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DESIGN CONSIDERATIONS FOR DEVELOPING AIRBORNE DUAL-POLARIZATION DUAL-DOPPLER RADAR

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1. INTRODUCTION

Recently, ground-based phased array radar (PAR) demonstrated the swift estimation of accurate Doppler velocity and reflectivity of precipitation and clouds when compared to mechanically scanning radar. PAR uses electronic scanning (e-scan) to rapidly collect radar measurements. Since an airborne radar has only a limited amount of time to collect measurements over a specified sample volume, the e-scan will significantly enhance temporal and spatial resolutions of airborne radar observations. At present, airborne weather radars, such as NCAR's Electra Doppler radar (ELDORA), use mechanical scan and they are not compatible for collecting dual-polarization radar measurements.

The ELDORA is a slotted waveguide array with a dual-transmitter, dual-beam, rapid scan and a step-chirped waveform. These attributes significantly improved the spatial scale from >1 km to 300m (Hildebrand et al. 1996, Bluestein and Wakimoto, 2003). To date ELDORA is the most sensitive scanning airborne radar while also collecting measurements at the highest possible spatial and temporal resolutions. However, ELDORA's X-band frequency limits penetration into heavy precipitation owing to attenuation, and it is not designed, nor can it be modified, to collect polarimetric microphysical measurements. Signal attenuation in precipitation at X-band is about a factor of five to seven times larger when compared to C-band (Bringi et al, 2001).

NCAR/EOL is investigating potential configurations for the next generation of airborne radar that is capable of retrieving dynamic and microphysical characteristics of clouds and precipitation (Lowe et al. 2007, Moore et al. 2007). NCAR maintains a C-130 aircraft in its fleet for airborne atmospheric measurements, including dropsonde, in-situ sampling and remote sensing of clouds, chemistry and aerosols. Therefore, the addition of a high resolution precipitation radar to the NSF/NCAR C-130 platform will produce transformational enhancement in its mission to benefit of cloud and aerosol physics, precipitation physics, chemistry and convective dynamics communities, among others.

This paper presents the concept, and preliminary design of a C-band, airborne, dual-polarization, dual-Doppler precipitation radar. EOL proposes to develop a novel airborne phased array radar (APAR) to be operational on NSF/NCAR C-130 aircraft with improved spatial resolution and polarimetric measurement capability. Preliminary design specification of the APAR that may replace the ELDORA are described in this paper. Design specifications of PAR are more stringent than a ground-based PAR.

2. RATIONALE FOR NEXT GENERATION AIRBORNE RADAR

Airborne Doppler radar is a powerful tool to observe weather systems, in particular, storms over complex terrain, the ocean and in forest regions not easily observable by ground-based radars (Bluestein and Wakimoto, 2003). In recent years, hurricane genesis (Montgomery et al. 2012) and intensity change involving eye-eyewall interactions (Montgomery et al. 2006; Bell and Montgomery, 2008), and tropical convection related to the Madden-Julian Oscillation (Zhang 2013) have drawn research attention. These systems have their origin over the ocean and can only be sampled by radars aboard ship, spaceborne radar or from aircraft.

A critical weather research area is quantitative precipitation estimation/forecasting (QPE/QPF). Hurricane intensity/super-intensity change involving eye-eyewall interactions has drawn research attention in recent years. Both numerical simulations and Doppler radar observations suggest that the energy exchanges between the mostly clear and cloudy eye region and the heavy precipitation eyewall region (especially at the low levels), is a critical factor controlling the hurricane intensity change (Houze et al. 2007). However, structures of the hurricane eye and their roles in hurricane intensity change remain largely unknown. The unique combination of APAR capabilities, allowing the measurement of 3-D kinematics in the eye and in the eyewall simultaneously and water vapor measurements using dropsonde and *in situ* measurements from a single airborne platform, will help scientists to examine the role of the hurricane eye with regard to intensity changes.

In the case of convective precipitation, two issues, namely, (1) when and where convection will be initiated, and (2) determining the organization and structure of ensuing convection, are key for quantitative precipitation forecast (QPF). Therefore collocated measurements of 3-D winds and precipitation microphysics are required for achieving significant skill in QPF and quantitative precipitation estimation (QPE). Multiple radars in dual-Doppler configuration with polarization capability estimate dynamical and microphysical characteristics of clouds and precipitation are mostly available over land. However, storms over complex terrain, the ocean and in forest regions are not observable by ground-based radars (Bluestein and Wakimoto, 2003).

