6.5

UNCERTAINTIES IN THE RAIN PROFILING ALGORITHM FOR THE TRMM PRECIPITATION RADAR

Toshio Iguchi[1*], Toshiaki Kozu[2], and Robert Meneghini[3]
[1]Communications Research Laboratory, Japan, [2]Shimane University, Japan,
[3]NASA/Goddard Space Flight Center, Greenbelt, Maryland

1. INTRODUCTION

The Precipitation Radar (PR) on-board the Tropical Rainfall Measuring Mission (TRMM) satellite operates at 13.8 GHz and observes the swath of 220 km with 49 beams every 0.6 s from 350 km above the surface. Each beam width is about 0.7 degree and the footprint diameter is approximately 4.3 km at nadir. The pulse width of 1.67 μs corresponds to a range resolution of 250 m. Information available from the radar is essentially only the radar echo power, from which we need to estimate the rainfall rate at each radar resolution volume. There are many uncertain factors involved in this estimation process. This paper summarizes major uncertain factors in the rain-profiling algorithm used in the TRMM's standard data processing called 2A25.

2. ALGORITHM

The 2A25 algorithm estimates the true effective radar reflectivity factor (Z_e) at the PR frequency of 13.8 GHz at each radar resolution cell from the vertical profiles of measured apparent radar reflectivity factor (Z_m). The rainfall rate (R) is then calculated from the estimated effective reflectivity factor (Z_e). Conversion from Z_m to Z_e requires attenuation correction in which we need to assume a relationship between the specific attenuation (k) and Z_e. Conversion from Z_e to R needs a Z_e–R relationship. Both relations depend on the raindrop size distribution (DSD) and a few other factors. Initial k–Z_e and Z_e–R relations are assumed for each type of rain, but to avoid the instability associated with the Hitschfeld-Bordan attenuation correction method and to realize a reliable attenuation correction, the path-integrated attenuation to the surface estimated with the surface reference technique (SRT) is used as a constraint when the information from the SRT is considered reliable. This constraint effectively adjust the DSD and hence the k–Z_e and Z_e–R relations. An outline of the whole algorithm can be found elsewhere (Iguchi et al., 2000).

3. UNCERTAINTIES

There are two kinds of uncertainties in the rain estimation. They are uncertainties in measurement itself and those in the rain retrieval algorithm. The former includes uncertainties in the radar system parameters, Rayleigh fading and random noise. The latter includes uncertainties in the modeling of the actual rain structure and micro-physics.

3.1 Radar System Parameters and Calibration

The calculation of Z_m from the radar echo needs the radar system parameters such as the transmitting power, the received power and the antenna gains. All the necessary parameters of the PR were measured before the launch of the satellite and some of them are calibrated after the launch as well. According to the calibrations conducted by the National Space Development Agency of Japan (NASDA), the overall radar system is calibrated within the absolute error of less than 1 dB. Although the error of 1 dB is very small as a calibration error of weather radar, this error causes a bias in Z_m, and hence in the estimates of Z_e and R. Since the attenuation correction is a function of Z_e, a bias in Z_m is amplified in Z_e and R when the attenuation is significant.

3.2 Rayleigh Fading and Quantization

The standard deviation due to Rayleigh fading is reduced to approximately 0.7 dB for strong signals by averaging 64 independent samples. Although this value itself may not be very small for individual estimates, fading does not cause any statistical bias in the mean of Z_m. In the estimation of the path-integrated attenuation by the Hitschfeld-Bordan method, the integral of αZ_m^β with respect to range is used. In this integral, most of fading error will be averaged out because fading at each range bin is independent of other bins. Therefore, Rayleigh fading is not a major source of error in the estimation of rain accumulation. In a similar way, the error due to the quantization of the received power by a step size of approximately 0.38 dB is not a source of serious error at all.

3.3 Drop Size Distribution

If the drop size distribution $N(D)$ can be estimated at each point, we can calculate almost all useful quantities related to rain. In fact, both Z_e and k can be calculated for a given $N(D)$ once the drop's phase state, temperature and shape are given. As far as rain is concerned, variations of Z_e and k due to natural fluctuations of temperature and shape from standard models are insignificant in comparison with those caused by the variation of $N(D)$.

Since $N(D)$ has an infinite degree of freedom as a function of a continuous parameter D, it is impossible to determine it from radar observations that only give the integrated quantity (approximately the sixth moment) of $N(D)$. To make the estimation possible, $N(D)$ is generally approximated by a model functions with a few parameters. For example, in the TRMM PR algorithm, $N(D)$ is assumed to be approximated by a Gamma distribution with a fixed shape parameter μ,

$$N(D) = N_0 D^\mu \exp(-\Lambda D). \tag{1}$$

Variations of $N(D)$ at different positions and different time are assumed to be explained by variations of N_0 and Λ. In 2A25, a functional relationship is assumed between N_0 and Λ for each type of rain. Thus, the changes in Z_e or R can be explained by changes of a single parameter in the DSD model. In other words, for each type of rain, variations in R and Z_e can be explained by changes in a parameter θ_1.

$$N(D|\theta_1) = N_0(\theta_1) D^\mu \exp(-\Lambda(\theta_1) D). \tag{2}$$

Once we fix μ and define the functions $N_0(\theta_1)$ and $\Lambda(\theta_1)$, then Z_e–R and k–Z_e relations can be calculated. In 2A25,

* Corresponding author address: Toshio Iguchi, Communications Research Laboratory, Tokyo 184-8795, Japan; e-mail: iguchi@crl.go.jp

we introduce another parameter θ_2 to describe the deviation of DSD from the initial DSD model for each rain type: $N(D|\theta_1, \theta_2)$. θ_2 is adjusted according to the surface reference. Within a single radar beam, all variations of rainfall rate are attributed to variations in θ_1 while θ_2 is kept constant in it.

