Potential Performance of Boundary Layer Temperature Profile Microwave Remote Sensing: Results of Field Testing at Various Latitude Zones

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Introduction

Remote sensing of low-altitude temperature profiles is important for a variety of studies, including the interaction between the atmosphere and the earth's surface, air pollution, dissipation of fog and stratus clouds, forecasting of the distribution and dispersion of gases emitted from low level sources into the free atmosphere, and short-term meteorological forecasting.

During the period 1993-1998, several millimeter wave radiometric and simultaneous in situ measurements of atmospheric boundary layer (ABL) temperature profiles were conducted at various latitude zones: Cardington, United Kingdom; Tsukuba, Japan; Inuvik, Canada; Fairbanks, Alaska, USA; Barrow, Alaska, USA; Rome, Italy; Mestre, Italy; Helsinki, Finland; Moscow region, Russia; Yakutsk, Russia; and Boulder, Colorado, USA (Kadygrov 1995, Kadygrov et al. 1996, Khaikine et al. 1998, Matsui et al. 1996, Westwater et al. 1997). In situ measurements used in these experiments included those made from meteorological towers, tethered balloons, radiosondes, and some of the intercomparisons included remote sensing data from sodar, lidar, and a continuously scanning millimeter wavelength radiometer. Simultaneous multi-sensor measurements of ABL temperature profiles allowed an accurate analysis of profile retrieval accuracy for radiometric data. Based on the comparisons with other sensors, this report presents the potential capability of a discrete-angular-scanning millimeter wave radiometer with a working frequency in the center of the molecular oxygen absorption band to provide information on the temperature profile in the lower atmosphere.

Method, Retrieval Algorithms, and Description of the Instrument

We derive ABL temperature profiles by measuring thermal radiation of the atmosphere in the center of the molecular oxygen absorption band near 60 GHz, where the zenith optical depth is unity at about 300 m. The details of this method were described in Troitsky et al. (1993). One well-known microwave remote sensing method to measure temperature profiles in the troposphere used a zenith-viewing multichannel radiometer with frequencies (53 GHz to 58.8 GHz) in the wings of the molecular oxygen absorption band (Westwater 1993). In contrast, to measure ABL temperature profiles, we use an angular-scanning single channel radiometer at 60 GHz. Remote sensing of temperature at a frequency of about 60 GHz has some essential advantages over the 53-GHz to 58.8-GHz frequency range. Due to the large atmospheric absorption by oxygen, the temperature contrast in all directions of sensing is relatively small, and, as a result, the errors produced by antenna side lobes can be neglected. In addition, the measurements do not depend on changes of water vapor density or on the presence of fog or low clouds. But variations in the angular spectrum of radiation intensity of the ABL are small and the sensitivity of a radiometer must be very high (better than 0.1 K at a 1-sec integration time). There are also some additional difficulties in retrieving ABL temperature profiles T(h) if there are extreme spatial and temporal variations of T(h).

Three ABL temperature profile retrieval algorithms were used to derive profiles from scanning radiometer brightness temperature data. The first used a variation of linear statistical retrieval (Westwater 1993) that derives lapse rate profiles from a projection of angular brightness temperatures on a set of empirical orthogonal functions. The second modified the original algorithm to use a differential weighting function for different angles (Ivanov and Kadygrov 1994). The third was the application of the Tikhonov retrieval algorithm (Tikhonov 1983) in the form of a generalized variation (Troitsky et al. 1993).

In 1993, the commercial prototype of a Microwave Temperature Profiler (MTP-5) was made. A block diagram of the MTP-5 is shown in Figure 1 and its parameters appear in Table 1. The main unit of MTP-5 is a single-channel portable solid-state Dicke-type superheterodyne receiver with a sensitivity (without cooling) of 0.04 K at an integration time of 1 sec. A step-scan mirror provides 11 equi-angular views between the horizontal and vertical. The duration of temperature measurement cycle is about 2 minutes in the completely automatic mode. The instrument is self calibrated by using an external in situ temperature sensor and an internal noise generator (Kadygrov and Pick 1998). The absolute accuracy depends on the accuracy of the temperature sensors and could be as good as ± 0.3 °C. A meteorological protection system permits measurements practically in all weather conditions without manual operations even during snow and rain. The software consist of four main parts: a program for calibration and automatic monitoring of the instrument conditions by using data from special internal in situ sensors; a program for measurement of brightness temperature; a program to produce real time temperature retrievals, and a program for data storage.

