Orbit and Transmit Characteristics of the CloudSat Cloud Profiling Radar (CPR)

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Jet Propulsion Laboratory
California Institute of Technology
Pasadena, CA 91109

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Prepared by: S. Durden and R. Boain

Introduction

The CloudSat mission will fly the first spaceborne millimeter-wavelength (94 GHz) radar to provide a global survey of cloud profiles and cloud physical properties, with seasonal and geographical variations, that are needed to evaluate the way clouds are parameterized in global models, thereby contributing to improved prediction of weather, climate and the cloud-climate feedback problem (Bulletin of the American Meteorological Society, Vol. 83, No. 12, Dec 2002, pp. 1771-1790).

CloudSat will fly in on-orbit formation with two other NASA satellites: the CALIPSO satellite and the NASA-AQUA satellite. The unique feature of the CloudSat radar lies in its ability to observe most of the cloud condensate and precipitation within its nadir field of view. Combining the observations of the CloudSat radar with information from CALIPSO and Aqua is a key aspect of the observing philosophy of the CloudSat mission. The three satellites are in very nearly the same orbit but with each satellite positioned along the orbit with separation distances from one another which remain relatively fixed. So, in order to understand the CloudSat orbit and since Aqua leads this train of satellites in the so-called “A-Train”, one must first understand the characteristics of the Aqua orbit.

Orbit characteristics

In the most basic of terms, Aqua's orbit is nearly circular with an equatorial altitude of approximately 705 km, and the orbit is sun-synchronous such that the Mean Local Time (MLT) of the orbit's ascending node maintains a roughly fixed angle with respect to the mean solar meridian throughout the mission. Because Aqua uses a sun-synchronous orbit, the orbital inclination is constrained to be 98.2 degrees. Over the course of the mission, Aqua's inclination is perturbed slightly in a predictable way by luni-solar forces to cause small variations. These variations, in turn, cause a slight drift of the orbit's MLT. Thus, Aqua's Mean Local Time of the ascending node is controlled, by use of propulsive maneuvers to re-set the inclination as necessary, to be between 13:30 and 13:45 hours. This is equivalent to the node being in the angular range between 22.5 and 26.25 degrees with respect to the solar meridian.

The eccentricity of Aqua's orbit is approximately 0.0012 with the argument of perigee set to approximately 90 degrees. These values they are locked in a "frozen" relationship, which allows them to vary in a way to prevent precession of the perigee's position. This means that the orbital altitude with respect to the earth's ellipsoid remains the same as a function of latitude.

Aqua's mean semi-major axis (sma) has been selected to yield an orbital period such that the groundtrack repeats every 233 orbital revolutions or equivalently every 16 days. This also means that the orbital period is fixed at 16 * 86400 / 233 = 5933.0472 seconds or 98.88 minutes. The sma is subject to small perturbations, mostly due to atmospheric drag effects on the satellite. As a consequence, Aqua's period is allowed to vary by +/- 22 seconds relative to the nominal value. Periodic propulsive maneuvers are executed to adjust the sma decay due to drag and to sustain the orbital period within the indicated control band.

Aqua's groundtrack is carefully aligned with the World Reference System (WRS-2) grid and Aqua assumes a specific point on this grid as its reference point. This so-called reference point phases Aqua with other satellites also using the WRS-2 grid to avoid tracking conflicts with the other missions. With the requirements to maintain a 16-day repeat groundtrack and to overfly the WRS-2 grid, Aqua is in effect flying in formation with a virtual, zero-drag satellite which has the same orbital parameters and is positioned exactly over the reference grid in phase with the other satellites.

Aqua's groundtrack with respect to the WRS-2 grid drifts slowly in time back and forth. This cross-track drift is coupled with and is a direct result of changes in the sma, mentioned before. So to set bounds on the allowable cross-track deviations, Aqua controls and changes its sma to limit groundtrack deviations to +/- 20 km with respect to the WRS-2 as measured at the equator. This process of limiting cross-track deviation defines the degree to which the sma must be adjusted by maneuvers.

