CloudSat: The Cloud Profiling Radar Mission

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Abstract — **The Cloud Profiling Radar (CPR), the primary science instrument of the CloudSat Mission, is a 94-GHz nadir-looking radar that measures the power backscattered by clouds as a function of distance from the radar. This instrument will acquire a global time series of vertical cloud structure at 500-m vertical resolution and 1.4-km horizontal resolution. CPR will operate in a short-pulse mode and will yield measurements at a minimum detectable sensitivity of -28 dBZ.**

I. INTRODUCTION

The CloudSat Mission [1] is a new satellite mission jointly developed by the National Aeronautics and Space Administration (NASA), the Jet Propulsion Laboratory (JPL), the Canadian Space Agency, Colorado State University, and the US AirForce to acquire a global data set of vertical cloud structure and its variability. Such data set is expected to provide crucial input to the studies of cloud physics, radiation budget, water distribution in the atmosphere, and to the numerical weather prediction models. Shortly after launch in late April 2006, the primary science instrument aboard the CloudSat satellite, the Cloud Profiling Radar (CPR) will begin acquiring information about the vertical cloud structure profiles by measuring the cloud backscattered power as a function of distance from the radar. The CloudSat satellite also flies as part of a constellation of satellites that also includes the EOS Aqua, EOS Aura, an aerosol lidar (CALIPSO), another small satellite, PARASOL, carrying the POLDER polarimeter. Another NASA satellite, the Orbiting Carbon Observatory (OCO), will be inserted into the formation later. This constellation as depicted in Fig. 1 is referred to as the A-train.

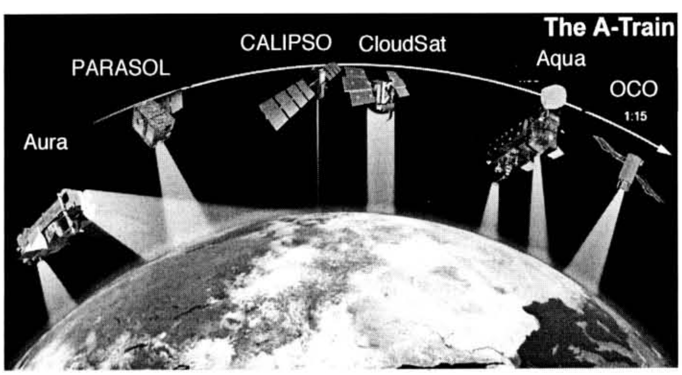

Figure 1: The A-Train constellation and its members.

CloudSat seeks to solve a number of outstanding cloud-climate problems and thereby spur improvements in both weather forecasting and climate prediction. It aims to evaluate quantitatively the representation of clouds and cloud processes in global atmospheric circulation models, and the relationship between the vertical profiles of cloud liquid water and ice content and cloud radiative properties, including the radiative heating by clouds. In so doing, CloudSat seeks to provide the first direct global survey of the vertical structure of cloud systems. It will also measure the profiles of cloud liquid water and ice water content and match these profiles of the bulk cloud microphysical properties to cloud optical properties. Optical properties contrasted against cloud liquid water and ice contents are a critical test of key parameterizations that enable calculation of flux profiles and radiative heating rates throughout the atmospheric column. To date this type of evaluation can only be carried out using data collected in field programs and from surface measurements limited to a few locations worldwide.

These primary objectives are also augmented by other science objectives. CloudSat data provides a rich source of information for evaluating cloud properties derived from other satellite data including those produced from Aqua as well as cloud information derived from operational sensors. CloudSat information will also improve when data from other sensors are combined with the radar. CloudSat and the A-train also offer an unprecedented resource for understanding the potential of aerosol for changing cloud properties and thus the radiative budget of clouds. The aerosol context provided by other constellation measurements include MODIS on Aqua, the lidar on CALIPSO, the polarimeter on PARASOL and aerosol chemistry from Aura measurements. This information can be combined with the cloud water, ice and precipitation information of CloudSat and AMSR (on Aqua) to a lesser degree, and the cloud optical property information of MODIS and PARASOL to explore aerosol-chemistry-cloud interactions.