The NWRT (The National Weather Radar Testbed) phased array radar (PAR) has demonstrated the estimation of accurate Doppler velocity and reflectivity in ground-based configuration in a single polarization mode (Foresythe et al. 2006; Weber et al. 2007; Zrnic et al. 2007). Recent NWRT measurements showed the phased array radar's ability to reduce scan time at least by a factor of two by rapidly steering the beam to a set of spatially diverse pointing angles using beam multiplexing (Yu et al. 2007). Beam multiplexing reduces errors in radar measurements while providing rapid updates of scan volumes. Since the airborne radar has only a limited time for collecting measurements over a specified region, beam multiplexing will significantly enhance its ability to collect high resolution, research quality measurements.

One of the engineering challenges is a precise estimate of polarimetric measurements using phased array radars at scan angles > 20^o from bore sight (Zhang et al. 2009). Reduction in polarization purity of the signals and a mismatch between orthogonal polarization beams at scan angles away from the bore sight will compromise polarimetric measurement accuracy. Limiting the polarization measurements within a 20^o scan angle will mostly guarantee accurate polarimetric measurements.

The atmospheric science community has enthusiastically endorsed the development of a phased array radar to replace the aging ELDORA (Smith et al. 2012). This next generation radar can be mounted on the fuselage of the NSF/NCAR C-130 aircraft as described in the next section. The rapid and versatile scanning capabilities of phased array radar systems lend themselves particularly well to airborne applications. Technical specifications and configuration of an airborne phased array radar capable of providing dual-Doppler wind fields and dual-polarization measurements are discussed in the following sections.

3. APAR INSTRUMENTATIONAND TECHNICAL BACKGROUND.

The proposed centimeter wavelength dual-polarization Doppler radar is intended to replace the aging ELDORA and provide new research capabilities as well. A design with multiple radars on different faces of the C-130 fuselage is shown in Figure 1. A tail radar configuration is not supported by the C-130 due to lack of support structure in the tail. Preliminary studies recommended flat aperture planar array antenna on its fuselage can be flown with a minimal impact on its flight performance. Due to the availability of large surface area of the C-130 fuselage, an antenna large enough to achieve a beamwidth comparable to ELDORA can be obtained either at C- or X-band.

Figure 1. Proposed configuration of C-band active electronically scanned array (AESA) radars on C-130. Four AESA radars are strategically mounted

on the fuselage of the NSF/NCAR C-130 turboprop aircraft

The proposed system consists of four removable, C-band active electronically scanned array antennas (AESAs) strategically mounted on the fuselage of the NSF/NCAR C-130 turboprop aircraft using aerodynamic fairings as shown in Figure 5. Two AESAs 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 is approximately 1.5 m x 1.9 m in size. The AESA's will be operated in two primary 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 be scanned in azimuth and elevation. Scanning in azimuth will be between two fixed angles, one fore and one aft. The fore and aft azimuth angles will be separated by 35°. It is likely given the proposed configuration on the C-130 that the fore and aft azimuth angles will not be symmetrical about 0° (normal to the flight track) as is the case for the present ELDORA system. Fore and Aft azimuth values are more likely to be +5°/-30° normal to the flight track. 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. This strategy will produce optimal resolution dual-Doppler data. In order to implement this scan strategy, switching in both azimuth and elevation scan angles must be accomplished in less than 5 ms. Doppler velocity will be computed on pairs of pulses separated by the pulse repetition time (PRT) at a given azimuth and elevation. The beam will then be steered to another position and another pair of pulses will be transmitted. This process will continue until the time to independence, or decorrelation time, has been reached for the original starting position and the sequence will repeat again. Once enough independent pairs have been collected, the velocity estimates from the pairs of pulses at each elevation and azimuth can be averaged for reducing standard error in radial wind and reflectivity estimates. Based on the decorrelation time, the entire spatial quadrant that each radar is required to cover can be divided into a finite number of such sequences.

