Surface Clutter Due to Antenna Sidelobes for Spaceborne Atmospheric Radar

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Abstract

A spaceborne radar for atmospheric observation must be able to detect atmospheric backscatter in the presence of clutter due to antenna sidelobes. Here, we analyze the problem in detail, deriving a method for computing clutter which includes effects of all contributing transmit pulses, Doppler shifting, finite receiver bandwidth, and curved earth's surface. The results are applied to analysis of existing radars and design of future radar systems.

Introduction

A spaceborne atmospheric radar must be well-designed to provide a detectable signal from distant and often weak atmospheric targets. In addition to minimizing thermal noise, it must also be designed to minimize interfering return, or clutter, coming from the earth's surface through the antenna sidelobes. Calculation of surface clutter for the same pulse as that illuminating the atmosphere has been addressed in [1], [2] with application to cross-track scanning spaceborne precipitation radars. Here, we extend this work to include effects of all contributing transmit pulses, Doppler shifting, finite receiver bandwidth, and curved earth's surface. The results are first demonstrated using data from existing radars and then applied to the design of future radar systems.

Approach for Signal-to-Clutter Calculation

The geometry of a spaceborne radar observation of the atmosphere is shown in Fig. 1. The radar antenna's main beam is assumed to be scanned in the cross-track dimension, and, for our analysis, the main beam may be pointed at nadir or off-nadir to either side of the satellite track with scan angle α. While the main beam illuminates the atmospheric target, antenna sidelobes illuminate the surface. The atmospheric signal return power P_a is calculated by the Probert-Jones equation [3]:

$$P_a(r) = \frac{P_t \lambda^2 G^2 \theta_1^2 \Delta \eta}{512 \pi^2 \ln 2 r_a^2} \tag{1}$$

where P_t is the transmitter power, λ is the wavelength, G is the antenna gain, θ_1 is the half-power beamwidth, Δ is range resolution, r_a is the range to the atmospheric target, and η is the reflectivity.

In addition to the signal from the atmosphere, the radar will simultaneously receive echoes from all targets which differ in range by $nc/2PRF$, where n is an integer, c is the speed of light, and PRF is the pulse repetition frequency. The range to the surface r_s is equal to $r_a + nc/2PRF$. As discussed in [1] and[2], the surface clutter through sidelobes for a given n is due to an annulus on the earth's surface, assuming a rectangular pulse, as was also assumed in the derivation of (1). The power received from the annulus P_s can be written as a surface integral over the azimuth angle ϕ and the angle γ between the earth radius to the nadir point and the earth radius to the annulus (shown in Fig. 1). This integral can be simplified, giving the following expression for P_s

$$P_s(r) = \frac{P_t \lambda^2 G^2}{64 \pi^3} \frac{R_e}{R_e + h} \frac{(r_2^2 - r_1^2)\sigma^o}{2 r_s^4} \int_0^{2\pi} g^2(\theta, \phi) d\phi \tag{2}$$

where R_e is the earth's radius, h is the spacecraft altitude, r_1 and r_2 are the ranges to the inner and outer edges of the annulus, σ^0 is the surface cross section, and g is the antenna pattern.

The integral over ϕ is evaluated numerically, since the antenna pattern varies with ϕ when it is scanned off-nadir. Since the receiver has a finite bandwidth, the return from a direction ϕ is also weighted by the receiver output energy for a Doppler shifted input. The antenna pattern is modeled as a Gaussian shaped main-beam with sidelobes which are either flat or fall off as a monotonically decreasing function. When the antenna is scanned off axis a coordinate transformation is made from the global coordinate (θ, ϕ) to local antenna coordinates. The surface σ^o is modeled as a function which decreases linearly in the log-domain and is similar to to measurements of σ^o [4], [5].

