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Temperature profiles by ground-based remote sensing and in situ measurements

S Argentini[1], **I Pietroni**[1,2], **C Gariazzo**[3], **A Conidi**[1], **G Mastrantonio**[1]
A Pelliccioni[3], **I Petenko**[1, 4], **A Viola**[1] and **A Amicarelli**[3]
[1] ISAC-CNR, Via del Fosso del Cavaliere, 100, 00133 Roma, Italy

[2] Università di Siena, Via del Laterino, 8, 53100 Siena, Italy

[3] ISPESL Dipartimento Insediamenti Produttivi e Interazione con l'Ambiente, Via Fontana Candida, 1, 00040 Monteporzio Catone (RM), Italy

[4] IAPh RAS, Pyzhevskiy, 3, Moscow, Russia

E-mail: s.argentini@isac.cnr.it

Abstract. This study focuses on the accuracy of the temperature profiles measured with a Doppler Radio-Acoustic Sounding System and a Microwave Temperature Profiler during a period of about 3 months in winter 2007-2008. The experiment was carried on at the experimental facility of the Institute of Atmospheric Sciences and Climate (ISAC) of the Italian National Research Council (CNR). The temperature data measured with remote sensors were verified with *in situ* measurements on a mast as well as with tethered balloon data. The facsimile echograms obtained with the ISAC Doppler SODAR were analysed to understand to which extent the RASS and Radiometer temperature profiles behaviour can represent the real thermal structure of the atmosphere.

1. Introduction

Although the Radio Acoustic Sounding System (RASS) suggested by Atlas [1] is very clear in its physical base and was easily realised [2], the practical use for operational measurements needs a correct understanding of the received frequency and power variations with height, and their dependence on various system parameters such as transmitted power, antenna gain, wavelength, etc. The main difficulty in the correct description of the received signal arises from the fact that the echo signal parameters are strongly influenced by a variety of environmental variables existing in the real atmosphere. The environmental variables which influence the RASS measurements are: the vertical and horizontal winds, the atmospheric turbulence, humidity, the vertical temperature gradients, and the absorption of acoustic wave. These errors were discussed in many works (see, for example, [3], [4], [5]). To accurately quantify the effect of these factors on the received signal is difficult. A rigorous approach to the description of the RASS theory, which takes into account the diffraction effects in the Fresnel approximation, has been developed by Kon and Tatarskii [6]. Both experimental and theoretical results are summarised by Kallistratova and Kon [7] which mostly consider a bistatic configuration with separated transmitting and receiving radar antennas. Later, Petenko [8] used the same theoretical approach to improve the estimate of the errors due to the antenna geometry for the Bragg-RASS based on a monostatic radar wind profiler. Görsdorf and Lehmann [9] improved the algorithm for the range correction of the Bragg RASS, which currently is used in the network of wind profiler/RASS measurements.

Using a RASS with a continuous wave Doppler radar and a pulsed acoustic source (the so called Doppler RASS) the violation of the Bragg condition influences not only the echo power, but also the frequency of the received signal. This effect can reduce the accuracy of the temperature measured by the RASS, especially when estimating the temperature gradients. The origin of this effect was explained by Petenko and Bedulin [10]. The same authors proposed a method for compensating this error by using acoustic pulses with a linearly modulated frequency.

The RASS temperature profiles were compared in the past versus *in situ* sensors located over meteorological towers, the thersondes and radiosondes. Engelbart et al. [11] made a comparison of the SODAR/RASS data with the AIR TMT-5A thethersondes and the 99 m Lindenberg tower data. The comparisons of the SODAR/RASS-derived profiles with in-situ measurements showed an accuracy within 0.1 K.

The radiometric techniques and the comparison of the performance of these techniques with the RASS were discussed by Westwater et al. [12]. The results of a comparison study of the temperature profiles by a continuously and a discrete scanning radiometer, a RASS and the data of the BAO tower in Colorado were shown. The temperatures of the microwave radiometer and the tower showed an agreement within one degree while the results of the comparison with the RASS data, which are shown only at 200 m present a lower level of agreement as the measurements experienced severe radio frequencies interference.

Taking advantage of the ISAC-CNR experimental facility a scanning microwave radiometer (MTP5-P) of the same type described by Kadygrov et al. [13], was used and the profiles compared with those of a METEK 1290 MHz SODAR/RASS. Tethered balloon measurements have been carried out in a few cases for comparison in the first 150 m a.g.l. To study the capability of RASS and the MTP5-P to catch the layer structure of the temperature field we compared the temperature profiles with the thermal structure of the atmosphere obtained by the backscattered echo of ISAC-Doppler SODAR.

2. Description of the experiment

A field campaign is in progress at the experimental facility of the ISAC-CNR located at Tor Vergata (RTV), in the suburbs of Roma. The purpose of this field experiment is to compare, under a wide range of meteorological conditions, the remote measure of the temperature profiles given by a SODAR/RASS and a scanning microwave radiometer. The results presented in this study refer (unless different specification) to the period 2 November, 2007 - 7 February, 2008.

