8B.2 AN AIRBORNE PHASED ARRAY RADAR CONCEPT FOR ATMOSPHERIC RESEARCH

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1. INTRODUCTION

Airborne phased array radars have been used in military aircraft for more than twenty years (Klass 1984), but have yet to find their way into a platform for atmospheric research. This was largely due to the huge costs associated with such systems. The principle cost driver of these radars is the transmit/receive (T/R) module (Hommel & Feldle 2004). Advances in Monolithic Microwave Integrated Circuit (MMIC) technology has reduced the per element cost of an Active Electronically Scanned Array (AESA) by nearly two orders of magnitude. This has enabled their consideration for use in atmospheric research.

An airborne centimeter wavelength dual-polarization, Doppler, phased array radar has been proposed as one component of the Community Airborne Platform Remote-sensing Interdisciplinary Suite (CAPRIS). This paper describes the features and characteristics of this radar. Three possible airborne configurations will be discussed: X-band, C-band and Wide-band, covering frequencies from C-band thru X-band. A mobile, ground-based configuration will also be presented.

2. BACKGROUND

The T/R module is the key enabling technology for an AESA (Hommel & Feldle 2004). It provides the following functionality to the radar:

- Transmit power amplification (HPA)
- Phase shifting for electronic beam steering
- LNA
- Receiver protection
- Amplitude adjustment for antenna aperture weighting

The T/R module effectively amalgamates the functionality of the transmitter, circulator, limiter, LNA and antenna pedestal or gimbal. Figure 1 shows a block diagram of a typical single polarization T/R module. Present generation X-band T/R modules for airborne applications cost between $1000 - $3000 and were capable of producing 10 W of peak power at duty cycles of up to 30% (Hommel & Feldle 2004). Given that several thousand modules are required for an AESA, this is a significant cost driver. These modules typically require liquid cooling which also adds complexity and cost to the array.

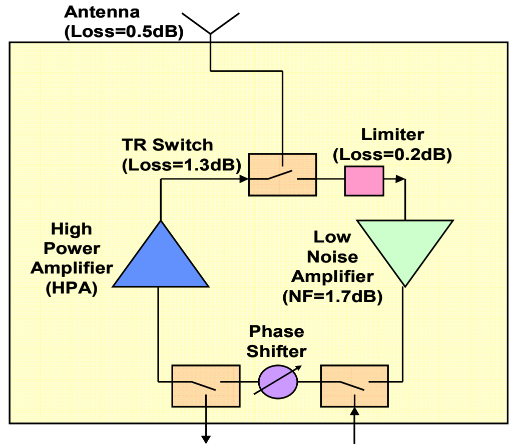

Figure 1: Single Polarization T/R Module

The next generation of T/R modules leverages advances in MMIC technology. This enables single chip (integrated) modules, which can be mass produced in an IC foundry. The per module cost is reduced to ~$30 at the expense of peak transmit power, which drops to 0.25 W – 0.4 W. The use of pulse compression (transmit duty cycles are ~10%) and over-populating the AESA with T/R modules, help combat the lack of peak transmit power. An additional benefit of this technology is that forced air cooling can be employed, reducing cost, complexity and weight. At around $30 per T/R element, the AESA can begin to be considered for use in atmospheric radars.

3. CAPRIS, WHAT IS IT?

CAPRIS is a response to a unique opportunity to access funds in the Mid-Size Infrastructure (MSI) account at the National Science Foundation (NSF). The CAPRIS team has developed a plan to develop and implement up to eight instruments in modular fashion for both airborne and ground-based deployment. CAPRIS will provide the geosciences community the capability for measuring key components of clouds, aerosols and

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chemistry to advance basic understanding of related processes in a warming planetary environment (Moore et. al. 2007).

CAPRIS will provide unprecedented combinations of coincident observations of precipitation, winds, cloud microphysics, water vapor, ozone, CO2, biomass, and aerosol. It will serve the observational needs of the broader scientific communities of weather, climate, chemistry, aerosol and biogeosciences in conjunction with a wealth of in situ sensors on the NSF/NCAR C130 and HIAPER, and complementary measurements possible from ground based platforms.