Operationally, CloudSat and CALIPSO fly in formation with Aqua separated by as little as 15 seconds along track and as much as 120 seconds. CloudSat and CALIPSO both use sun-synchronous, frozen orbits, as does Aqua. The only notable difference between the orbits is that the CloudSat/CALIPSO nodal position is shifted 215 km (along the equator) east of Aqua's node in order to avoid a sun-glint conflict on the CALIPSO satellite. This has the effect of displacing the groundtrack for these two satellites to the east of the WRS-2 by 215 km.

Like Aqua, CloudSat and CALIPSO are also affected by drag perturbations which cause their actual groundtracks to deviate slightly with respect to the nominal. This deviation, like Aqua's, can be up to +/- 20 km.

The table below provides the Mean Orbital Elements for CloudSat's operational orbit. In order to use these elements to identify the nominal groundtrack, the satellite needs to be positioned over 297.3314 degrees East Longitude at the initial epoch.

Table. CloudSat Mean Orbital Elements

Orbital Elements	Values
Semi-Major Axis	7083.4456 km
Eccentricity	0.0012
Inclination	98.2 degrees
Argument of Ascending Node	N/A
Argument of Perigee	90 degrees
Mean Anomaly	90 degrees

The Radar Instrument

The 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. Figure 1 shows the operational geometry of CPR. CloudSat is expected to launch in April 2005, with a planned two-year mission. This document summarizes those features of CPR that may be relevant to the radio astronomy community and other interested groups.

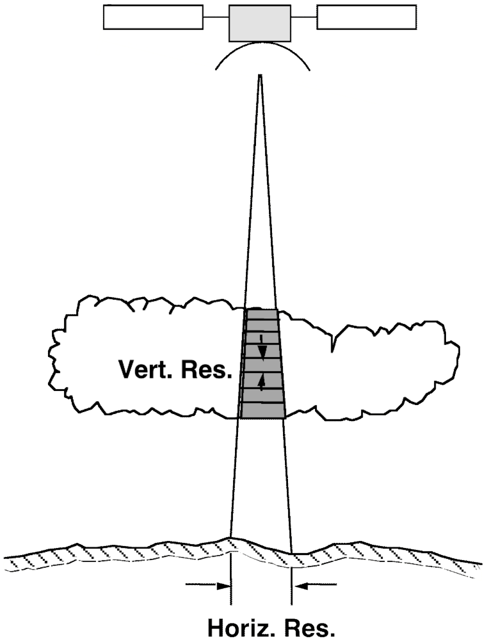


Figure 1. CloudSat Cloud Profiling Radar (CPR) operational geometry.

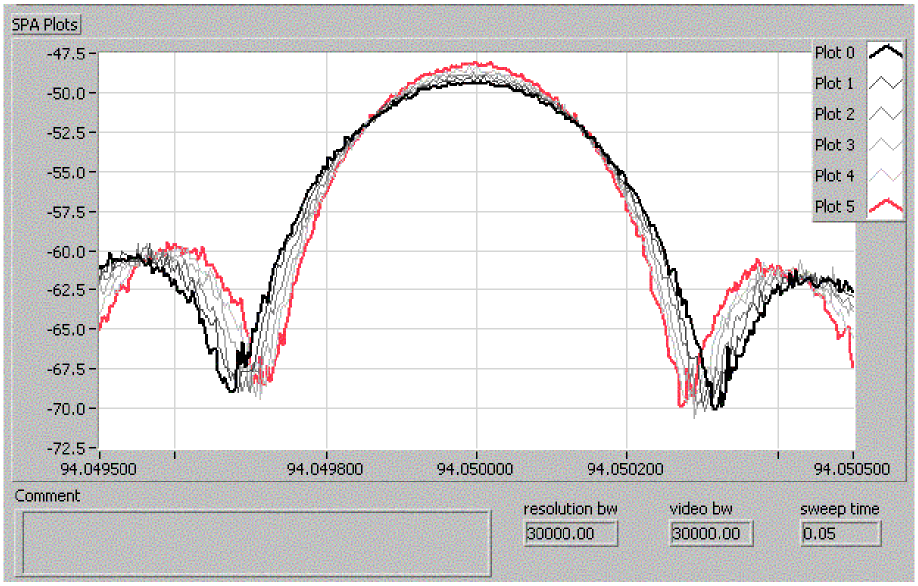
The design of CPR is driven by the CloudSat science and mission requirements. The primary science requirement is a minimum detectable cloud reflectivity of -26 dBZ at the end of the mission. This low reflectivity is needed since clouds are weak scatterers. (By comparison the reflectivity for rain is typically 20-50 dBZ; the Tropical Rainfall Measuring Mission (TRMM) Precipitation Radar (PR) has a sensitivity of around +20 dBZ.) For the reader not familiar with weather radar, dBZ is dB relative to 1 mm^6/m^3. These are the units of *Z*, known as reflectivity or more properly reflectivity factor. *Z* is proportional to the reflectivity ▯, which is the radar cross-section per unit volume, measured in units of m^{-1}. To achieve the required sensitivity, CPR must use a large antenna, large peak transmit power, sensitive receiver, and averaging and noise subtraction. In addition to thermal noise, clutter return from the surface could potentially mask cloud return. This requires that antenna far sidelobes be very low.

