Defense Threat Reduction Agency
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TECHNICAL REPORT

DTRA-TR-03-45

Frequency Selective Materials for Control of Radiated Emissions and Interference Suppression, Phase 2

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April 2006

DTRA 01-00-C-0121

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (*Leave blank*)

2. REPORT DATE: April 2006

3. REPORT TYPE AND DATES COVERED: Technical 020701 - 030930

4. TITLE AND SUBTITLE

Frequency Selective Materials for Control of Radiated Emissions and Interference Suppression

5. FUNDING NUMBERS

C - DTRA 01-00-C-0121
PE - 134D
PR - CO
TA – XX
WU - DH01210

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Mission Research Corporation
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3975 Research Blvd.
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8. PERFORMING ORGANIZATION REPORT

MRC-R-DN-3-008

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Defense Threat Reduction Agency
8725 John J. Kingman Road, MSC 6201
Fort Belvoir, VA 22060-6201

NTES/ R. Davis

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

DTRA-TR-03-45

11. SUPPLEMENTARY NOTES

This work was sponsored by the Defense Threat Reduction Agency under RDT&E RMC code B 134D D 3000 CO XX 01210 25904D

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12B. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

A frequency selective surface was applied to a radome mounted inside the aerodynamic radome of a host vehicle. This inner radome then provided very little attenuation to electromagnetic signals in a narrow band and a specific polarization, but effectively blocked signals outside the band or in the cross polarization. Measured results were nearly identical to theoretical predictions.

14. SUBJECT TERMS

Radome
Frequency Selective Surface
Passband

15. NUMBER OF PAGES: 27

16. PRICE CODE

17. SECURITY CLASSIFICATION OF THIS PAGE	18. SECURITY CLASSIFICATION OF REPORT	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Sta. 239-18, 298-102

CONVERSION TABLE

Conversion Factors for U.S. Customary to metric (SI) units of measurement.

MULTIPLY ⟶ BY ⟶ TO GET

TO GET ⟵ BY ⟵ DIVIDE

angstrom	1.000 000 x E -10	meters (m)
atmosphere (normal)	1.013 25 x E +2	kilo pascal (kPa)
bar	1.000 000 x E +2	kilo pascal (kPa)
barn	1.000 000 x E -28	meter^2 (m^2)
British thermal unit (thermochemical)	1.054 350 x E +3	joule (J)
calorie (thermochemical)	4.184 000	joule (J)
cal (thermochemical/cm^2)	4.184 000 x E -2	mega joule/m^2 (MJ/m^2)
curie	3.700 000 x E +1	*giga bacquerel (GBq)
degree (angle)	1.745 329 x E -2	radian (rad)
degree Fahrenheit	$t_k = (t^o f + 459.67)/1.8$	degree kelvin (K)
electron volt	1.602 19 x E -19	joule (J)
erg	1.000 000 x E -7	joule (J)
erg/second	1.000 000 x E -7	watt (W)
foot	3.048 000 x E -1	meter (m)
foot-pound-force	1.355 818	joule (J)
gallon (U.S. liquid)	3.785 412 x E -3	meter^3 (m^3)
inch	2.540 000 x E -2	meter (m)
jerk	1.000 000 x E +9	joule (J)
joule/kilogram (J/kg) radiation dose absorbed	1.000 000	Gray (Gy)
kilotons	4.183	terajoules
kip (1000 lbf)	4.448 222 x E +3	newton (N)
kip/inch^2 (ksi)	6.894 757 x E +3	kilo pascal (kPa)
ktap	1.000 000 x E +2	newton-second/m^2 ($N\text{-}s/m^2$)
micron	1.000 000 x E -6	meter (m)
mil	2.540 000 x E -5	meter (m)
mile (international)	1.609 344 x E +3	meter (m)
ounce	2.834 952 x E -2	kilogram (kg)
pound-force (lbs avoirdupois)	4.448 222	newton (N)
pound-force inch	1.129 848 x E -1	newton-meter (N-m)
pound-force/inch	1.751 268 x E +2	newton/meter (N/m)
pound-force/foot^2	4.788 026 x E -2	kilo pascal (kPa)
pound-force/inch^2 (psi)	6.894 757	kilo pascal (kPa)
pound-mass (lbm avoirdupois)	4.535 924 x E -1	kilogram (kg)
pound-mass-foot^2 (moment of inertia)	4.214 011 x E -2	kilogram-meter^2 ($kg\text{-}m^2$)
pound-mass/foot^3	1.601 846 x E +1	kilogram-meter^3 (kg/m^3)
rad (radiation dose absorbed)	1.000 000 x E -2	**Gray (Gy)
roentgen	2.579 760 x E -4	coulomb/kilogram (C/kg)
shake	1.000 000 x E -8	second (s)
slug	1.459 390 x E +1	kilogram (kg)
torr (mm Hg, 0^0 C)	1.333 22 x E -1	kilo pascal (kPa)

*The bacquerel (Bq) is the SI unit of radioactivity; 1 Bq = 1 event/s.

**The Gray (GY) is the SI unit of absorbed radiation.

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Figures

Section 1
Introduction

The Frequency Selective Radome (FSR) was a one-year period of performance program. Mission Research Corporation (MRC) was instructed to develop a method to map the FSS from the previous program on to a 3D contour, account for an existing reflector system, manufacture and test one radome and iterate if necessary.

Under this effort Mission Research Corporation continued the development of a proof-of-concept FSR performed under Phase 1. This endeavor included replacing an existing radome and fabricating a complex curved FSR. Though this radome was for a particular application, the technologies and processes investigated and validated during this program are quite general and have wide application throughout the DoD community.

It was discovered during the program that the reflector system could be integrated with FSR by changing the FSR elements. This discovery had two key results; 1) it greatly simplified the manufacturing of the FSR, and 2) provided improved system performance.

