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EQUIPMENT SYSTEMS IMPROVEMENT PROGRAM – DEVELOPMENT

INVESTIGATION OF BODY-MOUNTED ANTENNAS FOR LAW ENFORCEMENT APPLICATION

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EQUIPMENT SYSTEMS IMPROVEMENT PROGRAM—DEVELOPMENT

INVESTIGATION OF BODY-MOUNTED ANTENNAS FOR LAW ENFORCEMENT APPLICATION

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ABSTRACT

The development of a new body-mounted antenna for a police officer's single-frequency, single-channel, personal radio set is described. The multiturn loop antenna is small and compact, rugged, low profile, lightweight, and measures 2.9 in. x 2.9 in. x 0.9 in. high. VSWR and radiation patterns are presented for the antenna mounted on a man's shoulder and for the body in a standing, stooping, and prone position, with various head and arm movements, and with light and heavy clothing. Radiation patterns are also presented to show the body absorption loss caused by the antenna being mounted at waist level as compared with mounting at shoulder level. The radiation patterns are referenced to a 6.6-in. helical whip that is commonly used by police officers. The instantaneous bandwidth is 1.4 MHz for a VSWR $\leq$ 3:1. A dual-frequency model for use in a two-frequency simplex push-to-talk mode is also shown to be practical.

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ACKNOWLEDGEMENTS

The author wishes to thank the interest and support of H. W. Nordyke of the Law Enforcement Development Group. Special appreciation and thanks go to D. G. Coder for his technical assistance and aid in establishing the loop parameters and the measurements set up, C. O. Yowell for his advice and technical consultatation throughout the program, L. Martinez for his cost estimates, O. L. Reid and B. A. Jacobs for their construction and testing of the various antennas, and to J. T. Shaffer and L. U. Brown for special assistance during various phases of the testing program.

SUMMARY

There is a present tendency among police departments to convert to multichannel communication operations in both the VHF and UHF bands. In multichannel service, the user has the option of switching to one of several channels, depending upon traffic congestion or his requirements for specific types of service; for example, dispatch coordination, file lookup information, vehicle maintenance requests, etc. These various channels may be dispersed in frequency over a large segment of the band assigned for law enforcement. Consequently, antennas designed for this type of communication require relatively broad-band characteristics. The input and output networks of the newer radio transceivers have also been designed to operate properly over relatively wide frequency ranges. Because electrically small antennas are necessarily relatively narrow band, these small antennas are generally not suited for multichannel operation.

The technology of electrically small antennas that have been developed within the laboratories of The Aerospace Corporation and at other laboratories is now at a level where it appears advisable to again recycle the requirements. It is important to redetermine just what the requirements are for body-mounted antennas and see what specific need exists for narrow-band antennas. One should also determine what the actual mechanics of operation entail; for example, is the transceiver also to be body mounted or is it hand held? If the transceiver, or a major part of it, is to be mounted inside a helmet, would a helmet-mounted antenna also be suitable?

In summary, the Aerospace body-mounted antenna feasibility program has contributed important empirical performance and design data relating to such small antennas and has defined the capability of the present technology. A preliminary examination of the cost factors indicate that the cost of the body-mounted antennas is substantially greater than the cost of the existing simple whip antennas. In view of these considerations, it is the recommendation of The Aerospace Corporation that this project be concluded and that a re-examination of the requirements be made to determine if, in fact, a need exists for the presently developed body-mounted antenna (e.g., two-frequency simplex applications) or if a need exists for a broad-band, multichannel, body-mounted antenna.

For single-frequency, single-channel operation in the 150 to 170 MHz band, the development of a new body-mounted antenna for a police officer's personal radio set is described. The antenna, which measures 2.9 in. x 2.9 in. x 0.9 in. high and weighs less than 3 oz, is a small, compact multiturn loop designed to be mounted on a man's shoulder. Laboratory measurements demonstrated that the loop provides 3.8 dB (azimuthal average over 360°) more gain than a shoulder-mounted, 6.6-in. helical whip.

The multiturn loop consists of a 3/8-in. copper strip wound on a styrofoam form 2.7 in. x 2.7 in. x 0.7 in. high. The coaxial cable and capacitors are assembled to a metallic "ground" plate, after which the assembly is foamed-in-place to make an integral rugged unit. The loop has a bandwidth of approximately 1.4 MHz (VSWR = 3:1). For a two-frequency system where the transmitter and receiver frequency separation is greater than the

bandwidth, a dual-frequency multiturn loop that uses a push-to-talk mode is also demonstrated to be feasible. In contrast to the loop, the 6.6-in. whip has a bandwidth of 11 MHz. The same whip is often used in the UHF band (450 to 470 MHz) as the $\lambda/4$ mode; thus, for the record, VSWR measurements were made showing that the whip is poorly matched to 50 ohms.

Experimentation was performed on a variety of multiturn loops before finalization of the configuration, size, number of turns, and capacitor sizes. Details for making radiation pattern measurements of a body-mounted antenna are described. The effects of body positions on a shoulder-mounted loop antenna are demonstrated with a series of measurements for a man standing at attention, stooping, and kneeling on the ground with his face to the ground. Measurements are given also for a man standing with his head bent and rotated to the left, his left arm raised, his head rocked forward and then backward, and with the man lying on his stomach and then on his back. In each case, the patterns for the various body positions were compared with a shoulder-mounted, 6.6-in helical whip.

Experiments indicate that the loop antenna must be tuned when it is on the man's shoulder. However, the VSWR characteristics do not change from person to person nor with the amount of clothing worn underneath the counterpoise. A heavy leather jacket worn over the multiturn loop causes some degradation in performance.

Radiation pattern measurements were made for both the loop and whip antennas when they were mounted at waist level. A 10- to 20-dB loss in gain exists when the antennas are dropped from the shoulder to waist level, and there is more nonuniformity in the azimuthal directional characteristics. The optimum counterpoise size for the shoulder-mounted multiturn loop was established. When the counterpoise is made smaller than the selected size of 4.5 in. x 6.5 in., a noticeable reduction in antenna gain occurs. Without a counterpoise, the antenna gain was lower by several dB. The electrical characteristics were also recorded during the various fabrication processes to note the effects of foam, epoxy, and paint. Preliminary noise comparison studies between the multiturn loop and a whip connected to a transceiver revealed nonconclusive results, as the receiver itself was the outstanding contributor of the measured noise.

The report points out that an optimum communication system should be designed with an integrated transceiver antenna. In order to provide maximum power transfer, minimize the battery size, or to prolong the life of the battery, both the transmitter and antenna must be properly impedance matched. A mismatch loss in either the transceiver or antenna means a reduction in transmission efficiency, with a corresponding shorter communication range and area coverage.

CHAPTER I. INTRODUCTION

In this report, the results of an investigation to determine the feasibility of a body-mounted antenna for use with police transceivers in the 150 to 170 MHz band are described. A survey of the radiators applicable to the Law Enforcement Assistance Administration (LEAA) police personal radio was made prior to this feasibility program for the body-mounted antenna.[1]

The antenna is a small, compact, multiturn loop designed to be mounted on a man's shoulder.[2,3] 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, inaccessible to an assailant through grabbing, and yet be an efficient radiator. All of the foregoing physical requirements indicate an electrically small 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.[4]

Shepherd and Chaney investigated personal radio antennas and described a series of tests under laboratory conditions. Following this, a coverage study was made under service conditions in city streets to evaluate the relative performance of small antennas and to accumulate propagation data for system design.[5] The laboratory measurements included a study of the properties of ferrite-loop antennas, coils, whips, and short-wire antennas. It was concluded that $\lambda/4$ whips, even when working against the radio set chassis as a poor ground plane, offered the best performance. 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 is required to be inconspicuous, another 5- to 15-dB-average system loss may result. With operation at 150 MHz, the whip length is approximately 17 in., which is too long as a body-mounted antenna. However, a flexible-helical antenna* that is approximately 6-in. long is considered to be a reasonable substitute for the λ/4 whip. The 6-in. helical whip is considered to be an acceptable antenna as it is reasonably short, mechanically flexible, has wideband VSWR characteristics, and is relatively efficient and convenient to use. Because of the whip's attractive features, it was used as a reference antenna for gain and pattern measurements of the multiturn loop.

One objective of this development program is an improved antenna design for portable transceivers. It would have the potential benefits of allowing operation of the personal radios with free hands, having an all-body position operation, being less awkward, and less easily grabbed by an assailant. Selection of the candidate antenna for development was based on many factors that included the use of recent advancement in loop antenna technology developed for aircraft and missile** applications.[2, 3] Other technical

*Such as that manufactured by Antenna Specialists, Inc., Model P-4 series.

**Harry Diamond Laboratory (HDL) developed a multiturn loop in cooperation with Ohio State University (OSU) for a missile that will withstand the impact of striking the ground.

factors that led to the selection of the multiturn loop were: relatively high efficiency for its size, small and compact, low silhouette, elliptical polarization, simple to tune, rugged, less sensitive to nearby objects than a whip, use of low-loss tuning capacitors, and sufficient bandwidth for single-channel operation. After demonstrating that the shoulder-mounted loop antenna provided gain performance characteristics comparable to a shoulder-mounted helical whip, a dual-frequency antenna was also developed for push-to-talk mode operation.

CHAPTER II. DESCRIPTION OF ANTENNA

The loop antenna is shown schematically in Fig. 2-1. Capacitor C_1 is used to set the impedance level, and C_2 tunes the loop to the resonant frequency.* Capacitor C_2 can be adjusted to tune over the 150-to170-MHz band without any adjustment of C_1. Loops with 3, 3.5, and 4 turns were constructed with both 1/4-in. diam copper tubing and flat copper tape. The loop was attached to a metallic plate that was used as the "ground" for the capacitor C_2 and the coaxial cable.

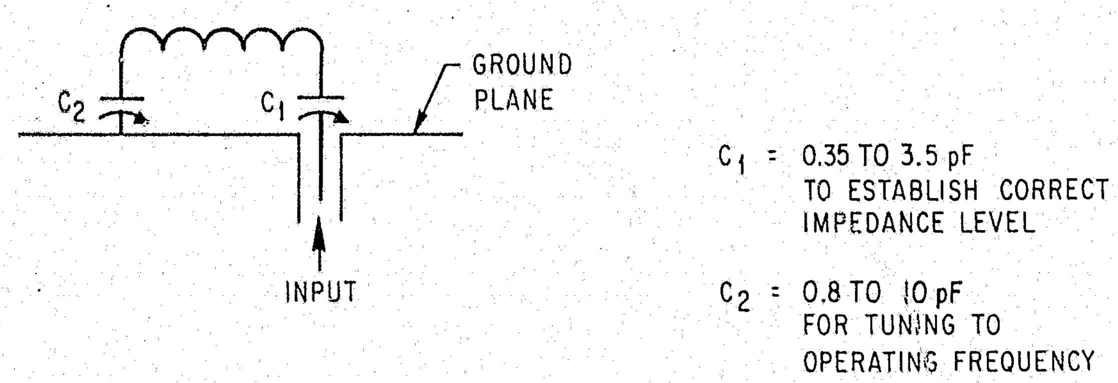


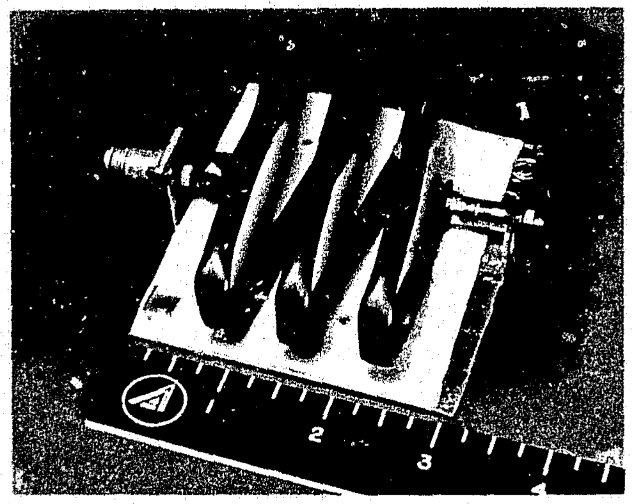
Fig. 2-1. Multiturn Loop Schematic.

*The capacitors are air dielectric, tubular construction manufactured by the JFD Electronics Co. or the Johanson Manufacturing Corp.

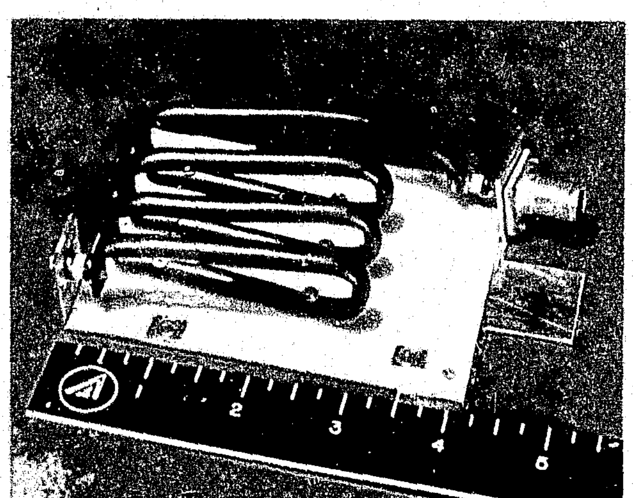
In Fig. 2-2, photos of three breadboard multiturn loop antennas are presented. A 3-turn loop constructed with 1/4-in. diam copper tubing and identified as Antenna No. 4 is shown in Fig. 2-2a. The loop dimensions are 3.45 in. x 2.2 in. x 1.06 in. high. A 3-1/2 turn loop constructed from 1/4-in. diam copper tubing and 3/8-in. wide copper foil and identified as Antennas No. 5 and 5S, respectively, is shown in Figs. 2-2b and c. The centerline dimensions of No. 5 are 2.63 x 0.75 in. and an overall loop length of 2.5 in. The dimensions of the copper foil model No. 5S are identical to those of the No. 5 model.

Gain and VSWR measurements indicated that comparable results can be achieved with either the 1/4-in. tubing or the flat-strip conductors. Thus, the flat-strip loop was eventually chosen because of the simplicity in construction, lighter weight, and smaller volume. The 3/8-in. copper strip is wound on a styrofoam form 2.7 in. x 2.7 in. x 0.7 in. high. The coaxial cable and capacitors are assembled to the loop and metallic ground plate. The assembly is then foamed-in-place* to make an integral rugged unit. An epoxy resin compound coats the foam surface. In Fig. 2-3, the 3-1/2-turn loop is shown before and after being foamed-in-place. This antenna is identified as 8F, which is considered the engineering model. It was used for many of the measurements and as a baseline for comparative measurements. Additional models of 8F were identified with a suffix number (e.g., 8F-4), and their dimensions are shown in Fig. 2-3.

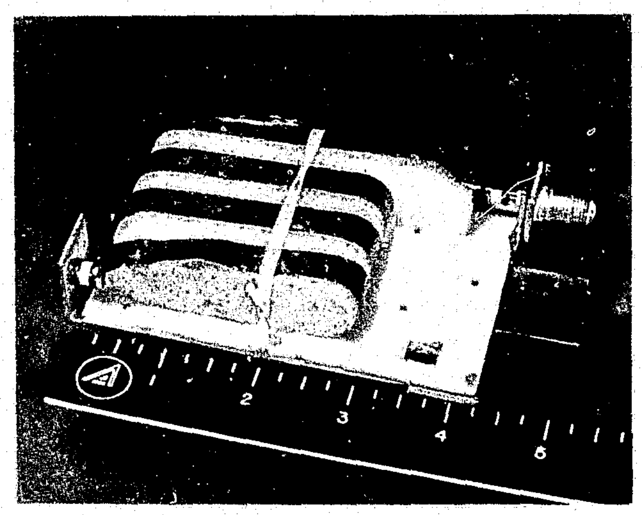
*Emerson and Cumming, Inc., Type FPH



a. Antenna No. 4

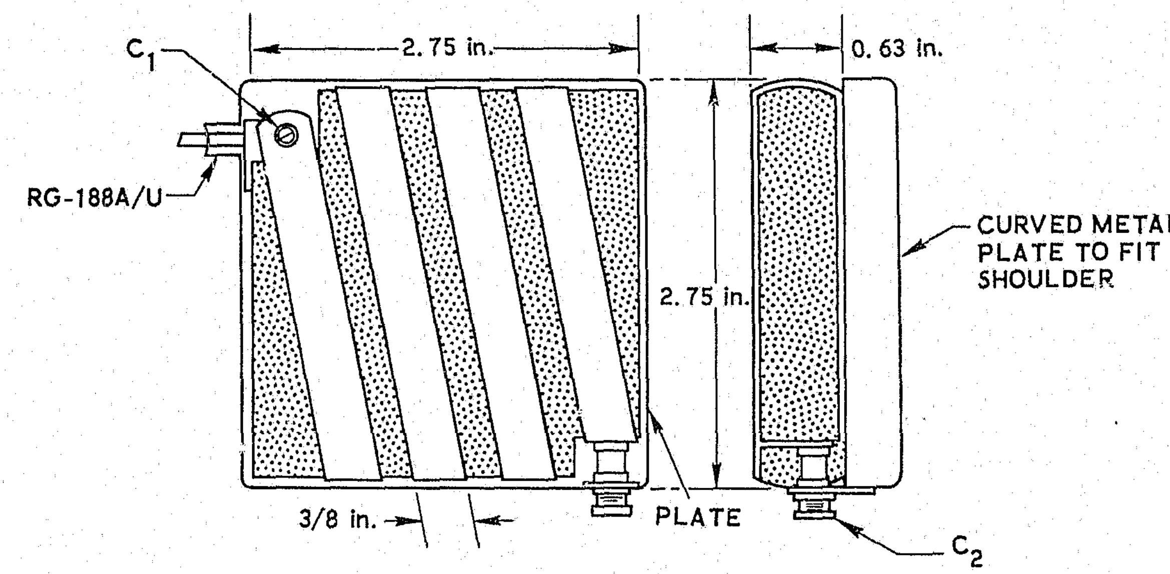


b. Antenna No. 5



c. Antenna No. 5S

Fig. 2-2. Breadboard Multiturn Loop Antennas.



