P2A.3 THE CLOUD RADAR SYSTEM

Paul Racette* and Gerald M. Heymsfield
NASA Goddard Space Flight Center
Greenbelt, Maryland

Lihua Li and Lin Tian
Goddard Earth Sciences and Technology Center
University of Maryland, Baltimore, Maryland

Ed Zenker
Science Systems Applications, Inc.
Greenbelt, Maryland

1. INTRODUCTION

Improvement in our understanding of the radiative impact of clouds on the climate system requires a comprehensive view of clouds including their physical dimensions, dynamical generation processes, and detailed microphysical properties. To this end, millimeterwave radar is a powerful tool by which clouds can be remotely sensed. The NASA Goddard Space Flight Center has developed the Cloud Radar System (CRS). CRS is a highly sensitive 94 GHz (W-band) pulsed-Doppler polarimetric radar that is designed to fly on board the NASA high-altitude ER-2 aircraft. The instrument is currently the only millimeterwave radar capable of cloud and precipitation measurements from above most all clouds. Because it operates from high-altitude, the CRS provides a unique measurement perspective for cirrus cloud studies. The CRS emulates a satellite view of clouds and precipitation systems thus providing valuable measurements for the implementation and algorithm validation for the upcoming NASA CloudSat mission that is designed to measure ice cloud distributions on the global scale using a spaceborne 94 GHz radar.

This paper describes the CRS instrument and preliminary data from the recent Cirrus Regional Study of Tropical Anvils and Cirrus Layers - Florida Area Cirrus Experiment (CRYSTAL-FACE). The radar design is discussed in Section 2. Characteristics of the radar are given in Table 1. A block diagram illustrating functional components of the radar is shown in Fig. 1. The performance of the CRS during the CRYSTAL-FACE campaign is discussed in Section 3.

Corresponding author address:
Paul Racette, NASA Goddard Space Flight Center,
Mail Code 555, Greenbelt, MD 20771;
email: Paul.E.Racette@nasa.gov

2. INSTRUMENT DESCRIPTION

The NASA Cloud Radar System (CRS) is a 94 GHz (W-band) Doppler polarimetric radar designed for autonomous operation on board the NASA ER-2 high-altitude aircraft and for ground-based operation. The radar is capable of measuring high-resolution profiles of reflectivity and Doppler velocity in cloud and precipitation regions. On the ER-2 that flies at 20 km above the surface, the CRS detects cirrus clouds with the advantage of operating at closer range than ground-based systems and without suffering the attenuation in the lower troposphere. The CRS can observe meteorologically significant cloud systems from the surface to the lower stratosphere.

TABLE 1: CRS System Characteristics

Freqeuency	94.155 GHz
IF Frequency	59.86 MHz
Duty Cycle	0.01 max
PRF	0.5 - 10 kHz
Pulse width	0.25 - 2 us
Peak Power	1.5 kW
Transmit Polarization	V or H
Receive Polarization	V and H
Noise Figure	7 dB
Receiver Bandwidth	1, 2 or 4 MHz
Total Mass (airborne)	90 kg
Antenna Beamwidth (deg) Antenna Gain	0.6 x 0.8 (Airborne) 0.3 (Ground based) 46.4 dBi (Airborne) 55 dBi (Ground based)
Minimum Detectable Signal*	-28 dBZe (Airborne) -45dBZe (Ground based)

