Cloud Profiling Radar for Cloud Radiation Study

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CLOUD PROFILING RADAR FOR CLOUD RADIATION STUDY

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1. INTRODUCTION

Cloud profiling radar (CPR) is a potential sensor for providing global vertical distribution of clouds with accuracy sufficient for determination of the associated radiation budget effects (Brown et al. 1995). Particularly, information of cloud base and top heights, multi-layer structure, and vertical profiles in liquid or ice content provided from CPR is essential in studying cloud role in earth radiation budget. A frequency near 94 GHz (a wavelength of 3.2 mm) has been proposed for a spaceborne CPR primary because of the high sensitivity it provides, relatively small atmospheric attenuation, and existing radar components and technical experience available in this frequency. In a proposed cloud aerosol radiation budget experiment in Japan (3D-CLARE: satellite name is ATMOS-B1), CPR and lidar are the main sensors onboard. In this report, brief introduction to measurement, sensor design, and retrieval techniques for CPR are given.

2. CPR MEASUREMENT

The radar reflectivity factor for distributed spherical particles that are small relative to the wavelength is defined as

$$Z = \int_0^{\infty} N(D) D^6 dD \qquad (1)$$

where $N(D)$ is the particle size distribution with diameter D. Since radar reflectivity measurements are usually referred to in terms of the equivalent reflectivity of water Z_e, we use the relation for ice particle

$$Z_e = Z_i \left(\frac{K_i^2}{K_w^2}\right) \qquad (2)$$

to represent the equivalent Z_e of ice, where Z_i is given by (1). Here, the coefficients K_i and K_w depend complex refractive indices of ice and water, m_i and m_w, respectively and K is expressed as

$$K_j = \left|\frac{m_j^2 - 1}{m_j^2 + 2}\right| \qquad (j = i, w) \qquad (3)$$

The relation between Z_e and radar backscattering coefficient η is

$$\eta = Z_e K_j^2 \frac{\pi^5}{\lambda^4} \qquad (4)$$

The radar measurable Z_e is connected with liquid and ice water content (LWC and IWC) using relations proposed as (Sassen and Liao 1996)

$$Z = (\frac{3.6}{N_d})LWC^{1.8} \qquad \text{(water clouds)} \qquad (5)$$

and

$$IWC = 21.7Z_e^{0.83} \qquad \text{(ice clouds)} \qquad (6)$$

where, N_d is cloud particle concentration. The attenuation coefficient in water clouds is given as

$$k = 0.434 \cdot 6\pi / \lambda \cdot \mathrm{Im}(-K_w)LWC \quad (\mathrm{dBkm}^{-1}) \qquad (7)$$

The attenuation in ice clouds is generally negligibly small.

With respect to necessary sensitivity for spaceborne CPR, assessments carried out have presently suggested a threshold as -30 dBZ (dBZ=$10\log_{10}Z$; IGPO 1994). A recent study for cirrus clouds gives an estimate that the threshold of -30 dBZ should detect 99 % of "radiatively significant" clouds in the midlatitudes and 92 % in the tropics (Brown et al. 1995). Slightly lower detection probability (84%) for this threshold was given by Atlas et al. (1995).

3. SPACEBORNE CPR DESIGN

Major parameters for spaceborne CPR obtained from a conceptual design study are listed in Table 1. The required sensitivity has been attained provided with low satellite altitude and a 2-m diameter antenna at 94 GHz frequency. Still further improvement in radar sensitivity needs to be considered. It is noted that the radar pointing is fixed to nadir. This design will meet the mission objective of the cloud radiation study which intends to collect samples for global 3-D cloud distribution. Cloud imaging by antenna scanning is presently not feasible due mainly to long dwell time necessary for data integration at each footprint.

4. COMBINED TECHNIQUES

A remote sensing technique to estimate cloud effective radius has been proposed using radar and lidar combined measurements. Because both radar and lidar are proposed as onboard sensors in the cloud aerosol radiation mission, cloud sizing could be feasible using the two sensors. Comparison of backscatter coefficients between the two sensors at the wavelengths in large separation gives information of the effective particle radius. This technique has been applied to the cirrus clouds using ground based X-band and Ka-band radars with CO_2 lidar. Reasonable results with effective radius between 75 and 190 μm have been obtained, although there are several difficulties in obtaining correct backscattering coefficients in the two co-located measurements such as correction of attenuation. (Intrieri et al. 1993). Other combined techniques between radar and microwave or infrared radiometers are also potential to provide with useful information concerning effective radius or attenuation correction in cloud profiles.

