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ABSTRACT

This paper provides a management overview of a new joint Navy/Army millimeter wave (MMW) seeker technology development initiative. The goal of the program is to provide advanced seeker components for endoatmospheric interceptors for theater and strategic missile defense. The technologies are driven by requirements for low weight/volume interceptors, high interceptor and target velocities and a desire for "hit to kill" guidance accuracy (i.e., no interceptor warhead or fuzes). The efforts are focused on Ka (35 GHz) and W (94 GHz) band seeker components. The paper outlines development programs which address high output RF power using solid state transmitters and integrated transmit/receive modules for potential use with active electronically steered arrays. A significant part of the program is directed towards radome development for the severe hypersonic aerothermal environment. This includes development and testing of passive and cooled ceramic radomes. The program also addresses means of achieving body fixed or "strap down" seekers (i.e.,-no gimballed, mechanically stabilized antenna platforms). Several approaches are described for implementing both planar and conformal body fixed antennas. The hit to kill guidance issue is addressed in terms of means for achieving high angular tracking accuracy including adaptive boresight error compensation. In keeping with the theme of this "1992 AIAA Aerospace Design Conference," the efforts to be described can be expected to impact future missile seeker design concepts and practices.

INTRODUCTION

The Naval Air Warfare Center - Weapons Division (NAWC-WNS) and the Army Strategic Defense Command have initiated during government FY91 a new effort in MMW seeker technology under sponsorship of the Strategic Defense Initiative Organization's Interceptor Technology Directorate (SDIO/TNC). This initiative was motivated by a need for advanced endoatmospheric interceptors for theater and strategic missile defense. The main focus of this technology program is provided from the requirements of another SDIO program, ENDO LEAP, which is described in another session of this conference.[1] These top level requirements are summarized by:

- low weight/volume constraint (total seeker weight <6 kilograms)
- hit to kill guidance accuracies (no warhead or fuze)
- high interceptor velocities (>2 kilometers/second)
- high interceptor/target closing speeds (>4 km/sec)
- low altitude endoatmospheric intercepts (<25 kilometers)

In addition to these "ENDO LEAP type" requirements our technology program also addresses adverse weather performance which, in effect, drives us towards high power output for active RF seekers. Figure 1 provides a conceptual view of the environment in which the future MMW seeker can be expected to operate.