*R = 10 km, dR = 150m, 1 second averaging

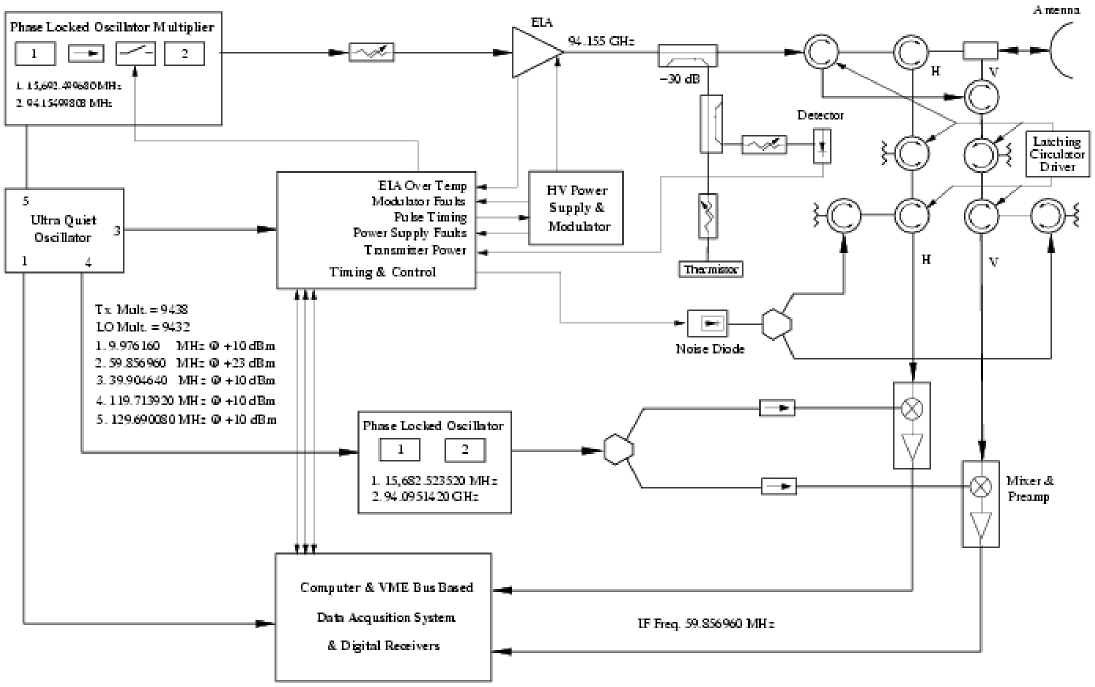

Figure 1: Block diagram of the Cloud Radar System

2.1 RF Subsystem

The RF/IF subsystem utilizes an Extended Interaction Amplifier transmitter tube (labeled EIA in Fig. 1) to transmit 1.7 kW peak power pulses at 94 GHz. This subsystem has a custom-made modulator, power supply, and timing control unit designed for ER-2 autonomous operation. The radar has built-in flexibility to transmit a wide variety of modulation schemes with a range of pulse widths between 0.25 and 3.0 μs at pulse repetition frequencies (PRF) up to 20 kHz (limited to 1% duty cycle). The radar also has the capability to transmit staggered PRFs.

The entire radar system is referenced to a shock mounted ultra stable oscillator which generates five coherent frequencies. Among these five frequencies, the 9.976 MHz from a crystal oscillator serves as the phase reference for the other four frequencies and is used to synchronize the data acquisition system. In the transmitter chain, a phase-locked oscillator and times-six multiplier assembly generates the 94.155 GHz RF frequency and serves as the carrier frequency of the pulsed input of the EIA. A second phase-locked oscillator and times-six multiplier assembly produces a signal that is 59.85 MHz apart from the RF signal and functions as the local oscillator signal for the receiver.

A network of latching circulators protects the receiver during the pulse transmission. The switch network permits switching transmit polarization and simultaneous detection of co- and cross-polarization for the measurements of the linear depolarization ratio (LDR), differential reflectivity (ZDR), and differential phase. A noise diode is used as a reference to monitor changes in the radar receivers. A diode detector monitors the average transmitter power.

Timing and control boards designed using a proprietary bus control the sequence of radar operation and checks for various fault conditions. Radar pulses can be triggered internally by 32 preset pulsewidth and PRF combination pairs or by an external trigger signal source. All system status data, including EIK and receiver temperatures, internal canister pressure, fault conditions, high-voltage and input voltage levels, etc., are recorded by the data system. The radar transmitter and receiver were developed by Pulse Technologies, Inc. in Marietta Georgia under the Small Business Innovative Research (SBIR) program.