II. CLOUD RADAR SYSTEM DESIGN

Clouds are weak scatterers of microwave radiation especially in contrast to the reflection of the underlying Earth's surface. The overriding requirement on CPR is to achieve a minimum detectable cloud reflectivity (Z) of -28 dBZ. By comparison, the reflectivity for rain is typically 20-50 dBZ; the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) [2] has a sensitivity of around +17 dBZ.

Maximizing the cloud detection sensitivity requires careful tradeoff among several competing and often conflicting parameters, including the cloud backscattering sensitivity, atmospheric absorption, resolution, and radar technology. The detection sensitivity is primarily determined by the radar received power and the noise level. The radar received power can be written as [3]

$$P_a(r) = \frac{P_t \lambda^2 G^2 \theta^2 \Delta \eta L}{512\pi^2 \ln 2 r^2} \tag{1}$$

where P_t is the transmitter power, λ is the wavelength, G is the antenna gain, θ is the antenna half-power beamwidth, Δ is range resolution, r is the range to the atmospheric target, η is the cloud reflectivity, and L is the signal loss. $P_a(r)$ is the received power from the atmosphere versus range. The product $G^2 \lambda^2 \theta^2$ is proportional to the antenna effective area. Thus, the received power is increased by increasing antenna area, range resolution, transmit power, and reflectivity. The antenna size is limited by the physical launch constraints such as volume and mass. Transmitted power is limited by the technology of the transmitter itself and by the power supply capability of the spacecraft.

The amount of power received is strongly influenced by the cloud reflectivity and the atmospheric absorption. In general, the cloud reflectivity increases by increasing the radar frequency. On the other hand, signal absorption due to atmospheric gases may be prohibitively large at higher frequencies. From these considerations, the use of 94 GHz provides an increase of 33 dB as compared with the use of the TRMM PR frequency of 14 GHz, and thus, allows the sensitivity requirement to be met using available technology.

Sensitivity is also related to the pulse length *(τ)*. CPR will operate using 3.3-μs monochromatic pulses to provide the required sensitivity while meeting the range resolution requirement of 500 m. Other approaches taken to improve sensitivity involve reducing noise from various sources. The receiver noise is minimized by using a low noise amplifier and by reducing the losses between the antenna and the low noise amplifier. The total noise power is reduced by matching the receiver bandwidth to the transmit bandwidth. The thermal noise contribution is further reduced by averaging many samples of the measured power and subtracting the estimated noise level. The number of independent samples can be increased by increasing the pulse repetition frequency (*PRF*). However, the maximum *PRF* is set by range ambiguity considerations. For CPR, the nominal range window size is set at 30 km and the nominal *PRF* of 3700 Hz is used. The actual *PRF* used in flight is varied slightly to accommodate for the change in orbital altitude.

The CPR measurements along the nadir track are averaged in 0.48-sec time intervals. This corresponds to an effective along-track horizontal resolution of 3.8 km after averaging. The 0.48-s averaging at 3700 Hz provides nearly 1800 independent samples. The noise subtraction approach should allow signals that are 15 dB below the thermal noise to be detected. Figure 2 graphically depicts the CPR instrument, and Table 1 shows the expected functional and performance parameters of CPR during normal operations.

Figure 2: Cloud Profiling Radar (CPR) and CloudSat satellite in flight configuration.

Table 1: CPR instrument and performance parameters.