CPR has only one operational mode; in this mode the antenna beam is always pointed within less than 0.1 degrees of nadir. There is no antenna scanning. CPR transmits a train of quasi-monochromatic pulses, each 3.3 microseconds long. The pulse width is commandable between 3.1 and 3.7 microseconds; the operational width is expected to be close to 3.3 microseconds. The pulse rate is approximately 4000 Hz. The actual rate varies slightly over the orbit since the variation in satellite altitude requires that radar timing parameters be updated periodically. This keeps the surface and atmosphere 25 km above the surface within the radar's data window. In addition to the operations mode, monthly calibrations are planned in which the spacecraft rolls so that CPR is pointed off nadir by about 10 degrees. These will be done only over ocean.

Transmit Signal Characteristics

Table 1 shows the characteristics of the transmitted signal. The emission bandwidths in item 12 are calculated, based on the measured characteristics of the transmitted pulse. The 3 dB and 20 dB bandwidths are close to measurements. Accurate measurement of the 40 and 60 dB bandwidths has not been possible due to dynamic range limitation of 94 GHz test equipment. The transmit pulse envelope is nearly rectangular, with finite rise and fall times. Uncertainty in measured transmit power is at least 0.5 dB. Spurious signal requirements for the signal going into the high-power amplifier are –40 dBc. The output spurious levels should be well below this due to attenuation by the amplifier. Harmonic levels have not been measured due to test equipment limitations, although very rough estimates have been made based on amplifier characteristics. Figure 2 shows spectrum analyzer measurements of the transmit frequency spectrum over a 1 MHz bandwidth.

Table 1: Transmitter Characteristics	
1. NOMENCLATURE , MANUFACTURER'S MODEL NO. CloudSat Cloud Profiling Radar (CPR)	2. MANUFACTURER'S NAME Jet Propulsion Laboratory
3. TRANSMITTER INSTALLATION Cloudsat Spacecraft	4. TRANSMITTER TYPE Pulsed Radar (non-Doppler)
5. TUNING RANGE 94.05 GHz	6. METHOD OF TUNING fixed frequency using crystal reference
7. RF CHANNELING CAPABILITY none	8. EMISSIONS DESIGNATOR(S) 2M00P0N
9. FREQUENCY TOLERANCE stability is 10 PPM	
10. FILTER EMPLOYED (x one) a. YES X b. NO	
11. SPREAD SPECTRUM (x one) a. YES X b. NO	12. EMISSION BANDWIDTH (X and complete as applicable) X Calculated Measured
13. MAXIMUM BIT RATE N/A	a. -3 dB 0.3 MHz
	b. -20 dB 2 MHz
14. MODULATION TECHNIQUES AND CODING None – nearly monochromatic nominal 3.3 us pulse train, commandable 3.1 to 3.7 us	c. -40 dB 16 MHz
	d. -60 dB 80 MHz
	e. OC-BW
	15. MAXIMUM MODULATION FREQUENCY N/A
16. PRE-EMPHASIS (x one) a. YES X b. NO	17. DEVIATION N/A
	18. PULSE CHARACTERISTICS (measured)
19. POWER	a. RATE 4340 Hz (max)
a. MEAN 26 Watts (approximate)	b. WIDTH 3.3 us (nominal)
b. PEP 1800 Watts (approximate)	c. RISE TIME 50 ns
20. OUTPUT Extended Interaction Klystron	d. FALL TIME 23 ns
	e. COMP RATIO N/A



resolution bw 30000.00

video bw 30000.00

sweep time 0.05

Figure 2. Spectrum analyzer measurement near 94.05 GHz center frequency (+/- 0.5 MHz).

