A Multi-Frequency Scanning Microwave Radiometer for Temperature Profiling

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Introduction

In surface-based experiments in central Oklahoma and at a 300-m meteorological tower near Erie, Colorado (Westwater et al. 1999), angular-scanning single-frequency radiometer have shown potential for measuring low altitude temperature profiles. The Atmospheric Radiation Measurement (ARM) Program has purchased from the ATTEX Corporation, Moscow region, Russia, and is currently operating, one of these scanning instruments on the North Slope of Alaska/Adjacent Arctic Ocean (NSA/AAO) Cloud and Radiation Testbed (CART) site. This instrument derives temperature profiles up to about 300 m with a root mean square (rms) accuracy of about 1.0 K. The minimum temporal resolution is 2 min., but, frequently, 10-min. to 20-min. averages are provided. To extend the accuracy of such instruments to higher altitudes, ARM has funded the Radiometrics Corporation, Boulder, Colorado, to develop a multi-frequency scanning radiometer that operates in the frequency region of the 60-GHz oxygen absorption band. This paper describes the instrument and presents a theoretical evaluation of the technique.

Description of Instrument

The Radiometrics ground-based TP/WVP-3000 portable water vapor and temperature profiling radiometer measures well calibrated brightness temperatures; these data are inputs to a profile retrieval algorithm, which derives profiles of temperature, water vapor, and limited vertical-resolution profiles of cloud liquid water from the surface to 10 km. The radiometer system consists of two separate subsystems in the same cabinet and share the same antenna and antenna pointing system. A highly stable synthesizer acts as receiver local oscillator, allowing tuning to a large number of frequencies within the receiver bandwidth. The water vapor profiling (WVP) subsystem receives atmospheric emission at five selected frequencies between 22 GHz and 30 GHz. The temperature profiling (TP) subsystem measures emission at 7 selected frequencies between 51 GHz and 59 GHz. The radiometers are complemented by surface meteorological sensors that measure air temperature, barometric pressure, and relative humidity. To improve measurement of water vapor and cloud liquid water density profiles, cloud base temperature information is obtained with an infrared thermometer. The salient characteristics of the temperature and moisture channels are shown in Table 1. In this paper, however, we only evaluate the temperature sensing characteristics of the instrument.

Table 1. Characteristics of radiometrics TP/WVP-3000 angular-scanning radiometer.

Frequencies (GHz) for Water Vapor and Liquid Sensing	22.235, 23.035, 23.835. 26.235, 30.00
Frequencies (GHz) for Temperature Sensing	51.25, 52.85, 53.85, 54.94, 56.60, 57.29, 58.80
Absolute Accuracy (K)	0.5
Sensitivity (K)	0.25
FWHP Beamwidth (deg)	2.2 - 2.4
Gain (dB)	36 - 37
Sidelobes (dB)	<-26

Accuracy Analysis

The accuracy of a ground-based system is a function of instrument characteristics, as well as the climatological location where the instrument operates. The primary instrumental characteristics are the absolute accuracy in determining the brightness temperature and the beam width. We performed an error analysis of the multi-frequency system for four diverse climatologies: Barrow, Alaska; Fairbanks, Alaska; the Oklahoma CART site; and Denver, Colorado. For brevity, we will only show results for the location with the highest variability: Barrow, Alaska. About 5000 radiosondes over a 5-year period from each of the four sites were collected as statistical ensembles. Calculations of brightness temperatures at the frequencies shown in Table 1, as well as 50 elevation angles distributed between 5° and 90° were carried out. Gaussian noise was added to the calculated brightness temperatures with the assumption that there are no correlations among measurements. Figure 1 shows the expected accuracy of deriving temperature from the seven-channel radiometer, for two assumed noise levels. As is seen, the predicted error is better than 1 K up to 2 km, and improves the prediction based on surface temperature alone by roughly a factor of 5.

Vertical Resolution Analysis

Because of overlapping weighting functions, the characterization of vertical resolution in radiometric atmospheric profiling has been rather difficult to define. One definition, as was applied by Backus and Gilbert (1970) to remote sounding of the solid earth, is applicable, and, as extended by Rodgers (1976) to include *a priori* statistics, lends itself rather well to radiometry. The basic idea is, for each height at which a retrieval is desired, to construct a linear combination of weighting functions that approximates as closely as possible some function that has ideal resolution characteristics (e.g., a Dirac delta function, or a gaussian with small standard deviation centered about the point in question). Backus and Gilbert chose a function called the spread $s(z_0)$ as a measure of resolution at the altitude z_0 and show that there is a tradeoff between $s(z_0)$ and error variance $e^2(z_0)$ at the same point. The minimum spread is independent of the error characteristics of the instrument and is a measure of the inherent resolution of the system.