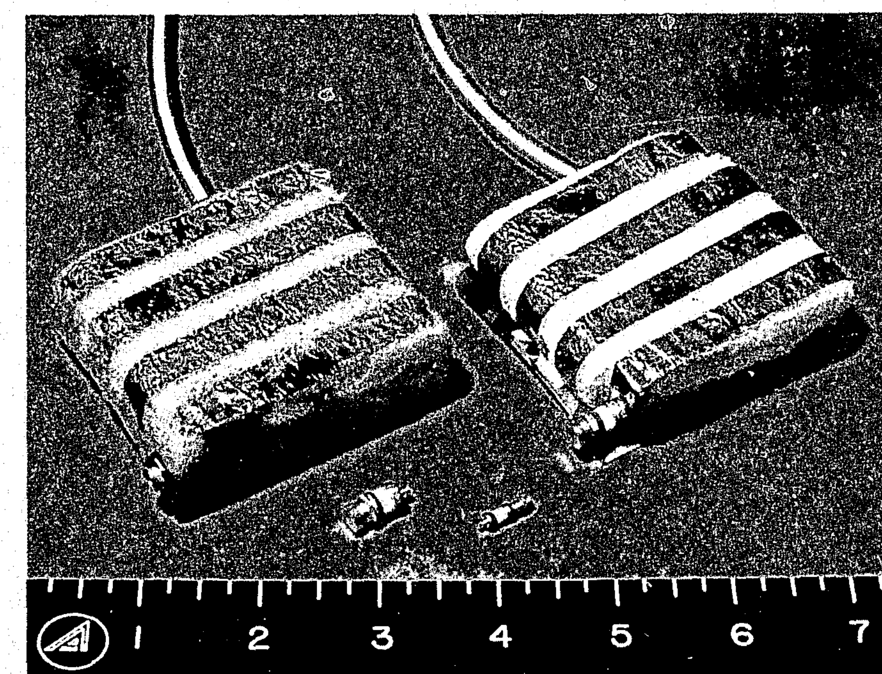
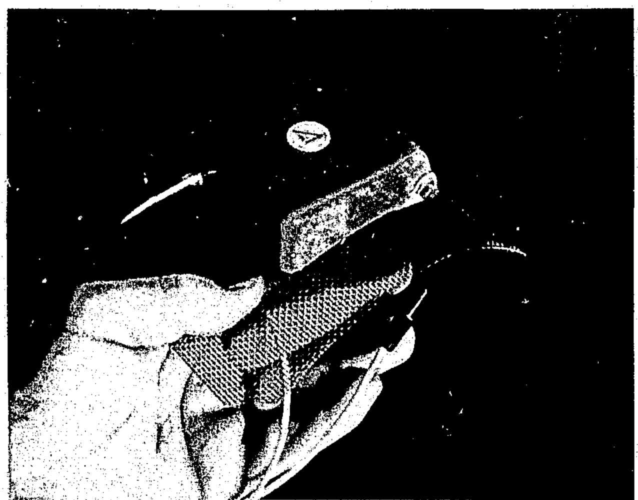


Fig. 2-3. Engineering Model of Multiturn Loop, Antenna No. 8F.

a. Shoulder-Mounted Breadboard Model



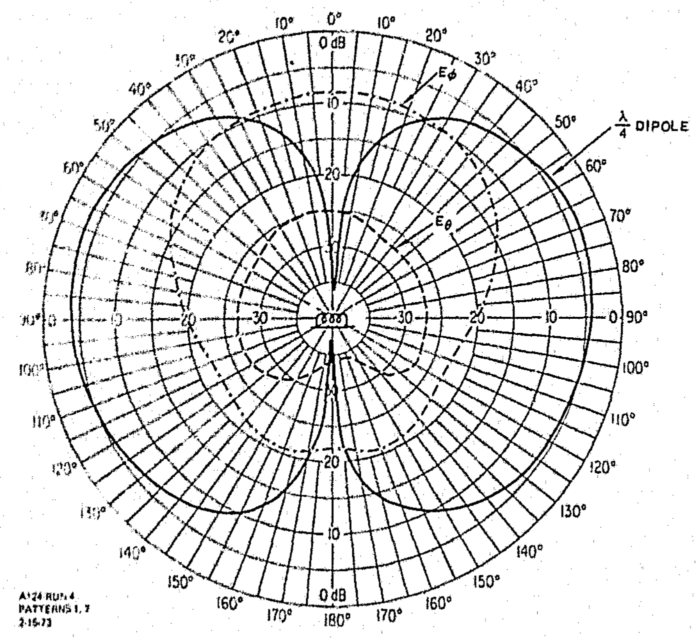
b. Engineering Model

Fig. 2-4. Multiturn Loop With 4.5-in. x 6.5-in. Metal Counterpoise.

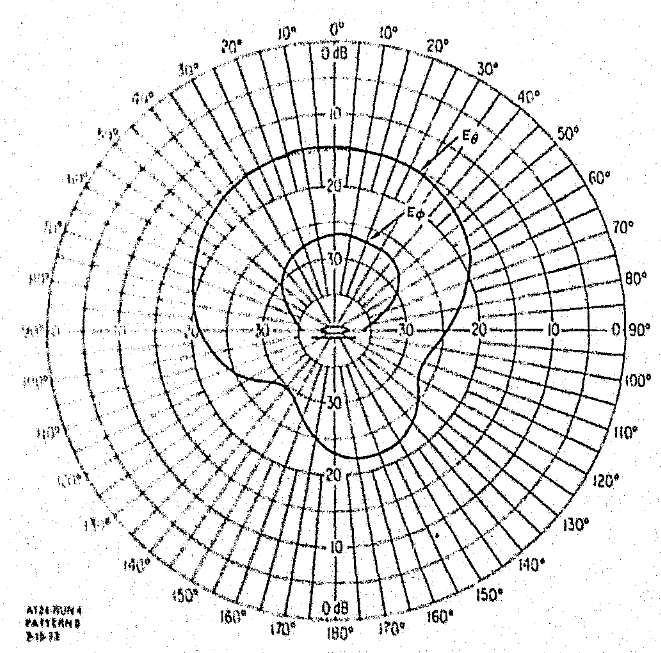
The antenna dimensions were determined by what was considered to be a reasonable size for a shoulder-mounted configuration and the number of turns dictated by the tuning range of the capacitors. The 3- to 4-turn loops yielded almost identical VSWR characteristics and gain.

As a body-mounted antenna, the loop must be mounted on a shoulder counterpoise (i. e., a metallic surface in the area of the shoulder) as depicted in Fig. 2-4a. Also, the axis of the loop must be aligned in the fore and aft direction (i. e., the axis is not directed toward the head). An engineering model of the antenna is shown in Fig. 2-4b.

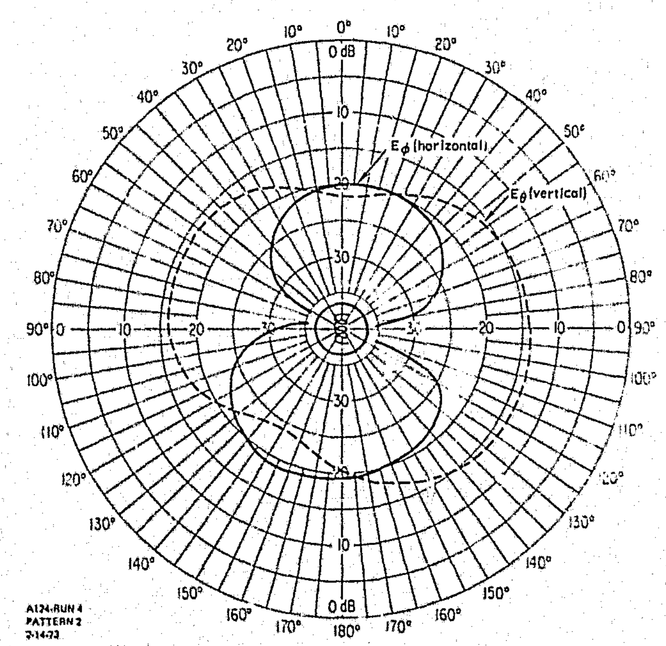
Prior to the concerted effort on the body-mounted antenna, a multiturn loop was installed on a 36-in. diam ground plane and the patterns in the three principal planes were measured, as shown in Fig. 2-5. These patterns provide a qualitative demonstration of the radiation and polarization characteristics of the multiturn loop. For reference, the pattern of a $\lambda/4$ monopole mounted on the same ground plane is shown. These patterns were not intended to provide a measure of the loop efficiency, but to indicate that the loop does radiate effectively and with elliptical polarization, which is a feature desired for the body-mounted antenna.



PATTERN IN PLANE OF LOOP AXIS



PATTERNS IN PLANE NORMAL TO LOOP AXIS



PATTERNS IN PLANE OF GROUND PLANE

Fig. 2-5. Principal Plane Patterns (164 MHz) of Multiturn Loop Mounted on a 36-in. Diam Ground Plane.

CHAPTER III. MEASURED ELECTRICAL CHARACTERISTICS

A. Reference Antenna, 6-Inch Whip

A relative reference level for the multiturn loop gain and pattern measurements was provided by a helical wound monopole (nominally 6 in. long). This monopole was selected because the whip is widely used for the present personal transceivers. Thus, it appears to be a reasonable choice to compare the loop pattern levels with that of the 6-in. whip.

An indication of the efficiency of the 6-in. whip was determined by mounting the whip on a 36-in. diam ground plane and comparing its measured pattern level with that of a $\lambda/4$ monopole mounted on the 36-in. ground plane, as illustrated in Fig. 3-1. From three such pattern measurements, the average difference in level between the two monopoles was 5 ± 0.5 dB. The $\lambda/4$ whip (17.75 in. from the ground plane to the monopole tip at 164 MHz) has a VSWR of 1.65:1. The helical monopole length is 6.7 in., and its VSWR = 4.2:1 (12-ohms resistance).

As a shoulder-mounted reference antenna, the whip was mounted on a metal counterpoise as shown in Fig. 3-2. A solid metal counterpoise was selected over a flexible one to provide constant and repeatable mechanical conditions. The VSWRs of the shoulder-mounted whip at the VHF and UHF frequencies are shown in Fig. 3-3. The UHF data were recorded, as the 6-in. whip is often simultaneously used for both the VHF (150 to 170 MHz) and UHF (450 to 470 MHz) bands. The whip is approximately $\lambda/4$ long in the UHF band. The VSWR curves indicate that several lengths of whips may be

Fig. 3-2. Shoulder-Mounted 6.6-in. Length Whip with Metal Counterpoise.

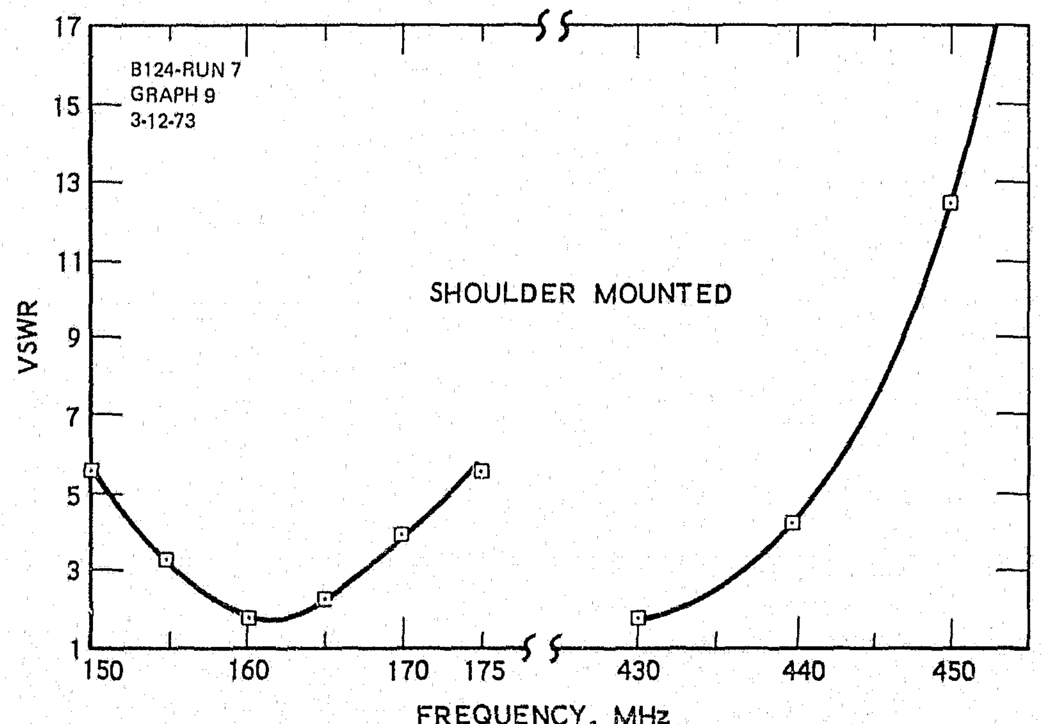


Fig. 3-3. VSWR Characteristics of a 6.6-in., Shoulder-Mounted Whip.

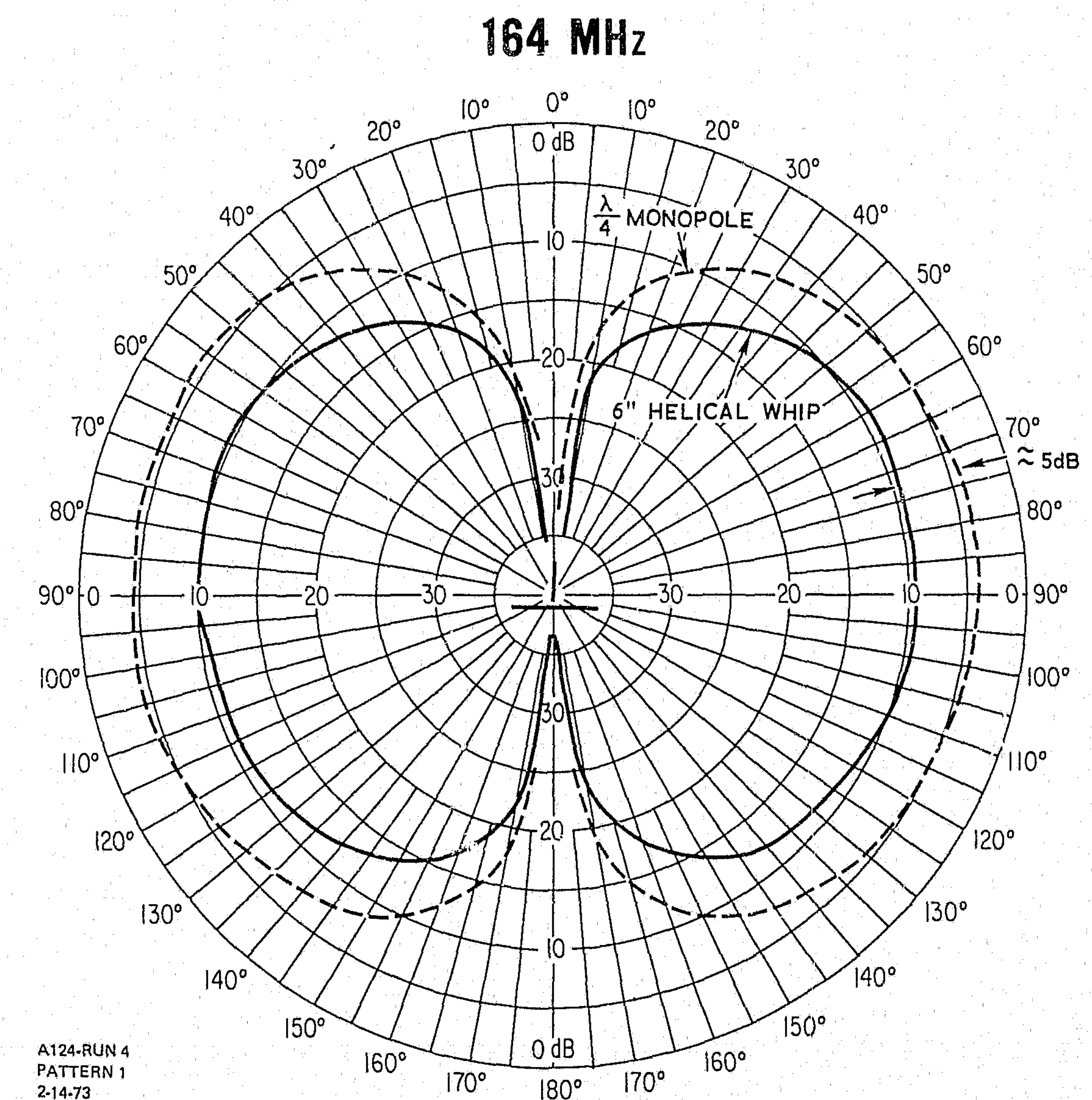


Fig. 3-1. Measured Radiation Patterns of a 6.6-in. Length Whip and λ/4 Monopole Mounted on a 36-in. Diam Ground Plane.

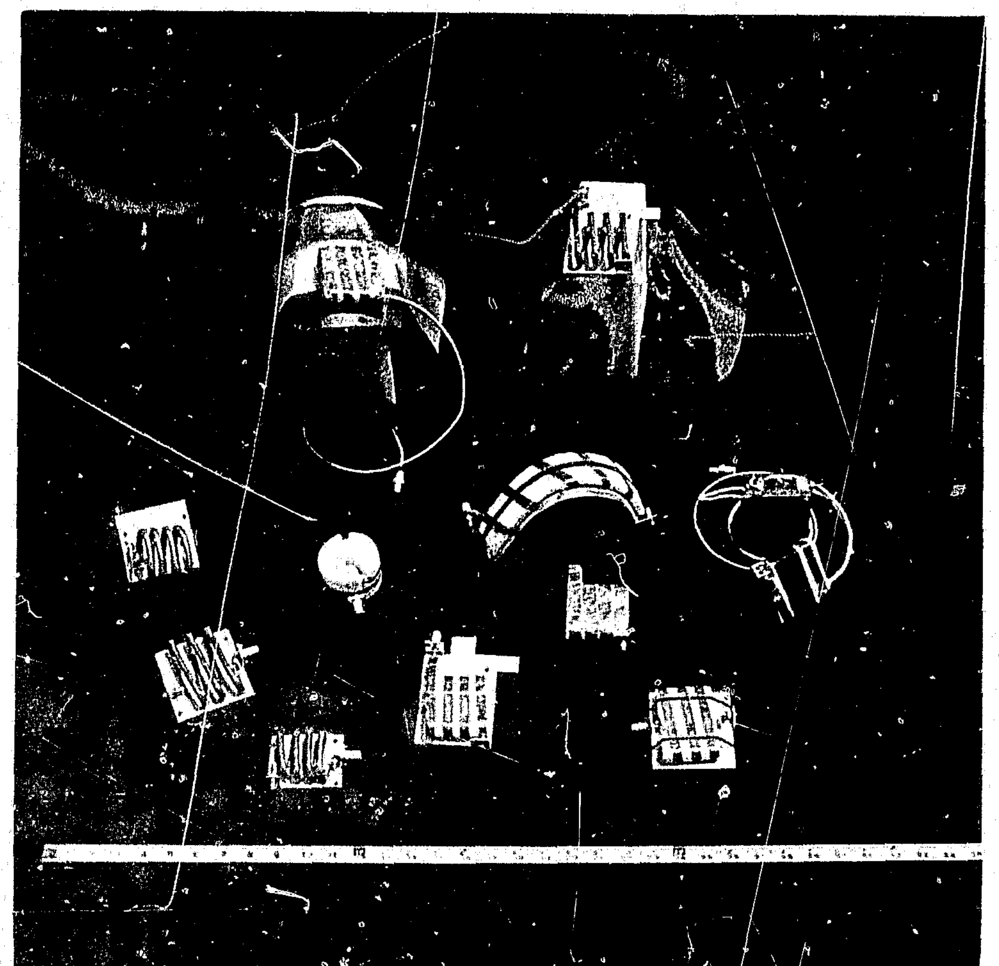


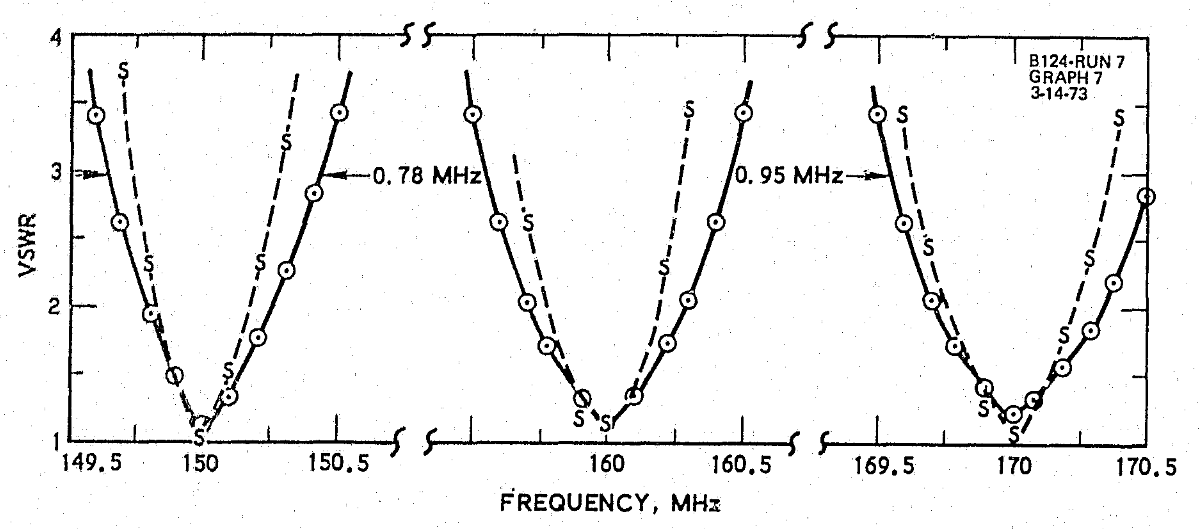
Fig. 3-4. Various Forms of Multiturn Loops.

required for optimum performance in the VHF band. Simultaneous use of the whip in the UHF band will cause considerable reduction in communication range because of the high VSWR that results in a large mismatch loss. In the remainder of Chapter III, patterns of the shoulder-mounted whip will be shown with the pattern measurements of the loop.

