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The performance characteristics of custom and commercial off-the-shelf antennas were determined by analysis or measurement for the GPS and soldier radio (1755-1850MHz) bands. Several locations for these antennas on the body were considered. Based on the analysis and measurements, a state-of-the-art off-the-shelf patch antenna with integrated low-noise amplifier was selected for GPS, coupled with a broadband planar fan monopole fed against the shield of the GPS amplifier. The complete assembly measures 2" long by 1" wide and 0.25" thick. A shoulder epaulet type pouch was designed and fabricated for mounting on the MOLLE which contains the antenna assembly. A survey of miniature GPS integrated receivers was also conducted. One unit was selected and delivered. Brassboard soldier radios were fabricated using off-the-shelf components. The latter were used to test the integrated epaulet antennas over two 400m links, one nearly flat tree covered path, and the second a more obstructed path also with tree coverage. Results of link testing with the radios having an output power of ~20dBm showed that single or multiple repeats of the simple test message were only required when both test subjects were prone at 400m over the flat path and beyond 200m on the more obstructed path.

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1.0 Summary

The Army is in the process of developing a new generation of soldier navigation and communication (NAVCOM) equipment that will be miniaturized, body conformal and make maximum use of commercial-of-the-shelf (COTS) designs. Of specific interest here are the soldier radios and computers fabricated on flexible circuit board materials that could be integrated into worn equipment such as the Modular Lightweight Load Carrying Equipment's (MOLLE) fighting load vest. The former will provide for very short range (less than 1/4 mile) voice links between squad members using the 1755-1850 MHz band and the latter for providing the soldier with his 1575 MHz Global Positioning System (GPS) location, shown on a displayed moving map. Both of these emerging, conformal systems require equally conformal antennas that are capable of being integrated into worn equipment as well as functioning regardless of the soldier's position (standing, kneeling or prone) or azimuthal orientation in urban or forested environments.

Working with the government program office, we developed a set of desired characteristics and performance goals for an integrated soldier radio/GPS antenna system, conducted an extensive survey of COTS designs, obtained and tested COTS samples and where necessary designed and tested candidate solutions. Key issues resolved early into this project were where on the soldier's body and into which piece of worn equipment the antennas should be integrated. We found that considering coverage only, the helmet is preferable to the vest. However as a practical matter the latter is preferred since helmet mounted antennas require connecting cables to the vest which in turn limits soldier effectiveness and flexibility. Computer modeling and field testing have shown that it is possible to place a combined soldier radio and GPS antenna system into an epaulet and satisfy the performance goals while containing all components of this system within the vest itself.

As part of this project we fabricated, tested and delivered six of these epaulet antenna systems as well as a seventh example which contains a miniature GPS receiver in addition to the antennas. We also fabricated and delivered four brassboard, low power soldier radios, that were used to evaluate the epaulet antennas over short distances in forests. Figure 1-1 shows the three deliverable items.

From our work on this project we have concluded that, using a mixture of COTS and custom designed antenna elements, it will be possible to obtain the desired characteristics and performance at a very low cost (less than $100 per system). We recommend that the epaulet antenna design be transformed from a laboratory prototype into a fully ruggedized and military qualified item.

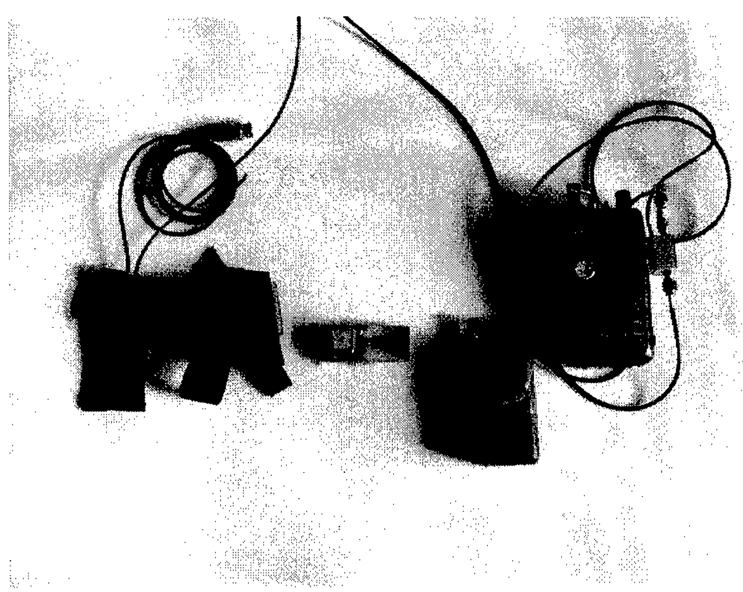


Figure 1-1 Deliverable Epaulet Antennas, Miniature Integrated GPS Receiver and Brassboard Soldier Radios

2.0 Introduction

Since the longest wavelength for the two bands of interest is 7.5", antennas capable of being contained in an epaulet on the order of a few square inches will probably be electrically and certainly physically small. However some electrically small antennas achieve this status by increasing their thickness, which for our purposes is limited by the desire to maintain the epaulet as conformal to the shoulder as possible. It is well established that over the two bands of interest the human body and its appendages will shield or "block" radiation as well as absorbing a portion of it. It has been shown by both theory and extensive measurements that the human head absorbs approximately 50% of the power radiated from the ubiquitous PCS band (1900 MHz) portable phone when the antenna is a few inches from the ear.

It has also been learned from link tests conducted by the PCS industry that in a multipath environment, typical of urban areas, polarization becomes somewhat unimportant since multipath is caused by reflections which tend to rotate the transmitted signal's polarization. This suggests that antennas responding to mixed polarization will provide better coverage. Circular polarization is one method for generating mixed polarized signals but will fail to provide connectivity in the soldier radio band under certain combinations of soldiers' positions and orientations, although its use is required for GPS. Also with regard to polarization, there is no advantage to one or the other considering free-space or through-forested area paths in the soldier radio band.

For GPS, 98% of the COTS antennas used are dielectrically loaded patches: essentially two thin parallel metal plates separated by a low-loss high dielectric material such as ceramic. The advantages of this type of antenna are: generation of the required right hand circular polarized response through manipulation of the ratio of the top metal plate's dimensions, better than 0dBi gain at elevation angles greater than 10 degrees or so, small physical dimensions compared to a wavelength (0.75 by 0.75 square by 0.25 inches thick typical). The disadvantage of the loaded patch is its narrow bandwidth (not of concern for GPS) and need for a ground plane albeit a small one. Since the loaded patch is not a high-gain antenna, low noise amplifiers (LNAs) are usually collocated with the patch to both provide gain to overcome foliage attenuation and eliminate the effect of the coaxial cable's loss as both degrade the system's noise figure. The challenge for a GPS epaulet antenna is not what type to use but rather where exactly to mount it on the soldier to reduce the effects of: appendage shielding, orientation and position (standing-to-prone).

The soldier radio antenna is required to have a relatively low (5%) bandwidth but be as compact and conformal as possible, consistent with a reasonable power gain (>0dBi) and low (<2:1) standing wave ratio (SWR). Methods and specific designs to achieve these desired characteristics have been documented in classic textbooks such as Fujimoto et al. "Small Antennas", Hirasawa et al. "Analysis, Design, and Measurement of Small and Low-Profile Antennas" and Siwiak's "Radiowave Propagation and Antennas for Personal Communications". In general there are only three strategies for achieving an electrically small antenna: geometry loading, internal and external impedance loading or some combination thereof. A planar dipole with triangular "fanned" elements can provide acceptable performance nearly one half octave below its physical length. Placing it near a dielectric substrate allows additional shortening by increasing its electrical length. Placing it just above a human body provides for some polarization conversion due to the refractive index of the human tissue/air interface as discussed in King's "Antennas in Matter" textbook.

The following section, Section 3, lists the methods, assumptions and procedures used to design, fabricate and test both the GPS as well as the soldier radio antennas. Section 4 presents the results of our work in that it documents the design and performance of the: epaulet contained combined antenna system and the alternatives studied in arriving at this design, this same system with an embedded miniature GPS receiver and the brassboard, low-power soldier radios used in the link testing of the epaulet antenna. Sections 5 and 6 present our conclusions concerning our work and recommendations respectively.

3.0 Methods, Assumptions and Procedures

This section discusses the assumptions, methods and procedures used in the design and testing of: the combined GPS/soldier radio epaulet antenna, a second version of this combined epaulet antenna which also contains a miniature GPS receiver and brassboard, low power soldier radios used for the link testing of the epaulet antennas in forests.

The key assumptions made were: that the performance goals and potential locations for the epaulet antenna on the MOLLE's fighting load vest, as discussed with the government program office in October, 1999 and March, 2000 are still valid as well as its desired physical and electrical characteristics in the two bands of interest, included in Section 4.4.1 of this report.

The work described in this report involved the use of several computer codes, laboratory test setups and measurements made in the field: GPS reception and soldier radio link tests. The following paragraphs describe these in turn.

3.1 Computer Codes

The analysis performed under this contract was carried out using two standard, well-tested, electromagnetic codes: the moment method program NEC-4.1[1] and the Finite Difference Time Domain Code XFDTD [2]. The specific types of antenna studied during this effort are described in Section 4.1.2. Certain types of antennas such as patch antennas can be analyzed using XFDTD since they involve the use of dielectric substrates of limited extent. An example of a patch model used in XFDTD is shown in Figure 3.1-1. The patch parameters such as input impedance and patterns were computed with the patch mounted on a small perfectly conducting ground screen which is also seen in the model. The NEC-4.1 program cannot handle dielectric features. Likewise, although head and body models are incorporated by other users in XFDTD, the amount of memory and run time becomes prohibitive. Therefore the patch was approximated by a pair of crossed dipoles in NEC and used with MegaWave's existing wire grid head model to estimate radiation pattern data. This model is shown in Figure 3.1-2. XFDTD was also used to compute the performance of other planar antennas considered during the study an example of which is shown in Figure 3.1-3.

