WIDEBAND PRINTED ANTENNA FOR TACTICAL TERRESTRIAL VEHICLES

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Abstract: **There is a need for efficient, wideband radiators that can support multiple waveforms (JTRS, WNW, etc) over 225 – 2500 MHz and be readily mounted on tactical ground vehicles. Such antennas must be efficient and robust, occupy as little volume as possible, and direct most of the radiated power towards the horizon. This last requirement is very beneficial for improving terrestrial communication link performance. We have investigated a slot-based antenna that can meet these requirements. We created a wideband printed slot antenna and used exponential tapers to expand the slot. The resulting structure gives a very wideband efficient response and it also has inherently good impedance matching. To create a vehicle mount version of the antenna we placed the slot on its side perpendicular to the vehicle, avoiding the need to develop a cavity backed solution. A ruggedized version of the antenna has been developed and tested. The radiator has a gain greater than 0 dBi across the entire 225 – 2500 MHz frequency range and also directs most of the radiated power between the horizon and 45° elevation. In this paper we outline the design procedure for the antenna, present the test data, and compare the performance with other wideband technologies.**

1 Introduction

One of the prime objectives of the Joint Tactical Radio System (JTRS) is to realize a single software radio capable of processing different waveforms from many different RF services over a wide band of frequencies [1]. The JTRS waveforms supported in the 2 MHz – 2 GHz frequency range include future Wideband Networking Waveform (WNW), Single Channel Ground Air Radio System (SINCGARS), UHF SATCOM, High Frequency (HF) Independent Side Band (ISB) with Automatic Link Establishment (ALE), Link-16, Identification Friend or Foe (IFF), Digital Wideband Transmission System (DWTS), Soldier Radio, Wireless Local Area Network (WLAN), Cellular Radio, Personal Communication Services (PCS), and future expansion of Mobile Satellite Services (MSS) [2]. The implementation of these services in JTRS will require the development of a wideband, vehicle mount antenna platform including a very sophisticated filtering procedure. The radiating structure is the key enabling technology for the proposed software defined radio since wideband amplifier technologies as well as the supporting control software for these communication links are reasonably well

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advanced. The schematic in Fig. 1 highlights the multitude of communication levels and therefore the overall complexity of communications in a battlefield environment [3].

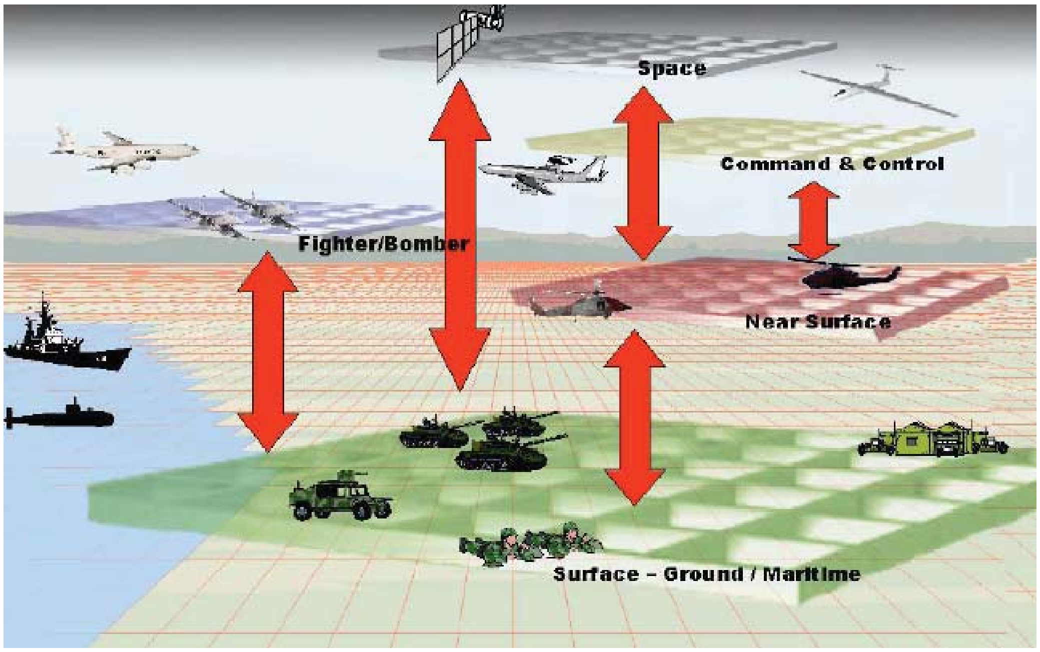


Fig. 1 Schematic showing the levels of communications in a battlefield environment (from [3])

Of all the possible forms of radiators, probably the only class of antennas that operates over such wide bandwidths is traveling wave based. There are a variety of traveling wave based antennas that may appear suitable for this application and a summary of their general properties is given in Table I. Spiral antennas are the most common solution for wideband applications [4]. Although the cavity backed spiral antenna can give the required radiation performance, the size and weight associated with the cavity make this alternative not particularly attractive, especially for mounting on a vehicle. In contrast, the printed spiral with resistive or absorber loading [5] has all the features required for the WNW vehicle mounted antenna. However this antenna is still quite large due to the requirement of operating at frequencies near 225 MHz and also due to the loads it suffers from relatively poor efficiency, especially at the lower frequency edge.

Tapered slot antennas [6] can provide excellent bandwidth and are also very efficient as no power is wasted and dumped into a load element. However, tapered slots are usually quite large especially when required to operate at low frequencies. In addition, the radiation pattern of a tapered slot antenna is directional which prevents the use of this form of radiator for the vehicle mount since omni-directional coverage is required. The coupling to the tapered slot from a standard unbalanced transmission medium can also be inefficient, with losses greater than 3 dB.

Table I Comparison of wideband antenna solutions

Type of antenna	Overall complexity	Size	Band-width	Radiation pattern	Polarization	Efficiency	Feed complexity
Cavity backed spiral	High	Large (volume)	Large	Omni-directional	All	moderate	Complicated
Printed spiral	Low	Moderate	Large	Omni-directional	All	Moderate	Moderate
Tapered slot	High	Large	Large	Directional	Linear	High	Complicated
Bow tie	Low	Small	Large	Omni-directional	Linear	Moderate	Complicated
Log periodic	Moderate	Large	Large	Directional	Depends on element	High	Moderate
Beverage	Simple	Long	Large	Directional	All	Moderate	Simple

As can be seen from Table I, bow tie slot antennas can provide a physically small radiating solution, however there is a drawback associated with this technology; in its conventional form this antenna needs a cavity backing, similar to the spiral radiator, and therefore is not really a practical solution. Also, the bandwidth of 225 – 2500 MHz is very large for conventional bow-tie slot or dipole radiators [7]. Other forms of low profile antennas such as log-periodic and Yagi-Uda arrays are simply too large for this application, even if applying fractal engineering techniques. Another point that should be made here is that fractal engineering could be applied to most of the antenna concepts summarized in Table I in order to reduce the size. However this is achieved at the expense of efficiency which can be dramatically reduced depending on the type and order of the unit cell.

The Beverage or long wire antenna in its original form is not suited to the WNW application. As summarized in Table I, this antenna is relatively long (of the order of 5 – 10 wavelengths) and its radiation pattern is typically oriented along the direction of propagation on the wire. We have recently developed printed versions of this form of radiator and have also folded the radiator back onto itself to create compact versions with omni-directional radiation patterns [8]. However as with the previously mentioned spiral radiators, these antennas suffer from relatively low efficiency due to the required loading.

