2-3 Global Precipitation Measurement program and the development of dual-frequency precipitation radar

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The Global Precipitation Measurement program is a mission to measure precipitation from space, and is a similar but much expanded mission of the Tropical Rainfall Measuring Mission. Its scope is not limited to scientific research, but includes practical and operational applications such as weather forecasting and water resource management. To meet the requirements of operational use, the GPM uses multiple low-orbiting satellites to increase the sampling frequency and to create three-hourly global rain maps that will be delivered to the world in quasi-real time. A dual-frequency radar (DPR) will be installed on the primary satellite that plays an important role in the whole mission. The DPR will realize measurement of precipitation with high sensitivity, high precision and high resolutions. This paper describes an outline of the GPM program, its issues and the roles and development of the DPR.

Keywords
Global Precipitation Measurement, Dual-Frequency Radar, Precipitation Distribution, Water Cycle, Weather forecast

1 Introduction

Among the most pressing concerns facing the world is the changing world environment. But assessing how and to what degree various factors affect the environment requires an understanding of the current status of these factors, the interaction of multiple factors, and the extent of their effects on the environment. Countless factors affect the environment. Among the most significant is precipitation, which is also closely connected to our daily lives. Too much rain results in flooding; too little causes drought. Crop yields depend on precipitation. Along with temperature and wind, precipitation is also among the three major parameters of weather forecasts. Precipitation also determines the global circulation through latent heating and reflects climate changes. Lastly, precipitation is a key factor in atmosphere-ocean interactions.

Despite its central role, precipitation remains one of the least-known factors in cloud models, meteorological models, and climate models. Due to significant spatial and temporal variations, a precise understanding of global precipitation distribution remains beyond our current reach. Nevertheless, knowing the spatial and temporal distribution of precipitation around the globe will be essential in improving our understanding of weather and climate systems.

The Global Precipitation Measurement (GPM) satellite program is expected to improve weather forecasts and climate models and deepen our understanding of water circulation through precise, high-frequency measurement of global precipitation. The National Aeronautics and Space Administration (NASA) in the U.S. and the National Space Development Agency of Japan (NASDA) have been examining the feasibility of the

GPM program. This paper gives an overview of this program and describes the dual-frequency precipitation radar to be installed on the primary satellite of the GPM satellite group, with which the Communication Research Laboratory (CRL) is actively involved.

2 Global Precipitation Measurement (GPM) Program

GPM related-activities lie in three fields: satellite precipitation measurements, validation of satellite data, and data distribution. The first field, satellite precipitation measurement, is further subdivided into two broad areas. One involves satellite tasks similar to those carried out by the Tropical Rainfall Measuring Mission (TRMM), for which the primary satellite carries on board a precipitation radar to perform active measurements and a microwave radiometer to perform passive measurements. Both types of equipment perform high-precision measurements. The second area involves measurements carried out by a group of multi polar-orbiting satellites, each carrying a microwave radiometer. The role of the primary satellite is to observe the structure of precipitation distribution with sufficient accuracy and estimate quantities relevant to microphysics. The other satellites are used to increase measurement frequency and ensure adequate sampling frequency for precipitation systems that change quickly.

Since precipitation varies dramatically, with frequent shifts, low-orbit satellite systems such as TRMM with long sampling intervals are poorly suited to accurate monitoring. To improve quantitative forecasts, data integration, and flood forecasts, precipitation information must be gathered at least once every three hours or so. Meeting this requirement with orbiting satellites requires at least eight polar-orbiting satellites, each carrying a microwave radiometer unit such as the SSM/I.

The TRMM-type primary satellite will play a central role in GPM, since the data for microwave radiometers installed on the other satellites will be calibrated and validated based on detailed information on precipitation obtained by the precipitation radar and the multi-frequency microwave radiometer, both of which are installed on the primary satellite. The precipitation radar, which is the key sensor of the overall GPM program, is to be developed by CRL and NASDA. This radar will use two frequencies: one in the Ku band and one in the Ka band. Adhering to virtually the same specifications as the TRMM precipitation radar (PR), the Ku-band radar will use the 13.6-GHz radio waveband. The Ka-band radar will use a 35.5-GHz channel; Use of dual frequencies increases the range of observable precipitation intensity; in particular, it enables the observation of light rain and snowfall in the mid- and high-latitudes. The attenuation differences in echoes measured at two frequencies are expected to enable classification of raindrop size distribution (DSD). Information obtained by the dual-frequency precipitation radar (DPR) is used not only by the radar itself, but also to reduce errors in estimates of rainfall rate made by the microwave radiometers. The primary satellite is scheduled to be launched by a NASDA H-IIA rocket around 2007. The secondary satellites that carry the microwave radiometers and fly polar orbits are to be launched through joint international efforts involving NASA, NASDA, and other organizations. The acquired data will be transferred to a data center for processing and be used to create a global precipitation map every three hours.

