Antenna Developments for Military Applications

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Abstract **—** A review of current, past and projected activities in antenna development indicates a broad spectrum of requirements, and subsequently a variety of innovations to meet these requirements for military radar and communications systems. Designing the antennas in the operating environment, known as in-situ design, is an important factor in guaranteeing the successful operation of the antenna in the field. This paper presents the basic blocks in antenna development, followed by examples of some antennas developed at the Army Research Laboratory for military systems and applications. These include Rotman lenses as beam formers for electronically scanning arrays; phased arrays using MEMS phase shifters at 30 GHz; a 76-GHz narrow beam, low-sidelobe antenna for collision avoidance radar; and other specialized antennas. Of special interest is an effort on developing and using metamaterials in antenna designs, where practical realizations of such materials have the potential of improving the performance and reducing the size of antennas.

Index Terms **—** Antenna Modeling, Army, Military, In-Situ.

I. INTRODUCTION

Antenna requirements for military applications include low profile, high efficiency, wide frequency band, highly integrated and conformability to the host platform. The low profile and conformality stem from the desire to blend the antenna into its surroundings to avoid easy visible detection and identification. These applications often require novel antenna solutions.

In general, the more complex the antenna, the more it can be effected by the platform and operational environment. This is not always addressed by designers, even though it is the in-situ antenna performance that will determine the system performance. The earlier in the acquisition process that the in-situ performance can be verified the more savings can be realized.

Another important parameter in the antenna design is the choice of materials that meet structural, electronic, and electromagnetic requirements. Material issues are paramount in integration, packaging, interference, and performance parameters such as efficiency and bandwidth. Material selection also plays important roles in antenna appearance and identification, as well as its in-situ performance.

In the following sections we go through the elements of the antenna development, discuss the roles of government laboratories, industry and academia in such developments, and present some examples of recent and on-going research.

II. ELEMENTS OF ANTENNA DEVELOPMENT

A successful antenna development is a collaborative effort between the customer, who sets the requirements, in this case Government laboratories, academia or universities, and industry. The sequence of development from concept to fielding is shown in Figure 1, along with the main areas that constitute the development. The requirements for the specific applications, the modeling in the environment, and the field testing of the antenna occur at different stages of the development and are specific to the Army, Navy, or Air Force laboratory that is involved. The last stage of production is specific to the industry.

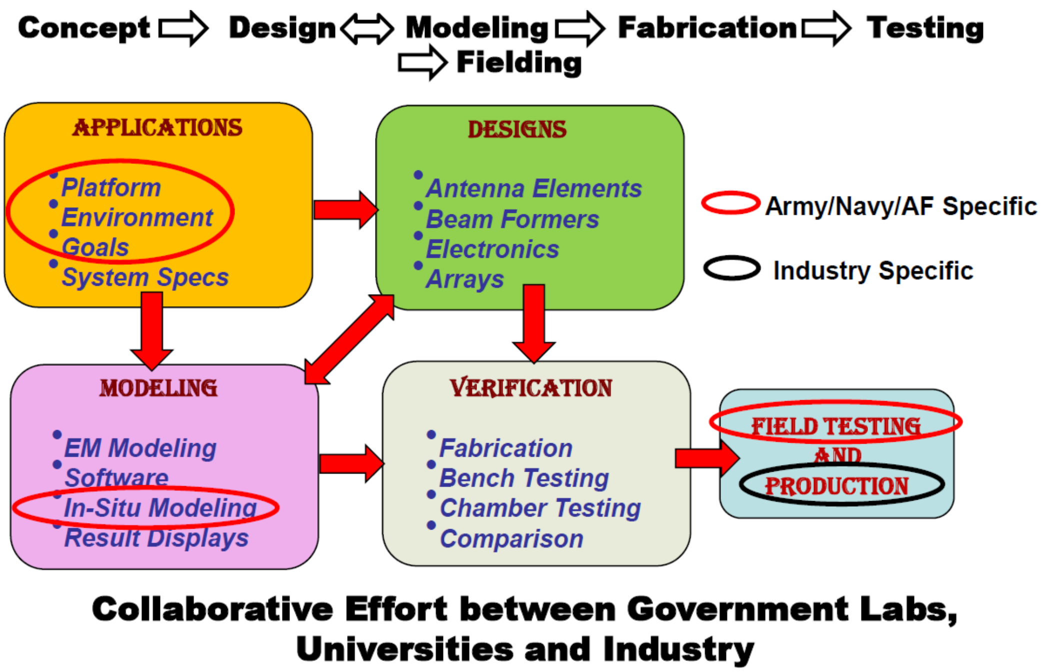


Fig. 1. Components of antenna development for military applications.

