

# BALLISTIC RADOMES FOR COMMUNICATIONS ANTENNAS

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## ABSTRACT

The Army Digitized Force requires a robust communications infrastructure for its superior IT/C4ISR (Information Technologies / Command, Control, Communications, Computers, Intelligence, Surveillance, and Reconnaissance). It will lose its cohesion and combat effectiveness with the loss of communications connectivity. Ballistic radomes protecting communications antennas will increase the survivability, and maintain the lethality of combat platforms. Legacy antennas on combat platforms are vulnerable to small arms fires and munitions fragments. Antennas on platform with active threat protection system have the added threat from the munitions fragments generated by the system that can shoot down and pre-detonate incoming warheads. Current radomes do not protect the antenna from these threats, as they are usually thin-walled composite structures to minimize RF transmission loss. In this effort, a combined ballistic and electromagnetic design and testing methodology has been formulated to develop radomes capable of providing ballistic protection to the antenna system with low RF loss. Technologies developed is applicable to frequencies from 225 MHz up to 45.5 GHz, with specific receive and transmit bands, for dish, phased array and other types of low profile antenna systems. Results to date have demonstrated the potential for efficient radome designs (less than 1 dB transmission loss), while meeting ballistic requirements using multi-layer thick-section sandwich constructions. Non-traditional radome materials (ballistic fibers with thermoplastic matrices) are evaluated; where as thick radomes with traditional materials (Quartz/Cyanate Ester) would be cost prohibitive.

## 1. INTRODUCTION

Current radomes for dish, phased array and other types of low profile antennas mounted on vehicles are vulnerable. Conventional radomes are typically thin-walled composite structures. The reinforcing fiber, polymer matrix and sandwich core are all selected to

provide the lowest possible transmission loss, while providing enough structural performance to meet the expected load profile, whether it is an air, sea or ground system. Materials of choice are typically Quartz fiber for the reinforcement and Cyanate Esters for the polymer matrix, especially at higher frequencies ( $> 10$  GHz). Penetration of the radome results in reduced antenna efficiency and/or complete destruction of the antenna due to physical damage. The challenge is to develop radomes with ballistic protection with reasonable cost, size and weight. Future requirements may also include blast protection.

These radomes will be utilized on antennas for Satellite Communications (SATCOM) for the Warfighter Information Network-Tactical (WIN-T) program and line of sight communication antennas for Future Combat Systems program. The on-the-move SATCOM antennas are for high data rate communications between dispersed on-the-move vehicles. The line of sight communication antennas will allow for high speed networking between co-located FCS assemblages while on-the-move.

## 2. BACKGROUND

The Army Tactical Network and Communications Antennas (TNCA) Army Technology Objective (ATO) is for the development of antenna systems with improved combat survivability. Funded research and development includes projects on low-profile multi-band antennas and initial investigation into low-cost ballistic radomes. The low-profile multi-band antennas reduce the visual signature of the vehicle platform with smaller antennas and reduce the number of antennas. Command vehicles with these low profile antennas will be more difficult to be identified in a convoy by the enemy.

The size of legacy terrestrial and SATCOM antennas made their ballistic protection impractical. Only with the successful development of low-profile antennas (Figure 1) does it become possible to provide ballistic protection to antennas. The TNCA ATO investigation into a low-cost ballistic radome for a

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terrestrial antenna had limited success. Radomes made of layers of Kevlar fibers, with consideration of size, weight, and internal stand-off distance to the antenna elements, exhibited too much displacement/flexing after ballistic impact and damaged the antenna elements.



Figure 1 Example Vehicle Mounted SATCOM Dish Antenna System with Non-Ballistic Radome

General requirements for radomes capable of ballistic protection include minimal RF transmission loss, ability to withstand standard environmental conditions, vehicle mobility loads and costs. Ballistic protection requirements range from NIJ III to NIJ IIIA, with additional requirements on backface deflection (must not damage antenna). Consequently, the radome must not only be able to stop the projectile, but also be stiff enough to minimize deflection. This requirement reduces the ability to use material deflection as an energy absorbing mechanism.

The main scientific barrier is the need to reconcile the low areal density requirement from an electromagnetic perspective with the high areal density requirement from energy absorption perspective. This is compounded by the need to use low loss, low dielectric constant materials for the SATCOM antennas due to their higher frequencies of operation and the need to minimize material deflection while stopping the projectile. Our approach is to identify suitable materials with appropriate properties and exploit geometry to achieve the desired multifunctional performance.