Several mechanical/manufacturing challenges were also met during this program. The first challenge was finding a low electrical loss, machineable material that was able to have a conductive coating applied to its surface with satisfactory peel strength. MRC examined many materials and coating techniques before deciding on using ULTEM® with 20,000 angstroms of copper vapor deposited on to both the top and bottom surfaces.

The second manufacturing challenge was mapping the Frequency Selective Surface (FSS) circuit to a 3D geometry, and determining how to impose this geometry onto the conductive ULTEM® surface. It was decided to brute force the mapping on to the radome (a tedious job) and the circuit would be milled into both sides of the ULTEM® structure that had been previously milled to the proper contour.

Though some trades needed to be made in the FSS performance due to manufacturing constraints, a successful design was fabricated that met all of the stringent electrical requirements. This design was tested at MRC for transmission performance and at a government test facility against a HPM threat. The radome met all of the requirements.

For this specific application the threat band included all frequencies below 4 GHz and the pass-band was given in X-band. The performance criteria for the radome were as follows:

- Transmission less than –30 dB for all signals below 4 GHz
  - For all polarizations,
  - For all angles of incidence ranging from bore-sight to 80° off-bore-sight,

- Transmission degradation less than -.25 dB at the X-band frequency
  - For a linearly polarized field,
  - For all angles of incidence ranging from bore-sight to 25° off-bore-sight,

The angular dependencies shown above for both the threat- and pass-band were not specified in the original statement of work, but were deduced after inspection of the host body.

Section 2
Radome Panel Design

The phase II panel design required redesign of the Phase I FSS panel for several reasons. First, this radome is a 3D structure, which if made using the same manufacturing process as used in the first phase would be very difficult. Therefore we wanted to change the design to ease manufacturing. This radome also needed to replace the existing internal radome/reflector. For this reason, the reflector portion of the existing radome needed to be accounted for in this design since the phase I proof of concept FSR was fit over the existing radome, and thus did not need to duplicate these same electrical properties. The design trades and processes are described in the subsections below.

- Inclusion of reflector (include X-ray photos of existing inner radome)
- Material Selection
  - Requirements
  - Choices
  - Advantages (no epoxy layers)
- Conductive Plating
  - Conductive paints
  - Plating
  - PVD
- Manufacturing process
  - Mapping
  - Milling
  - Paint (paint in slots, protection of PVD copper)

2.1 Frequency Selective Circuit Design.

As mentioned above, the FSS that was designed in Phase 1 was not practical for the Phase II implementation. This was primarily due to the fact that the Phase II FSR needed to be a one for one replacement of the existing inner radome. This required the FSR to be reflective to one polarization in X-band and transmissive to the opposite polarization in the same band while blocking all out of band energy regardless of polarization. The Phase I radome was transmissive to all polarizations in X-band and thus needed to be redesigned for Phase II.

The first step in redesigning the radome was to change the element used in the FSS circuit. In this case the three-legged elements of Phase I are replaced by linear slot elements. The linear slot elements are transmissive to one polarization at X-band and reflective to the orthogonal polarization, thus satisfying one of the requirements for the Phase II radome design. The linear slot elements have the added advantage of being easier to map onto a 3D surface and easier to manufacture on a 3D surface.

2.2 FSR Material Selection.

Several considerations had to be taken into account when choosing the materials for the Phase II radome. Since the Phase II radome has curvature in both planes, the method of construction used on the Phase I radome was not practical. Thus a new manufacturing process had to be determined which included the selection of new materials. The requirements for the new materials are;

- Is easily machined into complex geometries,
- Has a low loss tangent at X-band,
- Is structural,
- Is amenable to plating, vapor deposition and/or painting,
- Is able to handle reasonable temperature profiles.

Two materials were initially considered Ultem® and Rexolite®. A comparison of these two materials is shown in below:

Table 1. Material Comparison.

Attribute	Ultem®	Rexolite®.
Machinability	Very Good	Very Good
Thermal Stability	Very Good	Very Good
Strength/Fatigue	Very Good	Very Good
Plating	Very Good	Good
Dielectric Constant	3.02	2.9
Loss Tangent	.0015	.0007
Cost	$$	$$$$

Each of these materials is excellent for this application. Ultem® was chosen, in this case, despite having a larger loss tangent, because it showed better adhesion to copper than did Rexolite® and was considerably less expensive.

During the selection process multiple coupons of each material had copper vapor deposited on to them and additional samples were plated. During these tests it was discovered that the plating process was not a adequate for putting conductor onto either of these materials. However, copper was successfully vapor deposited on to each material with Ultem® exhibiting better adhesion properties than Rexolite®. A thickness of at least 20,000 angstroms was required in order to ensure a three skin depth thickness at the operating frequencies. This is unusually thick for the vapor deposition process and can cause localized "mounding" of copper atoms on the surface. The PVD vendor, VaporTech, did an excellent job of controlling this process and provided excellent performance throughout this program.

Multiple coupons were also painted with a silver-based paint. Conductive paints provide the lowest cost solution to applying a conductive material to the Ultem® substrate. Unfortunately, we found that these paints (five types were tested) did not have the necessary conductivity to allow us to meet the in-band transmission loss requirement.

Having determined the circuit element, substrate material, and conductive substrate application process, the complete radome could be designed.

2.3 FSR Design.

Based on our Phase I experience, a bi-planar symmetric hybrid design is needed to achieve the sharp roll-off and scan independent nature required. Although the primary purpose of the radome used in the present application is the shielding of signals below 4 GHz, it was designed as a band-pass, as opposed to band-stop, filter. In this case the radome was designed to pass a narrow band of frequencies in X-band, with -.25 dB or less attenuation. Periodic structures of a band-pass nature are typically designed using slot type elements since they are, at least in principle, transparent at the resonant frequency and opaque above and below.