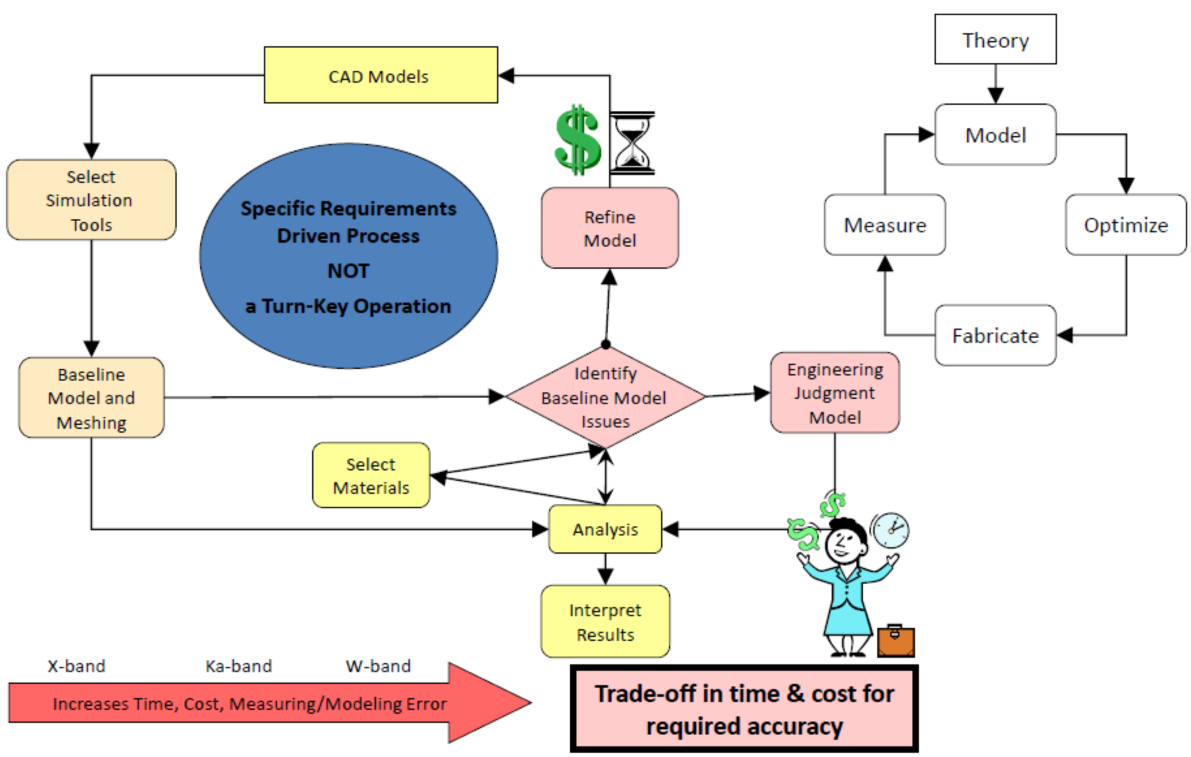


Fig. 2. Modeling flow-chart for electromagnetic simulation.

Modeling has become a central and essential part of the antenna development. Commercial software packages for electromagnetic modeling have seen significant advancements over the last four decades. They continue to be improved as new designs and new materials call for new modeling paradigms. High performance computing (HPC) tools have made it possible to model complex structures over broad frequency bands in ways that were not possible a few decades ago. However, expert users are always required and expected to make full usage of the available modeling and computational tools. Engineering judgment is often required to meet time and cost constraints, as modeling is a trade-off in time and cost for the required accuracy. A modeling flow chart that shows the different steps in the electromagnetic modeling is shown in Figure 2.

III. IN-SITU ANTENNA DESIGN

A major objective for military applications is to develop and evaluate electromagnetic models of in-situ antenna designs in operational environments to support the design and analysis of multifunction radar and communication systems. “Bolt-on” antenna solutions often have reduced performance whereas vehicle integrated designs can dramatically improve performance and avoid costly redesign and increased Test and Evaluation (T&E) costs. The earlier in the acquisition process that the in-situ performance can be verified the more savings can be realized. In-situ antenna modeling refers not just to the sensor platform but also its environment such as urban terrain and the presence of a ground plane. Army applications often require novel antenna solutions but in general the more complex the antenna the more it can be effected by the operational environment. The highly integrated antenna designs will emphasize low cost, lightweight approaches with optimum performance on the next generation RF sensor platforms. This is often not addressed by industry even though it is the in-situ antenna performance that will determine the system capability.

Army Research Laboratory (ARL) has developed a significant measurement and simulation-based infrastructure for modeling antennas and antenna platforms. Antennas are critical elements for all radar and communication systems. Therefore, it is necessary to fully characterize and understand antenna performance in the presence of the platform to assess system performance. Poorly designed antennas can lead to electromagnetic interference (with other systems on the platform), decreased range and underutilization of bandwidth. In addition, poorly integrated antennas can adversely affect the aerodynamic and structural performance for the case of airborne platforms. This can lead to costly overruns for re-designs. ARL is using simulation-based design techniques (with spot measurements for validation) to model the antenna and platform over the complete design trade space in order to arrive at the optimal solution the first time.

ARL uses a combination of in-house developed and contractor-developed software for modeling antennas. The primary production codes in use at ARL include commercial software for antenna design and analysis such as FEKO (http://www.feko.info), Ansoft High Frequency Structure Simulator (http://www.ansoft.com), EMPiCASSO (http://www.emagware.com), XFDTD (http://www.remcom.com) and the General Electromagnetic Model for the Analysis of Complex Systems (GEMACS) (http://www.gemacs.com). These are general purpose computational electromagnetic (CEM) codes but are often specialized to certain antenna types such a planar or guided wave structures. ARL has on-going efforts with code developers to incorporate specialized features into such tools. Examples are research contracts with Remcom and Ansoft to apply specialized methods for modeling electrically large devices with application to the design of Rotman Lenses for beam forming networks. Such codes along with in-house developed software allow the design and evaluation of complex antenna arrays for military applications.

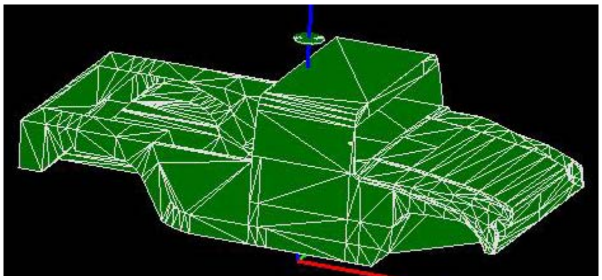
In many cases, antenna design and analysis is platform specific where the antenna modeling must be done in-situ to incorporate the influence of the antenna installation on antenna performance. Hybrid techniques such as incorporated in FEKO and GEMACS enable the Department of Defense (DoD) laboratories to design – from first principle electromagnetics – in-situ wideband multi-functional antennas for a wide range of DoD activities including communication, acquisition, target identification, surveillance, and electronic attack. These codes have a large user base and have been extensively validated for a wide range of radiation and scattering applications. Current DoD requirements for large arrays and apertures are too complex (geometrically and materially) to be handled by traditional analytical methods, such as element-pattern times array-factor. What is required today is sophisticated antenna software that uses exact physics to accurately predict near field quantities like the currents flowing on the antenna and the fields in the antenna's housing. DoD requirements have expanded to include antenna arrays that are very large in terms of free-space wavelengths so that fast methods and parallel implementations are required.