Frequency	94.05 GHz
Altitude	705 km
Range resolution	500 m
Cross-track resolution	1.4 km
Along-track resolution	3.5 km
Pulse width	3.33 μs
Peak power (nominal)	1.7 kW
PRF	3700 Hz
Antenna diameter	1.85 m
Antenna gain	63.1 dBi
Antenna sidelobes	-50 dB @ $\theta > 7°$
Integration Time	0.48 sec
Data window	0 – 30 km
Min. detectable reflectivity	-28 dBZ

III. RADAR HARDWARE

CPR is implemented by the following subsystems: Radio-Frequency Electronics Subsystem (RFES), High-Power

Amplifier (HPA), Antenna, Digital Subsystem (DSS), and Power Distribution Unit (PDU). The simplified version of the CPR instrument block diagram is shown in Fig. 3.

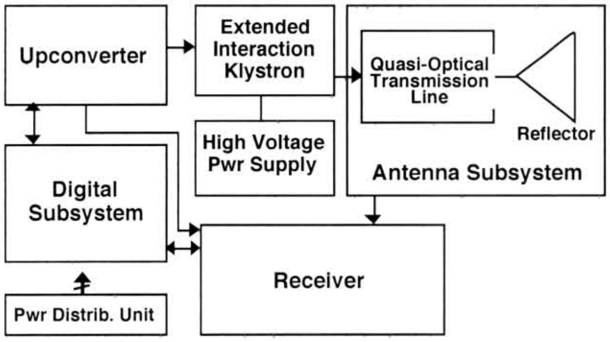

Figure 3: Simplified CPR block diagram.

The Radio-Frequency Electronics Subsystem (RFES) [4] consists of an upconverter which accepts a 10 MHz oscillator signal from the DSS and upconverts it to a pulse-modulated 94 GHz signal. The signal is amplified to approximately 200 mW by a MMIC power amplifier. A switch within the upconverter is used to provide the modulation for generating pulses. The receiver accepts the received signal from the antenna and downconverts it to an intermediate frequency. A MMIC low-noise amplifier (LNA) provides the first stage of amplification. The gain of the LNA is large enough that additional stages have only a small contribution to the system noise temperature. The IF signal following downconversion is detected using a logarithmic amplifier.

The High-Power Amplifier (HPA), which amplifies the transmitted pulse to a nominal power level of 1.7 kW, consists of an extended interaction klystron (EIK) and a high-voltage power supply (HVPS). Both a primary and a backup HPA are used to enhance system reliability. Figure 4 shows one of the two CPR HPA flight models. The EIK tube is manufactured by Communications and Power Industries, Canada, Inc. The EIK differs from standard klystrons by using resonated bi-periodic ladder lines as a replacement for conventional klystron cavities. The high-voltage power supply (HVPS) provides 20 kV needed to operate the EIK and provides telemetry data necessary to system needs. The design uses a boost supply to minimize input current transients during the pulsing period and control EMC problems.

The CPR Antenna Subsystem consists of the collimating antenna reflector and the Quasi-Optical Transmission Line (QOTL) [5]. The collimating antenna is a fixed 1.85-m diameter reflector, made from space-qualified composite graphite material to reduce mass. The antenna provides more than 63 dBi gain, has beamwidth < 0.12°, and has sidelobes less than -50 dB for angles greater than or equal to 7° from boresight. This low sidelobe level is achieved using an offset feed design. Instead of using conventional waveguide, the antenna is fed by the QOTL for low loss. This QOTL approach is based on free-space transmission of Gaussian RF beams, with beam direction and focusing achieved by shaped metallic mirrors. The CPR Antenna Subsystem flight model is shown in Figure 5.

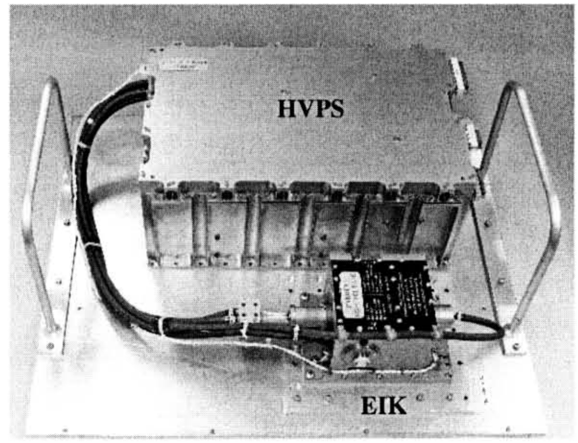

Figure 4: CPR High Power Amplifier flight model S/N-2.