As stated in Section 2.1, a linear slot array was chosen for this Phase of the program. The remaining design aspect of the FSR is how thick to make the Ultem® substrate that comprises the radome. The thickness of the Ultem® substrate is determined by three factors: 1) Ultem® dielectric constant, 2) phasing between circuit layers and 3) structural needs. Multiple samples of Ultem® were measured at 10 GHz to determine the dielectric constant and loss tangent of the material (results shown in

Table 1). Having established the dielectric constant of the material, this information along with the circuit design, was used in an MRC proprietary optimizer to determine the optimum design based on electrical requirements. The results of this design were then examined for structural stability and manufacturing ease. The resulting design is shown in Figure 1. The predicted performance of this radome is shown in Figure 2. This design meets all of the mechanical requirements of the program and requires no adhesive layers. The absence of adhesive layers is important since these layers are usually responsible for the most transmission loss. For this design the lack of adhesive layers is somewhat offset by replacing the foam spacer of the Phase 1 design with a more lossy material, namely Ultem®. As shown in Figure 2 an insertion loss of approximately 0.25 dB is predicted in-band, with out of band insertion losses greater than 30dB out to a 60°-incidence angle.

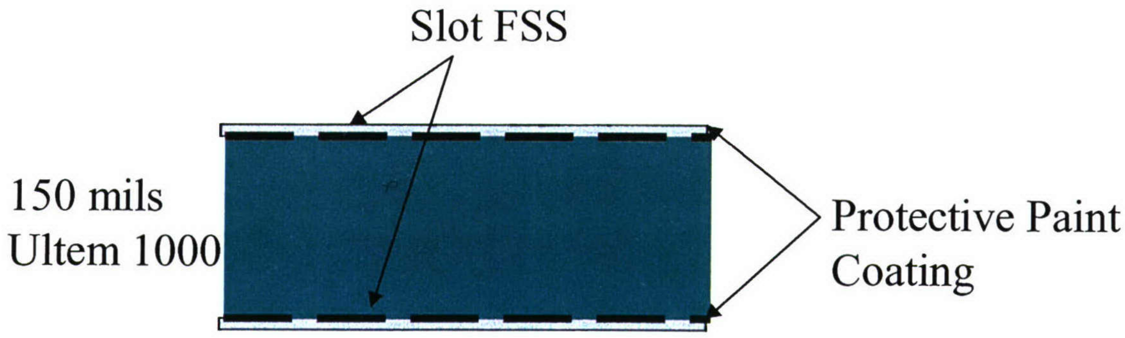

Figure 1. Frequency Selective Radome design.

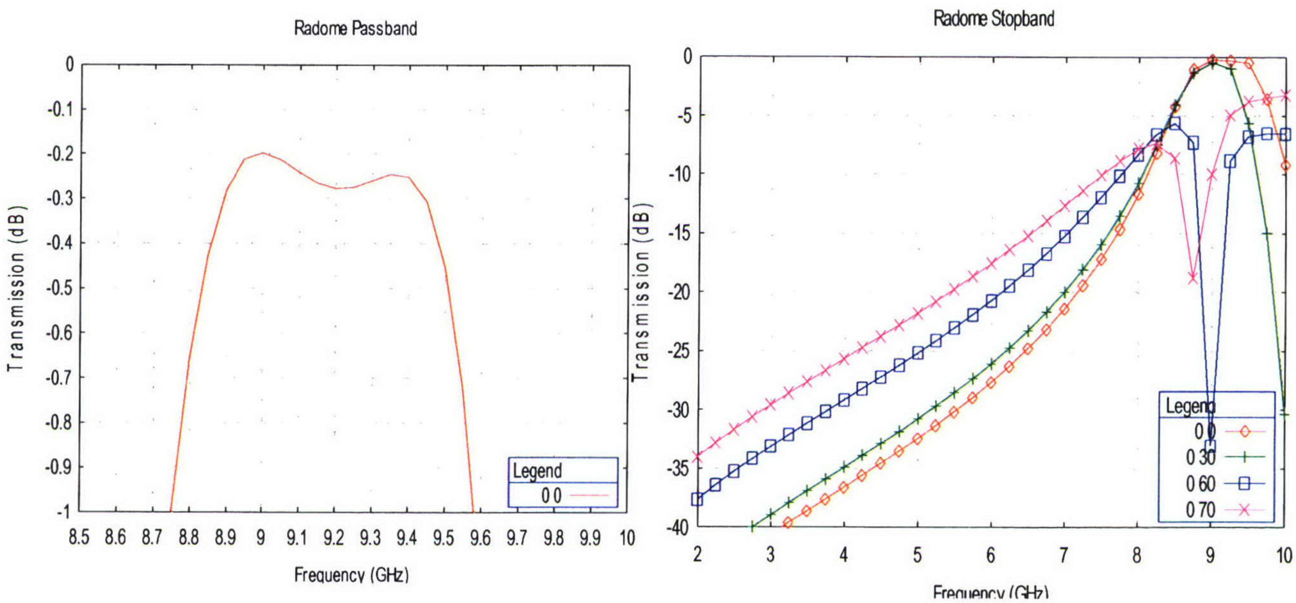

Figure 2. Predicted FSR performance.

Section 3
FSR Manufacture

Before manufacture of the radome could begin, steps to ensure that new radome had the proper geometry (meaning it would fit the existing test fixture) were taken. This first step entailed measuring the existing radome using a coordinate measuring machine (CMM). The CMM is a very accurate, industry-standard method of measuring the physical dimensions of complex geometries. After employing this machine a geometrical representation of the radome was produced using ProEngineer CAD software. Once the CAD model was created it was turned over to the shop for manufacture. In this instance, two separate parts were manufactured the can and the radome. The can is the hallow, aluminum cylinder that supports the radome. The can is mounted to the test fixture by a series of screws space throughout the diameter of the cylinder.