B. Characteristics of Body-Mounted Antennas

1. Effects of body positions on shoulder-mounted multiturn loop. Experimentation was performed on a variety of multiturn loops (Fig. 3-4) before finalization of the configuration, size, number of turns, and capacitor sizes. Because of the police requirements for a small and compact antenna, the loop was made, in so far as possible, with a low profile and small in size commensurate with efficient radiation characteristics. It was found that 3 to 4 turns were required, with the input capacitor (C_1) and frequency-tuning capacitor (C_2) having values of 0.35 to 3.5 pF and 0.8 to 10 pF, respectively. Generally, the VSWR and pattern characteristics did not change significantly for the 3-, 3.5-, and 4-turn loops. The antenna heights were chosen to be approximately 3/4 in., and, for mechanical convenience, the 3.5-turn loop was chosen because of the location of the input cable at the front of a man's body and the convenient side location of the frequency-tuning capacitor. Thus, configuration No. 5 (3.5 turns, with 1/4-in. diam copper tubing) and its corresponding flat copper strip version with the same centerline dimensions, No. 5S, was selected for more detailed development.

The VSWR characteristics of the two shoulder-mounted, 3-1/2-turn loops (No. 5 and 5S) are shown in Fig. 3-5. Each of the curves required



ANTENNA No. 5 AND 5S, 3-1/2 TURNS, 1/4 in. TUBING AND FLAT STRIP CONDUCTORS

Fig. 3-5. VSWR Characteristics of a Shoulder-Mounted, 3-1/2-Turn Multiturn Loop

retuning of capacitor C_2, but with C_1 fixed. The curves indicate that the loop can be tuned over the 150- to 170-MHz frequency band with a single capacitor C_2. For a VSWR $\leq 3:1$, the instantaneous bandwidth is 520 to 720 kHz and 780 to 950 kHz for the flat strip and round conductor loops, respectively.

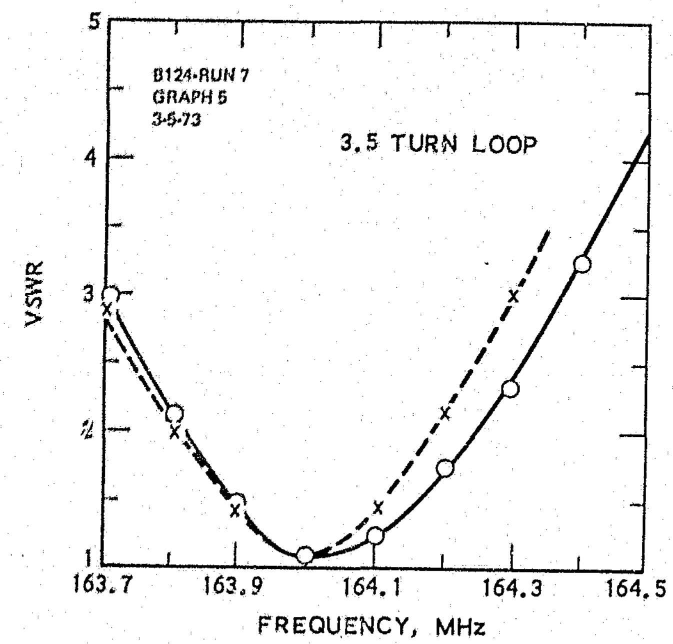
The dimensions of antenna No. 8F, the engineering model, are based on antenna No. 5S. The loop dimensions are approximately the same, except that antenna 8F does not have the extra 1.2-in. lead length at the input cable (Fig. 2-2). Subsequent models of antenna 8F were made slightly smaller in height, as shown in Fig. 2-3.

Orientation of the loop axis was found to be important, as shown in the measured radiation patterns (164 MHz, vertical polarization) of Fig. 3-6. The patterns indicate that a loop with the axis fore and aft provides substantially more gain than a loop with a sideways axis. With the loop axis at 45 deg, it was found that the pattern was in between those of Fig. 3-6. Thus, all future data were taken with the loop axis along the forward direction.

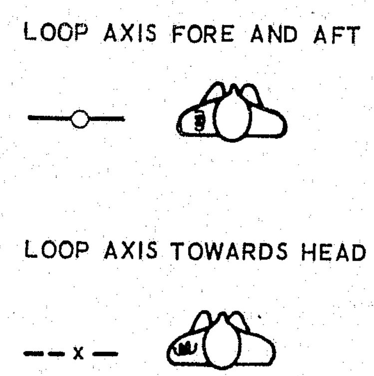
The VSWR and radiation patterns* for a shoulder-mounted No. 8F antenna with the man standing erect are plotted in Fig. 3-7. The loop radiation pattern is compared with that of a shoulder-mounted whip antenna (Fig. 3-2). The top of the polar chart represents the front of the man, and the left side of the chart represents the man's left side. Integration of the pattern over 360 deg shows that, as an average, the multiturn loop is 3.8 dB better than the whip antenna. For a VSWR $\leq 3:1$, the bandwidth is 1.4 MHz.

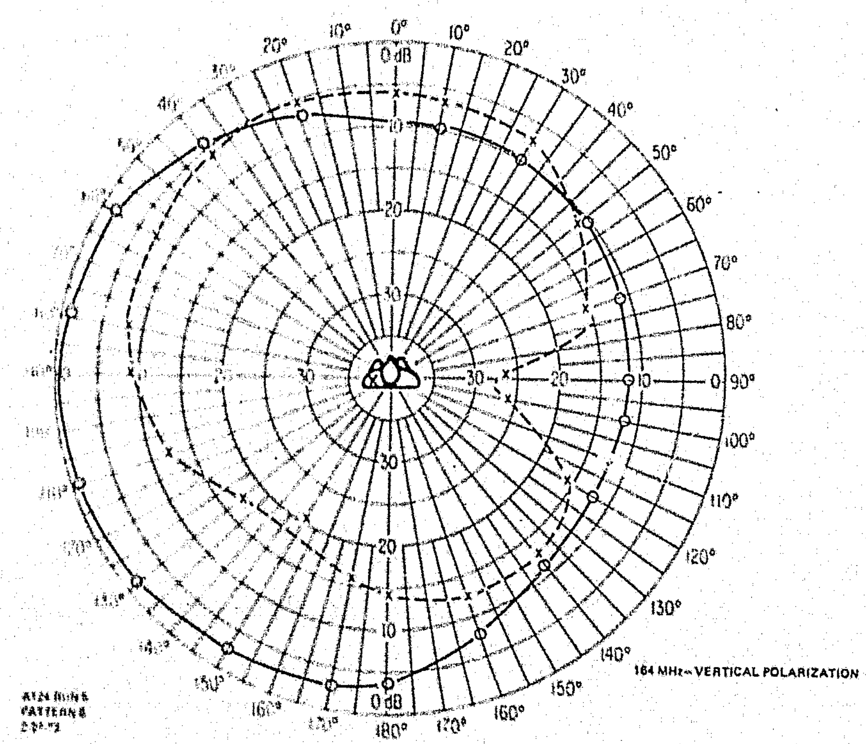
VSWR and pattern data were recorded for many conditions to allow for the head, arm, and body positions of the police officer during operation. Not all of the data are presented herein, however, as the results were not unusual compared with what has already been presented. Various body positions with the corresponding figure number for VSWR and pattern data are given in Table 3-1. Measurements were made for such positions as the head

*The majority of the radiation patterns were taken at 160.15 MHz, which is the transmit frequency of the Motorola transceiver, Model HT 200/H23DCN-1100AW. The receiving antenna is a vertically polarized corner reflector with a Hewlett-Packard Vector Voltmeter, Model 8405A, as a detector.



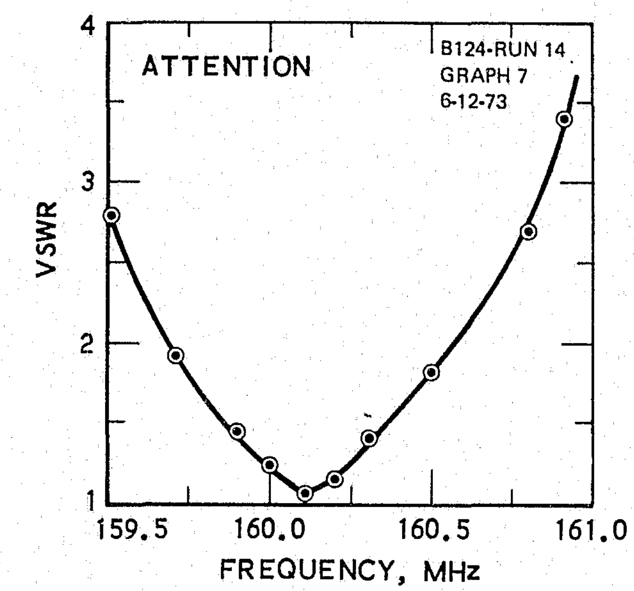
a. VSWR



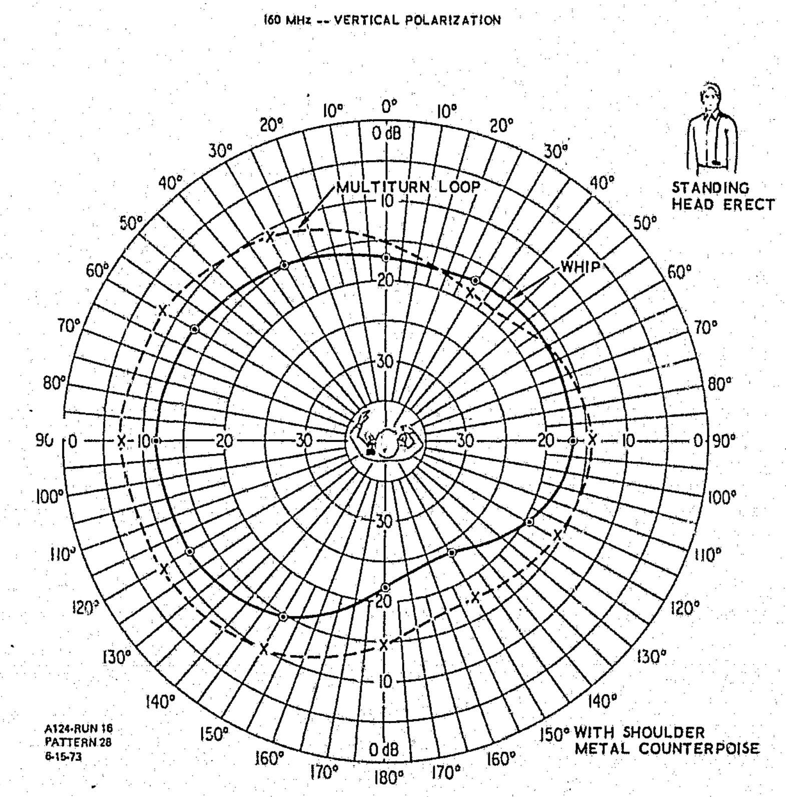


a. Patterns

Fig. 3-6. Characteristics of a Shoulder-Mounted Multiturn Loop with its Axis in Two Orientations.



a. VSWR



b. Radiation patterns

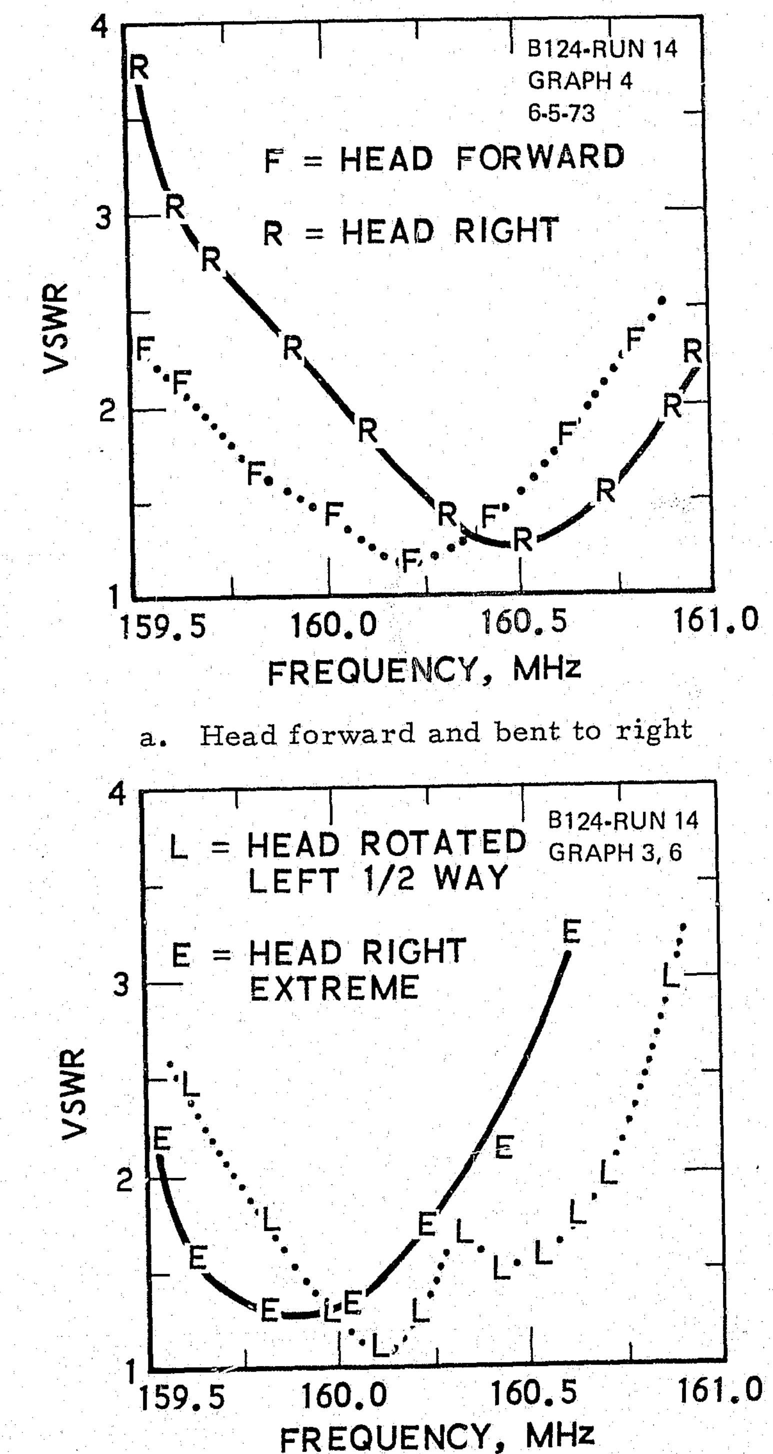
Fig. 3-7. Measured VSWR and Radiation Patterns of a Shoulder-Mounted Multiturn Loop (Antenna 8F) with a Man Standing at Attention.

Table 3-1. VSWR and Pattern Data for Body at Different Positions.

Condition	Figure	
	VSWR	Pattern
Head forward and bent to right	3-8	-
Head rotated to left half way and rotated to right	3-8	-
Head bent to left	3-9	3-9
Head rotated to left, extreme position	-	3-9
Left arm raised	3-10	3-10
Stooping (crouched) and on knees with face to ground	3-11	3-11
Lying on back and on stomach	3-12	3-12

tilted back, the head rotated to the right, and the right arm raised; however, the results were essentially the same as those for the man standing at attention.

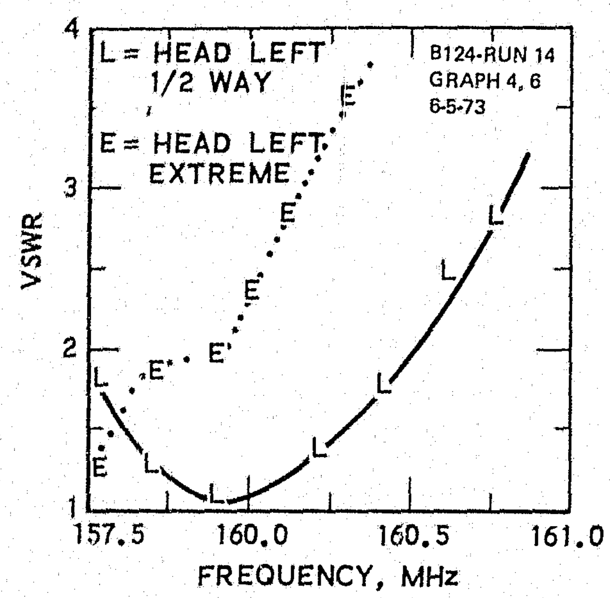
Changes in the characteristics of the shoulder-mounted antenna for different body positions as compared with the VSWR and radiation patterns of a man standing at attention (Fig. 3-7) are shown in Figs. 3-8 through 3-12. The antenna was not retuned for the data of Figs. 3-7 through 3-12; i.e., it was tuned for resonance at 160.15 MHz. All of the radiation patterns were measured relative to a vertically polarized wave. The scales for the patterns of Figs. 3-7 through 3-12 are all relative to each other; thus, one can make a direct comparison of the antenna gain for different positions. The multiturn



a. Head forward and bent to right

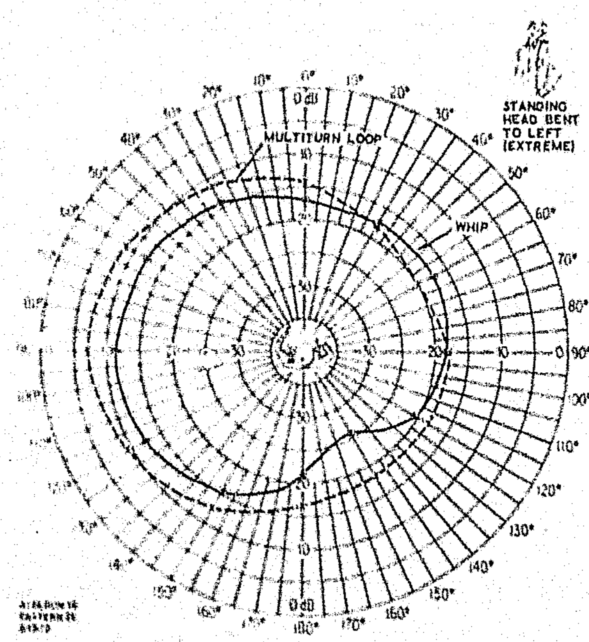
b. Head rotated to the left, 1/2 way, and rotated extremely to the right

Fig. 3-8. VSWR of a Shoulder-Mounted Antenna with the Man Standing and his Head in Various Positions.