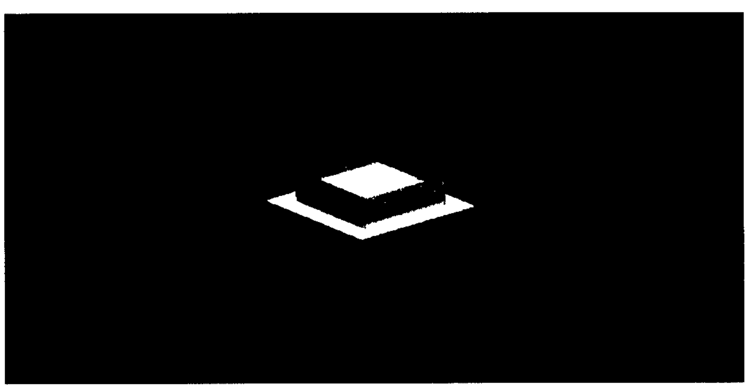


Figure 3.1-1 XFDTD Patch Antenna Model

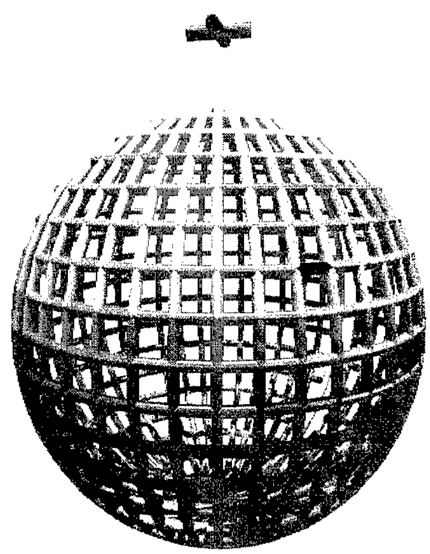


Figure 3.1-2 NEC-4.1 Wire Grid Head Model with Crossed Dipoles

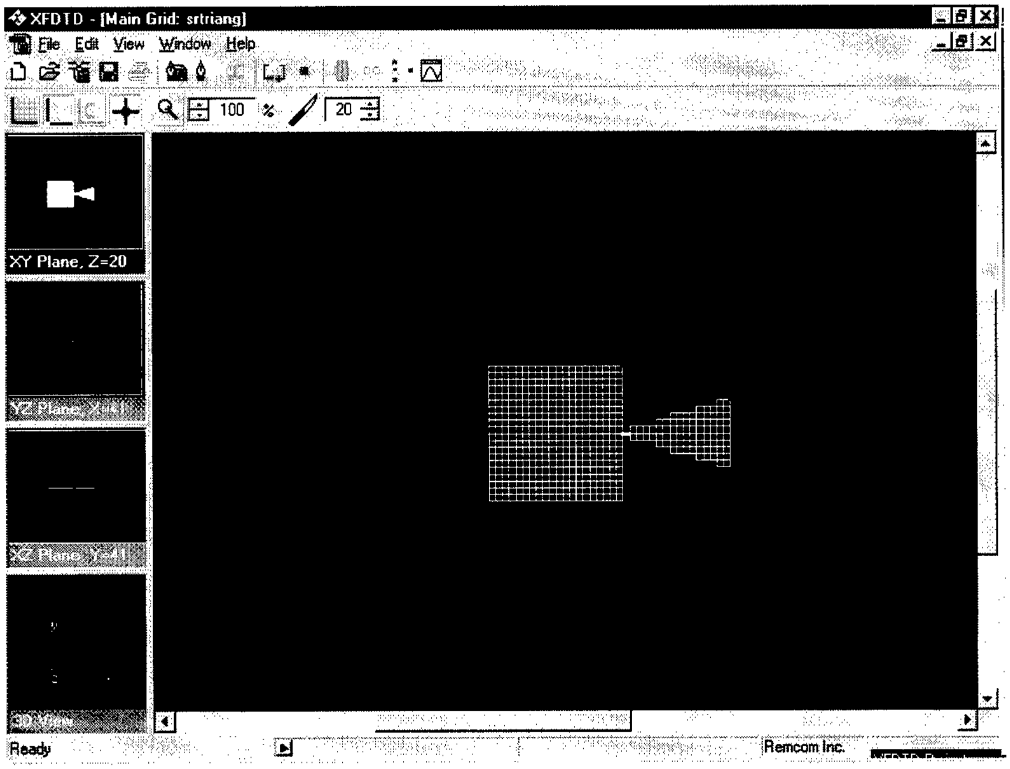


Figure 3.1-3 Planar conical monopole XFDTD Model

3.2 Laboratory Testing

3.2.1 GPS and Soldier Radio Antennas

The VSWR and zenith power gain of each GPS and soldier radio antenna was measured using the test setup shown in Figure 3.2-1. This setup was based around the HP-8753C vector network analyzer (VNA). Each antenna was mounted at the various candidate locations near the dummy's shoulders or on its helmet. The VNA was then used to measure VSWR at the end of the 1 meter coaxial cable leading from the antenna connected to port 1 of the VNA and then the zenith (overhead) power gain was measured using the HP 85024A High Impedance Probe connected to port 2 of the VNA as shown. For those antennas using a low noise amplifier (LNA) their power consumption was measured using a Fluke 87 DMM and an Astron variable voltage power supply.

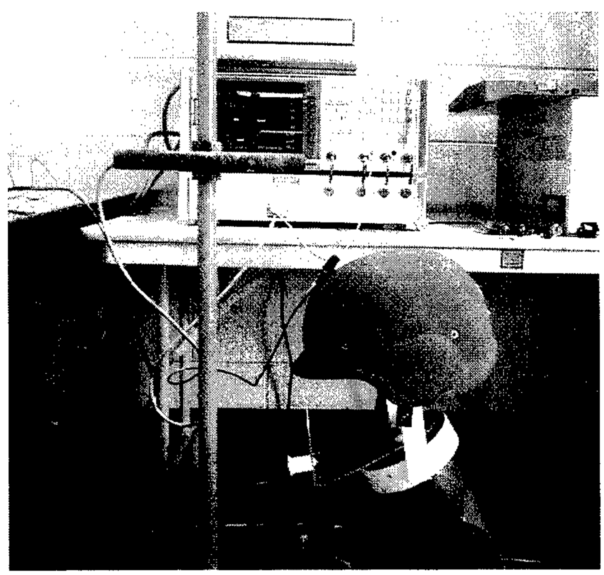


Figure 3.2-1 Laboratory Antenna Evaluation Setup

3.2.2 Brassboard Soldier Radio

The electrical characteristics of the brassboard soldier radio were measured using the equipment shown in Figure 3.2-2. The HP 8660C Synthesized Signal Generator shown at the bottom left of the photograph was used to measure the minimum detectable signal (MDS) or receive sensitivity of the brassboard soldier radio by connecting its output to the antenna port on the soldier radio and increasing its output starting at -130 dBm until squelch break was observed. The power output of the soldier radio was measured using the HP 8591A Spectrum Analyzer seen to the right in the photograph by connecting it to the antenna port on the soldier radio and noting the displayed carrier level in dBm using the analyzer's cursor. The AOR AR-5000 receiver atop the signal generator was used to evaluate the FM modulation quality of the radio.

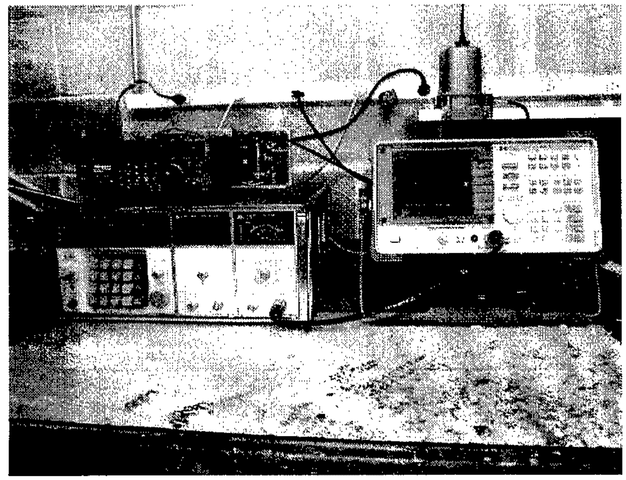


Figure 3.2-2 Equipment used to measure electrical characteristics of brassboard soldier radios

3.3 Field Testing

3.3.1 GPS and Soldier Radio Antennas

The COTS GPS antennas mounted at various locations on the helmet and shoulders were evaluated by connecting them to the Garmin "Street Pilot" receiver and noting the total signal strength (from the bar graph display) and accuracy with the dummy in the standing and prone positions and cardinal orientations in an open parking lot and then under fully leafed trees, typical of New England forests. This test was repeated using the JRC miniature receiver in place of the Garmin, whose signal quality display is illustrated in Figure 3.3-1. In this example, 9 satellites are being received (but #09 is very weak), where their total signal strength is 78. For each position/orientation/location encountered during a particular test, the number of satellites being received, their total signal strength and the resulting estimated accuracy were noted.

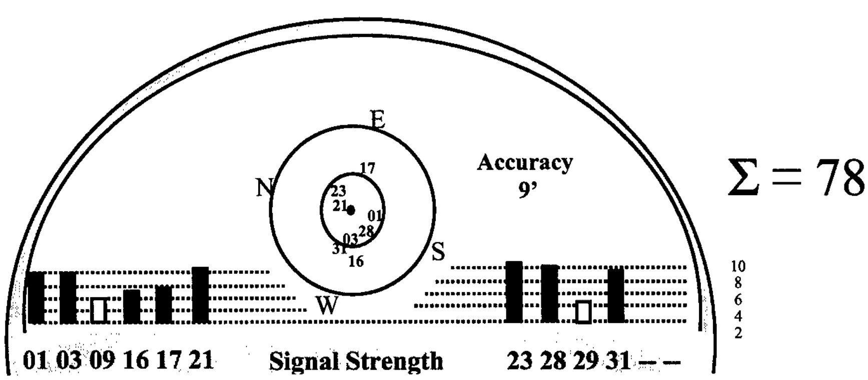


Figure 3.3-1 GARMIN GPS Receiver Signal Quality Display

3.3.2 Brassboard Soldier Radios

The propagation of radio waves in the 1755 MHz band is affected mostly by path length, terrain, foliage and man made structures rather than ground moisture content or wave polarization. We estimated the expected path loss at representative soldier-to-soldier distances of 1/16, 1/8 and 1/4 miles (approximately 100, 200 and 400 meters respectively) for various types and combinations of these paths using both measured data and computer codes [3-12]. This data was used to assist in selecting representative forested test paths in Boylston and Stow, Massachusetts and to estimate the required radiated power from the brassboard soldier radio/epaulet antenna combination. The Boylston test path shown in Figure 3.3-2(a) was over gently rolling terrain with foliage as shown. The Stow path shown in Figure 3.3-2(b) was essentially flat and mostly through foliage. One person remained at the origin, standing and prone, and the second stopped at the 100, 200, 300 and 400 meter points where data was then taken standing and prone. Voice test messages, ten characters in length where each number and character were sent as ICAO phonetics, were transmitted and acknowledged at each distance/position/orientation and the number (if any) of repeats required were noted. A typical ten-character message being: Bravo niner foxtrot x-ray sierra fiver echo three six delta. Tests were conducted at these two locations in June, 2001.

