Abstract—A new method to suppress the surface clutter interference with precipitation measurement from space by the Dual frequency Precipitation Radar (DPR, 13.8 GHz and 35.5 GHz) is introduced for the Global Precipitation Measurement (GPM) Mission, which is planned in succession to the Tropical Rainfall Measuring Mission (TRMM). The DPR has very high sensitivity and its minimum detectable rain rate is designed to be 0.3 mm/h (attained by the 35.5 GHz radar) at the rain top. In this study, the radiation pattern of the slotted wave guide planar phased array antenna was calculated by considering the Taylor distribution with random errors in excitation current. The Signal (S) to Clutter (C) power ratio (S/C ratio) was evaluated for the antenna pattern given by the Taylor distribution (designed peak side lobe level = -35 dB, n = 6; these values are same as the TRMM PR), where the S means received power from rain scattering volume, and the C means the backscattered power from sea/land surface. A uniform rain rate of 0.3 mm/h was assumed for the calculation of signal S at 35.5 GHz and 0.5 mm/h for S at 13.6 GHz. A side lobe clutter interferes the rain echo severely when the strong side lobe illuminates the nadir direction, where the specular component of the scattering coefficient of sea/land surface is dominant. The introduced method to suppress the side lobe clutter is to tilt the antenna beam a few degrees in coordinate plane determined by the satellite flight direction and the nadir direction. The radiation pattern of the phased array antenna is characteristic in that the region of the strong side lobe arises in crisscross. By tilting the antenna beam, the strong side lobe illuminates the off nadir direction. So that makes it possible to suppress the side lobe clutter. Calculation results show that the surface clutter interference is suppressed well at the main beam tilt angle 2 degrees.

1. INTRODUCTION

The Global Precipitation Measurement (GPM) Mission is intended to measure global precipitation as a successor to the Tropical Rainfall Measuring Mission (TRMM). The GPM Mission is unique in that it consists of a core satellite with a dual-frequency precipitation radar (DPR, 13.6 GHz and 35.5 GHz) and eight companion satellites that have microwave radiometers that measure radiation from precipitation and the Earth surface. The 35.5 GHz precipitation radar has very high sensitivity, with a minimum detectable level rain rate of 0.3 mm/h at the rain top.

One problem with rainfall measurement by spaceborne radar is that, because the radar observes precipitation over the earth's surface, the radar receives both weak rain echoes and strong surface echoes simultaneously. Hanado and Ihara [Hanado (1992)] evaluated the surface clutter interference prior to the launch of the TRMM Precipitation Radar (PR), which observes precipitation at 13.8 GHz. They optimized a side lobe level of the antenna radiation pattern that effectively suppresses the side lobe clutter interference. But, unexpectedly strong side lobe clutter has been observed after the launch of the TRMM PR. It arouses a need for a further suppression of side lobe clutter interference. In this paper, the results of an introduced method to suppress the side lobe interference are shown.

2. FORMULATION OF SURFACE CLUTTER INTERFERENCE CALCULATION

A. Geometry

Fig. 1. A pattern diagram of surface clutter interference with precipitation measurement

A pattern diagram of an instantaneous observation is shown in Fig. 1. The flight direction is indicated by Y-axis, and the cross track direction is indicated by X-axis. The main beam points the rain scattering volume (dotted volume), and the side lobe illuminates the hatched area, where the surface clutter takes place. The extent of a clutter area depends on the beam scan angle and the range from the radar. The hatched area is the range from the satellite that is the same as the rain scattering volume. Severe surface clutter also arises from the shoulder of the main lobe, which illuminates the surface at the same range...
as the rain scattering volume when the rain scattering volume is adjacent to the sea. It is valid to assume a locally flat Earth to simplify the calculation within a swath width of ±125 km. The S/C ratio (signal-to-clutter power ratio) is calculated to evaluate the surface clutter interference. A large S/C ratio means that the interference of surface clutter with the rain echo is weak; a small S/C ratio means that the interference is strong.

The received power of surface clutter, $P_s$, at the same range gate as that of the rain echo is

$$P_s = \frac{P_t \lambda^2}{2\pi^3} \int_A \int G^2(\theta, \phi) \sigma^0 d\theta d\phi$$  \hspace{1cm} (1)

where

$dS = r^2 \tan \theta d\theta d\phi$

$P_t$: received power from surface
$P_t$: transmitted power
$\lambda$: wavelength
$G(\theta, \phi)$: antenna pattern
$\sigma^0$: normalized radar cross-section of land/sea surface
$A_s$: rain attenuation of surface return
$S$: surface clutter area at the same range gate as that of rain echo

An incidence angle $\theta$ has a following relationship.