FEKO is an example of a state-of-the-art PC-based code that incorporates fast methods and hybrid techniques to solve electrically large problems in practical times. GEMACS can use a combination of exact and asymptotic methods to solve electrically large problems. This parallel code is available on the DoD Supercomputing Resource Centers (www.hpcmo.hpc.mil) and shows good scalability to a large number of processors. The types of computations needed to obtain antenna performance data lend themselves to a natural parallelism – that is, angles and frequencies of interest can be spread across many processors in a very efficient manner. Thus a combination of PC software and HPC codes are often used to develop antenna designs and efficiently evaluate those designs as installed on air, land or sea-based military platforms. Military sensor platforms on the modern battlefield range from ground/air vehicles to munitions and even the individual Warfighter. Using in-situ modeling early in the acquisition process can ensure that the antenna meets requirements in the operational environment and lead to cost/schedule savings especially during T&E.

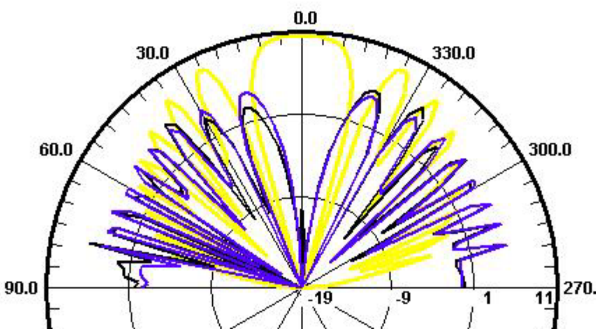
A generic example of in-situ antenna analysis using GEMACS is shown in Figure 3 for a roof mounted spiral antenna on a HMMWV (M998) at 750 MHz. The EM model is shown in Figure 3(a) where the antenna support and radome structure are not included and the ground plane is not shown. GEMACS provides a hybrid solution for these type problems with the antenna modeled using method of moments (MoM) while the vehicle is modeled using the geometrical theory of diffraction (GTD). The ground plane is modeled as a large GTD plate except that edge and corner diffractions are not included. A typical radiation pattern comparison is shown in Figure 3(b) when including first order reflections only (blue), reflection and edge diffraction (black) and then with the ground plane only (yellow). The radiation pattern at this height over ground (yellow) would be severely distorted if installed as shown on the host vehicle. In many cases the edge diffraction contribution to the pattern perturbations are negligible and can often be neglected to reduce the simulation time. Multipath/blockage effects are good examples of where the in-situ environment includes nearby structures and ground. In this example, scattering from the host vehicle significantly perturbs the radiation pattern with reduced gain and a null in the overhead direction.

The Army is using more unmanned aerial vehicles (UAVs) as sensor platforms where the ground plane may not be important aspect of the operational environment. Another example of in-situ antenna modeling is direction finding antennas on a generic UAV platform where a reliable in-situ (and platform specific) knowledge of the radiation pattern is required for algorithm calibration. The FEKO model and calculated radiation pattern for monocone antennas at 300 MHz are shown in Figure 4. Compared to a wing only model the UAV platform introduces additional perturbations primarily in the back lobes (aft direction). In this example the two antennas are not exactly symmetrically located on the UAV wing and this small difference can be seen in the pattern asymmetries. As can be seen the in-situ pattern would be required to analyze system performance and an infinite ground plane or wing only model is not sufficient.

Composite construction requires verification of CEM tools and approximations through measurements on the actual airframe materials. An example is the UAV wing with bent monopole antenna shown in Figure 5(a) when covered with metal foil. The difference in radiation pattern for the antenna on metal versus the graphite skin wing is small (<2.5 dB) as can be seen in Figure 5(b) for the elevation plane. The metal model of the UAV used in the *FEKO* simulations should be a reasonable representation of this type composite [1]. With increasing frequency even small platforms will require more computational resources and/or the use of hybrid or asymptotic methods. But to use these methods accurately, users must have significant experience in their applications and limitations. In many cases engineering judgment is required to meet project objectives.



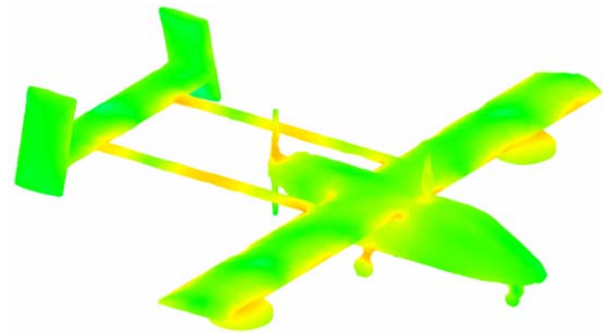
(a)



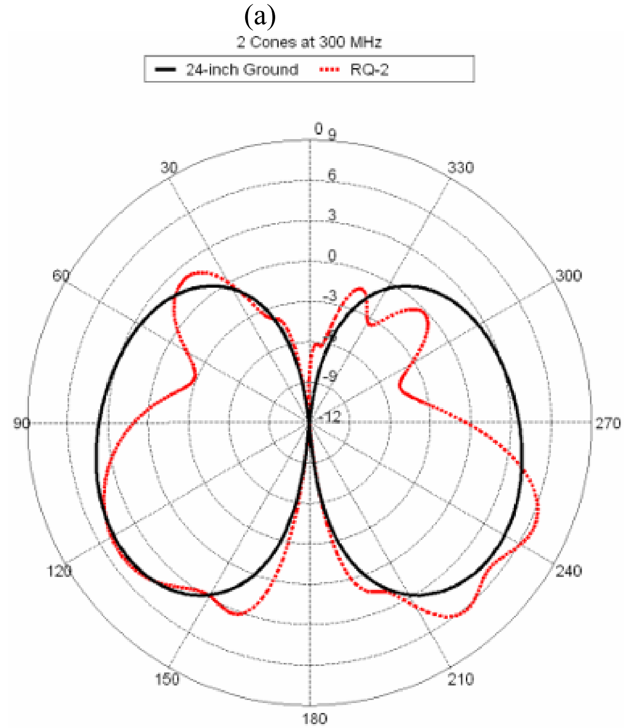
(b)

Fig. 3. Spiral antenna (a) on M998 over large ground plane, and (b) radiation pattern with reflections only (blue), reflection and diffraction (black) and without vehicle (yellow).