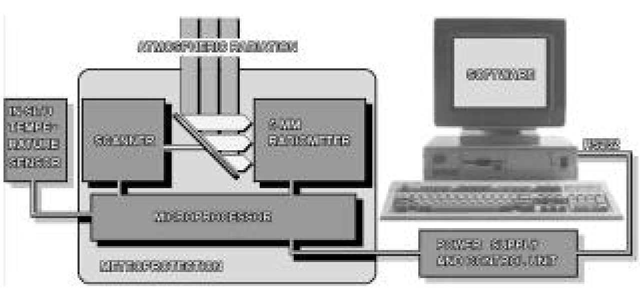


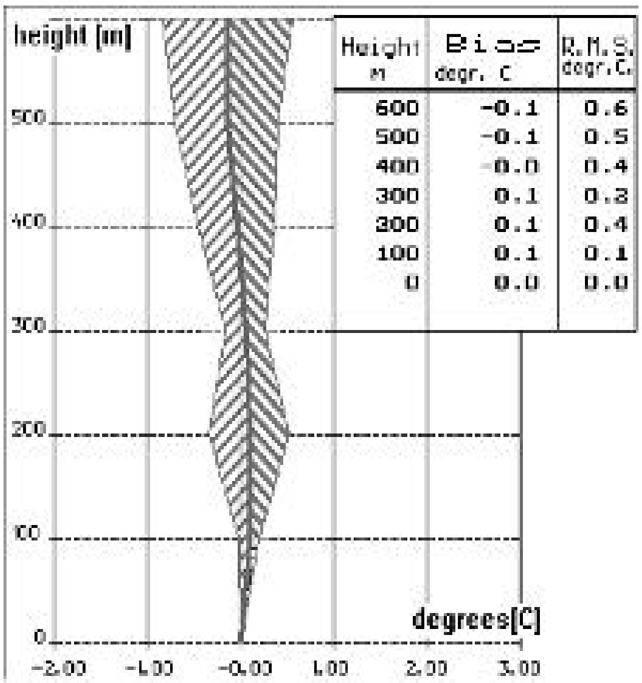
Figure 1. Block diagram of MTP-5.

Table 1. The main parameters of MTP-5.

Altitude range	0 - 600 m
Height resolution	50 - 100 m
Sensitivity (at the integration time 1 sec)	0.04 K
Antenna beam width	6 degree
Cycle period of measurement one profile	120 sec
Accuracy of temperature profile retrieval	0.2 – 0.5 K (depends on type of profile)
Mass of hardware	20 kg
Power requirements	100V, 1A, 50-60 Hz (DC 27V 3A and 12V 1A)
Power consumption	
Max	60W
Nominal	20W
Outside temperature range	-40 °C - +40 °C
Center frequency	59.6 GHz
Number of angles	11
Calibration	self calibrated by external and internal temperature sensors

Statistical Comparisons

During the last 5 years the MTP-5 was successfully tested at a number of field campaigns and comparisons. Some of comparisons were associated with the Atmospheric Radiation Measurement (ARM) Program: comparison of MTP-5 data with in situ sensors on a 300-m meteorological tower, radiosondes, a continuously scanning mm wave radiometer, and with a 915-MHz Radio Acoustic Sounding System (RASS) at Boulder, Colorado, USA (Westwater et al. 1998); and comparisons with in situ sensors on tethered balloons and radiosondes at Fairbanks, Alaska, USA. As a part of the ARM Program, a MTP-5 was purchased and has been deployed on the North Slope of Alaska (Barrow) since May 1997. In this short report, we will present some typical examples of statistical results of comparisons of the MTP-5 with other instruments; other comparisons have had approximately the same results: ABL temperature retrieval errors in the range from the ground up to 600 m were 0.2° C to 0.3° C for linear profiles and 0.4° C to -0.6° C for profiles with temperature inversions. In Figure 2, statistical results are shown of comparisons of MTP-5 data with 71 simultaneous radiosonde flights (Moscow region, Russia, winter season, 1995/1996). Root-mean-square (rms) errors were less than



Height m	Bias degr. C	R.M.S. degr.C.
600	-0.1	0.6
500	-0.1	0.5
400	-0.0	0.4
300	0.1	0.3
200	0.1	0.4
100	0.1	0.1
0	0.0	0.0

Figure 2. Comparisons of 5-mm radiometer data and radiosonde data < N =71 > (Moscow region, Russia).

