Clear-Air Forward Microwave and Millimeterwave Radiative Transfer Models for Arctic Conditions

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Abstract

In March-April of 2004, a radiometric experiment was conducted at the U. S. Department of Energy's Atmospheric Radiation Measurements (ARM) Program's field site near Barrow, Alaska. During this experiment, multi-wavelength measurements of clear-air brightness temperature were taken by three upward-looking radiometers: the Ground-based Scanning Radiometer (GSR), the Microwave Radiometer (MWR) and the Microwave Radiometer Profiler (MWPR). Brightness temperature measurements over a frequency range from 22.235 to 183.31 GHz are compared with calculations based on Vaisala RS90 radiosondes and five contemporary absorption models. These models include two by H. J. Liebe (1989, 1993), two by P. W. Rosenkranz (1998, 2003), and a recently-published model by J. C. Liljegren et al. (2005). Although no one model is superior in all cases, the Liljegren et al. model provides the best overall choice above 50 GHz.

Introduction

Accurate measurements of water vapor, especially in the Arctic, have been difficult to obtain or to evaluate. In March-April of 2004, a radiometric experiment was conducted at the U. S. Department of Energy's Atmospheric Radiation Measurements (ARM) Program's field site near Barrow, Alaska. The primary purpose of the experiment was to compare several techniques for the measurement of water vapor during cold (surface temperature < –20 ° C) and dry (Precipitable Water Vapor-PWV-< 2 mm) conditions. Included in the suite of instruments were three types of radiosondes, three ground-based microwave and millimeter wavelength radiometers, and a Global Positioning System (GPS) receiver. Comparisons of radiosonde profiles between the radiosondes types, and in PWV with the microwave radiometers and the GPS measurements are given by Mattioli et al. (2006). From this set of inter-comparisons, we believe that we have an accurate set of radiosonde measurements. In addition, our primary research instrument, the Ground-based Scanning Radiometer (GSR) produced accurate and well-calibrated measurements of brightness temperatures T_b (Cimini et al., 2006a; 2006b). In addition, the ARM Microwave Radiometer (MWR) and Microwave Radiometer Profiler (MWRP), also yielded well-calibrated radiances. The optimum use of radiometric measurements, either from a satellite-based or a surface-based platform, requires an accurate forward model. Here, over a frequency range of 22.235 to 183.31 GHz, we compare well-calibrated multi-wavelength measurements of clear-air T_b with calculations based on five frequently used clear air absorption models, and measurements of vertical profiles of temperature, water vapor, and pressure, from Vaisala RS90 radiosondes.

The Arctic Winter Radiometric Experiment (WVIOP2004)

An Intensive Operating Period (IOP) was conducted at the ARM Program's field site near Barrow, Alaska, during March 9 to April 9 2004. The major goal was to demonstrate that millimeter wavelength radiometers can substantially improve water vapor observations during the Arctic winter. Secondary goals included forward-model studies over a broad frequency range, demonstration of recently developed calibration techniques, and the comparison of several types of *in situ* water vapor sensors. During this IOP, radiometers were deployed over a broad frequency range (22.235 to 400 GHz), including several channels near the strong water vapor absorption line at 183.31 GHz. These radiometers were supplemented by frequent radiosonde observations and other *in situ* observations, including several 4-times per day Vaisala RS90 radiosondes and eight dual launches of the RS90 and "Snow White" Chilled Mirror radiosondes. The radiometers deployed are also useful for measuring clouds during these cold conditions. Radiometers that were deployed include the GSR, the MWR and MWRP of ARM, and a GPS receiver belonging to the Suominet network was operating. In addition, all of the ARM active cloud sensors (Millimeter Wave Cloud Radar and lidars) were operating. The remote sensors are all located at the so-called "Great White" GW site, and radiosondes were launched both at the GW and at the ARM Duplex, a structure about 4 km from the GW. A list of the instruments that were deployed is shown in Table 1.

During the one month duration of the experiment, a suitable range of atmospheric conditions were encountered. At the cold and dry range, the surface temperatures Ts were around – 40 °C and the PWV around 1-2 mm. At the warm and wet range, Ts approached 0 °C and the PWV reached 16 mm. As shown in Fig. 1, a variety of cloud conditions were also encountered

Forward models and Radiosonde comparisons: Methods

For the radiometric channels, we evaluated the differences between five forward models and each of the radiosonde types. As was shown by Mattioli et al. (2006), the humidity sensor of the GW and Duplex RS90 radiosondes, as well as the "Snow White" chilled mirror, agreed closely with each other, while the resistive-type sensor of the VIZ radiosondes were biased by about 20 % in the upper troposphere-lower stratosphere. Consequently, we show here only comparisons with the more accurate radiosondes. Table 2 shows the forward models and radiosonde types used in our comparisons.