Typical specifications for the antenna assembly for a terrestrial vehicle-mount JTRS WNW antenna are summarized in Table II. As can be seen from these specifications/requirements it is imperative that most of the gain of the antenna be directed towards endfire (the horizon). This requirement is extremely difficult to meet with radiators that are integrated within the structure of the vehicle such as spirals, Beverage antennas, or conventional bow-tie slot antennas, where the maximum radiation is typically directed towards broadside (directly above the antenna).

Table II Pharad JTRS WNW vehicle mount antenna

Frequency	225 – 2500 MHz
Gain	0 to +3 dBi from 0 – 30º above horizon < 1000 MHz +3 to +5 dBi from 0 – 30º above horizon >1000 MHz
Response	Linear
Polarization	Vertical, Horizontal, or Circular
VSWR	< 2:1
Impedance	50 ohms
Pattern	Azimuth: omni-directional
	Elevation: Hemispherical, horizon to horizon
Power	100 Watts
Connector	Type N/TNC female, single feed
Ground Plane	None required
Mounting	4 × 3/8" bolts, 90º each on 4.5" bolt hole center
Size	
Height	10"
Length	19.75"
Width	7.5"

In this paper we present a wideband printed antenna designed for efficient operation over the JTRS WNW band of 225 – 2500 MHz and which also meets the size constraints highlighted in Table II. The antenna can be classified as a coplanar waveguide (CPW) fed profile optimized slot antenna, where we have shaped the expansion of the slot to optimize the return loss performance and efficiency of the radiator. For the vehicle mount application the slot resides perpendicular to the surface of the vehicle and therefore does not require any modifications to the vehicle surface. Importantly, such a mount directs the radiation of the antenna towards the horizon.

In this paper we summarize the design procedure for the vehicle mount antenna element as well as its radiation and return loss performance. We also present the physical design of the antenna. The paper is organized as follows. Section 2 gives an overview of the concept of the profile optimized slot antenna highlighting its generic shape and the design philosophy behind its creation. Also in this section, we summarize the design procedure for the antenna. In Section 3 we give an overview of the physical design of the antenna such as how the antenna is mounted onto a standard Army vehicle and also describe the interface to the RF cable. In Section 4 we present the measured responses of the antenna including its radiation performance and return loss response. In this section we also compare the performance of the antenna to another wideband printed antenna: the flared monopole. Finally we summarize our findings in Section 5.

2 Profile Optimized Slot Antenna

2.1 Overview

As mentioned earlier, the fundamental radiating structure we are proposing to use in this vehicle mount application is an optimized profile slot. A general schematic of the profile optimized slot is shown in Fig. 2. Here the radiator is fed by a CPW transmission line and in this particular example an exponential profile is used to taper the slot, while a parabolic tapered shape is incorporated to enclose the slot. These electromagnetically smooth transitions help give the radiator broadband characteristics. We use a CPW feed to reduce the manufacturing cost of the antenna as uni-planar structures are significantly cheaper to realize. In Fig.2 the impedance of the slot lines where the 50 Ω CPW transmission line is terminated is 100 Ω, ensuring an efficient transfer of power to the two arms of the radiator.

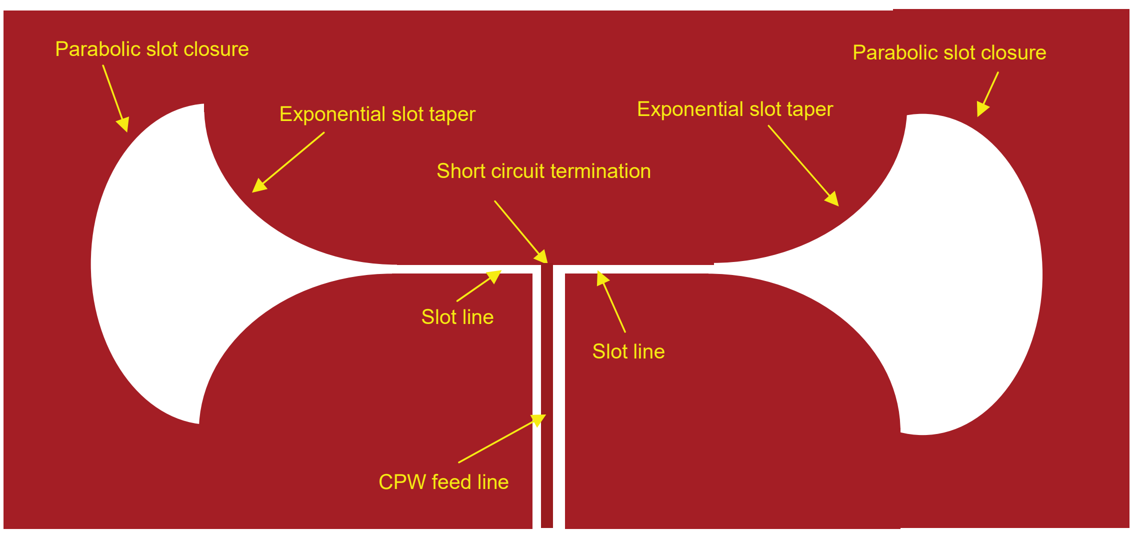


Fig. 2 Schematic of the generalized profile optimized slot radiator

As described above, the input impedance of each half of the profile optimized slot radiator is matched to the required impedance in order to maximize the power transfer to the antennas. Fig. 2 shows the transition from the coplanar waveguide to the two slot lines of the antenna. Here a simple short circuit is used in conjunction with matching the parallel combination of the slot line impedances to the CPW impedance, in order to ensure optimum power transfer to the radiators. This design of using an impedance ratio to appropriately distribute the power inherently gives an efficient power divider. We have found through simulation that the simple transition shown in Fig. 2 gives very good wideband performance, without the need to implement more complicated transitions. We will discuss this further in the next sub-section.

2.2 Design Procedure

2.2.1 Starting Point

The design procedure always starts with the size constraints associated with the location and mounting of the antenna. As with all antennas, the larger the antenna the more efficient it will be, particularly at the lower end of the intended operating frequency range. The key is to maximize the size of the antenna for the given physical constraints. One advantage of the profile optimized printed slot is that there are many degrees of freedom in the design and we can take advantage of these to given an efficient solution for an area that may not be symmetric. Fig. 3 gives some examples of how we can apply the profile optimized printed slot to different conical geometries. As can be seen from the schematics, we can vary the individual slot profiles to accommodate different shapes.