0.6° C for all altitudes. However, during the presence of elevated inversions, the differences between radiosonde and MTP-5 data were sometimes 1.0° C to 1.5° C in the altitude range 500 m to 600 m.

Two independent techniques for deriving low-altitude temperature profiles were evaluated at an experiment conducted from November 1996 to January 1997 at the Boulder Atmospheric Observatory (BAO): MTP-5 and RASS; in situ ground truth was provided by the instrumented 300-m tower. In Figure 3, standard deviations are shown of the differences for the two methods: MTP-5 vs. tower (δT_R,2000 profiles) and RASS vs. MTP-5 (δT_{RASS}, 100 profiles). The lowest altitude of the RASS was centered at 135 m and the range gate spacing was 60 m. Figure 4 shows the differences in systematic errors between MTP-5 temperature data vs. RASS data ($\Delta T_{R\text{-}RASS}$), and MTP-5 vs. tower data ($\Delta T_{R\text{-}tW}$). Results in Figure 3 and Figure 4 show that MTP-5 gave excellent comparisons with in situ temperature measurements during winter conditions; several days of data were obtained during a snow storm, with no degradation of the quality of the data.

Measurements of the ABL using MTP-5 and a Mie scattering lidar were conducted simultaneously at Tsukuba, Japan (Matsui et al. 1996). Figure 5 shows a comparison of the mixed-layer heights determined from the MTP-5 and lidar data. The results obtained using the two methods agreed well with a correlation coefficient of 0.98.

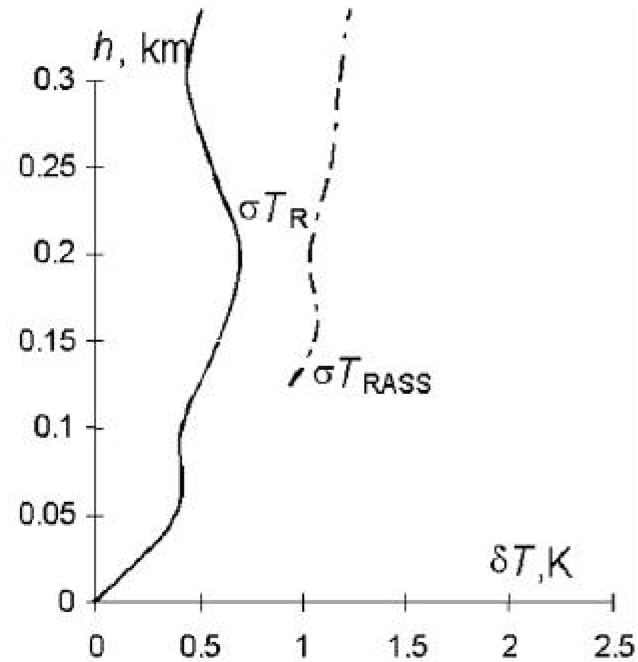


Figure 3. Standard deviations of the differences for the two independent methods of measurement.

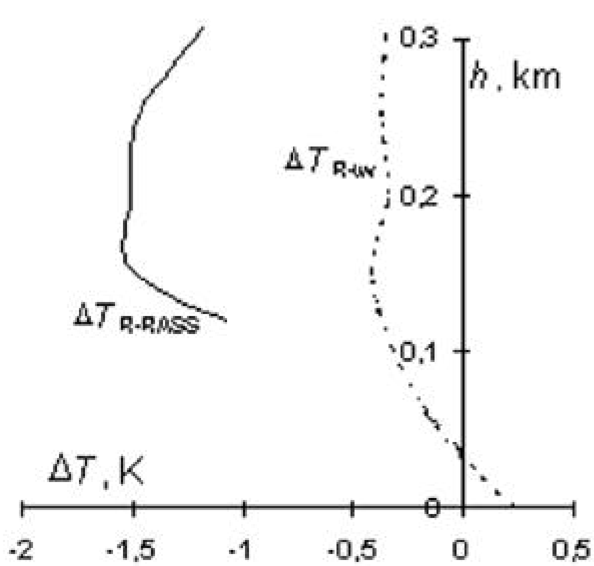


Figure 4. MTP-5 temperature retrieval bias statistics compared to RASS and tower data.