5. ONGOING AND FUTURE ACTIVITIES

Development of a W-band (95 GHz) airborne radar is ongoing by CRL, the first test flight of which is scheduled in fall or winter 1997. The main objective of this system is to establish technical feasibility for the satelliteborne CPR. Also, scientific usefulness of CPR will be demonstrated in the flight experiments. Data will be collected to evaluate the design of spaceborne system particularly concerning radar sensitivity and polarimetric capability. An in-orbit experiment using CPR on Japanese Experimental Module (JEM) to be attached to the space station is also proposed aiming at the first CPR demonstration in space mainly for the sensor technology validation. The scheduled time for this experiment is about 2002 at earliest.

Table 1: Major design parameters for spaceborne CPR

Altitude	420 km
Antenna	Offset Parabolic: 2 m-dia. (nadir pointing)
Antenna Gain	64 dBi
Tx power (peak)	1500 W
Tx path loss	1 dB
Pulse width	3.33 ms
PRF	3500 Hz
Receiver NF (incl. Rx path loss)	7 dB
IFOV	860 m
Along track resolution after integration	5 km
Frequency channels	1 (2)
Duty ratio	1.2 (2.3) %
Zmin @ 10 km height	-31.3 (-32.8) dB
Weight	140 kg
Power consumption	350 (600) W

REFERENCES

Atlas, D., S. Y. Matrosov, A. J. Heymsfield, M-D Chou, D. B. Wolff, 1995: Radar and radiation properties of ice clouds, J. Appl. Meteor., 34, 2329-2345.

Brown, P. R. A., A. J. Illingworth, A. J. Heymsfield, G. M. McFarquhar, K. A. Browning, and M. Gosset: 1995, The role of spaceborne millimeter-wave radar in the global monitoring of ice cloud, J. Appl. Meteor., 34, 2346-2366.

IGPO, 1994: Utility and feasibility of a cloud profiling radar, IGPO Pub. Series10, International GEWEX Program Office.

Intrieri, J. M., G. L. Stephens, W. L. Eberhard, and T. Uttal, 1993: A method for determining cirrus cloud particle sizes using lidar and radar backscatter technique, J. Appl. Meteor., 32, 1074-1082.

Sassen, K. and L. Liao, 1996: Estimation of cloud content by W-band radar, J. Appl. Meteor., 35, 932-938.

CLOUD PROFILING RADAR (CPR)

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17 December 1996
International Workshop on Spaceborne Lidar

Activities to date: study and plans

- Pre-Phase A
  - JFY93: for TRMM F/O (PR, CPR) by NASDA
  - JFY94, 95: for ATMOS-B and JEM by CRL(MOPT)
- Plans
  - Satellite:
    - »ATMOS-B1 (3D-CLARE: CPR & LIDAR)
    - »JEM:
      - A proposal is being written for the use of Exposure Facility (Technical validation and demonstration experiment)
      - Operation starts in 2002 for earliest opportunity.
  - Airborne
    - »CRL Airborne system at 95 GHz (Development 95-97)

Merits and limitations of CPR

- Merits
  - 3-D cloud measurements for denser clouds: Cloud base height is detected for most clouds
  - Quantitative LWC or IWC profiling: Rayleigh scattering and small propagation attenuation
  - Measurement at much longer wavelength than optical instruments: Dual wavelength techniques
- Limitations
  - Sensitivity to clouds is marginal
  - Only nadir pointing
- Issues in development
  - No existing MMW high power transmitter for space use
  - Frequency allocation requirement for 94 GHz is in underway

Radar measurements (1)

Radar reflectivity factor for distributed spherical particles:

$$Z = \int_0^\infty N(D) D^6 dD \qquad (1)$$

where $N(D)$ is the particle size distribution with diameter D.