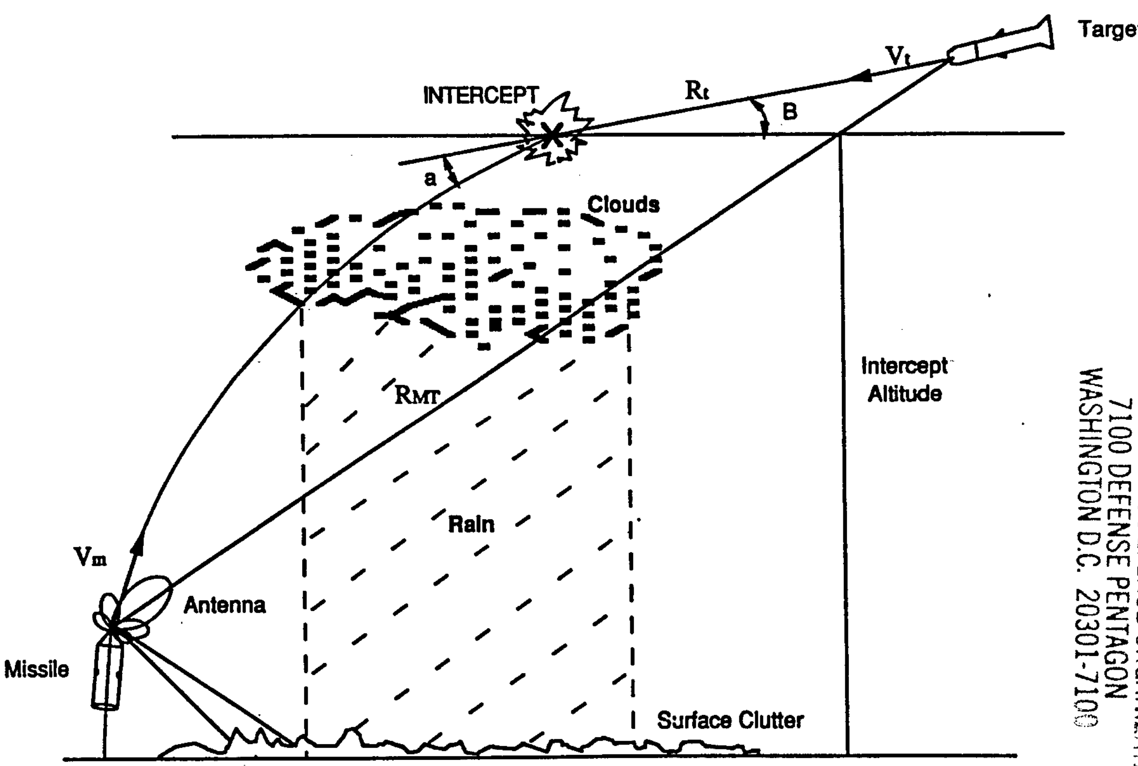


FIGURE 1.

Interceptor vehicle and complete seeker design is not the subject of this paper or of the MMW seeker technology program. It is not difficult, however, to state qualitatively the performance issues that help focus our technology program. Referring to Figure 1, an operational interceptor would be expected to fly out towards a predicted target intercept location, acquire the target, initiate target tracking and steer towards a collision aim point. For endoatmospheric ballistic missile intercepts the time from target acquisition to intercept is not likely to exceed 2-4 seconds. This guidance time/acquisition range issue is the main driver for active MMW seeker power. The choice of frequencies (Ka and W bands) is, of course, determined by well known atmospheric microwave absorption windows. The presence of clouds or rain also strongly impacts transmitter power requirements. This is especially true at 94 GHz for which one way attenuation due to rain is about three times that at Ka band and due to clouds up to six times that of Ka band. It is unlikely that sufficient power will be available at 94 GHz to permit true all weather operation. Fortunately, for most weather models, rainfall rates and cloud densities drop sharply above about 6 kilometers and are virtually non-existent above 20 Kilometers. Hence, available power at 94 GHz effectively limits the altitudes for adverse weather operation. Ka band operation with power levels addressed in this program will not be as severely limited by weather.

The hit to kill guidance requirement primarily impacts the seeker angular tracking accuracy. For typical proportional navigation guidance intercepts, the required angle tracking accuracy is likely to be less than 1 milliradian during the terminal engagement. Typical radar seeker angular tracking error (σ) is estimated from

$$\sigma \propto \frac{\theta_{BW}}{\sqrt{SNR}}$$

where θ_{BW} is the antenna half power beam width and SNR is the signal to noise ratio. The antenna beam width relates to wavelength (λ) and antenna diameter (D) by

$$\theta_{BW} \propto \frac{\lambda}{D}$$

Overall systems requirements of low weight and volume limit the antenna diameter. Hence, narrow beam widths are achieved by going to shorter wavelengths (such as 94 GHz). The SNR increases as the interceptor/target range decreases. However, the tracking error, σ, does not approach zero since other factors become significant as the target is approached. The other source of angle tracking error is due to the finite angular extent of the target (i.e., glint) which can be reduced by limiting the finite angular extent with very high range resolution. Range resolution of less than 1 meter is likely for ballistic missile interceptors. This high range resolution in turn drives towards variable transmitter waveforms with pulse compression and wide bandwidth receivers.

The severe aerothermal environment due to the high interceptor velocities presents a major challenge for radome design. There are two approaches to dealing with this environment. The first is to provide during flyout a removable protective shroud which is jettisoned immediately before target acquisition. The short times (less than 2-4 seconds) from acquisition to intercept somewhat alleviates the heat dissipation problem while thermal shock (especially near stagnation points) is likely to be a driving design issue. The second approach is to use actively cooled radomes throughout the flight. In this case, overall heat dissipation and mechanical survival in rain are the key design issues.