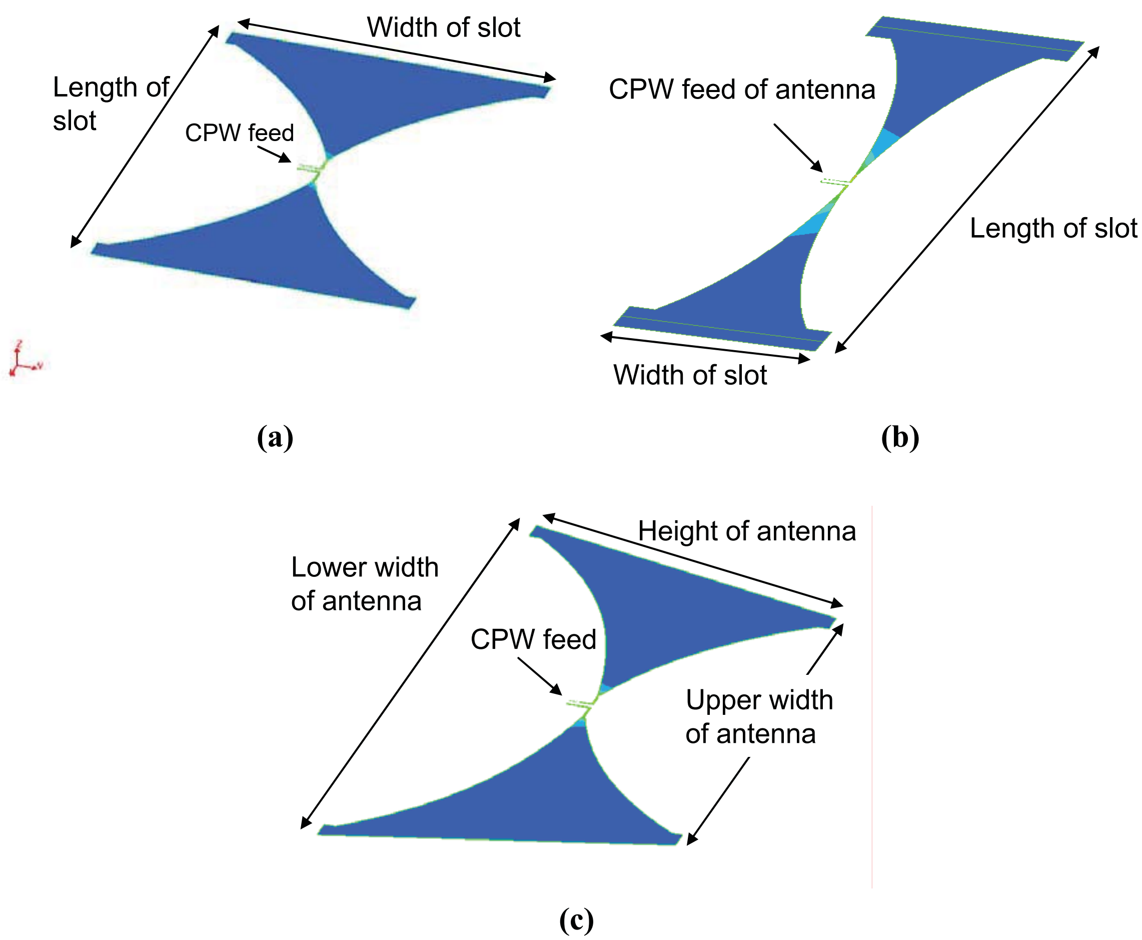


Fig. 3 Examples of profile optimized slot shapes: **(a)** square; **(b)** rectangle; and **(c)** non-symmetric polygon

Once the size constraints have been established we then select the material to fabricate the radiator. As with most printed antennas, the higher the dielectric constant of the material, the physically smaller the radiator can be. Also, a higher dielectric constant material assists in the fabrication of the feed structure. As the profile optimized printed slot is typically fed by a CPW transmission line, the impedance of this line is directly related to the gaps between the 'hot' electrode and the two ground-planes. For CPW transmission lines, the higher the dielectric constant of the material, the larger the gaps for a 50 Ω transmission line. Having larger gaps simplifies the fabrication process of the antenna. For the case presented here we selected a material with a thickness of 0.16 cm and a dielectric constant of 4.5 (Arlon AR 450).

2.2.2 Impedance transformer

Once the overall size constraint is known and the material to develop the radiator has been selected, the feed can be designed. As mentioned before, the feed for the profile optimized printed slot is relatively straightforward to design. Fig. 4 shows a photograph of the important junction of the feed, where power is delivered to each arm of the slot. Here we have a simple transition from CPW to two slot-line transmission lines. To ensure power is distributed to both arms and not reflected back to the source, we need to impedance match the ports. For a 50 Ω CPW line, the impedance of the two slot lines must be 100 Ω to ensure an efficient transition.

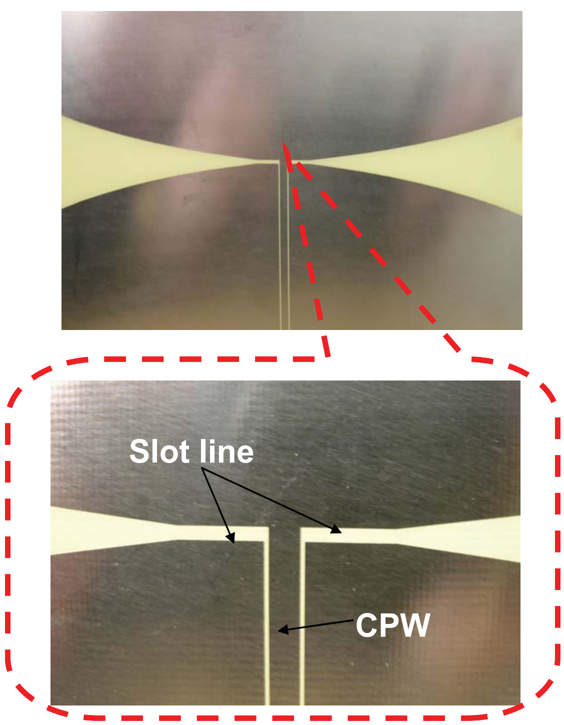


Fig. 4 Photograph of transition for profile optimized slot

Fig. 5 shows the theoretical S-parameters of the transition shown in Fig. 4 designed on material with a dielectric constant of 4.5 and a thickness of 0.16 cm. As can be seen from the plot, S_{11} (where port 1 is the CPW port) is better than -10 dB for all frequencies across the 0.1 – 4 GHz frequency range and the power delivered to each slot line port is just below 3 dB, highlighting the efficiency of the transition. An interesting point to observe is that a complicated balun is not required for this transition, even over the large bandwidth shown in Fig. 5. This makes the solution very attractive as is simplifies the design and fabrication processes of the antenna.

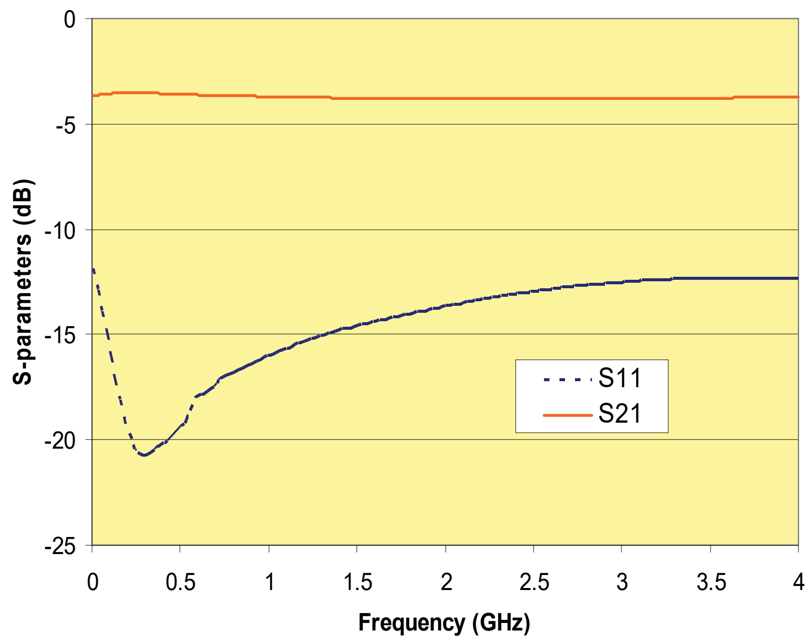


Fig. 5 Predicted S-parameters of the transition

2.2.3 Profile Design

The next step in the design procedure is to develop the slot profile. There are several profiles that can be used, such as linear or piece-wise linear, however we have found that exponential profiles give the best bandwidth performance for a constrained size. This result is not surprising as it is similar to the findings for tapered slot antennas [9], with which the proposed solution shares several characteristics.

The opening factor of the profile (R) is very important for the VSWR bandwidth of the antenna. Fig. 6 shows two cases for a profile optimized printed slot antenna, where the size of the antenna is kept constant, however the opening rate is different; R = 0.1 and R = 0.3 (the definition of R is highlighted in the insert of Fig. 6). As can be seen from the results presented, the lower the opening rate of the profile, the better the return loss (VSWR) performance, particularly at the lower frequency edge. For most profile optimized printed slot antennas we use profiles of less than 0.15.