Antenna solutions for munitions could be another case where the ground is not an important part of the operational environment. Concepts for null steering using an endfire antenna array have been investigated for this application. An example is shown in Figure 6 for a four-element aperture-fed patch array with 1:2:2:1 amplitude weights. The array was designed with a 2.5-D model (EMPiCASSO) but the 3-D model (FEKO) shows the true effect of a finite size ground plane. A simple wedge model is used to approximate a nose cone installation where the radome is not included. Two arrays are combined to produce a boresight null and this model is used to further investigate pattern perturbations. For instance, including a metal backing plate reduces but does not eliminate the back lobes [2]. A full 3-D model of the in-situ antenna is required to fully evaluate and optimize performance to meet system requirements.



(a)

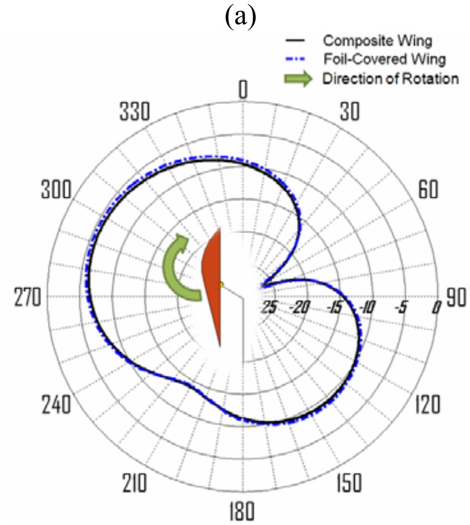


(b)

Fig. 4. Generic UAV example (a) with monocone antennas and (b) azimuthal pattern perturbation at 300 MHz compared to the wing only result.

The Warfighter can be one of the most challenging platforms for high performance antennas. Operation over realistic ground is a unique Army requirement. Free space designs are typically not appropriate for Army applications and could require redesign leading to cost and schedule impacts. A generic body model is used with parameters of typical skin to demonstrate in-situ effects for a lapel mounted RFID antenna as shown in Figure 7. Ground does not perturb the antenna input impedance but leads to a split main beam pattern. Close proximity to the body changes the antenna input impedance to the point that redesign would be required. Realized gain is reduced ~3 dB and becomes more frequency dependent. Placement further from the body or antenna redesign is required to compensate for these loading effects. Optimum performance requires an in-situ design that accounts for the operational environment which includes operation in different body positions over realistic terrain or in vehicles.

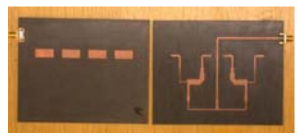
(a)



(b)

Fig. 5. UAV wing with bent monopole antenna example (a) when covered with metal foil and (b) azimuthal pattern perturbation at 144 MHz compared to composite wing.

To summarize, we showed some generic antenna modeling examples and how performance can be impacted by the operational environment such as the presence of a lossy ground plane. We highlighted some applications of in-situ antenna design/analysis and how modeling might be used to evaluate and/or optimize the antenna performance in its operational environment. For electrically large problems HPC resources are required and ARL has access to some of the latest HPC platforms and CEM tools. The next generation of CEM software developed by the DoD will be focused on useable, accurate and efficient tools for in-situ antenna design in order to meet the every increasing computational challenges of advanced antenna technologies.



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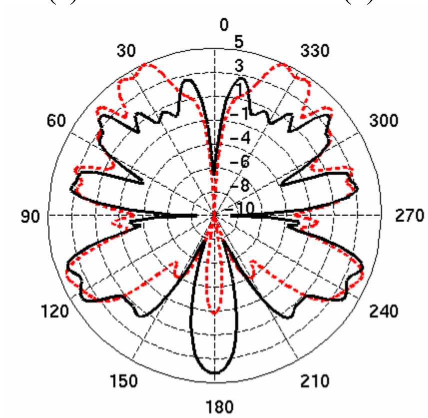


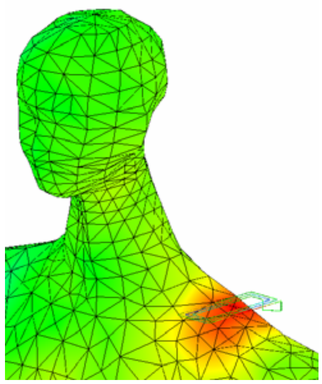
(c)

Fig. 6. FEKO example for (a) an endfire array, (b) the in-situ model and (c) the azimuthal pattern perturbation with (red) and without (black) a metal backing plate.

IV. DEVELOPMENT EXAMPLES

Rotman Lens:

Since the inception of the Rotman Lens in 1963 [3], there has been considerable interest in using such beamformers in array applications. The spatial beamforming aspect of such lenses has historically been of interest to the Army as a scanning mechanism for small arrays in a multifunctional environment [4 - 6]. Recently, the Rotman lens has become appealing as a beamformer for terrestrial communication applications [7 – 8]. In this section, we present an example of such a lens from inception to first prototype.