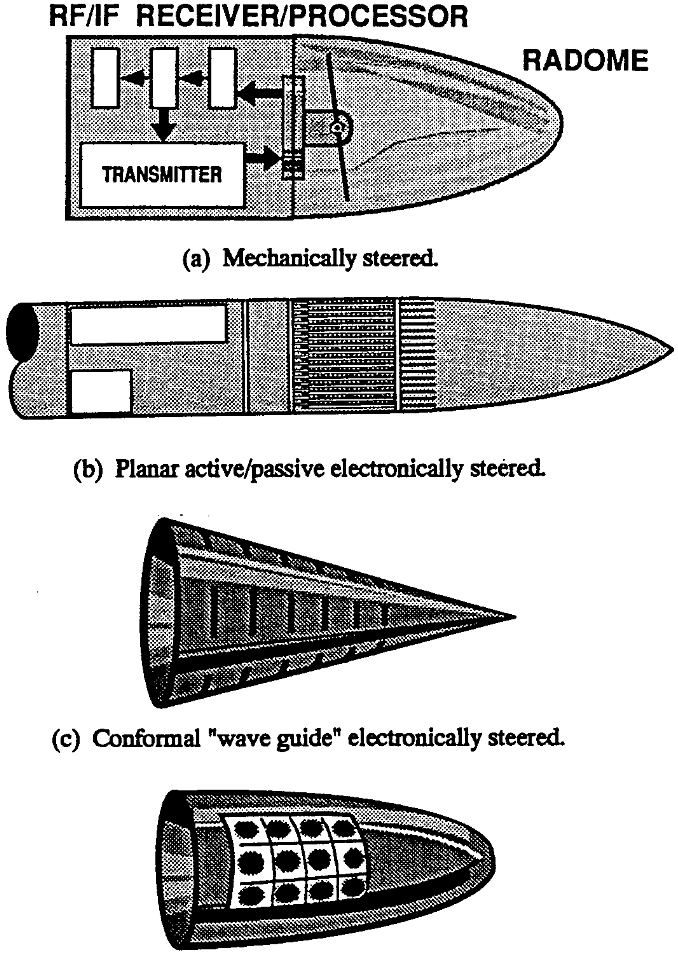
Another issue associated with the aerothermal environment is distortion of the RF wavefront in passing through the hot boundary layer/shock wave flow fields. For RF seekers boresight errors and external noise generation increases as the free electron density increases due to ionization. These design issues are especially important for interceptor velocities in excess of about 3-4 km/sec and are also influenced by chemical species (especially sodium and potassium) introduced by ablation of radome thermal protection materials.

These top level requirements discussed in this introduction section are, obviously, not of sufficient detail for a specific MMW seeker design. They are, however, adequate for defining and focusing the broad based technology development efforts to be described below.

SEEKER CONCEPTS

Figure 2 portrays the generic types of RF seeker design concepts that are likely to be used for endoatmospheric interceptors. The MMW seeker technology program intends to provide advanced components and design tools that address all of these generic types. Current intercept missiles employ the mechanically stabilized, gimballed antenna approach and this is likely to continue into the future. This approach generally requires a "single spigot" output RF power sources (for example, a traveling wave tube) and its associated manifold to distribute the power across the antenna. face. A major part of our program is devoted to replacing the traveling wave tube (or other) source with high power solid state transmitters for both Ka and W bands. Conventional gimballed systems consume significant seeker weight and volume and the design becomes increasingly complex under high acceleration conditions.

An attractive alternative to gimbals is to use a body fixed (or strap down) electronically steered array (ESA) concept as depicted in Figure 2b. An ESA, as depicted, would contain hundreds (at Ka) or thousands (at W) of individual radiating elements with amplitude and phase control of each element. The same RF power source from Figure 2a could be used, power distributed over all elements (via a space or corporate feed network) and beam steering achieved by phase control only. This constitutes a "passive" ESA or classic phased array antenna. A more advanced approach is to actually generate the RF power within each element. In this case both amplitude and phase at each element can be digitalled controlled allowing very rapid and agile beam shaping and steering. The transmit/receive (T/R) modules development described below represents the enabling device technology for active ESA at Ka and W bands. The ESA approaches are well described in the basic radar literature.[2]



(a) Mechanically steered.

(b) Planar active/passive electronically steered.

(c) Conformal "wave guide" electronically steered.

(d) Conformal active electronically steered.

FIGURE 2. National Seeker Concepts.

The seeker concepts of Figures 2a and 2b both require conventional radomes. An alternative approach is to use a conformal ESA as indicated in Figures 2c and 2d. This is also a body fixed approach but radiating elements are now in the skin of the interceptor. This approach avoids a radome development (only the individual elements need be protected from the environment) and, potentially, saves weight and volume. There are numerous approaches for conformal antenna design including the "waveguide" and active ESA concepts depicted. The waveguide approach could, for example, use the same power source as for Figure 2a (gimballed) with power distributed and radiated via slots in the waveguide. The active ESA concept would use the same T/R modules as required for the planar array of Figure 2b. Providing precision beam forming and angle tracking for a hit to kill interceptor is a challenge for both planar and conformal antennas.