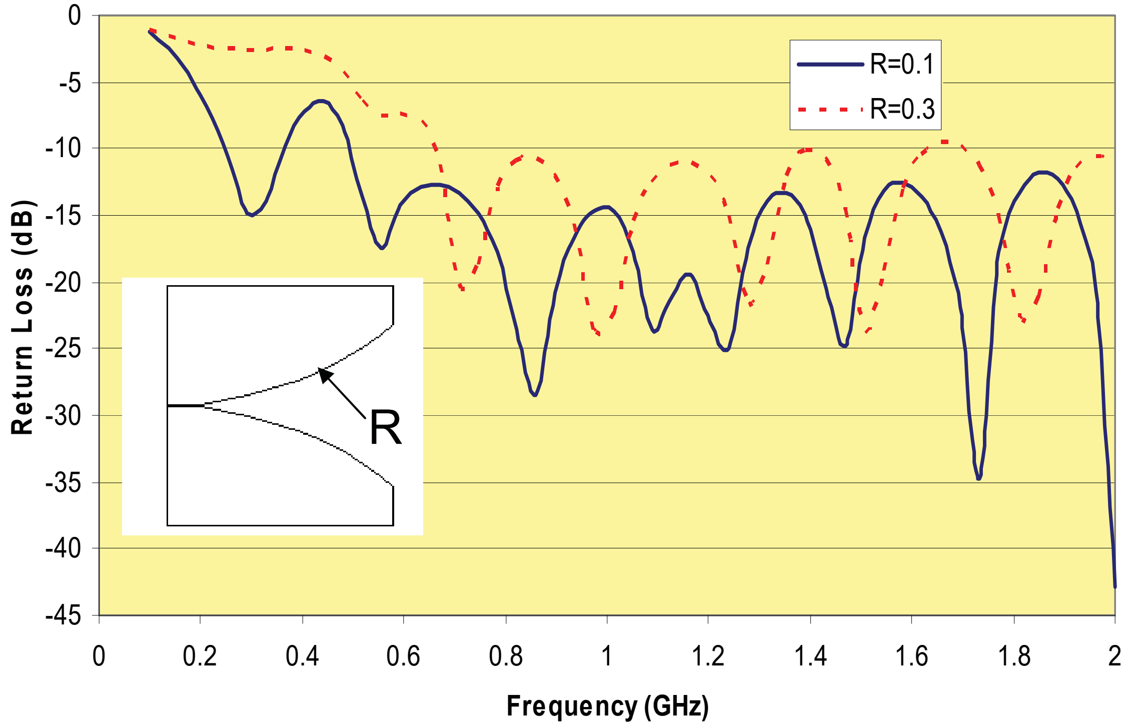


Fig. 6 Impact of R on the return loss performance

2.2.4 Design Trade-off Space

Naturally, as is the case with any antenna, size is very important and constraining the physical size compromises the performance of the radiator. It is important to establish the trade-off space in order to ensure that we achieve the best performing radiator for the given size constraints. For our base-line case a profile optimized slot of dimensions 27.6" × 15.8" × 0.06" has a VSWR < 2:1 between 100 MHz and 4 GHz and a gain greater than 0 dBi over this band.

We undertook a numerical investigation to determine the trade-offs associated with the size and the performance of the profile optimized slot. A profile optimized slot antenna constrained to 13.8" × 7.9" × 0.06" had the following characteristics: VSWR < 2:1 from 225 MHz to greater than 4 GHz; and a gain of greater than 0 dBi across this matched band. At 100 MHz, the smaller version of the profile optimized slot had a gain of -2.6 dBi and the return loss is only -4 dB. Intuitively this degradation in performance is logical as we have effectively halved the dimensions of the antenna, which we would expect should impact the return loss and gain performance. The return loss performance is directly related to the length of the tapered section of the slot; an electrically shorter tapered section will not provide effective matching between the impedance of the guided medium and free space. Therefore we would expect more power to be reflected back to the input port of the antenna.

The gain trade-off associated with the size of the antenna is, once again, a relatively simple relationship; reducing the size of the antenna reduces the effective capture area and subsequently the gain. Through undertaking many numerical simulations we have established the following design guideline: the effective length and width of the profile optimized slot radiator must be greater than 0.25 $\lambda_0 \times$ 0.15 λ_0 to achieve a gain of more than 0 dBi at the lowest 2:1 VSWR frequency. Here λ_0 corresponds to the free-space wavelength at that frequency. It should be noted that this is a general guideline and does not take into consideration the properties of the material to fabricate the printed antenna.

Further size reduction of the profile optimized slot radiator can be achieved if high dielectric constant material is used, although the material needs to have low loss to ensure that the gain is not compromised. Using high dielectric constant material can improve the return loss response as it helps in the development of an efficient impedance transition from a CPW track to the coplanar stripline (CPS) (as shown in Fig. 4). As the dielectric constant of the substrate increases, it is easier to develop 50 Ω transmission lines in CPW and also 100 Ω transmission lines in CPS.

Another radiation characteristic that is directly related to the size of the antenna is the amount of ripple in the radiation patterns. Because the optimized profile slot is wideband in nature, at higher frequencies there is more ripple in the radiation patterns than at the lower frequencies. Simplistically this can be attributed to the excitation of more than one mode at higher frequencies. We have observed this phenomenon for many wideband radiators. Also, the depth of the ripple is dependent on the mounting platform.

2.2.5 JTRS WNW Vehicle Mount Design

Using the design strategies described in the previous paragraphs and the established radiator performance trade-off space, we designed a profile optimized slot that can perform efficiently over the 225 × 2500 MHz band and is compliant with the size constraints highlighted in Table II.

Fig. 7 shows a photograph of a prototype radiator developed. In this photograph, the gold-colored metal square below the antenna is 12" × 12" in area. To maximize the dimension of the antenna, we placed it in the diagonal plane of the cube. For the radiator in Fig. 7, a profile of 0.15 was used for the slot opening. We used a rectangular section for the closure of the slot which extends 0.4" beyond the end of the exponential taper in the vertical direction and 0.7" in the lateral direction. Beyond this, we use a metallic border of 0.4" to enclose the slot. The antenna is CPW fed, which cannot be seen in Fig. 7.