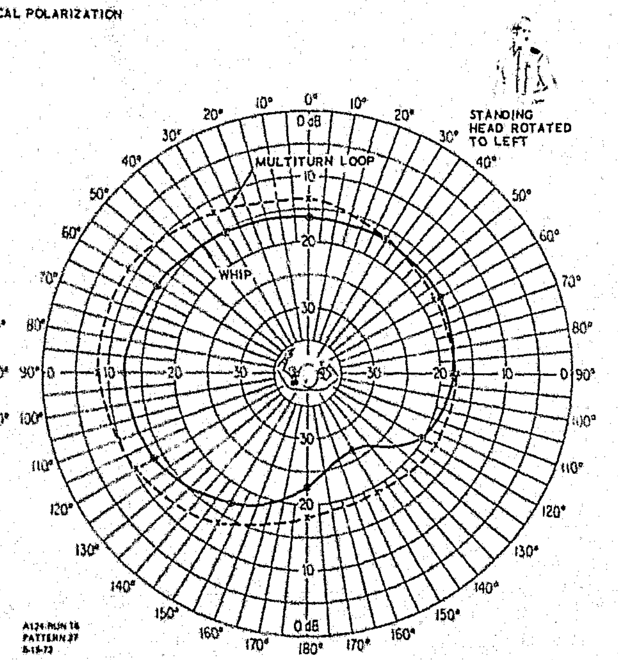


a. VSWR with head bent to left

160 MHz -- VERTICAL POLARIZATION

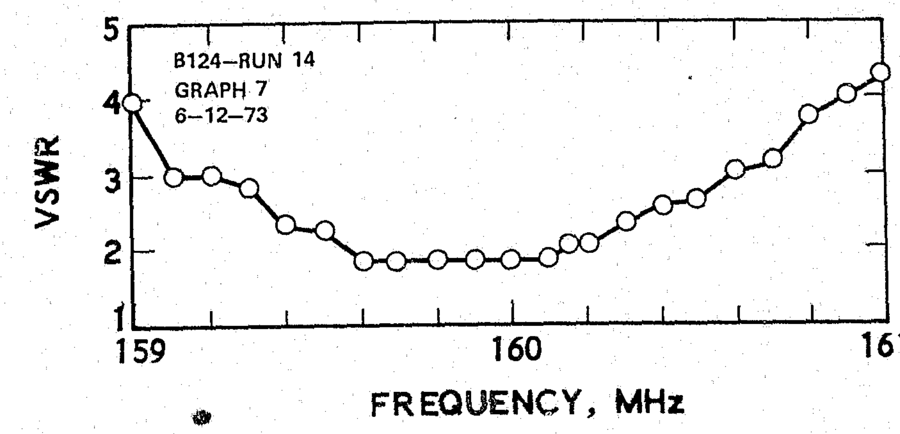


b. Radiation pattern with head bent extreme left

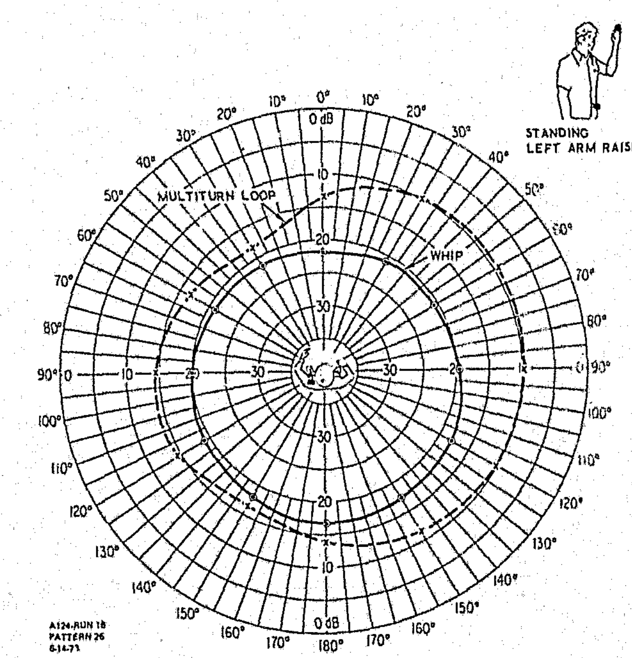


c. Radiation pattern with head rotated to extreme left

Fig. 3-9. VSWR and Radiation Patterns of Shoulder-Mounted Antennas for a Man Standing and with his Head Bent or Rotated to the Left.

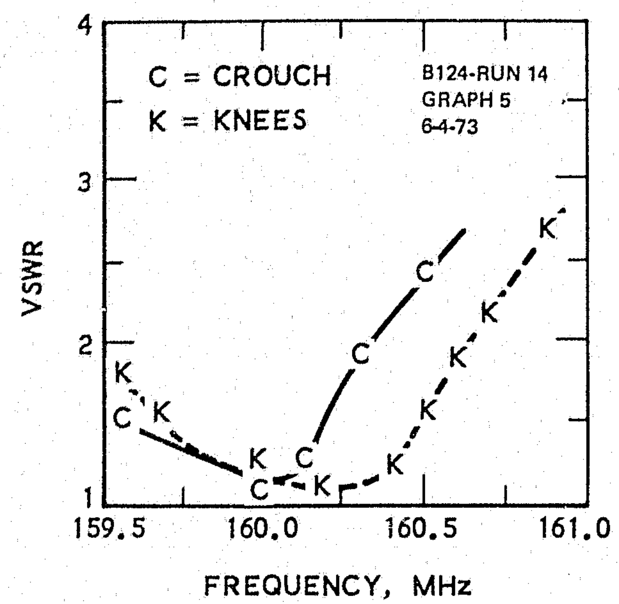


a. VSWR of multiturn loop

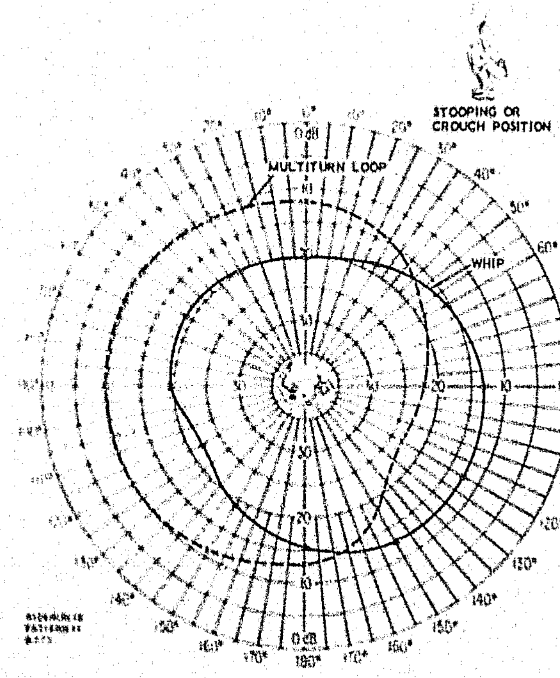


b. Radiation patterns

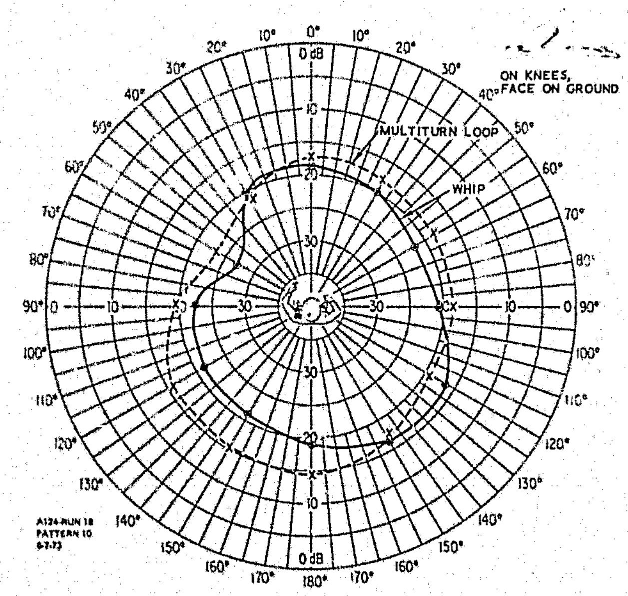
Fig. 3-10. VSWR and Radiation Patterns of Shoulder-Mounted Antennas for a Man Standing and with his Left Arm Raised.



a. VSWR of multiturn loop with man in a crouch position and on his knees, face to ground

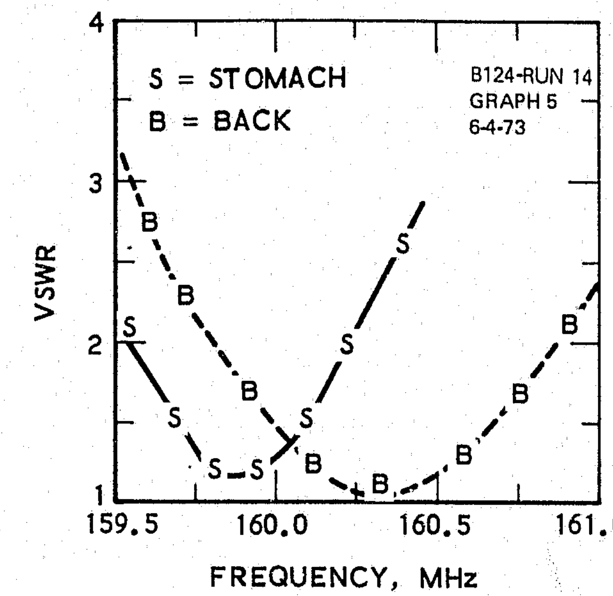


b. Radiation patterns in a stooping position

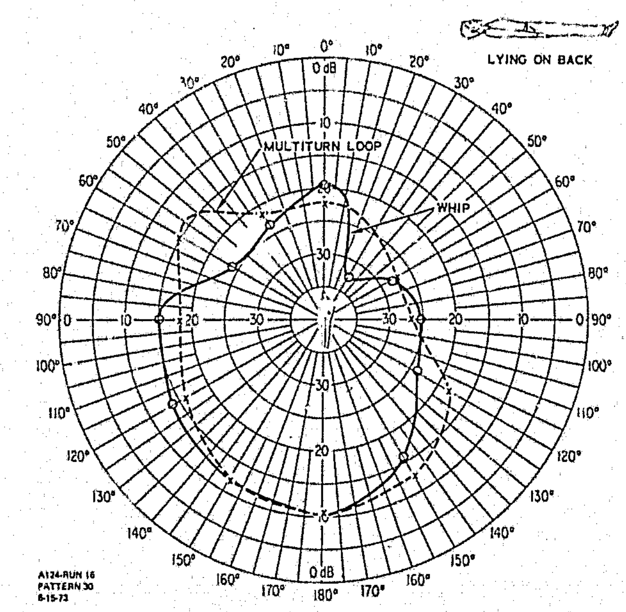


c. Radiation patterns with man on his knees

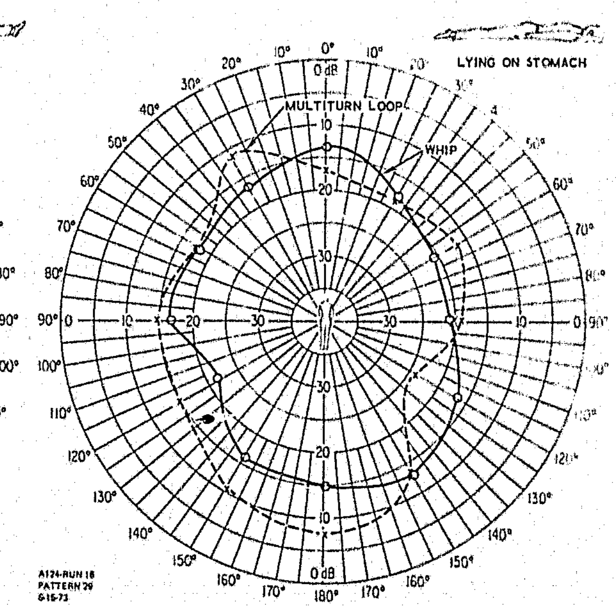
Fig. 3-11. VSWR and Radiation Patterns of Shoulder-Mounted Antennas for a Man in a Stooped (Crouched) Position and also on his Knees.



a. VSWR



b. Radiation patterns--lying on back



c. Radiation patterns--lying on stomach

Fig. 3-12. VSWR and Radiation Patterns of Shoulder-Mounted Antennas for a Man Lying on his Stomach and on his Back.

loop measurements were compared with a shoulder-mounted whip for the corresponding body positions. For example, when the man is lying down, the whip is essentially horizontal.

The VSWR data for the multiturn loop with the head rotated to the extreme left position was not included. It was found that, when the man's chin touched the loop, the VSWR would have severe fluctuations, as high as 20:1, depending upon how much pressure was applied to the antenna.

2. Body and clothing effects on a shoulder-mounted multiturn loop. Antenna tuning is susceptible to the presence of the body; however, the VSWR response does not change as the antenna is transferred from one person to another. That is, the antenna must be uned in the presence of the body. The VSWR of the antenna mounted on a shoulder counterpoise and placed on a laboratory bench is shown in Fig. 3-13. The figure also shows the antenna-counterpoise assembly placed on the shoulder and with clothing underneath the counterpoise. The effect of clothing (shirt or a jacket) on the VSWR characteristics are also shown in Fig. 3-13. The curves, which pertain to a laboratory model of a 3-turn loop (identified as No. 4 in Fig. 2-2a), were recorded sequentially and likewise identified in the following order:

- The loop and shoulder counterpoise assembly on a laboratory bench (free space).
- The same antenna, without retuning, mounted on the shoulder of a person wearing a light shirt.
- Shoulder-mounted antenna and with the antenna retuned from above.

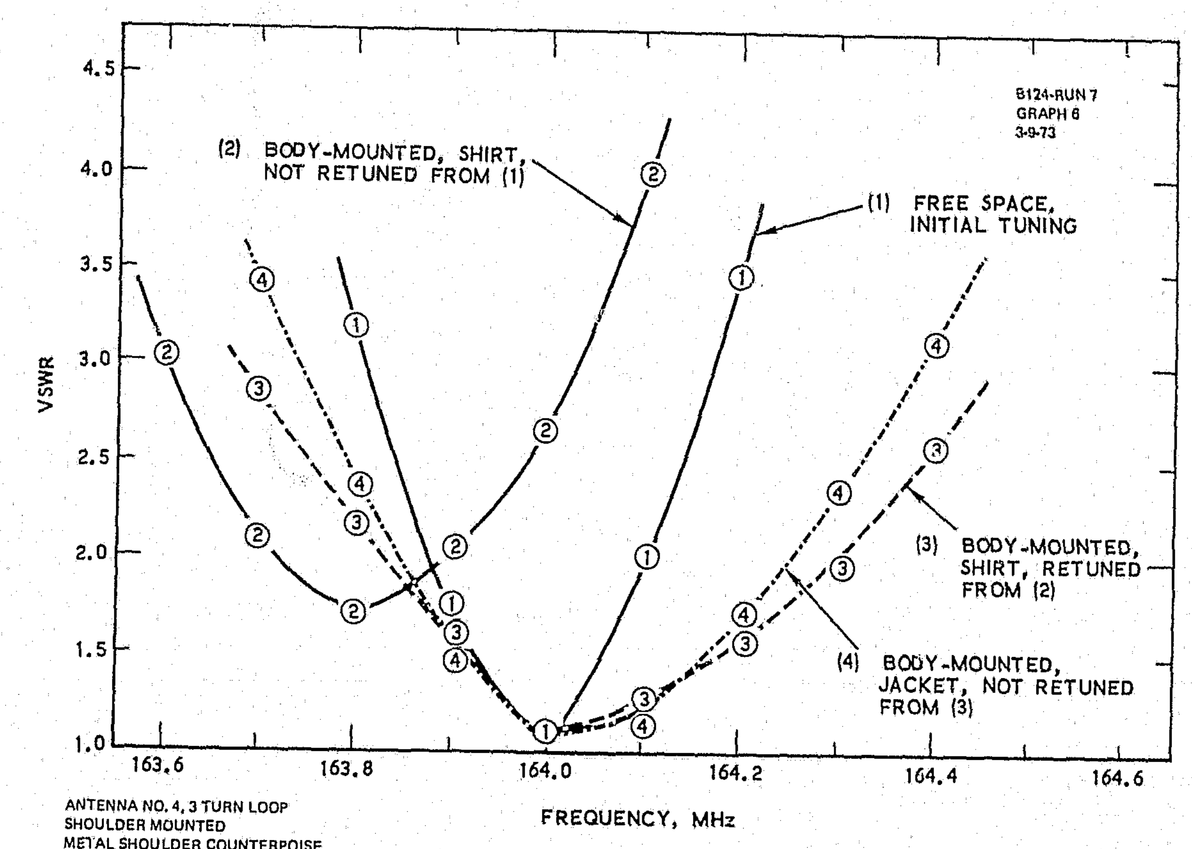


Fig. 3-13. Effects of Body and Clothing Upon the VSWR Characteristics of a Shoulder-Mounted Multiturn Loop.

- Same as above except the person is wearing a heavy jacket. The antenna was not retuned.

The curves of Fig. 3-13 indicate that the body causes the VSWR bandwidth to widen, which indicates some body absorption. With the heavy jacket, the VSWR bandwidth was slightly less as compared with the case with the shirt.

The radiation pattern changes of a multiturn loop when the man is wearing a heavy leather motorcycle jacket over the antenna is shown in Fig. 3-14. It was noted that the VSWR fluctuated, depending upon how much pressure was applied to the antenna by the weight of the jacket. Less VSWR fluctuations were noted with a man wearing a lightweight laboratory coat.

The VSWR responses of an antenna that was measured on seven different persons of varying sizes, both male and female, are shown in Fig. 3-15. The reference curve is shown, and the shaded area indicates the range of VSWR for the seven people. This curve indicates that the antenna can be tuned on any person, and it should stay tuned for use by others.

A counterpoise is necessary for optimum gain, as illustrated in the data of Fig. 3-16. Various counterpoise sizes (ground screen) ranging from zero to 7 x 20 in. were used in a series of measurements. A counterpoise 4.5 x 6.5 in. was selected because it yielded almost identical gain as compared with the large counterpoise. Furthermore, minimal retuning of the antenna was required for the large counterpoises down to the 4.5 x 6.5-in. size. With no counterpoise, a drop in gain of 2 to 3 dB occurred and retuning of the antenna was necessary. The amount of detuning was not recorded.

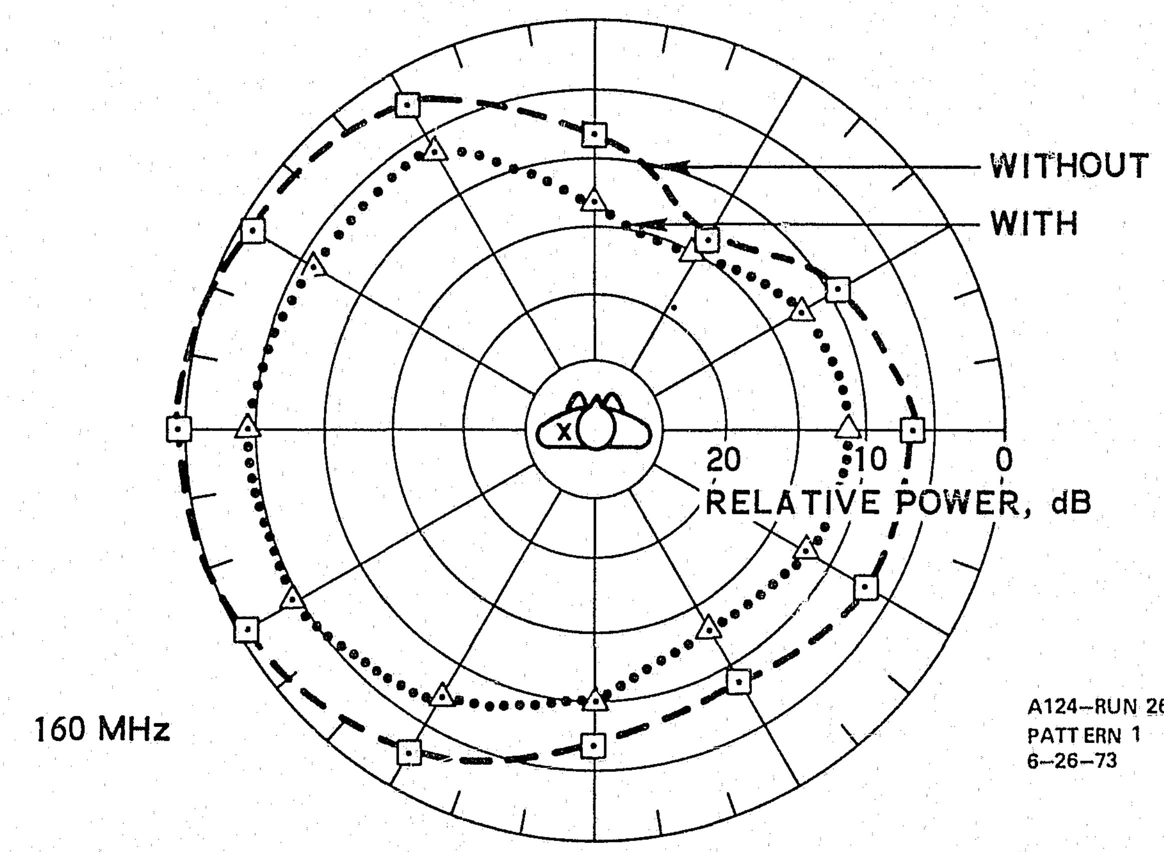


Fig. 3-14. Radiation Patterns of Shoulder-Mounted Antenna (8F) With and Without Heavy Leather Jacket.