An explicit formula for the SCR can be found by combining (1) and (2):

$$SCR = \frac{\pi \theta_1^2 \eta \Delta (R_e + h)}{4 \ln 2 r_a^2 R_e \Sigma} \tag{3}$$

where

$$\Sigma \equiv \sum_n \frac{\sigma^o (r_2^2 - r_1^2)}{r_s^4} \int_0^{2\pi} g^2(\theta_n, \phi) w(\phi) d\phi$$

Here, the summation over n includes all contributing annuli, or pulses. The maximum value of n corresponds to the edge of a spherical earth model, while the minimum value corresponds to nadir return. For nadir-looking radars, the minimum value of n is 0. For scanning radars this is no longer true, and n can become negative. For each range bin starting with the surface, we compute the range of n. We then find Σ and solve (3) for the minimum detectable reflectivity η_m by setting SCR to 1. η_m is converted to the minimum detectable reflectivity factor Z_m.

Application to Radar Analysis and Design

The Precipitation Radar (PR) on the Tropical Rainfall Measuring Mission (TRMM) [6] is the first spaceborne atmospheric radar. Table 1 summarizes the PR performance characteristics. Fig. 2 shows data acquired by the TRMM PR over the Indian ocean at 17^o incidence angle. In the TRMM PR processing, data below the thermal noise level are set to a flag which indicates that no signal is present. The points shown in Fig. 2 (as circles) are the only ones with valid data. Also shown in Fig. 2 are calculations of Z_m due to clutter using the method developed in the previous section. The parameters used in the calculation are shown in Table 2. In Fig. 2 there is good agreement between the calculated and observed Z_m, with differences most likely due to differences between the ocean σ^o model and the actual ocean σ^o and between the antenna pattern model and the actual pattern. The $n = 0$ pulse is the dominant source of clutter for the 17^o scan angle α. At nadir the $n = 0$ pulse does not contribute to range bins above the surface. Using our method, we find that Z_m is nearly constant with altitude, having a value near -3 dBZ. This reflectivity is well below the TRMM PR thermal noise.

Because of the TRMM PR's success, a second generation spaceborne precipitation radar (PR-2) is being investigated [7]. One of the goals of the new radar is to provide a Z_m several dB better than that of the TRMM PR. Hence, clutter is a concern. Table 1 provides the proposed performance characteristics of the 14 GHz channel for the PR-2. To design an antenna with acceptable performance, clutter calculations were performed for a variety of antenna patterns. Fig. 2 shows the Z_m for the PR-2 due to clutter for the parameters in Table 2; σ^o is a land surface model. The calculation in Fig. 2 is for the maximum PR-2 scan angle α of 37^o, much larger than the TRMM PR maximum of 17^o. The clutter near the surface is dominated by the $n = 0$ pulse, although the first pulse to contribute is $n = -2$. Calculations were also made for PR-2 at nadir. In this case, only pulses with $n \geq 1$ can contribute to range bins above the surface, and the method developed here is needed. The clutter is approximately -5 dBZ and nearly constant with altitude.

In addition to measuring precipitation, spaceborne radars are planned for cloud measurements. In particular, NASA will launch the CloudSat mission in 2003, which will carry a 94 GHz radar for cloud studies. Table 1 shows the expected Cloud Profiling Radar (CPR) performance characteristics for CloudSat. The calculated Z_m for a land surface (Table 2) is approximately -22 dBZ at all altitudes, which is well above the required value of -28 dBZ and is not acceptable. This can be reduced by using frequency diversity. Specifically, CPR will transmit a sequence of frequencies, changing the frequency for each pulse. The receiver will track the transmit frequency with a delay corresponding to the pulse roundtrip time. At a given instant, the clutter from most previous pulses is outside the receiver passband. By using frequency diversity with 2 MHz spacing between frequencies and 16 frequencies. Z_m is lowered to -34 dBZ, meeting requirements.