The proposed CAPRIS suite includes (i) a quasi-conformal, dual-polarization, Doppler, phased array precipitation radar; (ii) a pod-based dual-wavelength, dual-polarization, Doppler cloud radar; (iii) a water vapor differential absorption lidar (DIAL)/aerosol lidar; (iv) a UV ozone DIAL; (v) a UV molecular clear air Doppler wind lidar; (vi) a heterodyne boundary layer Doppler wind lidar; and (vii) vegetation canopy lidar. These instruments (in any combinations) can be mounted on the NSF/NCAR C130 and GV (HIAPER) (except the precipitation radar) to address specific scientific needs. These instruments can also be deployed in a ground-based mode to maximize lifetime, utility and flexibility. It is the centimeter phased array precipitation radar (i) which is the focus of this paper.

NCAR recognized early on that it lacked the technical expertise to develop the AESAs and sought a technology partner for this purpose. Massachusetts Institute of Technology (MIT) Lincoln Laboratories (LL) was selected based on their expertise in both AESA technology and weather radar applications. Cost and performance data used in this paper are based on estimates and simulations provided by LL.

4. AIRBORNE DUAL POLARIZATION DOPPLER RADAR

The centimeter wavelength dual polarization Doppler radar is intended to replace the aging airborne, dual-beam X-band ELDORA (Hildebrand et. al. 1996) and provide new research capabilities as well. It should provide twice the along-track resolution of ELDORA to yield higher resolution wind fields, while dual-polarization capability will provide microphysical information and aide in QPE.

The proposed system consists of four flat AESAs strategically mounted on the fuselage of the NSF/NCAR C130 turboprop aircraft using aerodynamic farings. Figure 2 shows the proposed configuration. Two will be mounted on either side of the fuselage behind the rear doors, the third will be mounted on the top of the fuselage and the fourth on the upper portion of the tail ramp. Each AESA measures approximately 1.5 m x 1.9 m. Unfortunately, due to the required size of the four AESAs and aerodynamic limitations, operation of this antenna system on HIAPER would not be possible. However, this technology would lend itself to a ground-based application which will be discussed in Section 5.

Each AESA will transmit alternating “fore” and “aft” beams separated by ~40° in the azimuth or longitudinal plane. These simultaneous beams could be

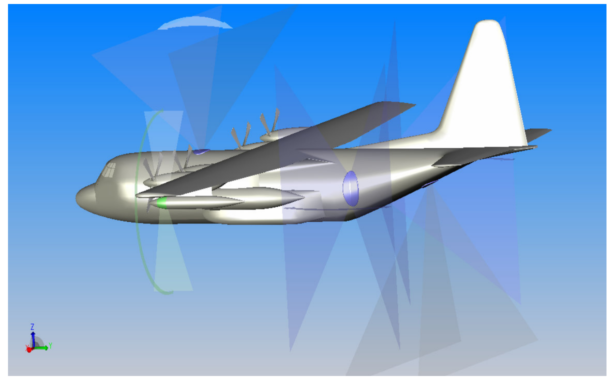

Figure 2: C-130 showing location of two of four AESAs (blue), plus beam envelopes (depicted as blue fans) of all four radars (one each port and starboard, one top, and one on the rear cargo door). The pod based cloud radar is depicted in green.

electronically scanned +/-50° in the elevation or transverse plane. The “composite” scanning of all four AESAs yields full 360° dual Doppler coverage, as in the current ELDORA. This is illustrated in Figure 3. An important advantage of the AESAs over ELDORA is the ability to scan in azimuth as well. This feature, used in

Figure 3: C-130 Front view showing beam envelopes of all four AESAs

conjunction with data from the WXR-700C weather avoidance radar, will be exploited to produce a composite PPI “surveillance” scan as depicted in Figure 4.

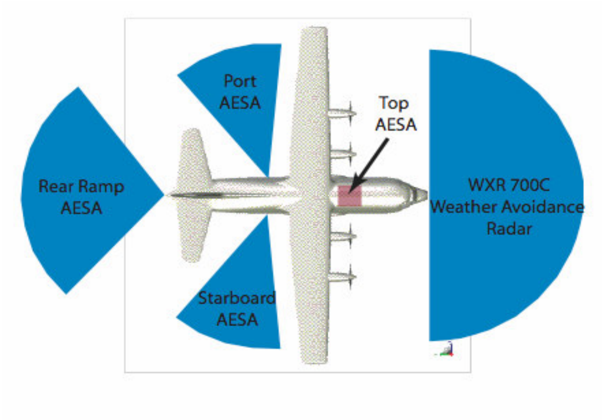

Figure 4: Composite "surveillance" scan, plan view for the C130 using both CAPRIS centimeter radar and existing aircraft weather avoidance radar.

