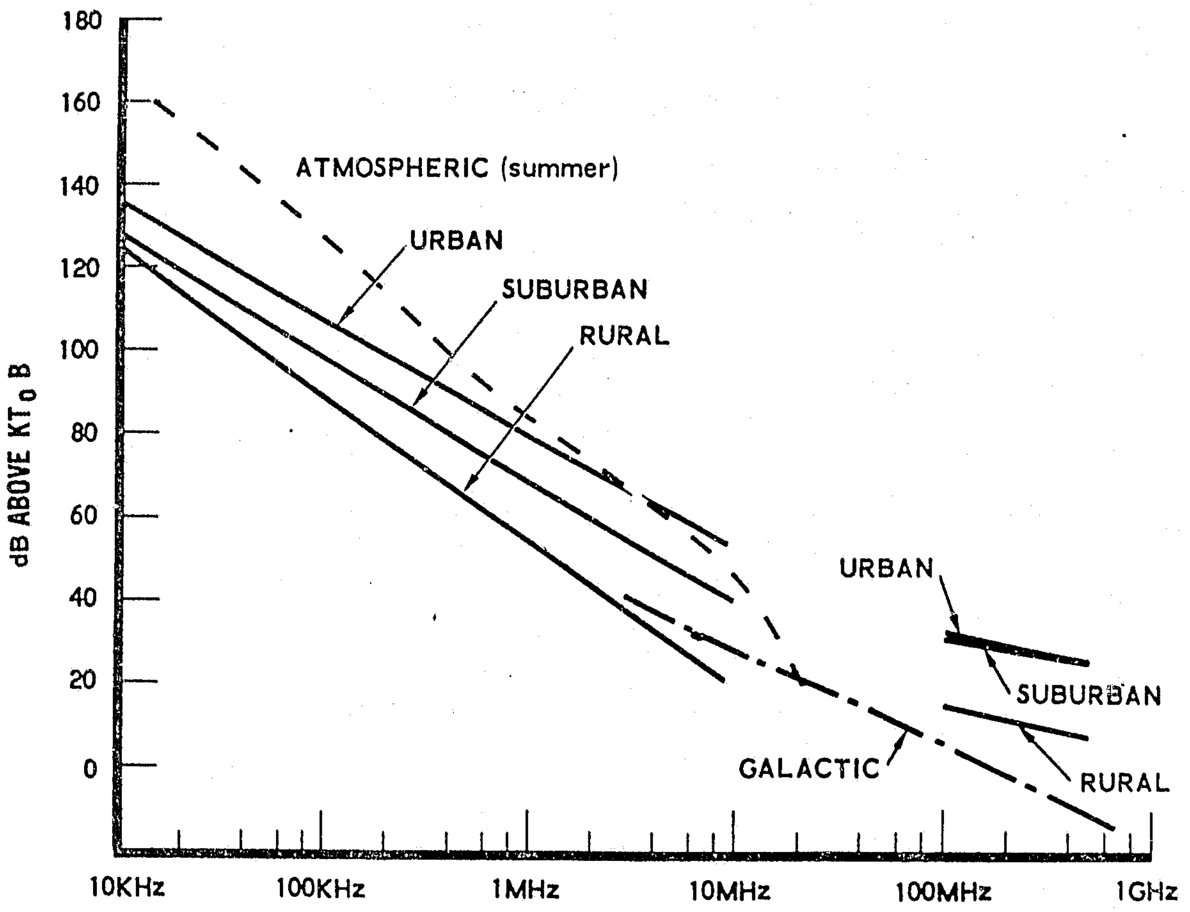


Figure 11. Composite source noise[3]

B. Propagation Losses

Transmitter and receiver locations should be selected for maximum height and line-of-sight coverage. In downtown city streets, coverage will be restricted because of heavy shadow losses and, thus, will severely restrict the communication range of personal transceivers. Transmission loss over irregular terrain and wooded areas is another factor to be considered.

Shepherd and Chaney,[9] in 150-MHz tests with small antennas that were installed in a personal radio, found that 20- to 25-dB of shadow loss exist in city streets. The Detroit Police Department determined the transmission efficiency, under varying conditions within the metropolitan area, with 5000 data points.[26] The measurements relate to the total effectiveness of all portable transmissions and do not provide quantitative propagation values. The mode of operation was two fold: The antenna was positioned at window or belt level while the officer was in the vehicle, and at face and belt level while he was out of the vehicle. The personal radio was a 450-MHz Universal Handie-Talkie, which is manufactured by Motorola Communications and Electronics Inc. The 0.7-W power output was radiated from a $\lambda/4$ antenna that was mounted to the unit. The central receiving station consisted of either a 10-dB gain omnidirectional or a 12.3-dB directional antenna. In summary, the test results indicated that 90% of the city area had a 92% transmission efficiency. The original target, 99% transmission reliability in 90% of the city area, was not met in their measurements; nevertheless, the personal radio system is doing a fine job for the police officers. These results do, however, indicate actual conditions experienced within high-rise and residential urban areas.

Computer-obtained predictions of tropospheric transmission loss over irregular terrain are compared with measurements in a report by Longley and Reasoner.[31] Measurements of transmission loss with low antennas over irregular terrain have been made in several areas in the United States, including Colorado, Idaho, Ohio, Virginia, Washington, and Wyoming. These measurements cover a wide range of frequencies, with structural heights ranging from <1 m to >15 m, in areas where the terrain characteristics range from smooth plains to rugged mountains. Frequencies ranged from 20 to 9200 MHz, and their data for 230, 410, and 910 MHz are directly applicable for police use. Losses of 20 to 40 dB over the free-space loss are not uncommon for distances of 6 mi.

Propagation through wooded areas is also of concern in police communications. Attenuation measurements were made in an eucalyptus grove for frequencies from 50 to 100 MHz by the Stanford Research Institute.[32] For 100 MHz, the attenuation over a range of 2.25 to 4 mi varied from 19 to 27 dB and 8 to 14 dB for vertical and horizontal polarizations, respectively. These results indicate that there are less losses for horizontal polarization when propagating through an eucalyptus grove.

CHAPTER VI. TEST PLAN

During the remaining portion of this LEAA study on body-mounted antennas, it is proposed that VHF experimental measurements be made on the following tasks:

- Multiturn loop. A multiturn loop (OSU design) will be configured for a body-mounted antenna.
- Body effects on antenna gain. The gain and patterns of body-antenna combinations will be measured and determined.

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