### 3. MATERIALS SELECTION

Initial efforts focused on the selection of fibers and resins that have the potential to meet both energy absorption and dielectric requirements. Composite materials were fabricated from selected fiber/resin combinations and characterized for both energy

absorption capability and high frequency dielectric properties. Candidate materials were selected based on combined energy absorption and dielectric performance. In parallel, electromagnetic simulations were performed for radome design to evaluate the candidate materials.

#### 3.1 Candidate Fibers and Polymers

Potential fibers are documented in Tables 1 and 2 below, along with the relevant properties for ballistic and electromagnetic performance.

Table 1 Mechanical Properties of Candidate Fibers

Fiber Type	Density (g/cc)	Tensile Strength (MPa)	Elongation (%)	Cost (\$/lb)
A	2.58	3445	4.8	~1
B	2.46	4890	5.7	~7
C	2.15	6000	7.7	>100
D	1.47	3120	3.3	~10
E	1.44	3410	6.4	~35
F	0.97	3000	3.0	~24

Table 2 Dielectric Properties of Fibers (@10 GHz)

Fiber Type	Density (g/cc)	Dielectric Constant	Dielectric Loss
A	2.58	6.1	0.004
B	2.46	5.21	0.006
C	2.15	3.78	0.0002
D	1.47	3.85	0.01
E	1.44	3.85	0.01
F	0.97	2.3	0.0004

Based on the properties listed, Fiber B and F provide the best combination of mechanical, dielectric properties and cost. While Fiber E has good mechanical properties, its dielectric loss is comparatively high. This limits its use to low frequency radomes. Consequently Fibers B, E, and F are candidates for ballistic radomes.

#### 3.2 Energy Absorption Characterization

Rather than perform a number of ballistic tests of various materials, the energy absorption capability of the candidate materials was quantified using the Mini Quasi-Static Punch Shear Test (Gama et al, 2003; Gama et al, 2005). This method provides a penetration resistance curve which can be used rank a materials' ballistic penetration resistance capability.

The test fixture (Figure 2) allows using right circular cylindrical specimens of diameter of 25.4-mm and thickness from sub-millimeter to 15-mm. A circular cylinder punch of diameter 6.299-mm is designed with a 12.7-mm punch head. Right circular cylinder supports with variable support span diameter allow us to conduct the punch shear experiment at variable support to punch diameter ratios (SPR) in the range  $0 < SPR < 2.0$ . The

step cylinder design of the cover plate allows clamping of the specimen at a predefined load level. An Instron 4484 loading frame with a 133-kN (30 kips) load cell is used in the quasi-static tests. Displacement control tests are performed at a cross-head displacement rate of 1.27-mm/min for SPR 1.0, 1.5, and 2.0 tests and a rate of 0.508-mm/min for SPR 0.0 tests. The load and cross-head displacement data are acquired using the Instron Series IX software. All specimens were surface ground to the desired thickness and then core drilled using a water cooled drill press. Punch shear damage for SPR greater than 0.0 shows a number of damage modes which can be grouped as a function of displacements as (a) Initial Damage (ID), (b) Compression-Shear (CS) Damage and (c) Tension-Shear (TS) Damage. Figure 3 shows the identification of these energy absorbing damage mechanisms. Data reduction method details have been previously published.

