SPONSORED PROJECT TERMINATION SHEET

Date: 7/6/83

Project Title: Consulting Services: Radome Considerations

Project No: A-3315

Project Director: J. A. Fuller

Sponsor: MIT-Lincoln Lab.

Effective Termination Date: 10/1/82

Clearance of Accounting Charges: 10/1/82

Grant/Contract Closeout Actions Remaining:

- [ ] Final Invoice and Closing Documents
- [ ] Final Fiscal Report
- [ ] Final Report of Inventions
- [ ] Govt. Property Inventory & Related Certificate
- [ ] Classified Material Certificate
- [ ] Other

Assigned to: ECSL/EED (School/Laboratory)

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EORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

PROJECT ADMINISTRATION DATA SHEET

Project No. A-3315
Project Director: J. A. Fuller

Sponsor: Massachusetts Institute of Technology, Lincoln Laboratory

Type Agreement: Purchase Order No. AX-28380 (under Gov't Prime No. F19628-80-C-0002)
Award Period: From 8/1/82 To 10/1/82 (Performance) 10/1/82 (Reports)
Sponsor Amount: $9,967.00

Contracted through: GTRI/SkX

Title: Consulting Services: Radome Considerations

ADMINISTRATIVE DATA

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Defense Priority Rating: DX-A7, under DPS Reg. 1

Security Classification: N/A

RESTRICTIONS

No Attached N/A Supplemental Information Sheet for Additional Requirements.

Travel: Foreign travel must have prior approval — Contact OCA in each case. Domestic travel requires sponsor approval where total will exceed greater of $500 or 125% of approved proposal budget category.

Equipment: Title vests with N/A

COMMENTS:

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Project File
Library
Other GTRI
RADOME CONSIDERATIONS FOR THE
SUMMER 1982 ENNK SEEKER STUDY

By
J. A. FULLER and G. K. HUDDLESTON

Prepared for
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY
P. O. BOX 73
LEXINGTON, MASSACHUSETTS 02173

CONTRACT NO. F19628-80-C-0002
PURCHASE ORDER NO. AX-28380

1 August through 1 October 1982

GEORGIA INSTITUTE OF TECHNOLOGY
A Unit of the University System of Georgia
Engineering Experiment Station
Atlanta, Georgia 30332
GEORGIA INSTITUTE OF TECHNOLOGY
Engineering Experiment Station
Atlanta, Georgia 30332

RADOME CONSIDERATIONS
for the
Summer 1982 MIT Lincoln Laboratory
ENNK SEEKER STUDY

By
J. A. Fuller and G. K. Huddleston

FINAL REPORT
Prepared under
Prime Contract No. F19628-80-C-0002
Purchase Order No. AX-28380
Georgia Tech Project No. A-3315

For
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Lincoln Laboratory
P. O. Box 73
Lexington, Massachusetts 02173
PREFACE

This report contains the supporting material and results that were presented by Georgia Tech as "Radome Considerations" during the August-September 1982 Endoatmospheric Non-Nuclear Kill (ENNK) Seeker Study. The study was conducted for the Ballistic Missile Defense Advanced Technology Center (BMDATC) by a working group organized by the MIT Lincoln Laboratory. The BMDATC contact was Mr. Joe Butler, and the Lincoln Laboratory coordinator was Dr. Soon Hong. The Georgia Tech project monitor was Dr. James Fuller, in the Engineering Experiment Station (EES), and the analytical radome calculations were performed by Dr. Keith Huddleston, in the School of Electrical Engineering.

The study was organized to address two areas: system requirements, under the direction of Dr. Soon Hong, and seeker design, under the direction of Dr. Roger Sudbury. Radome considerations were addressed as part of the seeker design task. The study was initiated by meetings of the working group at Lincoln Laboratory on 2-3 August 1982, and it was essentially concluded by meetings there on 8, 9, and 10 September. The conclusions were presented to BMDATC by Lincoln Laboratory personnel in subsequent briefings.

The Georgia Tech contributions to the study were briefings to the working group that covered the background of radome development for BMDATC applications and electrical analyses of concepts under consideration. Briefing materials delivered at the time are included in this document with supplementary discussion.