The major emphasis of our MMW seeker technology program which addresses the above seeker concepts can be divided into three distinct categories: power (solid state) generation, radome (hypersonic speed) developments and implementation of strapdown antennas. This does not mean that other RF seeker components (for example, signal processors) are unimportant. Required performance of these components tend to be more system specific and generalized technology "drivers" have not yet been identified. We anticipate that such "drivers" will appear as the result of efforts from other missile defense programs such as ENDO LEAP.

MILLIMETER WAVE POWER GENERATION

The emphasis for RF power generation in our program is on solid state devices for the advantages listed in Table 1. Solid state devices are currently low power (less than 1 watt at 94 GHz and low efficiency (typically from 8-20% for total DC input to RF output). Hence, transmitters for active seekers require a method for combining the power from many individual devices. The IMPATT (Impact Ionization Avalanche Transit Time) diode is a well known two terminal device for power generation at MMW frequencies. The state of the art for pulsed operation of a single IMPATT at 35 GHz is summarized in Table 2.

TABLE 1. Advantages of Solid State Transmitters.

Potential weight/volume savings
Potential low cost
Reliability/maintainability
Rugged
Instant turn on
Graceful degradation with device failure
Distributed heat sinking of active devices
Low voltage dc biasing supplies (<40 volts)

TABLE 2. Performance of IMPATT Diodes (35 GHz).

State-of-the-art RF performance @ 35 GHz (average values of 14 discrete IMPATTS)

Peak output power (chip)	=	11.75 watts
Ave output power (chip)	=	3.6 watts
DC to RF efficiency	=	16.6%
Total thermal resistance	=	6.9°C/watt
Pulse	=	300 ns
Duty	=	30%

These diodes are:
- GaAs double-drift read (DDR)
- Single-mesa with integral beam leads
- Standard ceramic package on diamond III-a heat sink
- Refractory contact metal to ensure stability against diffusion

The output from many IMPATT diodes can be combined with a resonant cavity combiner consisting of two or four diodes which couple to the magnetic field at the side wall of a waveguide cavity. This approach is adequately described in the literature.[3] At the NAWC and Raytheon Company this method has been successfully exploited by combining the output from numerous rectangular resonant cavities to produce peak powers in excess of 200 watts at 35 GHz. This approach is being extended under the MMW technology program to demonstrate transmitters with the power levels listed in Table 3. Another effort has been initiated to demonstrate 94 GHz transmitters using IMPATT diode power combining with expected performance levels as indicated in Table 4.

TABLE 3. Ka-band IMPATT Transmitters.
Pulse = 300 ns, duty = 30%.

Power, W Peak	275.0	550	1,000
Power, W Ave	82.5	165	300
Weight, kg	2.32	3.36	6.14
LxWxH, cmxcmxcm	14.7x17x6.7	21.0x17x6.7	21.0x17x10.9
Volume, cm^3	1074.3	2,001.9	3,001.9
Available	FY92 (3Q)	FY93 (1Q)	FY93 (2Q)

TABLE 4. W-band IMPATT Transmitters.
Pulse = 200 - 300 ns, duty = 30%.

Power, W Peak	40	120	330
Power, W Ave	12	36	100
Weight, kg	1.74	2.52	4.61
LxWxH, cmxcmxcm	13x15x6.5	16x14x6.5	18x14x10
Volume, cm^3	1,231.4	1,750.8	2,803.6
Available	FY93 (4Q)	FY94 (4Q)	FY95 (4Q)

The MMW transmitter goals shown in Tables 3 and 4 do not fully achieve the SDIO requirements for low weight and volume. The limiting factor is the low power available from each individual device. One way of reducing the weight would be to develop IMPATT diodes with much higher power than that available from today's state of the art gallium arsenide technology. We have included in our program an effort to develop IMPATT diodes using silicon carbide (specifically, beta or cubic polytypes). Silicon carbide as the basic semiconductor material has the advantage relative to gallium arsenide of high operating temperature, high carrier drift velocities and high band gap. All these combine for a potential of producing 3 to 5 times the power (at 35 GHz) of that from current devices. Success in this area could effectively reduce the transmitter weights of Table 3 by factor of 2 to 3.