The radome, which is parabolic, is machined from Ultem® with special tabs to aid in the Physical Vapor Deposition (PVD) and machining processes. Verifying the proper contour of the radome and ensuring that the inner surface of the radome was an exact distance from the bottom of the can were critical to the operation of the radome and the system as a whole.

A picture of the machined Ultem□ radome is shown in Figure 3. The complete radome/can assembly is shown in Figure 4.

Figure 3. Ultem® Radome.

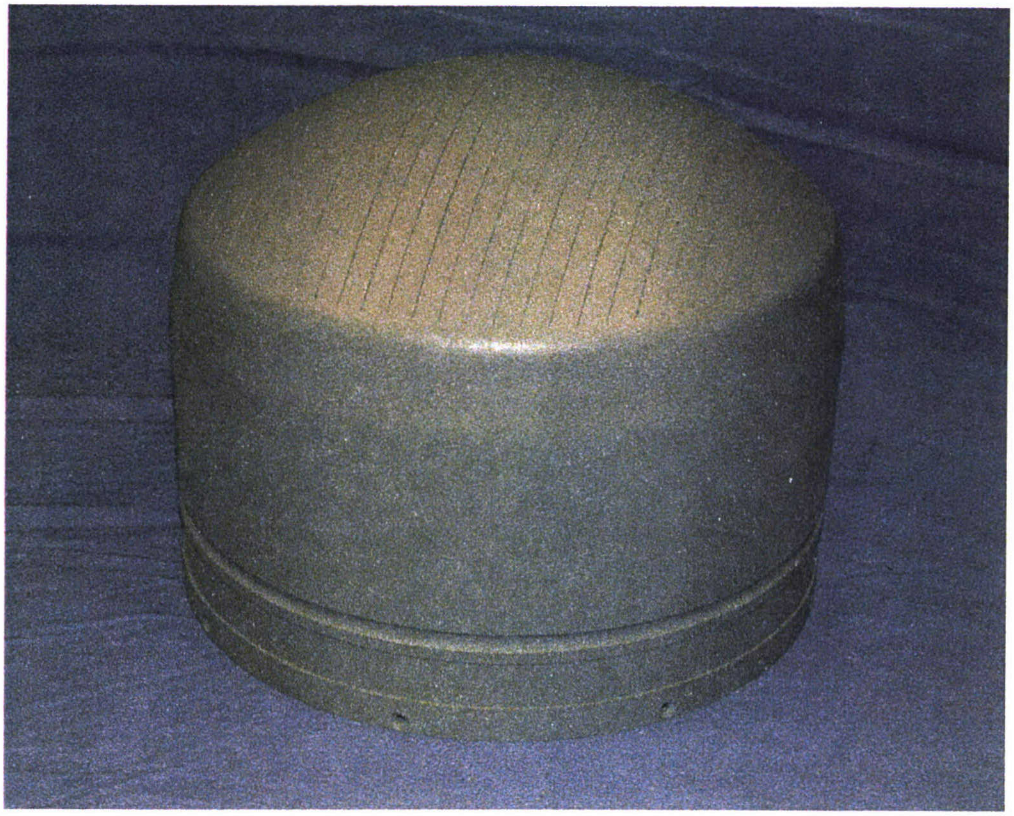

Figure 4. Radome/can assembly.

After the first set of radomes and cans were completed the FSR was fit checked with the test fixture. During the fit check it was noted that can/radome assembly did not properly mate to the test fixture. This was due to the fact that the test fixture and the pre-existing radome were made out of round. The MRC part was not made out of round since only two points on the diameter were measured by the CMM. . The pre-existing radome was re-measured on the CMM using multiple points around the diameter to identify the out of round condition. After this measurement the can was modified and a second fit check was performed successfully. The complete system (outer radome, inner radome/can assembly and test fixture) is shown in Figure 5.

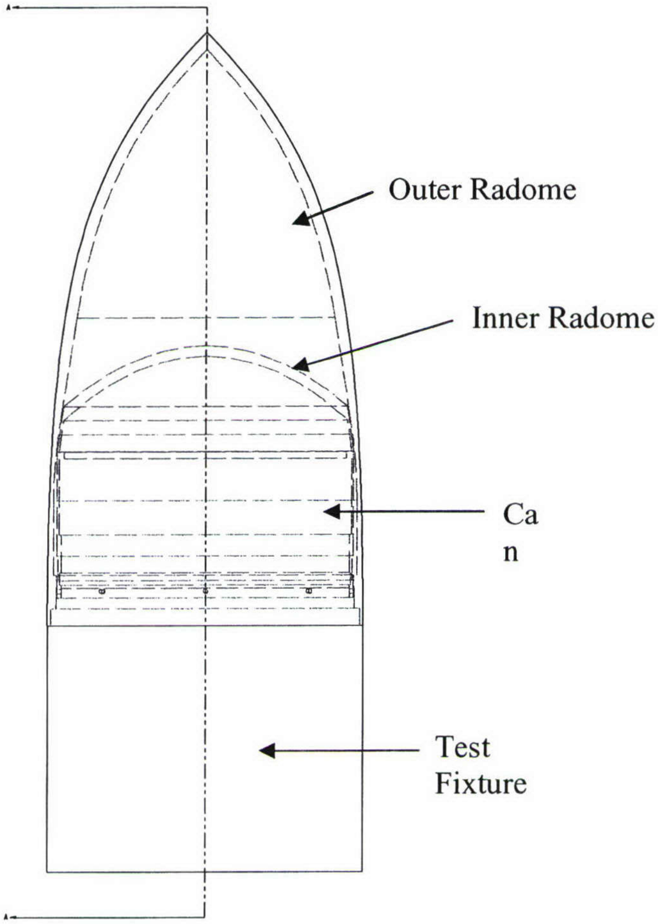

Figure 5. Radome/Test Fixture cross section.

