DESIGN OF THE HIAPER CLOUD RADAR

Wen-Chau Lee Jothiram Vivekanandan Eric Loew Gorden Farquharson
Earth Observing Laboratory
National Center for Atmospheric Research[1],
Boulder CO, 80307

1. Introduction

One of the attractive features of a millimeter wave radar system is its ability to detect micron-sized particles that constitute clouds with lower than 0.1 g m^{-3} liquid or ice water content. Scientifically, cloud initiation, microphysics, and climate studies have driven the development of cloud radars in the last two decades. The remote sensing of cloud kinematic and microphysical properties using millimeter wave radars was proposed in late 1980s (e.g., Lhermitte 1987). Detail kimematic structures in none to light precipitation clouds have been revealed by these millimeter wave radars (e.g., Hamazu et al. 2003; Kollias and Albrecht 2000; Kollias et al. 2001; Pazmany et al. 1994). Smaller raindrops fall into Mie regions for the 95 GHz (W-band) radar. Kollias et al. (2002) demonstrated how vertical air motion and mean drop diameters in clouds can be retrieved by taking advantages of the Mie scattering in W-band cloud radars.

A number of airborne real aperture radars exist for cloud and precipitation remote sensing. For example, the NASA cloud radar system (CRS on ER-2, Li et al. 2004), Wyoming cloud radar (WCR on King Air, Galloway et al. 1997), Canadian Convair-580 cloud radar, UMass/JPL ACR, UMass CMR ARM UAV, and Spider (Japan; deployed on a Gulfstream III) are capable of sensing -10 to -30 dBZ at 10 km range. Most of these radar systems lack scanning capability, except the Spider which has limited cross-track scanning. Also, measurement of 2-D winds, full-polarimetric observations or advanced signal processing of radar time series is uncommon. The HIAPER cloud radar (HCR) initiative provides an opportunity for expanding the envelope of airborne radar systems by delivering high spatial and temporal resolution observations with improved accuracy on a long range HAIPER aircraft in comparison to existing systems. The envisioned capability of a millimeter wave radar system on HIAPER is enhanced by coordination with onboard LIDAR, microwave radiometer and in situ probes. The radar measurements would be suitable for quantifying both kinematics and microphysical parameterization schemes in cloud modeling and verifying temporal and spatial scales of cloud systems. This paper described the preliminary design of the HCR.

2. Design considerations

The technical specifications of a radar primarily depend on the scientific expectations of the research community. A questionnaire was created to address the following important issues: (1) scientific requirements, (2) system requirements, and (3) the usage of radar with other sensors on board the HIAPER platform. The survey results indicated a common preference for a narrow beamed W-band radar with polarimetric and Doppler capabilities. Additional capabilities included a second wavelength and/or dual-Doppler winds.

Requirements for cloud and precipitation radar remote sensing are very stringent due to the need for high sensitivity (> -25 dBZ @ 10 km) and wide dynamic range of received signal strengths (90 dB or more). The absorption of millimeter wave signals due to water vapor, and the effects of Mie scattering (i.e. hydrometeor size comparable to radar wavelength) also greatly affect radar performance. In addition to the above-mentioned basic system requirements, it is also important to consider various configurations of a typical airborne weather radar system:

- Single vs. dual-Doppler observations: Both microphysics and kinematics are closely related. A dual-beam configuration is capable of retrieving both radial and cross-beam winds, i.e. more accurate depictions of the vertical motion and entrainment in clouds.
- Co- and cross-polarization measurements: Polarization observations are routinely used in a number of research radars for retrieving cloud microphysics such as delineating regions of liquid and ice and mixed phase vs. single phase clouds (Vivekandanan et al. 1994, 1999a, 1999b). Also polarization observations can be used for quality control of the data.
- Scan vs. a simple stare mode: A scan mode offers better spatial coverage but accurate Doppler observation in a scan mode requires

[1] Corresponding author address: Dr. Wen-Chau Lee, NCAR Earth Observing Laboratory, Boulder, CO 80307. NCAR is sponsored by the National Science Foundation.

precise beam-pointing information. As the radar will be mounted on a wing-pod, it is important to compensate for both aircraft motion and wing deflection.

- Planar phased array vs. reflector type antennas: A low weight conformal phased array antenna may offer adaptive scanning for accomplishing rapid scanning and also reduction of Doppler spectral broadening due to beam motion during Doppler observation. However, a phased array system at millimeter wave band is expensive and it might be risky to build such a system. A reflector or lens type antenna may satisfy the research community's present requirements for sensitivity, Doppler velocity measurements and polarization capability.