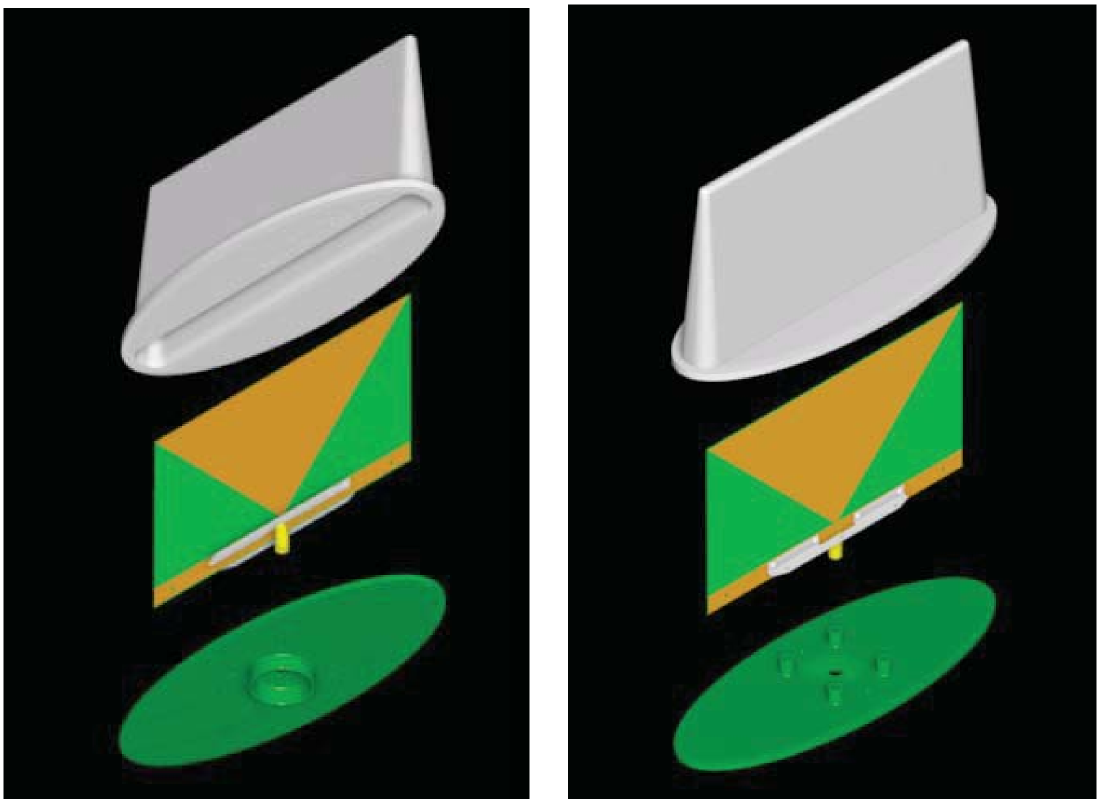
Fig. 7 Photograph of a prototype of the vehicle mount profile optimized slot

3 Physical Design of Wideband Vehicle Mount Antenna

Due to the environment in which the antenna is to be mounted, it is imperative that a ruggedized package for the radiator be developed. Here we developed a ruggedized, environmentally compliant prototype, illustrated in Fig. 8, suitable for testing in its intended environment. In this photograph, the radiator resides under the black-colored radome and its ground-plane is oval in shape. The antenna is shown sitting on a cylindrical mount in an anechoic chamber.

Fig. 8 Photograph of the ruggedized vehicle mount antenna

The vehicle mount antenna assembly has three major components as shown in Fig. 9: (i) the radiator, (ii) the mounting plate, and (iii) the radome. In the exploded view shown below, the antenna is represented by a flared monopole for simplicity.



(a) **(b)**

Fig. 9 Exploded view of the vehicle mount antenna assembly: **(a)** from above, and **(b)** from below

As discussed earlier, the radiator is constructed from an Arlon 450 polytetrafluoroethylene (PTFE) microwave laminate. The radiator is attached via aluminum brackets to an aluminum mounting plate, which takes all of the stress related to the mounting. We decoupled the radiator from the TNC input connector by using coaxial cabling rigidly attached to the mounting plate between the TNC connector and the radiator. This decoupling shown in Fig. 10 ensures that the vibration of the radiator will not result in stresses on the feed connection to the radiator.

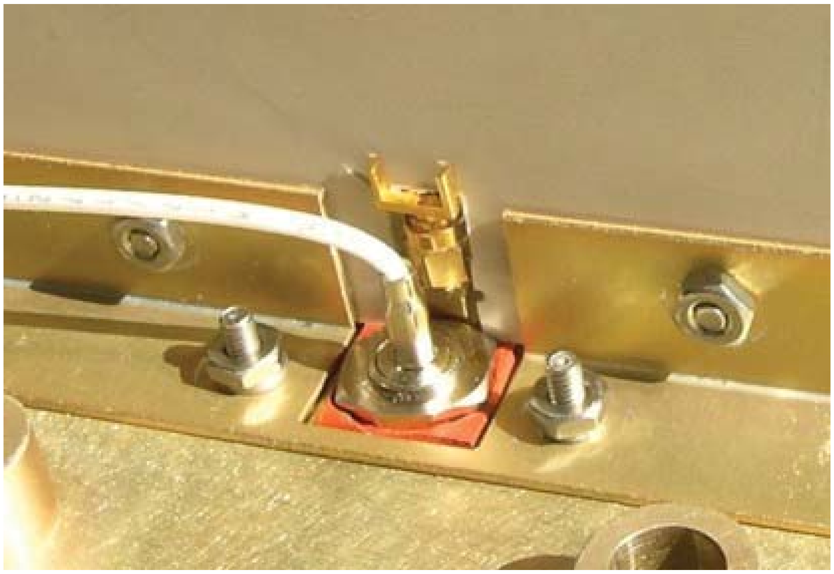


Fig. 10 Photograph of the physical decoupling between the input TNC connector and the radiator

The entire antenna assembly is covered with a polyurethane radome. For this version we selected BJB Enterprises TC-854 rigid polyurethane for its physical properties and low cost. The silicone rubber gaskets are shown in Fig. 11 and are fitted to the inner opening of the radome and around the TNC connector, providing a weather tight seal around the radiator.

(a) **(b)**

Fig. 11 Photographs of sealing gaskets for the vehicle mount antenna assembly: **(a)** radome to mount seal, and **(b)** connector to mount seal

The antenna housing was also designed for ease of installation. An Army technician can simply attach the vehicle's TNC terminated cable to the antenna and then drop the antenna into the standard 4-hole US Army vehicle antenna mounting platform. The antenna assembly is secured to the vehicle via the four standard ⅜" bolts. A protective outer ring on the bottom of the antenna assembly shown in Fig. 12 protects the cable/antenna connection. The aluminum mounting plate detailed in Fig. 13 assumes all of the stress from the ⅜" bolts, thereby preventing damage to the radome.

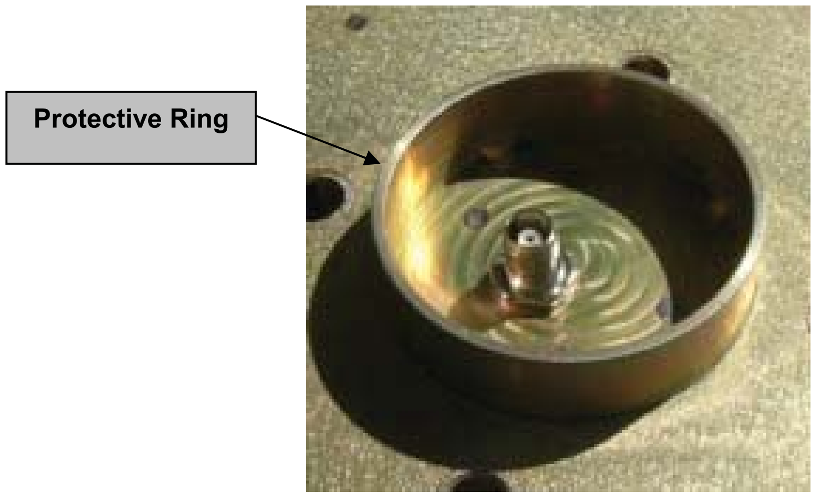


Fig. 12 Photograph of the connector/cable protective ring

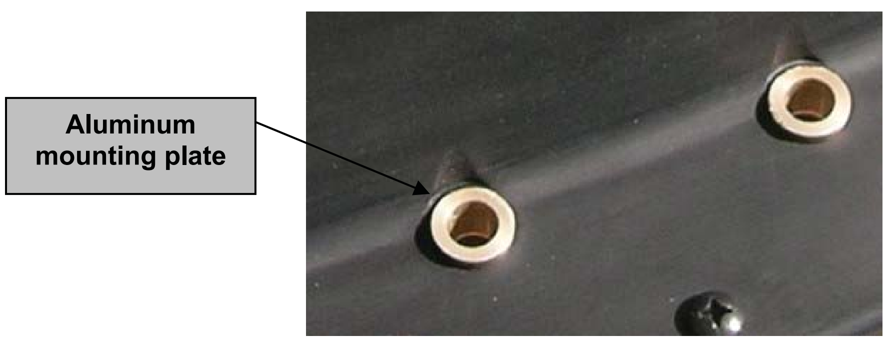


Fig. 13 Photograph of the aluminum structure for the mounting bolts

4 Results and Discussion

In this section we summarize the experimental results for the wideband antennas developed. The return loss performance of the antennas was measured at our facilities at Pharad and the radiation patterns (including gain) were measured at NAVAIR, Patuxent River, Maryland. The coordinate system of the antenna measurement referenced in the radiation pattern plots is shown in Fig. 14.