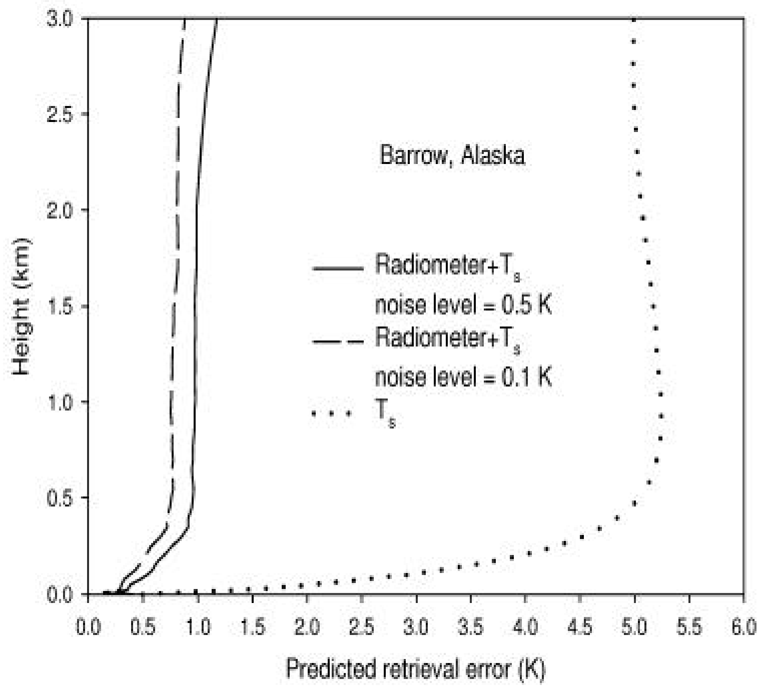

Figure 1. Estimated retrieval accuracy as a function of altitude. Assumed radiometric noise level = 0.1 and 0.5 K rms. T_s = surface temperature.

Minimum Spread of 7-Channel Scanning Radiometer with No *a priori* Statistics

We evaluated minimum values of the spread for 11 altitudes between 0 km and 3 km. First, we projected the weighting functions for 7 frequencies and 50 angles onto the first 9 singular functions, and evaluated the spread for these projections. The results are shown in Table 2. We note that the resolution, without the input of *a priori* data, is roughly equal to the height in question.

Table 2. Minimum spread of 7-channel angular-scanning radiometer.

z_0(km)	0.025	0.050	0.100	0.150	0.250	0.500	0.750	1.000	1.500	2.000	2.500
$s(z_0)$	0.020	0.046	0.097	0.151	0.232	0.469	0.789	0.953	1.651	1.770	3.544

Backus-Gilbert Method Using *a priori* Statistics

As discussed by Rodgers (1976), information other than radiation measurements can be incorporated into the spread-error analysis. For example, we frequently have *a priori* climatological statistics, a forecast from a numerical model, or some other source of information. To use such information, the error characteristics of the source of information are needed. Here, we use *a priori* climatology and assume that the error characteristics of **f** are completely described by its covariance matrix over some representative ensemble of profiles.

Spread Analysis of the Seven-Channel Radiometer + *a priori* Statistics

Using the *a priori* statistics of Barrow, Alaska, we evaluated the spread versus error of the measurement system consisting of the seven-channel scanning radiometer (assumed noise level of 0.5 K) and the climatological mean, conditioned on T_S. Again, the 350 weighting functions were projected onto the first 9 singular functions. The tradeoff curves are shown in Figure 2. We note, as expected from the decaying nature of the temperature weighting functions, that the vertical resolution $s(z_0)$ becomes poorer with height, but that good resolution and accuracy are achievable to about 300 m. As another figure of merit, we show in Figure 3 the spread at which the error standard deviation becomes 1 K rms.