Equivalent radar reflectivity factor Z_e ; for ice particles:

$$Z_e = Z_i \left(\frac{K_i^2}{K_w^2}\right) \qquad (2)$$

where, coefficients K_i and K_w depend on complex refractive indices of ice and water, m_i and m_w as

$$K_j = \left|\frac{m_j^2 - 1}{m_j^2 + 2}\right| \qquad (j = i, w) \qquad (3)$$

The relation between Z_e and radar backscattering coefficient η is

$$\eta = Z_e K_j^2 \frac{\pi^5}{\lambda^4} \qquad (4)$$

Radar measurements (2)

Z_e is connected with liquid and ice water content (LWC and IWC) as (Sassen and Liao 1996)

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where N_d is cloud particle concentration.
The attenuation coefficient in water clouds is given as

$$k = 0.434 \cdot 6\pi / \lambda \cdot \mathrm{Im}(-K_w)LWC \quad (\mathrm{dBkm^{-1}}) \quad (7)$$

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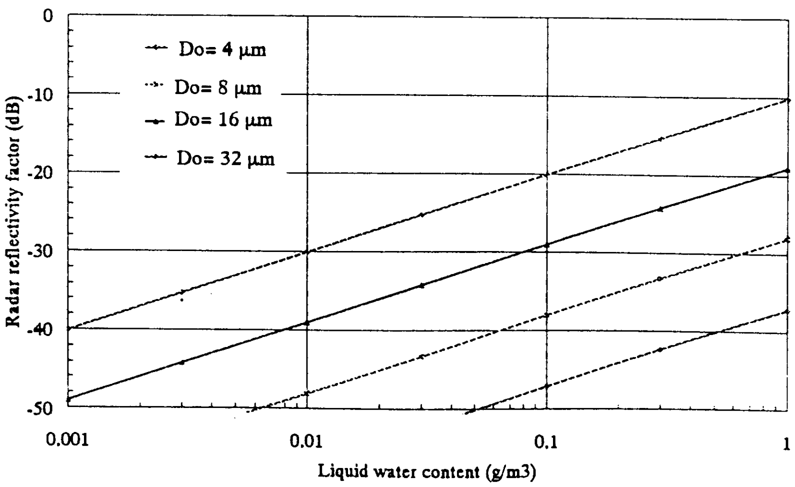
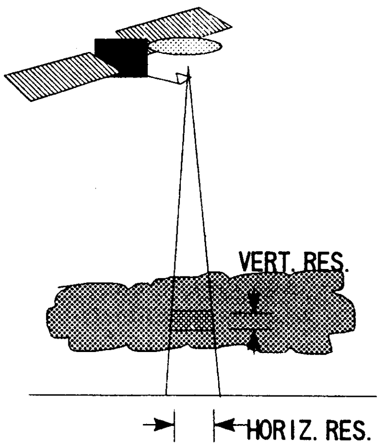
Cloud parameters vs. Z



Concept of Spaceborne CPR



- Key Design Parameters
  - » Nadir-looking radar
  - » S/C altitude: 420 km
  - » Frequency: 94 GHz
  - » Antenna diameter: ~2m
- Performance
  - » Horizontal resolution: 0.9 x 5 km
  - » Vertical resolution: 500 m
  - » Sensitivity: *-30 dBZ*
- Power and Mass Estimates
  - » Power: 300W
  - » Mass: 150 kg
  - » Data rate < 5kbps