Respectfully submitted,

James A. Fuller
Project Director

Approved:

Charles E. Ryan, Jr.
Chief,
EM Effectiveness Division
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RADOME CONSIDERATIONS
for the
Summer 1982 MIT Lincoln Laboratory
ENNK SEEKER STUDY

I. INTRODUCTION

The Ballistic Missile Defense Advanced Technology Center (BMDATC) is developing technology for a hypersonic interceptor with terminal homing guidance suitable for a non-nuclear warhead. This work is identified as the Endoatmospheric Non-Nuclear Kill (ENNK) Program. A radar seeker based on a Ka-band phased-array antenna is believed to offer the best chance of meeting the requirements for range, angular tracking accuracy, and beam-scan rates. A conformal array is under development as a "technology" program, but a planar array is also a candidate, particularly for near-term applications.

The previous emphasis on the conformal array is based on the possibility of eliminating the need for a large radome shell. Instead, with a conformal array, the individual elements or small groups of elements can be protected by small windows that penetrate the missile skin. However, a lack of proven design techniques makes such an antenna difficult to develop. A review of the technical literature readily shows that the theory of planar arrays is very advanced, while for conformal arrays it is in an early stage of development [1,2]. The advanced state of the planar-array theory is in large measure due to high level of activity that occurred in the late 1960's and early 1970's during development of ground-based radars for BMD systems. For near-term applications, a planar-array antenna development entails significantly less risk than a conformal array. However, radome development for a planar array may introduce considerable risk, depending on several interceptor parameters, particularly velocity and boresight error requirements. BMDATC requested this study to evaluate the potential of a planar-array seeker for satisfying near-term requirements.

The study was organized to answer the following specific questions:

(1) What kind of seeker can be developed with today's components?
(2) Which requirements can be met?
(3) What will be the risks, if the desired development schedule
is two and one-half years?

The scope of the study was defined by the following guidelines:

(1) The tactical application is Option C in the 1982 ENNK Study Report.

(2) The objective of a near-term development is to verify miss-distance predictions at a specified altitude.

(3) The seeker design, includes transmitter, receiver, antenna, radome, and packaging; the signal processor is not included.

(4) Schedule and technology risks are evaluated, but cost is not considered.

To ensure system compatibility and to allow utilization of certain components that are currently under development, the following ground rules were imposed:

(1) The antenna aperture is limited to a twelve-inch diameter.

(2) A Ka-band (frequency = f₀) planar array is used.

(3) A particular new klystron transmitter tube is used.

(4) The seeker must be ready for integration into an experimental interceptor in two and one-half years.

The reporting requirements for the study were interim and final briefings to be presented by Lincoln Laboratory to BMDATC. The principal Georgia Tech contributions to the study were contained in briefings presented on 2 August and 9 September. The briefing charts used are included in this report as Appendices A and B, respectively. Sections II and III present a summary of activities accomplished by Georgia Tech, and Section IV summarizes our conclusions and recommendations.
II. SUMMARY OF ACTIVITIES

The Georgia Tech Project Director, Dr. J. A. Fuller, attended meetings with the Working Group at Lincoln Laboratory on 2-3 August, 12 August, and 8-10 September. Related meetings that involved Georgia Tech were held at Georgia Tech and Electromagnetic Sciences, Inc., on 21 July, at General Electric Co. in Syracuse, New York, on 13 August, at BMDATC in Huntsville, Alabama, on 25-26 August, and at Georgia Tech on 27 August.

The first meeting of the full Working Group was held on 2-3 August. Mr. Butler and Dr. Hong established the background and purpose of the study. The group was organized into sub-groups on "Seeker Requirements" and "Seeker Design." Georgia Tech briefed the Design Group on the general status of the radome problem and on radome-related work being conducted by BMDATC. Copies of the viewgraphs used in the Georgia Tech briefing are included in Appendix A.

The 12 August meeting of the Working Group concentrated heavily on seeker requirements. There was considerable discussion of angle measurement errors, including how boresight-error slope (BSES) is defined and how BSES influences miss-distance. Georgia Tech reported the types of radome structures that were being analyzed for boresight error (BSE) characteristics, as part of the design effort. The Georgia Tech computer code was modified to provide for a planar phased-array antenna, as an alternative to a gimballed, fixed-beam antenna, but calculations of radome errors were barely initiated.