GPM has been designed to broaden the range of precipitation measurement performed by TRMM to include high altitudes, in order to obtain a more precise and complete global precipitation distribution. The TRMM precipitation radar (PR) has provided precise rainfall data and 3-dimensional rainfall structures over both sea and land. Such unique data, obtainable only by radar, will be expanded to the whole globe. The global precipitation maps updated every three hours are expected to be used for such tasks as numerical weather forecasts and water resources management.

3 Scientific Objectives

The GPM program touches on three areas of scientific study: the climate, weather, and water cycle.

For climate research, rainfall data accumulated by GPM over extended periods can be used to test and improve climate models. Existing global climate models are thought to be unable to give precise predictions regarding changes in precipitation associated with global warming. Data obtained by GPM may enable the detection of long-term drifts in precipitation distribution, particularly in combination with data provided by TRMM or other satellites, or with surface observation data.

Assimilating precipitation data into numerical weather forecasting models significantly improves the accuracy of weather forecasts. This improved accuracy has been demonstrated in case analysis using TRMM data. The three-hourly precipitation data obtained by GPM will enable data assimilation that further enhances forecast accuracy. Researchers also believe GPM data will contribute to high-precision analysis of global precipitation and water vapor distribution, as well as precise, high-frequency observations and analyses of typhoons and strong low-pressure systems, analyses that will improve numerical weather forecast models and long-term forecasts at various scales.

For global water circulation research, the frequent observations of precipitation made possible by GPM, both spatial and temporal, will reduce uncertainties currently surrounding global water cycle, thereby improving hydrological models. GPM data is also expected to lead to a much-improved qualitative grasp of water cycle issues, making it possible to distinguish the effects of human activity and natural variations on water cycle, as well as leading to much more sophisticated flood predictions and water resource management.

Compared to TRMM, GPM will make possible scientific research across an even broader field. This is because mission research subjects include not just climate, but also hydrology and weather forecasting: three fields that are mutually related. The results will allow analyses and synthesis of data from these different fields, thus clarifying interdisciplinary problems. How do rainfall and the structure of rainfall vary in response to variations in the temperature of the earth and other climate parameters? How much water on the land surface is directly associated with rainfall and evaporation? How is the global system changing, and how will these changes affect life on earth? These are some of the questions that the GPM mission will help resolve or clarify. The mission will do so by improving our understanding of the rate at which water cycles through the climate system, and by clarifying patterns in these changes, it will provide information that will help us build more powerful models. Currently, researchers suspect that accelerating the circulation of water through the global climate system will accelerate evaporation, increase global precipitation, and generate extreme phenomena, making floods and droughts more frequent.

GPM will also affect many bordering research fields, including studies of cloud systems and radiation, interactions between sea surface/land surface and the atmosphere, the effects of fresh water forcing on ocean process, salinity modeling of the ocean, and hydrometeorology. It will also help improve models of carbon and ground water and their effects on flood and drought prediction, water vapor transport, and other effects.

4 Significance of DPR in GPM

The significance of the DPR in GPM is that its radar data enables estimates of physical quantities that cannot be obtained by other passive-type observation equipment, such as rainfall rate, raindrop size distribution (DSD), and path integral values of attenuation.

The latest DPR design involves both Ku-band and Ka-band radars. The Ku-band radar is fundamentally the same as the TRMM precipitation radar (PR), although several refinements have been introduced. The Ka-band radar enables the detection of light rain or snowfall (Fig.1). Combining data from these two channels allows more precise estimation of various parameters associated with raindrop size distribution than a single-frequency radar. Current plans call for the Ka-band radar to be equipped with two alternating observation modes. One is a high-sensitivity mode used to detect light rain or snowfall, while the other is a mode in which the measuring beam of the Ka-band radar is tailored to match the Ku-band radar. In the second mode, called beam matching mode, the radar observation volumes of the Ka- and Ku- bands are made to coincide to permit echo observations from the same scatterers. The data obtained in this mode will be used to estimate DSD parameters. Range resolution for beam matching mode is slated to be 250 m for normal observations and 500 m in high-sensitivity mode. Based on TRMM experiences, phased array antennas will be used for both the Ka- and Ku-bands.