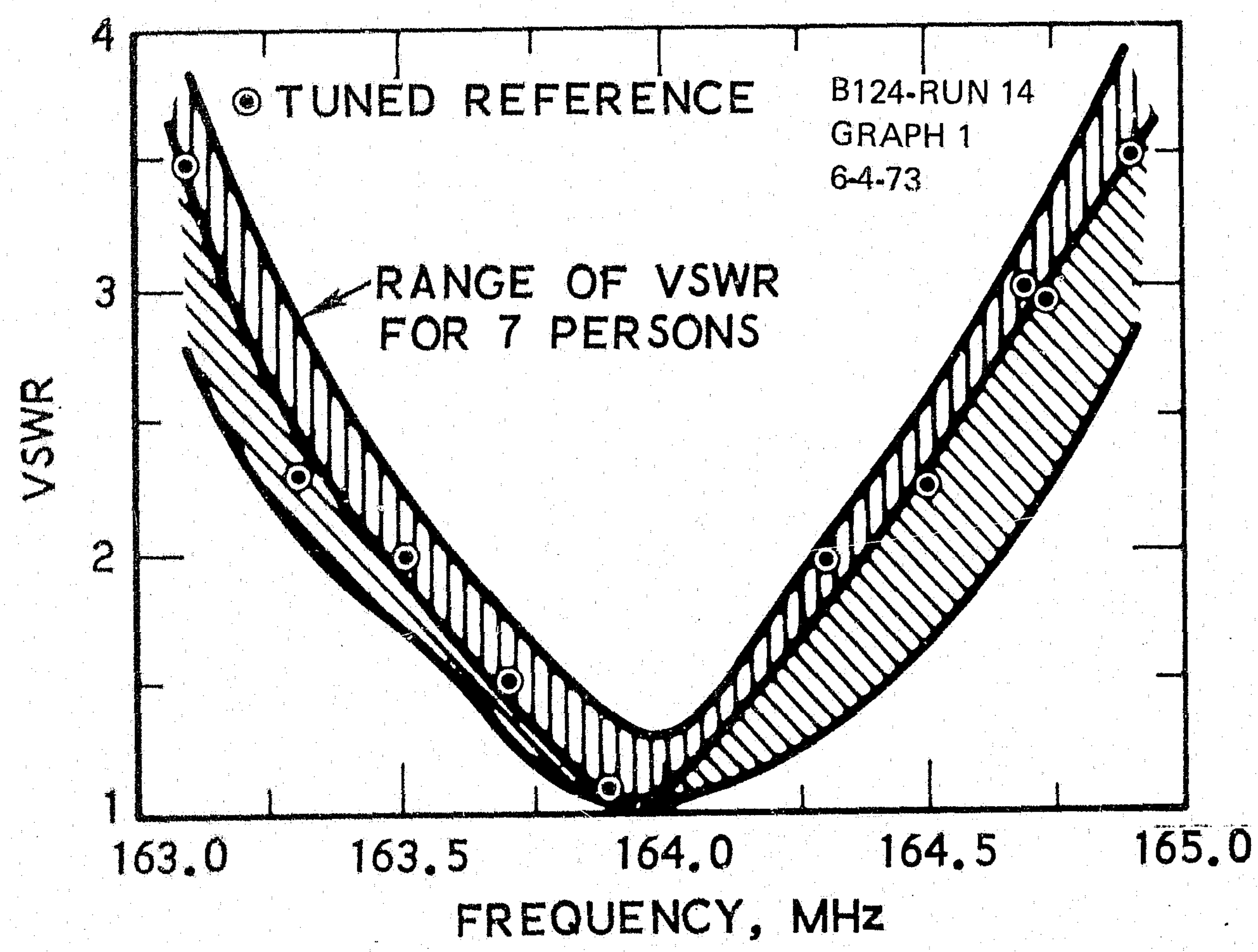
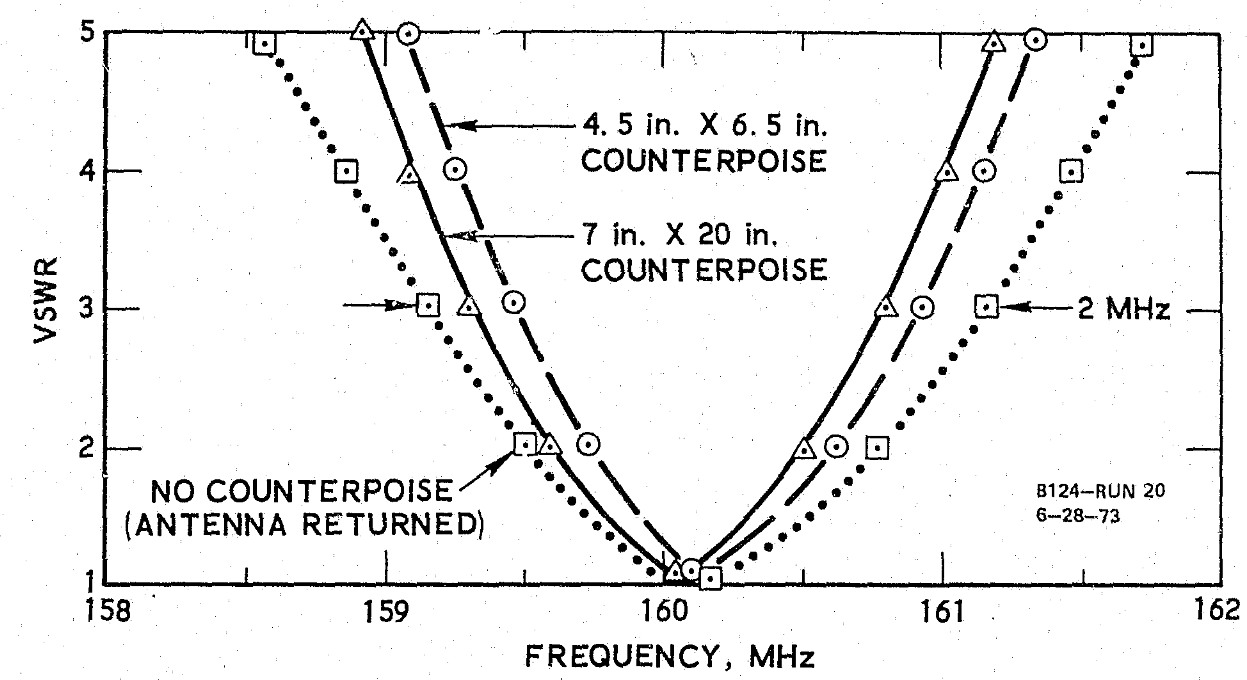
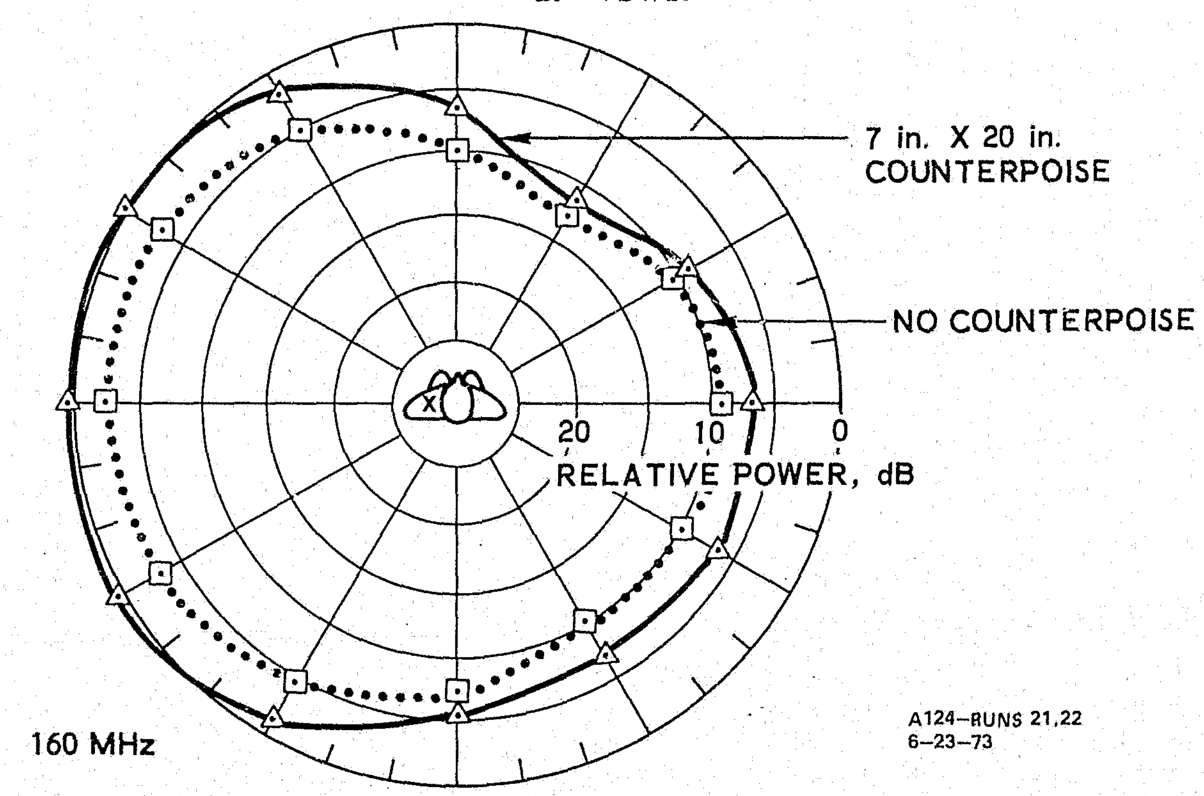


Fig. 3-15. Comparison of VSWR Characteristics of a Shoulder-Mounted Antenna on Different Persons.



a. VSWR



b. Radiation patterns

Fig. 3-16. VSWR and Radiation Pattern Characteristics of Multiturn Loop (Antenna No. 8F) With Various Size Counterpoises.

Without the counterpoise, the bandwidth is 2 MHz (VSWR = 3:1) as compared with 1.45 MHz for the 4.5 x 6-in. counterpoise. The selected counterpoise is shown in the photograph of Fig. 2-3.

Head and arm movement effects on the electrical characteristics of shoulder-mounted antennas have been described previously. Preliminary measurements were also made to show how the proximity of nearby objects affect the VSWR characteristics. Proximity of a metal wall within 5 in. of the loop has no effect on the VSWR; but, within 3 in., spacing the VSWR detunes to approximately 3:1. It should be noted, however, that the shoulder-mounted 6-in. helical whip antenna is more sensitive to the proximity of nearby objects as compared with the loop antenna. The whip will show a change in VSWR when a metal wall is within 9 in. of the antenna, and it detunes to approximately 19:1 when the whip is within 3 in. of a metal wall.

3. Other body-mounted antenna locations. With the multiturn loop installed directly on top of the Motorola transceiver and with the transceiver mounted at waist level, two patterns were recorded, as shown in Fig. 3-17. The patterns are for the loop axis either in the horizontal or vertical direction. The pattern scale is relative to the patterns of Figs. 3-7 through 3-12; thus, a direct comparison of the gain levels can be acquired. The waist-level, multiturn loop shows a significant drop in antenna gain as compared with the shoulder-mounted antenna.

Pattern measurements for the 6-in. helical whip mounted at waist, stomach, chest, and shoulder levels are shown in Fig. 3-18. When the antenna is raised higher, there is a distinct enhancement in signal level. For the

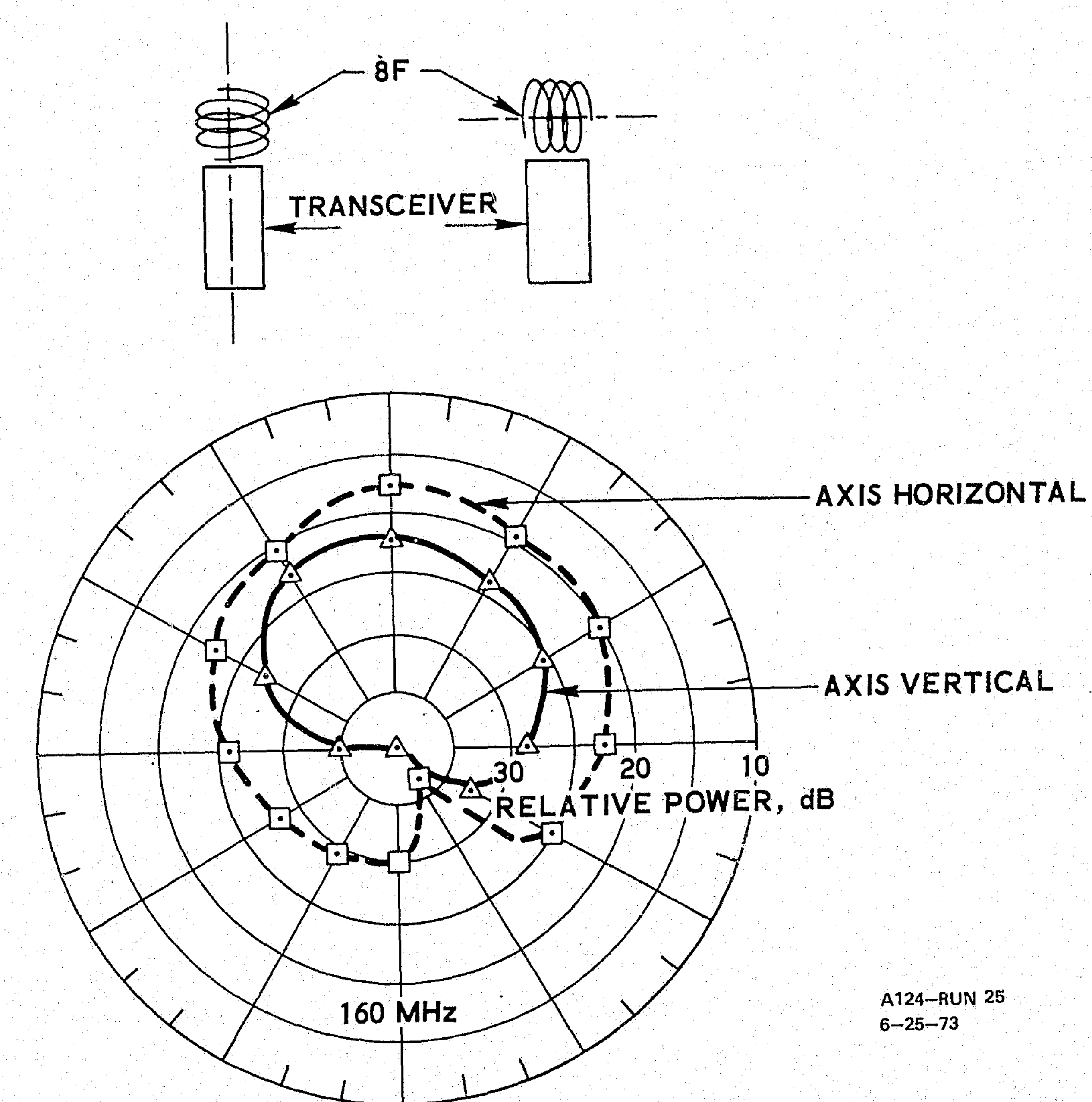


Fig. 3-17. Radiation Patterns of Waist-Mounted Transceiver with Attached Multiturn Loop.

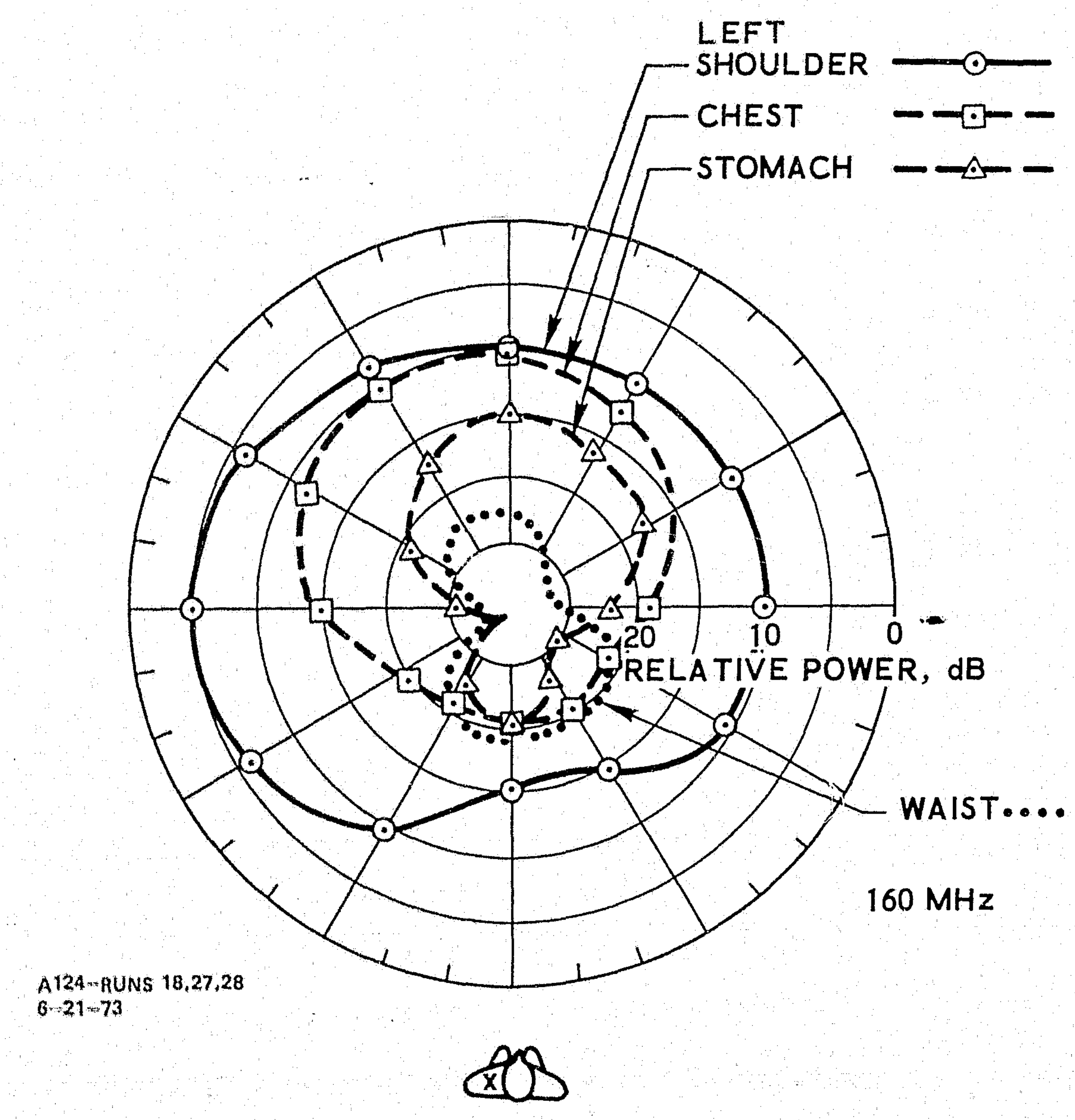


Fig. 3-18. Measured Radiation Patterns of Whip Located at Waist, Stomach, Chest, and Shoulder Levels.

shoulder-level antenna, the whip was connected to the transceiver (mounted at the waist) with a coaxial cable, while the whip was attached directly to the transceiver for the other three positions.

C. Dual Frequency Antenna

With the completion of the single-frequency antenna described thus far, a dual-frequency loop antenna was constructed and tested. The schematic is shown in Fig. 3-19. Capacitor C_3 is adjusted for the receive frequency for the normally closed switch position. C_2 is tuned to the transmit frequency, and the switch would be activated with the push-to-talk button of the transceiver. Two models were constructed, one with PIN diodes and the second with a relay switch.