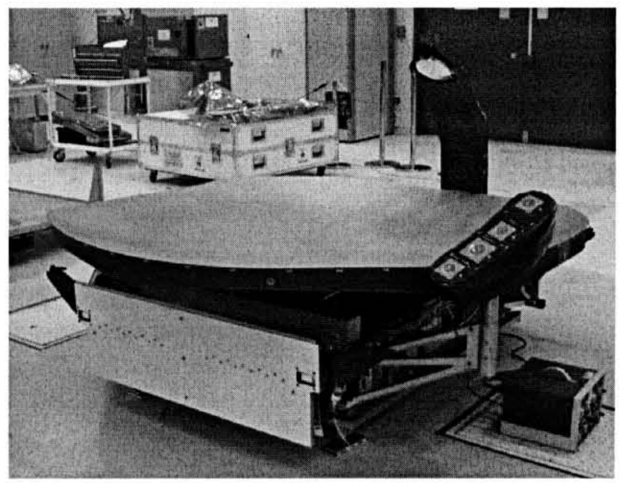
Figure 5: CPR Antenna Subsystem flight model.

The Digital Subsystem (DSS) provides the following functions: (1) receives commands from the spacecraft and transmits them in the correct format to the rest of the radar; (2) digitizes the telemetry from the rest of the radar and incorporates the digitized words in the science and telemetry data streams; (3) digitizes the radar echo, performs data processing and routes the data to the spacecraft data system for downlink; (4) generates the radar timing signals including the STALO; (5) routes the critical radar telemetry to spacecraft for real-time health monitoring. The Digital Data Handler (DDH) accepts the analog signal from the RFES logarithm detector. It digitizes the signal and performs the required averaging at each of 125 range bins. The averaged power is converted to a floating-point format prior to being sent to the solid-state recorder. The use of floating point reduces the required number of bits and data rate. No flight computer or flight software is used by DSS, most of the DSS functions are implemented using FPGAs.

The Power Distribution Unit (PDU) accepts the nominal 28V DC prime power from the spacecraft, and converts the 28V input to appropriate secondary DC voltages to operate those lower voltage electronics subsystems. The PDU is based on commercial off-the-shelf power supplies. The PDU supplies power to the RFES, DSS, and the antenna subsystem (HPA selection switch). The HPAs accept the 28 V power from the spacecraft directly. The spacecraft also directly supplies 28 V power to replacement heaters. These will be operated whenever the radar is off, in order to maintain the electronics at temperatures within the survival range.

IV. Radar Calibration

For volume scattering, the quantity of interest is the radar cross section per unit volume, or the radar reflectivity, η. From Eq. (1), η is calculated as

$$\eta = \frac{P_a (4\pi)^3 r^2 L_a}{P_t \lambda^2 G^2 \Omega \Delta} \qquad (2)$$

where Ω is the integral of the normalized two-way antenna pattern, Δ is the integral of the received waveform shape (i.e., range resolution), and L_a is the two-way atmospheric loss. Correction of η for atmospheric attenuation will be done as part of the science data processing. Accuracy of radar reflectivity depends on the precise knowledge of r, λ, G, Ω, Δ, P_a, *and* P_t. During pre-launch calibration, the radar parameters are obtained from either direct laboratory measurements or analysis of experiment data. During flight, the transmit power and the receiver gain will be routinely measured via the CPR internal calibration channel. Clear-air atmospheric absorption loss will be estimated from collocated airborne radiosonde date and water vapor maps. Based on the pre-launch measurements and the estimated post-launch variations, the overall CPR calibration error budget (see Table 2) has been derived. It is anticipated that the CPR radiometric calibration accuracy shall be within 2 dB over the life of the mission.