On 13 August, F. Rose, W. Courtney, and J. Fuller, from the Design Group, met with D. Kuhn at General Electric in Syracuse, New York, to discuss the GE concept for a planar array with a metallic radome. Several technical issues associated with angle accuracy and flight duration were discussed, and the potential of the metallic radome was impressive. However, GE projected a minimum two-year development period, without flight qualification, and that clearly exceeded the allowable schedule for the subject program.

On 25-26 August, J. Fuller and G. Huddleston met informally with R. Sudbury to discuss the initial results of the electrical design analysis. This meeting took place in Huntsville, Alabama, in conjunction with a review of the ENNK Radome Program. It was clear from the analyses that
systematic errors associated with an ideal resonant-wall radome could not be reduced to the desired levels, and, therefore, some form of on-board error correction would be necessary. The remaining issue was to what degree could errors be measured and corrected.

During the following two weeks, J. Fuller made several inquiries with regard to the Patriot missile program to determine what degree of error correction is considered practical. These inquiries, which went through BMDATC, the Army Patriot Office, and Raytheon, ultimately led to a helpful discussion with Mr. Mathew Fassett, of Raytheon, on 10 September. Although this was the day after the final meeting of the full Working Group, the essential result was reported immediately to R. Sudbury. Based on experience with Patriot, AMRAAM, and several other error-compensated systems, we would do very well to achieve an effective (error-corrected) slope of one percent. The main limitation is anticipated to be the difficulty of accurately measuring the boresight errors at millimeter-wave frequencies.

On 8-9 September, the Working Group met to review the results of the study and to organize conclusions and recommendations. Copies of the viewgraphs presented by Georgia Tech are included in Appendix B. In addition, Georgia Tech provided two enlarged color photographs of the slip-cast fused silica (SCFS) Patriot radome. It was of interest to the Working Group that the Patriot radome is actually larger than that required for the ENNK system.

On 21 July and 27 August, meetings were arranged in Atlanta at Georgia Tech and at Electromagnetic Sciences, Inc., to discuss ferrite phase-shifter technology. The issues were the current status and size limitations of Ka-band phase shifters. These meetings were attended by R. Sudbury and others from the Design Group.
III. SUMMARY OF RESULTS

The radome configurations considered in the electrical design process were based on preliminary results of a mechanical analysis conducted by MIT Lincoln Laboratory and of an aerodynamic analysis conducted by Coleman Research, Inc. The aerodynamic analysis indicated that two acceptable shapes were a cone with a ten-degree half-angle and a tangent-ogive with a 3:1 fineness ratio. (The tangent-ogive is truncated and joined, where it becomes tangent to a ten-degree cone.) The mechanical analysis indicated that two acceptable radome walls were HPSN, with thickness 0.125 inch, and a silica/alumina (Si/A1) woven composite, with thickness 0.500 inch. The Si/A1 composite, which is being developed by GE Re-Entry Systems Division, has a dielectric constant close to that of SCFS, and SCFS was assumed for purposes of electrical design.

The electrical design effort considered three shapes -- a ten-degree cone, a 3:1 tangent-ogive, and for comparison purposes, a very blunt 1:1 tangent-ogive. The effect of a two-inch diameter metal tip was represented as aperture blockage. The design considered two materials -- HPSN, with a nominal dielectric constant of 8.50, and SCFS, with a dielectric constant of 3:33; in both cases, the loss tangent was assumed to be 0.001. For each shape and each material considered, the wall thickness was chosen to be resonant (i.e., a multiple of a half-wavelength) at the incidence angle corresponding to that of an axial ray passing through the tip of the radome. For HPSN, this nominal wall thickness was two half-wavelengths (e.g., N=2 for a 2-nd order wall), and for SCFS, the nominal thickness was five half-wavelengths (N=5). For the 3:1 ogives, the corresponding wall thicknesses are 0.122 inches in HPSN and 0.540 inches in SCFS.

For each radome configuration, a ray-tracing analysis [3] was used to evaluate the boresight error (BSE), the boresight-error slope (BSES), and the one-way transmission losses (reflection and dissipation) caused by the radome. The antenna was assumed to be vertically polarized, with the E-vector in the pitch plane. Errors were calculated as a function of beam scan angles from zero to sixty degrees in the pitch and yaw planes.