In addition to having accurate radiosondes, reliable radiometric forward model comparisons also require a well-calibrated radiometer. The details of our GSR calibration are given in Cimini et al. (2006a); the calibration uses three sources of information: (1) emission from hot and cold internal calibration loads, sampled at 10 ms intervals; (2) emission from hot and cold external blackbody targets; and (3), for weakly absorbing channels, tipcal calibrations are used (Han and Westwater, 2000). The calibration of the MWR and the MWRP is discussed in http://www.arm.gov/measurements/

Finally, when doing our forward model calculations, we used band-pass functions which describe the GSR frequency response. For the channels shown in Table 1, both single- (Oxygen band from 50 to 56 GHz) and double-side band (all other channels) filters were used. For the MWR and MWRP, we assumed a rectangular band-pass over each side of the double-side band radiometers.

Table 1 Instruments used during the 2004 Arctic Winter Radiometric Experiment. The NOAA GSR is now operated by University of Colorado's Center for Environmental Technology (CET). T(z) is the vertical temperature profile as a function of height z, and LWP is the liquid water path.

Instrument	Frequencies (GHz)	Parameters
ARM Microwave Radiometer (MWR)	23.8, 31.4	PWV, LWP
NOAA Ground-based Scanning Radiometer (GSR)	50.300, 51.760, 52.625, 53.290, 53.845, 54.400, 54.950, 55.520, 56.025, 56.215, 56.325	T(z), LWP
ARM Microwave Radiometer Profiler (MWRP)	22.235, 23.035 ,23.835, 26.235, 30.000, 51.250, 52.280, 53.850, 54.940, 56.660, 57.290, 58.800	PWV, LWP, T(z)
NOAA GSR	89 (H & V)	LWP
NOAA GSR	183.31 ± (0.55, ± 1.0, ± 3.05, ± 4.7, ± 7.0, ± 12.0, ± 16.0)	PWV
NOAA GSR	340 (H & V)	LWP
NOAA GSR	380.197 ± (4.0, ± 9.0, ± 17.0)	PWV
UMontana Infrared Cloud Imager (ICI)	8-14 µm	Cloud Images
NOAA GSR,ARM MWRP	10 µm	Cloud
NOAA GPS	1.22760,1.57542	PWV