Figures 3 - 5 show transmit spectra calculated using the nominal 3.3 microsecond pulse width and realistic rise and fall times. The peak surface flux integrated over all frequencies is approximately $P_t+G_t-10\log(4\pi)-20\log r = 33+64-11-117 = -31$ dB(W/m^2) peak, where P_t is the peak transmit power, G_t is the antenna gain including measurement uncertainties, and r is the distance to the earth's surface.

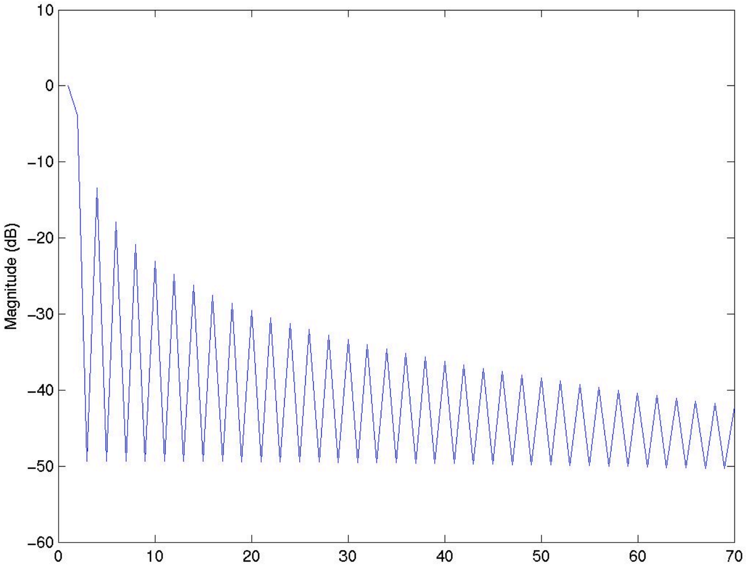


Figure 3. Calculated Spectrum of Transmitted Signal. Horizontal axis corresponds to 0-10 MHz, approximately, relative to 94.05 GHz carrier frequency. Frequency bins are roughly .15 MHz.