Having resolved the manufacturing issues associated with the radome geometry, our attentions turned to issues of manufacturing the FSR. The remaining manufacture issues to be solved were mainly associated with the mapping of the FSS geometry onto the 3D curved surface, vapor depositing copper on to both sides of the radome, and machining the FSS into the radome.

3.1 FSS Geometry Mapping.

The difficulty in mapping an FSS geometry to a 3D surface is the standard complication of designing a planar (2D) geometry to a complex surface. In going from a 2-D to 3-D geometry the geometrical relationships as a whole become distorted (depending upon the severity of the 3-D curvature). As such, the geometrical relationships between the FSS elements will become distorted to some degree or another, manifesting itself in a slight change of electrical properties. An added difficulty is the fact that this is a two-layered FSS, which brings in the issue of FSS alignment between circuit layers.

The three main techniques possible are 1) brute force technique in which every element on each surface is individually aligned, 2) a Z-normal mapping technique in which the planar design is vertically mapped on to the curved surface and, 3) a hybrid combination of 1 and 2.

Due to the success of the brute-force method and the limit in funds, only the brute force method was examined during this effort. In determining how best to map the FSS circuit onto a 3D surface a number of experiments were performed. The results of these experiments led us to several conclusions.

- the length of the slot element is the most critical factor to maintain,
- the end to end spacing between the elements is the next critical factor to maintain,
- the side to side spacing of the elements was not critical for this design,
- alignment between the two FSS layers is not critical, other than having the same orientation.

With these findings in hand the FSS circuit was mapped onto both sides of the radome and machine code was written so the elements could be milled out of the copper on the radome.

3.2 Vapor Deposition.

Mission Research Corporation subcontracted to VaporTech Inc. in Boulder, Colorado to perform the PVD of the Ultem® radome. In developing the radome the PVD process had to be accounted in the radome design and processing. Initially the radome was machined with a ring that was used to hold the part during the PVD process.

In order to meet the necessary skin depth requirements 20,000 angstroms of copper needed to be deposited onto the radome. This is much thicker than normally required for the plating process. Typical depositions are a few hundred angstroms. The reason for the required thickness was to prevent energy at the threat frequencies to penetrate the copper layer. This effect was verified by transmission measurements during early examination of the vapor deposition process. In early measurements in which samples were deposited with 300 angstroms of copper, the energy passed through the board with very little degradation.

Depositing large amounts of copper on both sides of the radome had an additional problem typically described as "blow-over". Blow-over is copper that is intended to be deposited on one side of the material blowing over and adhering to the backside of the material. Since both sides were being deposited blow over was not an issue for this effort, though masking may be required for one-sided efforts. Thus, the only possible impact of blow-over for this program was the aesthetics of the PVD part. Blow-over has absolutely no practical impact on the operation of this radome.

3.3 Manufacturing the FSS.

Having mapped the FSS circuit and deposited the radome with copper, the FSS was ready to be machined on to the radome. Milling the copper off the radome presented some issues. The first issue was due to the fact that a 3-axis milling machine was used opposed to a 5-axis milling machine. A 5-axis milling machine would allow the mill to machine the slot normal to the surface of the radome. The 3-axis machine required the mill to cut the slots normal to the z-axis. This presented a problem as to how the FSS circuit was going to be mapped on to the surface of the radome. For a 5-axis machine the mill is always normal to the slot, thus accurate slot lengths and depths can be maintained over the entire radome surface. For the 3-axis machine, milling the ends of the slots is problematic, since the closer the mill gets to the edges of the radome, more material is left in slot. An illustration of the over-and-under cut caused using a 3-axis mill is shown in Figure 6. The over-and-under cut was accounted for when the circuit was mapped on to the 3D surface. The adjustments made were verified by testing of flat panels.

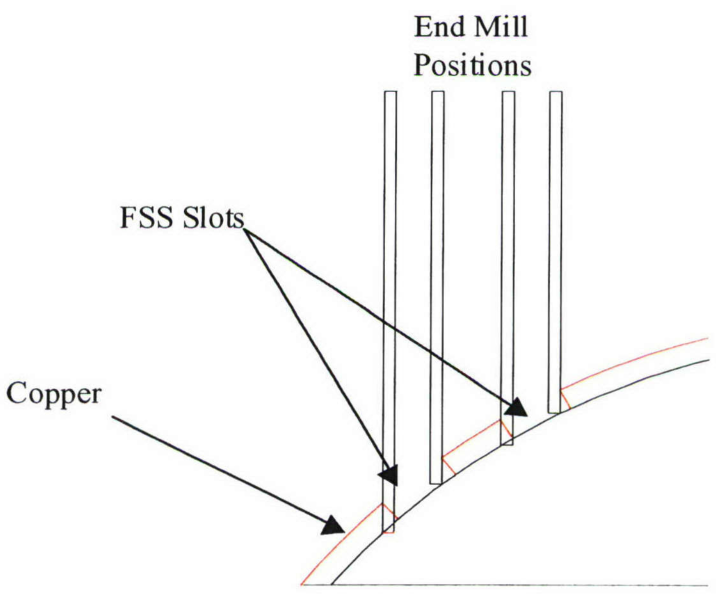

Figure 6. Three-axis mill over- and under-cut.

During the testing of the flat panels an unexpected result was found. It was found that the amount of radome material removed from the slot (along with the copper) impacted the resonant frequency of the slot. This caused a redesign of the slot FSS to account for this phenomenon. The removal of material also had to be accounted for in the mapping process. The frequency shift due to material removal is apparent when comparing Figure 7 with Figure 8.