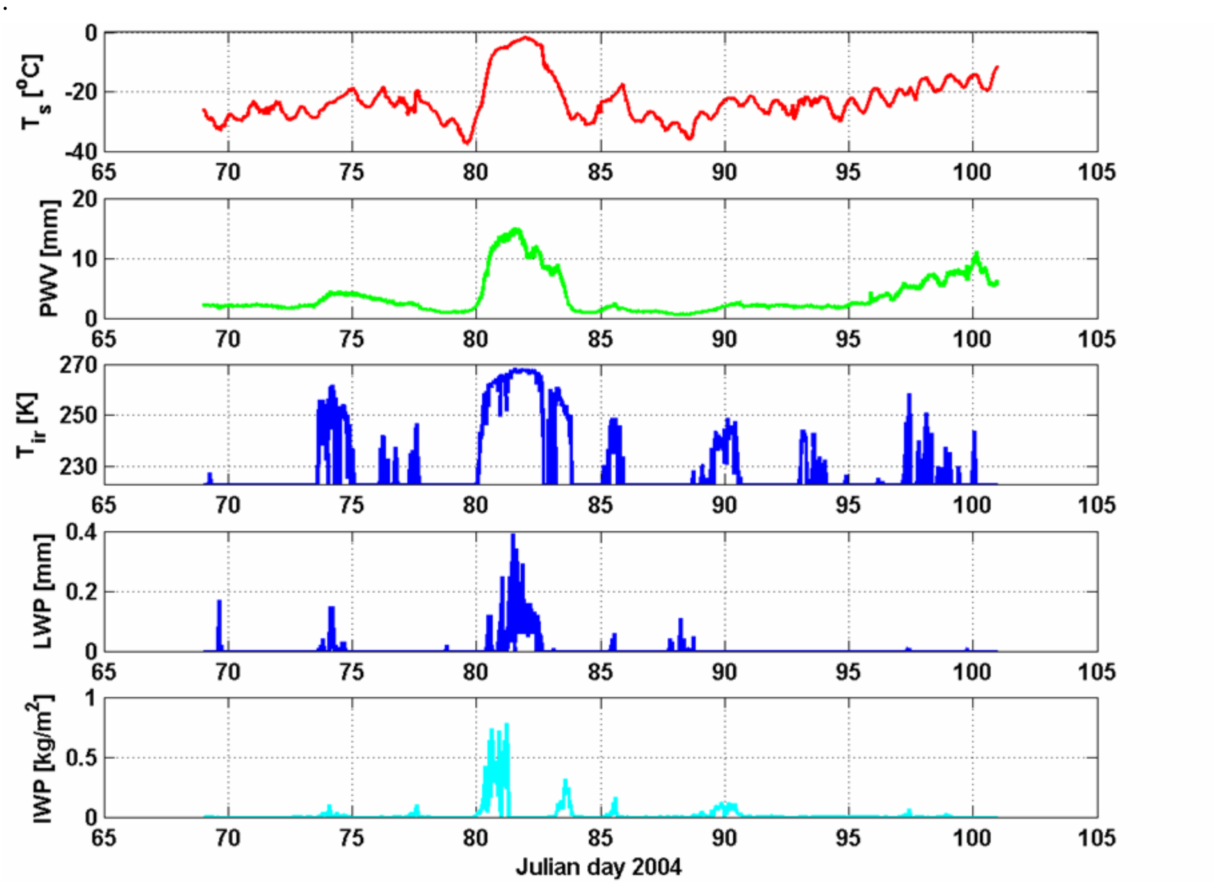

Fig. 1. Time series of meteorological variables during the 2004 Arctic Winter Radiometric Experiment.

Table 2. Forward model and radiosondes used in the study. References for the forward models are included in the reference portion of the paper. VIZ radiosondes were launched by the U. S. National Weather Service (NWS) and by NASA. The Chilled Mirror radiosondes are also called "Snow Whites."

Models	Radiosondes
• Liebe (1987)	• Vaisala RS90 (Dplx)
• Liebe (1993)	• Chilled mirror(NASA)
• Rosenkranz (1998)	• VIZ MARK-II (NASA)
• Rosenkranz (2003)	• Vaisala RS90 (GW)
• Liljegren (2005)	• VIZ-B2 (NWS)

Forward models and Radiosonde comparisons: Results

For our radiometric channels, we computed statistics between measurements and calculations for each of the five models, and for each of the three radiosonde possibilities discussed. A typical result, for the Liljegren et al. (2005) model is shown in Fig. 2.

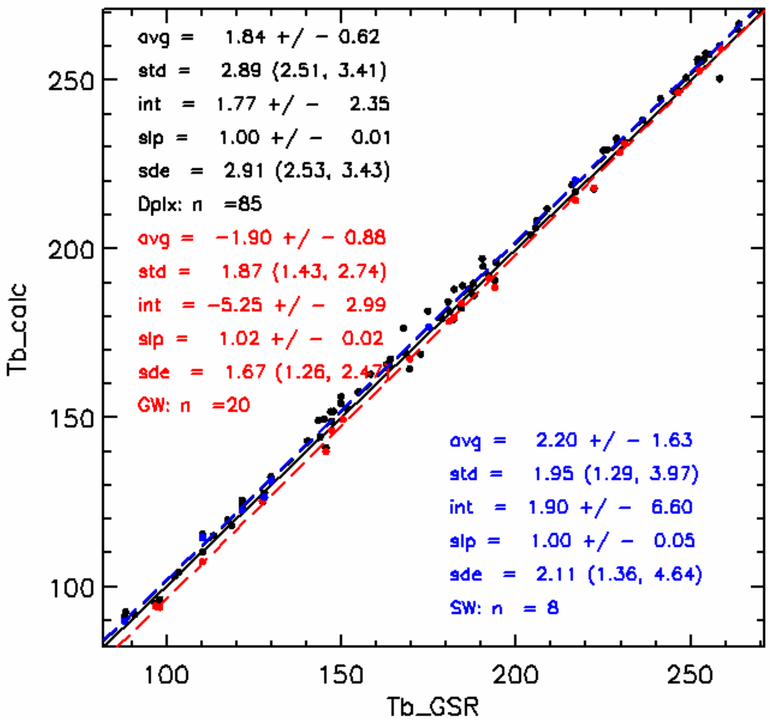

Fig. 2. Typical results of Forward Model Analysis for the 183.31 ± 3 GHz channel. Model used: Liljegren et al. (2005). Black-Duplex RS90 radiosondes. Red- Great White RS90 radiosondes. Blue-Snow White radiosondes launched at the Duplex. All statistical quantities refer to calculated minus measured.

