6.1 SPACEBORNE PRECIPITATION RADARS IN TRMM AND GPM

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1. INTRODUCTION

The Tropical Rainfall Measuring Mission (TRMM) satellite, which carries the world-first spaceborne precipitation radar, has been collecting precipitation data flawlessly for more than five years. Simultaneous measurements of rain with the Precipitation Radar (PR), the TRMM Microwave Imager (TMI), and the Visible and Infrared Scanner (VIRS) onboard the satellite enable us to intercompare the data and products from three different kinds of sensors, and to reveal problems associated with the rain retrieval algorithms for these sensors. The data brought by TRMM and comparisons among them have deepened our knowledge of global rain distribution and characteristics.

Based on the success of the TRMM mission, a new satellite mission called the Global Precipitation Measurement mission (GPM) was proposed. Its major objective is to measure precipitation globally and frequently so that the data can be used not only for scientific research but also for operational applications such as weather forecasts and water resource management. It consists of a core satellite in a non-sun-synchronous orbit and a fleet of sun-synchronous constellation satellites that carry microwave radiometers. A dual-frequency precipitation radar (DPR) on the core satellite is expected to play a significant role in GPM, by providing important information of rain characteristics that can be used for accurate estimation of precipitation rate with constellation radiometers.

This paper first reviews the major characteristics of spaceborne precipitation radar in comparison with ground-based weather radars. It then mentions some of the achievements brought about by the PR observations and issues raised by the intercomparisons of PR data with the corresponding TMI data. Finally, the prospects of the DPR in GPM are discussed.

2. SPACEBORNE AND GROUND-BASED RADARS

General comparison of space-borne precipitation radar with ground-based weather radar is not simple because there are variety of ground-based weather radars with different characteristics. Having said that, we can still write down some advantages and disadvantages of space-borne radar over ground-based radar.

Sever constraints on the mass, size, power consumption, and data rate for a space-borne instrument generally prohibit the use of a radar system similar to the ground-based one as a spaceborne sensor. To realize a reasonable horizontal resolution and a high gain from a limited size of antenna, we are forced to use a higher frequency band than those generally used for a ground-based system such as the S or C band. The use of such a relatively high microwave specturm suffers from rain attenuation that has to be corrected.

The obvious and most significant difference is the fact that ground-based radars are stationary whereas spaceborne radars are in motion all the time. This difference causes a fundamental difference in coverage and sampling of radar echoes. Spaceborne radars can cover nearly global regions but with a very sparse sampling in time.

Because of the measurement geometry, however, the space-borne radar can collect rain echoes nearly with the same performance and characteristics at any place. The ground-based radar has to measure rain from a lateral direction. Because of the Earth's curvature, it cannot measure rain near the surface at a large distance. To look at a large distance, the radar is placed at a high altitude such as at the top of a mountain. But the surface clutter and anomalous propagation prevent us from high sensitivity measurements of rain near surface at a large distance. A ground-based radar usually measures rain from a very close distance to a few hundred kilometers. Because of this large ratio of distance, the scattering volume defined by the pulse width and the beam shape changes significantly. A typical beam width of a ground-based radar is about 1°. This beam width will give the beam diameter of about 1.7 km at 100 km from the radar. The vertical extent of 1.7 km blurs the bright band echo significantly, althought the horizontal extent of blurring by the same amount is hardly a problem.

The surface clutter is a serious issue in observation of rain from space. The mainlobe clutter defines the lowest altitude above the surface we can measure in the case of off-nadir observation. This is the reason why the TRMM PR scans only up to 17 degrees from the nadir. Clutter caused by the antenna sidelobes must be suppressed in order to detect a weak rain echo at off-nadir.

The operational environment for the radar is quite different in space. The temperature of the spaceborne radar is controlled very well. The space-borne radar does not need a radome that sometimes causes unknown attenuation when it is wet in the ground-based system. In the case of TRMM PR, the whole system is composed of solid state devices that do not degrade with time. All these factors contribute to the extreme stability of the PR. In fact, the monthly averages of sea surface echoes measured by the PR have not changed more than 0.1 dB at 9.75 degrees of incidence angle over three years.

Advantages of commonly used ground-based radar systems are high sensitivity due to the use of a high power transmitter, the short distance from the radar to a rain area, small attenuation due to the use of the S or C band, and the possible use of polarimetric and Doppler measurements.

