P1.11 DETECTION OF ARCTIC CLOUD ICE PROPERTIES USING SUBMILLIMETER-WAVE RADIOMETERS

S.G. Dowlatshahi*[1], A.J. Gasiewski[2], T. Uttal[2], M. Klein[3], E.R. Westwater[3], D. Cimini[3]

[1]Science and Technology Corporation/NOAA Environmental Technology Laboratory, Boulder, CO
[2]NOAA Environmental Technology Laboratory, Boulder, CO
[3]Cooperative Institute for Research in Environmental Sciences/NOAA Environmental Technology Laboratory, Boulder, CO

1. INTRODUCTION

The surface energy budget of the Arctic is strongly influenced by clouds, which are particularly relevant to Arctic climate changes (Zuidema et al. 2004). While radiometric techniques exist to measure water vapor and liquid water path, there are currently no radiometric techniques to accurately measure ice water path. In response to this need, the Arctic Winter Water Vapor Intensive Operating Period 2004 (WVIOP'04) was conducted at the U. S. Department of Energy's Atmospheric Radiation Measurement (ARM) Program field site near Barrow, Alaska from March 9 to April 9, 2004 (Westwater et al. 2004). The main goal of WVIOP'04 was to demonstrate the capability of millimeter wavelength radiometers to improve water vapor observations during the Arctic winter. One of the secondary goals included evaluation of the sensitivity of millimeter-wave window channels to Arctic clouds. The focus of this paper is to analyze the sensitivity of millimeter and submillimeter-wave radiometers to Ice Water Path (IWP) and explore the possibility of developing radiometric IWP retrieval techniques.

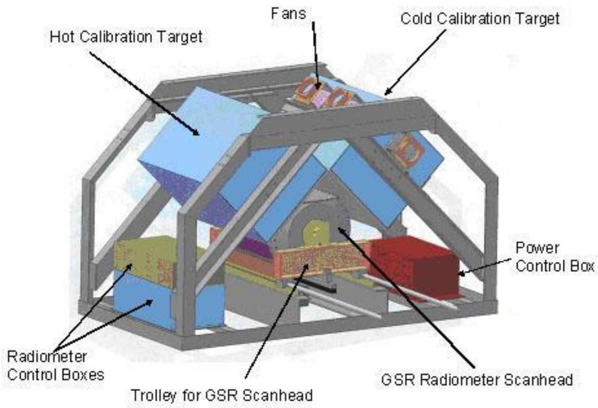
2. INSTRUMENTS

Active cloud sensors from the ARM program were used to determine presence and types of clouds during the WVIOP'04 campaign. A ground-based optical remote sensing system, the Micropulse Lidar (MPL), determines the altitude of cloud base overhead and measures backscatter from up to 20 km altitude. Relative backscatter profiles at 523 nm are retrieved through post-processing of the raw signal and give some indication of the location of cloud liquid or ice layers. At 35 GHz, the millimeter wave cloud radar (MMCR) measures radar reflectivity (*Z*) of the atmosphere at up to 20 km altitude and determines cloud liquid (and to a lesser extent) ice boundaries. The ARM microwave radiometers (MWR) operate at 23.8 and 31.4 GHz and are used routinely to determine precipitable water vapor (PWV) and cloud liquid water path (LWP).

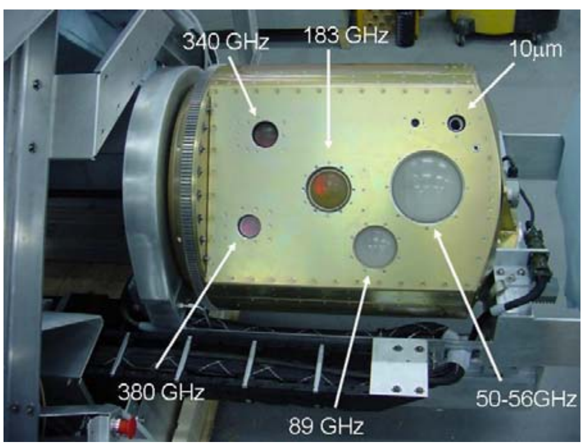
Theoretical studies have shown that microwave radiometers operating in the frequency range of ~150 GHz to ~1.5 THz are useful for measurements of ice water path (Klein and Gasiewski 2000). The enhanced sensitivity to both clouds and water vapor in this range promoted the design and deployment during WVIOP'04 of the Ground-based Scanning Radiometer (GSR) by the NOAA Environmental Technology Laboratory (http://www.etl.noaa.gov/technology/gsr). The GSR uses a new submillimeter-wave Polarimetric Scanning Radiometer/Sounding (PSR/S) sensor head with 11 channels in the 50-56 GHz oxygen band, dual linearly polarized channels at 89 and 340 GHz, 7 channels around the 183.31 GHz water vapor absorption line, and 3 channels around the 380.2 GHz water vapor line. Figure 1a shows a schematic of the GSR. A pair of thermally stabilized calibration targets with high emission coefficients were designed and incorporated. External views of these two precision references provide absolute calibration. Figure 1b shows the PSR/S scanhead which houses the five millimeter-wave and submillimeter-wave radiometers, a 10.6 µm IR radiometer, and a video camera. In addition, all of the radiometers have two internal reference temperatures for more frequent calibration using fast switching schemes.