4.0 Results and Discussion

4.1 Combined GPS and Soldier Radio Epaulet Antenna System

4.1.1 Performance Goals

The purpose of this section is to summarize the desired physical and electrical characteristics and performance goals for a combined GPS and soldier radio antenna system contained in an epaulet. They were developed based on meetings with the Natick program office on 22 October, 1999 and 15 March, 2000.

- Host system: MOLLE fighting load bearing vest primary, helmet secondary
- Weight: As light as possible, probably less than few ounces
- Maximum protuberance beyond worn gear: 0.75 inches vertical, 1.5 inches horizontal
- Frequency coverage: GPS 1575.42 +/- 2MHz, Soldier Radio 1755-1850 MHz
- Polarization: right hand circular for GPS, dual (TE and TM) for soldier radio.
- Impedance: 50 ohms
- VSWR: 2.5:1 or less
- Radiation pattern: omnidirectional within +/-6dB standing to prone positions.
- Power gain: 0dBi or greater for soldier radio and GPS with sufficient low noise amplification for the latter to allow reliable reception under trees.
- Power handling: 0.5 watts; soldier radio

4.1.2 GPS And Soldier Radio Alternative Antennas Considered

COTS GPS Antennas

Three basic types of COTS GPS antennas were considered: dielectrically loaded patches and helices and planar, some of which are shown and whose properties are summarized in Figure 4.1-1. An excellent recent survey of 218 GPS antennas from 28 manufacturers is found in [13]. The loaded helices all exceeded the 0.75 inch (19 mm maximum protuberance goal). The planar film antenna was withdrawn from the market by its manufacturer, Linx Technologies, prior to delivery.

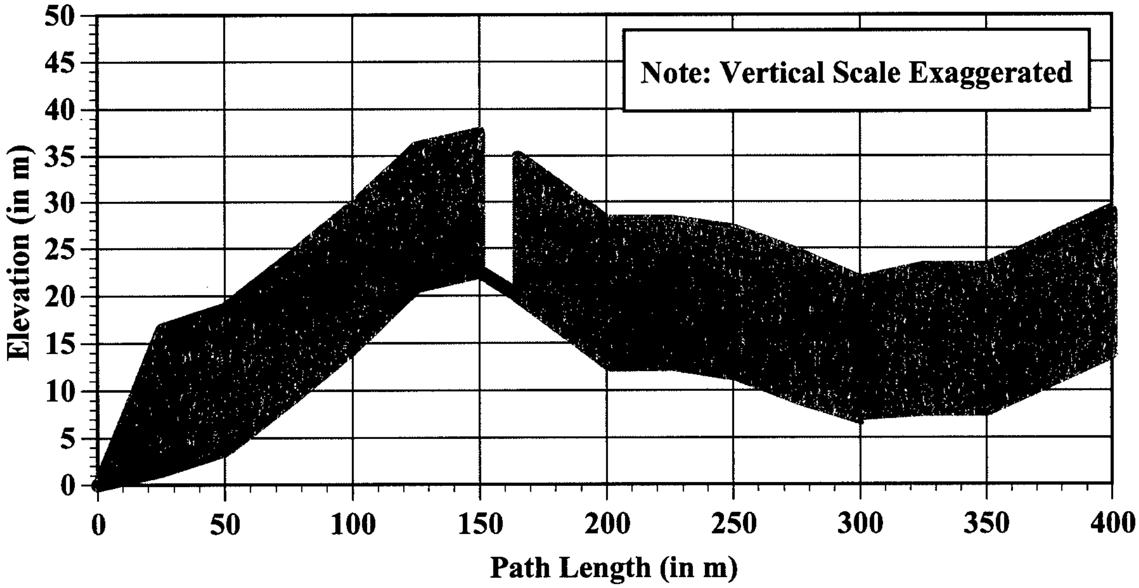


Figure 3.3-2 (a) Boylston, MA Test Path Profile and Foliage

Average Tree Height = 15m

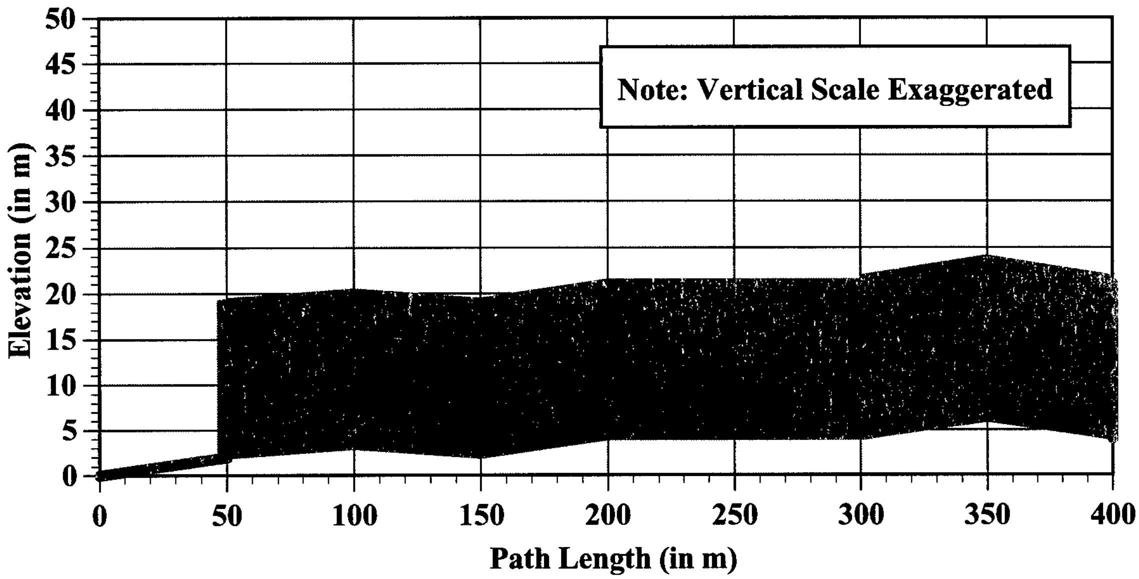
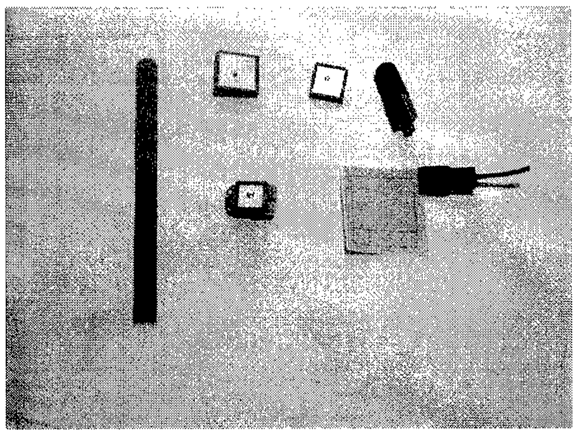


Figure 3.3-2(b) St ow, MA Test Path Profile and Foliage

Average Tree Height = 17m

Manufacturer	Type	Size (mm)	Weight (gms/ozs)	Power (mW)
Toko	Patch*	25 x 25 x 4	8/0.3	-
Trans-Tech	Patch*	19 x 19 x 4	6/0.2	-
San Jose	Patch/LNA	27 x 20 x 7	8/0.3	75
Symmetricon	Helix	30 x 13	8/0.3	-
Linx	Planar/LNA	50 x 45	12/0.4	100



* Requires ≥ 40 x 40 mm Ground Plane

Figure 4.1-1 Candidate COTS GPS Antennas

COTS Soldier Radio Antennas

Figure 4.1-2 shows the COTS Soldier Radio Antennas and their characteristics. They are all below the maximum desired height and weight goals. It should be noted that the loaded patch shown is a modified stock Toko GPS antenna. It and the Xertex microstrip antenna (at the top of photo) were the only two capable of operating in the soldier radio band.