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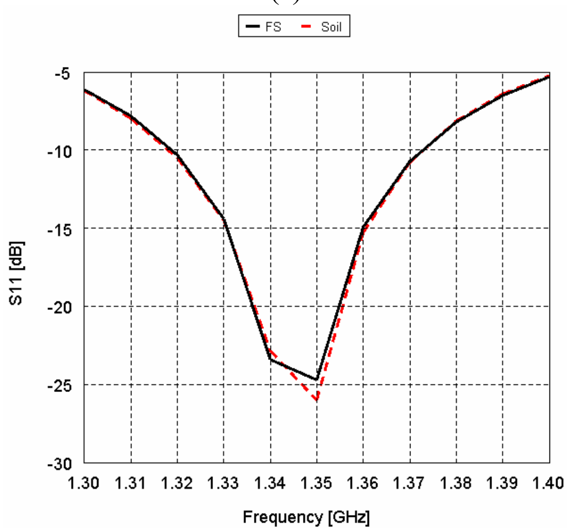

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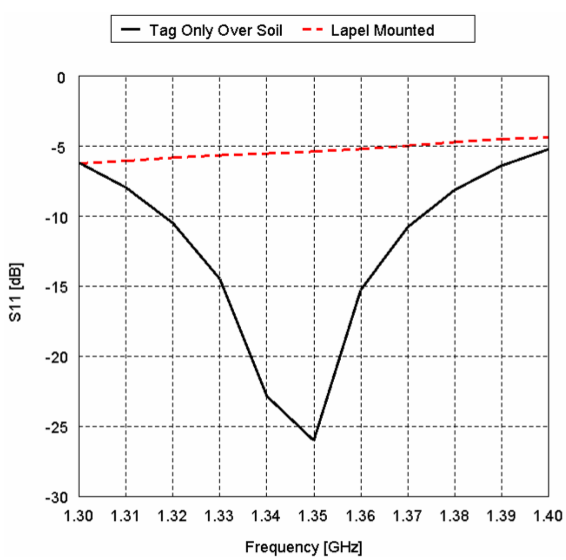


(c)

Fig. 7. Body worn antenna (a) in-situ model, (b) S_{11} when in free space (black) compared to soil (red) and (c) over soil with (red) and without (black) the body.

Through an Army sponsored SBIR, REMCOM was contracted to develop software to simulate Rotman Lens structures realized with microstrip and stripline geometries. A software called "Rotman Lens Development" (RLD) was used to realize the lens discussed here. The software itself is based on geometric optics and gives accurate first cut performance results. The lens, connected to a linear array of patch antennas, is shown in Figure 8.

Of particular interest, was the measured progressive phase shift at the output ports, given a particular input port was excited. Because of symmetry, ports designated (1, 8), (2, 7), (3, 6), and (4, 5) exhibit the same behavior with measured phase shifts on the array side exhibiting the desired progressive phase shift behavior. This is readily seen in Figure 9a [7]. Additionally, as the lens is a "time delay" beamformer, it should exhibit a linear change in phase shift over frequency. This was measured and validated [7], Figure 9b.

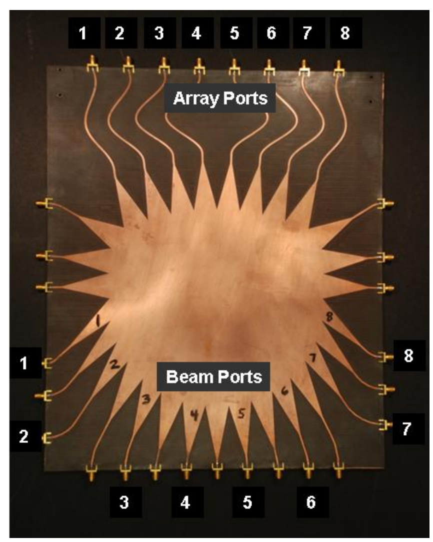
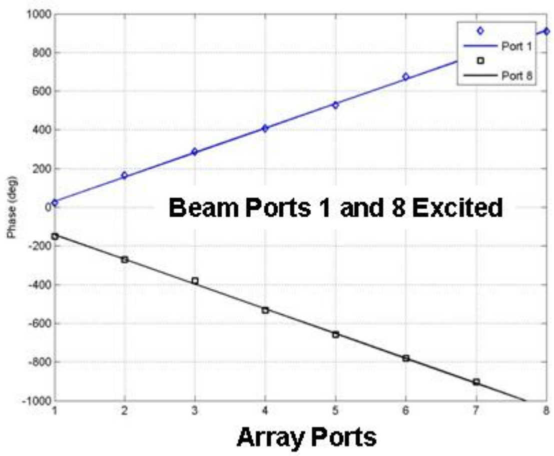
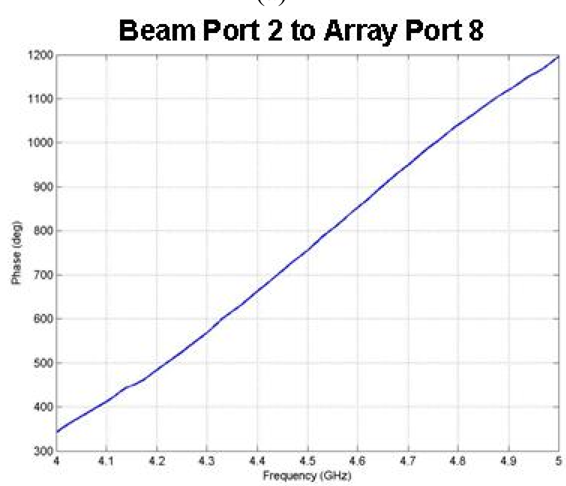


Fig. 8. Microstrip Rotman lens.

With such good measured performance, the lens was felt to be a suitable candidate for a beamformer in the C-band. A photo of the lens connected to an eight element patch antenna array is presented in Figure 10. The lens is made of a thin (20 mil thick) dielectric (5870 Duroid.) Because of the thin nature of the structure, it is easily bent as seen in Figure 10. This bending did not affect the performance of the lens, so one could use the array in an application where it may need to be gracefully bent. For example, the lens could be located on the roof of a vehicle and the bending could be exploited so that the antenna array itself could be flush to the side of the same vehicle [8, 9].



(a)



(b)

Fig. 9. Measured phase shift of microstrip.

