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GROUND-BASED W-BAND FMCW CPR FOR COORDINATED OBSERVATION WITH SPACEBOURNE CPRS

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1. INTRODUCTION

CPR (Cloud Profiling Radar) is designed to monitor cloud structure with millimeter wavelengths at 35, 78 and 94 GHz, which is the most effective remote sensing instrument to study cloud inside structure by observing cloud vertical profiles of radar reflectivity factor and doppler velocity. Cloud microphysical properties (e.g., cloud boundaries, vertical profiles of liquid and ice water content, effective radius) can be provided from observation by CPRs, which leads to better understanding of cloud radiative forcing and the earth's energy balance.

Chiba University has developed the solid-state ground-based FMCW (Frequency Modulated Continous-Wave) CPR named as FALCON-I (FMCW Radar for Cloud Observations) since 1999, evaluated theoretically (Takano et al. 2008) and systematically (Yamaguchi et al. 2009a). FMCW system can achieve higher range and time resolution than pulsed radars, and is expected to reveal more detailed cloud vertical structure.

FALCON-I is also expected to calibrate the spaceborne CPR of EarthCARE (Kimura and Kumagai 2008; ESA 2004) as one of the ground calibration systems.

This paper mainly reports the performance of FALCON-I from the past studies and the validation result with spaceborne CPR.

2. FMCW CPR FALCON-I

Although many CPRs operate in pulsed mode, CPRs with FMCW mode has been developed recently such as the bistatic airborne FMCW CPR at 94.8 GHz by ProSensing Inc. and University of Miami in America (Mead et al. 2003), the ground-based FMCW CPR at 94 GHz by STFC Rutherford Appleton Laboratory and the UK Met Office (Huggrad et al. 2008).

Fig.1: Outlook of FALCON-I

Table 1: Specifications of FALCON-I

Frequency	94.79 ± 0.01 GHz
Modulation Shape	Sawtooth (Ramp)
Observation Range	20 km
Temporal Resolution	1 min or 15 s (Variable)
Transmitter	Solid-State Amp, 27 dBm
Antenna	Bistatic Cassegrain
Antenna Gain	57 dBi
Antenna Beamwidth	0.18 deg
Range Resolution	16.6 m (Variable)
A/D Sampling Rate	10 MHz
Sensitivity	About -30 dBZ at 5 km
Doppler Velocity	± 4 m/s

Since Chiba University radar group has developed FALCON-I in 1999, FALCON-I has joined many outfield observations to obtain various cloud data in many regions and seasons. The outlook of

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FALCON-I is shown in Fig.1, and the specifications are listed in Table 1. As shown in Fig.1, FALCON-I was designed as a bistatic radar looking at zenith direction, which can operate only with standard 100 V power outlet. All systems including the transmitting, receiving systems, power supplies and the observation PC are in the box. It is loaded on a truck at outfield observations, and set in a container at cruise observations and nominal observations in Chiba University.

Advantages of FMCW mode are: (1) higher range resolution by wide FM bandwidth and (2) higher S/N ratio by longer observation term. Although range resolution at pulsed mode, usually about hundreds of meters, is determined by pulse length which needs certain length, wide FM bandwidth makes range resolution of FMCW CPR much higher from a few meters. Although usual PRF (Pulse Repetition Frequency) at pulsed mode for CPR is about thousands of Hz which means a few profiles every 1 ms, FMCW mode keeps digiting signals at higher than 10 MHz of sampling rate, which leads to higher S/N ratio by averaging effect of FFT (Fast Fourier Transform). Because this higher S/N ratio allows the system to use less power, a solid-state transmitter is used to transmit signals in spite of high power transmitters like such vacuum emitters, which is safer and more moderate cost.

The original IF signal is generated at 150 MHz with 10 MHz frequency modulation, combined with three local signals to create the transmitted signal at 94.79 GHz ± 10 MHz shown at the block diagram in Fig. 1. Received echo signal is downmixed with local signals to create the beat signal. The beat signal is sampled at A/D converter in the Observation PC at 10 MHz sampling rate. Total gain and attenuation of the receiving system is estimated as about 75 dB, and noise level power at antenna input is about -140 dBm.

