Cloud Profiling Radar (CPR) for the CloudSat Mission

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INTRODUCTION

The CloudSat Mission is a new satellite mission currently being developed by NASA and the Canadian Space Agency (CSA) to acquire a global data set of vertical cloud structure and its variability. Such data set will provide crucial input to the studies of radiation budget and water distribution in the atmosphere, and to the numerical weather prediction models. One key science instrument aboard the CloudSat satellite is the Cloud Profiling Radar (CPR). CPR is a 94-GHz nadir-looking radar that measures the power backscattered by clouds as a function of distance from the radar. These data will provide an along-track vertical profile of cloud structure. Fig. 1 shows the operational geometry of CPR. In this paper, we will present the system design and the expected performance of this instrument, as well as the state-of-the art millimeter-wave technologies employed by this instrument.

CONCEPTUAL DESIGN

The design of CPR is driven by the CloudSat science objectives. The primary science objective is a minimum detectable cloud reflectivity of -26 dBZ at the end of the mission. This low reflectivity is needed since clouds are weak scatterers. By comparison the reflectivity for rain is typically 20-50 dBZ; the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) [1] has a sensitivity of around +20 dBZ. The sensitivity required by CPR dictates the use of 94 GHz. A lower frequency would require either an impractically large antenna or an impractically large peak transmit power. Use of 94 GHz allows the sensitivity requirement to be met using available technology.

Sensitivity is also related to pulse length; longer pulse lengths provide better sensitivity but poorer vertical resolution. As its primary, or nominal, mode CPR uses a 3.33 μs monochromatic pulse. This provides the required sensitivity while also meeting the range resolution requirement of 500 m. The required vertical resolution can be maintained when using longer pulses by employing pulse compression techniques [2], [3]. In this case a frequency-modulated chirp is transmitted and the received signal is compressed by correlation with a replica of the transmitted signal. While pulse compression can be used to enhance the vertical resolution, it has the disadvantage of creating range sidelobes. CPR has as a goal a second mode which uses pulse compression. In this mode data are acquired by alternating between sets of short pulses and sets of 33.33 μs linear frequency-modulated chirp pulses with pulse compression. Both types of pulses provide the required range resolution and both meet the sensitivity requirement. However, the data acquired using chirp waveform have improved sensitivity by 4-5 dB but are not useful below 5 km altitude due to the contamination of range sidelobes from the surface. The required sidelobe suppression to make the chirp data useful down to the surface is at least 75 dB, probably greater for a smooth ocean surface. This is considered beyond the current state of the art.

To detect the low-reflectivity clouds, the CPR averages many samples of the measured power and subtracts the estimated system 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, allowing capture of the surface return and cloud return up to an altitude of 25 km. System noise level is estimated using the clear air radar return from 25 to 30 km altitude. A data window of 30 km allows a maximum PRF of 5000 Hz. However, because the altitude varies over the orbit, such a high PRF would require continuous updating. Instead, a PRF around 4300 Hz is used. This PRF still requires that the satellite update the radar configuration according to altitude approximately once per minute. The maximum PRF for chirp pulse operations is reduced to 800 Hz due to power consumption considerations. In the baseline design, the radar measurements along the nadir track are averaged in 0.3-sec time intervals. This corresponds to an effective along-track horizontal resolution of 3.5 km (i.e., 0.3 s x 7 km/s + 1.4 km) on the CPR measurements after averaging. In order to provide enhance capability to discriminate cloud features, the CPR measurements are sampled at 250-m in range, and 0.15-sec along the nadir track. In the second mode CPR alternates between chirp and short pulse blocks with length of 0.15 s.

In addition to thermal noise, the backscattered signal may be contaminated by surface clutter through antenna sidelobes or pulse compression sidelobes. For a nadir-pointed antenna, the primary clutter source is the surface returns from previously transmitted pulses that are received through the antenna sidelobes. The CPR uses a frequency diversity scheme

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and a designed antenna pattern with -38 dB sidelobe performance to reduce the surface clutter through antenna sidelobes. In this frequency diversity approach, the transmitter transmits a sequence of pulses with carrier frequencies separated by approximately 2 MHz. The receiver tracks these frequencies, so that the desired echo from clouds is within the receiver bandwidth, while surface return from previous pulses leaking through antenna sidelobes is outside the receiver bandwidth. Calculations have shown that this approach provides sufficient clutter suppression even for a land surface and an antenna with constant sidelobes [4].

The planned operational scenario calls for continuous radar science data acquisition. Mode 1 consists of entirely short pulse (SP) operations, while Mode 2 consists of 50% SP operations and 50% chirp pulse (CP) operations. In the nominal satellite orbit, Mode 1 is planned to operate 80% of the time, while Mode 2 operates 20%. As such, about 90% of each orbit the CPR will make SP measurements, and for the remaining 10% of each orbit the CPR will make CP measurements. Table 1 shows the expected performance of CPR in both modes.

Science requirements call for an absolute calibration of CPR to 1.5 dB. This is accomplished by making frequent estimates of the transmit power by a power meter, and by frequent receiver gain monitoring through periodically coupling of the output of a noise diode into the receiver. These measurements, along with pre-launch measurements of the antenna pattern and transmit and receive path losses, are used by the ground data processing system to calibrate the data. Calibration accuracies are also monitored by examining ocean surface backscatter.