Rotman lens: (a) Measured array aperture phase taper when beam ports 1 and 8 are excited, (b) Measured phase shift from beam port 2 to array port 8 over frequency.

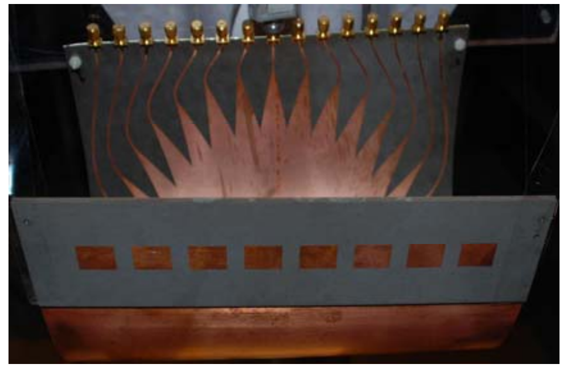


Fig. 10. The Rotman lens portion of the array is flexible and can be shaped to accommodate the geometry of the platform.

The lens discussed is flexible and lends itself to conformal integration onto a platform. Additionally, the manufacturing cost is not high. The biggest drawback is the insertion loss of the Rotman lens and the associated feed lines – measured to be on the order of 9 dB. ARL has addressed the loss issue with a lens made using a cavity and waveguide feeds [4 - 7]. Such a lens is shown in Figure 11. The lens on the left was machined from Aluminum and weighed about 14.65 lbs. Because of the solely metallic realization of the structure, the insertion loss was measured to be on the order of 3 to 4 dB – a significant improvement over the photo-etched Rotman lens design. However the cost and complexity of the design were greatly increased. Shown on the right is a duplicate design made of Ultem 1000 and gold plated. This lens was significantly lighter (6 lbs) and achieved comparable (actually, slightly better) performance. This design remains an item of study because of the possibility of realizing the structure through injection molding, thus reducing the cost significantly.

Integrated Phased Array Designs:

Integrated phased array designs can pose some special design challenges depending on the application of interest. For satellite communications in tactical environments, low-profile electrically scanned antenna arrays are particularly desirable. One possible candidate for this challenging implementation is the wafer level antenna arrays. These arrays tend to be of interest for applications where the wavelength of the operation tends to be small relative to the size of the wafer. As an example, ARL is investigating a linear 4-element array with integrated MEMs phase shifters (from Raytheon Corp.) for concept validation.

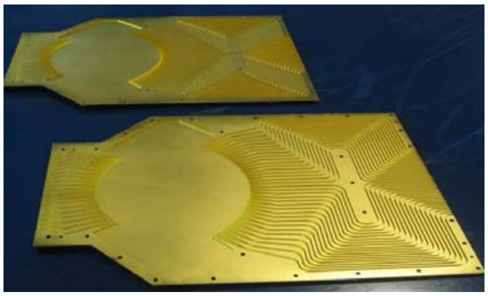
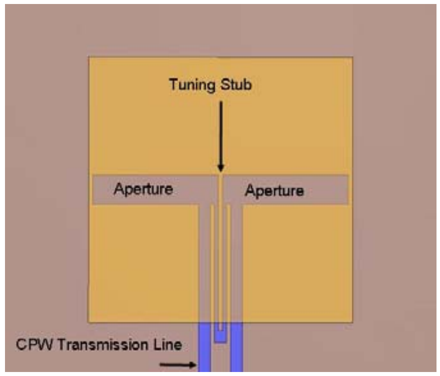


Fig. 11. Ka-band Rotman lens realized with a cavity and waveguide transmission lines.

The individual wafer-level element itself is constrained by the physical parameters of the wafer. For our case study, a high resistivity silicon waver substrate (relative dielectric ~ 11.7) was used. The thickness of the wafer was 500 μm. A key challenge became the feeding mechanism for the radiating element (a patch antenna) after the wafer was processed. Figure 12 illustrates ARL's unique feed mechanism that will permit an integrated phased array design. Note that the antenna is fed by a slot (aperture), but the feed line is on the same level as the slot itself. This is a departure from the traditional slot fed patch antenna that requires a separate patch and feed layer to be bonded together. The transmission line is coplanar waveguide (CPW) that facilitates integration to MEMs phase shifters that have CPW RF ports.



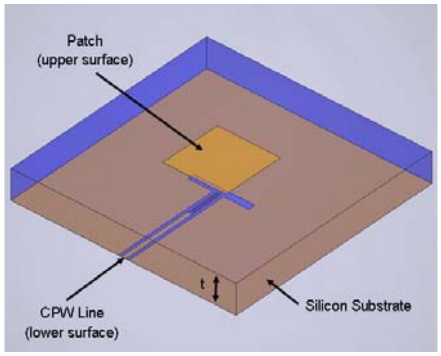


Fig. 12. Geometry of the wafer level patch antenna – top view and a perspective view.

This antenna was fabricated and measured to validate its performance. In Figure 13, one can see the construction of the individual element. Also shown is the back side of the wafer with 4 MEMS phase shifters integrated into the design. Figure 14 presents measured data validating scanning (for a progressive phase shift of +/- 45 Degrees.) While the patterns demonstrated the scanning, much work needs to be done on optimization. In particular, the tolerances on the phase of the MEMs devices has been significantly improved on subsequent fabrication runs.

In conclusion, this wafer level phased array design has illustrated the conceptual approach used by ARL when faced with a design that has constraints dictated by the fabrication environment – in this case the wafer itself. We were able to realize a unique feed that facilitated integrated MEMs phase shifters into the architecture of the feed layer. The design was built and tested validating preliminary simulated results.