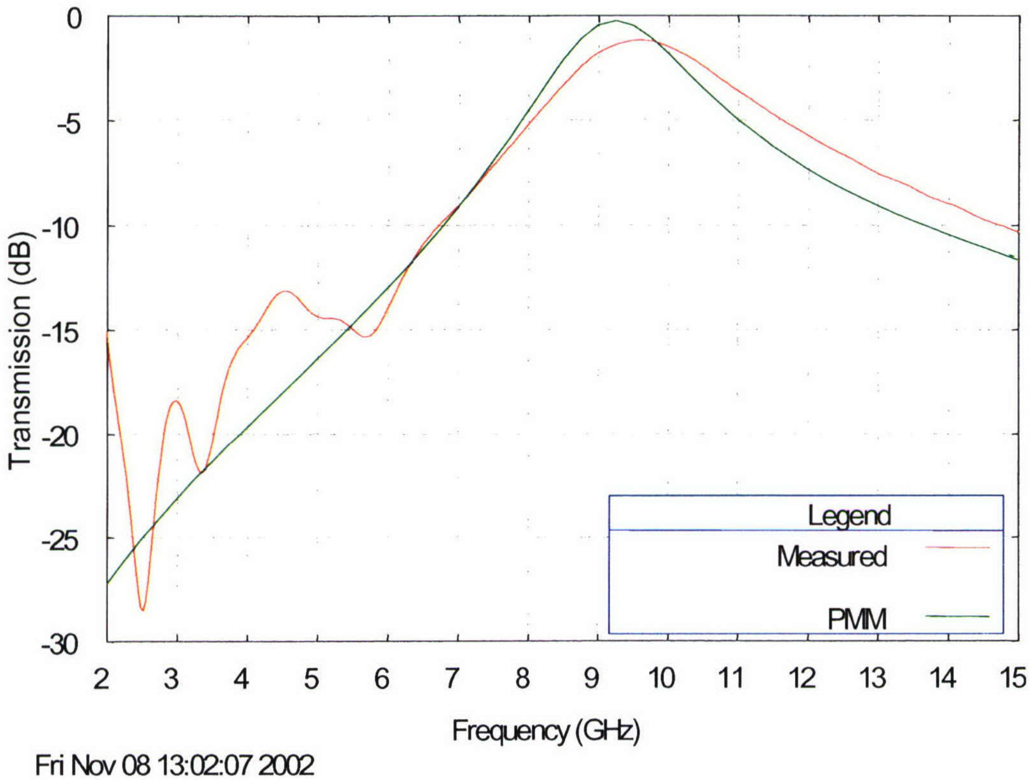

Figure 7. Transmission performance vs. prediction with material removed from the slot.

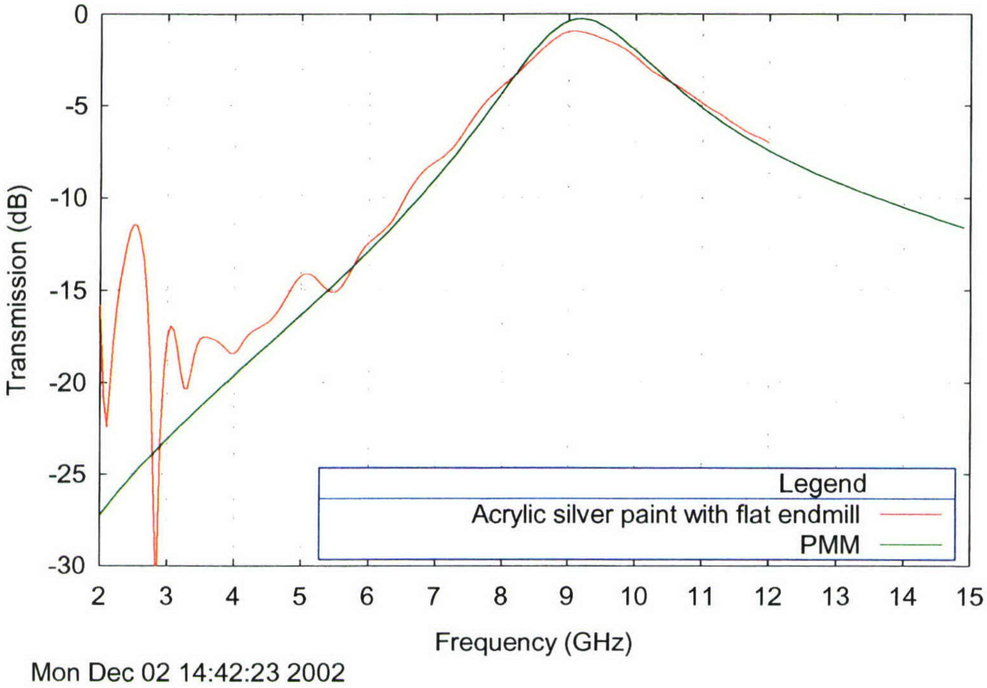

Figure 8. Transmission performance vs. prediction with minimal material removed from the slot.