This "surveillance" mode is essential to provide safety in single aircraft missions and will also aide in mission flight planning while in the air.

4.1. Radar Characteristics

Given the fairly generous antenna aperture available, the radar could operate at either X-band or C-band. X-band has the obvious advantages of a narrower beamwidth, higher antenna gain and greater scattering efficiency. C-band is affected far less by attenuation through heavy precipitation, which plagues the present X-band ELDORA. Another option, which capitalizes on the higher bandwidth inherent in both the T/R module and the notch radiating element, is a Wide-band system which covers both the C and X frequency bands.

NCAR and LL considered ten possible AESA configurations. Of these, three were selected as possibilities for use in CAPRIS based on physical constraints, performance and cost. All three options are based on custom designed MMIC T/R modules which will be cooled by the forced air moving between the fuselage and the AESA as a result of aircraft motion. Thus relocating most of the radar's heat dissipation outside the cabin.

The three possible AESA configurations are:

i. X-band dual-pol, alternating H,V transmit/receive

ii. C-band dual-pol, simultaneous H,V transmit/receive

iii. Wide-band (X,C) dual-pol, simultaneous H,V transmit/receive

The characteristics of these options along with those of ELDORA are shown in Table 1. It turns out, over 10,000 T/R modules per AESA are required to obtain the radar sensitivities presented in Table 1. Option i is the least expensive, while options ii and iii are 16% and 19% more expensve, respectively. It should be noted that the wide-band AESA cannot operate simultaneously at X and C bands, but can operate at either wavelength. The user can switch between wavelengths (~1 minute) during a mission, but not pulse to pulse..

Options	Beamwidth (θ_h x θ_v)	Sensitivity dBZ @ 10 km	Co-Polar Variables	Cross-Polar Variables	Along Track Res. (m)
X-Band Dual-Pol	1.3° x 1.1°	-9	Z_H,Z_{DR},K_{DP}, RHO_{HV}	LDR	150
C-Band Dual-Pol	2.0° x 1.6°	-4	Z_H,Z_{DR},K_{DP}, RHO_{HV}	None	130
Wide-Band (X,C) Dual-Pol	1.2° x 1.0° (X) 2.0° x 1.6° (C)	-10 (X) -2 (C)	Z_H,Z_{DR},K_{DP}, RHO_{HV}	None	150 (X) 130 (C)
ELDORA	1.8° x 2.0°	-11	Z_H	None	300

Table 1: Technical characteristics of AESA airborne configurations, with ELDORA specifications for comparison.

4.2. Design Considerations for the AESA

As previously stated, the three radar options presented in Section 4.1 were the result of a tradeoff between performance, cost and physical constraints of the AESA. A figure of merit (FOM) criteria was established to equitably compare AESA performance.

$$FOM = \frac{P_t * G_t * G_r * \phi_H * \phi_V}{(NF - 1) * \lambda^2} \qquad \textit{where,}$$

P_t = Peak Transmit Power @ Antenna
G_t = Antenna Gain on Transmit
G_r = Antenna Gain on Receive
Φ_H = Horizontal Antenna Beamwidth in radians
Φ_V = Vertical Antenna Beamwidth in radians
NF = AESA Noise Figure
λ = Wavelength in meters

The FOM is based solely on the T/R module characteristics, transmit wavelength and antenna aperture. Thus all proposed AESAs, C and/or X band, could be compared on an equal performance basis. LL initially proposed ten AESA configurations, five C-band, four X-band and one Wide-band (C/X). The FOM was held fixed, while antenna aperture, polarization implementation (simultaneous or switched transmit) and T/R module technology were varied. By using this approach, it soon became obvious that certain configurations were too large, too heavy or too expensive to be considered viable. These configurations were removed from further consideration. The final three options appearing in Table 1 no longer have equal FOM; option ii was included because we felt the research community should consider C-band, and option iii was scientifically and technically compelling.

