Cloud Profiling Radar (CPR) for the CloudSat Mission

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CloudSat Mission Overview

**Key Features**
- **Science payload:**
  - 94-GHz Cloud Profiling Radar (CPR)
  - Oxygen A-band Spectrometer/Imager
- **BATC’s RS-2000 spacecraft bus**
- **Co-manifested on Delta launch vehicle with the PICASSO-CENA spacecraft**
- **Flies in on-orbit formation with PICASSO-CENA and EOS-PM - 705 Km sun sync**
- **Launch date: March 2003**
- **Operational life: 2 years**

**Science**
- Will measure vertical structure of clouds and quantify their ice and water content
- Will improve weather prediction and understanding of climatic processes
- Will improve cloud information from other satellite systems, in particular those of EOS-PM
- Will investigate the way aerosols affect clouds and precipitation

**Programmatic:**
- CloudSat is the 4th NASA Earth System Science Pathfinder (ESSP) mission
- Cost capped at $111M (includes L/V)
  - Design to cost
- Mandated 3-year pre-launch development
  - Design to schedule
NASA/JPL/UMASS AIRBORNE CLOUD RADAR (ACR)

- At left are photos of ACR operator's console and RF electronics and antenna installation in NASA DC-8.

- Below is a nadir image of cloud and precipitation reflectivity acquired near severe thunderstorms in northeastern Kansas on 24 June 1998.
  (Horizontal axis is along-track distance, vertical axis is altitude.)

DC-8 95 GHz radar operator station

Nadir radar installation in aft cargo hold.
CPR Overview

- Nadir-pointing 94-GHz radar to measure cloud reflectivity vs. altitude
- Transmit 3.3-μs monochromatic pulses
  - Vertical resolution ~500 m
- Use 1.85-m dia. antenna for transmission/reception
  - Horizontal resolution ~1.4 km
- Nominal sensitivity: -28 dBZ
- Dynamic range:
  - Capture both low reflectivity clouds and ocean return
  - 0-25 km data window
- Physical characteristics:
  - Mass: 195 kg
  - Power: 234 W
  - Data rate: 25 kbits/sec
# System Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal frequency</td>
<td>94.05 GHz</td>
</tr>
<tr>
<td><strong>Antenna:</strong></td>
<td></td>
</tr>
<tr>
<td>Aperture diameter</td>
<td>1.85 m</td>
</tr>
<tr>
<td>Peak Gain</td>
<td>63 dBi</td>
</tr>
<tr>
<td>Beamwidth (3-dB)</td>
<td>0.12°</td>
</tr>
<tr>
<td><strong>Sidelobes:</strong></td>
<td></td>
</tr>
<tr>
<td>&lt;7° from boresight</td>
<td>-20 dB</td>
</tr>
<tr>
<td>&gt;7° from boresight</td>
<td>-50 dB</td>
</tr>
<tr>
<td>Peak power</td>
<td>1500 W</td>
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<tr>
<td>Dynamic range</td>
<td>70 dB</td>
</tr>
<tr>
<td>PRF</td>
<td>4300 Hz</td>
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<tr>
<td>Pulse width</td>
<td>3.3 μs</td>
</tr>
<tr>
<td>Minimum reflectivity</td>
<td>-28 dBZ</td>
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<tr>
<td>Integration time</td>
<td>0.32 sec</td>
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<tr>
<td>Vertical resolution</td>
<td>500 m</td>
</tr>
<tr>
<td>Cross-track resolution</td>
<td>1.4 km</td>
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<tr>
<td>Along-track resolution</td>
<td>3.6 km</td>
</tr>
<tr>
<td>Along-track sampling</td>
<td>1 km</td>
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<tr>
<td>Vertical sampling</td>
<td>250 m</td>
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<tr>
<td>Science Data window</td>
<td>0-25 km</td>
</tr>
<tr>
<td>Data rate</td>
<td>25 kbps</td>
</tr>
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</table>
Key Science and Mission Requirements Related to CPR

- CPR electrical boresight misalignment error < 0.0540°.
- Vertical resolution of CloudSat measurements shall be < 550 m.
- Measurements from surface to 25 km above the mean geoid.
- Detect reflectivities down to -26 dBZ at end-of-life.
- Calibration accuracy of 1.5 dBZ.
- The instantaneous radar footprint < 2 km.
- After along-track averaging, footprint < 5 km along-track and < 2 km crosstrack.
- Oversampling by at least 2x in the alongtrack direction.
- No systematic, geographically correlated gaps in the CPR data.
- Boresight at geodetic nadir to within 0.0678°.
- CPR placed in standby or off mode of operation during maneuvers.
- Orbit average data rate for the CPR < 25 kbps.
- Mass < 235 kg.
- Orbit average power consumption < 322 watts.
- Lifetime of 24 months.
- CPR electrical boresight misalignment error < 0.0540°.
Design Considerations