$$\theta = \cos^{-1}(\cos \Theta \cos \alpha)$$  \hspace{1cm} (2)

where

$\Theta$: main beam scanning angle (in X-Z plane)
$\alpha$: main beam tilt angle (in Y-Z plane)

The received power from a rain echo, $P_r$, is expressed as the Probert-Jones equation with attenuation:

$$P_r = \frac{P_t G^2 \lambda^2 \epsilon r^2}{2\pi^3 r^2 \ln 2} \eta A_r$$  \hspace{1cm} (3)

where

$P_r$: received power from rain echo
$G_0$: antenna peak gain
$\theta_0$: half power beam width
$\eta$: rain radar reflectivity
$A_r$: rain attenuation of rain echo

B. Antenna Pattern $G(\theta, \phi)$

The planar phased array antenna of the 13.8 GHz precipitation radar onboard the TRMM satellite is fed with a Taylor distribution [Taylor (1955)] (designed peak side lobe level of -35dB, n=6) to suppress the side lobe clutter. The dual frequency precipitation radar antenna onboard the GPM core satellite will also be fed with a Taylor distribution for the same reason.

The planar phased array antenna consists of many slotted waveguides, with PIN diode phase shifters (5 bit) for each waveguide. As the antenna beam scans, the phase of the excitation current fed to each waveguide is changed. In calculation of $G(\theta, \phi)$, random errors in the excitation current (including thermal noise, quantization error at phase shifters, etc.) are considered.

C. Precipitation Model

The dependency of the radar reflectivity, $Z$ (dBZ) and the attenuation coefficient, $k$ (dB/km), on rainfall rate $R$ (mm/h) is expressed as [Mega (2002)],

$$k = 0.215 R^{1.07} \text{ (at 35 GHz)}$$  \hspace{1cm} (4)

$$Z = 245 R^{1.33} \text{ (at 35 GHz)}$$  \hspace{1cm} (5)

The dependency was determined from the measured rainfall rate and raindrop size distribution.

The value of $\eta$ in Eq. (3) is calculated as,

$$\eta = \frac{\pi^5}{\lambda^4} \left( \frac{\epsilon - 1}{\epsilon + 2} \right)^2 Z \geq 1.3276 \times 10^{-5} R^{1.33}$$  \hspace{1cm} (6)

where $\epsilon$ takes the value at 10 degrees Celsius

D. Land/Sea Surface Backscattering Coefficient

The values of land/sea surface backscattering coefficient are taken from the experimental results of Grant and Yaplee [Grant (1957)]. To consider the worst case of surface clutter, the standard deviations of the scattering coefficient of land and sea surface, observed by the TRMM PR, are added to the experimental results (Fig. 2).

3. CALCULATION

A. Conditions for Calculation

A slotted waveguide phased array antenna is employed for the DPR. The antenna size for 35.5 GHz radar is 80 cm by 80 cm, which will achieve a designed half power beam width of 0.71 degrees. There are 128 waveguides, with 142 slots on each waveguide.

Random errors in magnitude and phase (1.0 dB and 5.0 degree) in the excitation current at each element are considered.

The case of the TRMM PR, a non-resonant waveguide slotted phased array antenna is used to obtain a broader frequency range. A distance of each slots is placed so that a phase difference of each slots takes a place to improve VSWR [Chang (1989)]. As a consequence of this phase difference, an antenna main beam tilts a few degrees from the normal line of the waveguide axis. This fact is true with the DPR onboard the GPM core satellite. The antenna of the TRMM PR is attached aslant to the satellite to direct the antenna beam to nadir by the same
magnitudes of the beam shift. So the antenna beam scans in X-Z plane of Fig. 1. The case of the DPR onboard the GPM core satellite, the antenna does not scan in X-Z plane, but scans in a plane tilted around X axis (Fig. 3) by φ degrees. In Fig. 3, the tilted antenna beam is directed to the off nadir direction in the Y-Z plane (the plane determined by the satellite flight direction and the nadir direction, and orthogonal to the antenna scanning plane). The relationship between the antenna pattern and the \( \phi \) integrated antenna pattern \( F(\theta) \) is shown in Fig. 3. \( F(\theta) \) is defined as below.

\[
F(\theta) = \int_{-\pi}^{\pi} G_1(\theta, \phi) G(\theta, \phi) \frac{d\phi}{2\pi G_0^2}
\]

(7)

Here, Eq. (1) is simplified as following,

\[
P_s = \frac{P_x \lambda^2}{2 \pi h^2} \int_0^{\pi} F(\theta) \sigma(\theta) \sin 2\theta A_s d\theta
\]

(8)