The three shapes of radomes were compared in the HPSN material. For small scan angles, the angle errors increase as the shape becomes more pointed, but there is not much difference between the cone and the 3:1
ogive. For large scan angles, the 3:1 ogive has the smallest angle errors, and the 1:1 ogive has the largest errors. The 1:1 ogive is worse, because the antenna beam intercepts the radome tip, even for wide scan angles. With the cone and the 3:1 ogive, the beam intercepts the tip only for small scan angles. (For this argument, the near-zone "beam" cross-section is assumed to be confined approximately to the projected area of the antenna along the beam-scan direction.) It is clear that the tip region of the radome is the dominant source of angle errors. The small curvature of the 3:1 ogive gives a slight improvement over the cone, but the advantage is not sufficiently significant to affect a decision between shapes.

The HPSN and SCFS materials were compared for the 3:1 ogive shape. The angle errors for the thick wall SCFS radome were worse by approximately a factor of five. Transmission losses for the SCFS radome exceeded 3 dB, while losses were well under 1 dB for the HPSN radome. In both cases, the losses are caused primarily by reflection. There is no reflection from a resonant wall (i.e., a planar wall with plane-wave incidence), but the fifth-order SCFS wall detunes with varying scan angle far more rapidly than the second-order HPSN wall.

The performance of a resonant wall radome varies in approximately the same manner, if the wall thickness is increased by a small amount, X percent, if the frequency is increased by X percent, or if the dielectric constant is increased by 2X percent. The HPSN and SCFS 3:1 ogives were analyzed for the nominal thicknesses and for ±3 percent changes from nominal thicknesses. The results can be used to judge the sensitivity to a ±3 percent variation in frequency or to a ±6 percent variation in dielectric constant. Over a range of 1,200°C, the dielectric constants of HPSN and SCFS both increase by approximately 6 percent. For this change, the angle errors double or triple, and it is clear that if the radome is designed for high-temperature operation, it will exhibit large errors in cold tests. If the antenna can operate over sufficient bandwidth, it should be possible to simulate high-temperature performance by testing above the nominal frequency.

Two modified designs were analyzed as part of a small effort to determine whether the basic resonant wall designs could be improved.

For the HPSN 3:1 ogive, the wall was tapered in a manner designed to keep the thickness resonant near the beam centroid, as the beam scans away.
from the tip. The thickness decreased in proportion to \((K - \sin^2 A_i)^{-\frac{1}{2}}\), where \(K\) is the dielectric constant, and \(A_i\) is the angle of incidence on the radome for a ray drawn in the scan direction from the center of the antenna. This design did not produce any substantial improvement in angle errors; it did give a small reduction in reflection losses at wide scan angles.

For the SCFS 3:1 ogive, a quarter-wave matching layer was included on the inner wall to serve as an impedance-matching transformer. The results indicate that a matching layer can reduce reflection losses in a given scan direction. However, the matching layer does nothing to offset the scan dependence of the resonant wall, and this straightforward design increases the maximum angle errors by more than fifty percent.

The analyses developed for this study are believed to provide a valid electrical comparison of several mechanically acceptable radome structures and to provide reasonable estimates of the angle errors that should be expected. More accurate error estimates could be developed with a surface-integration model for the radome; but such an analysis could not have been completed within the available time, and computer costs would have been far greater. For the electrically large radomes considered here, the ray-tracing model is generally considered to be entirely adequate for preliminary design purposes.
IV. CONCLUSIONS AND RECOMMENDATIONS

This study has indicated that an HPSN cone or 3:1 ogive with a second order wall offers the best mechanical margin and the lowest angle errors. A fifth order Si/Al composite radome has an adequate mechanical margin, but it has angle errors that are worse by a factor of five. Neither material is immediately available. A Si/Al composite radome could possibly be fabricated in one year, and an HPSN radome could be fabricated in two years. There is some risk associated with scaling the HPSN technology to produce large thin shells. The only material that could be considered for a two and one-half year flight schedule is SCFS, but some constraints might be imposed on velocity and/or acceleration. To achieve the projected requirements for angle errors (BSE AND BSES), a substantial amount of error correction will be necessary. Based on experience with error corrections for automatic network analyzers in a laboratory environment, it seems reasonable to expect to reduce errors by a factor of ten. If this is achieved, the HPSN radome is acceptable, and a thick Si/Al composite or a SCFS radome is marginal. In any case, a very substantial effort will be required to develop adequate measurement techniques and error-correction algorithms.