A secondary surveillance scan mode will be interleaved periodically with the primary mode to produce a "composite" PPI scan which incorporates data from the three aft mounted AESAs and the weather avoidance radar located in the nose of the aircraft. In surveillance mode, the elevation angle is held fixed at 0^0 and the beam is scanned in azimuth. It is envisioned that other scan strategies will be incorporated over time, but scan limits will remain unchanged. Figure 2 shows the locations of the four AESA radars with respective beam scanning modes (Dual-Doppler and Reflectivity) and the weather avoidance nose radar on the C130 as well as a composite surveillance scan.

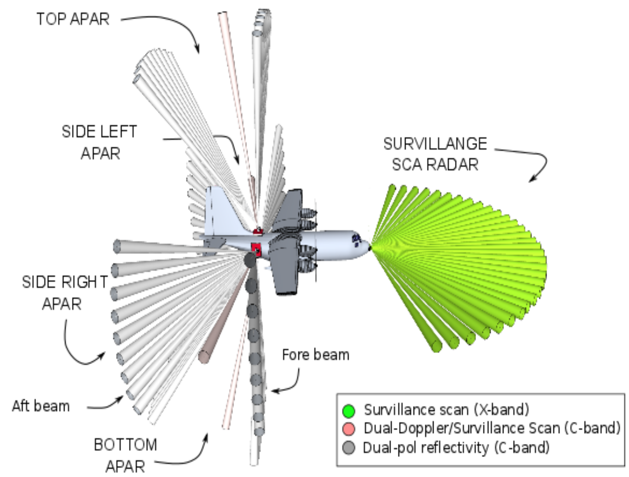

Figure 2. Typical beam positions of the proposed four AESA radars and weather avoidance radar on the C-130.

The "composite" scanning of all four AESAs yields a full 360° dual Doppler coverage, as in the current ELDORA. An important advantage of the AESAs over ELDORA is the ability to scan in azimuth as well. This feature, used in conjunction with data from the C-130 weather avoidance radar, will be exploited to produce a composite PPI "surveillance" scan as depicted in Figure 2. This "surveillance" mode is essential to provide safety in single aircraft missions and will also aid in mission flight planning while in the air.

3.1 SELECTION OF WAVELENGTH

S-band, due to the limited antenna aperture area on C-130 fuselage, will have significantly diminished spatial resolution of radar measurements, therefore X-band and C-band were considered for use in APAR. Using the available aperture at C-band will produce a radar beamwidth of ~2º. Using the same size aperture at X-band will produce a radar beamwidth of ~1º; while this option may be attractive for improved spatial resolution, it would require four times the number of radiating elements and consequently would be prohibitively expensive to build.

Sensitivity at X-band is about 5 dB better than C-band in the absence of any significant attenuation due to precipitation, given comparable antenna gain and transmit power. However, attenuation due to precipitation at C-band is five to seven times smaller when compared to X-band and X-band cumulative attenuation through precipitation is significant. C-band radar transmit signals will penetrate deeper into squall lines and rainbands. Due to these considerations, C-band was selected.

3.2 SENSITIVITY

The proposed airborne phased array radar (APAR) will estimate dynamical and microphysical properties of clouds and precipitation in conjunction with in situ sampling of the same. Various technical specifications of AESA radar were investigated. Technical characteristics of one such configuration that has similar or better sensitivity for measuring reflectivity and more accurate radial mean velocity than ELDORA are listed in Table 1.

Each APAR is composed of 3584 active, radiating elements, arranged in a rectangular array of 7 X 8 line replace units (LRU). Each LRU is composed of 64 radiating elements. Each radiating element will use a stacked patched microstrip antenna radiator coupled to transmit/receive (T/R) module. The microstrip patch antenna elements can transmit in either horizontal (H) or vertical (V) polarizations. The radiating elements are spaced less than half a wavelength apart to avoid grating lobes over the full scan extent (Wang et al. 2008). In the transmit mode all of the T/R modules transmit at the peak power for the best power aperture efficiency. The resulting uniform illumination will produce side lobe that is 13 dB lower than the main lobe in the transmit mode. In the receive mode antenna sidelobe level is reduced by tapering receive aperture antenna illumination by a 2-D Taylor distribution weighting function.