*Corresponding author address: Sally G. Dowlatshahi, NOAA/ETL, R/ET1, 325 Broadway, Boulder, CO 80305; e-mail: sally.dowlatshahi@noaa.gov

The GSR scanhead periodically moves out of the enclosure on a trolley system for horizon-to-horizon scanning during which the radiometers view the external environment using lens antennas. The primary application of the GSR is to measure temperature, water vapor, and cloud profiles within dry (PWV < 5 mm) and cold (-20 to -55 °C) environments.



(a)



(b)

Figure 1. The GSR system: (a) schematic block diagram of the calibration and scanning mechanism, and (b) the PSR/S scanhead with radiometer lens antennas visible on the face plate.

3. RETRIEVAL TECHNIQUES

PWV and LWP are retrieved from the 23.8 and 31.4 GHz channels of the ARM microwave radiometer, but with low sensitivity to PWV due to the dryness of the environment. The lidar backscatter signal is derived from the ARM MPL and radar reflectivity is measured using the ARM MMCR. Ice water content (IWC) is derived from radar reflectivity, following Matrosov (1999):

$$\mathrm{IWC} = aZ^b\ (\mathrm{gm}^{-3}) \qquad (1)$$

where a and b are the empirically determined values which were used during the case study presented in this paper. IWP (gm^{-2}) is the vertical integral of IWC.

The preliminary GSR brightness temperatures (T_B) were calculated using radiometer gain and offsets derived from the internal hot and cold calibration sources and radiometer voltages by the standard linear calibration method (e.g., Janssen 1993). Calibration target emissivities were found to be close to 0.995. The T_B's from near zenith angles within 90±5° were selected using the scanning angle data and used for further analysis in this study. Final GSR T_B's are calculated using internal calibration and the tip curve method (Han and Westwater 2000).

4. CASE DESCRIPTION

Based on the data from the ARM cloud sensors, an all ice cloud period with a variation in IWP of 0 to 130 gm^{-2} over four hours was selected to test the sensitivity of the GSR channels to IWP. The active cloud sensors showed low-level clouds during that period (Figs. 2a and b). From the ARM calculations, the LWP retrieval error is ~0.03 mm and since the LWP was less than 0.01 mm for that period (Fig. 2c), it was concluded that the clouds detected were free of liquid. At 183.31±15 GHz, a 10 K increase is observed from 0 to 4 UTC (Fig. 2f). At 340 GHz vertical (V) and horizontal (H) polarizations an increase of about 30 K is observed for that period (Fig. 2g) and at 380.2±17 GHz an increase of about 20 K is observed (Fig. 2h).

ARM MWR brightness temperatures at 23.8 and 31.4 GHz as well as GSR brightness temperatures at 50.3, 89 V and H, 183.31±15, 340 V and H, and 380.2±17 GHz are plotted versus radar derived IWP and the results are shown in Fig. 3. An increase in T_B is observed with increase in IWP. The linear approximation of the slope (plotted in red) provides an estimate of the sensitivity of the radiometric brightness temperatures to IWP, along with an influence from PWV. The sensitivity of both MWR and GSR brightness temperatures to PWV and IWP was investigated for very dry conditions (0.32<PWV<0.38 cm) and results are shown in Table 1. The empirical sensitivity to PWV (σ_{PWV}) is derived using clear-air period of seven hours on March 11, 2004 (0.16<PWV<0.23 cm). PWV is retrieved from the 23.8 GHz channel of MWR and the response of the T_B to PWV is ~12.5 Kcm^{-1}. With an increase in the frequency of GSR channels, the sensitivity increases at water