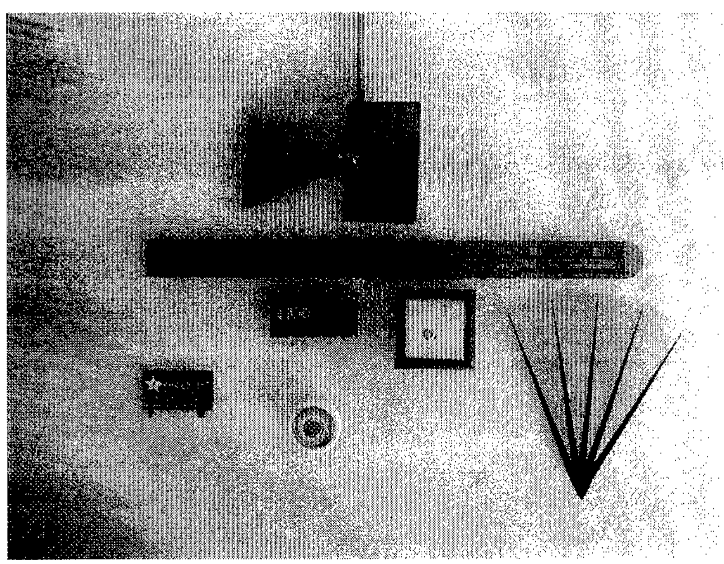


Figure 4.1-2 Candidate COTS Soldier Radio Antennas

Custom Soldier Radio Antennas
Several candidate designs were initially considered for the soldier radio (SR) antenna that could be combined with an off-the-shelf GPS antenna. These included:

- Patches
- Slant dipoles
- Crossed dipoles
- Surfacewave antenna
- Broadband monopole

Of these, the analytical effort focused on the patches and the broadband monopole. The others were rejected on the basis that: the slant dipole requires a balun which would complicate the design and add volume and weight; the crossed dipoles would require two baluns and a quadrature hybrid; and the surfacewave antenna, which had been previously considered as a helmet mounted antenna requires a larger ground plane than the other configurations and would not therefore be practical for a shoulder mounted antenna. The patch antenna was deemed to be a practical solution since it is a planar antenna. Since the bandwidth required for the soldier radio band is 5.5%, a custom patch design was required. The other remaining practical candidate, the planar broadband monopole, requires a ground plane, but this can be provided by the GPS patch antenna's ground plane resulting in a compact easily fabricated planar package containing both the GPS and soldier radio antennas.

The computed results using XFDTD for the broadband patch and a planar broadband conical monopole fed against a small ground plane are shown in Figures 4.1-3 and 4.1-4. The patch results show that greater than the 5.5% bandwidth required for the SR band can be achieved with a 5mm patch on a high dielectric constant substrate. The computed VSWR is also shown in Figure 4.1-3. A 12mm wide by 30mm long conical monopole fed against a small 40mmx40mm planar ground plane was also found to have more than sufficient bandwidth to cover the SR frequencies.

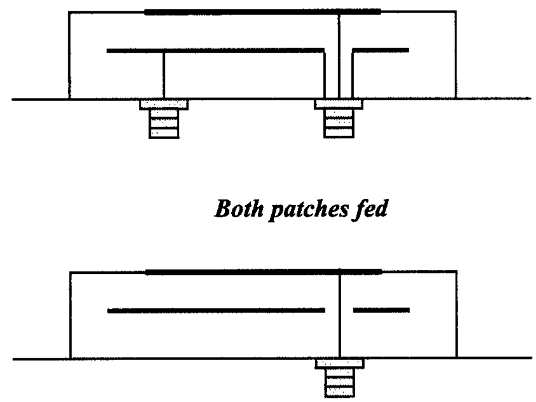
Combined GPS/Soldier Radio Antennas
In addition to the above, custom antenna designs that were capable of operating in both the GPS and soldier radio bands were also considered. These fell into two categories:

- ***Broadband patches that have sufficient bandwidth to cover both GPS and soldier radio bands***
  Patch antennas typically have very narrow bandwidth i.e. on the order of a few percent. Many researchers describe methods for increasing the bandwidth of patch antennas [14][15][16]. To cover both the GPS and the SR frequencies requires a bandwidth of 16.7%. Two possible approaches for broadbanding were considered, both vertically or horizontally stacked patches in which one patch is excited and the others are parasitically coupled to the fed patch. Horizontal stacking increases the antenna footprint significantly and is difficult to implement for mounting on curved surface such as helmet where element orientations will change from ideal. Vertical stacking increases the element height but does not increase the footprint. It is also easier to implement. Some of the benefits of broadbanding are that it provides a single antenna with single feed, would have the same footprint as for single GPS patch, requires only one cable for helmet mounting and is a less sensitive design i.e. plenty of margin in bandwidth to cover both bands so that temperature stability and dimensional tolerances are not a critical. An issue with this design approach is that it requires a multicoupler with good isolation between ports so that the soldier radio does not damage GPS receiver. The multicoupler would also be custom design since these do not exist off-the-shelf.

The computed results for a broadband patch antenna based on a dielectric constant of 20.3 are shown in Figure 4.1-5. The computed VSWR is seen to have two minima in its response, one near the GPS center frequency and the other at 1800MHz i.e. at the center of the soldier radio band. The computed bandwidth for 2.5:1 VSWR was 19% from 1536-1857 MHz. The steady state fields in the plane through the center of the patch are shown in Figure 4.1-6.

- ***Dual frequency patches with one or two feeds that operate in both the GPS and soldier radio bands***

Like the broadband patches, dual frequency patches are used for operation in more than one frequency band and are commonly used in vehicular and SAR operations [17][18][19]. A dual frequency patch avoids the need for two separate antennas, one for GPS and one for SR. For dual frequency operation, patches can be stacked vertically and both patches fed separately or one feed can be used to both patches where the feed to the lower patch is then capacitively coupled since it passes through a hole in the lower patch to connect to the upper patch as shown in Figure 4.1.2-7 As an added alternative, the upper patch can be broadbanded using a third parasitically coupled patch. The benefits of dual frequency operation are that a single antenna with one or two feeds is achieved with the same footprint as for a single GPS patch and only one cable is required for helmet mounting if a single feed is used. However using a single feed would again require a multicoupler as discussed above.



Both patches fed

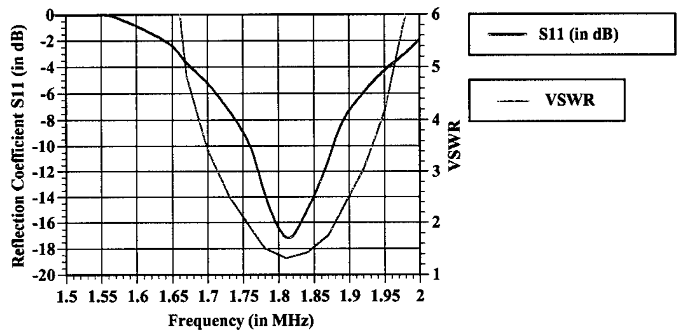
Lower patch capacitively fed

Figure 4.1-7 Dual frequency patch configurations

Typical results obtained are shown in Figures 4.1-8 through 10. Figure 4.1-8 shows results for a dual frequency two-layer patch with two feeds. One feed excites the bottom patch at the GPS frequencies and the second feed excites the upper patch at the soldier radio frequency. The feed through for the second feed inserts an inductive post into the lower patch. The design parameters were adjusted until the two resonances occurred near the desired frequencies. The design would need further adjustment to fine-tune the frequencies. However, the concept is demonstrated. Figure 4.1-9 shows the results for a three-layer patch with two feeds. The results show adequate bandwidths in both the GPS and soldier radio bands for an overall structure thickness of 8mm. Figure 4.1-10 gives the results for a two layer single feed dual frequency patch. With this configuration, the best results obtained showed resonant frequencies separated by a larger ratio than desired. Resonances were obtained at 1525 and 1900MHz.

SR Antenna Candidates: Patch Antenna

- Dielectric constant: 20.3
- Patch size: 16x16mm
- Ground plane: 31x31mm
- Thickness: 5mm
- Bandwidth for 3:1 VSWR: 1715-1921 MHz (11.3%)
- Bandwidth for 2:1 VSWR: 1730-1897 MHz (9%)



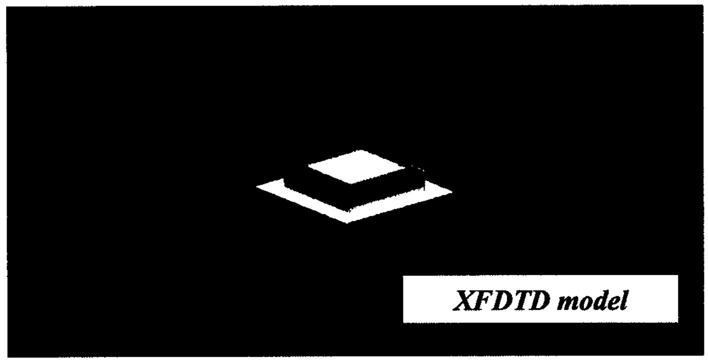
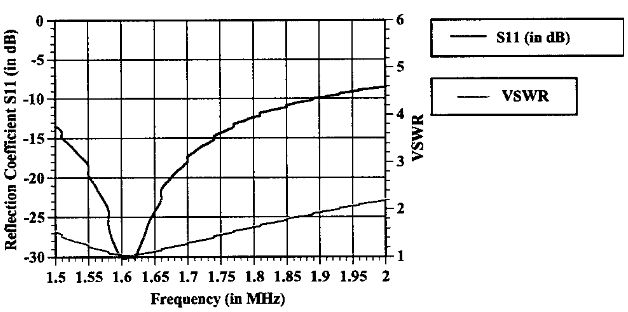
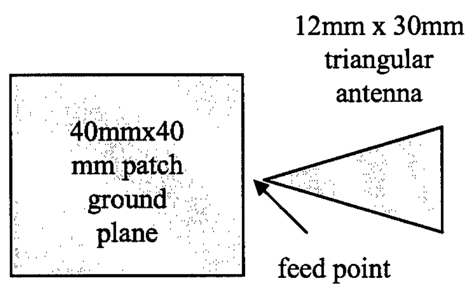


Figure 4.1-3 XFDTD Results for Soldier Radio Patch Antenna

SR Antenna Candidate: Broadband Monopole





- Planar conical antenna fed against ground plane of GPS antenna
- Patterns/gain equivalent to dipole (+2dBi)

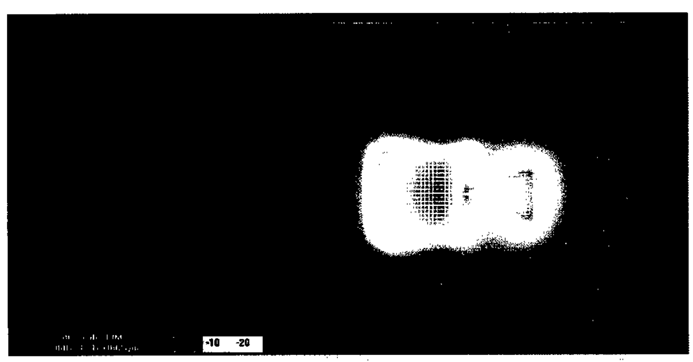
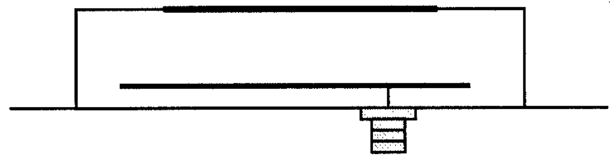