3. Radar system concept

The basic HCR concept was distilled from responses to a selectively distributed scientific community survey, a thorough examination of millimeter wave radar technologies, as well as from input provided in discussions with engineers and scientists at JPL, NASA Goddard, and the University of Wyoming. These discussions led to a proposed millimeter wave radar system which is capable of measuring both full spectral moments (e.g., reflectivity, velocity, and spectrum width) and the full complement of polarimetric variables with sufficient sensitivity (>-25 dBZ @ 10km) and accuracy to be useful in the study of cloud microphysics. In addition, dual-Doppler winds and a second wavelength (K_u or K_a band) are highly desirable capabilities. Given cost constraints, and to obtain the greatest spatial coverage, we propose the vast majority of the radar system be housed in HIAPER's 20" wing pod, designated the NCAR pod. The HIAPER instrumentation philosophy dictates that only power and a high-speed network connection will be available to equipment located in the wing pods. This necessitates that nearly the entire radar system be located within the pod; the exception being the radar control and data display/archive computer(s). The pod will be attached to the mid-wing hardpoint as depicted in Figure 1, which shows a top view scale drawing of the pod in relation to the aircraft's left wing.

The dimensions of the NCAR pod limit the performance and capabilities of the HCR in two ways. First, the antenna aperture of the HCR is limited to less than 15". This limits both sensitivity and spatial resolution as the gain of an antenna is directly proportional to its aperture, while its beamwidth is inversely proportional to its aperture. This aperture constraint is necessary to avoid beam blockage by the pod's internal support structure as well as to enable zenith viewing through the use of a rotating reflector (splash plate). It also makes a Ku band (2.2 cm wavelength) impractical, owing to its 3.9 degree beamwidth and its significantly reduced sensitivity (-11 dB @ 10 km). Second, dual wavelength and dual Doppler are mutually exclusive properties of the HCR as space is lacking to accommodate the equipment necessary for both. This conclusion is based on a volume analysis which calculated the ratio of estimated equipment volume to the available volume for radar instrumentation. Ratio's of greater than 0.85 were considered unacceptable. Equipment volume was estimated based on manufacturer's specifications, when available. Pod volume was estimated based on current NCAR pod dimensions.

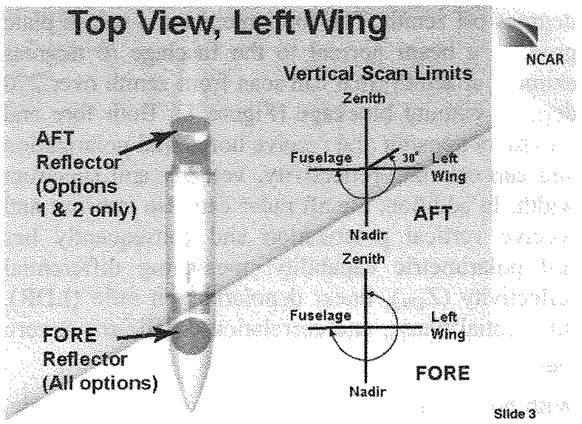

Figure 1: A perspective view of the pod from top of HIAPER above the left wing. The axes show the scanning limits of HCR for the fore and aft beams as viewed from the front of the aircraft.

Pod volume constraints led to the following radar system designs

- W-band dual-Doppler, dual-polarization radar
- K_a-band dual-Doppler, dual-polarization radar
- Dual-wavelength (K_a and W band), dual-polarization radar

These conceptual radar systems are discussed in detail in the following sub-sections. For each concept, radar system performance was calculated based on manufacturer's specifications and reasonable engineering assumptions. This was done for both scanning and non-scanning systems. A millimeter wave radar with a continuously scanning beam (360° coverage) was analyzed and rejected due to a loss of sensitivity (~4 dB) and unacceptable along track beam spacing (~3 km). A rotation rate of 30 degrees/sec is the fastest which can be achieved while still keeping velocity errors under 50 cm/s and reflectivity accuracy under 1 dB. This limits the dwell time to about 13 milliseconds, which in turn reduces the number of samples to incoherently average as well as the number of independent samples. Hence, the loss is sensitivity and greater velocity errors.