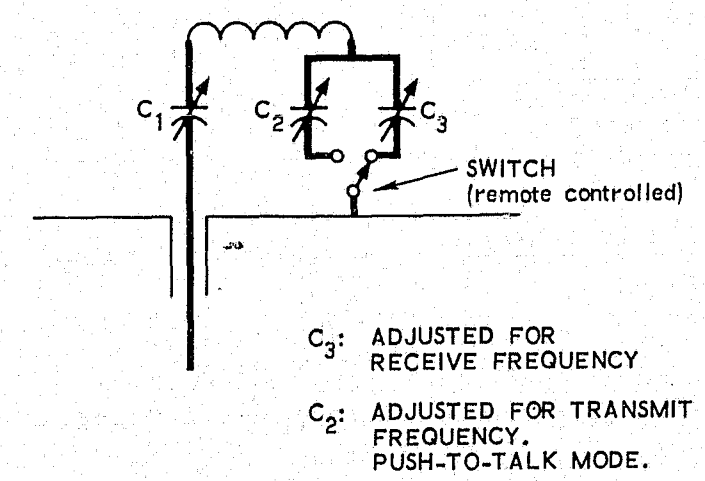
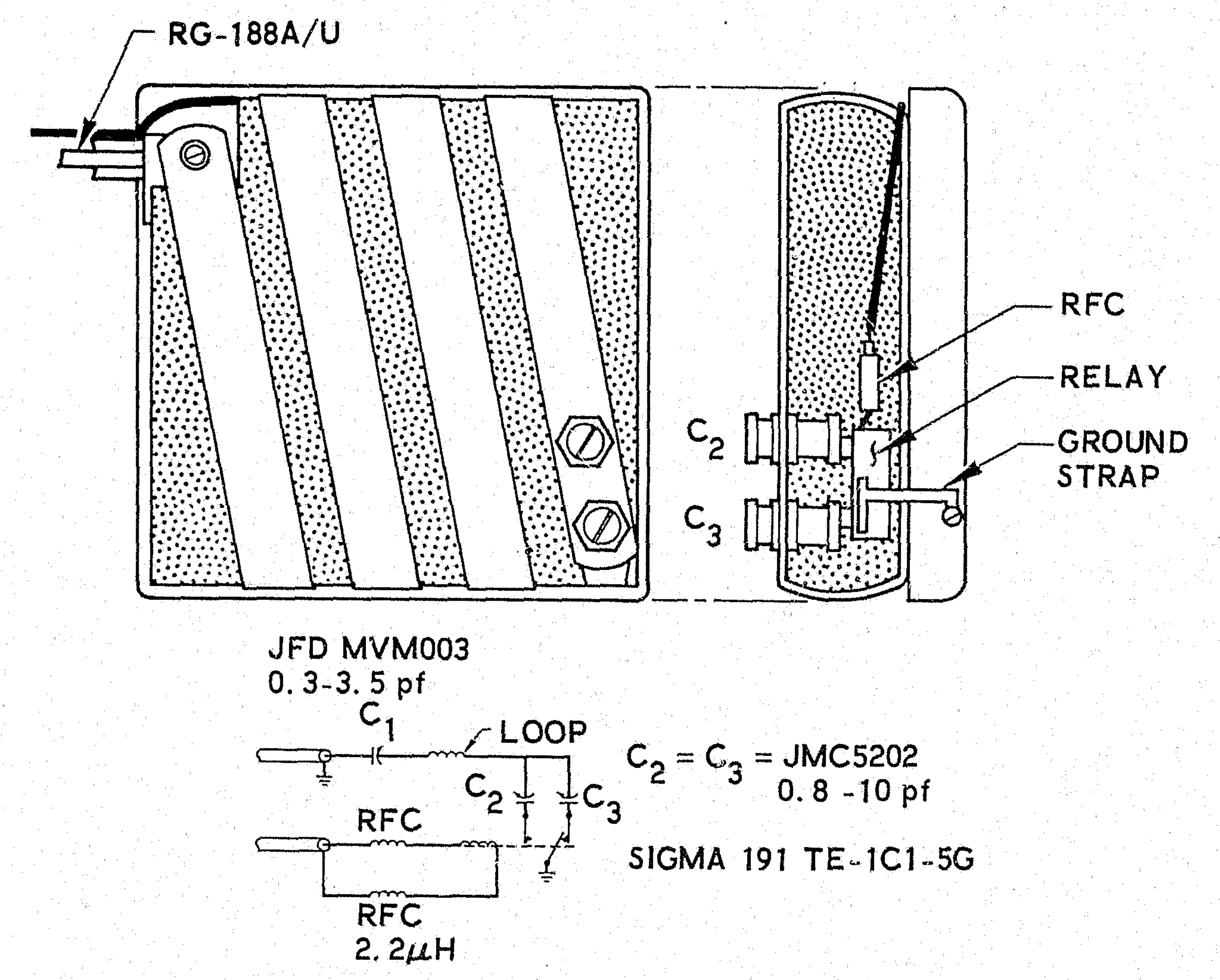


Fig. 3-19. Dual-Frequency Multiturn Loop Schematic.

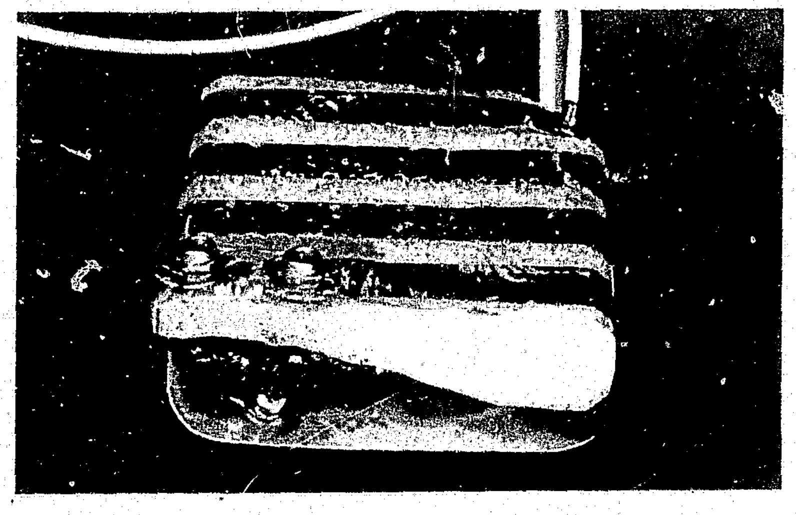
A sketch of the multiturn loop, plus a schematic, and a photograph of a dual-frequency antenna with a relay switch are shown in Fig. 3-20. The VSWR characteristics are shown in Fig. 3-21. Capacitors C_3 and C_2 are able to tune over the 150- to 170-MHz band without readjustment of C_1. Additional VSWR curves indicate that the antenna can also be tuned over the mid-band region without noticeable interaction between the two capacitors. The bandwidth (VSWR = 3:1) varies from 1.45 to 2.50 MHz.

The pattern of the dual-frequency antenna recorded at 160 MHz is shown in Fig. 3-22, and it is compared with the pattern of a single-frequency antenna (8F). Less gain exists in the dual-frequency antenna as compared with the single-frequency unit; however, for all practical purposes, the dual-frequency loop is usable.

Lower antenna gain was achieved by the use of a PIN diode as a switch, as shown in Fig. 3-23. The two dual-frequency patterns represent the cases where either C_2 or C_3 were tuned to the transceiver frequency 160.15 MHz. The lower gain is expected, as the PIN diodes have a forward resistance of 0.8 ohm, which is probably appreciable to the radiation resistance. The VSWR curves are shown in Fig. 3-23, and the physical layout of the capacitors and diodes is presented in Fig. 3-24. The capacitor arrangement shown in Fig. 3-24 was also tried for the relay switch with results very similar to that shown in Fig. 3-22.



a. Sketch and schematic



b. Photograph

Fig. 3-20. Dual-Frequency Multiturn Loop.

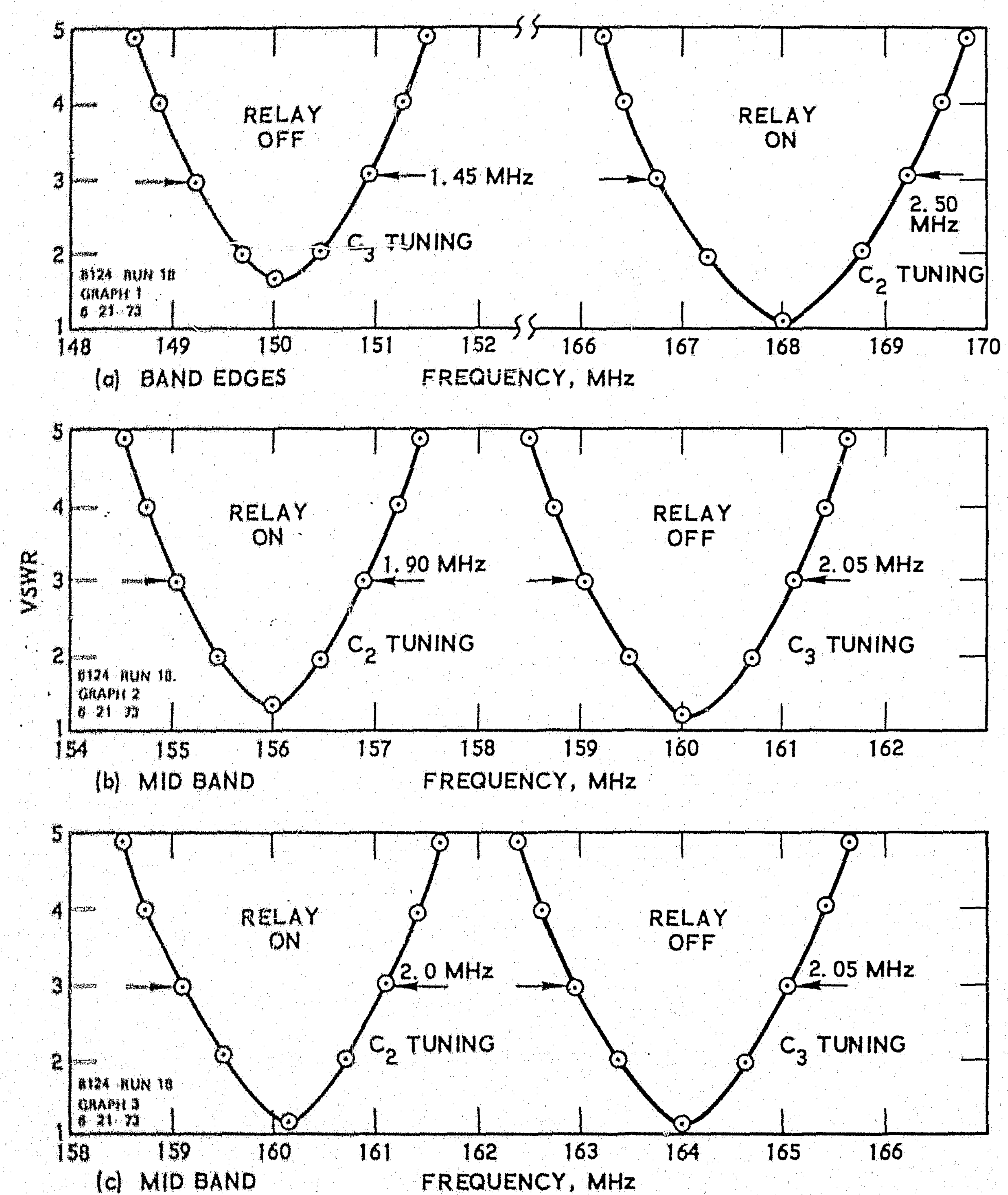


Fig. 3-21. VSWR of Dual-Frequency Loop (No. 14) with Reed Relay Switch.

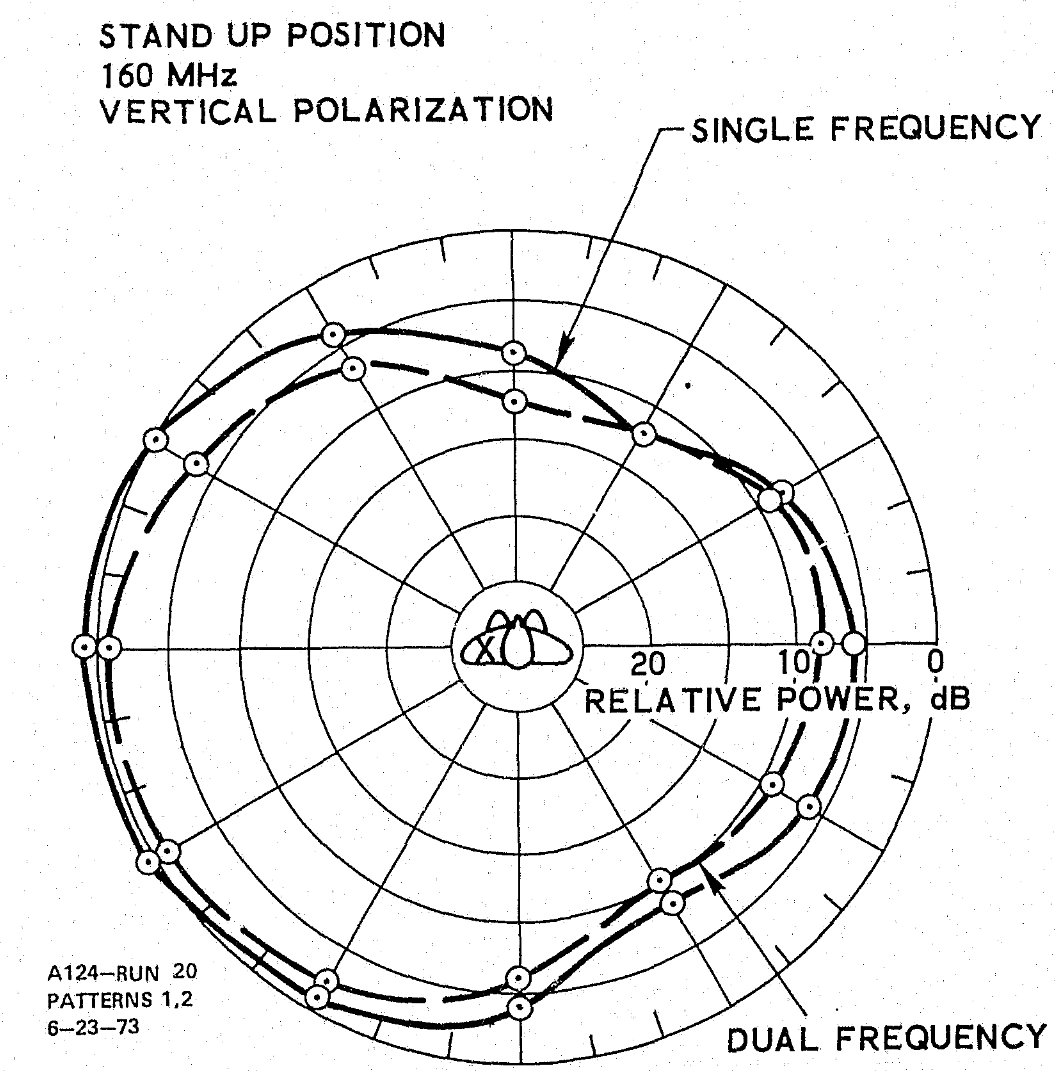
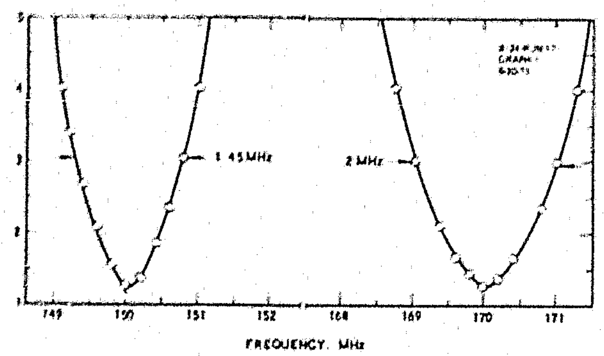
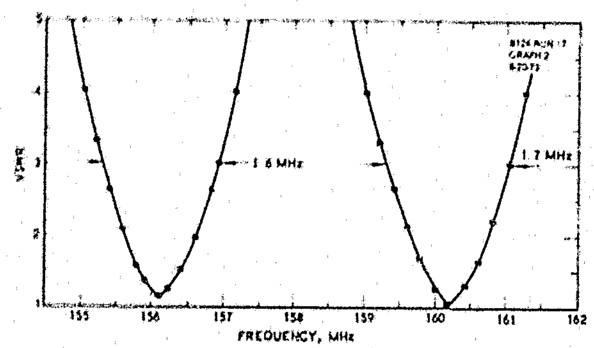


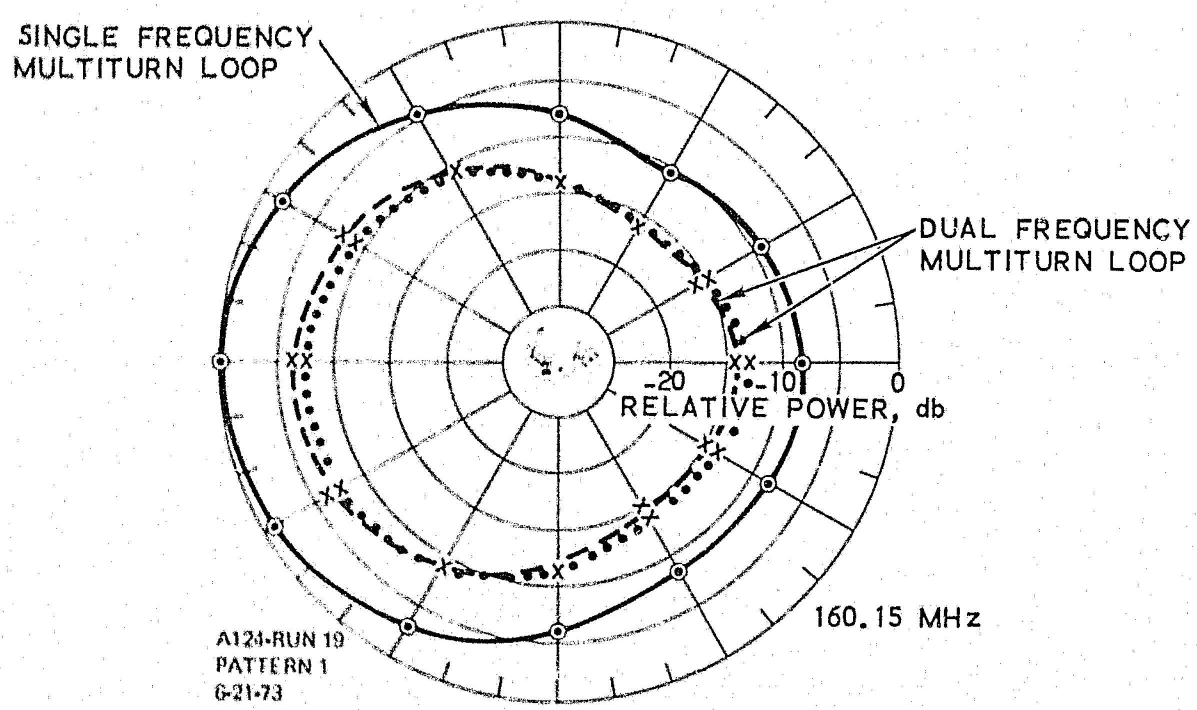
Fig. 3-22. Radiation Pattern of Shoulder-Mounted, Dual-Frequency Loop with Relay Switch.



a. VSWR at band edges



b. VSWR and midband



c. Comparison of patterns with single-frequency loop

Fig. 3-23. VSWR and Radiation Patterns of a Shoulder-Mounted, Dual-Frequency Multiturn Loop with PIN Diode Switching.

