P2.1 AN OVERVIEW OF NOAA/ETL'S SCANNING K_a-BAND CLOUD RADAR

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1. INTRODUCTION

NOAA/ETL originally built and operated its scanning K_a -band cloud radar in the early 1980's. This millimeter-wave radar, known as NOAA/K (Fig. 1), has been continually upgraded and refined since then. It has been used extensively in atmospheric field experiments across the United States and in other countries. In the 1990's it was particularly useful in cloud observation programs motivated by climate change, aircraft icing, and weather modification research. The radar characteristics, capabilities, and applications are described in this article.

Millimeter-wave radars possess many valuable attributes for remote sensing of cloud structure and processes (Kropfli and Kelly 1996). Foremost among these attributes are excellent sensitivity and spatial resolution (~50 m). These allow the small hydrometeors of nearby non-precipitating clouds to be detected with fine-scale detail from the ground. Airborne and satellite platform applications are also feasible because the size and power requirements are small compared with longer wavelength precipitation radars. The major disadvantages of using these short wavelengths are severe attenuation by rain and limited maximum ranges (~30 km) for ground-based collection of useful cloud data.

2. BASIC CAPABILITIES

NOAA/K was one the first cloud radars to add scanning, Doppler, and polarimetric capabilities to further extend the realm of cloud features and processes that can be observed. Basic characteristics of the radar are listed in Table 1. Either of two antennas is used on a versatile scanning pedestal. The radar is transported to locations in North America on its 15-m flatbed trailer or it can be disassembled and transported overseas in two standard 6.1-m

Figure 1. The NOAA/K radar's offset Cassegrain antenna. The rotatable phase retarding plate is located directly above the dish.

Table 1. NOAA/K Radar Characteristics

Major Capabilities: transportable, scanning, Doppler, polarization diversity.
Primary Uses: observations of clouds, drizzle, snowstorms of any intensity, and very light rain.
Frequency: 34.66 GHz ($\lambda = 8.6$ mm).
Peak Transmit Power: 80 kW.
Antenna A1: 1.2-m diameter offset Cassegrain.
Antenna A2: 1.8-m diameter center-feed.
Beam Width: 0.3-0.5 deg., circular.
Pulse Length: 0.25 μs (37.5-m resolution).
PRF: selectable (2000 typical), double-pulse method to extend Nyquist.
Scans: PPI, RHI, sector, fixed beam, all with elevations through zenith and below horizon; scan rates up to 30 deg/s.
Sensitivity: approx. -30 dBZ at 10 km range.
Polarizations: RHC, LHC, and ellipticals with QWP; or H, V, and tilted linear with HWP on antenna A1. H or tilted linear with antenna A2.
Doppler Processing: pulse pairs or time series.
Data System: VME-based with DSP & SPARC.
Platform: 15-m flatbed trailer, or 2 seatainers.

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sea containers. The radar is normally powered by three-phase line power, but a 60-kW diesel generator is also available for operations at sites where commercial power is unavailable. Overall system calibration is checked using a trihedral corner reflector mounted atop a 25-m wooden pole at the radar's home base in Colorado.

Although pre-programmed scan sequences permit some unattended operation, the radar is normally attended by an engineer and a scientist. However, efforts have begun to make the system more robust and automated, with the eventual goal of fully unattended and remotely controlled operations. Remote near-realtime display of data on the worldwide web has already been demonstrated with the NOAA/ETL radars.

3. DATA SYSTEM

A new programmable realtime data processing and display system, known as the Radar Acquisition and Display System (RADS), was installed in NOAA/K in 1999. RADS controls the radar's scan and signal characteristics, and processes, displays and records the data (Campbell and Gibson 1997). It consists of a VME bus with an UltraSPARC-10 processor and DSP, A/D, timing generator, and synchro/digital cards. The programmable DSP allows the flexibility to incorporate new and revised algorithms for the data processing. Pulse pairs, time series, Doppler spectrum and other modes have been programmed and demonstrated with this system. The RADS realtime color display includes PPI, RHI, time-height, VAD profile, and amplitude-range ("A-scope") displays of the various fields. Data are currently recorded on a pair of 8-mm tape drives; one tape typically covers 12 h or longer, depending on the operating mode.

4. POLARIZATION AND ANTENNAS

NOAA/K has unique dual-polarization capabilities that are used for identifying cloud hydrometeor types based on particle shape information contained in the depolarization ratio (DR) measured by the radar. Two antennas are available. One is a 1.2-m offset Cassegrain dish with a phase retarding plate, built for NOAA/ETL by Millitec, Inc; the other is a 1.8-m center-feed dish commercially available from Alpha, Inc. The larger antenna has higher sensitivity and is used for projects where the ability to detect very weak clouds is of paramount importance. Linear polarization (H or 45-degree-tilted linear) is transmitted with this antenna and the co-polar and cross-polar returned signals are received simultaneously.