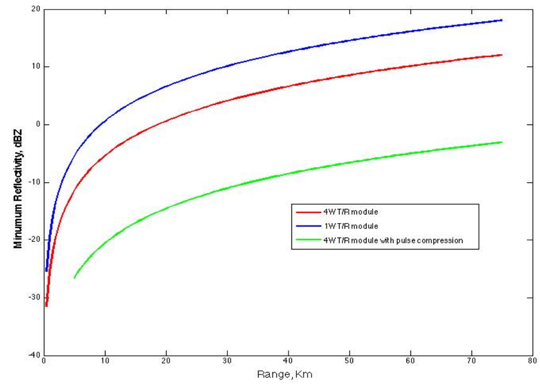

Figure 3. Sensitivities of the APAR for 4W and 1W transmit/receive (T/R) modules and 4W T/R modules with 33:0.3 pulse compression are shown as a function of range.

Commercial T/R modules at C-band have been identified which can transmit either 1W or 4W peak power. Solid state T/R modules are capable of transmitting long pulses for significantly improving average transmit power. They can transmit variable pulse lengths between 0.5 ms and 50 ms. In the case of 1W T/R module with 1 ms pulse width, the total peak transmit power is 3.6 kW. Radar sensitivity is linearly proportional to the peak transmit power. As shown in Figure 3, sensitivity of a 4W T/R element is better than a 1W T/R element by 6 dB. But, the 4 W T/R module does not meet the requirement of -12 dBZ sensitivity at 10 km. By transmitting 33 ms pulse, 4 W T/R module and using a pulse compression scheme, the sensitivity is improved to -20 dBZ at 10 km. The long pulse of 33 ms creates a blind zone of 5 km around the aircraft. The blind zone can be eliminated by transmitting an intermittent short pulse of 1 ms. PAR is designed to transmit long pulse and short pulse concurrently (Salazar et al. 2010). For simultaneous reception of long and short pulses, a dual-channel down converter is included. Transmission of short and long pulses leads to abrupt change in sensitivity at a 5 km range. Since at a range less than 5 km, the radar will detect better than -10 dBZ, the abrupt change in sensitivity due to long and short pulses will have no impact on detecting precipitation echo at close ranges.

3.3 ALONG TRACK RESOLUTION AND SAMPLING OF RADAR SIGNALS

One of the key benefits of electronically scanned (e-scan) radar is beam multiplexing. Since the beams can be instantaneously steered from one position to the next in an e-scan mode, scan sequences can be programmed for collecting only independent samples over the desired scan volume. Typically, only two pulses are transmitted for acquiring a pulse-pair estimate and then the beam is pointed at a different scan angle to collect the next sequence of independent samples. The beam is returned to the previous scan position only after the time to decorrelation is elapsed. At C-band, time to decorrelation (T_D) is 6.2 ms for a Doppler spectrum width of 1 m/s. The beam multiplexing technique allows for a reduction in the dwell time needed to acquire a sufficient number of independent samples. Averaging the signals of independent samples reduces fluctuation in radar estimates of wind and reflectivity. Figure 4 shows independent samples verses along track resolution for a specified aircraft speed and PRF. The larger the overlap between beams, better angular resolution is obtained, but it will lead to fewer independent samples as it requires more time for scanning for a specified angular sector. Limiting the beam overlap to 35%, for an along track resolution of 400 m, 20 independent samples can be obtained. It should be noted, the number of independent samples in the mechanically scanned antenna is determined by the dwell time of the beam, which is primarily determined by aircraft speed for a specified scan rate.

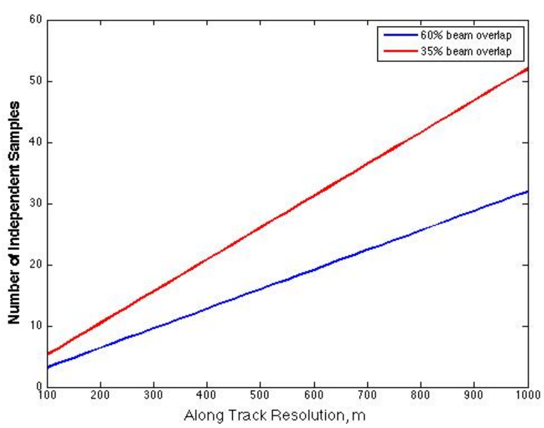

Figure 4. Number of independent samples verses along track resolution are shown for 35 and 60 % beam overlaps. The PRF is assumed 2000. Aircraft speed is assumed to be 125 m/s.