The ability to re-position the radar beam in a matter of microseconds enables extremely rapid scan volumes to be obtained. A technique known as Independent Pairs Sampling (IPS) (Orescanin et. al. 2005) makes this possible. The scanning agility and the ability to form multiple beams inherent in AESAs will undoubtedly lead to advanced radar scanning techniques and with them the ability to make faster and higher resolution measurements than the current ELDORA system. It is for this reason that the AESAs will be built initially with four phase centers (the ability to form up to four independent, simultaneous receive beams), but will be designed so they can be readily upgraded to 16 phase centers for possible future needs.

4.2.1. T/R Module Technology

Two T/R module technologies were explored: a hybrid module consisting of commercially available disrete MMICs and a custom integrated MMIC based

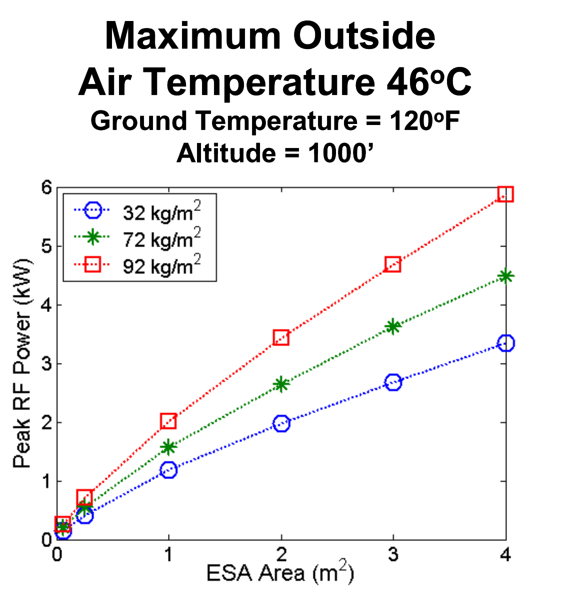

Figure 6: Graph of AESA Peak Power vs. Area for three types of heatsinks

on a new design by LL. The hybrid T/R modules offered between 1 W and 3.6 W of peak power – 2 to 14 times that of the integrated modules (0.25 W to 0.4 W). But, the hybrid modules have significantly higher cost and associated weight. The increased weight resulted from the increased thermal mass required for convective cooling. This is illustrated in , which shows the relationship between peak power and AESA area for three types of extruded aluminum heatsinks. Our concept AESA is approximately 3 m2 in area and can dissipate approximately 2.5 kW with a mass of 96 kg. To increase the peak power to 3.5 kW, requires a mass of 216 kg! The goal is to limit the weight of each AESA to 270 kg to minimize the cost of airframe modifications.

Due to cost and weight constraints, hybrid T/R modules were ruled out and an integrated T/R module approach was adopted. This presented a sensitivity issue for the C-band configuration (option ii), since a C-band array would require approximately ¼ the number of elements as an X-band array of the same physical aperture size, assuming the same relative element spacing. The solution was to overpopulate the C-band array by a factor of 4 to regain sensitivity. Although this increased the cost of the C-band option, it was still half the cost of the comparable hybrid T/R based AESA.

4.2.2. Polarization

Two types of polarization were considered for the AESA, switched transmit and simultaneous transmit. Both types are implemented within the T/R module. Figure 7 and Figure 8 show block diagrams of switched transmit and simultaneous transmit T/R modules, respectively. The switched T/R topology allows the full polarization backscatter matrix to be computed but, sensitivity is reduced by 2.6 dB as a result of the polarization switch (1.3 dB one-way loss). Using the simultaneous transmit T/R increases the overall cost of the AESA because it contains nearly twice as many components as the switched T/R.

Another factor affecting polarization performance is the design of the radiating element (antenna). Two types of radiating elements were considered: the stacked patch and the notch. Stacked patches offer superior cross-pol isolation but, have relatively large size and narrow bandwidth. Notch radiating elements possess much wider bandwidth characteristics but, have less cross-pol isolation (LL estimates ~23 dB broadside). Figure 9 shows the co-pol and cross-pol patterns for a stacked patch radiator. E and H plane co-pol patterns are well matched and cross-pol isolation exceeds 30 dB for +/- 10 degrees about broadside (0 degrees). Of course mutual coupling between array elements will likely degrade this performance.