We note several features from this plot. First, with a 180 K range in T_b , the differences between measurements and calculations are about at the 1 to 1.5 %, level. Second, there is a difference of almost 4 K between the RS90 radiosondes launched at the Duplex, and the radiosondes launched at the Great White site adjacent to the instruments. We also note, that the Snow White radiosondes, launched at the Duplex, agreed well with the RS90's launched on the same balloon..

There is a significant difference between models and measurements, depending on the models used. We illustrate this in Fig. 3, where we show the differences at all of the 183.31 channels for the Liebe et al. (1993) and the Liljegren et al. (2005) models (hereafter called LBE93 and LIL05, respectively). We note, that for a few channels, the LBE93 model differs from the measurements by about 8 K. Differences with the LIL05 model are less than 2 K.

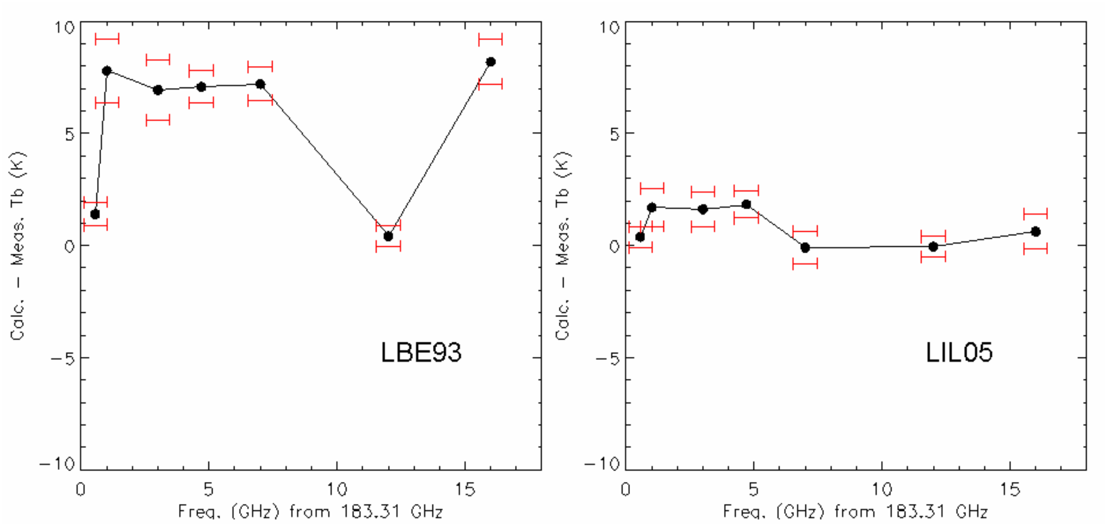

Fig. 3. Comparison between GSR measurements near 183.31 GHz and the LBE93 Liebe et al., 1993) model and the LIL05 (Liljegren et al. ,2005) model. Statistics refer to calculations minus measurements. For these result, 85 Duplex radiosondes were used. The red brackets indicate 95 % confidence intervals.

The MWRP radiometer has five channels near the weak 22.235 GHz water vapor line. However, the sensitivity of these channels to low amounts of water vapor (PWV < ~ 2 mm) is quite small and the total range of variation of T_b during the one month of clear skies of our experiment was about 3 K. As shown in Fig. 4, the better of the two models in this case was the LBE93 model in which the maximum bias was about - 0.35 K and the differences in the two models was less than about 0.2 K. With an average PWV of about 2 mm, this corresponds to a 15 to 20 % difference between measurements and calculations.