Table 2: CPR calibration error budget.

CPR Parameter	Pre-launch measure	Launch effects	Stability	RSS
λ^2	0	0	0	0.0
r^2	0	0	0	0.0
Δ	0	0	0.1	0.1
P_t	1.1	0	0.4	1.2
$G^2\Omega$	0.9	0.4	0.4	1.1
P_r	0.5	0	0.4	0.6
La	0.0	0	1.0	1.0
RSS (dB)	1.5	0.4	0.7	2.0

In addition, cloud-free clear ocean backscatter measurements are routinely acquired to validate of the CPR radiometric calibration. The ocean backscattering coefficient at Ku-band (14 GHz) is known to have minimum sensitivity to wind speed and wind direction at approximately 10 degrees, and several spaceborne Ku-band scatterometers and the TRMM Precipitation Radar have used ocean surface backscatter measurements acquired at ~10 degree incidence angles to successfully validate their radar calibration [6], [7]. Recent airborne radar measurements also confirmed that the ocean surface backscattering coefficient is insensitive to surface wind conditions near 10° incidence angle even at 94 GHz [8]. At part of the post-launch instrument validation campaign, the CloudSat spacecraft will point the CPR antenna near 10 degrees incidence over the clear ocean once per month to acquire this type of external validation data. The CPR acquired nadir data over clear ocean are also routinely extracted for the monitoring of the long-term instrument stability.

V. Summary

The Cloud Profiling Radar (CPR) for the CloudSat mission is a 94-GHz, nadir-pointing, high-power pulse radar. It will be the first-ever millimeter-wave and the most sensitive radar even launched into space. Its –28-dBZ detection sensitivity will enable the first global view of the vertical structure of the atmospheric clouds at 500-m resolution. While the radar is fairly straightforward from a functional point of view, the required technology at millimeter wave frequencies have presented some challenges during hardware implementation.

The data acquired by the CloudSat radar will stimulate important new research on clouds and precipitation, and together with the A-Train, provide a unique opportunity to advance our understanding of the aerosol effects on clouds and precipitation. The CloudSat mission also provides an important demonstration of the 94 GHz radar technology in a space-borne application.

Acknowledgment

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References

[1] G. L. Stephens et al., "The CloudSat Mission and the A-Train," *Bull. Amer. Meteor. Soc.*, vol. 83, 1773-1789, 2002.

[2] T. Kozu et al., "Development of precipitation radar onboard the Tropical Rainfall Measuring Mission (TRMM) satellite" *IEEE Trans. Geosci. Remote. Sensing,* vol. GE-39, pp. 102-116, 2001.

[3] J. R. Probert-Jones, "The radar equation for meteorology," *Quart. J. Royal Meteor. Soc.*, vol. 88,

485-495, 1962.

[4] R. LaBelle, R. Girard, and G. Arbery, "A 94 GHz RF electronics subsystem for the CloudSat Cloud Profiling Radar," *Proc. European Microwave Conf.*, October 2003.

[5] S. Spitz, A. Prata, J. Harrell, R. Perez, and W. Veruttipong, "A 94 GHz Spaceborne Cloud Profiling Radar Antenna System," *Proc. IEEE Aerospace Conf.*, March 10-17, 2001.

[6] L.C. Schroeder et al., "The relationship between wind vector and normalized radar cross section used to derived SEASAT-A Satellite Scatterometer winds," *J. Geophy. Res.*, vol. 87, No. C-5, 3318-3337, 1982.

[7] L. Li, E. Im, S.L. Durden and Z.S. Haddad, "A surface wind model-based method to estimate rain-induced radar path attenuation over ocean," *J. Atmos. Oceanic Technol.*, vol. 19, pp. 658-672, 2002.

[8] L. Li et al., "Measurements of ocean surface backscattering using an airborne 94-GHz cloud radar - implication for calibration of airborne and spaceborne W-band radars," *J. Atmos. Oceanic Technol.*, vol. 22, 1033-1045, 2005.