When rain is weak, the attenuation information from the surface reference is not reliable. As a result, the surface reference does not give any new information to adjust θ_2. In such a case, the default value of θ_2 is used. This means that the initial choice of DSD parameters determines the attenuation correction and the Z–R conversion relation.

To define the initial Z–R and k–Z relations, the current PR rain retrieval algorithm uses a DSD model that was derived from an average of several Z–R relations reported in the literature. However, the use of an averaged Z–R relation does not necessarily imply that the initial DSD model will bring an unbiased total rain estimates. There is no obvious way to determine or verify a DSD model that would give statistically unbiased rain estimates. This is probably the largest uncertainty in the present algorithm.

In fact, the ratio of the total rain accumulations estimated by using the two extreme DSD models based on the DSD observations in different monsoon seasons at Gadanki, India, is more than a factor of two. This means, by changing the DSD model, the average rain estimate may change by up to $\pm 40\%$. Nevertheless, trials with some representative DSD models from oceanic sites show that the total rain accumulation does not change significantly, mostly within $\pm 10\%$.

3.4 Surface Reference

In heavy rain cases, attenuation correction is essential to estimate the effective radar reflectivity factor Z_e. In such cases, the initial choice of the DSD model is very important as well. Since the Hitschfeld-Bordan attenuation correction method becomes unstable when attenuation is large, we use a surface reference method to estimate the total attenuation to the surface. This attenuation gives a constraint on the attenuation coefficient. Since the attenuation coefficient is a function of DSD, the surface reference gives a constraint to the DSD. In fact, parameter θ_2 in the DSD model is adjusted to conform with the SRT. With this adjusted θ_2, all k–Z and Z–R relations are modified and used in rain estimation. The question is the accuracy of the attenuation estimate from the SRT. The SRT assumes that if the incidence angle is the same, the true surface radar cross section under rain is the same as those in the surrounding rain-free areas. This assumption implies that waves and wind conditions are basically the same inside and outside the raining region and that the scattering coefficient of the surface is not modified by rain hitting the surface. To what extent this assumption is valid is yet to be investigated.

Even when the SRT gives the total attenuation without any error, we cannot compare it directly with the attenuation estimates from Z_m, because rain echoes near the surface are obscured by the surface clutter due to the spread of the main beam and the pulse width. The attenuation by rain in the cluttered range must be estimated by assuming some rain distribution in it. This uncertainty is somewhat related to the uncertainty of the storm structure discussed in the next section.

Note that the measurement of the surface scattering cross section used in the SRT is also subject to fading noise.

3.5 Vertical Storm Structure

Conversion of Z_e into R depends on the phase state of precipitating particles. The k–Z_e relationship depends heavily on the phase state. If the precipitating particles are ice, attenuation by absorption is negligibly small, and we only need to include the attenuation by scattering. If they are water, attenuation by absorption dominates. In other words, the k–Z relation changes drastically between ice and water. Misidentification of phase state at each range bin, therefore, results in the error in attenuation correction as well as rain estimation.

In light rain, the total attenuation is small and the error in phase state identification does not cause any serious error except for the conversion of Z_e into R. In heavy rain, the misidentification of phase state may cause a large difference in attenuation correction.

In the current algorithm, except when the bright band is detected, the phase state is estimated from the freezing height calculated by using the climatological surface temperature. Although a change in the estimated freezing height does not alter the total rain accumulation very much (because the SRT gives a constraint of the path-integrated attenuation in heavy rain cases), the error in the estimated freezing height may cause a bias error in the final statistics.

Existence of hail is not assumed in the current version of 2A25. PR data in some heavy rain cases, however, show a sign of hail that large values of Z_m continue over a long range at a relatively high altitude without a significant attenuation that is expected from such large values of Z_m. This kind of extreme cases cannot be handled well by the PR data alone because the PR is a simple single frequency radar that can measure only the echo power.

Similarly, attenuation by cloud droplets and water vapor is ignored in 2A25 because the attenuation by them is generally very small (less than a fraction of dB) and because their distribution cannot be estimated directly from a radar echo pattern. We also ignore the effect of vertical winds that modify the falling velocities of rain drops and hence the Z_e–R relations. To include these effects requires reliable storm structure models.

3.6 Non-Uniformity of Rain

Non-uniformity of rain within the radar resolution cell modifies the effective Z–R and k–Z relations. In particular, horizontal non-uniformity of rain causes non-uniform path-integrated attenuation within the beam. The average of the non-uniform path-integrated attenuation is generally smaller than the attenuation due to the same amount of uniformly distributed rain. This difference causes bias in attenuation correction if the attenuation derived from the SRT is used as a constraint of the total attenuation.

4. SUMMARY

Possible error sources in the current rain profiling algorithm for the TRMM Precipitation Radar are summarized. There are quite a few of them. Some are important only in heavy rain. Some are small, but may result in a bias in the same direction in all cases, and cannot be ignored. Surprisingly, however, the statistics of the PR data show quite a good agreement with other data (See, for example, Liao et al. (2001) in this volume).

5. REFERENCES

Iguchi, T., T. Kozu, R. Meneghini, J. Awaka, and K. Okamoto, 2000: “Rain-profiling algorithm for the TRMM Precipitation Radar,” *J. Appl. Meteor.*, Vol. 39, No. 12, Part 1, 2038–2052.

Liao, L., R. Meneghini, and T. Iguchi, 2001: “Comparisons of measurements between the TRMM PR and the WSR-88D ground-based radar,” *30th International Conference on Radar Meteorology*, 6.11, (this volume).