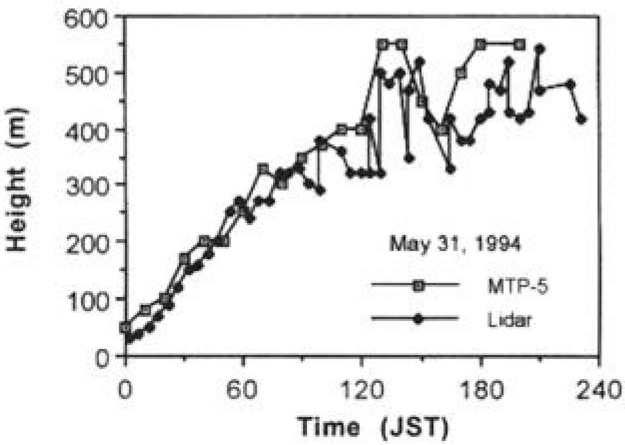


Figure 5. Comparison of the mixed-layer heights determined using the MTP-5 and the lidar.

The MTP-5 was also used for investigation of the impact of ABL temperature stratification on fog parameters at a highway between Venice and Trieste, Italy (Khaikine et al. 1998). Figure 6 shows the times of fog observation with the visibility less than 2000 meters (thick lines) and the times of occurrence of temperature profiles with inversions (thin lines). Thus, the occurrence of fog was closely related to the presence of thermal inversions. In Figure 7, examples are shown of three temperature profiles observed at the moment of fog formation, for heavy fog, and after fog dissipation.

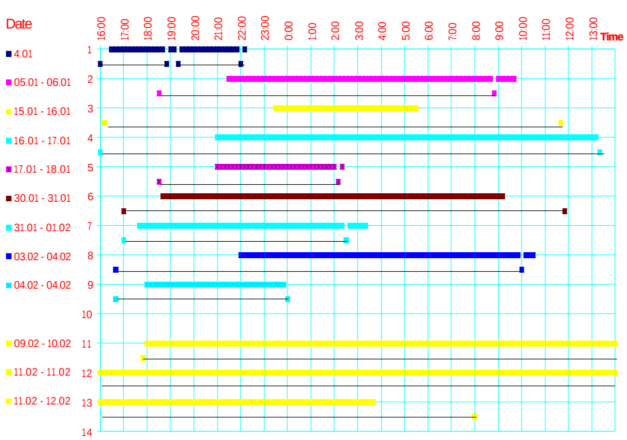


Figure 6. The dates and times of the observation of fog (thick lines)and temperature profile inversions (thin lines). (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/kadygrov-98.pdf*.)

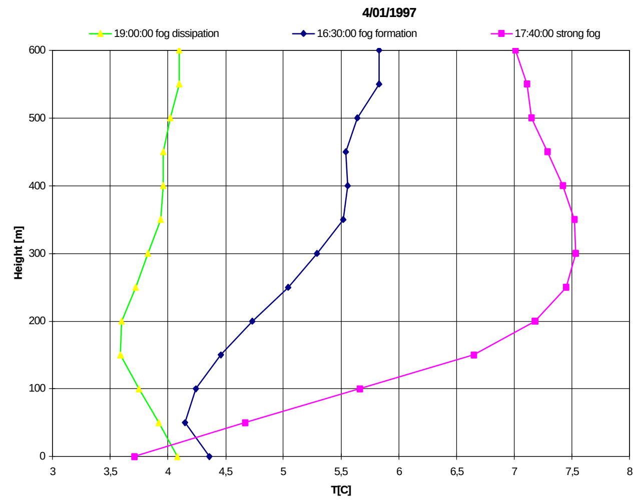


Figure 7. Different types of temperature profile for fog observed 4.01.97. (For a color version of this figure, please see *http://www.arm.gov/docs/documents/technical/conf_9803/kadygrov-98.pdf*.)

The potential of MTP-5 data for short-term meteorological forecasting is described in Kadygrov and Pick (1998). In Figure 8, examples are shown of the reduction in climatological variance using MTP-5 data; our climatological data used some 2300 radiosonde observations made every 12 hours at the UK upper air stations at approximately the same dates. As expected, a large reduction in variance in ABL temperature profile was achieved with the MTP-5.