3.4 Measurement Accuracy of Mean Velocity

Measurement accuracy of Doppler radial velocity is a function of time-to-decorrelation (T_D), PRF and signal-to-noise ratio (SNR) (Doviak and Zrnic, 1993). Time-to-decorrelation determines the interval between two radar measurements that are statistically independent. It is the function of transmit frequency and spectrum width (Bringi and Chandrasekar 2001). In the case of C-band, T_D is larger than in the corresponding value at X-band. However, beam multiplexing offers the option for collecting more independent samples in the case of e-scan.

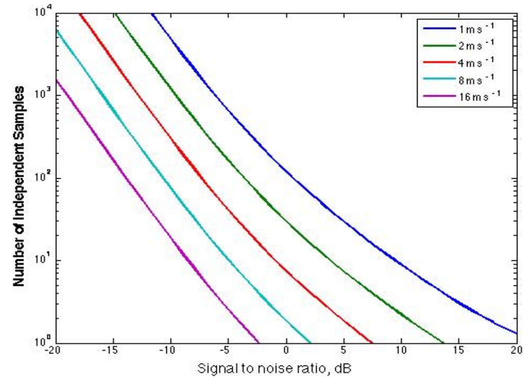

Figure 5. Requirement of number of independent samples as a function of signal-to-noise ratio for various mean velocity measurement accuracies are shown. Spectrum width is assumed 1 m/s and PRF is 2000 and transmit frequency is C-band.

Figure 5 shows the number of independent samples required as a function of signal-to-noise ratio (SNR) for various measurements of mean radial velocity accuracies. For 20 independent samples, SNR of 6 dB is required for estimating radial velocity within 1 m/s accuracy. Despite larger T_D at C-band, the e-scan feature of PAR allowed to estimate radial velocity within 1 m/s accuracy without much increase of SNR compared to ELDORA.

3.5 POLARIZATION OPTION FOR PHASED ARRAY RADAR

Conventional weather radars make polarimetric measurements in two distinct transmit/receive modes: (i) alternate transmit and simultaneously receive (ATSR), and (ii) simultaneously transmit and simultaneously receive (STSR). For STSR, any cross-coupling between horizontally (H) and vertically (V) transmitted/receive waves in the hardware and/or propagation medium due to canted hydrometeors would bias differential reflectivity (Z_{DR}) measurement (Hubbert et al. 2010a and Hubbert et al. 2010b). For example, in STSR mode, better than 44 dB isolation between H and V channels is required to insure that bias in Z_{DR} is less than 0.2 dB (Wang and Chandrasekar 2006); this requirement is extremely difficult to meet using stacked-patch microstrip antenna technology. Also, in the STSR mode, cross-polarization measurement is not feasible as the radar transmits in both horizontal and vertical polarizations simultaneously. In the ATSR mode 20 dB isolation between H and V channels is sufficient for limiting bias in Z_{DR} < 0.2 dB (Wang and Chandrasekar 2006, Bringi and Chandrasekar, 2001). As the most desired measurement in a polarization configuration is Z_{DR}, the alternate transmit mode is preferred for the proposed APAR.

The APAR system can be designed to operate in one of two alternating transmit modes: (i) ATSR which requires two receive channels and, (ii) ATAR (alternate transmit and alternate receive) which requires one receive channel. Figure 6 shows transmit and receive architectures for ATSR and ATAR modes. In the alternating transmit mode, both cross and co-pol measurements, such as full scattering matrix, are possible. A number of simulation studies and measurements of beam patterns suggest high quality polarimetric measurements could be collected over limited scan coverage from boresight (Zhang et al. 2009).