No space-borne precipitation radar with a Doppler

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measurement capability has been realized yet. The reasons for the difficulty is that the high velocity of the low altitude orbiting satellite creates a rather large spread of the Doppler spectrum of surface and rain echoes within the radar beam. To realize a Doppler system that has a measuremet error less than 1 m/s is not an easy task. Doppler measurements in microwaves need to measure the phase shift of echoes between two consecutive pulses. Coherence must be retained between these echoes. A combination of a large antenna (of the order of a few meters in the along-track direction) and a high pulse repetition frequency (PRF) (of the order of a few thousand herz) is required so that two pulses can be transmitted within the time that the satellite moves less than half the length of the antenna dimension along the flight direction.

Note that the horizontal satellite movement creates a phase shift between two consecutive surface echoes if the surface has a slope. This fact implies that the surface Doppler spectrum cannot be used as the reference of zero Doppler shift. Very accurate altitude and attitude information is required to estimate the vertical velocity of rain drops.

Polarimetric measurement from space is less promissing than Doppler measurement because no ZDR or KDP is expected in nadir looking observation of rain drops whose symmetry axes, on average, are lined up vertically. Some LDR may be measurable if we can realize a very sensitive system, although we can expect a significant increase of LDR only in the bright band.

3. TRMM AND PR

The TRMM PR has been in orbit for more than five years. The TRMM satellite was originally conceived as a flying rain gauge. Its major objective was to advance the understanding of global circulation of energy and water from observation of tropical and subtropical rain. To achieve it, it was necessary to measure accurately tropical rain which affects the global climate, and estimate vertical distribution of latent heat. Radar measurement of rain from space was envisioned to realize such measurements. In fact, unlike passive microwave sensors, radar can provide information on vertical rain profiles of rain with its range resolution.

Measurement of rain with passive microwave radiometers has a long history. Several algorithms to estimate the rainfall rate on the surface from PMR have been proposed. In all cases, however, the algorithms have to assume many parameters to estimate rainfall rates a priori, because the number of the parameters that are required to solve the inverse problem exceeds the number of independent pieces of information provided by the PMR measurements.

A unique feature of TRMM is that it carries three kinds of precipitation sensors. PR, TMI and VIRS. It enables us to compare the data taken with these different kinds of sensors nealy simultaneously. Not only the statistical comparisons, but also point-by-point comparisons were realized. Such comparisons reveal some inherent problems to the rain retrieval algorithms peculiar to each kind of sensor and gives clues and an opportunity to improve them.

PMR algorithms assume the vertical profile of storm structure either deterministically or statistically. The PR has been providing important data that can be used to test if the profiles assumed in PMR algorithms are consistent with the "truth". One of the most important parameters of vertical structure is the freezing level in the storm.

PR can measure the height of bright band accurately. The variations of bright band height with location and season have been compared with the freezing height assumed in the TMI rain retrieval algorithm. It turned out that the difference between them is not constant. it depends on the location and season. More importantly, the difference over the Pacific Ocean during the 1997-1998 El Niño period is much smaller than those in the other years (Berg et al. 2002). Since the difference cannot vary that much physically, and since the bright band height estimated by PR is rather reliable, we can conclude that the large variations mainly come from an inappropriate freezing height used in the TMI algorithm. Since the freezing height is the key parameter in rainfall estimation by the PMR algorithms, this finding has a large impact on the PMR algorithms. What has been thought as the variation of rainfall rate due to El Niño might be partly caused by a bias in freezing height estimates in such periods.

Another advantage of PR over TMI is that it can measure rainfall over land in the same way as over ocean. In the case of PMR, the absorption algorithm cannot be used over land. As a result, only the scattering signals are used to estimate rainfall rates over land. In other words, the algorithm used over land differs from that over ocean. Since the radar signals consist of scattered echoes of its own transmitted pulses, the signals are basically independent of its background.

However, PR is not perfect, either. It is a single frequency radar without Doppler or polarimetric functions. Because of that, it suffers from the problems common to all single frequency radars. Major uncertainties in PR retrieval of rainfall rate are summarized in Iguchi et al. (2001). They include radar system parameters and calibration, Rayleigh fading and quantization, drop size distribution (DSD), surface reference, vertical structure of storms, and non-uniformity of rain distribution. The most important one is the infamous uncertainty in the Z–R relationship or the drop size distribution. On top of it, since the PR uses Ku-band radio waves, it suffers from rain attenuation. Without attenuation correction, it is not possible to estimate the rainfall accurately. To correct for the attenuation, we need to know the relationship between the specific attenuation (k) and the radar reflectivity factor (Z_e). Therefore the Z–R issue and the attenuation correction issue are mutaully related through the DSD uncertainties.

One big advantage of the space-borne radar is that we have a surface echo behind the rain echo. The surface echo can be used to estimate the path integrated attenuation of radar signal through the rain above it. By using this information, we can estimate a parameter in the DSD model when the attenuation is significant and when we can assume the uniformity of rain within the instantaneous field of view.