Section 4
Radome Measurements

The electrical performance of the radome shown in Figure 4 was tested in MRC's microwave laboratory. Tests were performed to determine the transmission performance of the radome and the reflection performance of the radome in-band. The transmission performance of the radome from 8-12 GHz is shown in compared to the PMM prediction. Figure 10 illustrates that the radome meets performance requirements of less than 0.25 dB transmission loss in-band

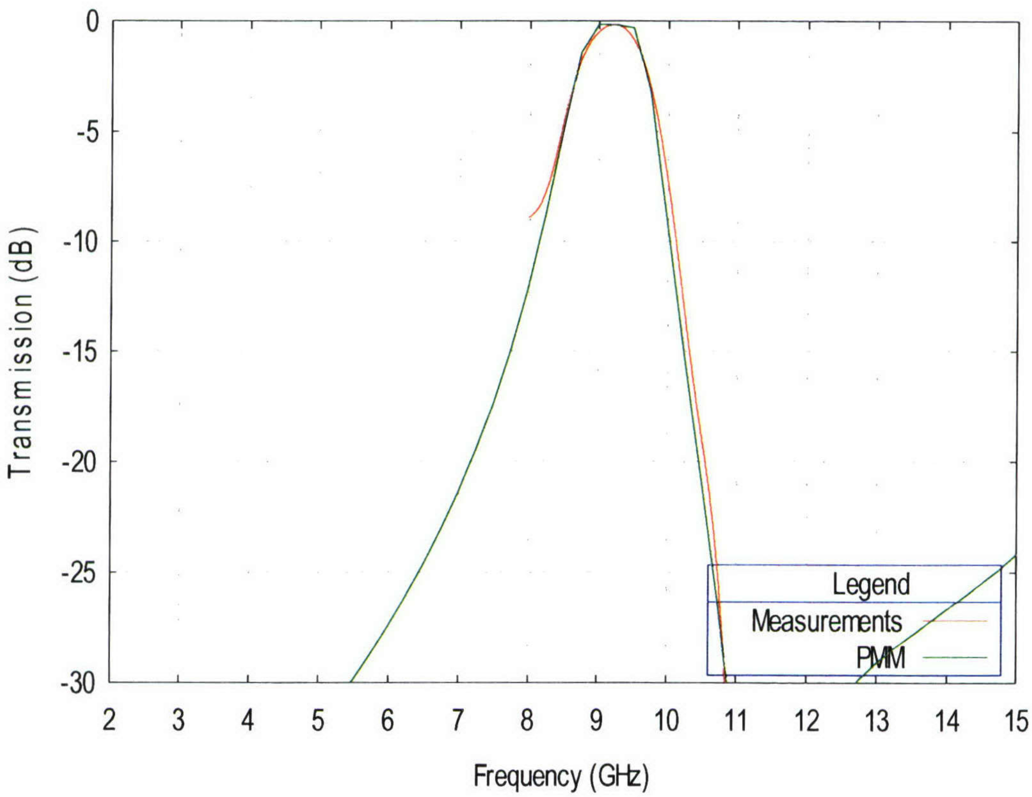

Figure 9. Transmission performance of the radome from 8 –12 GHz compared to prediction.

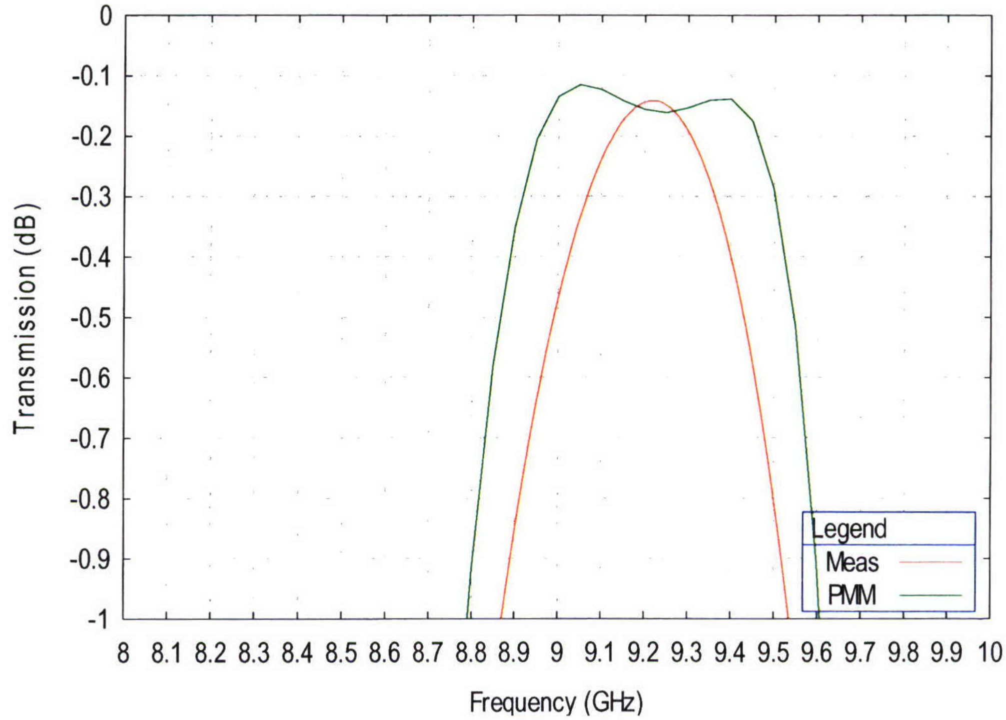

Figure 10. Transmission performance of the radome compared to prediction on an expanded scale.