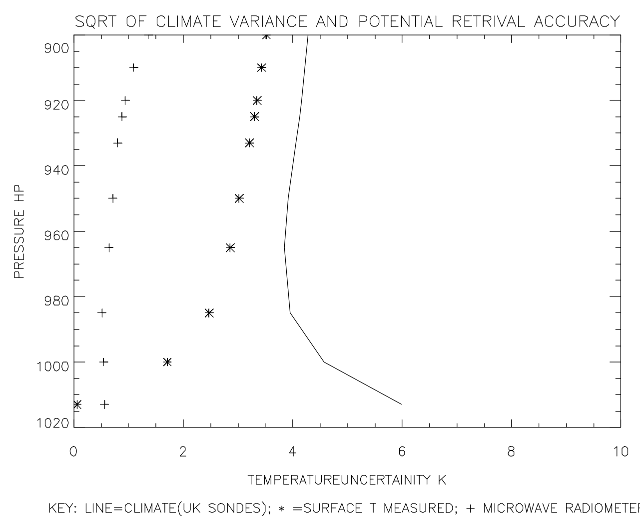


Figure 8. Comparison of MTP-5 data with climatological data from radiosondes.

Conclusions

An angular-scanning, single-channel, microwave radiometer, such as the MTP-5, with its working frequency at the molecular oxygen band center can provide continuous measurement of ABL temperature profiles in all weather conditions excluding heavy rain. For altitudes up to about 600 m, the accuracy of temperature profile recovery is about 0.2 K to 0.3 K in the case of linear profiles and about 0.4 K to 0.6 K in the case of profiles with inversions. However, elevated inversions above 500 m would be difficult to retrieve with this technique. Statistical results of field tests at various latitude zones showed a high level of accuracy of the instrument in deriving temperature profiles in the ABL. Because of ARM's need to monitor low-level temperature profiles in the North Slope of Alaska (NSA), its deployment there is of high importance.

References

Ivanov, A., and E. Kadygrov, 1994: The method and technique for remote measurements of boundary layer temperature profile. WMO Report N 57. Instruments and Observing Methods, WMO/TD N588, Geneva, pp. 407-412.

Kadygrov, E. N., 1995: Microwave remote sensing of atmospheric boundary layer temperature profile: Theory, equipment, results of field testing, application for mesoscale forecasting. XXI General Assembly IUGG, Abstracts, p. B282, Boulder, Colorado, July 2-14, 1995.

Kadygrov, E. N., A. V. Koldaev, and A. V. Troitsky, 1996: Ground-based microwave remote sensing of Arctic atmospheric parameters. *Proceedings of the International Radiation Symposium IRS'96*, Fairbanks, Alaska, 19-24 August 1996, pp. 675-678.

Kadygrov, E. N., and D. R. Pick, 1998: The potential performance of an angular scanning single channel microwave radiometer and some comparisons with in situ observations. *Meteorological Applications*, United Kingdom (in press).

Khaikine, M., E. Kadygrov, A. Koldaev, E. Miller, and B. Pani, 1998: The investigation of fog and aerosol parameters on the highway Venice-Trieste. *Proceedings of First Int. Conference on Fog and Fog Collection*, July 19-24, Vancouver, Canada (in press).

Matsui, I., N. Sugimoto, S. Maksyutov, G. Inoue, E. Kadygrov, and S. Vyazankin, 1996: Comparison of atmospheric boundary layer structure measured with a microwave temperature profiler and a Mie scattering lidar. *Jpn. J. Appl. Phys*, **35**, (1)4A, 2168-2169.

Tikhonov, A. N., A. V. Goncharovsky, P. V. Stepanov, and A. G. Jagola, 1983: Regularization algorithms and a priori information. Moscow, Nauka, 1983 (in Russian).

Troitsky, A. V., K. P. Gaikovich, V. D. Gromov, E. N. Kadygrov, and A. S. Kosov, 1993: Thermal sounding of the atmospheric boundary layer in the oxygen band center at 60 GHz. *IEEE Trans. Geosci. Remote Sens.*, **31**, (1), 116-120.

Westwater, E. R., 1993: Ground-based microwave remote sensing of meteorological variables. In: *Atmospheric Remote Sensing by Microwave Radiometry*, J. Wiley Sons, Inc., Michael A. Janssen, ed., Chapter 4, pp. 145-213.

Westwater, E. R., Y. Han, V. Leuski, Y. V. Irisov, E. Kadygrov, and S. A. Viazankin, 1997: Multi-sensor measurements of boundary layer temperature profiles. In *Proceedings of the Seventh ARM Science Team Meeting*. CONF-970365, pp. 311-315. U.S. Department of Energy.

Westwater, E. R., A. S. Viazankin, K. P. Gaikovich, E. N. Kadygrov, and D. Y. Moisee, 1998: Radiometric monitoring of atmospheric boundary layer temperature profiles. *Meteorology and Hydrology*, 1998, N 9, in press.