Because the candidate radomes cannot be available for testing during the next year or two, it is recommended that simulations be fabricated for use in developing test methods and for evaluating the ultimate improvements that can be realized by error correction. Aluminum oxide and chemical-vapor-deposited silicon nitride (CVDSN) have dielectric properties much like HPSN, and either material could be made into a full size radome immediately. SCFS has properties like the Si/Al composite, and an SCFS radome could be made immediately.

A major remaining issue is the establishment of a well-founded requirement for angle accuracy. The influence of angle errors on miss-distance is determined using six degree-of-freedom (6-DOF) analytical simulations of missile flights. Requirements should be derived from Monte Carlo simulations that include good estimates for deterministic and random errors in the flight system. The angle accuracy requirements adopted for this study are based on deterministic (linear) BSE characteristic and linear system stability criteria. There is some evidence that this model
over-constrains radome errors [4], but a more comprehensive 6-DOF simulation could not be assembled for this study. Because the very best projected radome performance is marginal, it is recommended that the requirements be re-examined, using a more sophisticated 6-DOF simulation.
V. REFERENCES


WINDOWS AND RADOMES

- EFFECTS ON ANTENNAS -
  - BEAM REFRACTION
  - BEAM DISTORTION
  - IMPEDANCE MISMATCH
  - POLARIZATION MISMATCH
  - SIDELobe DEGRADATION
  - MUTUAL COUPLING CHANGES (CONFORMAL ARRAYS)
WINDOWS AND RADOMES

- ALTERNATIVES -

- CERAMIC
- METALLIC
- ABLATIVE
- STATEMENT OF THE PROBLEM -

Proven Technology for Velocities > Mach 6 Does Not Exist

- REQUIREMENTS -

- MMW Transparency (Insensitive to Temperature)
- Thermal Shock Resistance
- Strength
- Rain Erosion Resistance
- Fabricability
MMW ISSUES: WINDOWS AND RADOMES

- BASELINE MMW REQUIREMENTS -

- Velocity ~ 8,500 fps
  Flight Time ~ 3 sec
  No Nuclear Flash

- Aerodynamic Forces

- Range ~ 12,000 ft.
  Antenna Gain (Size)

- Temperature ~ 1,000° C

- Flexural Strength ~ 40,000 psi

- Monolithic Frusta (13", 10")
  Hot-Pressed Silicon Nitride

- Temperature Limit ~ 1,200° C -
(U) TEMPERATURES THROUGH THE FORWARD ANTENNA WINDOW MATERIAL (HPSN) (WITH ANGLE OF ATTACK MANEUVERS) AT STATION 12

ADVANCED TECHNOLOGY CENTER

Temperature (°C)

Flight Time (sec)

0 0.4 0.8 1.2 1.6 2.0 2.4 2.8 3.2

OUTER SURFACE

INNER SURFACE

HPSN THICKNESS (in)

0.122

0.0976

0.0732

0.0488

0.0244

0
Fineness Ratio = 2:1

λ/4 Matching Layer on Inner Wall

<table>
<thead>
<tr>
<th>AXIAL RADOME COORDINATE (INCHES)</th>
<th>0</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
<th>45</th>
<th>50</th>
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<tbody>
<tr>
<td>RADIAL RADOME COORDINATE (INCHES)</td>
<td>-14</td>
<td>-12</td>
<td>-10</td>
<td>-8</td>
<td>-6</td>
<td>-4</td>
<td>0</td>
<td>4</td>
<td>6</td>
<td>8</td>
<td>10</td>
</tr>
</tbody>
</table>

14°
The graph shows the gain in decibels as a function of gimbal angle in degrees for different configurations:

- HPSN (N=20)
- Silica (N=11)

The graph includes two types of configurations:

- Cone
- Ogive

The gain values range from about -14 dB to 0 dB, and the gimbal angle ranges from 0 to 30 degrees.
## MMW Issues: Windows and Radomes