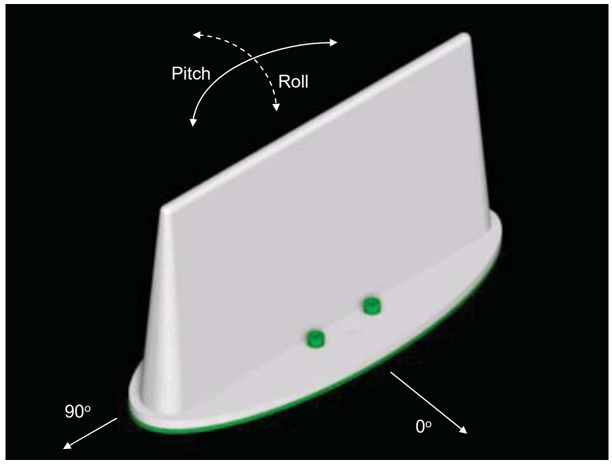


Fig. 14 Coordinate system for the tested antennas

A summary of the radiation performance (including gain) of the profile optimized slot across the 225 – 2500 MHz frequency band is shown in Figures 15 – 21. For all these measurements a 3' × 3' ground plane was attached to the underside of the radiator. The gain of the profile optimized slot is approximately 2 dBi at 225 MHz, peaks at approximately 7 dBi at 2000 MHz, and is still greater than 3 dBi at 2500 MHz. Across the entire frequency range the gain is concentrated within 45° of the horizon, which is very beneficial for terrestrial communications to the vehicle. In fact, the profile optimized slot tends to direct significant energy towards the horizon.