An emerging technology offers an alternate approach for achieving high power in low weights and volumes. In this approach, quasi optical power combining, the active power generating devices are usually embedded in or directly connected to radiating elements which can be separated by as little as a tenth wavelength. Two types of quasi-optical arrays have been reported to date.[4] One type uses a distributed oscillator approach in which the active devices (MESFET, IMPATT, Gunn diodes, etc) are mounted in a periodic structure and placed in an open quasi optical cavity. Power is coupled out via a partially reflecting mirror or an aperture in a spherical mirror. Figure 3 is a schematic of a resonant quasi optical combiner.

The other approach to quasi optical power involves arrays of weakly coupled individual oscillator/antenna elements. The system forms a classical antenna array in which each radiating element is itself a free running oscillator. The array elements are synchronized through mutual coupling mechanisms and the strength of the coupling elements is limited to ensure that each element operates close to its free running state.

Much work is needed to demonstrate that the quasi optical power combining approach is useful for an active MMW seeker. Sufficiently wide transmitter bandwidth and useful power levels at 35 and 94 GHZ have yet to be demonstrated. However, with success, quasi optical power sources can ultimately be integrated with other quasi optical components such as frequency tuning grids, mixer grids, amplifier grids, holographic beam steerers, etc. to construct very compact seekers.

A more near term method for power combining is through the use of fully active ESAs using transmit/receive (T/R) modules as mentioned earlier. A schematic of an integrated T/R module is shown in Figure 4. The antenna array would consist of over one thousand modules (at 94 GHz) built into the aperture. During transmission a low power RF signal generated by, for example, several IMPATT diode resonant cavity combiners is distributed to each active T/R module; the RF signal is amplified in the power amplifier and radiated through the radiating element. The total high power RF signal which is radiated from the interceptor results from spatially combining the lower power from each individual module. During reception, the return signal is amplified immediately at the face of the array by the low noise amplifier The system noise figure is established at the antenna front end by the low noise amplifier. The phase shifter losses on return are reduced since phase shifting occurs after the amplifier while during transmit phase shifting occurs before the high power amplifier. High costs of T/R modules using current hybrid technologies would be a major disadvantage for a single use interceptor seeker. However, there is reason for optimism in that several current programs (most notably, DARPA's Monolithic Microwave Integrated Circuit or MMIC effort) may reduce costs through integrated designs using gallium arsenide solid state technology.

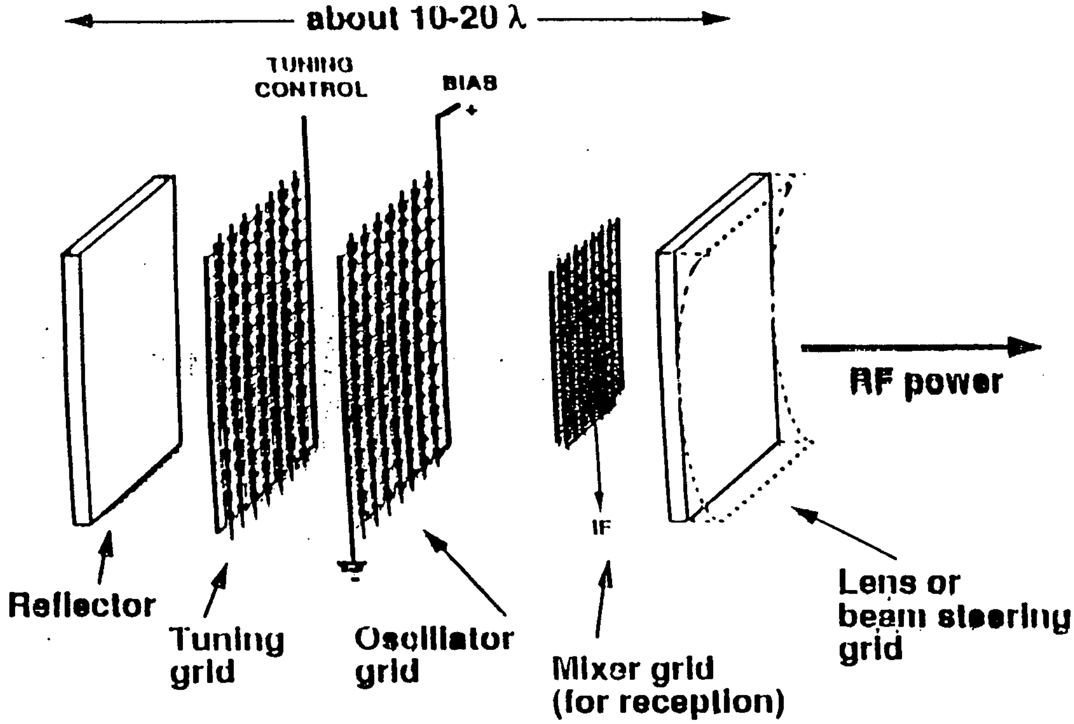


FIGURE 3. A quasi-optical component stack.