Figure 4.1-4 XFDTD Results for Planar Broadband Conical Monopole

Design Results:
Broadband High Dielectric Constant Patch

Dielectric constant: 20.3
Lower patch: 22x19mm
Upper patch: 15x15mm
Ground plane: 31x31mm
Overall thickness: 7mm
Bandwidth for 3:1 VSWR:
1521-1869 MHz (20.6%)
Bandwidth for 2.5:1 VSWR:
1536-1857 MHz (19%)



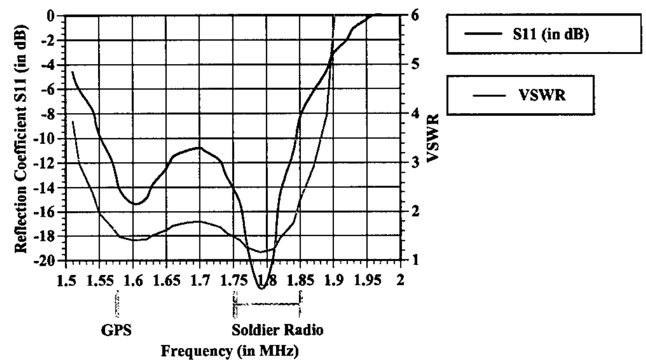
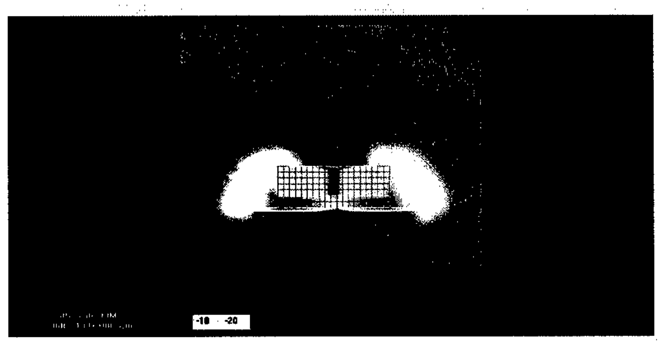


Figure 4.1-5 XFDTD Results for Broadband High Dielectric Constant Patch

Steady state fields in plane through the center of the patch at 1800MHz

Top: xz plane, E_t

Bottom: yz plane, E_t



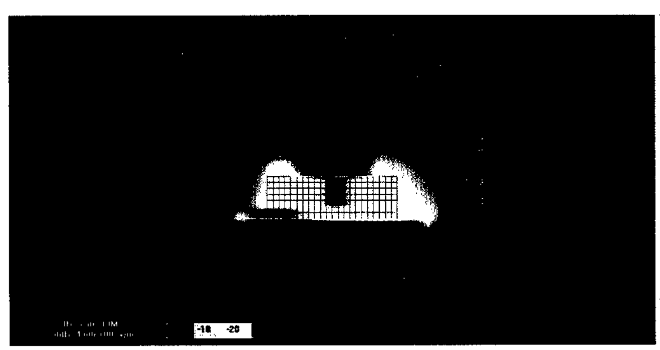


Figure 4.1-6 Computed Fields through the center plane of the broadband patch

4.1.3 On-Body Locations Considered for GPS and Soldier Radio Antennas

Figure 4.1-11 shows the six potential GPS and Soldier Radio antenna locations considered, four on the helmet and two on the shoulders. Depending upon the antenna type considered, some locations will be more suitable than others due to the antenna's radiation pattern and body shielding effects as can be seen from the measured data contained in the following section.

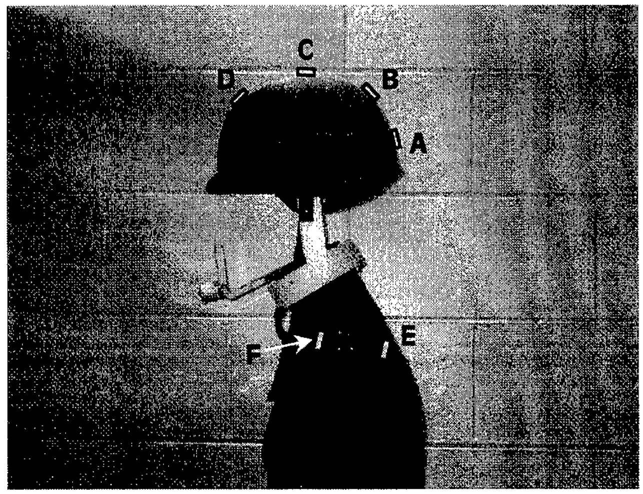


Figure 4.1-11 Candidate locations considered

4.1.4 Laboratory and Field Test Results

The COTS GPS antennas, which were shown in Figure 4.1-1, were evaluated in the laboratory and in the field using the procedures described in Sections 3.2 and 3.3. The laboratory results are summarized in Table 4.1-1 which indicates that the San Jose SK-4 element was superior to the others.

Antenna	VSWR	Bandwidth @VSWR (MHz)	Zenith Power Gain (dBi)	Power (mW)
Toko 25x25mm	1.48	± 13.0	1.5	0
Trans-Tech 19x19mm	1.73	± 3.5	1.0	0
Symmetricon 38x25mm	1.61	± 6.2	-1.8	0
San Jose SK-4 18x18x4mm patch	1.51	± 1.023	+4.9	0
San Jose SK-4 (patch+LNA)	1.34	± 1.1	+24.1	33

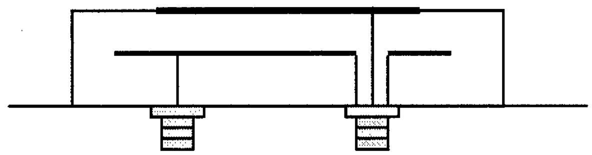
Table 4.1-1 Laboratory COTS GPS Antenna Test Results

This loaded patch element was also supplied to us mounted on an LNA which was found to provide an overall zenith power gain of approximately +24 dBi with a 1.5 dB noise figure (as claimed by the manufacturer). This assembly consumed 33 milliwatts of power (10 mA at 3.3 volts).

Tests were conducted to determine the effect of the various mounting locations shown in Figure 4.1-11 would have on GPS reception using the San Jose SK-4 (element and LNA) at positions A through C and at F with the dummy standing and prone in each of the cardinal orientations. Table 4.1-2 shows the results of the test, which indicate that locations B (back/halfway up helmet) and E (back side of the left shoulder) provided the best overall performance regardless of position or orientation. This result is consistent with earlier experiments using non-amplified 25x25 and 19x19 mm patches mounted at these same locations.

Design Results: Dual Frequency High Dielectric Constant 2-Layer Patch, Two Feeds

- Dielectric constant: 20.3
- Lower patch: 23x23mm
- Upper patch: 16x16mm
- Ground plane: 35x35mm
- Overall thickness: 6mm
- Bandwidth for 3:1 VSWR:
  - 1473-1584 MHz
  - 1735-1848 MHz
- Bandwidth for 2:1 VSWR:
  - 1480-1578 MHz
  - 1745-1836 MHz
- Final adjustments to dimensions needed to fine tune frequencies



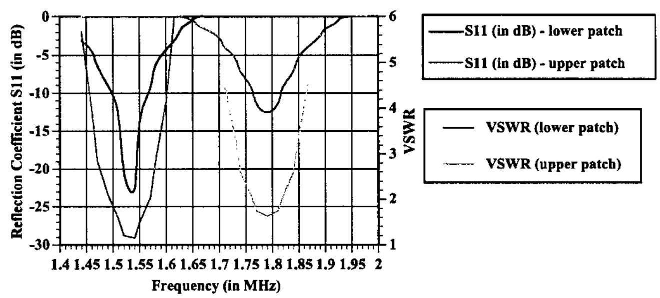
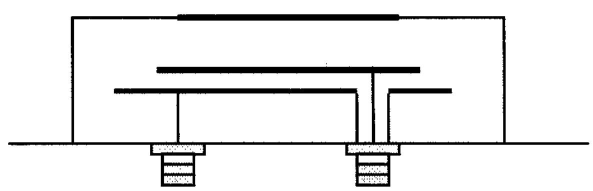


Figure 4.1-8 Computed results for dual frequency high dielectric constant two-layer patch with two feeds

Design Results: Dual Frequency High Dielectric Constant 3-Layer Patch, Two Feeds

- Dielectric constant: 20.3
- Lower patch: 19x19mm
- Upper patches: 15x16mm and 14x14mm
- Ground plane: 31x31mm
- Overall thickness: 8mm
- Bandwidth for 3:1 VSWR:
  - 1505-1610 MHz (GPS)
  - 1749-1956 MHz (SR)
- Bandwidth for 2:1 VSWR:
  - 1515-1599 MHz (GPS)
  - 1760-1935 MHz (SR)



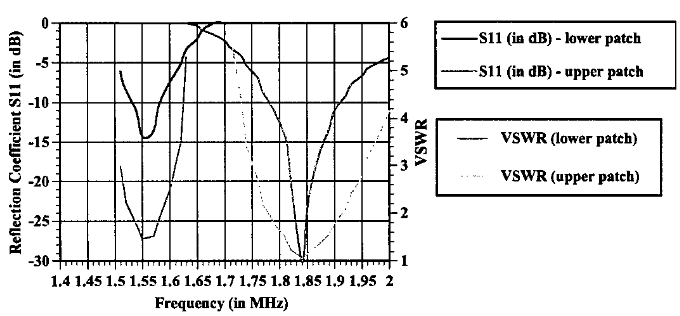
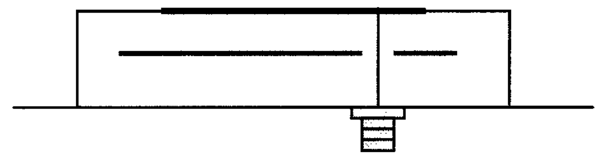