DPR will provide three-dimensional, high-resolution information on the distribution of precipitation particles, data that will prove invaluable in studying rain cloud structures. The high-accuracy estimates of rainfall intensity given by DPR will be used to calibrate estimates by the microwave radiometer installed on the same primary satellite. DPR will provide information on the regional and seasonal characteristics of rain cloud structures, together with DSD parameters. The rain retrieval algorithm for the microwave radiometer, which is a passive sensor, should assume the vertical structure of a rain cloud, whether deterministic or stochastic, and reliable information on the vertical structure of rainfall is a definitive factor that determines the accuracy of the rainfall estimate. Statistics on rainfall structures provided by DPR are used as data for the radiometer algorithm and to reduce the uncertainty of the rainfall structure. How to apply this radar data constitutes a major area of future research. TRMM PR data is currently being studied to improve the database that the TMI rain retrieval algorithm uses.

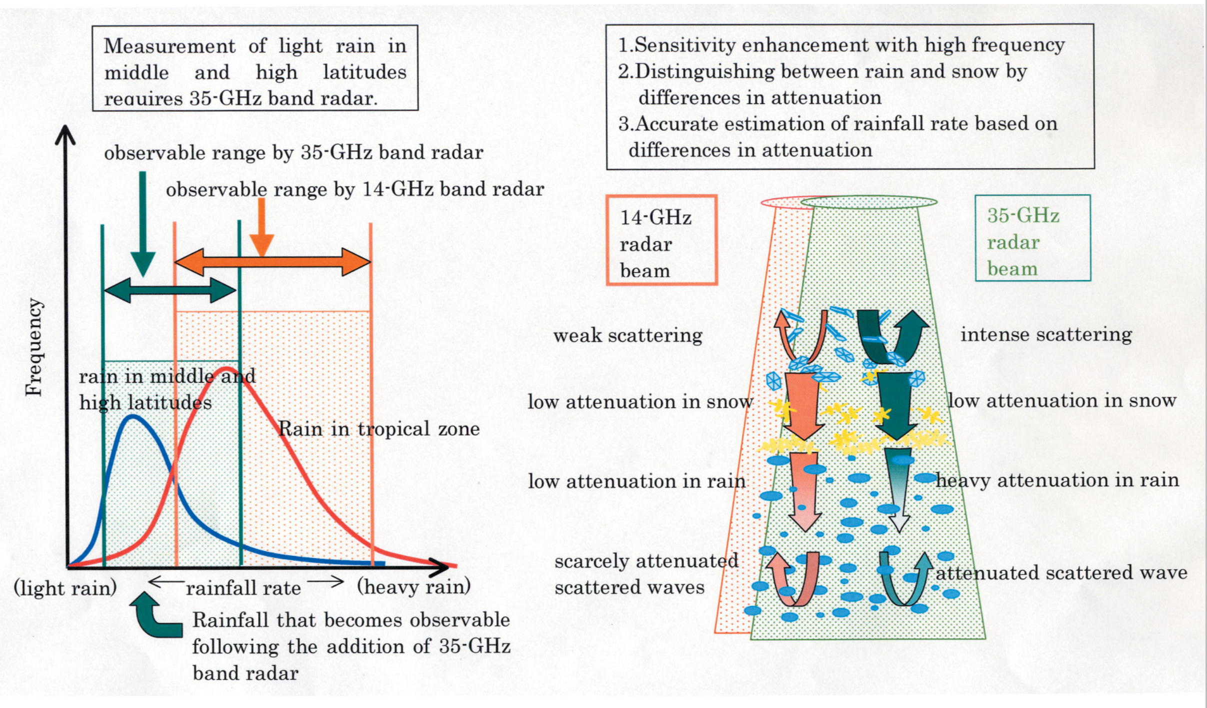

Fig.1 Benefits of measurement by dual-frequency precipitation radar

5 Issues

One problem associated with choosing the number of and arraying the secondary satellites is implementing three-hourly global observations. With the exception of two or three exclusive satellites, most GPM constellation satellites will have other primary missions. Although all will have sun-synchronous orbits, each satellite has a different altitude and hence circles the globe at a different time period. Even with eight satellites, intervals between measurements will sometimes be longer than three hours. In addition, the specifications for microwave radiometers installed on the different satellites vary, meaning that the observation ranges and resolution will differ, as well as satellite altitude. Satellite altitude is an unavoidable trade-off between high spatial resolution and the range of observation: higher altitudes mean wider observation ranges, but lower resolution. Conversely, even with microwave observation equipment having antennas of comparatively small diameter, sufficient resolution can be secured only if it is installed on a low-orbiting satellite.