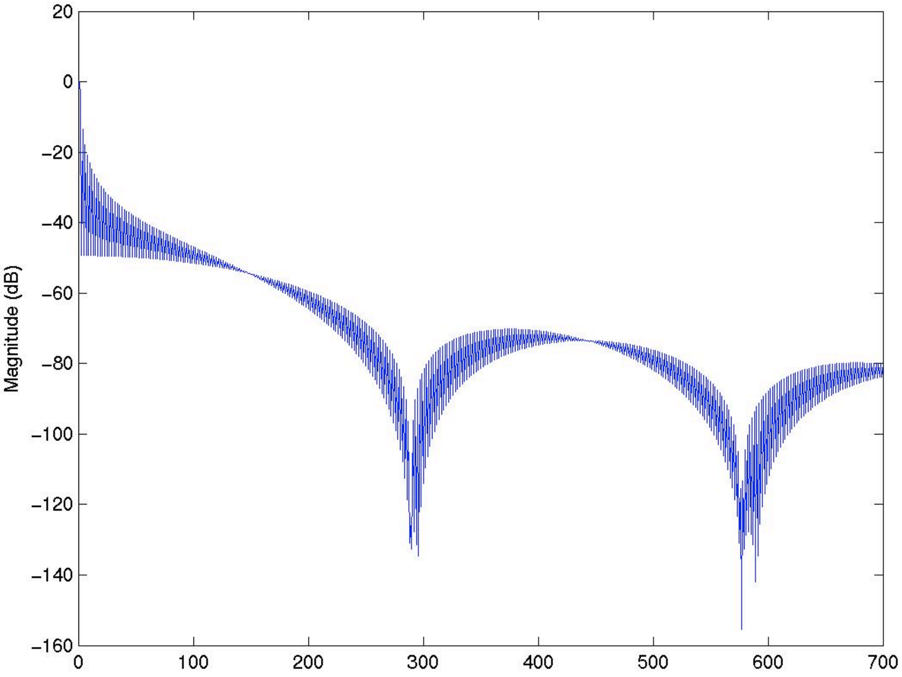


Figure 4. Calculated Spectrum of Transmitted Signal. Horizontal axis corresponds to 0-100 MHz, approximately.

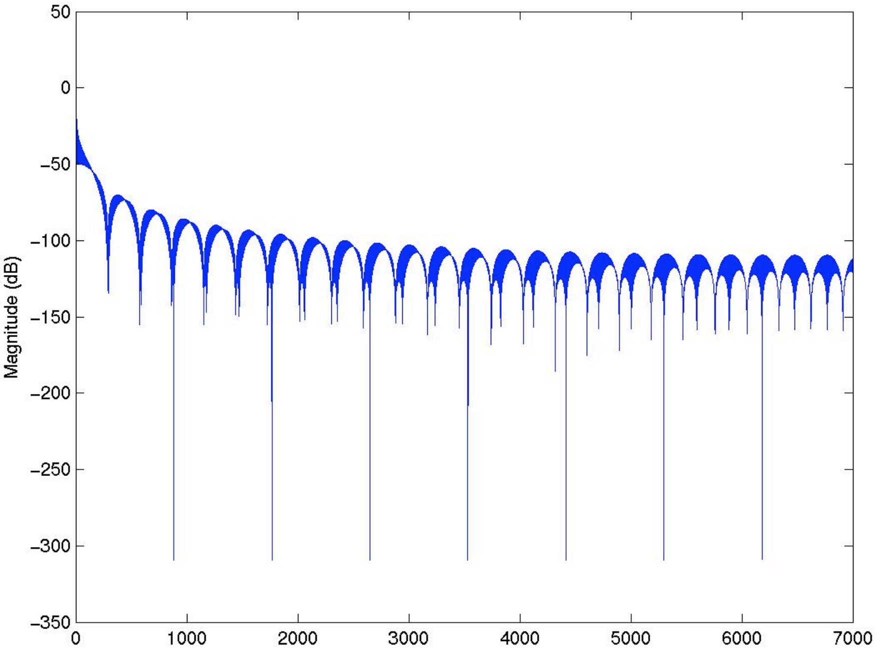


Figure 5. Calculated Spectrum of Transmitted Signal. Horizontal axis corresponds to 0-1 GHz, approximately.

Antenna Characteristics

The CPR antenna is a 1.85 m diameter reflector antenna that normally points at nadir. As required, it was designed with very low far sidelobes (well below 50 dB beyond 7 degrees from boresight) to minimize clutter. The gain is approximately 63 dBi. Measurements are 63.0 dBi for one antenna port and 63.5 dBi for the other antenna port. There is about 0.5 dB uncertainty on the gain measurements. Table 2 lists the antenna characteristics. Figure 6 shows the measured CPR antenna pattern using a far-field range; far sidelobes are around –75 dB. Figure 7 shows the pattern near boresight measured on a near-field range.

Table 2. Antenna Characteristics	
1. NOMENCLATURE , MANUFACTURER'S MODEL NO. CloudSat Cloud Profiling Radar (CPR)	2. MANUFACTURER'S NAME Jet Propulsion Laboratory
3. FREQUENCY RANGE 94.05 GHz	4. TYPE parabolic reflector
5. POLARIZATION single, linear	6. SCAN CHARACTERISTICS fixed pointing, no scan
	a. TYPE
7. GAIN	b. VERTICAL
a. MAIN BEAM 63 dBi (approximate) 64 dBi (including measurement uncertainty)	(1) Max Elev
	(2) Min Elev
b. 1st MAJOR SIDELOBE < 48 dBi (located at roughly 0.2 degrees from boresight)	(3) Scan Rate
8. BEAMWIDTH	c. HORIZONTAL SCAN
a. HORIZONTAL (Azimuth) 0.108	(1) Sector
	(2) Scan Rate
a. VERTICAL (Elevation) 0.108	