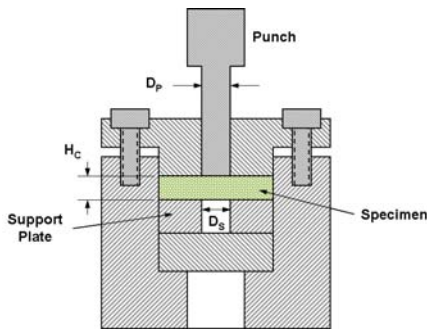


Figure 2 Schematic of the Quasi-Static Punch Shear Test Method

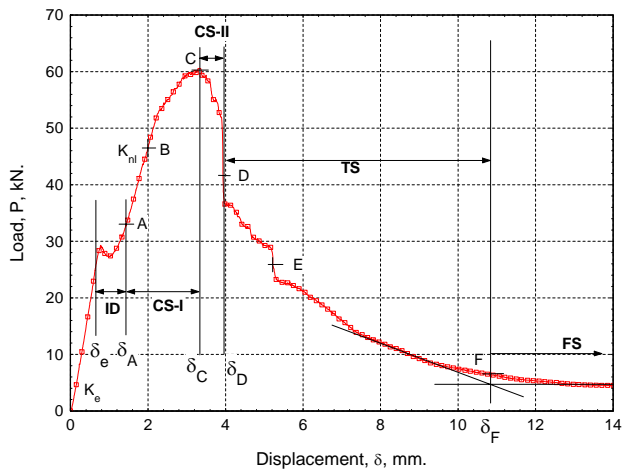


Figure 3 Identification of Energy Absorbing Damage Mechanisms

Selected composite materials made from fibers listed in Table 2 were evaluated using this method to calculate the total energy absorbed per unit areal density. Figure 4 shows preliminary results for energy absorption capability. Assessments of some of the materials are in progress and are a challenge due to the difficulty in

preparing clean samples. This reinforces our previous assessment that the systems of Fiber B in thermoplastic and Fiber F in a proprietary resin are the best candidates for energy absorbing radomes.

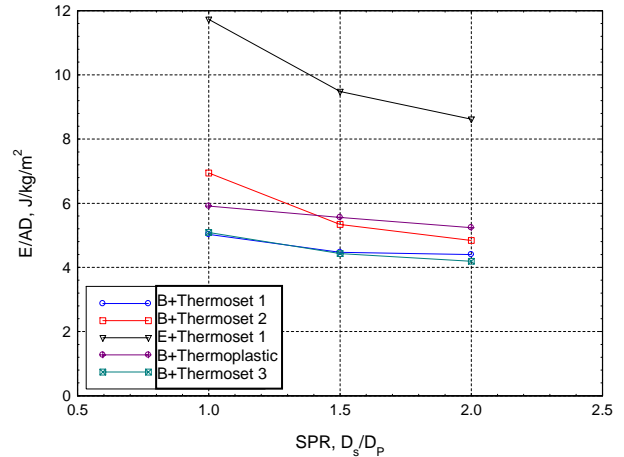


Figure 4 Relative Ranking of Energy absorption per unit Areal Density for various Fiber/resin combinations

### 3.2 Dielectric Property Characterization

In conventional non-ballistic radomes, typical resins used are Cyanate Esters (especially at high frequencies), primarily for its low dielectric loss characteristics. However, Cyanate Esters are generally poor ballistic resins due to their low elongation and strength and are also very expensive.

Standard resin systems used in ballistic applications are generally thermosets, which also tend to have relatively high dielectric loss factors. Thermoplastics are inherently tougher polymers compared to thermosets and are also good candidates for ballistic applications.

Fiber/resin combinations were fabricated for measurement of high frequency dielectric properties, in the range 15 – 20 GHz, using a cavity based method. Measurements of the various composite materials are listed in Table 3.

Table 3 Measured Dielectric Properties of Potential Energy Absorbing Radome Materials (16-20 GHz)

Composite Material	Dielectric Constant	Dielectric Loss
B + Thermoset 2	4.14	0.04
B + Thermoset 1	4.21	0.03
B + Thermoplastic	4.02	0.014
E + Thermoset 1	3.75	0.07
E + Thermoplastic	3.5	0.07

Additional materials testing and measurements are ongoing to develop improved solutions. Based on measurements to date, fiber B with a thermoplastic

polymer provides a good balance between energy absorption and dielectric properties.

#### 4. RADOME DESIGN

Using the materials selected above, designs for ballistic energy-absorbing radomes were developed. Conventional design process involves minimizing material thicknesses to reduce transmission loss and this can result in either monolithic or sandwich designs. Radome design was performed by evaluating monolithic and sandwich constructions of the selected materials. A simple multi-layered radome simulation code was developed for this purpose, which can predict the transmission loss for a specified multi-layer sandwich construction. The inputs to the code are:

- Frequency list
- Angles of incidence
- Number of layers
- Layer thickness
- Layer dielectric constant
- Layer dielectric loss

Outputs are the transmission and reflection for TE & TM waves (which are the same if angle of incidence is 0).