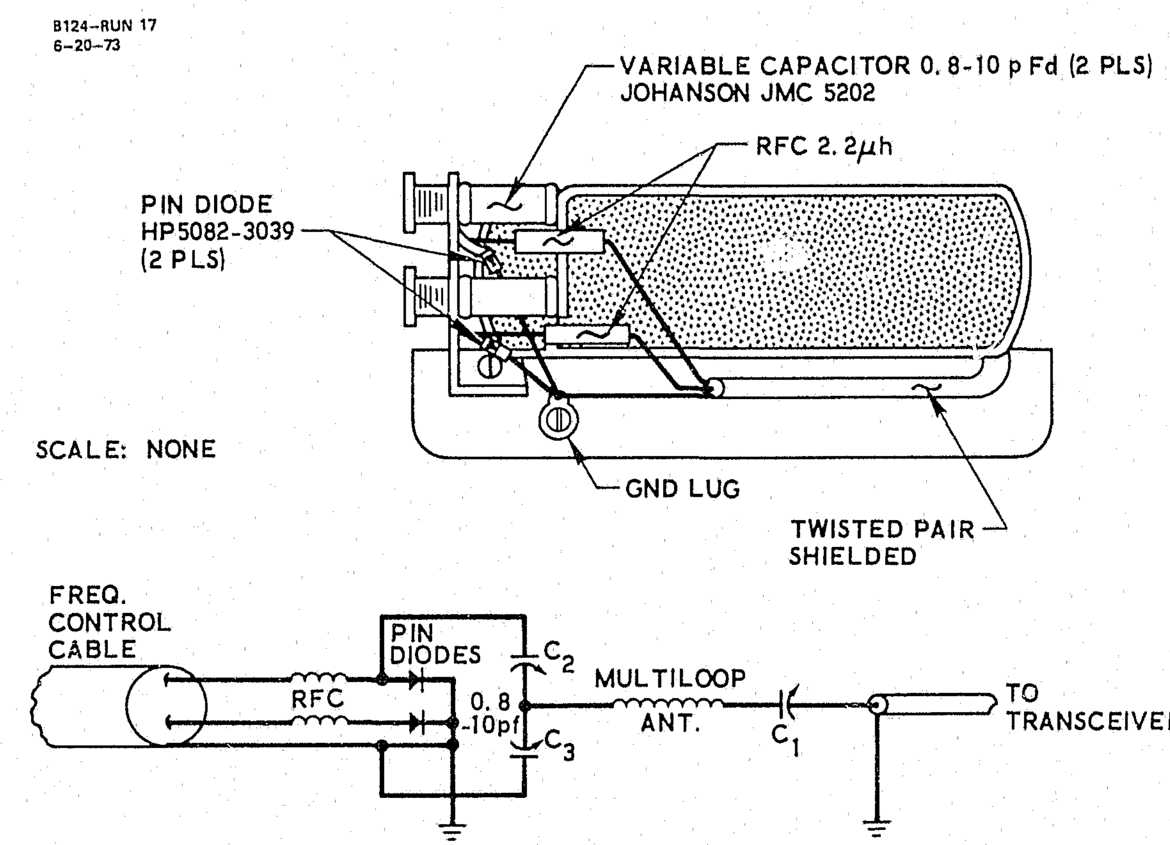


Fig. 3-24. Dual-Frequency Antenna with PIN Diode Switching

D. Effects of Materials Used in Fabrication

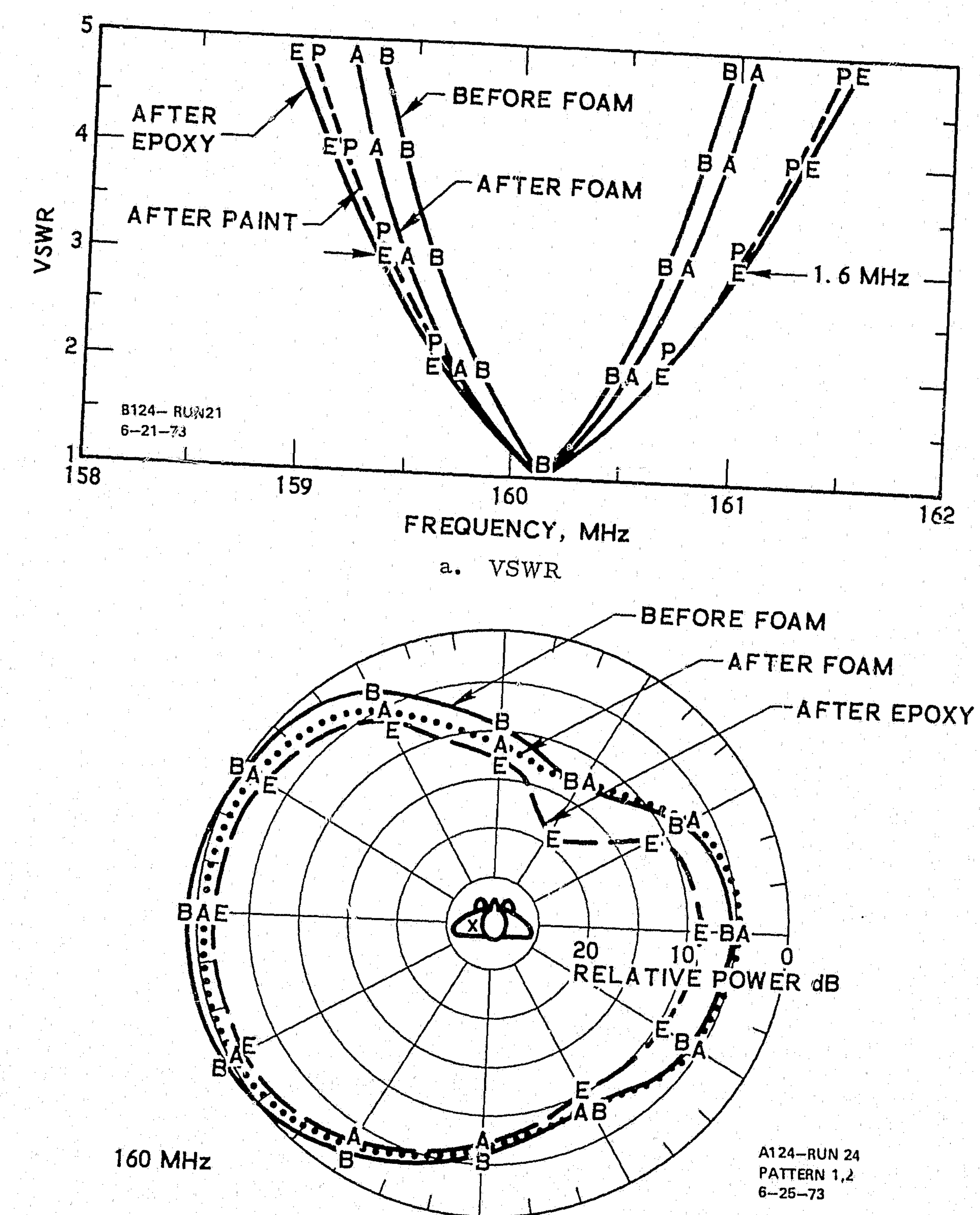
Construction of the flat copper strip, multiturn loop is shown in Fig. 2-3. The copper is wound on a styrofoam block, and the cables and capacitors are attached. In order to make a rugged, strong antenna, the foam block is foamed-in-place to the metal ground plate.* This is followed by an epoxy coating** to provide a hard surface, which is th · painted. VSWR and pattern measurements were made during the fabrication procedure to determine the effects of the foam, epoxy, and paint. Except for the final painted surface, noticeable changes are observed in each of the fabrication steps, as seen in the VSWR and patterns of Fig. 3-25. The after-painting pattern was not plotted, as it was almost identical to the previous step.

E. Noise and Operational Measurements

Preliminary noise measurements were made with the multiturn loop and the 6.6-in. whip connected to the Motorola transceiver to determine if there was a difference in noise levels between the two antennas. The test set up is shown in Fig. 3-26. It was found that, in an open area or directly adjacent to heavy air-conditioning machinery, the output noise level was the same whether the whip, loop, or no antenna was connected to the Motorola unit.

*Emerson and Cumming, Inc., Type FPH

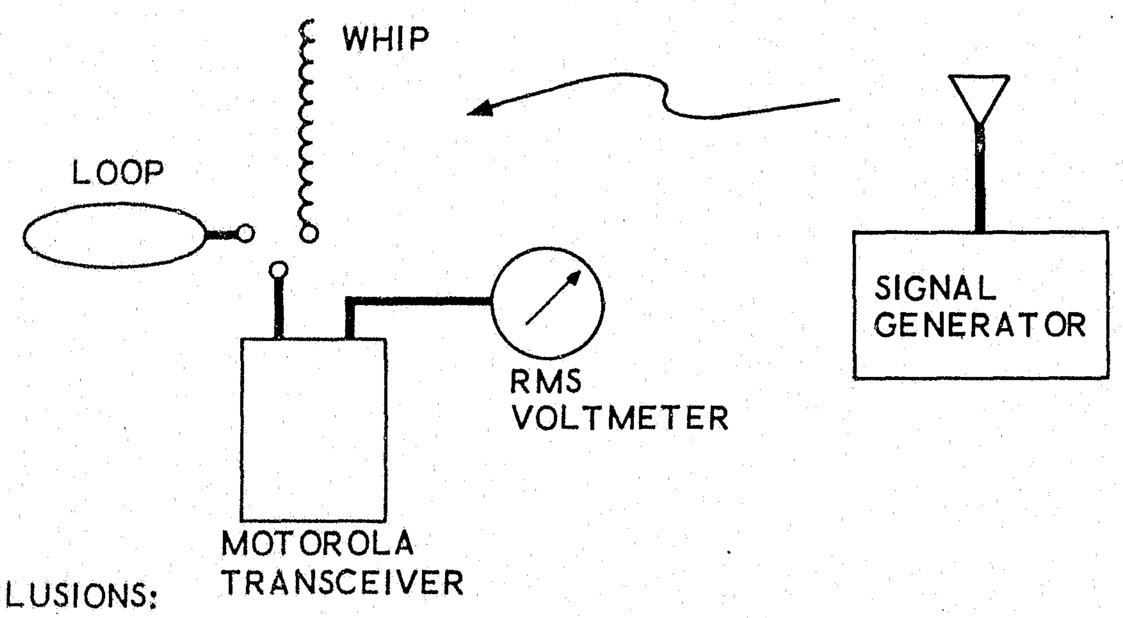
**Furane Plastics Inc., Hardener No. 9816, Epoxy EPOCAST 202.



a. VSWR

b. Patterns

Fig. 3-25. VSWR and Radiation Patterns of a Multiturn Loop Between Each Fabrication Procedure.



CONCLUSIONS:

1. OUTPUT NOISE LEVEL SAME WITH WHIP, LOOP OR NO ANTENNA CONNECTION
   - IN OPEN AREA
   - ADJACENT TO AIR-CONDITIONING MACHINERY

Fig. 3-26. Noise Comparison Studies for the Multiturn Loop and Whip.

In order to obtain preliminary user's reports and semiquantitative data on the shoulder-mounted loop antenna, tests were carried out by the security force of The Aerospace Corporation in El Segundo, California. The tests, which were performed over a period of several days, included comparative performance of transceivers with body-mounted antennas and those with existing whip antennas. These tests were carried out both inside and outside buildings, by officers on foot, in automobiles, and on patrol scooters. During his regular rounds, each Aerospace security officer in the test carried two independent transceivers: one unit with a whip and the other with a shoulder-mounted loop antenna. At various locations, the officer would use each transceiver to make number-count, verbal transmissions to the dispatcher. In turn, the dispatcher would return a number count for each transceiver. Both the security officer and the dispatcher evaluated the quality of their transmission and reception by use of a scale of 1 through 5 for loudness and a similar scale for clarity. Comparable performance was achieved even with this limited testing.

CHAPTER IV. SIGNIFICANCE OF BODY-MOUNTED ANTENNA DATA APPLICABLE TO POLICE OPERATIONS

One of the goals of this feasibility program was to design an effective and improved antenna for a policy officer's personal radio. A multiturn loop was selected as the antenna to be developed because of its many attractive features, such as the relatively high efficiency for its size, small and compact, low silhouette, rugged, less sensitive to nearby objects as compared with a whip, use of low-loss tuning capacitors, and with the requirement for a single-frequency operation. Detailed electrical characteristics of body-mounted antennas (whip and the multiturn loop) have been presented in Chapter III, which provides the antenna and communication systems engineer with factual data to optimize a system.

In order to provide conformity in antenna measurements, the body-mounted antennas were matched to a 50-ohm generator with VSWRs of 1.2:1 and 1.8:1 for the loop and whip,* respectively. One might wonder why the painstaking matching effort was required when it is known that the transceivers operate into a 6-in. whip with an unknown match or when a telescoping whip is used that has an almost infinite variation in impedance. The answer, of course, is that this program was a scientific development for the purpose of optimizing an antenna system that required systematic measurements.

*The length of the whip is the only means for matching.

Present-day transceivers are made to operate into almost any type of antenna load impedance (e.g., a telescoping whip antenna of arbitrary length) without damaging the power amplifier circuit. Furthermore, it appears that a radio will operate satisfactorily for any length of whip antenna. From basic circuit theory, it is known that the transmitter (or receiver) must be conjugate matched to the antenna to obtain maximum power transfer to the antenna. Thus, when the radios are operated with variable whip lengths, there must be a significant loss in efficiency. If propagation losses are accounted for in the metropolitan area (shadow losses of 20 to 25 dB) and in the suburban areas (20 to 40 dB over the free space loss for distances of 6 mi. caused by irregular terrain and 20 to 30 dB in wooded areas),[1] the police communication system must be designed for a very high signal-to-noise ratio region. Therefore, when operating in a signal-rich environment, a loss of a few dBs in the antenna and transceiver will probably not cause a noticeable loss in communications effectiveness.

In a fringe area communication system, a loss of a few dBs could make or break the link. Under this environment, optimization of the antenna-transceiver interface is important. That is, in order to have an efficient system, the transceiver output and antenna impedances should be matched to 50 ohms and to the antenna. In Table 4-1, note that a 6-dB loss would mean a 50-percent reduction in communication range and a 25-percent reduction in area coverage as compared with a no-loss system. Thus, a loss of a few dBs could be a very significant factor for the communication systems engineer. One should also recognize that a 3-dB saving in efficiency would mean a

Table 4.1. 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

savings of 2:1 in the transmitter power, which in turn could reduce the battery weight and power by the same factor. For example, a 2-Watt transmitter could be used instead of a 4-Watt unit with a corresponding lighter weight battery or a longer-life battery.

The bandwidth of the multiturn loop has been chosen at the point where the VSWR = 3:1 or that corresponds to a 1.3 dB loss (74 percent efficiency). The mismatch loss as a function of VSWR is plotted in Fig. 4-1. It should be recognized that this mismatch loss is only one of the many factors that contributes to the loss of a communication system. For reference, Table 4-1 lists the communication coverage vs system losses. A VSWR = 10:1 corresponds to a mismatch loss of 4.8 dB (33 percent efficiency), which is a VSWR that is considered unacceptable to antenna engineers. Should this criteria be accepted, then a wider bandwidth is available for multiple channel or duplex use. If this is the criteria, there is no need for a sophisticated antenna such

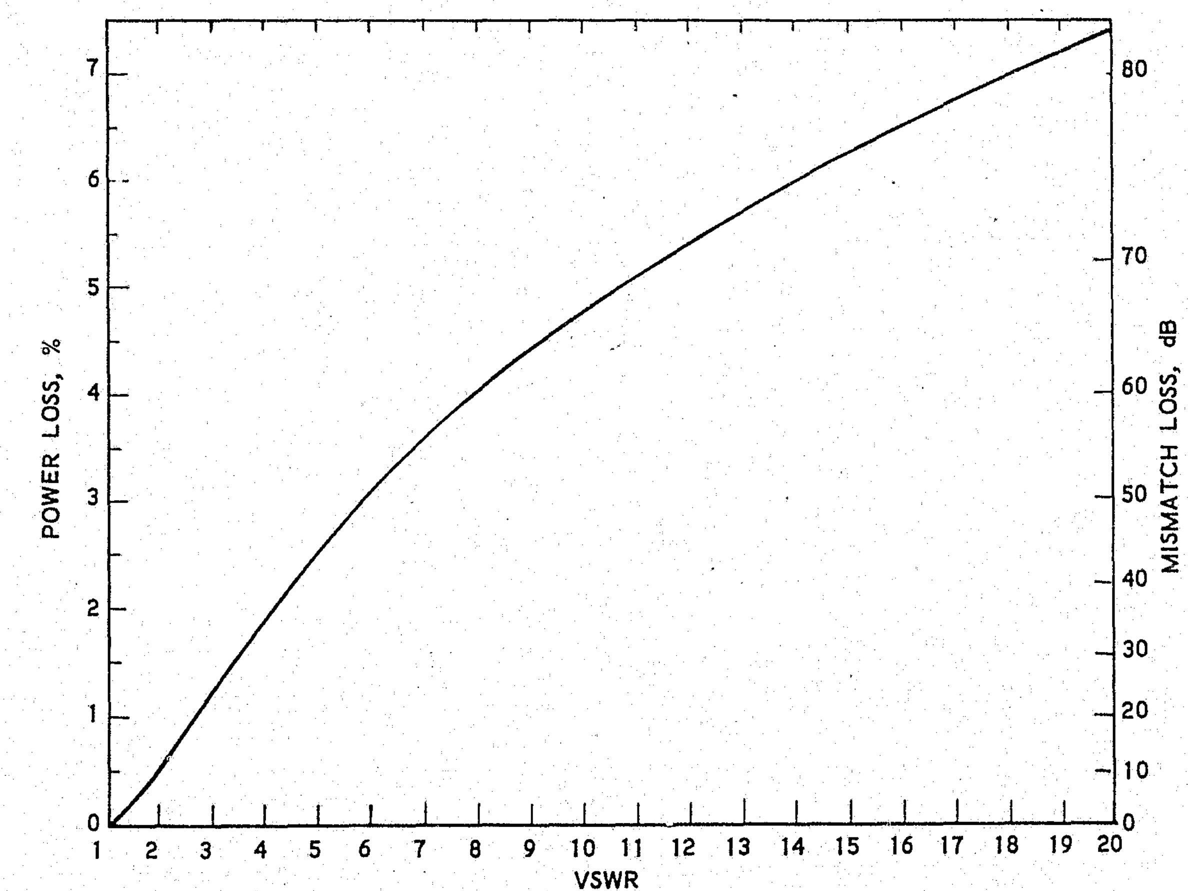
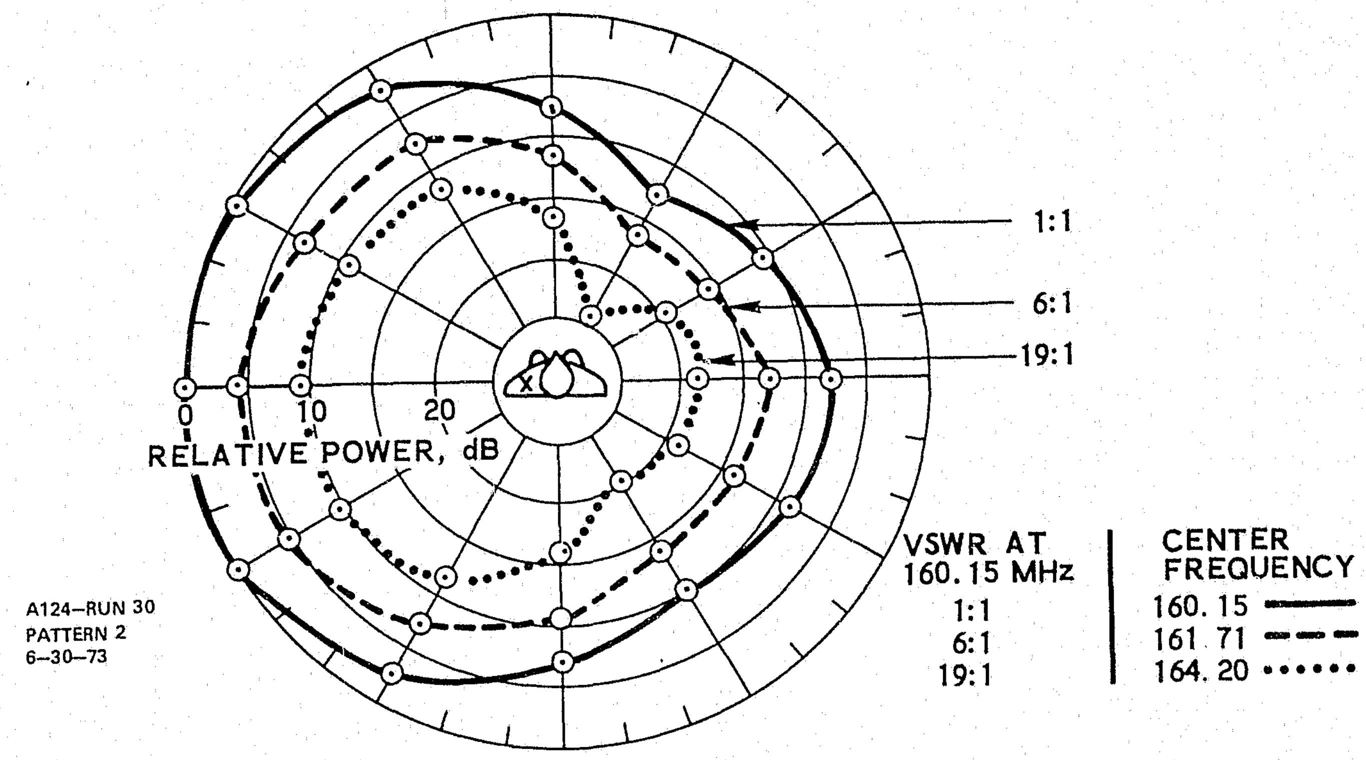


Fig. 4-1. Mismatch Loss vs VSWR.