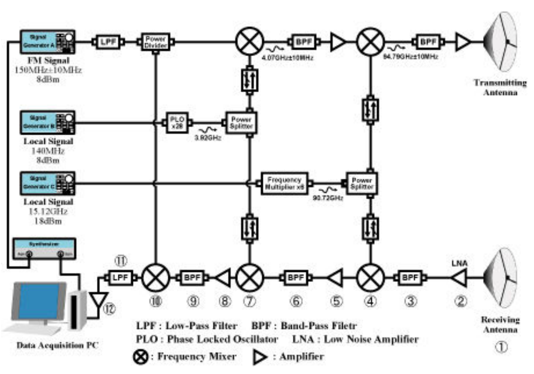

Fig. 2: Block Diagram of FALCON-I

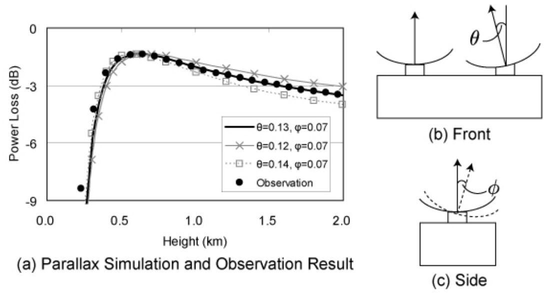

Fig. 3: Estimation of Parallax Correction

3. EVALUATION OF RADAR REFRECTIVITY

Although radar reflectivity factor is calculated from echo signal power with radar equation, some correction should be considered to estimate the true reflectivity. Major corrections are atmospheric attenuation, parallax, attenuation in clouds and rain, and multi-scattering in clouds. In this chapter, parallax correction and atmospheric attenuation correction are discussed.

3.1 Parallax Correction

Not only the position of transmitting and receiving antenna are different, the antenna axis is not guaranteed to point vertical direction completely, and it is pointed out that its conflict causes large power loss (Sekelsky and Clothiaux 2002).

Yamaguchi et al. (2009b) discussed Parallax correction of FALCON-I, which estimated power loss caused by parallax by comparing simulation and observation. Simulation was done for several angles of antenna axis with 0.01° accuracy. The transmitting antenna axis was fixed to complete zenith direction and electric field intensity was calculated when the receiving antenna axis has angle against zenith direction in 2 dimension θ and φ shown in Fig. 3 (b) and (c). The ratio of received power echo between monostatic radar and bistatic radar was calculated from simultaneous observation of FALCON-I and SPIDER, which is the 94 GHz Pulsed CPR developed by NICT (National Institute of Information and Communications Technology) (Horie et al 2002). The best fitting was θ=0.13° and φ=0.07°, thus parallax effect for echo power at each height was determined.

3.2 Atmospheric Attenuation

Although CPRs at millimeter-wave are more sensitive than lower frequency radars, attenuation due to the atmosphere, especially caused by water

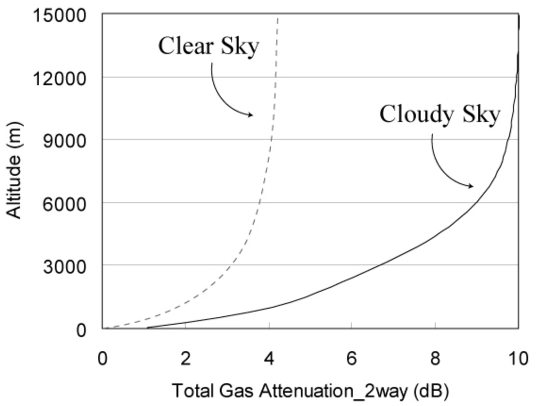

Fig. 4: Atmospheric Attenuation at 95 GHz in the case of a clear sky and cloudy sky from the past observation results.

vapour, is not ignorable. Fig. 4 shows atmospheric attenuation at 94.79 GHz from the past observation results, estimated from atmospheric parameters (e.g., temperature, pressure, density) by Ulaby et al. (1981). The figure tells that 4 dB attenuation occurs on the way from the ground to height of 9 km (2 way) in clear sky, 10 dB from the ground to height of 12 km in cloudy sky.