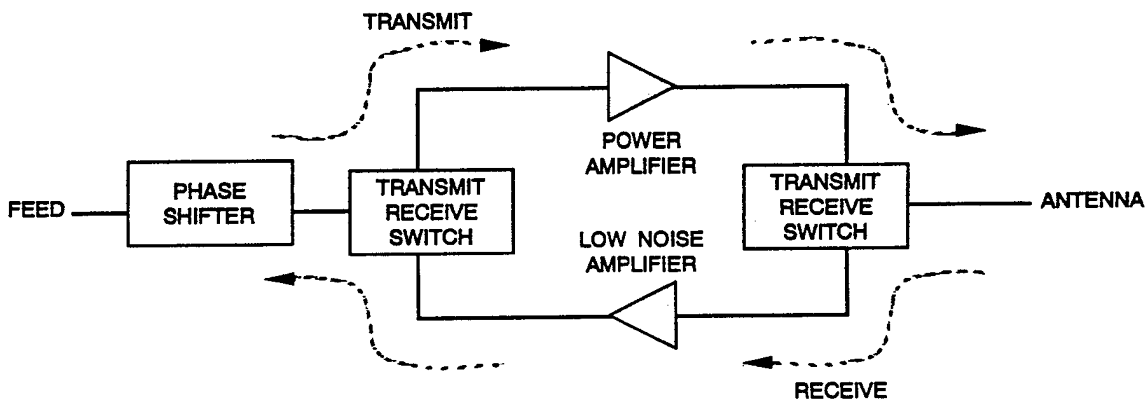


FIGURE 4. Transmit/Receive Module.

Power available (at 35 and 94 GHz) from the high power amplifiers currently is the limiting component for application of active ESAs to interceptor seekers. There are two primary competing device technologies for use in the high power amplifiers: heterojunction bipolar transistors (HBT) and high electron mobility transistors (HEMT). Our program includes efforts to demonstrate high pulse power (1.5 to 2.0 watts peak power) at 35 GHz using HBT devices and 0.5 watts CW power using HEMT devices. At 94 GHz the goals are for 0.5 watts pulsed peak power using frequency multiplied HBT devices and 0.1 watts CW power using HEMT devices. With these T/R module devices we should be able to demonstrate active seeker total powers of about 300 watts average at 35 GHz and 100 watts average at 94 GHz.

RADOME DEVELOPMENT

Table 5 provides a summary of current radome development efforts which are contracted through the Army Strategic Defense Command. The deliverable items (coupons, sub or full sized radomes) will be tested at the NAWC for electrical and aerothermal properties. As discussed in the introduction, the radome may be directly exposed to the environment for only a few seconds of the terminal engagements. Silicon nitride material is attractive in this environment for its ability to withstand thermal shock. However, above about Mach 10 unshrouded radomes probably require active cooling depending upon the altitude and time of exposure to high heat flux. The programs listed in Table 5 are all focused on 35 GHz operation. New efforts at 94 GHz are expected to be initiated during 1992.

TABLE 5. Millimeter Wave Seeker Technology, Radome Developments.