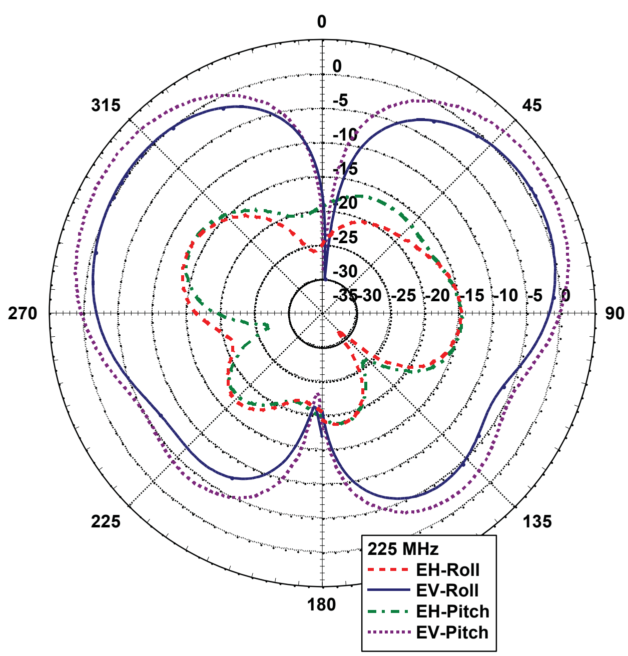


Fig. 15 Measured radiation performance of the profile optimized slot at 225 MHz

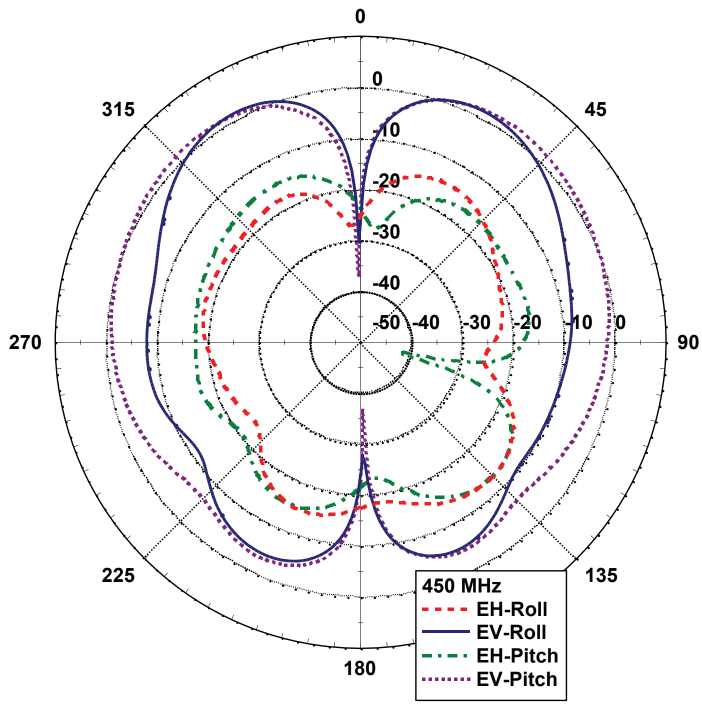


Fig. 16 Measured radiation performance of the profile optimized slot at 450 MHz

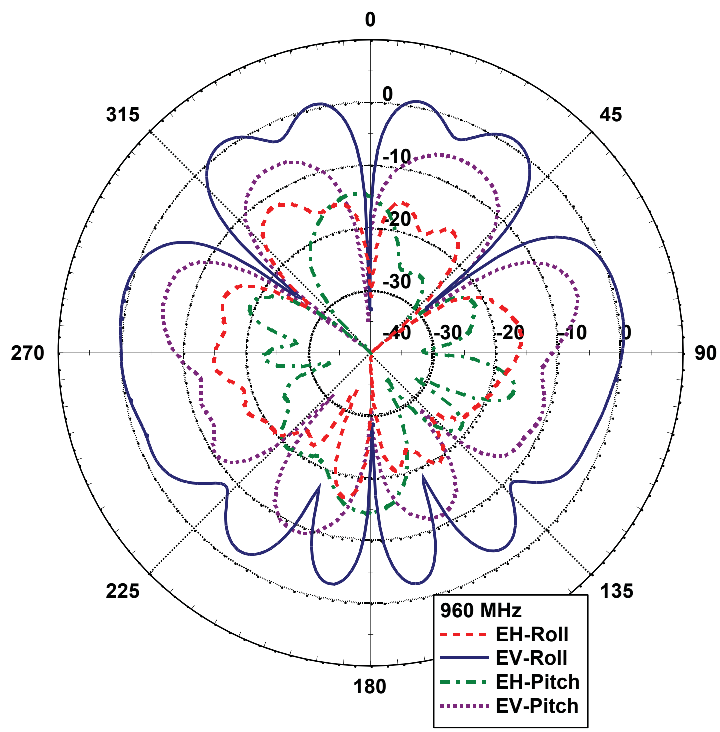


Fig. 17 Measured radiation performance of the profile optimized slot at 960 MHz

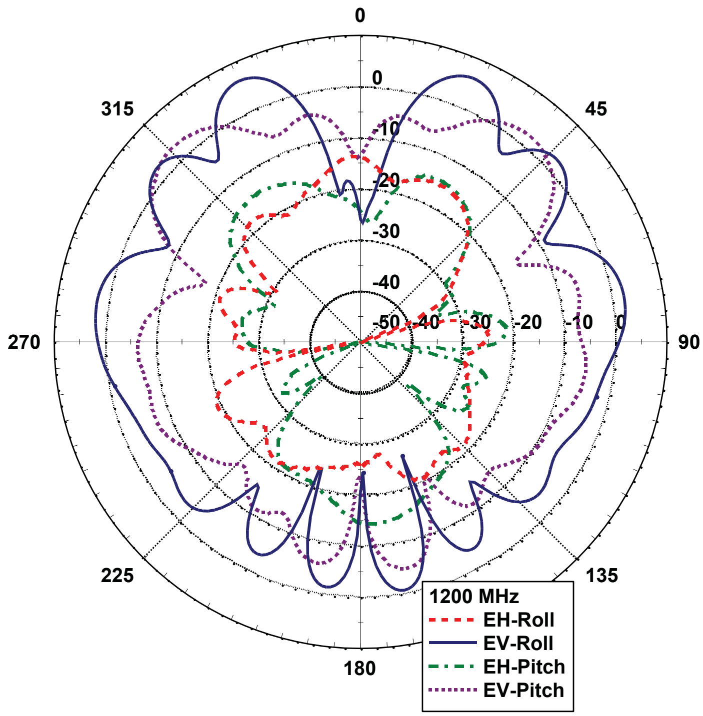


Fig. 18 Measured radiation performance of the profile optimized slot at 1200 MHz

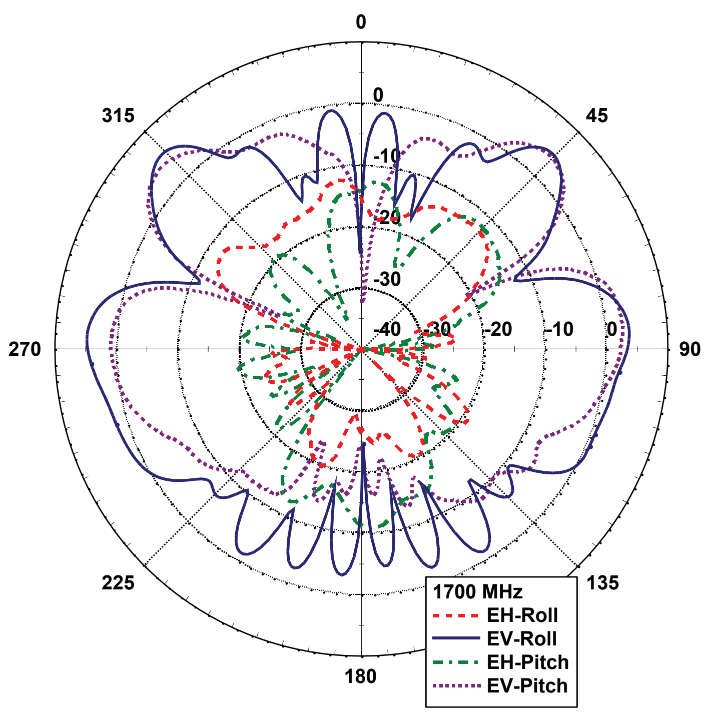


Fig. 19 Measured radiation performance of the profile optimized slot at 1700 MHz

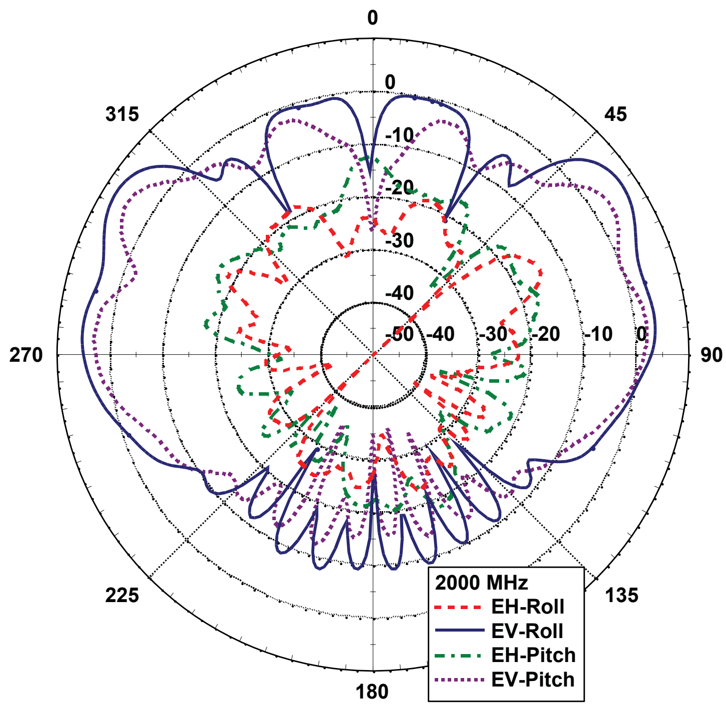


Fig. 20 Measured radiation performance of the profile optimized slot at 2000 MHz

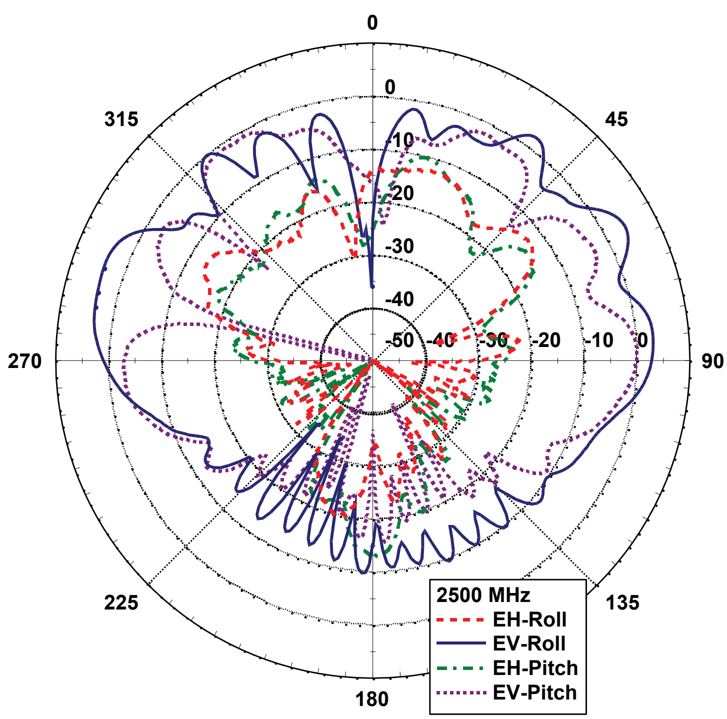


Fig. 21 Measured radiation performance of the new profile optimized slot at 2500 MHz

We can see from the measured radiation patterns that as the frequency increases, particularly above 500 MHz, more gain undulation is present in the radiation patterns. This is a consequence of the wideband nature of the antenna and the possibility of modes being excited across it. We are presently exploring techniques to reduce the undulation.

The measured return loss of the profile optimized slot is shown in Fig. 22. The wideband nature of the radiator is evident in this return loss plot. Despite the electrically small size of the antenna, the return loss performance is very good. We believe this is due to the impedance matching approach used at the transition of the CPW to CPS transmission lines and also the exponential flaring of the slot arms. The slight mismatch in the return loss at approximately 1 GHz we believe is due to modes being excited across the slot.