The TRMM experience shows that the surface reference technique works as expected when the attenuation is large. However, when rain is light and the attenuation is not significant, the estimated rainfall rate depends almost solely on the initial coefficients of Z_e–R and k–Z_e

relationships. If the error in the path integrated attenuation in the surface reference is 1 dB and if the initail coefficients in the k–Z_e relation has an error of 1 dB as well, the transition that the SRT becomes an constraint to the k–Z_e coefficient in the hybrid method (Iguchi et al. 2000) occurs when the PIA is about 3.5 dB. If we assume a stratiform rain layer of 5 km, this attenuation corresponds approximately to 10 mm/h of rainfall rate. In other words, the SRT gives some DSD information only when the rainfall rate is larger than 10 mm/h.

4. GPM AND DPR

The Global Precipitation Measurement (GPM) is planned as a follow-on mission to the TRMM. It is a satellite program to measure the global distribution of precipitation accurately with a sufficient frequency so that the information provided by this program can drastically improve weather predictions, climate modeling, and understanding of water cycles.

The GPM satellite program can be divided into two parts. One is the TRMM-type core satellite that will carry an active precipitation radar and a passive microwave radiometer. The other is a constellation of several satellites that will carry passive microwave radiometers. The core satellite will make detailed and accurate estimates of precipitation structure and microphysical properties, while the constellation of satellites will provide required temporal sampling of highly variable precipitation systems.

4.1 *DPR*

The precipitation radar on the core satellite will be developed by the National Space Development Agency of Japan (NASDA) in collaboration with the Communications Research Laboratory (CRL). The radar uses two frequency channels, Ku and Ka bands. The Ku-band radar is nearly identical to the TRMM Precipitation Radar (PR) with some improvements, whereas the Ka-band radar is a new addition to it, and the whole system is called the Dual-frequency Precipitation Radar (DPR) (Iguchi et al. 2003).

The Ku-band radar is similar to, but not exactly the same as, the TRMM PR. Firstly, the designed transmitting power is increased to 1000 W from PR's 500 W (the actual Tx power of the PR turned out to be about 800 W) to compensate the increase in range loss due to GPM's higher orbit of about 400 km than TRMM's 350 km. Secondly, the mass of the radar will be reduced by using thin waveguides for the phased array antenna and the newly developed monolithic ICs in the RF units. Thirdly, the operation and data processing system will be improved to accomodate to the new orbit and the requirement for the beam matching.

Since the Ku-band antenna dimensions remain the same as the TRMM Precipitation Radar, the antenna beam width remains the same and the footprint size will increase to about 5 km because of the higher orbit of the GPM core satellite compared with the TRMM orbit.

The Ka-band radar provides high sensitivity to weak rain and snow. The combination of data from two channels will provide more accurate estimates of drop-size distribution parameters than the TRMM PR. The Ka-band radar will sample the echo data in two different modes alternately from scan to scan. One is a high-sensitivity mode for weak rain and snow detection, and the other is a matched-beam mode in which the sampling volumes of Ka- and Ku-band radar channels are matched for collecting dual-frequency echoes from the identical targets. The data collected in the latter mode are used for the estimation of DSD parameters. In the matched-beam mode, a range resolution of 250 m is employed, while in the high-sensitivity mode, a range resolution of 500 m is planned. The current radar design adopts active phased array antennas in both radar channels to make full use of TRMM experience. The minimum detectable rainfall rate in the high sensitivity mode in the Ka-band will be approximately 0.2 mm/h.

The major importance of the DPR, however, lies in the fact that it can provide the regional and seasonal statistics of storm structure together with the DSD parameters. Since rain retrieval algorithms for passive microwave radiometers have to assume a vertical structure of storm either deterministically or statistically, reliable storm structure information is crucial for the accuracy of rain estimation. The statistics from the DPR can be used as a database in radiometer algorithms to reduce the uncertainties of the storm models. How to utilize the information from radar data is a challenging issue. A possibility of improving the database used in a PMR rain retrieval algorithm by using DPR data is currently under examination by using TRMM data.

4.2 *DSD*

As mentioned in section 3, the SRT can provide some DSD information of rain that is heavier than above 10 mm/h in the TRMM PR case. The condition is worse over land where the stability of surface echoes is much worse than over ocean. The use of the Ka-band will widen the applicable range of SRT. Since the specific attenuation at the Ka-band is about ten times larger than that at the Ku-band, some DSD information will be given by the Ka-band radar with the SRT when the rainfall rate is above a couple of mm/h.