Title	Goals	Frequency	Contractor
Actively Cooled Silicon Nitride Radome	Demonstrate feasibility of fabrication of lighweight, thin wall transpiration cooled radome shaped structure from silicon nitride. Measure aerothermal and electrical performance of flat plate and conical shaped specimens	35 GHz	Aerojet General Corp Sacramento, CA
Low Cost Ceramic Radome	Fabricate and test subscale domes made of reinforced barium aluminosilicate/silicon nitride	35	LTV Dallas, TX
Reaction Bonded Silicon Nitride Radome	Bring high purity reaction bonded silicon nitride from lab. to engineering status via fabrication and testing of subscale domes	35	Raytheon Co. Lexington, MA
Cooled Ceramic Radome	Demonstrate actively cooled alumina radome utilizing a ceramich sandwich structure for flat coupon samples and curved surfaces	35	Rockwell International Thousand Oaks, CA

STRAP DOWN ANTENNAS/GUIDANCE

As was mentioned earlier the goal of weight and volume reduction leads to a need for body fixed antennas to avoid the use of conventional gimballed and mechanically stabilized antenna platforms. The passive electronically scanned array (ESA) approach described earlier provides a near term, moderate risk approach for strap down seekers. However, at 94 GHz efficient, low loss distribution of RF power over the array is a significant issue. Our program includes development efforts to achieve greater than 50% aperture efficiencies using, for example, optically controlled, variable dielectric lens.

Key performance issues for both passive and active (using integrated T/R modules) are high accuracy angle tracking, boresight error compensation and body decoupling. Adequate angle tracking accuracy will be achieved via optimal beam forming which trades off requirements for aperture efficiency, low side lobe levels and depth of the difference beam null used for monopulse tracking.

The flexibility provided by both amplitude and phase control across an active ESA may allow in flight boresight error corrections. Our program includes efforts to develop and demonstrate techniques for achieving adaptive boresight error compensation.

Interceptors which utilize proportional navigation guidance require accurate measurement of the rate of change of the inertial line of sight angle from interceptor to target. Strap down antennas must have a means for decoupling the interceptor's body rotational motion from the inertial line of sight motion. In principal, this is readily accomplished by measuring body angular rates and then electronically scanning the antenna boresight direction to subtract out the body motion. A general rule of thumb requires at least 30 dB of isolation between body motion and seeker's inertial reference system. To date, this has not been demonstrated for millimeter wave seekers.

For planar arrays, body decoupling should be a straight forward integration of beam steering controller and the angular rate outputs from an inertial measuring unit. Conformal arrays add another complication when the conformal array surfaces are highly curved as is likely for very small interceptors. In this case, polarization direction from each element will have to be controlled as well as amplitude and phase. On the positive side, however, boresight error compensation may be less difficult for a conformal array due to the absence of a radome. Demonstration of accurate angle tracking, boresight error compensation and body decoupling for both planar and conformal arrays is included in our millimeter wave seeker technology program.

SUMMARY

Table 6 provides an estimate of availability dates for the millimeter wave seeker technology described in this paper. The items listed will change with time due to success or failure of individual efforts and on availability of funds to support the program. A good technology program is flexible and we would expect to see new items and concepts appear in the table in a future AIAA design conference. Successful completion of these efforts will have a major impact on interceptor seeker designs in the late 1990s and beyond.

TABLE 6. Demonstrated Millimeter Wave Seeker Technology Availability.

Item description	Frequency, GHz	Date available	Schedule risk
POWER GENERATION			
Solid State IMPATT transmitter (1 kw peak power)	35	1994	medium
Solid State IMPATT transmitter (330 w peak power)	94	1996	medium-high
T/R modules with HBT power amplifiers (1.5w peak/module)	35	1995	medium-high
T/R modules with HBT power amps, frequency multiplied (0.5w peak/module)	94	1997	high
T/R modules with HEMT power amps (0.5W CW power/module)	35	1996	medium -high
T/R modules with HEMT power amps (0.1w CW power/module)	94	1996	medium
Silicon Carbide IMPATT diodes (36w peak power/diode)	35	1996	high
Quasi optical power combining transmitters (100w CW)	35	1994	high
RADOMES			
Actively cooled ceramic radomes (subscale)	35	1994	high
Uncooled silicon nitirde radomes	35	1994	medium
DEMONSTRATED STRAPDOWN ESA TECHNIQUES			
Beam steering for passive ESA (>50% aperture efficiency)	94	1995	medium
Adaptive boresight error compensation	35	1995	medium
Adaptive boresight error compenstation	94	1997	high
Precision angle tracking (less than 1 mrad)			
planar arrays	35	1995	medium
planar arrays	94	1997	high
conformal arrays (waveguide types)	94	1994	medium
conformal arrays (active ESA)	35	1997	high
conformal arrays (active ESA)	94	1998	high
Body decoupling			
planar arrays	35	1995	low
planar arrays	94	1998	high
conformal arrays	35	1997	medium
conformal arrays	94	1995	medium

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