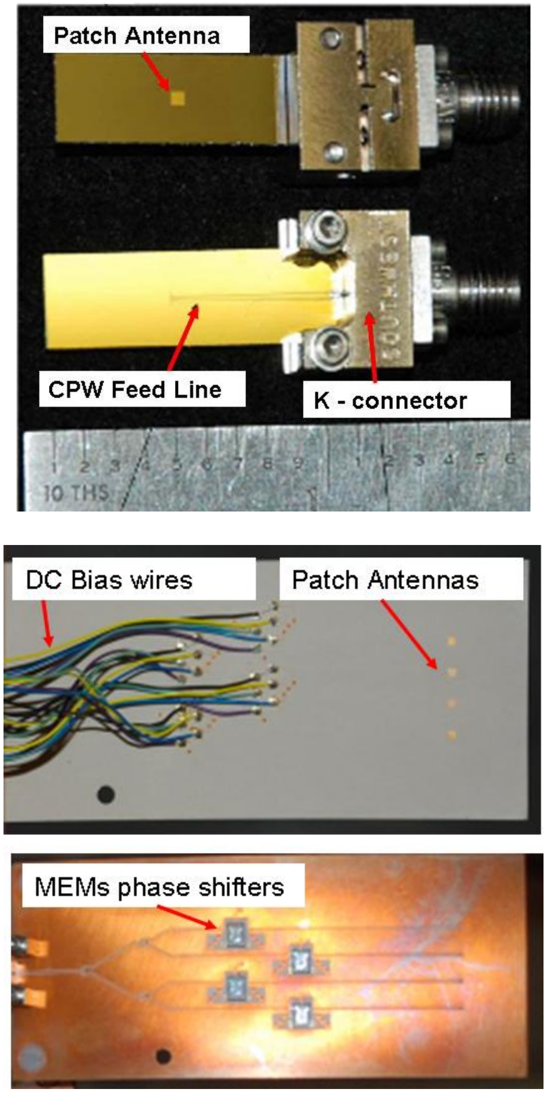


Fig. 13. Prototype wafer patch antenna and an integrated 4-element array on a wafer.

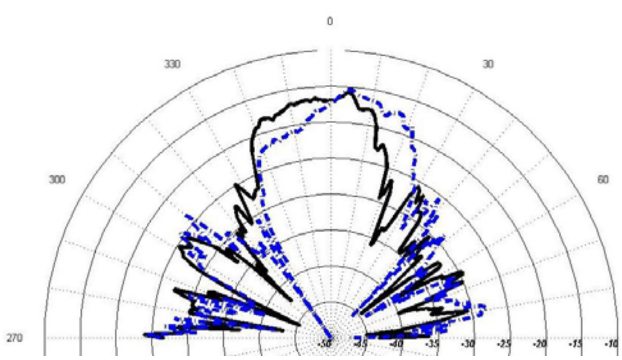


Fig. 14. Radiation pattern of the 4-element array demonstrating scanning.

<u>Collision Avoidance Radar:</u>

An application of basic antenna array with a tapered aperture for side-lobe control is in collision avoidance radar system for Army vehicles [10]. The requirements call for a broad beam (around 35 degrees) in azimuth and elevation for the transmit antenna and a narrow beam that scans in azimuth within certain view angle (around 30 degrees) for the receive antenna. The receive azimuth beam width is around 2 degrees, with side-lobe levels of 40 dB below peak. Elevation beam width is around 35 degrees. No electronic scanning is required in the individual array. However, individual arrays would be stacked and bore-sighted at 2-degree angle intervals in azimuth. The scanning is then achieved by switching the output of the receive array at the required scanning speed in the 2-degree steps. The array configuration is sketched in Figure 15. The pyramidal horn array is fed with a waveguide power divider that is designed to produce the required aperture taper in the horn array [11]. The tapered power distribution as simulated using the FEM-based software package HFSS is shown in Figure 16. One of the challenges in this design is fabrication accuracy needed at the operating frequency of 76 GHz. The horn array and its waveguide feed network are integrated and cut in two blocks as shown in Figure 17. The measured and simulated radiation patters compare favorably and are shown in Figure 18.

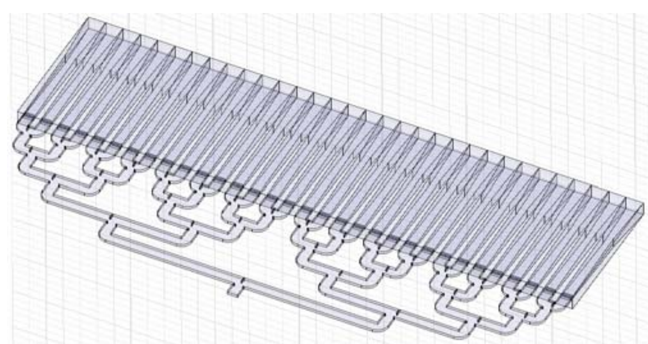


Fig. 15. Horn array configuration with feeding waveguide power divining network.

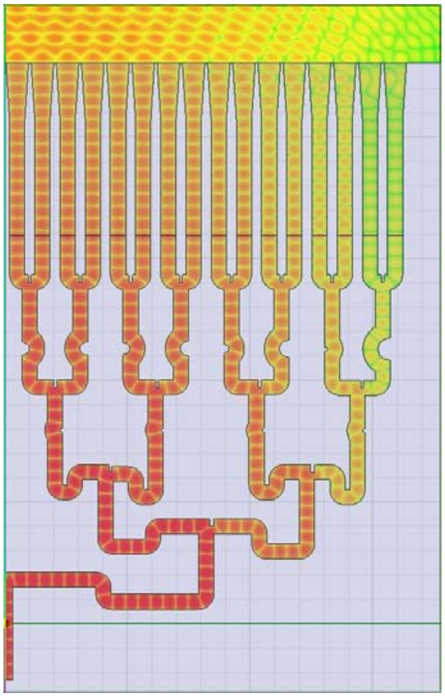


Fig. 16. HFSS model of the tapered aperture as produced by the waveguide power dividing network.