The offset Cassegrain antenna has lower side lobes for reduced ground clutter and it allows exceptional flexibility in selecting a desired transmit polarization state through the use of its phase retarding plate apparatus. Either a quarter-wave plate (QWP) or a half-wave plate (HWP) is used for this purpose. The plate's orientation can be set to select any of a wide variety of transmitted polarizations. The plate can also be slowly rotated (typically at 1 rpm) to cycle through many polarization states. The QWP produces (nearly) RHC, LHC, and a continuum of elliptical polarizations, depending on its orientation. The HWP produces (nearly) H, V, and a continuum of tilted linear states. In all cases, dual receivers measure the returned power in the co-polarized and cross-polarized states, from which the DR is computed.

5. CLOUD PARTICLE TYPE IDENTIFICATION

Knowledge of the particle types present in clouds is valuable for aircraft icing and cloud seeding applications, and studies of the radiative effects of clouds. The DR of various cloud and precipitation particle types has been calculated from theory for various transmit polarizations and angles of incidence, assuming realistic particle fall orientations, densities, and axis size ratios (Matrosov *et al.* 1996). Radar RHI scan observations of how DR varies with the antenna's elevation angle are then matched to these theoretical curves to identify the dominant particle type at each altitude. The RHI method assumes the particle type is horizontally homogeneous. *In situ* particle sampling has been used to verify the matches. Alternatively, the particles may also be identified by matching modeled theory to observation by holding the antenna elevation angle fixed and continuously rotating the phase retarding plate. Figure 2 shows the RHI-method DR signatures of several different particle types from separate clouds, all of which were verified by *in situ* sampling (Reinking *et al.* 2000).

6. CLOUD MICROPHYSICAL PARAMETERS

NOAA/K's reflectivity and Doppler measurements routinely reveal the heights, thicknesses, internal structure and kinematic features of most nearby clouds with intricate detail. This includes situations of multiple cloud

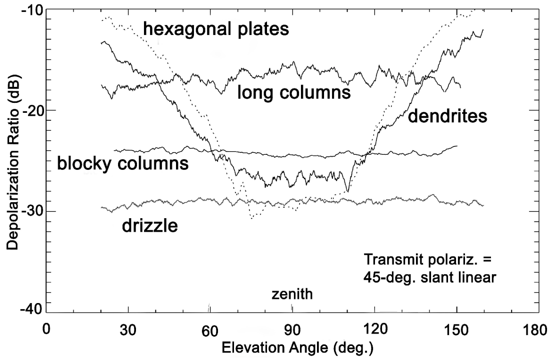

Figure 2. Particle type DR signatures from RHI scans with the NOAA/K radar (Reinking et al. 2000).

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layers and optically thick clouds, which are often impossible for optical remote sensors to penetrate. Microphysical features of clouds, such as median particle size, total concentration, and total mass content, can also be estimated by combining the radar reflectivity data with simultaneous observations of the same cloud region by radiometers or lidars. In the case of liquid water clouds, such as stratus, these techniques involve a combination of cloud radar and microwave radiometer measurements. For ice clouds, such as cirrus, the combination involves cloud radar and either lidar or infrared radiometer. An example of a retrieval using the radar/IR radiometer combination is shown in Fig. 3, plotted against *in situ* particle sampling by research aircraft. These methods, which were initially developed with NOAA/K data, are especially valuable for climate research.

7. OUTGROWTHS

The success of NOAA/K, in part, has inspired the development of several new cloud radars at NOAA/ETL and elsewhere. At ETL this includes the Millimeter Wave Cloud Radar (MMCR) for the U.S. Department of Energy for assessing the impact of clouds on climate (Moran *et al.* 1998), and the Ground-based Remote Icing Detection System (GRIDS) under development for the Federal Aviation Administration for automated aircraft icing condition warnings (Reinking *et al.* 2001). Both of these newer non-scanning systems are specifically designed for unattended operations. Meanwhile, NOAA/K continues to be a primary platform for testing new techniques and monitoring clouds and light precipitation for a wide variety of research topics.

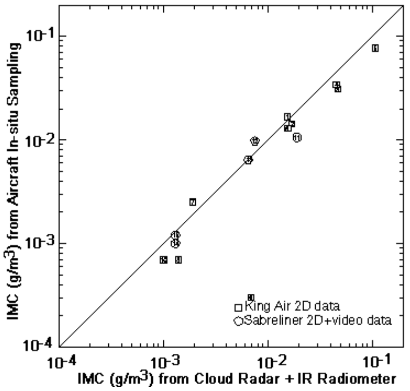

Figure 3. Ice mass content (IMC) in a cirrus cloud estimated from NOAA/K radar and IR radiometer measurements and from aircraft in-situ samples (Matrosov et al. 1998).

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More than anyone else, Robert Kropfli fostered the continuing development of the NOAA/K radar.

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