159 ARCHITECTURE OVERVIEW AND SYSTEM PERFORMANCE OF THE AIRBORNE PHASED ARRAY RADAR (APAR) FOR ATMOSPHERIC RESEARCH

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1. INTRODUCTION

The National Center for Atmospheric Research (NCAR) is investigating potential configurations for the next generation of airborne radar which is capable of retrieving dynamic and microphysical characteristics of clouds and precipitation, Loew et al. (2007), Moore et al. (2007). This radar is intended to replace the aging ELDORA, which is currently without an operational platform as of January 2013, Hildebrand et. al. (1996). A modular, dual-polarization, C-band phased array is currently under consideration. The airborne platform provides unique challenges for the radar design engineer. Mechanical stress, weight restriction, thermal management, prime power conservation, limited power aperture, lifetime and cost are factors, which must be managed effectively and taken in account for defining the APAR architecture.

This paper describes the architecture of a C-band, two-dimensional electronically scanned, dual–polarized phased array radar and presents the design specification and expected performance of the radar system. The paper highlights the high-level systems architecture and provides the design trade-offs for the radar development. Two companion papers have also been submitted to this conference; the first addresses the scientific needs and APAR concept, Vivekanandan et. al. (2013), while the second provides measured results from a small, prototype, 64 element, phased array radar front-end currently under development, Salazar et. al. (2013).

2. CONCEPT

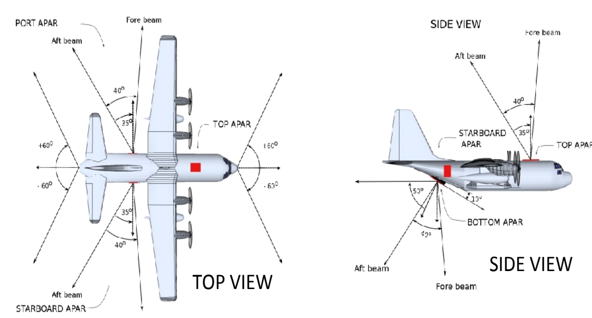
The proposed APAR system consists of four C-band active electronically scanned array (AESA) antennas strategically mounted on the fuselage of the NSF/NCAR C-130 aircraft. One AESA will be mounted on each side of the fuselage behind the rear doors; the third will be mounted on the top of the fuselage and the fourth on the upper portion of the tail ramp, as shown in

Figure ***1***.

The AESAs will be operated primarily in two modes: dual-Doppler and surveillance. Dual-Doppler mode will be the primary mode of operation.

In this mode, each of the four AESAs will generate a single "pencil" beam that will scan in azimuth and elevation. Scanning in azimuth will be between two fixed angles, one fore and one aft, separated by approximately 40^{o}. Given the proposed configuration on the C-130, the fore and aft azimuth angles will not be symmetrical around 0° (normal to the fuselage) as is the case for the present ELDORA system, which is likely to be +5°/-35°.

Scanning will be done to maximize the number of independent samples while covering the desired spatial domain (±50° in elevation) in the least amount of time. The "composite" scanning of all four AESAs yields a 360°, dual-Doppler coverage, as in the current ELDORA. It is worth mentioning that the dual-polarization data will only be collected on the fore beams and within ± 20^{0} elevation angles to ensure the best quality of the dual-polarization data, Salazar et. al. (2012). A composite surveillance scan, consisting of the bottom and side AESAs as shown in Figure 2 will also be performed periodically to establish situational awareness.



a) b)

Figure 1: Position of the four AESA's on the NSF/NCAR C-130: a) top view and b) side view

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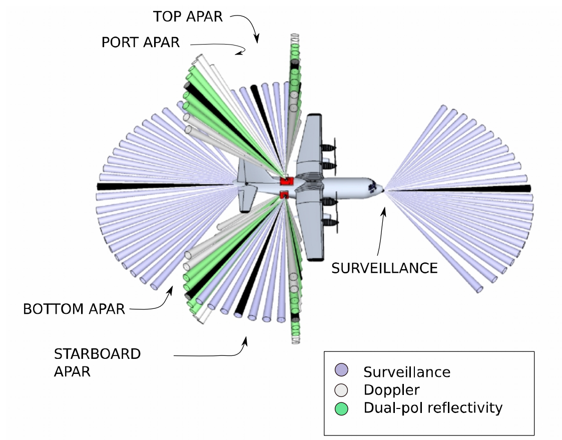

Figure 2: Illustration of the proposed radar scanning modes on the NSF/NCAR C-130. Note top antenna is displaced to better illustrate Doppler scanning.