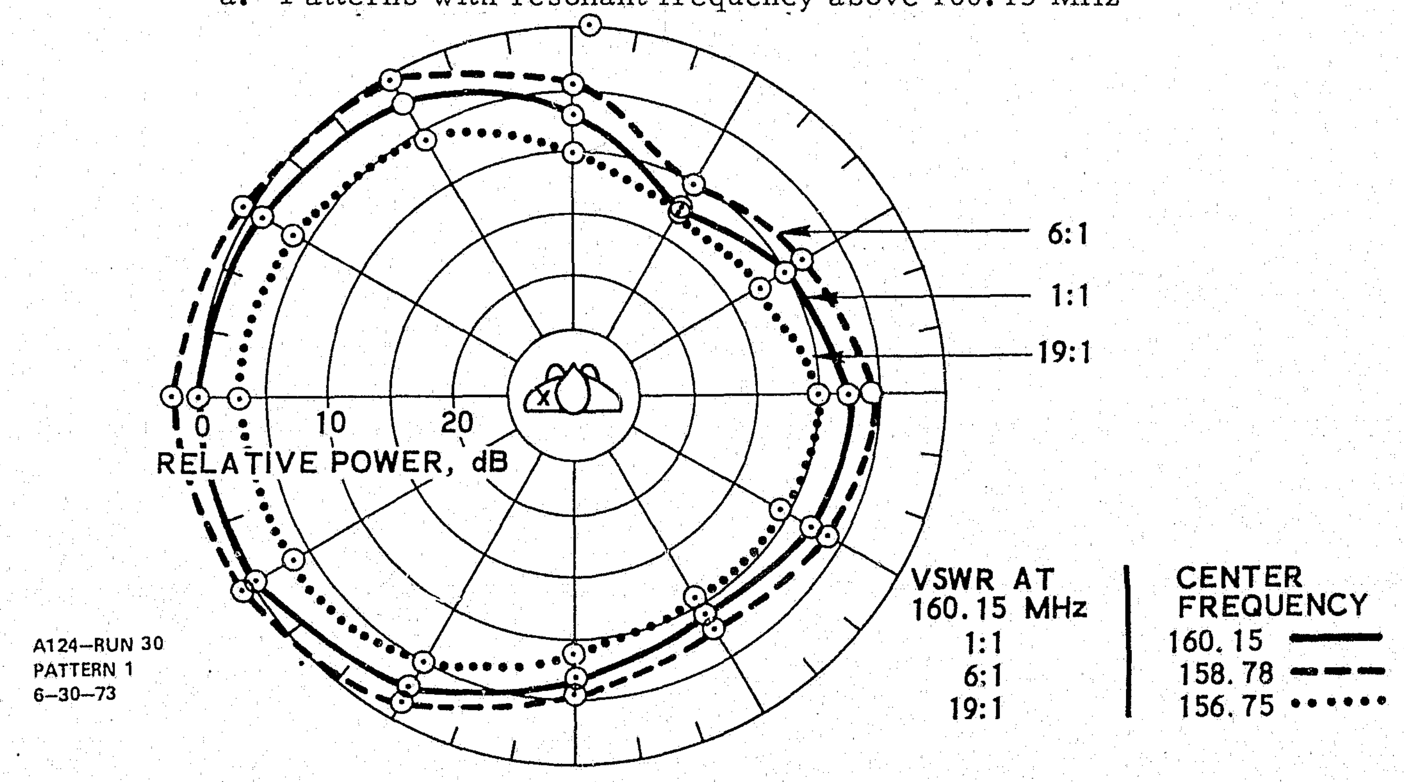
as the multiturn loop, and the commonly accepted whip antenna should be used. The shoulder-mounted multiturn loop, which is a small and compact antenna for single- or dual-frequency operation, can outperform a shoulder-mounted, 6-in. whip antenna.

An optimum communication system should be designed with an integrated transceiver-antenna. That is, the transceiver and antenna should be compatible to provide maximum power transfer. This approach would increase the effectiveness of the communications or conserve or use fewer batteries for a given transmitter power. During this feasibility program, the VSWR of the antennas was measured and retuned to a VSWR ≤ 1.3:1 at 160.15 MHz, which is the frequency of the Motorola transceiver. It is necessary that the antenna be tuned for maximum power transfer if it is assumed that the transceiver output impedance is also 50 ohms.

To illustrate the loss in effective radiated power (ERP) of the Motorola and shoulder-mounted loop, the antenna was purposely retuned to another resonant frequency such that it had a VSWR of 6:1 and 19:1 at 160.15 MHz, which would normally represent a mismatch loss of 3 dB and 7.2 dB, respectively. In Fig. 4-2, the radiation patterns are shown with the antenna's resonant frequencies above and below 160.15 MHz, but the patterns were recorded at 160.15 MHz. The patterns are also compared with the matched antenna. For patterns with resonant frequencies above 160 MHz, the reduction in ERP appears to be reasonable with the increased VSWR of the antenna. However, for patterns with resonant frequencies below 160 MHz, Fig. 4-2b indicates that, with a mismatch of a VSWR = 6:1, the maximum ERP is



a. Patterns with resonant frequency above 160.15 MHz



b. Patterns with resonant frequency below 160.15 MHz

Fig. 4-2. Relative ERP of Transceiver and Shoulder-Mounted Multiturn Loop (Antenna No. 8F) Combination at 160.15 MHz with Antenna Purposely Detuned.

obtained. This would seem to indicate that the transmitter does not have a 50-ohm output impedance. Thus, designing an antenna as a component may not necessarily provide optimum system performance. Patterns with other VSWR values were also measured but not plotted, as the curves of Fig. 4-2 were representative of the results.

CHAPTER V. CONCLUSIONS

A shoulder-mounted multiturn loop for the 150- to 170-MHz band has been demonstrated to provide 3.8 dB (average over 360 deg) more gain than a shoulder-mounted, 6.6-in. helical whip. Comparison of the antenna radiation patterns between the loop and whip are also presented for other head, arm, and body positions, including stooped and prone positions. The loop's instantaneous bandwidth is approximately 1.4 MHz for a VSWR = 3:1. The loop can also operate over a wider bandwidth in a push-to-talk mode by switching in a second capacitor that tunes the antenna to the transmit frequency. The loop is a small, compact, rugged, lightweight unit with dimensions of 2.9 in. x 2.9 in. x 0.9 in. high and weighs 3 oz.

Measurements show the deleterious effects of body absorption with waist-level antenna locations for both the loop and the whip. The shoulder-mounted, 6.6-in. whip has a bandwidth of 11 MHz (VSWR = 3:1) in the VHF band and a high VSWR for the 450- to 470-MHz (UHF) police communication band.

APPENDIX A. COST ANALYSIS OF DUAL-FREQUENCY ANTENNA

This appendix summarizes the principal cost factors relating to the dual-frequency body mounted antenna which The Aerospace Corporation has developed under Law Enforcement Assistance Administration Task No. A-73-COM-01. Detailed below are cost estimates for initial production of this antenna in quantities of 100 and 1,000 pieces. The cost includes the detailed engineering and production drawings, specifications, initial tooling, fabrication and testing of the antenna.

1.0 <u>One Time Start Up Charges (Non-recurring)</u>

1.1	Engineering and design, preparation of production drawings, specifications, bill of material acceptance tests procedures, instruction sheets, and procurement of parts.	$9,000
1.2	Tooling charge (plastic case)	1,000
1.3	Production set-up charge for jigs, production aids, and nonstandard tools.	1,500
1.4	Punch and die for simple sheet parts (e.g., counterpoise, ground plane, etc.)	1,000
	Total non-recurring	$12,500

2.0 <u>Bill of Material</u>

	Quantity 100	1000
Relay	6.00	4.20
Capacitor (2), C_2 and C_3	4.90	4.00
Capacitor, C_1	4.10	3.30
RF Cable	.50	.35
Counterpoise	.10	.08
Metal ground plane	.10	.08
Mounting/body attachment device	1.00	.80
RF Connector	1.20	1.00
Cable clamp	.06	.04
Strain relief tubing	.06	.04
Coil form (e.g., foam)	.06	.05
Packaging and Instructions	.20	.15
	18.34	14.13

3.0 Direct Labor Estimates

	Time per Piece (minutes) vs. Quantity 100	1000
Coil winding	5	3
Mount and solder piece parts	10	6
Fabricate cable and attach connector	20	15
Perform final assembly and encapsulate	15	10
Final check and adjustment	20	15
Attach counterpoise and body mounting means	10	7
Quality assurance inspection	10	8
Package and ship	6	4
Total direct time, minutes	96	68
Direct Labor Cost @ $3.00/hr.	$4.80	$3.40

4.0 <u>Cost Summary and Final Price Estimate</u>

		First Production Quantity 100	1000
4.1	Tooling and start-up costs ($12,500)	$125.00	$12.50
4.2	Bill of Material	18.34	14.13
4.3	Direct Labor	4.80	3.40
4.4	Manufacturing Overhead 110% of Item 4.3	5.28	3.74
4.5	Sales Expense (+25%), G&A Expense (+12%) and Pre-Tax Profit (+25%)	6.24	4.42
	Estimated Unit Price (amortized for the initial production drawings and tooling charges)	$159.66	$38.19

5.0 <u>Field Installation and Test Cost</u>

5.1	For transceivers with connector	$ 5.00
5.2	For transceivers without connector (i.e., modify and put in connector)	$30.00

APPENDIX B. RADIATION PATTERN AND VSWR MEASUREMENT TECHNIQUES

To aid in the tuning of the multiturn loop and the VSWR measurements, a Hewlett-Packard (HP) network analyzer was used. The shoulder-mounted loop was connected directly to the network analyzer with a length of coaxial cable. The cable did not appear to be RF "hot." Because the cable to the network analyzer and the analyzer itself is part of the radiating system, it would have been difficult to separate the VSWR instrumentation from the antenna under test. In any event, fairly consistent VSWR measurements were obtained with the man standing at different distances from the instrumentation.

For pattern measurements, more consideration was devoted to the effects of the instrumentation and the connecting cables. It was felt that, when the multiturn loop was being tested as a receiving antenna, the cable to the detector (or transceiver), the cable to the VSWR meter, and the meter itself were all part of the radiating system. Thus, it was necessary to separate the effects of the instrumentation from the antenna to make the pattern measurements. A carbon-wire system, as shown in Fig. B-1, was used. The detector and the 1000-Hz preamplifier would simulate a transceiver. Reradiation from the high-resistance carbon wire is expected to be zero; thus, the measurement system would be a true representation of the body-mounted antenna, the coaxial feed cable, and the transceiver.

A corner reflector, vertically polarized, was used as an illuminating source. Measurements were made with the corner reflector at various distances and for several heights above the ground. It was found that the patterns

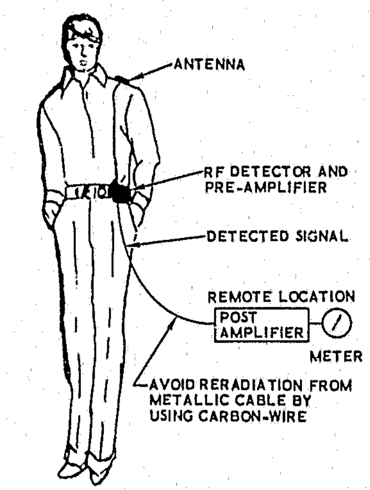


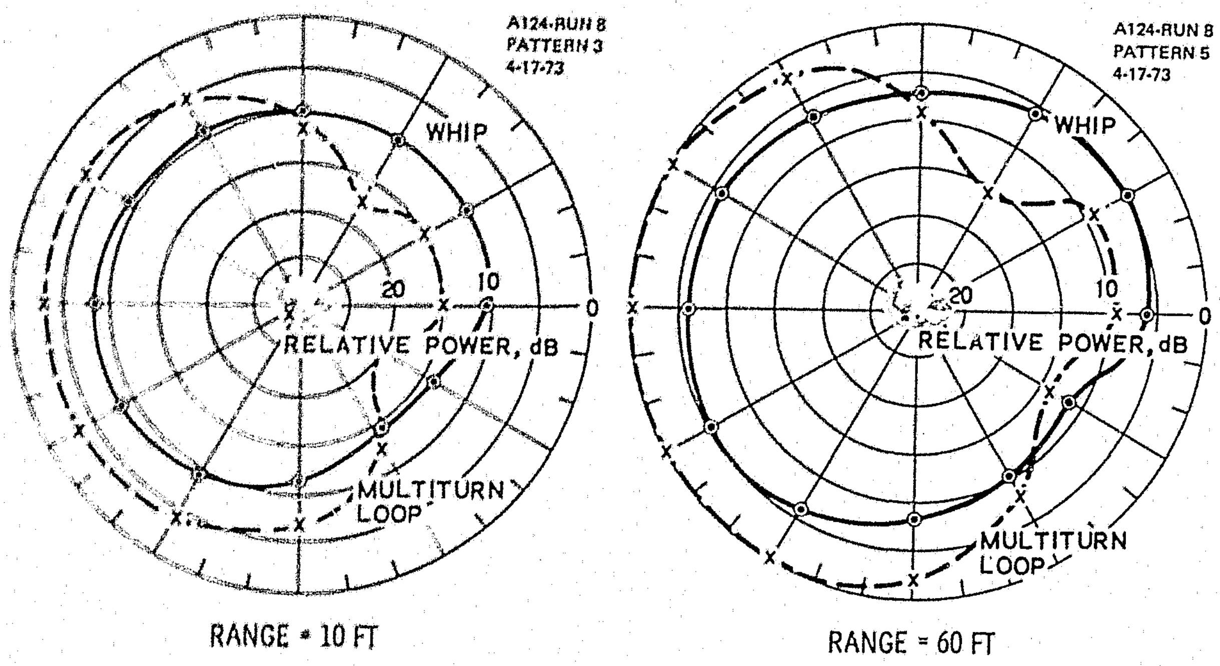
Fig. B-1. Carbon-Wire Measuring System for Body-Mounted Antenna Radiation Patterns.

were essentially identical when measured under these various circumstances. Typical patterns are shown in Fig. B-2 for distances of 10 and 60 ft.

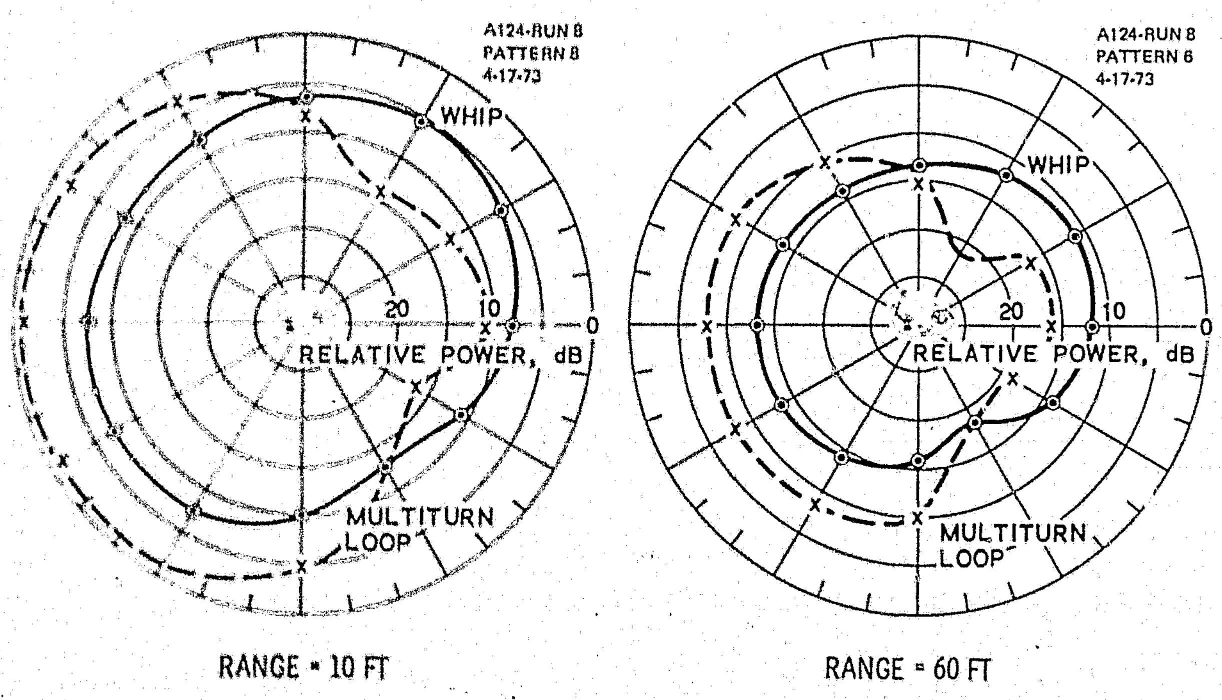
Patterns from the carbon-wire system measurements were compared with those that used a transmit mode, i.e., those that use the transceiver* as a transmitter. These measurements compared favorably, as shown in Fig. B-2. The received signal was detected with a HP vector voltmeter, Model No. 8405A.

As the antenna range facilities were on the roof of the laboratory building (Building 125), a question was raised as to the accuracy of

*Motorola Model HT 200/H23DCN-1100AW.



a. With carbon-wire system



b. With Motorola transceiver as transmitter

Fig. B-2. Comparison of Shoulder-Mounted Antenna Radiation Patterns Measured at Different Distances in an Open Field.

measurements made on the roof vs those that would be made in a clear open field. It was found that measurements made on the roof, on the lawn in front of The Aerospace Corporation Buildings (SAMSO), and in the open fields in Palos Verdes (Malaga Cove) yielded the same results within the measurement accuracy. The patterns of Fig. B-2 are those taken in the open fields. Repeated body-mounted antenna radiation pattern measurements showed that the repeatability was approximately ±2 dB in the maximum portion of the pattern and could be as bad as 7 to 10 dB in the minimum region. Factors that contribute to the statistics of the measurements are: head and arm movements that disturb the patterns, coaxial feed cable and transceiver that are not necessarily in the same position (which is a portion of the radiating system), the operator's reading error, and the state of the battery charge.

The conclusion of the measurement technique evaluation indicates that the carbon-wire system or the transmit mode, the roof or open fields, and the range (distance) were not critical. Because of the simplicity, all subsequent measurements were made using a Motorola transceiver as a transmitter and placing a corner reflector approximately 13 ft away from the subject. In this way, an absolute ERP (actually relative, as the transmitter power output and gain are unknown) of the transceiver-antenna system can be obtained for various antenna types and body conditions. The frequency of the pattern measurements was 165 MHz during the evaluation stage (Fig. B-2) and subsequently changed to 160.15 MHz for the majority of the patterns presented in this report.

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