- Clouds are very weak scatterers; detection of low reflectivity clouds requires
  - high peak transmit power
  - large antenna
  - large pulse width
  - low front end losses
  - low noise amplifier in receiver
  - receiver bandwidth matched to transmit pulse
  - estimation and subtraction of system thermal noise
- Besides thermal noise, clutter due to surface return must also be considered
  - surface clutter results from previous pulses returning from surface simultaneous with return from clouds
  - low antenna sidelobes are required
- Additional considerations
  - pulse compression cannot be used due to sidelobe contamination from surface
  - pulse width is limited by required range resolution
  - along-track averaging is limited by required along-track resolution
  - receiver bandwidth must accommodate STALO stability and Doppler shifts
  - maximum signal from surface is 80-90 dB above minimum detectable cloud return
Receiver Simulation Studies

Method
- generates detected signal from log amplifier using appropriate statistics
- simulates analog to digital conversion
- converts to linear domain
- averages
- codes for storage
- computes statistics of estimated power (signal+noise) and noise floor

Results
- maximum average signal should be several dB (4-6) below the maximum ADC input
- linear detection requires > 14 bits ADC; not available for space use
- log detection requires > 8-bits; use lad-detector with 12 bit ADC to get 10.5 effective bits
- antilog look-up-table should produce a power with > 20 bit representation; 24 are used
- accumulated powers must have proper representation to avoid bias; 32 bits integer or floating with 10 bits mantissa and 5 bits exponent seems sufficient; a (6,14) floating format provides a lower data rate than 32-bit integer and is chosen.
- log-detector must be linear for inputs that are at least 6 dB below the mean noise level at the log-detector input; 10 dB is preferred.
- system induced variations in the received power (due to transmit power variation or receiver gain variation must be < 0.5 dB over the integration time of 0.32 s)
Effect of Surface Clutter

- For a nadir-looking radar clutter is due to return of previous pulses from surface (ambiguities) simultaneous with cloud signal.
  - signals from ranges \( r+nc/2\text{PRF} \) arrive simultaneously
- A mathematical analysis and computer software were developed to compute radar signal-to-clutter ratio versus cloud altitude
- Simplest design (single transmit frequency) has problems with clutter for worst-case antenna pattern (-38 dB sidelobes).
- Frequency diversity can be used to reduce clutter:
  - transmitter transmits a sequence of up to 16 separate frequencies, separated by 2 MHz
  - receiver is designed to track transmit frequency with appropriate delay for spacecraft altitude; return from 1st 15 previous pulses are now outside receiver bandwidth
- Using frequency diversity, an antenna with -38 dB sidelobes 7 degrees from boresight and beyond meets requirements.
- Current antenna provides -50 dB sidelobes
  - frequency diversity not needed
Calibration

- Internal approach
  - monitor transmit power using by coupling power from antenna subsystem to a detector diode
  - monitor receiver gain by periodically injecting noise diode into receiver front end
  - requires pre-launch measurements of antenna gain and front end losses
  - accuracy depends on these measurements and their stability and noise diode and power detector accuracies
- External calibration using ocean surface measurements is also planned:
  - approximately once per month spacecraft will maneuver to point CPR antenna at 10 degrees in cross-track direction
  - CPR will acquire ocean sigma0 data during 10 minute data take
  - spacecraft will move antenna back to nadir
  - CPR will resume nominal science data collection
  - calibration data take will occur at night over ocean to minimize thermal effects
- The 10 degree angle is approximate and is based on observations at Ku-band
  - at Ku-band ocean sigma0 shows minimum sensitivity to wind speed
  - same physics should hold at W-band; however, angle of minimum sensitivity may differ somewhat
  - aircraft measurements could improve knowledge of ocean sigma0 prior to launch
- **Upconverter**: convert lower frequency pulse to 94 GHz pulse
- **High Power Amplifier (EIK+HVPS)**: Klyston tube amplifier which amplifies transmit pulse to ~1500 W
- **Antenna Subsystem**: ~2 m reflector and quasi-optical system (QOTL) for coupling transmit signal to antenna and received signal to receiver
- **Receiver**: amplify, downconvert, and log-detect received signal
- **Digital Subsystem**: generate transmit signal, provide control signals to other radar subsystems, interface with spacecraft, log-detect and digitize and sum data
Implementation Details

- CPR has only one science mode, short pulse data acquisition:
  - simple functional design allows control without microprocessor
  - FPGAs are used to implement radar control and processing functions
- RFES uses:
  - MMIC driver amps to generate medium power signal to drive EIKs
  - MMIC low-noise amplifier to minimize receiver noise figure
- A redundant high power amplifier is provided due to the EIK cathode's finite life.
- A quasi-optical transmission line (QOTL) implements duplexing function; reduces loss relative to conventional waveguide and circulator.
- Antenna is 1.85 m offset design, designed for high gain and low far sidelobes; peak sidelobes are not critical.
Antenna/QOTL Overview

Quasi-optics is used to minimize front-end losses

- Radar Antenna elements
- QOTL elements
Conclusions and Summary

- CPR on the CloudSat mission will be the first spaceborne radar for cloud profiling.
- It will measure cloud reflectivity versus altitude using a conventional short pulse, providing 500 m range resolution and -28 dBZ sensitivity.
- CPR system requirements are in place and have been reviewed.
- While the operation of CPR is simple (1 science collection mode), the development of CPR has a number of technology challenges
  - space-qualified high power source (tube and power supply)
  - large antenna and quasi-optical feed
  - W-band medium power and low-noise amplifiers
- Design of the CPR subsystems is proceeding according to schedule for launch in 2003.