2.1. The site

The RTV site (41°50’ N, 12°38’ E) is located 100 m a.s.l. and 25 km from the Thyrrenian sea (at SW). At 10 km, in the SE direction, the Albani hills lie, of 600 m of mean altitude (the top of the hills reaches 1000 m). At 20 km in NW direction the great urban centre of Rome, 20 km of diameter, lies.

2.2. The instrumentation

The sensors utilised in our study consist in a microwave radiometer and a SODAR/RASS for the remote measure of the temperature. In a few days the temperature measured with a sonde on a tethered balloon was used for comparison with the remote sensors profiles. Thermometers at 1.6 m, 2 m, 10 m, and radiometers for the estimate of radiative budget are located in the same site. A Doppler SODAR is used to record the thermal structure of the atmosphere. In the following a brief description of the instrumentation is given.

Microwave Radiometer (MTP5-P, Meteorological Temperature Profiler- Polar). The MTP5-P is an instrument for the remote measure of the air temperature profile from the ground level to 600 m. The MTP5-P was designed for the investigation of the atmospheric boundary layer in polar regions

[13] [14]. Unlike any other ground-based microwave temperature profiler the MTP-5P has a larger antenna (diameter = 0.6 m and a beam width of about 0.5°) and consequently a higher vertical resolution (10 m) in the lowest 100 m. The MTP5-P is an angular scanning single-channel microwave radiometer with the working frequency in the center of molecular oxygen absorption band at about 60 GHz which was designed to provide continuous, unattended observations in extreme meteorological conditions (very low temperature, strong wind, etc). It measures the thermal emission of the atmosphere with a high sensitivity (0.04 °C at 1 s of integration time) at different zenith angles. On the base of these measurements it is possible to retrieve the temperature profile with an accuracy of 0.5 °C. The angular-scanning system has the sharper height resolution in the lower 300 m and is used for the investigation of atmospheric boundary layer (ABL) [13].

Metek SODAR/RASS. Virtual temperature profiles measurements were performed with a commercial 1290 MHz Metek SODAR/RASS system. Narrow acoustic beams are obtained by means of a phased array of 16 loudspeakers. The system is able to derive the wind components and virtual temperature data up to 400 m a.g.l. with a vertical resolution of 28 m and 38 m as lowest measuring level. The 10 minutes averaged data were used in further analyses only if the acceptance test was satisfied. The latter is based on different parameters such as signal to noise ratio and statistical significance of measured signal and ambient noise. Signal to noise ratios were used for quality assurance, selecting only those data with positive values. The radial sound velocity was not corrected for the vertical wind component which in 78 % of cases was $\pm$ 0.2 m/s. Although the RASS measures the virtual temperature data were directly compared with the absolute temperature retrieved by the radiometer because the humidity and pressure vertical profiles were not routinely collected. However, we estimated that the difference between absolute and virtual temperature at ground level with the local meteorological conditions (1000 hPa, 10 °C and 60 % of relative humidity) is about 0.05 °C. The only correction was made to take into account the geometry of bistatic antenna configuration. The formula obtained by Kallistratova and Kon [7] and presented in [8] has been used for this kind of correction taking into account the diffraction effects in the Fresnel approximation. For the first range gate (38 m) this correction is $\approx$ 0.56 °C, for the second range gate (66 m) $\approx$ 0.36 °C, but these are an approximate estimate. This correction should be refined basing on the comparison with in situ measurements.

ISAC Doppler SODAR. This Doppler SODAR is an upgrade version [15] of the SODAR described in Mastrantonio and Fiocco [16] and Mastrantonio and Argentini [17]. It uses three antennas to radiate acoustic tones every 6 s, each at a different frequency: 1750, 2000, and 2250 Hz. The pulse repetition frequency allows for an instrumental range of approximately 1000 m. The echoes recorded by the three antennas, after suitable filtering, are added, sampled at a frequency of 1600 Hz, and analysed in real time. A fast Fourier transform is applied to the digitised echo, 256 points at a time, corresponding to a height interval of approximately 27 m, the first being centred at 40 m. A two step procedure [16] is used to minimise the influence of the ambient noise on the measures and to reject not reliable data.

Surface measurements. Meteorological surface parameters, such as wind speed and direction at two different heights (1.6 and 10 m a.g.l.), absolute air temperature and its surface gradient (1.6 and 10 m a.g.l.), soil temperature, net and global solar radiation, atmospheric pressure and relative humidity were measured at 1 Hz and averaged over 10 minutes. Air temperature measurements were conducted by means of PT1000 thermometers with 0.2 °C of accuracy. In addition data from an Automatic Weather Station (AWS) were available. The AWS is a Vaisala MILOS 520 equipped to measure the meteorological parameters: temperature, pressure wind speed and direction within the WMO standard. The anemometer and the wind vane are positioned at the top of a 10 m high pole. The thermo igrometer and radiation sensors are fixed on the same arm at 2 m from the ground. These data are used as reference for the other sensors of the experiment as well as to initialize the tethersonde before the launch. The meteorological data are recorded on a 10 minutes base average.