In Fig. 3, the intersection of two axes points nadir direction, and incidence angle \( \theta = 0 \) degree is constant on the concentric circle, azimuthal angle \( \phi \) is measured from the cross track direction. A \( \phi \) integrated antenna pattern \( F(\theta) \) calculated by Eq.(7) plays a significant role in estimating the surface clutter interference. The radiation pattern \( G(\theta, \phi) \) of the phased array antenna is characteristic in that the region of the strong side lobe arises in crisscross. By tilting the antenna beam in the Y-Z plane, the value of \( F(\theta) \) around an incidence angle \( \theta = 0 \) degree falls. Around an incidence angle \( \theta = 0 \) degree, the scattering coefficients \( \sigma(\theta) \) shown in Fig. 2 takes the maximum value over all the incidence angle. A received power from the earth surface calculated by Eq. (8) is an integration by \( \theta \) of the multiplication of \( F(\theta) \) and \( \sigma(\theta) \). To suppress surface clutter, we have to make the received power from the earth surface go down. It would be ideal if the value of \( F(\theta) \) falls around an incidence angle \( \theta = 0 \) degree, where the scattering coefficients \( \sigma(\theta) \) takes a large value.

B. Calculated \( F(\theta) \)

Calculated \( F(\theta) \) is shown in Fig. 4 for the cases of the antenna beam tilt angle \( \alpha = 0, 6 \) degrees. For \( \alpha = 6 \) degrees, the value of \( F(\theta) \) at incidence angle from 0 degree through 6 degrees is lower by 40 dB than the case of \( \alpha = 0 \) degree. This range of the incidence angle corresponds to the large scattering coefficients, so surface clutter is suppressed in terms of the lower surface return \( P_s \).

C. Optimal main beam tilt angle \( \alpha \)

The values to optimize are, (1) the number of the observing rain scattering volumes that are interfered by the side lobe clutter, (2) the worst S/C value of the observing rain scattering volumes that are interfered by the side lobe clutter. Both values are calculated assuming a uniform rain of rain rate \( R = 0.3 \) mm/h from an altitude 0 km to 10 km. The number of an angle bin is 25 (corresponds to the scanning angle \( \Theta \) from 0 through 17.04 degrees, it’s half of \( \pm 17.04 \) degrees). The number of range bin is 40, so the number of all the observing volumes is 1000, which is a multiplication of the number of a range bin 40 and an angle bin 25.

In Fig. 5 (a), numbers of the observing volumes that are interfered by the side lobe clutter and S/C values under 10 dB/20 dB are shown. The numbers of the observing volumes that are interfered by the main lobe clutter and S/C values under -10 dB/0 dB are shown in Fig. 6.

In Fig. 5 (b), S/C value at 10%, 80% percentage point is shown for the observation by 35.5 GHz radar over land.

According to Fig. 5 (a), the number of the observing volumes that are interfered by side lobe clutter decreases from the tilt angle \( \alpha = 0 \) degree through \( \alpha = 2 \) degrees. And the worst S/C value in Fig. 5 (b) improves drastically from the main beam tilt angle \( \alpha = 0 \) (the worst S/C = 0 dB) degree through \( \alpha = 2 \) degrees (the worst S/C = 10 dB). S/C value at 10%, 80% percentage point also shows gradual improvements.

On the other hand, the number of the observing volumes that are interfered by main lobe clutter increases as the tilt angle \( \alpha \) becomes larger. By tilting the antenna beam, the main lobe clutter worsens because the shoulder of the tilted main beam...
The number of observing volumes interfered by clutter

Fig. 5. The effect of the main beam tilt angle in the case of the side lobe clutter, (a) The number of volumes S/C < 10, 20dB, (b) S/C value at 10%, 80%, and the worst S/C value.

The number of observing volumes interfered by clutter

Fig. 6. The effect of the main beam tilt angle in the case of the main lobe clutter. The number of volumes S/C < -10, 0dB.

illuminates the surface, even when the antenna beam scanning angle θ = 0 degree. At α = 2 degrees, the worse of main lobe clutter is limited.

For the scattering coefficient of the sea surface, the side lobe clutter is suppressed gradually at the beam tilt angle α from 0 degree through 4 degrees, but the main lobe clutter worsens simultaneously.

4. Conclusion

In this study, a new approach to suppress the surface clutter interference is introduced. A phased array antenna fed with a Taylor distribution has a low side lobe level, but that's not enough to suppress the surface clutter interference in case the surface scattering coefficient takes a large value. By tilting the antenna beam in Y-Z plane (Fig. 1), the ϕ integrated antenna pattern F(θ) becomes small around θ = 0 degree. A side lobe clutter is suppressed efficiently at the beam tilt angle α = 2 degrees even when the surface scattering coefficient is large. The optimal value 2 degrees that is the same as the 35.5 GHz radar observation is obtained with the 13.6 GHz radar observation.

REFERENCES