<table>
<thead>
<tr>
<th>Primary Materials</th>
<th>DIEL.</th>
<th>SHOCK</th>
<th>STGTH.</th>
<th>RAIN</th>
<th>FAB.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Silicon Nitride</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Hot-Pressed (HPSN)</td>
<td>M</td>
<td>G</td>
<td>G</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>- Sintering Aids</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>- Heat Treatments</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- CVD</td>
<td>M</td>
<td>G</td>
<td>G</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>- Reaction-Bonded (RBSN)</td>
<td>M</td>
<td>P</td>
<td>P</td>
<td>P</td>
<td>G</td>
</tr>
<tr>
<td><strong>Fused Silica</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Slip-Cast (SCFS)</td>
<td>G</td>
<td>G</td>
<td>P</td>
<td>P</td>
<td>G</td>
</tr>
<tr>
<td>- Woven Composites (ADL-4DF, AS3DX)</td>
<td>G</td>
<td>G</td>
<td>P</td>
<td>P</td>
<td>P</td>
</tr>
</tbody>
</table>

N.B. Properties for large shapes in Mach 6+ dynamic environment.

- Good (G)
- Marginal (M)
- Poor (P)
### MMW Issues: Windows and Radomes

**Other Materials**

<table>
<thead>
<tr>
<th>Material</th>
<th>Diel.</th>
<th>Shock</th>
<th>Stgth.</th>
<th>Rain</th>
<th>Fab.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Alumina</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Slip-Cast</td>
<td>P</td>
<td>P</td>
<td>M</td>
<td>?</td>
<td>G</td>
</tr>
<tr>
<td>- Woven Composites</td>
<td>(Experimental)</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td><strong>Mixed Oxides</strong></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>(Pyroceram, Rayceram)</td>
<td>P</td>
<td>P</td>
<td>M</td>
<td>P</td>
<td>G</td>
</tr>
<tr>
<td><strong>Beryllia (HP, CVD)</strong></td>
<td>M</td>
<td>M</td>
<td>M</td>
<td>?</td>
<td>M</td>
</tr>
<tr>
<td><strong>Boron Nitride (HP, CVD)</strong></td>
<td>M</td>
<td>G</td>
<td>P</td>
<td>P</td>
<td>P</td>
</tr>
<tr>
<td><strong>Aluminum Nitride (HP, CVD)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
- Silicon Nitride:

- HPSN (Ceradyne, Norton)
  - Sintering aid required
  - Diamond grinding required

- SSN (GE/AMMRC)
  - Large amounts of sintering aids
  - Large amount of shrinkage

- SRBSN (Ford, Airesearch)
  - Good RBSN fab processes
  - No shrinkage in RBSN preform
  - Small sintering shrinkage
MMW ISSUES: WINDOWS AND RADOMES

- ALTERNATIVES FOR IMPROVED PERFORMANCE -

- Material Improvements
- Ablative Coatings
- Coolant Ejection
- Shroud during Boost
- Metal Radome
MMW ISSUES: WINDOWS AND RADOMES

- MATERIAL IMPROVEMENTS -

- Hot-Pressed Nitrides (Si$_3$N$_4, Al N, BN)
  - Heat Treatments
  - Sintering Aids
  - Powder Purity

- CVD Nitrides
  (High Purity Materials)

- Fiber and Filament Composites
  (Silica, Alumina, Boron Nitride)
  - Multidimensional Weaves
  - Filament and Tape Windings
  - Felted-Fiber Reinforcements
Flexural Strength of MgO- and Y$_2$O$_3$-Doped HP-Si$_3$N$_4$ Materials
Flexural Strength of BN-doped HP-Si$_3$N$_4$ Materials.
DIELECTRIC CONSTANT VARIATION AS FUNCTION OF TEMPERATURE

![Graph showing the variation of dielectric constant with temperature for different materials such as CVD Si$_3$N$_4$, HPSN (1% MgO), HPSN (8% Y$_2$O$_3$), and RBSN.](image)

Rockwell International Science Center
MEASURED LOSS TANGENTS OF VARIOUS SILICON NITRIDE SAMPLES

- INTERGRANULAR GLASS
- COMMERCIAL HOT PRESSED SILICON NITRIDE (NC132)
- REACTION BONDED SILICON NITRIDE
- SILICON OXYNITRIDE
- CVD SILICON NITRIDE