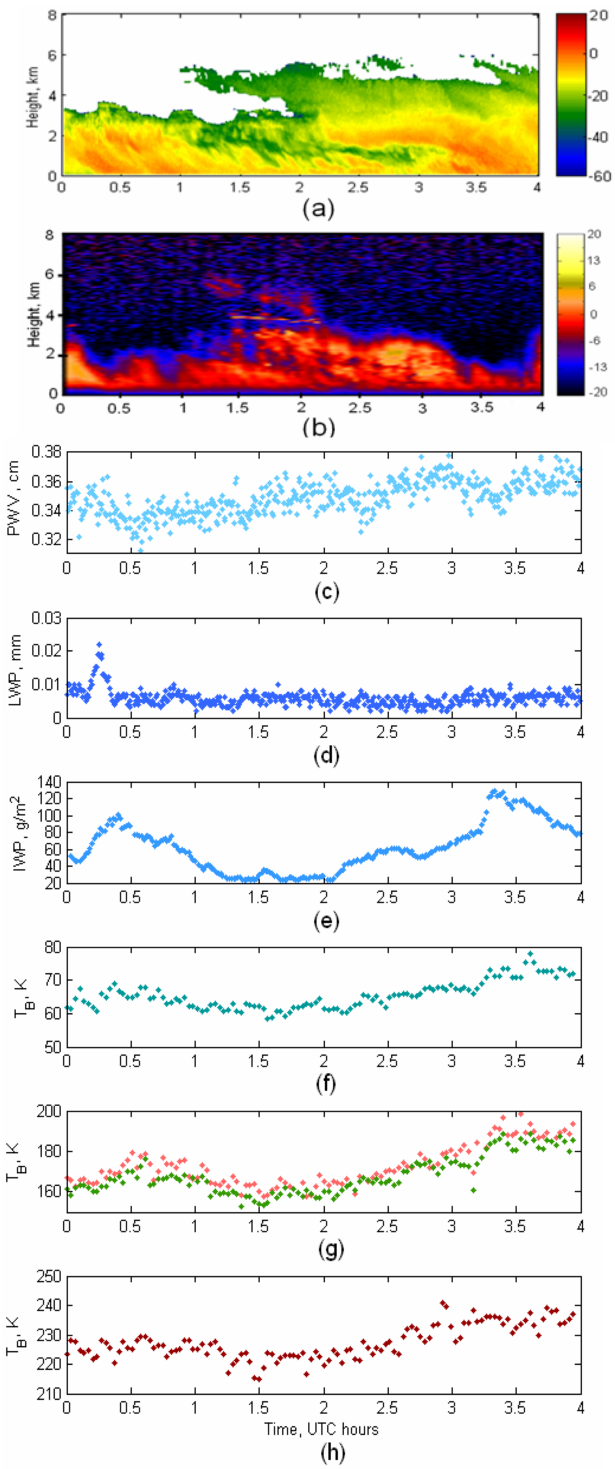


Figure 2. From 0 to 4 UTC on March 30, 2004: (a) reflectivity of cloud radar (dBZe), (b) normalized backscatter from micropulse lidar, (c) PWV (cm), (d) LWP (mm), (e) IWP (gm^{-2}), (f) brightness temperature (T_B) at 183.31±15 GHz (K), (g) T_B at 340 GHz vertical and horizontal polarizations (K), and (h) T_B at 380.2±17 GHz (K).