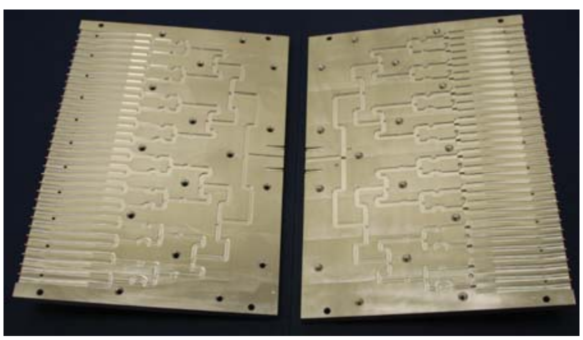


Fig. 17. Fabricated 76-GHz array.

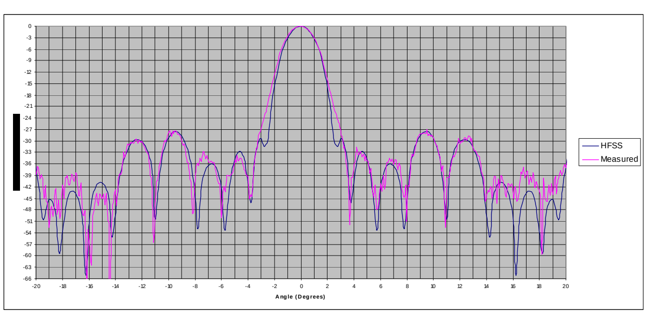


Fig. 18. Modeled and measured radiation patterns of tapered horn array.

Metamaterial Issues:

Metamaterial applications to military antenna systems have picked up considerable interest lately. The primary promise of this technology is the reduction in the antenna size without sacrificing its performance. One of the controversial issues associated with metamaterials is the realization of negative refractive index (NRI) in the medium. This results from dual negative constitutive parameters, which may be realized using a combination of split ring resonators, or capacitively loaded loops, for negative permeability, and conducting poles for negative permittivity. An HFSS simulation and corresponding fabrication of such a medium were the subject of an experiment conducted at the Army Research Lab to show the refractive focusing, or lens, that results from a dual negative medium [12, 13]. Figure 19 shows the parallel-plate configuration where a metamaterial slab is placed between a source (probe # 1) and three receivers at equi-distances from the source. Probe # 2 is centered in the receiving region, while probe # 3 designates any of the other two probes on the side. Without the metamaterial slab, transmission coefficients from probes 1 to 2 and from probes 1 to 3 are very close as shown in the HFSS simulated results in Figure 20(a). The insertion of the metamaterial slab causes negative refractions that result in focusing of the energy in the center probe # 2, with lower levels detected at probe # 3 as shown in Figure 20(b). Simulated results were verified experimentally [13].

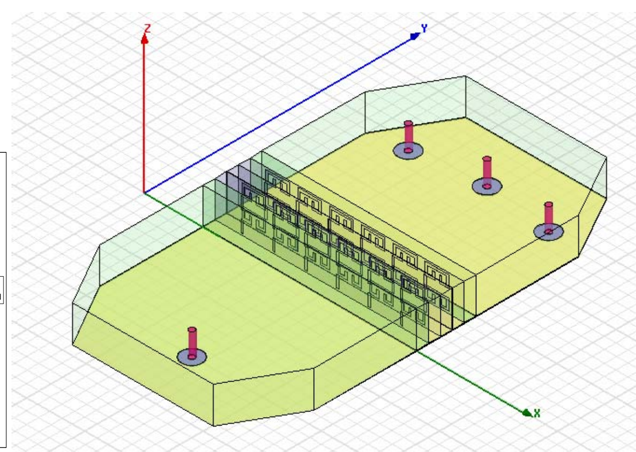
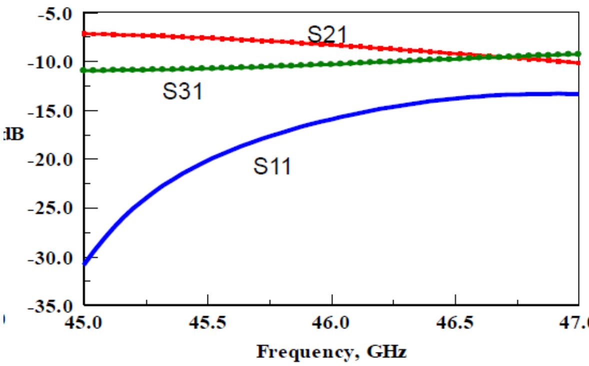
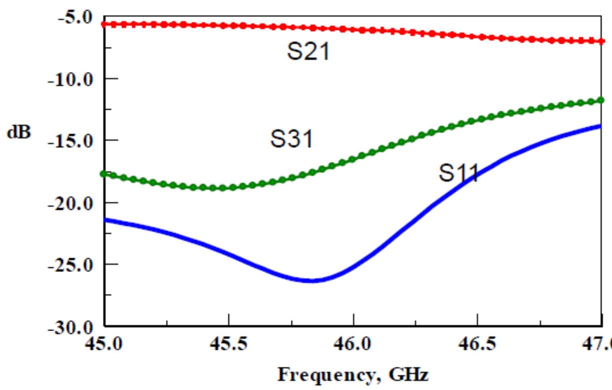


Fig. 19. Negative refractive index (NRI) block in parallel plate waveguide structure.



(a)



(b)

Fig. 20. S-parameters for the parallel plate structure (a) without and (b) with NRI block.

V. CONCLUSIONS

Antenna development for military applications is a collaborative process that involves government laboratories, universities and industry. Antennas have to be designed with the platform and environment in mind. This makes in-situ antenna designs and analyses essential to successful development. Antenna modeling is usually a trade-off between time and cost for a required accuracy. New simulation tools are still needed for new frontiers, such as metamaterials and nano-designs.

Examples of designs that were performed at the US Army Research Laboratory covered different technologies in waveguide and printed circuit media. Fully integrated, adaptive designs have been at the forefront of such antenna research and development. The basic goals of the designs continue to be wideband, low profile, high efficiency, polarization diversity and low cost.

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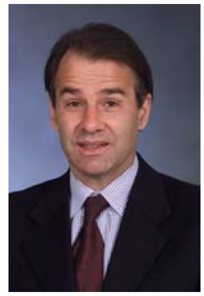

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