3.3 Ground & Satellite Observation Comparison

We conducted simultaneous observation with the Spaceborne CPR CloudSat operated by NASA/JPL in 2008 at Cape Hedo Aerosol and Atmosphere Monitoring Station developed by NIES (National Institute for Environmental Studies), Okinawa, Japan. CloudSat with 94 GHz CPR flies on the A-train sun-synchronous orbit. Its altitude is from 705-732 km above sea level. PRF (Pulse Repetition Frequency) is 3700-4300 Hz. Each vertical profile of received echo power and radar reflectivity is integrated for 0.16 s, corresponding to flight distance of about 1.1 km with 700m footprint radius (Stephens et al. 2008, Tanelli et al. 2008). Range resolution is approximately 500m.

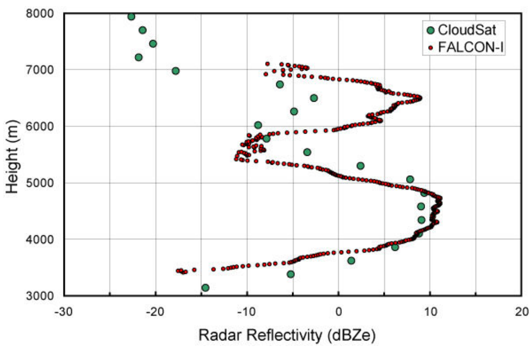

Fig. 5: Radar Reflectivity Profile from Simultaneous Observation Result of FALCON-I and CloudSat

Fig. 5 shows one of the vertical profile of the both CPRs on February 23rd, 2008. CloudSat's path of the profile starts 742m away and ends 353m away from the Hedo Station. The profile of FALCON-I is the average reflectivity of 1 minute. Atmospheric attenuation is corrected by CloudSat 2B-GEOPROF product. As shown in Fig. 4, atmospheric attenuation is large for ground observation because water vapor and oxygen are thicker at lower altitude. If atmospheric attenuation was not corrected, the vertical profile of ground-based FALCON-I underestimated more than 6 dB in reflectivity. Although the difference of reflectivity is smaller in lower layer (3000m - 5500m), the figure shows big difference in higher layer (above 5500m). Temporal and spatial stability of cloud should be considered carefully in this case for this comparison for future work.

4. MICROPHYSICAL PROPERTIES

We also retrieve cloud microphysical properties from radar reflectivity observed by FALCON-I. Fig. 6 is one of the examples of the evaluation of retrieval. COT (Cloud Optical Thickness) from cloud bottom to cloud top was estimated under the condition of single layered, non-precipitating and liquid water cloud for 4 cases. Using LWP (Liquid Water Path) observed by microwave radiometer with radar reflectivity factor, LWC (Liquid Water Content) and Re (Cloud Effective Radius) are estimated by Frisch et al. (1998) and Frisch et al. (2002). We obtained a result which implies aerosol indirect effect between the vertical profiles of retrieved Re and aerosol size distribution (Pandithurai et al. 2009). The vertical profile of COT is estimated from LWC and Re by Stephens (1978). Thus, the retrieved COT and SWD (Shortwave

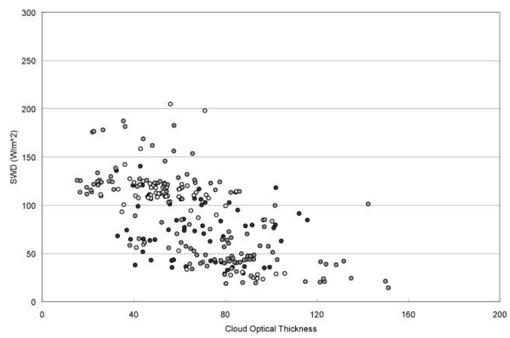

Fig. 6: Correlation of the Retrieved Cloud Optical Thickness of FALCON-I and the Short-wave Downward Flux Observed by Pyranometer.

Downward) radiation observed by pyranometer were compared. The exponential relation should be lie between COT and SWD, which is apparently shown in Fig. 6, and more detailed analysis is on progress.

5. SUMMARY

This study reported: (1) the outline of 95 GHz FMCW CPR (Cloud Profiling Radar) FALCON-I and the primary analysis and results from the past observation, (2) reflectivity of FALCON-I has been corrected and validated through simultaneous observations with the other CPRs (e.g., SPIDER and CloudSat), (3) primary studies of retrieval method from radar reflectivity to cloud microphysical properties.

We are summarizing primary studies from the past 10 years' observation to evaluate FALCON-I's performance for cloud microphysics using FALCON-I data.

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