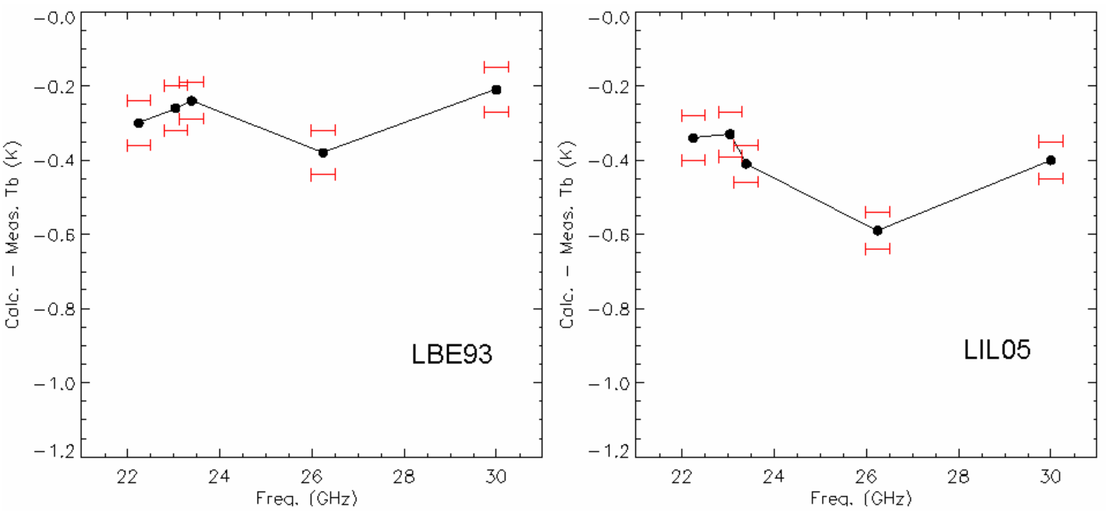

Fig. 4. Comparison between MWRP measurements near 22.235 GHz and the LBE93 and LIL05 models. For these result, 85 Duplex radiosondes were used. The red brackets indicate 95 % confidence intervals.

Both the GSR and the MWRP had channels in the 50 to 60 GHz O2 band, although only two channels were nearly at the same frequency: (MWRP-53.85 and 54.94 GHZ and GSR 53.845 and 54.95 GHz). We show in Fig. 5, comparisons of the two instruments for the models of LBE93 and LIL05. At the two frequencies where the two instruments have coincident frequencies, the T_b measurements are with 0.25 K of each other and the differences between the two models are also close. Nevertheless, the difference of almost 2 K at 53.85 GHz suggests a problem in common with both models. The MWRP results at 52.28 GHz are another indication that the O2 model implementation requires further study.

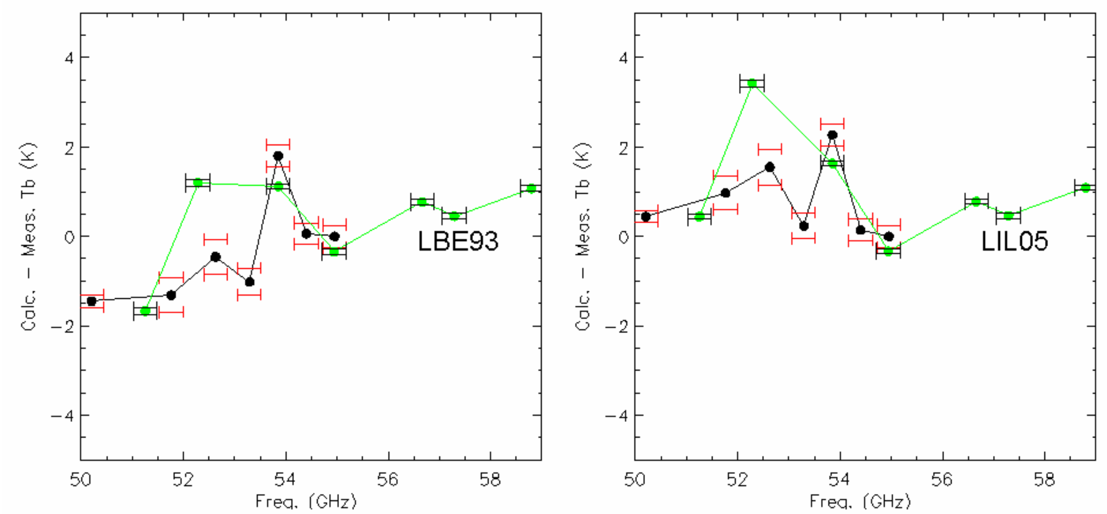

Fig. 5. Comparisons of MWRP (green) and GSR (black) measurements and calculations using LBE9 and LIL05. Note that the MWRP and GSR measurements near 53.85 and 54.95 GHz are within 0.25 K of each other.