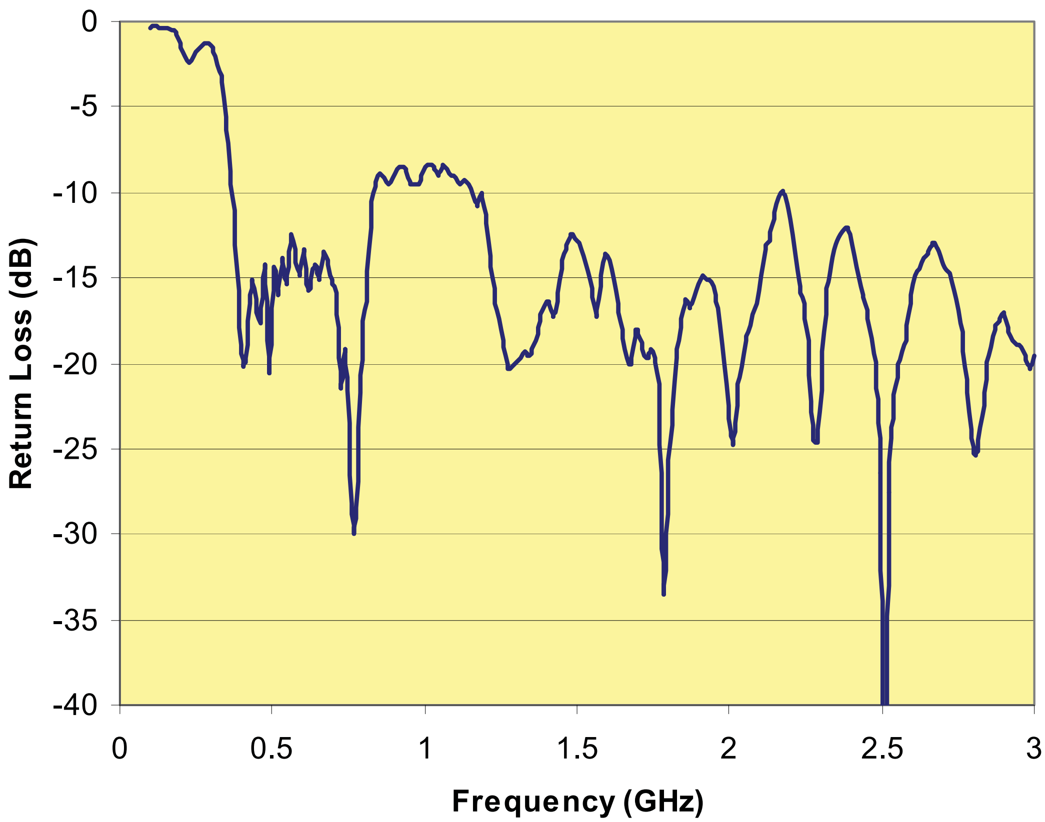


Fig. 22 Return loss performance of new profile optimized slot

As mentioned before, we have developed other wideband radiators suitable for JTRS WNW vehicle mount systems. One in particular, which has the same overall dimensions as the radiator described in this paper, is a form of the printed flared monopole. A photograph of the radiator is shown in Fig. 23. This antenna can be readily placed in the enclosure discussed in Section 3. We have also thoroughly evaluated the performance of this antenna and we will now compare the performance of the flared monopole to the profile optimized slot.

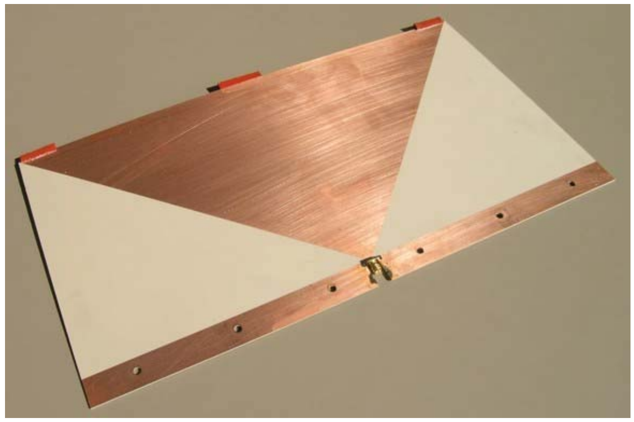


Fig. 23 Photograph of the CPW fed printed flared monopole

Probably the most important parameter is the radiation performance of the antenna, and here the flared monopole and the profile optimized slot performed similarly. The profile optimized slot does outperform the flared monopole at the lower and upper limits of the frequency range, however in the mid frequency band the flared monopole operates better. One distinguishing characteristic between the two radiators is the amount of energy directed towards the horizon. Both radiators direct most of their energy between the horizon and 45° elevation, however the profile optimized slot does have higher gain towards the horizon. This may be more advantageous for terrestrial communications to the vehicle.

There is one characteristic in which there is a substantial difference between the radiators and this is the return loss performance. The profile optimized slot has a better return loss response than the flared monopole and this can be attributed to the smooth transition between the transmission line used to feed the radiator and the antenna itself. The return loss of the flared monopole can be improved by using a different taper (in Fig. 23 it is a linear taper), however this is only a second order effect. A summary of the comparison between these radiators is shown in Table III.

Table III Comparison of the electromagnetic performance of the flared monopole and profile optimized slot radiators

Antenna	Gain	Horizon Coverage	Return loss Bandwidth
Flared Monopole	✓✓✓	✓✓	✓✓
Profile Optimized Slot	✓✓✓	✓✓✓	✓✓✓

5 Conclusions

In this paper we have presented a wideband terrestrial vehicle antenna based on a printed profile optimized slot radiator mounted perpendicular to the surface of the vehicle. The antenna operates efficiently over the JTRS WNW band of 225 – 2500 MHz and inherently directs its radiation towards the horizon in the azimuth plane. We gave an overview of the basic radiating structure and summarized the design procedure to achieve a wideband solution. We also established the performance trade-offs associated with varying the size of the antenna.

In this paper we highlighted the physical design for a ruggedized terrestrial vehicle mounted version of the antenna. The radiation and return loss performance of the antenna were experimentally examined and a comparison with another wideband printed radiator was provided. The printed profile optimized slot antenna mounted perpendicular to the surface of the vehicle appears to be very suited to wideband wireless systems where most of the power needs to be directed towards the horizon.

Acknowledgments

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References

[1] http://jtrs.army.mil/
[2] Joint Tactical Radio System Operational Requirements Document (Extract of JROC approved final with waveform Table 4-2 and Annex E), Version 3.2, April 2003.
[3] www.army.mil
[4] J. Dyson, "The equiangular spiral antenna", IRE Trans. Ant. & Propn., vol AP-7, pp. 181 – 187, April 1959.
[5] J. J. H. Wang, and V. K. Tripp, "Design of multioctave spiral-mode microstrip antennas", IEEE Trans. Ant. & Propn., vol. 39, pp. 332 – 335, March 1991.
[6] D. Schaubert, E. Kollberg, T. Korzeniowski, T. Thungren, J. Johansson, and K. Yngvesson, "Endfire tapered slot antennas on dielectric substrates", IEEE Trans. Ant. & Propn., vol. 33, pp. 1392 – 1400, December 1985.
[7] A. Serrano-Vaello and D. Sanchez-Hernandez, "Printed antennas for dual-band GSM/DCS 1800 mobile handsets", IEE Electron. Lett., vol. 34, pp. 140 – 141, January 1998.

[8] R. B. Waterhouse and D. Novak, "Printed Folded Beverage Antennas", to appear in Printed Antennas for Wireless Systems and Related Applications, R. B. Waterhouse, ed., Wiley, 2007.

[9] C. H. Chio and D. H. Schaubert, "Parameter study and design of wide-band widescan dual-polarized tapered slot antenna arrays", IEEE Trans. Ant. & Propn., vol. 48, pp. 879 – 886, June 2000.