HARDWARE IMPLEMENTATION

CPR is implemented by the following subsystems: Radio Frequency Electronics Subsystem (RFES), High-Power Amplifier (HPA), Antenna, and Digital and Synthesizer Subsystem (DSS). A block diagram is shown in Fig. 2. The RFES consists of an upconverter which accepts a video signal from the DSS and upconverts it to 94 GHz. The signal is amplified to approximately 200 mW by a state of the art MMIC power amplifier. The receiver accepts the received signal from the antenna and downconverts it to an Intermediate frequency (IF). The IF signal is detected using a logarithmic amplifier; this approach has been used on the TRMM PR to provide high dynamic range [1]. The receiver noise level is critical to achieving the required sensitivity. A state of the art MMIC low-noise amplifier is used.

The HPA, which amplifies the transmitted pulse to a power level of 1.5 kW, consists of an extended interaction klystron (EIK) and a high-voltage power supply (HVPS). Both a primary and a backup EIKA are used to enhance system reliability. The EIK tube is a space-qualified version of a commercial tube, manufactured by Communications and Power Industries, Canada, Inc. This family of EIKs has been used extensively in existing ground-based and airborne 94 GHz cloud radars [4]. The EIK differs from standard klystrons by using resonated bi-periodic ladder lines as a replacement for conventional klystron cavities. The EIK provides a large peak power in a very compact and lightweight package. The high-voltage power supply (HVPS) provides the voltages needed to operate the EIK (heater, cathode, collector and modulator) 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 antenna is a fixed 2 m diameter reflector, made from space-qualified composite graphite material to reduce mass. The precise diameter is determined by launch vehicle constraints and may be slightly smaller than 2 m. The antenna provides more than 63 dBi gain, has beamwidth $\leq 0.12^o$, and has sidelobes less than -38 dB for angles $\geq 7^o$ from boresight. The antenna is fed by a quasioptical transmission line (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. This approach has been used frequently in spacebomed radiometers at millimeter wavelengths (e.g., Microwave Limb Sounder on Upper Atmospheric Research Satellite.)

The DSS provides the command, control and telemetry interface to the spacecraft and also provides control signals to other portions of the radar. It includes a Control and Timing Unit (CTU), a Signal Generator (SG), and a Digital Data Handler (DDH). The SG uses an arbitrary waveform generator to generate the transmit waveforms. This provides the flexibility needed to implement the frequency diversity scheme. The DDH accepts the analog signal from the RFES logarithm detector. It digitizes it and performs the required 0.15 s averaging. Much of the DSS is implemented using FPGAs to reduce development time and cost.

CONCLUSIONS

The Cloud Profiling Radar (CPR) on the CloudSat mission will provide the first global view of the vertical structure of clouds. It is a nadir-looking radar operating at 94 GHz. While the radar is fairly straightforward from a functional point of view, the required technology at millimeter wave frequencies presents some challenges. A design has been developed which meets the requirements and can be implemented using available technology. The design, as known during the formulation phase, has been presented. This design is undergoing some refinement. CPR will be implemented during the next two years, in preparaton for a launch in 2003.

ACKNOWLEDGMENTS

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Table 1. CPR System Characteristics

Parameter	SP	CP
Frequency (GHz)	94	94
Altitude (km)	705	705
Range resolution (m)	500	500
Cross-track res (km)	1.4	14.
Along-track res (km)	3.5	3.5
Pulse width (μs)	3.33	33.33
PRF (Hz)	4300	800
Antenna diam (m)	2.0	2.0
Bandwidth (MHz)	0.3	0.3
Peak Power (W)	1500	1500
Integration Time (s)	0.3	0.3
Data Window (km)	0-25	5-25
Sensitivity (dBZ)	-28	-33

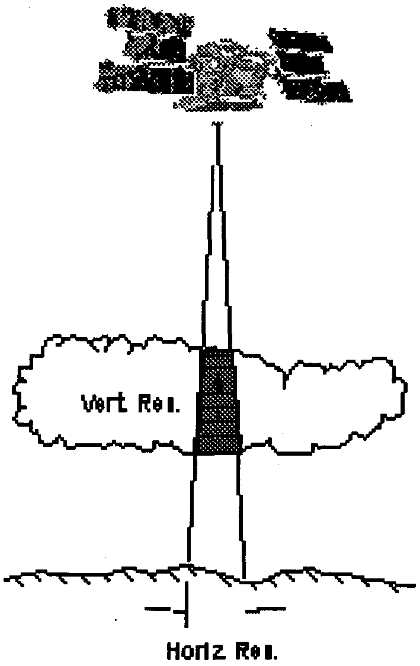

Figure 1. CloudSat Cloud Profiling Radar (CPR) operational geometry.

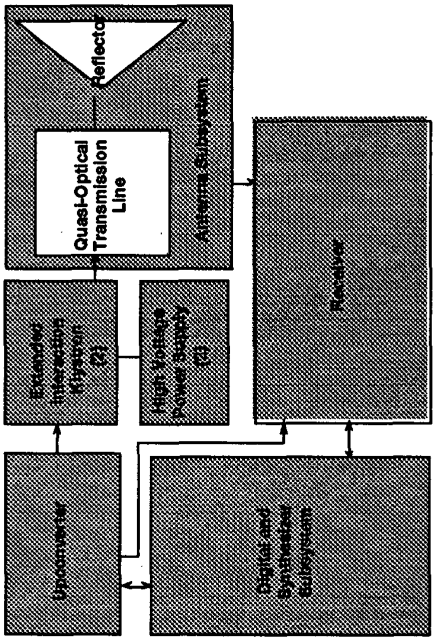

Figure 2. Simplified CPR block diagram.