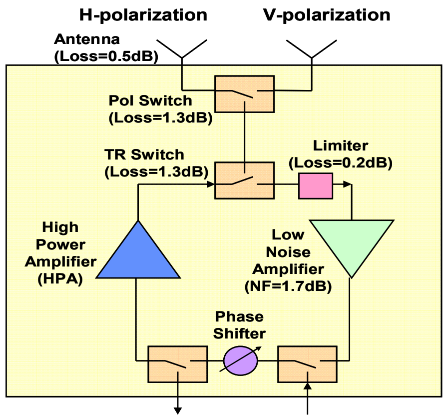

Figure 7: Switched Polarization T/R Module

It was ultimately an issue of sensitivity which determined the T/R Module topology used for polarization. The X-band AESA (option i) had sufficient sensitivity to absorb the 2.6 dB penalty for the polarization switch. The C-band AESA (option ii) and the Wide-band AESA (option iii) had marginal sensitivity and couldn't afford a 2.6 dB loss. In addition, both these systems required the use of notch radiating elements; option ii for reduced size and option iii for wider bandwidth. It was felt that the cross-pol isolation performance of the notch element was insufficient to make good LDR measurements.

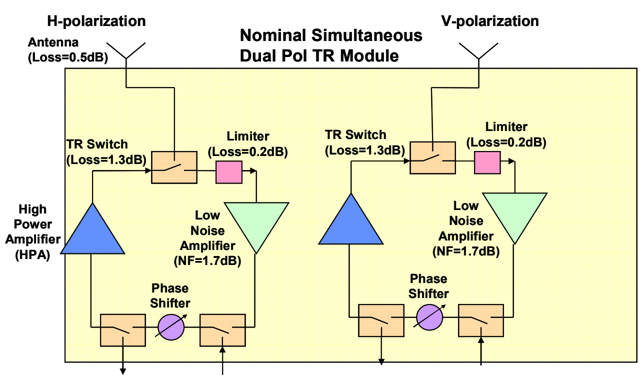

Figure 8: Simultaneous transmit dual polarization T/R module

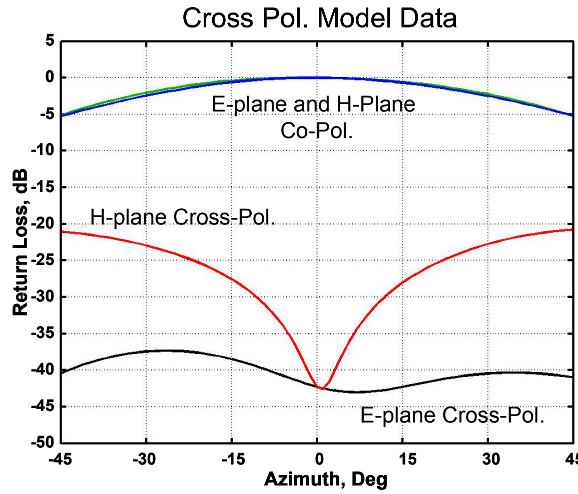

Figure 9: Graph of return loss vs. azimuth for simulated stacked patch radiating element

5. GROUND BASED CONFIGURATION

The ground-based centimeter wavelength radar concept combines two of the airborne AESAs into a single antenna, thereby halving the radar's horizontal beamwidth and increasing the radar's sensitivity by 6 dB over the values presented in Table 1. This antenna will then be attached to a pedestal to achieve hemispherical coverage. Mobility will be enhanced by mounting the pedestal on a diesel powered truck. This configuration could be duplicated for the other two AESAs as well. This approach gives the research community two highly mobile, rapidly scanning, dual polarization Doppler radars. This concept would also make dual-Doppler measurements possible if both radars were used in concert.

6. FUTURE WORK

There is still considerable work to be done in developing optimized scan strategies which incorporate dual-Doppler, dual polarization and surveillance measurements. In addition, the scientific tradeoffs between X and C bands need to be thoroughly explored. A more detailed T/R module design and analysis should be performed. The potential interference effects of the C-130 fuselage on the AESA beam patterns should also be studied. Some areas of future research using AESA include: spaced antenna (SA) techniques (Doviak et al., 2004) to measure cross-beam winds, scatterometry and volumetric synthetic aperture radar (SAR).

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