3.1 W-Band Dual-Doppler

The W-band dual-Doppler radar system concept is illustrated in Figure 2. It is comprised of two antennas fed by a single transmitter via a waveguide power divider. Both fore and aft antenna beams are capable of steering in elevation through the use of two rotating reflectors (splash plates). The aft antenna and splash plate produce a beam that is tilted approximately 40 degrees forward of nadir in azimuth and covers the complete lower hemisphere without blockage from the fuselage and up to 60 degrees off zenith. The fore antenna and splash plate produce a beam normal to the fuselage (0 degrees azimuth at zenith) that can scan from zenith over 270 degrees without blockage (Figure 1). Both fore and aft radars transmit and receive horizontal polarization and can estimate reflectivity, velocity and spectrum width. In addition, the aft radar can also transmit and receive vertical polarization and consequently has full polarimetric capability, measuring differential reflectivity (Z_{DR}), linear depolarization ratio (LDR), differential phase, and correlation coefficient at zero lag.

With both splash plates set at the same rotation angle, a dual-Doppler wind-field can be calculated for that plane. A dedicated receiver is required for each antenna to down-convert the radar returns to intermediate frequencies (IFs). The IFs are then digitized by commercial off the shelf hardware whose original application was Software Defined Radio (SDR). Fully demodulated quadrature data is then sent via high speed Ethernet to the in-cabin data system for further processing, display and archiving.

The characteristics for the W band system, fixed pointing angle, is given in 錯誤! 找不到參照來源。. The first column describes the characteristics for the forward-looking horizontally polarized beam, while the second column describes the characteristics for the aft- looking dual-polarized beam.

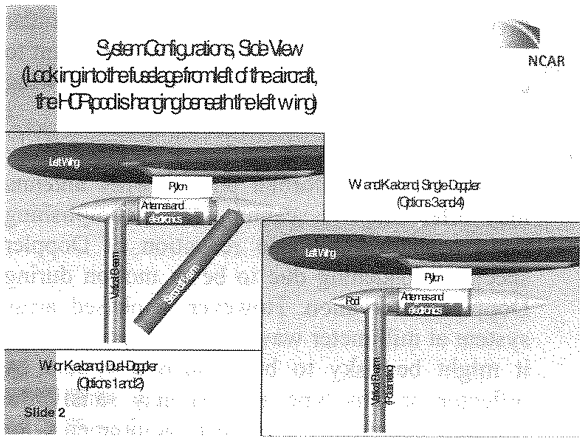

Figure 2: Single wavelength (W or K_a), dual-Doppler, dual-polarization radar concept (left) and the durl-frequency (W and Ka) dual-polarization radar concept (right). NCAR pod shown hanging from left wing.

3.2 K_a-Band Dual-Doppler

The K_a-band dual-Doppler radar system concept is identical to the W-band with the exception of wavelength.

3.3 Dual-Wavelength (W- and K_a-Band)

The dual W- and K_a-band radar system concept is illustrated in Figure 2. It is comprised of a single antenna with a dual-wavelength feed. Polarimetry is achieved on both wavelengths through the use of ortho-mode transducers (OMT's). As in the case of the single wavelength system, a rotating reflector is used to steer the beam in elevation. The antenna and splash plate produce a beam normal to the fuselage (0 degrees azimuth) that can scan from zenith over 270 degrees without blockage (Figure 1). The antenna is fed by two separate transmitters, one for each wavelength. Two receivers are required to down-convert the radar returns to intermediate frequencies (IFs). The IFs are then digitized by commercial off the shelf hardware for which the original application was software defined radio (SDR).

Fully demodulated quadrature data is then sent via high speed Ethernet to the in-cabin data system for further processing, display and archiving. A key issue for this system is whether to match the W and K_a antenna beamwidths. In general, matched beamwidths are desirable because they allow direct data retrieval with the fewest external assumptions. However, in the case of the HCR, matched beams result in a significant degradation of W-band sensitivity (~9 dB) which may limit the scientific usefulness of the W-band radar altogether. The characteristics for the W- and K_a-band system (unmatched non-scanning beams) are identical.