A Genetic Algorithm based optimization scheme was used to identify potential solutions for further analysis.

##### 4.1 Low-Frequency Radome

The low-frequency radome covers a 2:1 bandwidth at L-band, and is being designed to protect a low-profile communications antenna. A model of the radome design is shown in Figure 5.

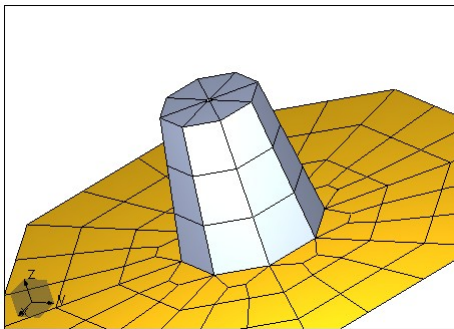


Figure 5. Low-frequency radome design

This radome is about 12 inches tall, and 12 inches in diameter at the base. It is being designed to be mounted to an armored vehicle, though it is shown on a 42-inch diameter ground plane in Figure 5. It will be constructed from Material 4 from Figure 4.

RF performance has been optimized by genetic algorithm to minimize degradation of the pattern or impedance. The predicted VSWR of the antenna rose

from 1.5:1 in free space to 2.2:1 underneath the radome, still below the specification of 2.5:1, and the pattern was modified to have higher directivity toward the horizon, where more gain is desired.

Loss due to the radome is predicted to be about 12%, or 0.6 dB, and it will be made from Fiber B+thermoplastic resin.

##### 4.2 Ka-band Radome

The Ka-band radome is being designed to cover the Ka SATCOM bands. Current predicted transmission performance is shown in Figure 6.

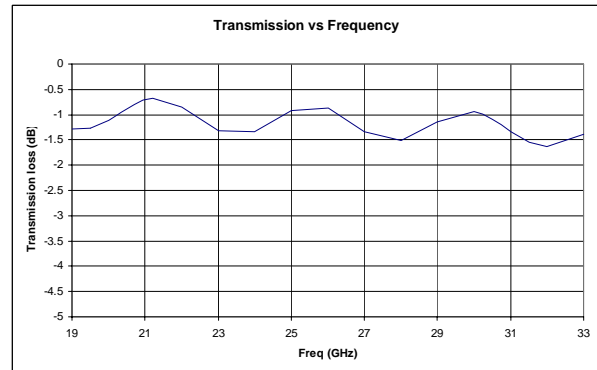


Figure 6. Predicted Ka-band radome RF performance at normal incidence

This radome will be a cylinder about 20 inches in diameter, and about 20 inches tall, made from Fiber F.

#### 5. BALLISTIC PERFORMANCE

Flat 2 ft x 2 ft panels were fabricated for the materials selected to evaluate ballistic performance at NIJ III and NIJ IIIA levels. While standard V50 tests were performed to evaluate the ballistic efficiency of these materials, it should be noted that the ultimate requirement is by necessity a V0 requirement (no penetration), with a maximum backface deflection requirement.

At the NIJ IIIA level, a ballistic solution in the 3-4 psf range for Fiber B + thermoplastic system is sufficient to meet the standard V50 requirement, with the upper range suitable to meet V0. While static after impact deflection of the backface appears to be within permissible limits, dynamic backface deflection measurements are ongoing and may require further increase in areal density to achieve the desired goals. Simulations have shown that the transmission loss at the high end of the areal density range are ~0.6 dB, which is well within the required limit of 1.5 dB. At the NIJ III level, the proposed solution is in the range of 4-5 psf for Fiber F + resin, with ongoing work on evaluating the dynamic deflection.

## 6. CONCLUSIONS

Multifunctional radomes that can provide both electromagnetic performance and energy absorption are desirable for the next generation antenna systems. Energy absorption requirements are driven by the need to protect the antenna system from small arms fire, fragments from IED's and backwash of active protection systems. In addition, radomes are uniquely different from standard armor due to the need to provide complete protection (V0 capability) with minimal dynamic deflection of the radome (to prevent damage to antenna).

A methodology involving materials selection, characterization of dielectric properties and energy absorption capability per unit areal density has been developed to screen candidate composite materials that can meet the desired radome requirements. Electromagnetic simulations based on the downselected materials have developed radome designs that can meet both electromagnetic and ballistic performance requirements.

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