3. SYSTEM ARCHITECTURE

Figure 3 depicts a simplified system architecture for APAR. It consists of six components: (1) the array antenna front end, (2) quad, transmit-receive (TR) modules, (3) array antenna backplane, (4) radar digital backend, (5) radar processor/display, and (6) radar scheduler. Components 1-3 reside outside the fuselage enclosed by fairings and present the greatest technical challenge. NCAR is currently working with the Massachusetts Institute of Technology's Lincoln Laboratories (MIT/LL) to develop a quad TR module (component 2). This module contains the necessary circuitry to control four radiating antenna elements. NCAR is developing the RF array front end and array antenna backplane (components 1 and 3). These will be combined with the quad TR modules to construct a functional prototype, 8x8 element, line replaceable unit (LRU). It is envisioned 56 (7x8 lattice) LRU's will be combined to form a single 1.5m x 1.9m aperture.

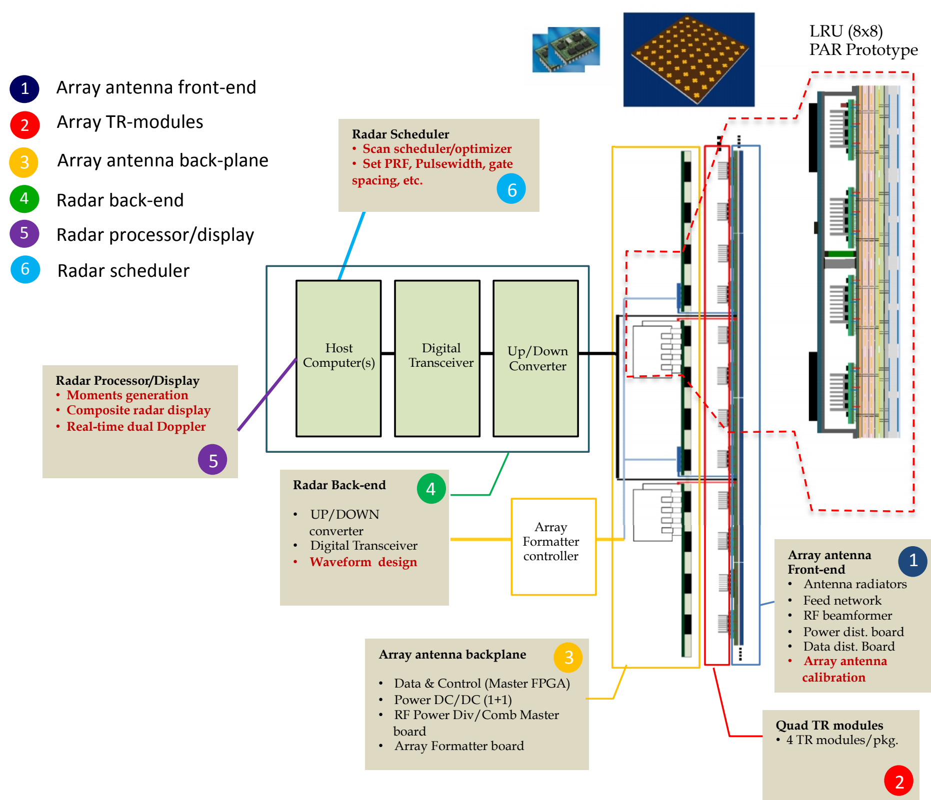

Figure 3: Simplified block diagram of APAR architecture. Subsystems 1-3 reside outside the fuselage, enclosed by a fairing/radome; the rest of the system resides in the cabin.

Parameter	Units	Eldora (X-band)	APAR(C-band)
Frequency	GHz	9.3- 9.8	5.35-5.45
Wavelength	cm	3.22-3.06	5.5
# Elements (El/Az)	-	-	64/56
# Total elements per panel	-	-	3,584
Beamwidth (El/Az)	deg	1.8/2.0	1.6/1.8
Antenna gain	dB	39	41
Min. detect. signal at 10 Km	dBZ	-10	-15
Sildelobe level	dB	-20 to -24	-25
Pulse repletion frequency	Hz	2000	2000
Peak transmit power	Kw	40	14.3
Spatial resolution at 10km	m	314	314
Along-track resolution	m	300	120
Pulse width	us	1.0-4.0	0.5-50
Polarization	-	Horizontal	Dual Linear
Beam overlapping	%	25	25
Unambiguous range	km	75	75
Unambiguous velocity	m/s	32	55
Transmitted waveform	-	Stepped Chirp	Pulse compression (PC)

Table 1: Comparison of expected APAR characteristics with current ELDORA radar

4. DESIGN GOALS

It is intended that the APAR will meet or exceed the performance of ELDORA in terms of sensitivity, spatial resolution, and along track resolution. Table 1 compares the expected APAR characteristics with that of ELDORA. Unlike ELDORA, APAR will be capable of making polarimetric measurements, both co- and cross-polar. Polarimetric measurements will occur on the forward (+5°) scans of the side-looking AESA's over a limited elevation scan (+15°/-15°). Limiting the polarimetric scan range, minimizes the rotation of the polarimetric basis and maximizes cross-pol isolation.