It is essential to choose the orbits of constellation satellites dedicated to GPM so that their observation ranges cover areas not covered by other satellites. How are optimal orbits to be determined? If we set sampling interval as the criterion, should we seek to minimize the worst sampling interval, or minimize the average of all sampling intervals? Moreover, what should be the duration of such a statistics period? A single day, a single month, or an entirely different period? How should the uniformity of sampled data be assessed? Determining the optimal criterion to resolve these problems represents a major undertaking.

A technical challenge in developing DPR is optimizing its performance given constraints involving mass, power consumption, and budget. Here, the priority of the requirements and criterion for the optimization of each given objective of the mission again becomes an issue. These include sensitivity, swath width, and degree of matching of the dual-frequency radar beams. Regarding the matching of the beams, it is technically possible to make the sampled volume for the Ku band and Ka band agree within a few hundred meters. However, it is extremely difficult to verify this degree of matching after the satellite is launched, and it will be necessary to arrange a number of synchronized receivers and transmitters within the radar's instantaneous field-of-view to obtain calibration data. The need to develop such a calibrating apparatus and procure expenditures for verification experiments is expected to be a major issue as well.

Another major undertaking is the design of the GPM ground data processing system. This system must be able to gather and process in quasi-real time not just data from the primary satellite, but data from microwave radiometers from the group of secondary satellites whose satellites are operated by different organizations. Finally, all data from the multiple satellites must be merged to create the three-hourly global precipitation distribution.

6 Rainfall Rate Estimation Algorithm and Validation

The rainfall rate estimation algorithms for DPR and the microwave radiometer aboard the primary satellite can be understood as an extension of the TRMM algorithms. Nevertheless, the following two points require further research. One is the development of a dual-frequency radar algorithm to process DPR data, while the other is the integration of data from the radiometers of multiple constellation satellites.

A new study initiative requires the processing of DPR data to extract information on raindrop size distribution, such as average drop size, using the dual-frequency radar algorithm. In general, with the dual-frequency algorithm, the difference between radar reflectivity factors measured at two frequencies is considered to result from differences in the scattering cross section (effective radar reflectivity factor) and extinction cross section (attenuation) at both frequencies. The radar beams of both frequencies are assumed to coincide completely, and rainfall distribution is assumed to be uniform within the beam at every distance. However, in reality, these assumptions are not justified. Since the statistics for the nonuniform distribution of actual rainfall are not fully understood, we must devise a way to determine the degree of the rainfall estimate error.

A method of obtaining the best estimate as of GPM by integrating data from more than one radiometer of a different standard gives rise to a new subject. Each radiometer provides data on a different field-of-view and different sampling intervals. To determine how several pieces of data obtained from different radiometers can be integrated temporally and spatially to interpolate an estimate, a quantitative guideline is required.

To ensure high-quality estimates, satellite data and the rainfall estimation algorithms must be thoroughly validated. The validation must be quantitative, including error analyses. Such efforts will be closely linked to algorithm development. The problem is of considerable scale, and will require careful planning to resolve.

7 Partnership

As the name suggests, the GPM mission has a global scope. International cooperation is required both in scientific research and in operation thereof. It is our hope that space agencies and governmental organizations of as many nations as possible, as well as international organizations and research organizations, will participate in this research.

The apportionment of developmental tasks for GPM has yet to be determined conclusively. At this point, we envision that NASDA will develop the primary GPM satellite in cooperation with NASA and contribute in other ways to the GPM project. NPOESS/IPO will collaborate with the program, developing two pieces of SSMIS observation equipment and three pieces of CMIS observation equipment. In addition, NASDA will prepare GCOM-B1, while NASA offers one or two secondary satellites for GPM only. ESA is also considering the possibility of offering one or two secondary satellites. ISRO/CNES intends to join GPM in the Megha-Tropiques program.