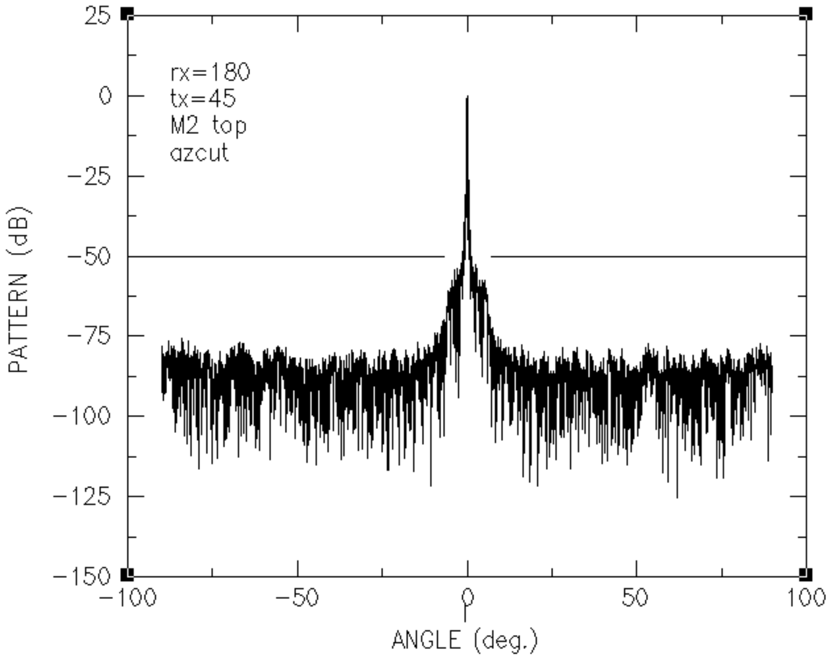


Figure 6. Antenna far-field pattern measurement

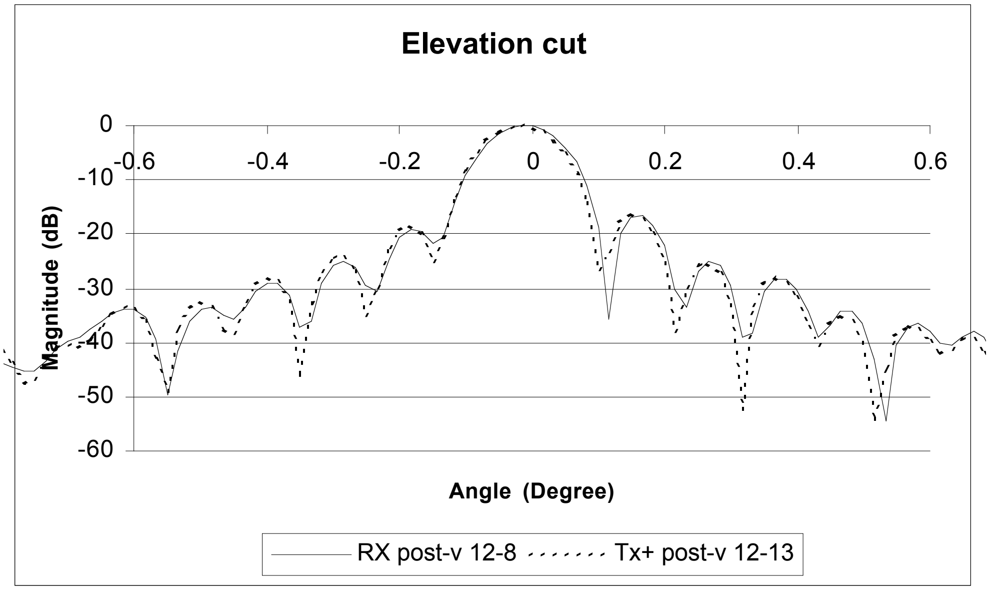


Figure 7. Antenna pattern over +/- 0.6 degrees using near-field measurement technique.