Conclusions

We have developed a method for calculating the surface return through antenna sidelobes for downward-looking atmospheric radar. The method is used to determine the minimum detectable reflectivity Z_m. It is new in that it calculates clutter due not only to the same pulse as that illuminating the atmosphere but also all previous and subsequent pulses that can cause clutter return to occur simultaneously with the atmospheric return. The clutter calculation method presented here also includes the effect of Doppler shifting and finite receiver bandwidth and effect of a curved earth's surface.

The method was applied to existing and planned spaceborne radars. Calculations for the TRMM Precipitation Radar are in reasonable agreement with observations. For the TRMM PR same-pulse clutter is significant at lower altitudes when the antenna is scanned to large angles, as would be expected. Clutter is also present when the antenna is pointed at nadir, due to previously transmitted pulses. However, the clutter contribution at nadir is well below the thermal noise. A second generation precipitation radar (PR-2) was also analyzed, and the method developed here was used to find an antenna pattern producing an acceptable clutter contribution. Finally, for a cloud radar it was found that the weak return from clouds can easily be obscured by clutter, even with an antenna with -38 dB constant sidelobes. A frequency diversity scheme was suggested and shown to substantially improve sensitivity.

Acknowledgment

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Table 1. Radar System Characteristics

Parameter	PR	PR-2	CPR
Frequency (GHz)	13.8	13.4	94
Altitude (km)	350	400	705
Max scan angle (^{o})	17	37	0
Range resolution (m)	250	250	500
PRF (Hz)	2800	2800	4300
Antenna diam (m)	2.0	5.3	2.0
Bandwidth (MHz)	0.6	4.0	0.3

Table 2. Antenna and Surface Parameters

Parameter	PR	PR-2	CPR
Antenna g_s	-29	-25	-38
Antenna c	1.5	4.0	0.0
$\sigma^o(0^o)$	12.0	0.0	0.0
β	0.7	0.17	0.1

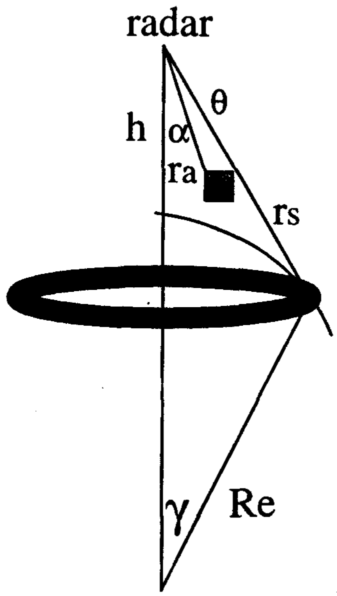

Fig. 1. Coordinate system for clutter calculations illustrating angle θ from nadir to surface clutter, angle γ between earth radii pointing at radar and pointing at source of surface clutter, and α, the angle of the antenna boresight relative to nadir. ra is the range to the atmospheric target (box), and rs is range to the surface.

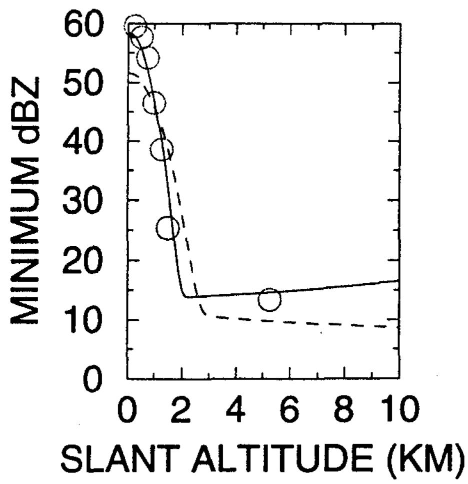

Fig. 2. Calculated Z_m at 17^o due to clutter for TRMM PR (solid) and observed Z_m due to clutter and thermal noise over the Indian Ocean (circles). Also shown is calculated Z_m at 37^o scan angle for PR-2 over land (dashed). Slant altitude is distance from surface to atmospheric target along radar look direction.