Data from ground validation sites is indispensable for increasing the accuracy of rainfall estimates by the GPM satellite constellation. In addition to Japan and U.S., Australia, Brazil, Canada, Britain, France, Germany, India, Italy, Spain, and Taiwan, among others, intend to provide ground validation sites. Other nations are likely to participate in the future. These validation sites will be crucial to the success of the GPM program.

8 Conclusions

TRMM has brought new information on El Niño, variations in tropical areas including monsoons, large-scale cloud dynamics, diurnal variations, and water circulation. GPM will broaden the research scope of TRMM, enable estimation of global precipitation with high precision, foster better understanding of water cycle, and improve forecast accuracy through data assimilation.

GPM is essentially a research program on a global scale. GPM includes many participants, cooperative organizations, cultures, satellites, pieces of equipment, perspectives, data sources, data flows, processing systems, processing environments, hardware and software, scientific interests, and applications. NASA and NASDA have established a cooperative relationship and nurtured various scientific and technological ideas. Nonetheless, to formulate and implement this mission successfully, even wider cooperation surpassing the Japan-U.S. relationship will be essential. Cooperation is the key to the success of GPM. (Note in proof: This text is a slightly revised translation of a paper, “Precipitation Observation from Space in the Next Generation: the Global Precipitation Mission,” presented at URSI Commission F, Open Symposium.)

Appendix: About 35-GHz radar under development at CRL

In fiscal years 1999 to 2001, CRL worked on developing a high-output solid-state power amplifier, phase shifter, and waveguide antenna for the 35.5-GHz satellite-borne precipitation radar. Table 1 lists the target specifications for the radar. Table 2 lists the design specifications of the antenna in this development. Tables 3, 4, and 5 summarize the performance of prototypes of these apparatuses resulting from these efforts. While calculations for radar sensitivity were based on the specifications of these prototypes, the conditions used to calculate sensitivity are as follows: satellite height of 400 km, beam width of 0.7 degree, range resolution of 250 m/500 m, logarithm detection, dual-frequency agility, transmitted power of 128 W, receiver noise of —110.0 dBm (at a range resolution of 250 m), feeding loss of 1.0 dB, and filter loss of 1.3 dB. For noise sampling, the sampling number of noise was four times that of echo, and the data was averaged. Under such conditions, the echo intensity at which the expected value of the SNR per pulse becomes unity corresponds to Z = 22.4 dBZ for a range resolution of 250 m and Z = 16.4 dBZ for 500 m. In actual measurements, since averaging is performed for a number of pulses, fading noise can be suppressed and the minimum detectable sensitivity improved. Table 6 shows the detection sensitivity when an echo intensity equal to three times the standard deviation of noise is assumed as the detection criterion of the echo, which is the same criterion used for rainfall detection in the TRMM PR algorithm. When the beam of the Ka-band radar is matched to that of the Ku-band radar, the number of sampling pulses of each beam is equal to the figure given in the table when the swath width is 245 km. The table indicates that rain of about 12 dBZ, corresponding to 0.2 mm/h by the Z-R relation of $Z = 200 R^{1.6}$, can be detected. Table 7 shows how sensitivity and power consumption change when the number of frequency agility is increased.

Table 1 Characteristics of the Ka-band radar installed on the GPM primary satellite

Radar type	Pulse radar
Antenna type	128-elem. WG slot array
Beam scanning	Active phased array
Frequency	35.55 GHz
Polarization	Horizontal
TX/RX pulse width	1.57 / 1.67μsec (3 μsec)
RX band width	0.6 MHz (0.3 MHz)
Pulse rep. freq.	2235 Hz
Data rate	93.5 kbps
Mass	290 kg (*)
Designed Life time	5 years
Sensitivity	< 0.5 mm/h (0.2 mm/h)
Horizontal resolution	5.0 km (nadir)
Range resolution	250 m (500 m)
# of indpdt samples	64 (fading noise < 0.7 dB)
Swath width	245 km
Observable range	Surface to 15 km (*)
Dimensions	1.0 x 1.0 x 0.5 m

(*: very likely to be altered)