Figure 4.1-9 Computed results for dual frequency high dielectric constant three-layer patch with two feeds

Design Results: Dual Frequency High Dielectric Constant Stacked Patch, Single Feed

Dielectric constant: 20.3
Lower patch: 23x23mm
Upper patch: 16x16mm
Ground plane: 31x31mm
Overall thickness: 6mm
Best results: frequency ratio larger than desired
Bandwidth for 2:1 VSWR:
    1476-1569 MHz
    1850-1950 MHz



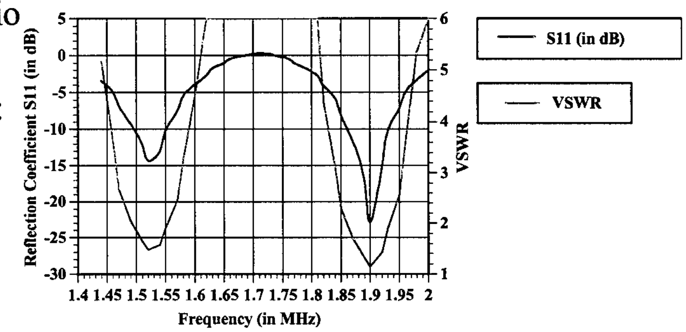


Figure 4.1-10 Computed results for dual frequency high dielectric constant two-layer patch with one feed

	A(S)	A(P)	B(S)	B(P)	C(S)	C(P)	E(S)	E(P)	F(S)	F(P)
0	31	57	54	47	58	35	51	49	51	29
90	32	53	48	44	51	33	46	48	41	24
180	30	56	49	52	56	31	43	51	52	22
270	34	51	41	45	57	34	47	44	49	23

Table 4.1-2 Measured SK-4 performance versus location on worn equipment for cardinal orientations

Notes: A(S)=SK-4 at location A (Figure 4.1-3) standing. A(P)=SK-4 at location A, prone.
Accuracy: 25 signal strength = 45 feet, 35 = 24 feet, 45 = 14 feet and 55 = 12 feet, using the Garmin Street Pilot Receiver.

The SK-4, mounted at position E (top/back of dummy's left shoulder) was also tested in an open parking lot and under a stand of 60 foot high oak/maple trees with the dummy in the standing and prone positions for each of the cardinal azimuthal orientations. Figure 4.1-12 is a photo of the dummy with a radome-protected SK-4 mounted at position E. The results of this test, designed to measure the effect of trees on GPS reception using the SK-4 mounted at this position are listed in Table 4.1-3 which indicates while there is some reduction in signal strength (and accuracy) position fixes better than 24 feet will be possible under trees using a late 1990s vintage commercial L1 GPS receiver.

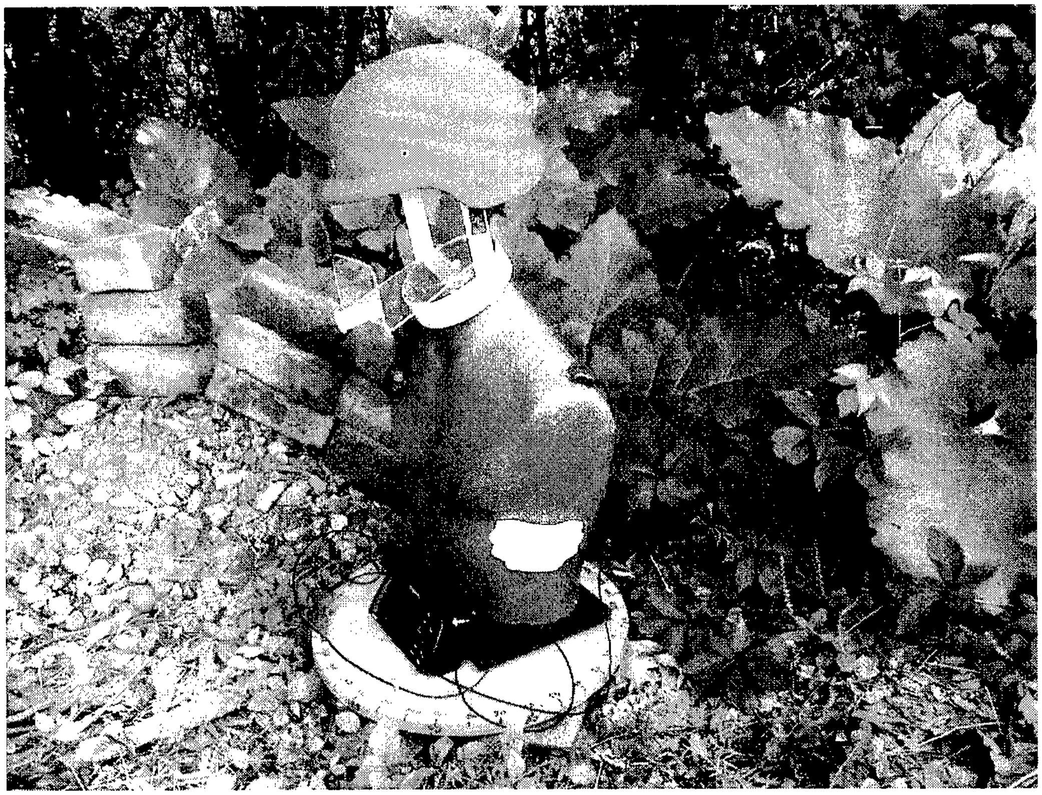


Figure 4.1-12 Dummy with radome protected SK-4

	Parking Lot		Woods	
	Standing	**Prone**	**Standing**	**Prone**
0	49	48	37	38
90	46	48	40	36
180	43	49	47	37
270	40	42	41	39

Table 4.1-3 Measured SK-4 performance on dummy's shoulder in parking lot and under trees

The Soldier Radio antenna is a MegaWave developed shortened version of the COTS Xertex microstrip antenna that can be seen at the top of Figure 4.1-2. (It should be noted that all of the antennas shown in this figure were evaluated for VSWR and power gain, however none were directly useable considering frequency coverage and physical size). The developed antenna uses a fanned monopole, planar element 0.75" wide by 1.25" long, fed against the SK-4's patch/LNA's ground plane/shield. This configuration's VSWR and power gain were measured in the laboratory using the same setup used for the GPS antennas as described in Section 3.2-1. Across the 1755-1850 MHz band of interest the antenna's VSWR was below 1.75:1 when mounted on a human's shoulder and produced a zenith power gain of at least +1.61 dBi when measured over this band. The following section contains additional details concerning the construction of this antenna.

4.1.5 Combined GPS and Soldier Radio Antenna Final Design

Figure 4.1-13 (a) is a dimensioned sketch of the combined GPS/Soldier Radio Antenna, ouside of its protective epaulet pouch. The San Jose SK-4 miniature GPS loaded patch sits atop a LNA contained in a shielded enclosure that offers both physical and electrical protection to this sensitive integrated circuit. The SK-4 is soldered to the copper clad substrate which also holds the fanned soldier radio monopole. The two 40" lengths of RG-174/U coaxial cable are terminated with a male BNC and male SMA for the GPS and soldier radios respectively. The overall dimensions of the unit are 2.5" long, 1.0" wide by 0.25" thick. This assembly is placed into a protective epaulet pouch whose dimensions are shown in Figure 4.1-13 (b). This pouch is fastened to and worn with the MOLLE fighting load vest as shown in the photograph in Figure 4.1-13 (c), with the two coaxial cables dressed through the vest's webbing loops to the GPS receiver and soldier radios contained in pouches attached to the vest's belt.

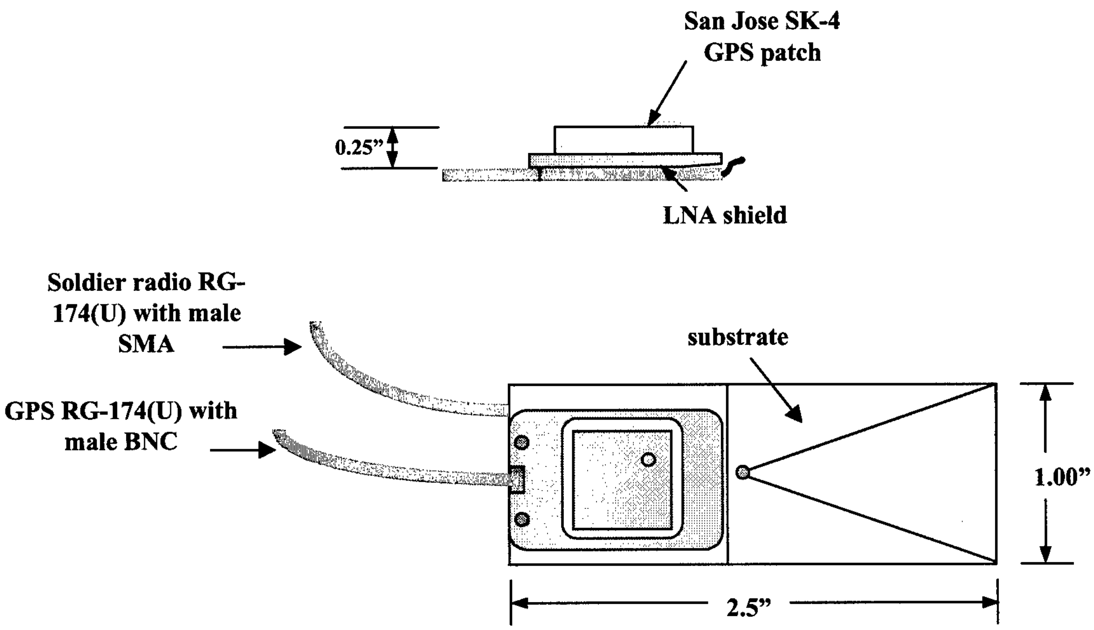


Figure 4.1-13(a) Dimensioned sketch of combined GPS/soldier radio antenna

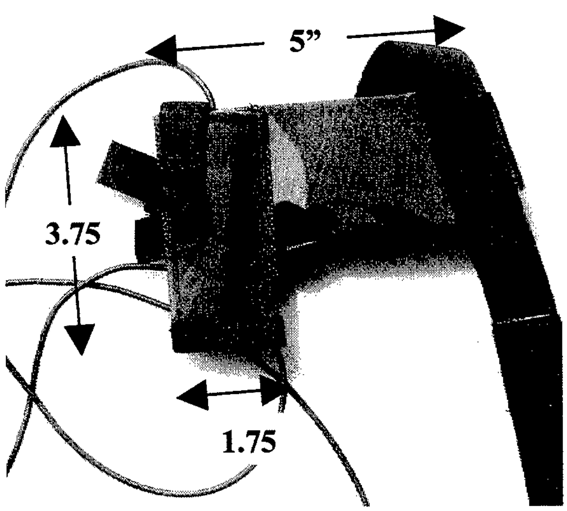


Figure 4.1-13(b) Fabric pouch for epaulet mounting of combined GPS/soldier radio antenna