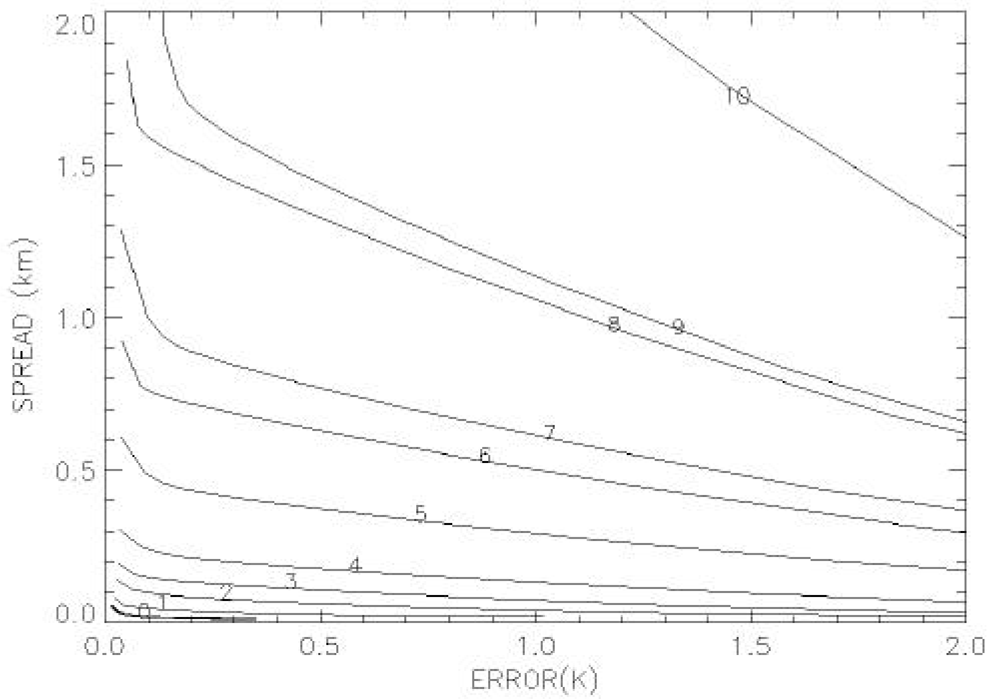

Figure 2. Spread versus temperature error standard deviation at several heights. The height labels from 0 to 10 indicate the heights: 0.025, 0.05, 0.1, 0.15, 0.25, 0.5, 0.75, 1.0, 1.5, 2.0, 2.5 km, and the assumed radiometric accuracy is 0.5 K rms.

Conclusions

We evaluated the expected accuracy during clear conditions at a severe arctic environment, for a scanning 7-frequency microwave radiometer, that has been developed for ARM by the Radiometrics Corporation. The results show that rms retrieval accuracies of better than 1 K rms are achievable up to 3 km with this system, although the vertical resolution degrades rapidly above 500 m.

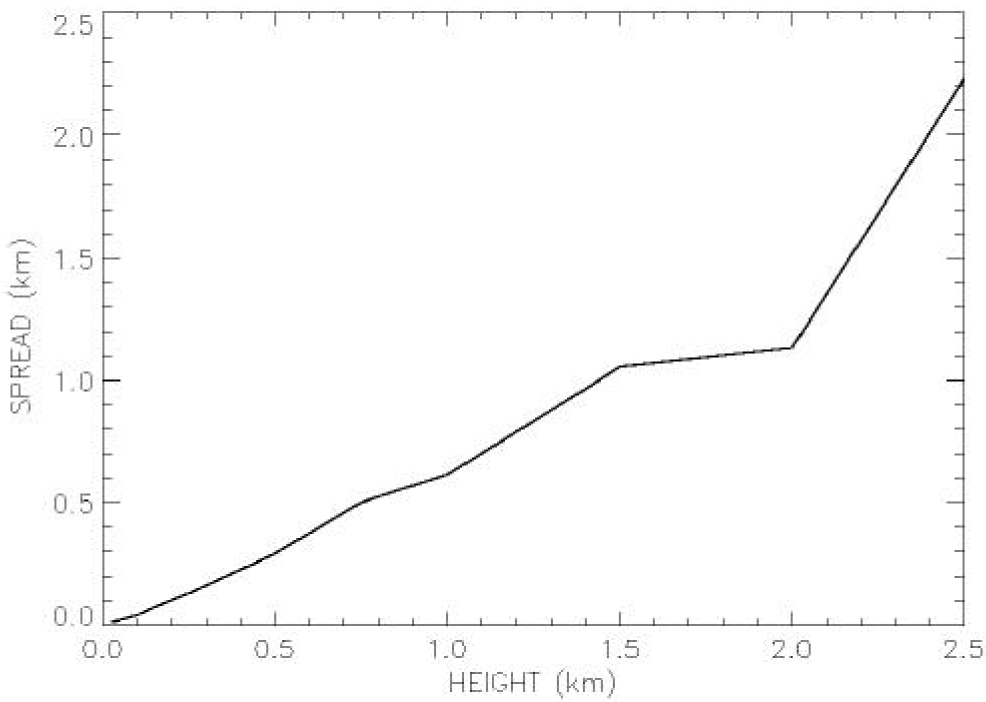

Figure 3. Spread versus height for a temperature error with standard deviation of 1.0 K rms.

Although the results were obtained under the assumptions of clear conditions, the complete TP/WVP-3000 radiometer has water vapor and cloud channels that should allow roughly the same temperature-profiling accuracy to be obtained during non-precipitating conditions. Previous experience obtained with a 6-channel zenith-viewing Radiometric Profiler showed that the effects of moisture could be taken into account with a dual-frequency water vapor radiometer. The multi-frequency WVP should only improve on this accuracy. Finally, we note that the Radiometric Corporation's TP/WVP-3000 was used at the NSA/AAO in Barrow, Alaska, during March 1999, along with 2 single-frequency, angular-scanning O_2-band radiometers. The data taken during this experiment should allow an excellent evaluation of the respective instruments during extreme arctic conditions.

References

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