Two antennas have been developed specifically for the radar. One antenna is used for ground-based operation and has 55 dBi gain. The other antenna designed for the ER-2 installation is an offset parabolic reflector antenna and has 47 dBi gain. The aircraft antenna has dual-linear fixed-position feedhorns; its primary reflector is mounted to a two-axis gimbals. This antenna has the capability to scan ±20° across track and ±5° along track for pitch correction. Motion control for automated positioning of the primary reflector is not yet implemented. Both antennas are novel designs incorporating Flat Parabolic Surface (FLAPS®) technology and were developed by Malibu Research in Calabasas, CA under the SBIR program.

The CRS installs easily into the unpressurized tail cone of an ER-2 superpod. The radar transmitter and receiver electronics are encapsulated in a temperature-controlled pressure vessel to permit the radar to operate in the low-pressure (about 40 mbar) and low-temperature (about -60°C) environment at the ER-2 cruising altitude. The pressure vessel, sealed by a V-band clamp, can easily be opened for routine maintenance. The data acquisition and processing system is located in a pressurized section of the superpod. In the ground-based configuration the CRS can operate with the higher gain antenna. The radar mounts to a two-axis gimbals platform that has wheels for mobility. Figure 2 shows a picture of the CRS mounted on the platform with the high-gain antenna.

Figure 2: Picture showing the CRS mounted onto the ground-based platform.

2.2 Data Acquisition and Signal Processing System

The data acquisition and signal processing system is based on a VME bus with a host computer that runs the Vxworks real-time operating system and provides basic control for complete autonomous operation of the radar system. Radar operation parameters can be modified through this host computer and pre-loaded into the data system before flight. The host computer records the processed radar returns and aircraft navigation data to a 2.6 GByte solid state disk drive. The solid-state disk drive provides improved reliability necessary for ER-2 operation. At the heart of the radar data system are processing boards designed by the National Center for Atmospheric Research (NCAR). The NCAR boards include a digital receiver that ingests the 59.85 MHz intermediate frequency (IF) signals from the radar receiver subsystem. The digital receiver has 90 dB dynamic range that is achieved using two 12-bit analog-to-digital converters operating in parallel. Within the digital receiver, the IF is digitized into the in-phase (I) and quadrature (Q) signal components and are then match filtered.

To overcome the range-Doppler ambiguity at 94 GHz, CRS uses a dual-PRF (4 kHz and 5 kHz) approach to extend the unambiguous range and Nyquist interval. The 4kHz/5KHz dual PRF mode extends the unambiguous Doppler measurements up to ± 17.5 m/s. Estimates of the Doppler velocities are performed using the auto-covariance (pulse-pair) processing. Three-pulse covariance products are calculated for 720 gates for each PRF. The covariance products are then averaged over a 0.5s interval. The pulse-pair estimator greatly reduces the computational requirement over frequency domain (spectral) processing. The 0.5s averaged real and imaginary auto-covariances for each gate are stored on disk; the mean Doppler and spectral width are estimated in post processing. In addition to the covariance products, the data system captures the standard (1 s) and high-speed (up to 64 Hz) aircraft attitude and navigation data for later use in correcting the Doppler velocities for aircraft motions.

The minimum detectable reflectivity of CRS is estimated from the minimum detectable signal, which is determined by the radar system noise level. The mean noise power Pn is calculated using $P_n=kT_oBF_n$, where k is the Boltzman's constant, T_o is the physical temperature of the antenna, F_n is the system noise figure. The CRS receiver noise figure is ~7.0 dB including waveguide and switch network losses. For a 1.0 µs RF pulse with a 1 MHz matched filter, CRS single-pulse minimum detectable reflectivity at 10 km range is -12 dBZe (equivalent radar reflectivity) with the airborne antenna, -29.2 dBZe with the ground-based antenna. Noise average and noise subtraction is necessary to improve the detection of weak cloud signals. For the typical CRS operation mode on ER-2 using the 4 kHz/5 kHz dual PRF mode, the effective PRF is 4.444 kHz. Using a one-second average and noise subtraction, the CRS minimum detectable reflectivity at 10 km range is about -30 dBZe. For ground-based operation, the corresponding minimum detectable reflectivity at 10 km range is about –47 dBZe.