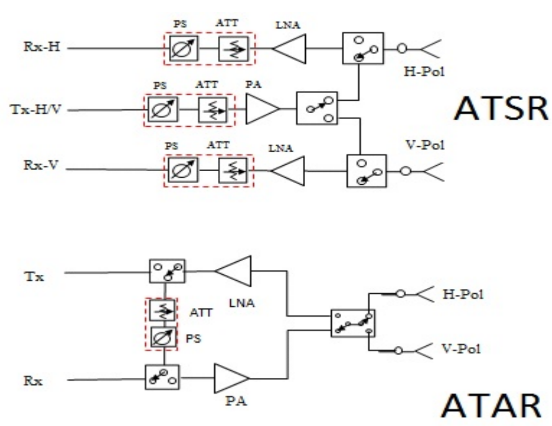

Figure 6. TR-Module architecture options for APAR:(a) dual-polarization alternate transmit and simultaneous receive (ATSR), (b) dual-polarization for alternate transmit and alternate receive (ATAR) modes.

In ATAR configuration, co- and cross-polarization returns are measured by alternating transmit pulses between horizontal and vertical polarizations. While LDR can still be measured, twice as many pulses will be required to achieve the same objective, thereby reducing spatial resolution by a factor of two over ATSR for cross-polarization measurements; co-pol measurements are made at the same spatial resolution. Since the strategy for APAR is to acquire polarimetric measurements over a restricted range of scan angles (5º in Azimuth and ± 20º in elevation), the reduction in spatial resolution of making cross-polarization measurements using an ATAR architecture is not significant. However, the cost of implementing the ATAR architecture over the ATSR architecture is significantly reduced due to the lower component count in each of the T/R elements.

The primary polarimetric capability is to estimate co-polar parameters (e.g. differential reflectivity (Z_{DR}), specific propagation phase (K_{DP}) and co-polar correlation coefficient ($r_{hv)}$) (Vivekanandan et al. 1999). For precise measurements of the above-mentioned polarimetric measurements, horizontal and vertical antenna patterns of the main beam must be in excellent agreement spatially. This not only applies to broadside, but also as the beam is scanned in azimuth and elevation. A secondary polarimetric capability is to produce quality cross-polar measurements, namely, linear depolarization ratio (LDR). To achieve this objective, integrated cross-polar ratio (ICPR) is the defining property. For estimating intrinsic LDR of -27 dB within 1 dB error, ICPR must be better than -30 dB (Bringi and Chandrasekar, 2001). Since the expected ICPR of microstrip patch antenna will be at the most -25 dB, the lowest LDR value detected by the APAR will be -22 dB. This applies not only to broadside, but also as the beam is scanned in azimuth and elevation. In order to limit the effect of differential gain and beam pattern on polarimetric measurements, co-polarization measurements will be collected only up to 20^{o} from bore sight.

4. SUMMARY AND DISCUSSION

Preliminary design specification of the APAR that may replace the ELDORA are described in this paper. The APAR is being designed to be capable of collecting microphysical and dynamical scientific products. Design specifications of APAR are more stringent than a ground-based PAR. The airborne platform allows the measurement and collection of dual-Doppler and dual- polarimetric measurements to retrieve microphysical quantities of precipitation. Multiple AESA radars on the C-130 fuselage enhance spatial and temporal resolutions of measurements.

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Table 1: Technical Specifications of C-band APAR

Parameter	C-Band
Frequency	5.4 GHz
Wavelength	5.55 cm
Element spacing along parallel and perpendicular to fuselage	2.78 cm, 2.78 cm
Number of Elements along parallel and perpendicular to fuselage	56, 64 (3584 elements)
Line Replacement Unit Size (LRU	8x8 (64 elements)
Number of LRU's per PAR	7x8 (56 LRU's)
Antenna Beamwidth (Elev, Azim) in Transmit mode (Uniform aperture illumination)	θ_0: 1.8°, 1.6° θ_{45}: 2.1°, 1.8°
Antenna Beamwidth (Elev, Azim) in Reception mode (Taylor aperture illumination)	θ_0: 1.9°, 2.2° θ_{45}: 2.2°, 2.5°
Antenna Directivity D_{Tx}, (Uniform) D_{Rx} , (Taylor aperture illumination)	40 dB 39 dB
Cross polarization for Alternate Transmit and Simultaneous Receive (ATSR)	Better than -20 dB
Transmit Power (max.) considering 4W/TR module	~14 kW
Radar Angular Resolution	~0.31 km @ 10km
Minimum Detectable Signal (at 10km)	-20 dBZ