5. DESIGN CONSIDERATIONS

Designers of airborne radar systems must consider a variety of factors when developing a new system. Among these are cost, prime power availability, restricted aperture size, limited size and weight, vibration, cooling, fluctuating temperatures and often, reduced atmospheric pressure. The final design is a compromise between these factors and desired system performance, mainly, sensitivity, spatial resolution, and along track resolution. AESA technology presents additional challenges, specifically in limiting cost, weight and prime power consumption.

5.1. Sensitivity

Weather radar sensitivity is directly proportional to:

- Peak transmit power
- Transmit Pulse-width
- Square of antenna gain
- Square of antenna beamwidth (-3dB)

It is also inversely proportional to:

- Square of wavelength
- Receiver noise figure

In past centimeter wavelength airborne radars, aperture size and spatial resolution requirements limited operation to X band. These radars suffer significantly from attenuation in moderate to heavy precipitation. With the larger real estate available (1.9m x 1.5m) on the C-130, both C and X bands were considered. If the array aperture size is held constant, all other factors being equal, an X band system will be ~12 dB more sensitive; it will also have twice the spatial resolution.

To minimize the effects of grating lobes in the antenna pattern while scanning over a large angular extent, AESA radiating element spacing needs to be ~1/2 of a wavelength. This results in an X band system having four times the radiating elements and consequently four times the number of TR elements than for a comparably sized C band system. Given that the TR elements represent 30-40% of the multi-million dollar hardware cost of the C-band radar, it wasn't cost effective to pursue a large aperture X band AESA. Reducing the size of the X band AESA to match the spatial resolution of the C band was also not desirable; the ~6dB increase in sensitivity of the X band was not sufficient to overcome the better attenuation performance of the C band.

Aircraft weight and prime power limitations have a direct effect on radar sensitivity. Each AESA on the C-130 is limited to 270 kg in weight and 5.5 KVA in power consumption. The TR modules consume the greatest fraction of the available power, the vast majority through the power amplifier (PA) and LNA(s). Figure 4 shows two TR module architectures considered for APAR: alternate transmit, simultaneous receive (ATSR) and alternate transmit, alternate receive (ATAR). Currently, ATSR is favored, because it allows for the simultaneous cross-pol measurements. Cost and power consumption are increased due to the increased component count.

The proposed APAR, contains 3584 TR modules per aperture, so each module must consume less than 1.5W. In order to achieve this goal, peak transmit power is limited to 4W at 10% duty cycle rather than the 8W the PA is capable of delivering. In addition, the LNA duty cycle is limited to 90%. This results in a total power dissipation of approximately 1.5W. Both the PA and LNAs are only biased during use; this is accomplished through drain switches in the TR module. Even if sufficient prime power were available to operate the PA at 8W, the additional heatsink weight required, would cause the array to exceed its weight limit.

As can be seen in Figure 5, 4W peak power per element is more than sufficient to exceed ELDORA sensitivity beyond 5 km. In this scenario, a 33 µsec phase coded pulse is used for ranges beyond 5 km, while a 0.5 µsec single frequency pulse is used to recover ranges inside 5 km. This Variation in the transmit pulse-width causes the discontinuity observed in the sensitivity curve.

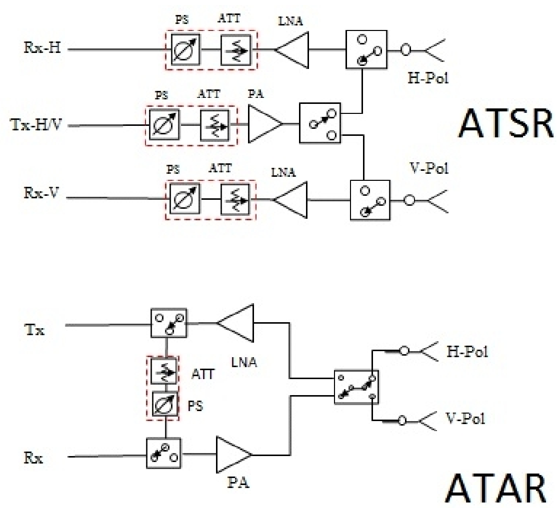

Figure 4: Simplified block diagram of dual-pol TR module architectures, ATSR and ATAR