Table 2 Designed characteristics of the Ka-band antenna

Antenna Type	Planar Array, 128-element Slotted Waveguide Edge Slot Array(=Slot in E-plane), Nonresonant Type			
Weighting	Taylor Distribution (SL = -35 dB, N = 6)			
Array Element	Along-Track	5.69 mm	142	807.98 mm
	Cross-Track	6.33 mm	128	810.24 mm
Beam Width	Along-Track	0.71 deg		
	Cross-Track	0.71 deg (nadir) – 0.74 deg (scan edge)		
Gain	47.4 dBi			
Sidelobe	< -27 dB			
VSWR	< 1.2	Waveguide Loss	0.71 dB	

Table 3 Electrical characteristics of the 8-element Ka-band array antenna

Antenna Type	8-element Slotted Waveguide$^{(1)}$		
Weighting	Taylor Distribution (SL = -35 dB, N = 6)		
Array Element	Along-Track	5.69 mm	142
	Cross-Track	6.33 mm	8
Beam Width	Along-Track	0.71 deg	
Gain	35.8 dBi		
Sidelobe	-27.03 dB(@-54.4 deg) -27.43 dB(@+42.4 deg) -28.55 dB(@-1.13 deg)		
Cross Pol	-24.29 dB(@+43.0 deg) -26.89 dB(@-53.8 deg)		
VSWR	< 1.1		

Table 4 Characteristics of Ka-band solid-state power amplifier (P-HEMT)

Serial Number	type	Output Power (dBm)	Average power Consumption	Estimated power consumption with lower supply voltage	Weight
SN01301	BA2500 X 4	34.58 (34.13-34.66)	1238 mW (1193-1329)	858 mW	472 g
SN01302	BA2900 X 2	34.57 (34.23-35.13)	1077 mW (1069-1100)	771 mW	471 g

(Measurement conditions: center frequency 35.55 GHz, frequency range 35.5 — 35.6 GHz, temperature —20℃ / +25℃ / +50℃, pulse width 1.67 μsec, duty 1%)

Table 5 Characteristics of the Ka-band 5-bit phase shifter

Serial Number	Insertion Loss Mean (Max-Min)	Phase Error (RMS)	Average Power Consumption	Switching Time	Weight
#1	7.9-8.2 (3.4)	1.3-4.5 deg.	132-136 mW	0.06 μ sec	220 g
#2	7.2-7.8 (3.7)	1.1-3.2 deg.	125-132 mW		
#3	7.4-8.0 (3.4)	1.5-4.2 deg.	131-134 mW		
#4	8.1-8.5 (3.4)	1.2-3.3 deg.	125-128 mW	0.065 μ sec	

(Measurement conditions: 35.55 GHz (35.5 — 35.6 GHz), (—20℃, +25℃, +50℃)

Table 6 Sensitivity estimates

Swath width	N of beams	Obs. Time /beam	N of pulses	Effective S/N(dB)	σ(dB)	3σ S/N(dB)	Min dBZ	Rain (mm/h) Ze=200R^1.6	Min dBZ	Rain (mm/h) Ze=200R^1.6
							Range res. = 250 m		Range res. = 500 m	
5 km	1	714.3 ms	4470	14.0	0.092	-16.3	6.1	0.053	0.1	0.004
40 km	8	89.3 ms	558	9.5	0.256	-11.1	11.3	0.185	5.3	0.078
100 km	20	35.7 ms	224	7.5	0.397	-8.5	13.9	0.270	7.9	0.114
245 km	49	14.6 ms	68	5.0	0.696	-4.4	18.0	0.486	12.0	0.205

Table 7 Variation of relationship between power consumption and sensitivity in various modes

	Sensitivity improvement	Minimum detectable Z	Equivalent rain rate	Total power consumption
basic model	0 dB	18.0 dBZ	0.486 mm/h	265 W
3-freq. agility	+0.9 dB	17.1 dBZ	0.427 mm/h	291 W
3-bit pulse compression	+4.7 dB	13.2 dBZ	0.244 mm/h	291 W
4-freq. agility	+1.5 dB	16.5 dBZ	0.392 mm/h	317 W
500-m res.	+6.0 dB	12.0 dBZ	0.205 mm/h	317 W
500-m res.+4-freq. agility	+7.5 dB	10.5 dBZ	0.165 mm/h	421 W

Basic model: 250-m resolution (pulse width: 1.67 μs), 2-freq. agility, PRF = 2820 Hz.

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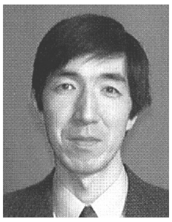

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