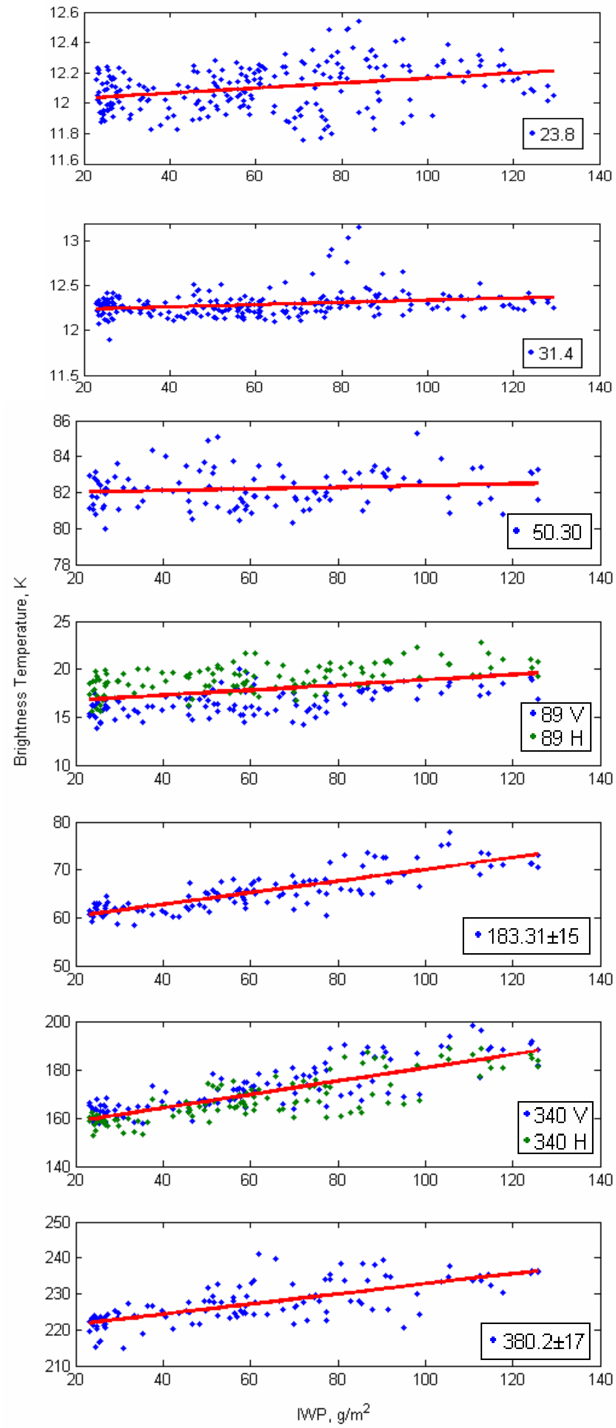


Figure 3. From 0 to 4 UTC on March 30, 2004: scatter plot of IWP vs. brightness temperatures at 23.8, 31.4, 50.3, 89 V and H, 183.31±15, 340 V and H, and 380.2 ±17 GHz, from top to bottom, respectively. The slope of the linear fit is an estimate of sensitivity to IWP, along with an influence from PWV.

Table 1. Empirical sensitivity of the ARM MWR and GSR channels to PWV and IWP (0.3<PWV<0.4 cm). An explanation of the entries is given in the text.

Fre-quency (GHz)	Clear-air sensitivity to PWV (Kcm^{-1})	Slope of IWP vs. T_B's (Km^2g^{-1})	Sensitivity to IWP (Km^2g^{-1})
23.8	12.5±0.07	0.002	0
31.4	2.1±0.12	0.001	0
50.3	110.6±1.5	0.005	0
89	169.5±1.7	0.027	0.01
183±15	238.7±2.3	0.122	0.10
340	428.3±5.0	0.278	0.24
380±17	553.7±4.6	0.269	0.10

vapor absorption lines of 183 and 380 GHz as well as the dual polarized channels of 89 and 340 GHz.

The slope of the line of T_B's vs. IWP (3rd column in Table 1) is affected by both PWV and IWP. To obtain the sensitivity to only ice, water vapor should be removed from the brightness temperatures. Based on the sensitivity of clear-air radiometric brightness temperatures to PWV, an estimate of sensitivity to IWP (σ_{IWP}) is calculated by removal of PWV following:

$$\sigma_{IWP} = \frac{\Delta T_{B,ice}}{\Delta IWP} \qquad (2)$$

where

$$\Delta T_{B,ice} = \Delta T_B - \sigma_{PWV} \Delta PWV$$
$$\Delta T_B = T_B - \min(T_B)$$
$$\Delta PWV = PWV - \min(PWV) \qquad (3)$$

The last column of Table 1 shows the estimated sensitivity of radiometric brightness temperatures to only IWP (Eq. 2). It is seen that ARM MWR channels are not sensitive to ice but GSR channels show useful sensitivity at 89 GHz and above. At 340 GHz, the greatest sensitivity to IWP is observed.

5. SUMMARY

Radiometric brightness temperatures near 22 and 31 GHz have been used operationally for several years to retrieve precipitable water vapor and cloud liquid water path amounts. Theoretical studies indicate that radiometric brightness temperatures at submillimeter-wavelengths are sensitive to ice within clouds, suggesting the possibility of retrieving ice water path. During the recent WVIOP'04 campaign, the GSR was successfully deployed to study this sensitivity. Based on active data from the cloud radar and lidar, case studies of zenith brightness temperatures at 50.3, 89, 183.31±15, 340, and 380.2±17 GHz were analyzed over the period when ice clouds were present. By using estimates of ice water path from 35 GHz radar retrievals, the sensitivity of several millimeter and submillimeter-wavelength channels to IWP was quantified.

The GSR submillimeter-wavelength channels showed an increased sensitivity to both PWV and IWP compared with the ARM microwave radiometer. This improvement suggests that brightness temperatures of GSR channels may be used for future retrievals of both PWV and IWP in polar regions.

6. ACKNOLEDGEMENTS

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