CPR specification

Altitude	420 km
Antenna	Offset Parabolic: 2 m-dia. (nadir pointing)
Antenna Gain	64 dBi
Tx power (peak)	1500 W
Tx path loss	1 dB
Pulse width	3.33 μs
PRF	3500 Hz
Receiver NF (incl. Rx path loss)	7 dB
IFOV	860 m
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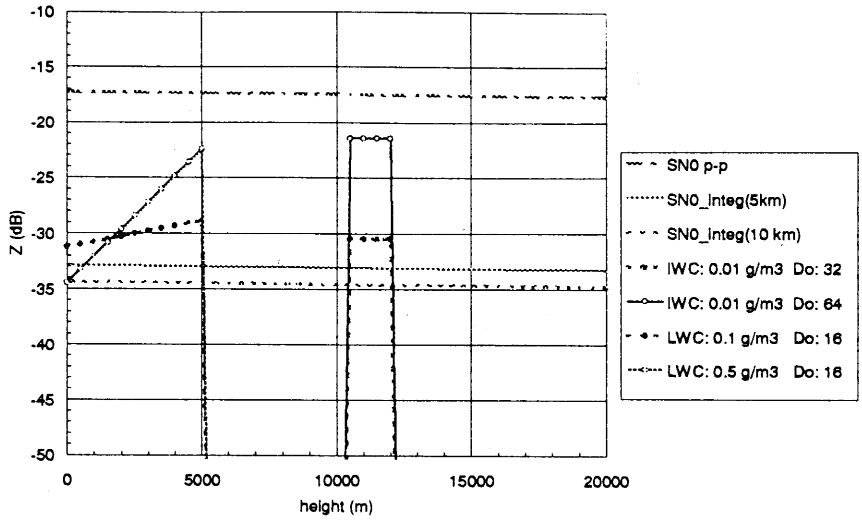
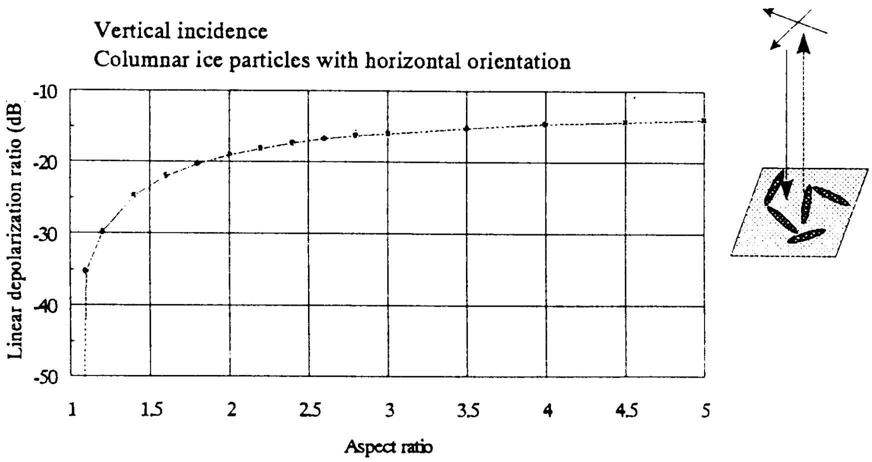
Power consumption	350 (600) W