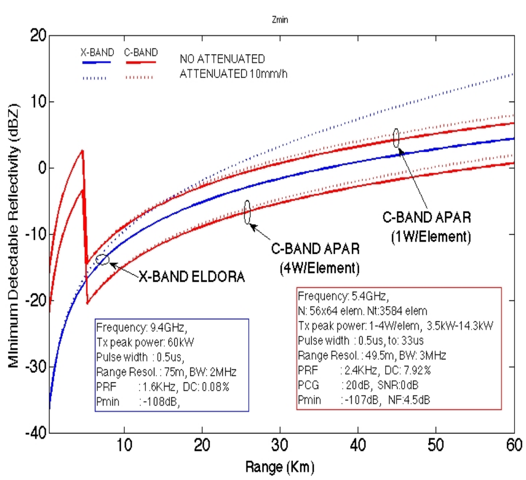

Figure 5: Minimum detectable reflectivity vs. range for ELDORA, APAR with 4W/element transmit power and APAR with 1W/element transmit power

5.2. Spatial Resolution

Spatial resolution is directly related to the antenna beam-width, which is inversely proportional to the aperture size and directly proportional to the wavelength. The choice of wavelength was chiefly determined by cost, as discussed previously, while the aperture size is constrained by the intended airborne platform. As shown in Table 1, the expected spatial resolution is 314m at a range of 10 km.

5.3. Along Track Resolution

The along-track resolution is proportional to the scanning rate and speed of the aircraft. The time required for a scan of a specific volume depends of the scanning strategy adopted in the radar system. When using phased array technology, the time to sample an entire volume can be less than 15 seconds. The scanning time depends on the antenna beam-width, number of beams, beam overlapping, pulse repetition frequency, and number of pulses. When the phased array is used for a continuous scan mode (the case with the mechanical scan radars) the scanning rate is determined by the time it takes to obtain independent samples. Time to independence is estimated using the expression (3.18) in Nathanson (1990). It is proportional to the wavelength and inversely proportionally to the spectrum width. Using this expression for different frequencies and a spectrum width of 1.0 m/s, X-band requires 6.4 ms to acquire a sufficient number of independent samples, while C-band and S-band require 11.1 ms and 20 ms, respectively.

Along-track resolution as a function of the independent samples is illustrated in Figure 6. The dashed lines represent the along-track resolution as a function of independent samples for continuous scan mode.

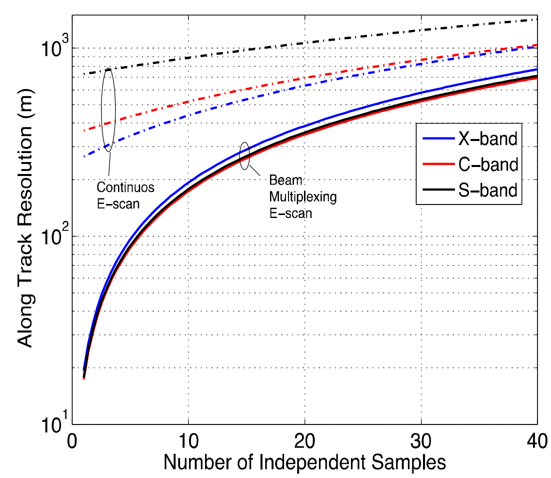

Figure 6: Along-track resolution as a function of the number of independent samples for S-band, C-band, and X-band. Scanning range of 90°, beam overlapped factor of 35 %, flight speed of 120 m/s, and PRF of 2000Hz.

Considering ten independent samples, an equivalent aperture, a flight speed of 120 m/s, scanning range of 90 °, beam overlap of 35%, and pulse repetition frequency of 2000 Hz, the along-track resolution is 350 m for X-band, about 430 m for C-band, and 800 m for S-band. In order to improve the current resolution to exceed the ELDORA along-track resolution of 300 m, phased array radar requires a spatial beam multiplexing scanning technique Heinselman (2011). A beam multiplexing scanning technique takes advantage of fast and flexible electronic scanning to point the antenna beam pattern in any arbitrary position. In this mode, the scanning rate is not limited by the de-correlation time. Figure 6 illustrates the along-track resolution using the beam multiplexing technique. Considering ten independent samples, the along-track resolution is below 200 m for the three bands (X, C, and S band). In contrast to the continuous scanning mode, in the beam-multiplexing mode, the along-track resolution is worse for higher frequencies.

6. FUTURE WORK

Over the next year, the plan is to integrate the quad TR modules into a fully functional LRU whose performance will then be characterized.

7. ACKNOWLEDGEMENT

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