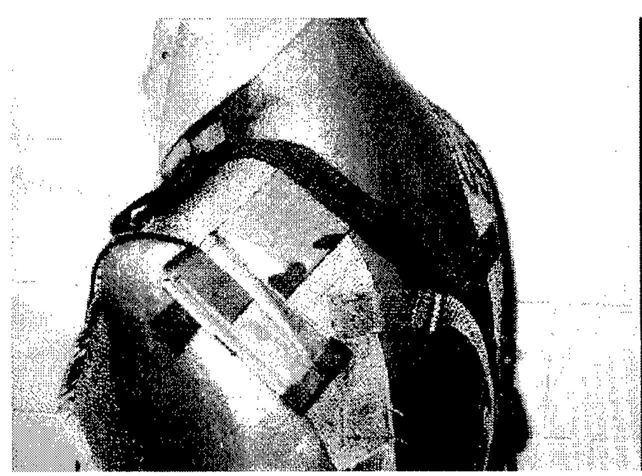


Figure 4.1-13(c) Epaulet pouch attached to MOLLE

4.2 Miniature GPS Receiver Integrated Into Combined GPS/Soldier Radio Epaulet Pouch

The objective of this task was to assess the feasibility of locating a miniature COTS GPS receiver within the epaulet antenna pouch described above to: eliminate the need for a coaxial cable connecting the SK-4 miniature patch/LNA with a belt-worn GPS receiver and to act as an enhanced ground plane for the SK-4 and soldier radio antennas. Connection from the receiver to processor could be via a stronger, lighter and more flexible cable carrying the NEMA 0138 data in one direction and 3 Vdc in the other. Alternatively, if a GPS receiver with ultra-low power consumption were available then the cable could be replaced with a Bluetooth data link between the epaulet and belt or other location on the body. Power for the receiver would then be provided using a lightweight battery or fuel cell in the epaulet pouch.

We proceeded by reviewing the state-of-the-art in COTS miniature receivers using sources such as the GPS World's Receiver Survey as recently updated [20]. The impetus for GPS miniaturization stems from an attempt to develop new consumer items, such as the Casio and Swatch wrist GPS receivers [21] but also for cell phones as one method to meet the mandated 911 position fixing capability and personal trackers such as the Digital Angel made by Applied Digital Solutions, Inc.. SiRF Technologies, Lucent, JRC, Fastrax, Axiom, Pharos San Jose Motorola, Asulab S.A. have all developed and are continuing to develop miniature chip sets/receivers. We then contacted these companies requesting price quotes to obtain not only the miniature receiver hardware but also the software necessary to process the NEMA data in a laptop or PDA. We obtained and evaluated hardware/software packages from: JRC, Pharos and Fastrax. Of these, the Pharos iGPS-180, the only one with an integrated antenna was judged to be too large for an epaulet application so only the JRC-CCA-450 and Fastrax iTRAX02 were tested in any detail. The measured characteristics of these two receivers are summarized in Table 4.2-1 using the manufacturers' supplied hardware connected to a WinBook Si laptop computer. It should be noted that other manufacturers' units were not evaluated because: they were not available, consumed more than 1 watt of prime power or lacked the necessary interface circuitry/software to allow their connection directly to a laptop computer or PDA.

Make/Model	# Channels	Size (mm)	Wt. (gm)	Power (mW)	Accuracy (m)	Sens (dBm)	H/W/C (sec.)
JRC-CCA-450	16	39x25x7	25	392	2.9	-140	8.5/37/52
FasTrax 02	12	25x25x4	20	110	1.3	-145	1.8/28/34

Table 4.2-1 Measured miniature GPS receiver characteristics

The above accuracy and time to first fix (hot/warm/cold) numbers were made using the San Jose SK-4 antenna pointed at zenith (best case) in a parking lot where there was an unobstructed view of the satellites. Of the two receivers tested, the FasTrax 02 provided superior performance in all categories, although a shielded version of the Fastrax was not received in time for final integration into the epaulet. Figure 4.2-1 is a photograph showing the JRC and FasTrax miniature receivers which both require 3.3 volts and external antennas.

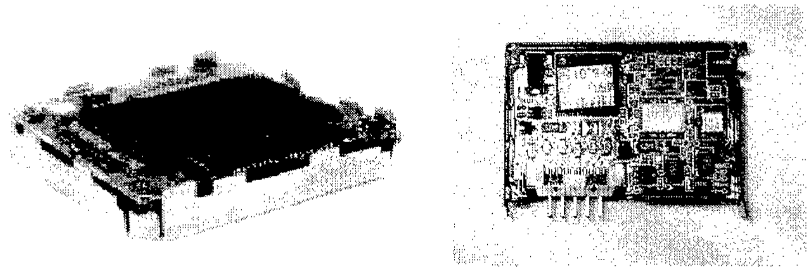


Figure 4.2-1 JRC-CCA-450 and Fastrax 04 GPS receivers

The above receivers were then tested when mounted with the SK-4 antenna on the dummy in the standing and prone positions for its cardinal azimuthal orientations located in the same two locations as used to evaluate the SK-4 with the Garmin Street Pilot receiver (Section 4.4.4): parking lot and under trees, Boylston, MA in June, 2001. The results of this test in terms of accuracy in meters, are summarized in Table 4.2-2.

Azimuth Orientation	Receiver	Parking Lot		Trees	
		Standing	Prone	Standing	Prone
0	JRC	3.40	3.95	6.66	7.10
0	FasT	1.38	1.67	5.48	5.67
90	JRC	3.13	4.20	6.09	6.98
90	FasT	1.59	1.73	5.10	5.53
180	JRC	3.55	3.83	5.85	6.37
180	FasT	1.44	1.67	3.90	5.45
270	JRC	4.03	4.42	7.49	7.10
270	FasT	1.36	1.37	5.98	5.31

Table 4.2-2 Measured accuracy in meters of miniature GPS receivers mounted with SK-4 antenna on back of dummy's left shoulder

From the above it can be seen that the FasTrax iTrax02 also outperformed the JRC in both the parking lot as well as when under a dense tree canopy.

4.3 Brassboard Soldier Radio: Design and Measured Performance

The objective of this task was to fabricate, using off-the-shelf modules, a portable transceiver capable of operating within the soldier radio band (1755-1850 MHz) as a means to evaluate the performance of the combined GPS/soldier radio epaulet antenna over short (<400 meter) forested paths. A survey of hand-held transceiver manufacturers both in the United States and aboard was negative in that: no company currently manufactures commercial two-way hand held radios for this band nor did any have one operating in a nearby band that could be easily modified to provide the required frequency coverage. This is probably due to the this allocation being a government exclusive and that all or a portion of it may be soon reallocated to non-voice (data) PCS devices.

We obtained several hand-held radios capable of operating in the 1240-1300 MHz band and studied the possibility of an out-board transmit/receive frequency converter or "transverter" to shift the frequency range upwards by 515 MHz. In general, a transverter consists of a fixed frequency local oscillator (LO), (in this case 515 MHz), driving two mixers: one for transmit and the other for receive conversion from the intermediate frequency (IF) (1240-1300 MHz) to the resultant (R) or 1755-1815 MHz for this example. Since the mixing process involves some loss, amplifiers for both receive and transmit are required as part of the transverter which also requires input and output transmit/receive (T/R) switching.

Several versions of a 1300 to 1755 MHz transverter were assembled and tested. In general they all met the performance objectives of at least +20 dBm output power and -115 dBm receive sensitivity (10 dB S/N/15kHz b.w.) but consumed considerable dc power: 1.54 watts receiving, 1.87 watts transmitting due mostly to the oscillator/multiplier chain, MMIC broadband amplifiers and the two T/R switching circuits. An alternative circuit that requires no dc power was then proposed as a way to eliminate the need for additional battery power. It is shown in Figure 4.3-1.