The GSR had two channels at 89 GHz, with horizontal (H) and vertical (V) measurements. We show in Fig. 6, the best of our comparisons (LIL05) for these two channels. We note the

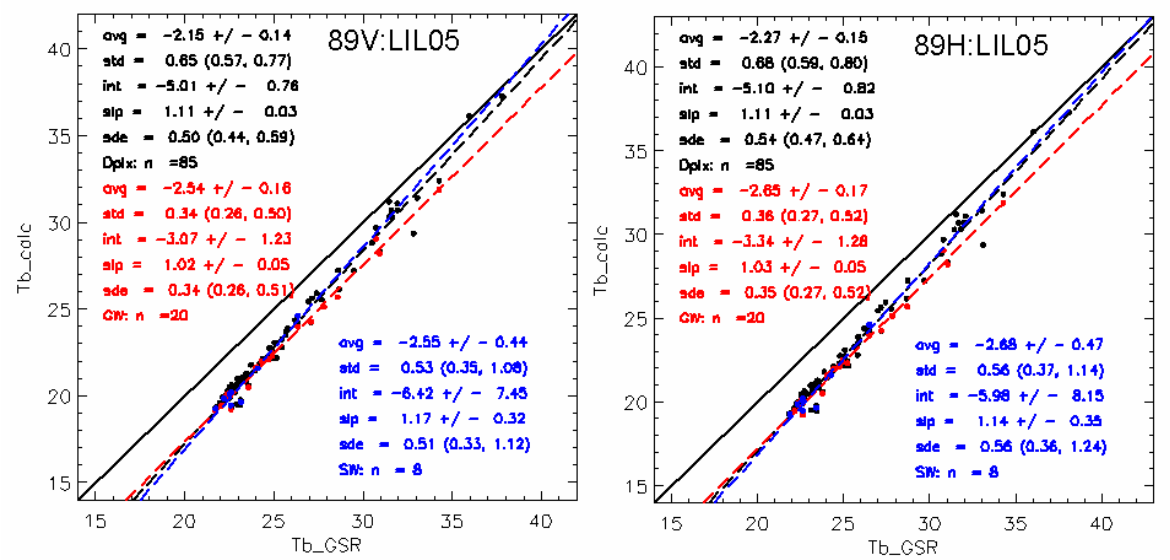

Fig. 6. Comparison of GSR 89 GHz vertical V and horizontal H Tb measurements with calculations based on the LIL05 model. Same color use as in Fig. 2.

encouraging fact that two polarized channels have the same T_b to within about 0.15 K. However, what is puzzling is that the model differs from the measurements by about 2.5 to 2.6 K. Possible causes for this difference could be antenna back-lobe contributions that are not removed by the tipcal procedure, or that there is some problem with the models near 89 GHz. This problem is still under investigation by us.

Conclusions and Discussion

Because of the absence of surface emission, upward-looking radiometers are an excellent tool for clear air forward model studies, especially in the more transparent portions of the spectrum. An additional benefit is that these radiometers can perform the tipcal technique which also improves accuracy of the radiometers. Another advantage can be the near proximity to radiosondes, at least in the earlier stages of the launch. In our Arctic experiment, we were also adjacent to both active and passive measurements of clouds so that cloud free data could be easily guaranteed.

We have compared measurements and calculations of brightness temperature over the frequency range of 22.235 to 183.31 GHz, and for five contemporary absorption models (see references). Although we showed here only results from LBE93 andLIL05, our complete set of comparisons indicates that above 50 GHz the LIL05 (Liljegren et al., 2005) model is generally superior to the other four. In the 22.235 GHz region, however, and for these Arctic conditions, the LBE93 (Liebe et al., 1993) model works well.

At the two frequencies for which the GSR and the MWRP had common channels, the difference between the channels was about 0.25 K. Nevertheless, the difference of almost 2 K at 53.85 GHz suggests a problem in common with both the LBE93 and LIL05 models. The MWRP results at 52.28 GHz are another indication that the O2 model implementation requires further study. Many of the channels in the 60 GHz O2 band are used in satellite-based temperature sounding, so that further study of the problem is justified.

Acknowledgements

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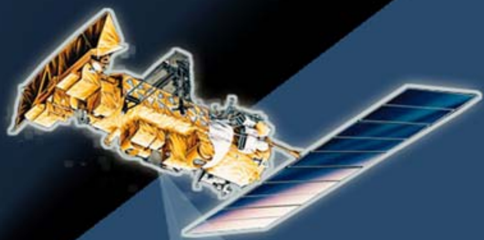

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