TEMPERATURE (°C)

LOSS TANGENT

Rockwell International
Science Center
- PERFORATED METALLIC RADOMES -

(GE TNT Radar)

Issues are Transparency and Angle Errors

- Model as Large, Space-Fed Array
- Achieve Full Element Density with Passive, Low-Cost Elements
- Enables Forward-Looking Active Antenna (Phased or Gimballed)
### WINDOWS AND RADOMES

- **ANTENNA**
  - CONFORMAL ARRAY
  - PLANAR ARRAY
  - GIMBALED ANTENNA

- **WINDOW**
  - CERAMIC: HPSN, SSN, SRBSN
  - METALLIC: HEAT-SINK OR COOL
  - ABLATIVE: DUROID OVER HONEYCOMB SANDWICH

- **OTHER OPTIONS**
  - X METALLIC: MUTUAL COUPLING SENSITIVE
  - X ABLATIVE: TO CHANGES IN WINDOW
### Advanced Sensor Development

- **Recommendations**

**Program**

- Develop radome concepts for forward-looking antenna

- Develop integrated sensor/guidance model, including radome and antenna errors

- Develop radome test facility, including:
  - High-speed air flow
  - Boresight error measurement

**Benefit**

- Improved range, accuracy, and (possibly) aerodynamic stability

- Realistic basis for defining system configuration and specifying performance

- Validated means to assess performance
APPENDIX B

RADOME DESIGN CONSIDERATIONS
FOR AN ENNK SEEKER

Georgia Tech Presentation to the
ENNK Seeker Study Group

MIT Lincoln Laboratory
8 September 1982
RADOME DEVELOPMENT

- CRITICAL AREAS -

- Physical Survivability
- Angle Accuracy
PHYSICAL SURVIVABILITY

- FAILURE MODES -

- Fracture
  - Acceleration
  - Aerodynamic Pressure
  - Thermal Shock

- Severe Erosion
  - Rain
  - Thermal Ablation

- RF Blackout
  - Aerodynamic Heat
  - Nuclear Heat
ANGLE ACCURACY

- SENSOR ERRORS -

- Boresight Error
- Boresight Error Slope
- Monopulse Error Slope
RADOME CONSIDERATIONS

-STATUS-

- MECHANICAL REQUIREMENTS SATISFIED BY
  - 1/8" HPSN
  - 1/2" Si/Al COMPOSITE

- ELECTRICAL REQUIREMENTS NOT SATISFIED WITHOUT
  CORRECTION OF ANGLE ERRORS
**RADOME CONSIDERATIONS**

- **REQUIREMENTS** -

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>MAX</th>
<th>APPROACH</th>
<th>RISK</th>
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</thead>
<tbody>
<tr>
<td>INTERIOR TEMPERATURE</td>
<td>70°C</td>
<td>INSULATION (e.g., SILICA FOAM)</td>
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<tr>
<td>OHMIC LOSS</td>
<td>1 dB</td>
<td>MATERIAL SELECTION</td>
<td>LOW</td>
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<tr>
<td>REFLECTION LOSS</td>
<td>2 dB</td>
<td>DESIGN FOR HI-TEMP.</td>
<td>MOD</td>
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<tr>
<td></td>
<td></td>
<td>DIELECTRIC STRATIFICATION</td>
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<tr>
<td>BORESIGHT ERROR</td>
<td>8 MR</td>
<td>RESONANT WALL DESIGN</td>
<td>MOD</td>
</tr>
<tr>
<td>COMPENSATED BSE</td>
<td>1.5 MR</td>
<td>ERROR-CORRECTED</td>
<td>HIGH</td>
</tr>
<tr>
<td>ERROR SLOPE</td>
<td>±0.4%</td>
<td>ANGLE CALCULATIONS</td>
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</table>
# Radome Considerations