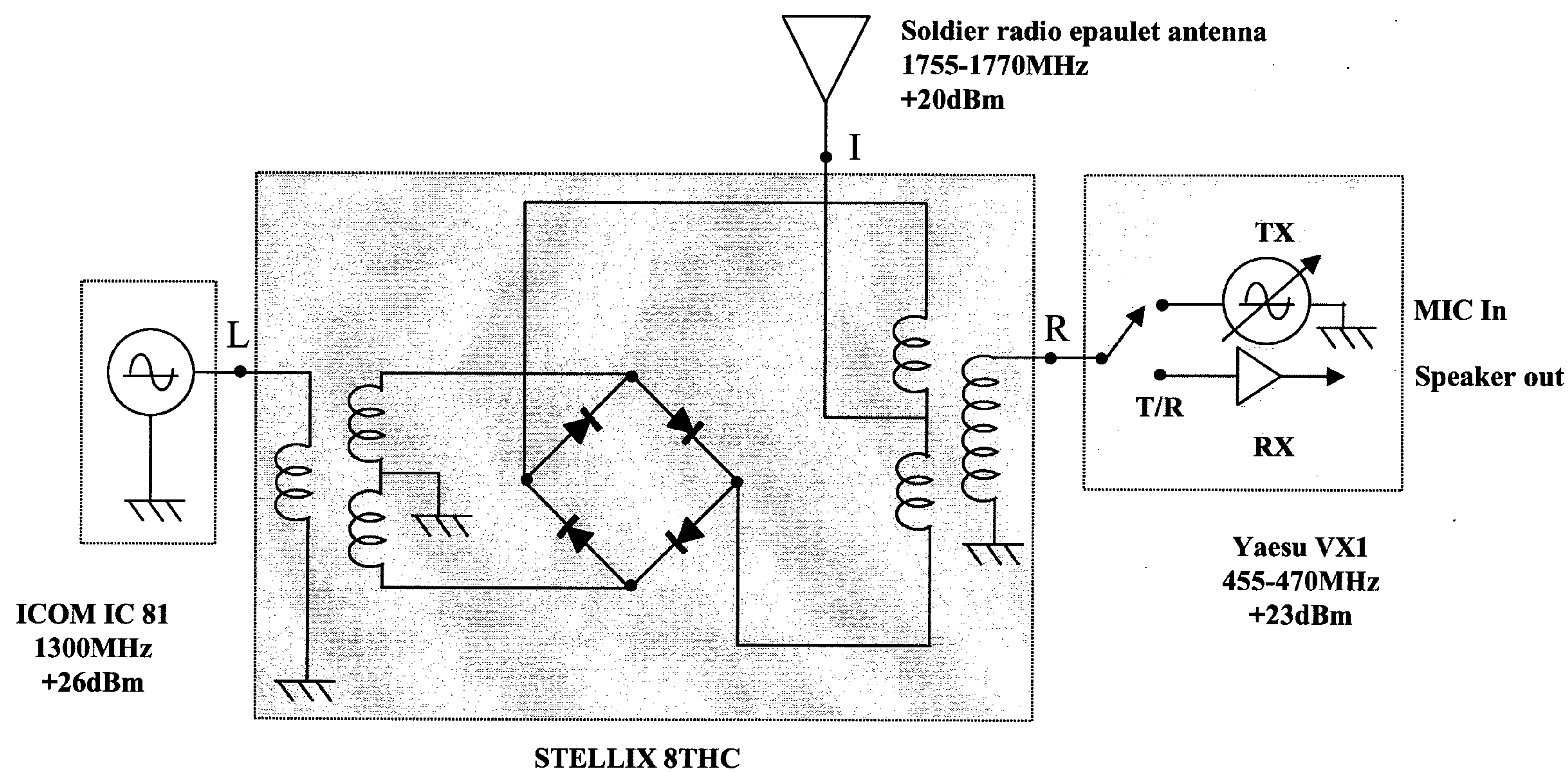


Figure 4.3-1 Block Diagram for Soldier Radio

The ICOM IC-81 transceiver [22] is used as a +26 dBm LO at 1300 MHz, driving a Stellix 8THC high level mixer [23]. A Yaesu VX1 miniature transceiver [24] (approximately the size of a conventional speaker-microphone used with transceivers) is used as the tunable (455-470 MHz) receiver-demodulator/modulator-transmitter and T/R switch connected to the "R" port of the 8THC. The 1755 MHz antenna contained in the epaulet is connected to the IF port of the 8THC, which functions as both a receive as well as transmit converter without the need for adding additional T/R switching. The IC-81 and Stellix 8THC are contained in a belt-worn MOLLE M16A2 Double Magazine Pouch. The Yaesu VX-1 functions as a hand-held control head (frequency selection/squelch/volume controls) and also contains the microphone and loud speaker. It is clipped to a convenient loop on the MOLLE's fighting load vest when receiving. Figure 4.3-2 shows the major components of this configuration, with the IC-81/Stellix 8THC partially out of its protective pouch.

Figure 4.3-2 Major components of brassboard soldier radio

The performance of the brassboard soldier radio transceiver was measured in the laboratory using the equipment and procedures described in Section 3.2.2. It has an output power that varies between +18.7 and +20.4 dBm over the 1755 to 1770 MHz portion of the soldier radio band and a receive sensitivity of -112 dBm. The rechargeable batteries in the IC-81 and VX-1 provide at least 85 minutes of continuous use which is sufficient for link testing.

The brassboard soldier radios were used to evaluate the communication performance of the combined GPS/soldier radio epaulet antennas over the paths shown in Figures 3.3-1 (a) and (b). The computed path losses for the hilly/forested Boylston path and essentially flat/forested Stow path are plotted in Figure 4.3-3. From this figure it can be seen that of the two, the Boylston path, due to its terrain exhibits greater path loss than Stow. Due to foliage, both paths also have greater than free space path loss, however the values plotted are for the types of foliage typical of New England and somewhat higher path loss values would be experienced in jungles.

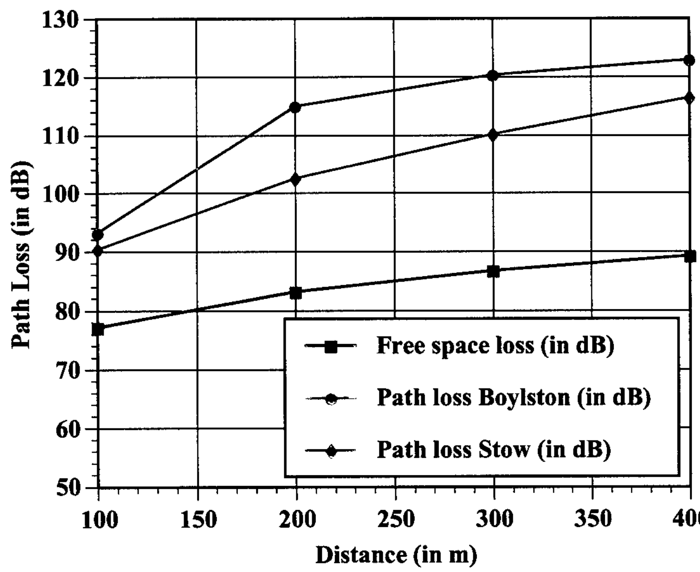


Figure 4.3-3 Path loss for the Boylston and Stow paths compared to free space

The results of the on-the-air tests are summarized on Table 4.3-1. Over the essentially flat Stow path, the only time a single message repeat was required was when both operators were prone at 400 meters. The more difficult (terrain-obstructed) Boylston path required single repeats at 200 and 300 meters for the prone-prone positions, a single repeat standing-prone at 400 meters and three repeats prone-prone at 400 meters.

Distance (in m)	Stow			Boylston		
	Standing-Standing	Standing-Prone	Prone-Prone	Standing-Standing	Standing-Prone	Prone-Prone
100	1	1	1	1	1	1
200	1	1	1	1	1	2
300	1	1	1	1	1	2
400	1	1	2	1	2	4

Table 4.3-1 Number of message transmissions required over two test paths (1 = 0 repeats, 2 = 1 repeat, 4 = 3 repeats)

5.0 Conclusions

From the work conducted and described in the previous sections of this report, the following conclusions were drawn:

Combined GPS and Soldier Radio Epaulet Antenna

- Of the three types of COTS GPS antennas considered, miniature loaded patches provided the required gain/pattern (standing/prone) and were conformal
- It was determined that in order to produce acceptable accuracy under foliage, the miniature patches required a collocated low noise amplifier (LNA)
- It was found that state-of-the-art miniature GPS patch antennas and LNAs such as the San Jose SK-4 are small enough to be contained in an epaulet pouch, draw little power (33 milliwatts) and have sufficient gain (+24dBi) and noise figure (1.5dB) to allow acceptable performance under dense foliage in both standing and prone positions.
- A key finding was that a simple planar triangular monopole provides the desired gain, mixed polarization and pattern (standing/prone) over the 1755-1850MHz band when fed against the GPS patch's ground plane/LNA shield. This antenna was also found to be small enough (1.25" long) to be enclosed with the GPS patch/LNA in the epaulet pouch.
- The combined GPS/soldier radio epaulet antennas appears to provide the desired performance within these two bands while at the same time not requiring cables between a helmet and the soldier-worn radio equipment.
- It was concluded that the epaulet antenna provides the best performance considering soldier orientation and position when mounted just below and to the back of the left shoulder.

Miniature GPS Receiver Integrated into the Combined GPS/Soldier Radio Epaulet Pouch

- It was determined that it is feasible to combine a COTS miniature GPS receiver with the GPS patch/LNA and soldier radio antennas to eliminate the need for a coaxial cable between the epaulet and a belt-mounted GPS receiver.
- Using a state-of-the-art (2001) 25x25x4mm receiver which consumed 110mW of power we obtained better than 2m accuracy while in a parking lot and 7 meters accuracy while under dense trees, regardless of the soldier position or orientation

Brassboard Soldier Radio Transceiver

- Due to high prime power requirements and T/R switching complexity, a transverter to convert a 1240-1300 MHz handheld transceiver to the 1755MHz soldier radio band was not practical
- An alternative, using a high level, passive mixer provides a workable alternative without the need for multiple T/R switches.
- Based upon testing in representative forested environments we conclude that the brassboard soldier radio's range, when connected to the epaulet antenna is at least 400 meters regardless of the soldier's position or orientation.

6.0 Recommendations

Based on the results obtained during this effort, it is recommended that the prototype epaulet antennas be transitioned into a fully qualified military item. As the design stands, the current units are not waterproof or launderable and although adequately designed for preliminary field testing, they would need to be ruggedized and tested for normal field use. Such a program would involve a mechanical engineering review of the design and recommendations for repackaging for ruggedness and encasing the units for waterproofing. Additional SAR testing of the soldier radio antennas is also recommended as part of gaining a safety release for these units. Future work could also encompass more extensive link testing of the antennas in various environments.

As far as the integrated GPS receivers are concerned, it was apparent during this conduct of this contract, that COTS technology is changing and advancing very rapidly. The size of the available patch antennas decreased significantly during an approximately 18-month duration and receiver designs are also constantly being improved and upgraded. It is therefore recommended that the state-of-the-art continue to be monitored, with new items being obtained and tested as they become available. In so doing, the US Army will maintain a constant awareness of what products are available that may be applicable for military use.

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