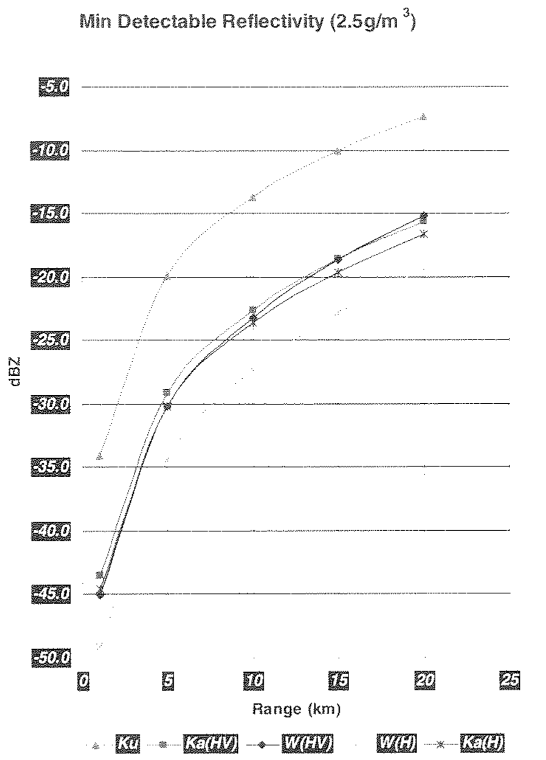

Figure 3: Minimum detectable reflectivity for a non-scanning radar at the various wavelengths considered in the presence of 2.5 g/m3 of water vapor.

3.4 Sensitivity Comparisons

Figure 3 shows radar sensitivity (non-scanning) as a function of range for the three wavelengths originally considered: K_u, K_a, and W. For W- and K_a-band two configurations are shown; single polarization only: W(H) and K_a(H) and fully polarimetric: W(HV) and K_a(HV). In all cases, atmospheric attenuation due to water vapor is included; the assumed density is 2.5 g/m3.

4 Recommendation

The aforementioned four options with their advantages and disadvantages were summarized in a second community survey. The majority of the second survey results (12 out of 16) favored the single-beam dual-wavelength option. As alluded to earlier, all four options meet the common requirements in the survey (i.e. vertical velocity and cloud phase discrimination) and provide additional capabilities, either focusing more on kinematics (options 1 and 2) or microphysics (options 3 and 4). Doppler observations along nadir or zenith support studies that relate to vertical mass or momentum flux measurements. The lack of 2-D winds using a dual-beam configuration limits entrainment studies. However, the measurement of 2-D winds in a single plane limits the scope of the entrainment studies normally performed with 3-D winds. Among the four survey results that favored the dual-beam option, two of them preferred W-band and the other two preferred K_a-band. The W-band was preferred due to its high sensitivity and better spatial resolution. The K_a-band was preferred for its better penetration into clouds and light precipitation and less Mie scattering effect when compared to W-band.

Polarimetric radar at W- or K_a-band can delineate regions of liquid and ice in the case of single phase clouds. However, W-band measurements are prone to Mie scattering and it is difficult to interpret polarimetric signatures with the interference of Mie scattering. It is almost impossible to detect mixed-phase clouds that are composed of cloud, liquid, and ice particles using single wavelength radar measurements because radar reflectivity is dominated by bigger size ice particles. The absorption measurement using dual-wavelengths can be used to detect cloud liquid presence and its amount. The dual-wavelength option with a nadir or zenith pointing beam was preferred due to the following:

(a) Rayleigh and Mie scattering at K_a- and W-band can be used for estimating mean particle size.

(b) Estimation of cloud liquid and droplet size using absorption measurement.

(c) Detection of mixed-phase precipitation.

(d) No other NSF instrumentation facility offers airborne dual-wavelength measurements.

(e) Potential of cloud microphysics retrieval using the dual-wavelength measurement is yet to be fully explored by the research community.

Most of the hydrometeors exhibit azimuthal symmetry in nadir or zenith axis that corresponds to a circular cross-section of hydrometeors. Polarization observations, such as differential reflectivity and propagation phase are insensitive to circular cross-sections. However, if the beam is steered away from nadir or zenith pointing directions, the corresponding polarimetric observations will be sensitive to non-spherical shape and size of hydrometeors.

Options 3 and 4 correspond to unmatched and matched beam dual-wavelength configurations respectively. The matched beam beamwidth is a factor of three larger in size than the corresponding unmatched beamwidth at W-band. The matched configuration eliminates uncertainty in microphysics retrieval due to sample volume mismatch but the sensitivity of the W-band is lower by more than 7 dB. On the other hand, the unmatched configuration offers best spatial and temporal resolutions. The uncertainty due to beam mismatch may be less significant in homogeneous precipitation event. Thus, the choice between dual-wavelength matched and unmatched beam configurations may depend on types of scientific missions and homogeneity in precipitation. To satisfy matched and unmatched beam requirements, two sets of dual-wavelength ortho-mode feeds can be built. It is practical to mount an appropriate feed as per the requirements of a scientific mission, provided the feeds are well-calibrated to assure quality of the measurements. The change in a feed configuration is independent of the rest of the system hardware. In summary, it is recommended to build a polarimetric Doppler dual-wavelength (K_a- and W-band) radar with both matched and unmatched beam configurations.

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