However, a more important fact is that by combining the Ku and Ka-band echoes, it may be possible to extact some DSD information without using the SRT (Mardiana et al. 2003). A preliminary study shows that if such DSD information is available, the error in the estimated rainfall rates will decrease significantly in the range between 2 and 15 mm/h of rainfall rate. Considering the fact that most rain in the Temperate Zones falls in this rain rate interval, the increase in measurement accuracy in this range will give an impact on the improvement of rain measurement from space.

Another very important piece of information that can be provided by the combination of the Ku and Ka-band echoes is the boundary between the region of ice particles (snow, graupel etc.) and the rain region. A significant difference in the specific attenuation between liquid water and ice should be detectable in the range profile of the radar dual frequency ratio (DFR) defined as $dBZ_{\mathrm{Ku}} - dBZ_{\mathrm{Ka}}$.

A new challenge in the DPR data processing is to extract accurately DSD information such as the mean drop radius by using a dual-frequency algorithm. Dual-frequency algorithms generally attribute the difference in observed radar reflectivity factors at two different frequency channels to the difference in scattering cross sections (effective radar reflectivity factors) and extinction cross sections (attenuations). They usually assume a perfect beam-matching and uniformity of rain distribution in a plane perpendicular to the beam direction within a footprint. Because actual statistics of non-uniformity of rain distribution is not known well, errors caused by these two factors must be quantified. Although the horizontal resolutions remain the same in DPR as in TRMM PR, over-lapping footprints of the Ka-band radar with the currently proposed way of scanning will provide better information about the horizontal inhomogeneity of rain distribution than the TRMM PR. This information is important to derive the effective k–Z_e and Z_e–R relations in inhomogeneous rain and to compensate the non-uniform beam filling effect on the attenuation correction and the DSD estimation.

4.3 *Variable PRF*

The TRMM PR uses a fixed pulse repetition frequency (PRF) of 2776 Hz. This PRF was chosen to cover the possible range of rain and surface echoes and to absorb the 10-km variation of the distance from the satellite to the surface due to the oblateness of the Earth.

In the case of the proposed orbit inclination of 65 degrees for the GPM core satellite, the altitude of the satellite changes about 20 km due to the oblate shape of the Earth when the satellite flies around the globe. If this increase of the variation of the distance to the surface is to be incorporated by increasing the receiving window with a fixed PRF, the maximum PRF will be 1.7 kHz. To improve the sensitivity from the TRMM PR, a higher and more efficient PRF is desirable.

Unlike the TRMM satellite, the location and orbit information is planned to be available on the GPM core satellite with an on-board GPS receiver. With this altitude information, we plan to adopt a technique of variable PRF to maximize the sampling efficiency. The current study shows that we can achieve the PRF higher than 4 kHz if the two channels of radar can transmit the pulses nonsynchronously without interference (Kobayashi 2003, Kobayashi and Iguchi 2003). If the pulse timings must be syncrhonized, the maximum PRF must be less than 2.6 kHz, which is still larger than 1.7 kHz without variable PRF operation.

4.4 *Beam Matching*

Matching the sampling volumes of Ku- and Ka-band radar data within a few hundred meters may be technically feasible. The most important information expected from the DPR is the drop size information obtained from the combination of Ku- and Ka-band radar echoes. All rain retrieval algorithms for dual-frequency radar assume that the scattering volumes at the two channels match perfectly and that the rain is uniform in the direction perpendicular to the range direction within the beam.

The degree of matching required depends on the structure of rain. If the rain is known to be uniform, no beam matching is necessary. If the rainfall rate changes across the beam, the matching becomes essential. In the current design of the DPR, we plan to adjust the relative locations of footprints at the two channels by adjusting the relative pulse timing between the two channels for along-track mismatching, and by adjusting the scan angles for the across-track mismatching.

However, it seems very difficult to verify the actual footprint and beam-matching after launch unless we can deploy a number of well-calibrated synchronized receivers and transmitters in radar's instantaneous field of view on the ground.

Possible methods for calibrating the radar after launch are under investigation. The calibration includes the determination of not only the fundamental radar parameters but also the degree of beam matching. Some of the hardware characteristics relevant to the rain detection and retrieval include the level of sidelobe contamination, stability of the system, effect of the variable PRF, and efficiency of data compression.

5. SUMMARY

The characteristics of spaceborne radars, in particular those of TRMM PR and GPM DPR, are described. The GPM core satellite is planned to be launched in 2008. The DPR on it is exected to provide some critical information about the storm structure (including the identification of the phase state of precipitation particles) as well as the drop size distribution, both of which are essential for the accurate rain retrieval from spaceborne microwave radiometer data. To quantify how much infomation we can extract from PR or DPR data is a challenge that should be dealt with.

6. ACKNOWLEDGMENT

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