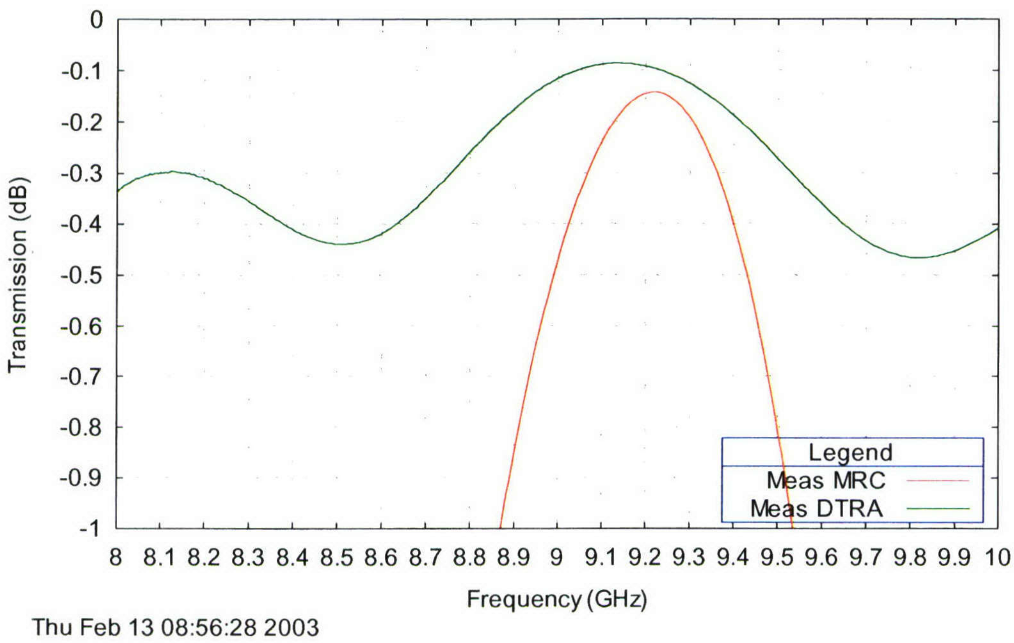

Figure 11. Comparison between the FSR and the existing radome.

Part of the unique requirements of this radome is that it must function as a reflector for one polarization in-band and pass the other polarization. The performance of the MRC radome as a reflector was measured and compared to the existing radome. Figure 12 shows the existing internal radome has a transmission coefficient 15-20 dB down at the frequencies of interest. The MRC radome has a cross-polarized transmission that is in the noise floor of the measurement setup. This is a 5 to 10 dB improvement over the existing radome, which translates into approximately a 0.1-dB improvement of the total system response. This offsets the difference between the radome performances shown in Figure 11. Thus we anticipate that when system tests are performed, the new radome will have no impact on the seeker performance while providing substantial protection against low frequency emitters.

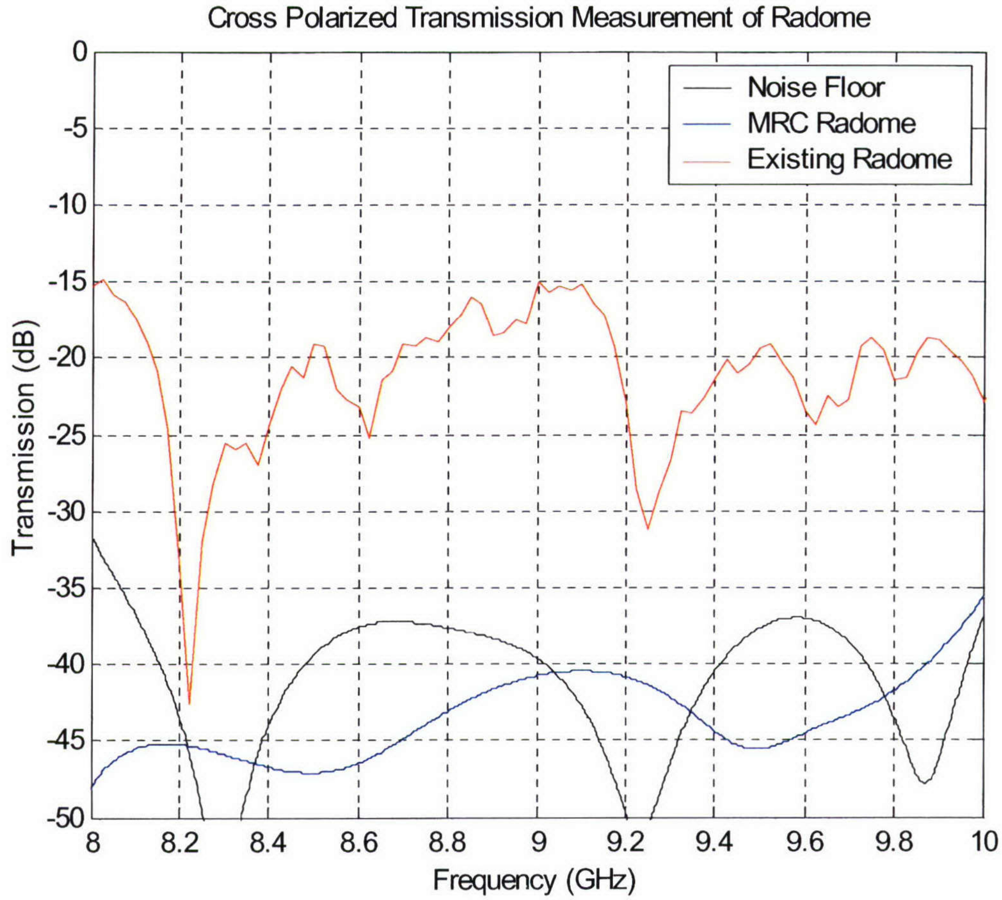

Figure 12. Cross polarized transmission measurements of the MRC, the existing radome and the noise floor.

Section 5
System Measurements

During July and August of 2003 system level tests of the radome were conducted at a government measurement facility. Tests were first conducted on the host-body with the original radome present. These tests determined what incident signal strength was required to adversely effect the tracking mechanism of the host-body. These same tests were next conducted with the radome affixed to the host-body. Test results proved the radome to work as predicted by the computer code PMM. Signals below 4 GHz were effectively blocked by the radome. Another important feature of the radome design was that there was to be no degradation of the host-body's antenna performance. Unfortunately, the tests performed were qualitative, not quantitative in nature. The test facilities could not produce large enough energy densities to show the limits of protection provided by this radome.

Due to the security classification of the tests conducted on the host body with and without the retrofitted radome, a more detailed summary than what is given above cannot be presented in this report. This information may be found in a classified test report written by Dr. Tim Andreadis.

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