## - Estimated Development Time -

<table>
<thead>
<tr>
<th>Radome Type</th>
<th>Years</th>
<th>Risk</th>
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<tbody>
<tr>
<td><strong>Silica</strong></td>
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<tr>
<td>- SCFS</td>
<td>1/2</td>
<td>Low</td>
</tr>
<tr>
<td>- Si/Si</td>
<td>1</td>
<td>Low</td>
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<tr>
<td>- Si/Al</td>
<td>1</td>
<td>Low</td>
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<tr>
<td><strong>Silicon Nitride</strong></td>
<td></td>
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</tr>
<tr>
<td>- CVD</td>
<td>2</td>
<td>Mod</td>
</tr>
<tr>
<td>- HPSN</td>
<td>2</td>
<td>Mod</td>
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<tr>
<td><strong>Perforated Metal</strong></td>
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<tr>
<td>- Heat-Sink</td>
<td>3</td>
<td>High</td>
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<tr>
<td>- Transpiration-Cooled</td>
<td>5</td>
<td>High</td>
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</table>
RADOME SHAPES
BORESIGHT ERROR FOR E-PLANE SCAN (MILLIRADIANS)
BORESIGHT ERROR SLOPE FOR E-PLANE SCAN
(DEGREE/DEGREE x 100%)
RADOME LOSSES FOR E-PLANE SCAN
(REFLECTION + DISSIPATION: dB)
BORESIGHT ERROR FOR H-PLANE SCAN
(MILLIRADIANS)
ERROR SLOPE FOR H-PLANE SCAN
(DEGREE/DEGREE x 100%)
RADOME LOSSES FOR H-PLANE SCAN
(REFLECTION + DISSIPATION: dB)
DIELECTRIC CONSTANT VARIATION AS FUNCTION OF TEMPERATURE

- CVD Si$_3$N$_4$
- HPSN (1% MgO)
- HPSN (8% Y$_2$O$_3$)
- RBSN
- SCFS
BORESIGHT ERROR FOR HPSN 3:1 OGIVE

(MILLIRADIANS)
ERROR SLOPE FOR HPSN 3:1 OGIVE
(DEGREE/DEGREE x 100%)
**RADOME LOSSES FOR HPSN 3:1 O GIVE**

(REFLECTION + DISSIPATION: dB)
BORESIGHT ERROR FOR SCFS 3:1 OGIVE
(MILLIRADIANS)
ERROR SLOPE FOR SCFS 3:1 OGIVE

(DEGREE/DEGREE x 100%)
RADOME LOSSES FOR SCFS 3:1 OGIVE
(REFLECTION + DISSIPATION: dB)
RADOME CONSIDERATIONS

-APPROACH-

- DEVELOP COMPENSATION TECHNIQUES USING SIMULATED RADOMES
  
  \[ HPSN \leftrightarrow \{ \text{Al}_2\text{O}_3 \} \quad \text{CVD-SN} \quad \text{Si/Al} \leftrightarrow \text{SCFS} \]

- PURSUE PARALLEL DEVELOPMENT OF HIGH PERFORMANCE RADOMES
  (MANUFACTURING TECHNOLOGY)
# Radome Development Schedule

<table>
<thead>
<tr>
<th>Task</th>
<th>Quarters After Start</th>
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<tbody>
<tr>
<td>Prelim. Elec. Design</td>
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<tr>
<td>Simulation</td>
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<td>Radome - Design</td>
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<tr>
<td>- Fab.</td>
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<tr>
<td>Gim. Ant. - Design</td>
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<td>- Fab.</td>
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<td>Bse Instr. - Design</td>
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<tr>
<td>- Fab.</td>
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<tr>
<td>BSE vs. SCAN - MEAS.</td>
<td>1 2 3 4 5 6 8 9 10 11</td>
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<tr>
<td>BSE/Slope - Correction</td>
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<tr>
<td>Radome Development</td>
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</tr>
<tr>
<td>Facility Scale-Up</td>
<td>1 2 3 4 5 6 8 9 10 11</td>
</tr>
<tr>
<td>Fab. Blanks (10-20)</td>
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<tr>
<td>Mech. Test Blanks</td>
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<tr>
<td>Finalize Elec. Design</td>
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<tr>
<td>Grind Radomes (5)</td>
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<tr>
<td>Elec. Test w/Gim. Ant.</td>
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</tr>
<tr>
<td>Integrate w/Array</td>
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</tr>
<tr>
<td>Measure BSE vs. SCAN</td>
<td></td>
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<tr>
<td>Demo. BSE/Slope Corr.</td>
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</table>