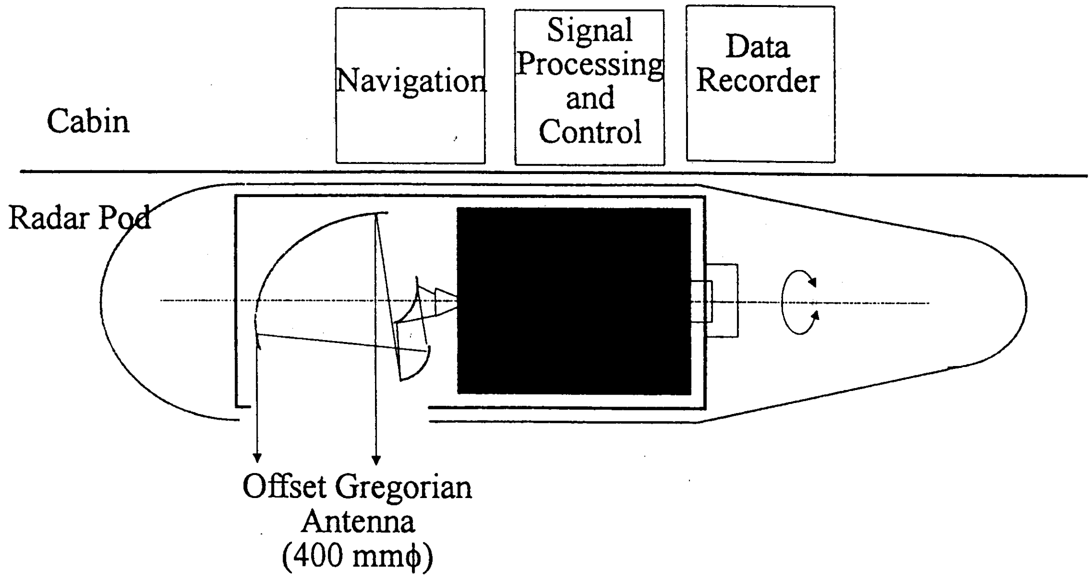
CPR SENSITIVITY



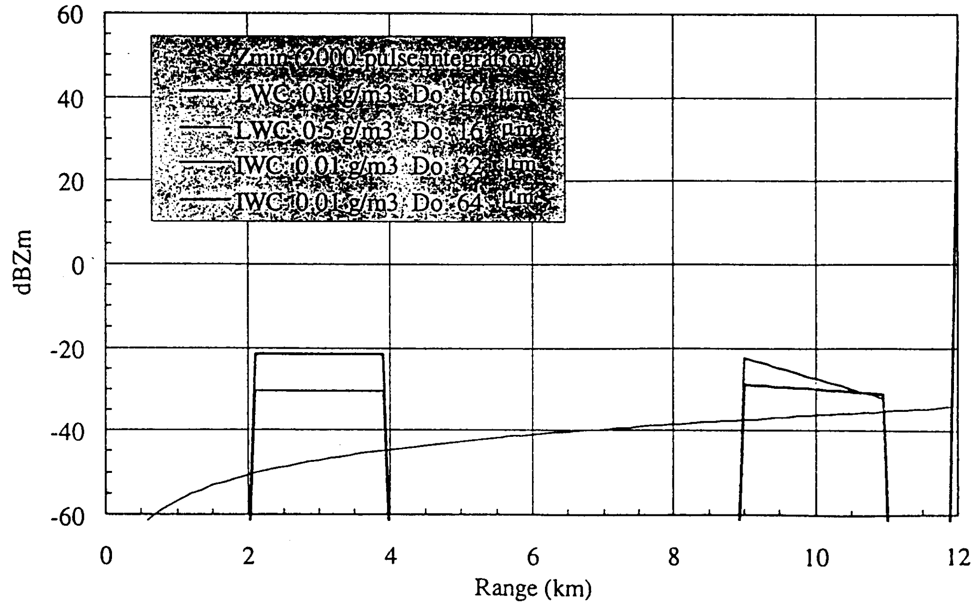
Ice crystal shape identification



CRL航空機搭載雲レーダ構成図

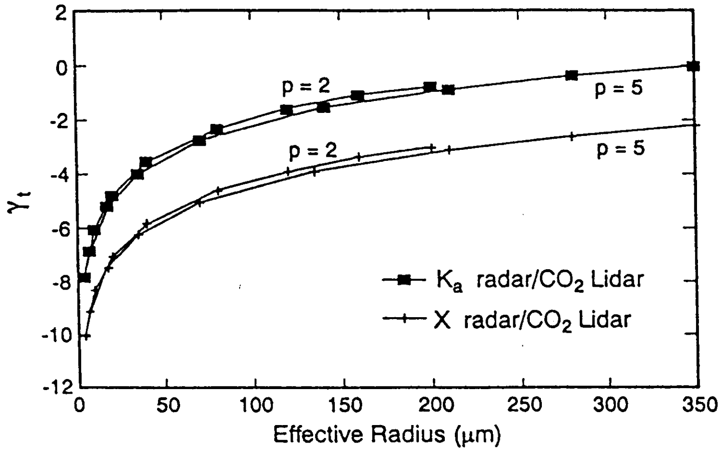


Sensitivity to model clouds



Radar-Lidar combination (particle sizing)

$\gamma_t = \frac{\sigma_{radar}}{\sigma_{lidar}}$ (for theory); $\gamma_0 = \frac{\eta_{radar}}{4\pi\beta_{lidar}}$ (in observation)



(Intrieri et al. 1993)

CRL Airborne Cloud Radar

- To validate technical and scientific feasibility
- 95 GHz short pulse radar
- Tx power: 1.5kW (peak)
- High performance antenna with high polarization discrimination
- Low noise Amplifier (NF 5.0 dB)
- Antenna scan over wide incidence angle
- Full polarimetric (linear polarization with arbitrary angle) and Doppler capability
- Platform: Gulf Stream-II cruising altitude: 12 km
- (Multi-sensor observation)
- Manufacturing: 1995- 1997