3. MEASUREMENTS FROM CRYSTAL-FACE

During July 2002, CRS was installed on the ER-2 and participated in CRYSTAL-FACE. The experiment was based around and near the southern Florida peninsula[1], where deep convection occurs frequently during the summer months. The CRYSTAL-FACE objectives include improving the understanding of ice water and water vapor fields in the upper troposphere and their relation to global radiative fields, and the dynamical and radiative processes that produce clouds. As one of the six aircrafts operated during the CRYSTAL-FACE, the ER-2 carried a full suite of sensors selected to meet the experiment objectives. The ER-2 was based at the Key West Naval Air Station and conducted twelve science sorties during the experiment. The CRS collected its first data sets from cirrus and thunderstorms during CRYSTAL-FACE. CRS operated exceptionally well collecting complete data sets on every flight.

Fig. 3 shows CRS radar reflectivity and Doppler velocity measurements made on 11 July 2002, for one of the flight legs between 16:38 and 16:44 UTC. The ordinate indicates altitude and the abscissa shows distance along the flight path, both are in units of kilometers. A strong surface return is observed at about 0 km altitude. Over the extent of the period shown, the CRS detected a complex convective system. The CRS signal was able to penetrate through thick multi-layer clouds and light rain to detect the ocean surface. In one region between 25 and 30 km the ocean surface is obscured by attenuation caused by heavy precipitation. Doppler velocity estimates must be corrected for aircraft motion before they represent hydrometeor motions. These corrections use the ER-2 navigation information and the antenna tilt angle, i.e., the angle offset of the antenna along-track. The Doppler velocities in the image shown have not been corrected for aircraft motions. Nevertheless, a great deal of structure in the hydrometeor velocity field is apparent in the figure.

1 http://cloud1.arc.nasa.gov/crystalface

4. CONCLUSION

The CRS is a 94 GHz Doppler radar that can operate either from the ground or from board the high-altitude ER-2 aircraft. CRS provides unprecedented capabilities to observe clouds. The radar is capable of measuring clouds and precipitation from the surface to the lower stratosphere. For cirrus cloud detection, it has unique advantages over other ground-based millimeter-wave radars and existing airborne radars. The CRS operates in a downward looking mode from a high-altitude platform, thus providing nadir-viewing observations of nearly all cloud types. Operating from ER-2, CRS is able to measure altocirrus clouds at a closer range than ground-based radars and upward looking radars operated on middle- or low-altitude research aircrafts. Water vapor and oxygen absorption have minimum affect on its measurements of cirrus clouds. Thereby, the CRS is capable of detecting more of the high level cirrus than these other radars. During CRYSTAL-FACE, the CRS collected its first airborne data. Preliminary data analysis shows that CRS functioned well during the flights and has achieved most of the original scientific objectives.

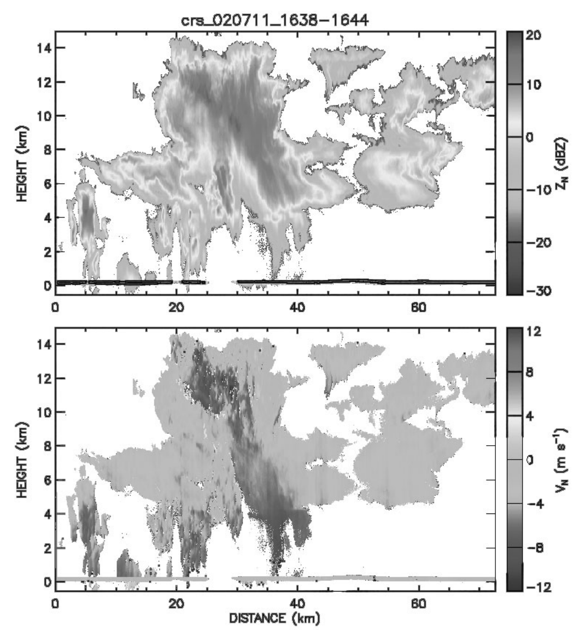

Figure 3: CRS measurements made on 11 July during the CRYSTAL-FACE campaign.