Tethered balloon meteorological sounding. The system consists of a receiver operating in the range of meteorological frequencies 395 - 410 MHz, a tethersonde, a helium inflated balloon and a winch with a 1000 m tetherline. The balloon, properly shaped to facilitate orientation upwind retrievable by the winch is used to fly the tethersonde. The tethersonde package sensors include a three cup anemometer, a magnetic compass, an aneroid barometer, a thermo-resistance and a humicap sensor for wind speed and wind direction, pressure, temperature and relative humidity measurements respectively. The temperature sensor has an accuracy of ± 0.5 °C, the wind speed has an accuracy of ± 0.5 m/s, the wind direction measured with the magnetic compass that relies on the orientation of the balloon within an accuracy of ± 10°, when the balloon is suitably stable. The pressure measurement has an accuracy of ± 1 hPa.

The altitude of the sensor package above the surface is determined from the pressure and temperature. During flight, the electronics of the tethersonde sequentially scans the sensors and transmits every 6 s the raw data to the ground station. After the acquisition the data are processed and plotted on line by the PC connected to the receiver. The correct data acquisition can be checked on line so that possible modification of the flight can be done.

3. Results

3.1 Comparison of MTP5-P and SODAR/RASS temperature time series and profiles

Figures 1a,b show the temperature time series of the MPT5-P and the RASS for one week of December 2007 at 40 m and 200 m, respectively. In each graph is also plotted the difference $T_{MTP5} - T_{RASS}$ between the two temperatures. This behaviour is the same at both levels and was observed during the whole field experiment. The larger disagreement is observed during the night when $T_{MTP5} - T_{RASS}$ is mostly negative. During the warmer hours of the day $T_{MTP5} - T_{RASS}$ is positive in most of the cases.

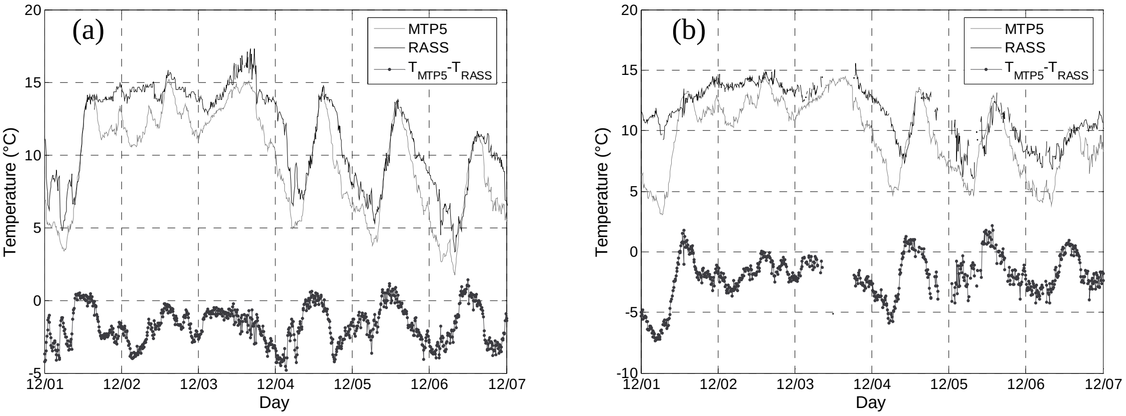

Figure 1. Time series MTP5-P (grey) and RASS (black) at 40 m (a) and 200 m (b) for one week of December. $T_{MTP5} - T_{RASS}$ is also given in the same graph.

At 40 m and 200 m the bias are -1.2 ± 1.0 and -1.8 ± 1.3 respectively. As the temperature difference varies during the day we studied the behaviour of $T_{MTP5} - T_{RASS}$ for different incident solar radiation conditions. We considered the net radiation time series. Negative values of the net radiation at the surface correspond, in almost all the cases, to nocturnal (up to sunrise) cases. The net radiation over the period 2 November – 7 February has been calculated using the data from radiometers located in the same area. The scatter plot of $T_{MTP5} - T_{RASS}$ at 40 m and 200 m versus the net radiation is shown in the Figures 2a and 2b respectively. These figures confirm the results of Figures 1a and 1b which indicate that for negative values of the net radiation $T_{MTP5} - T_{RASS}$ is negative and large (in most of the cases the difference ranges between 0 °C and – 4.5 °C) in some cases, especially at 200 m may also reach -6 °C. For positive values of the net radiation $T_{MTP5} - T_{RASS}$ is generally positive and less than 1°C, in a few cases is negative, but the scatter reduces to -1.5 °C - 2 °C. Similar results are obtained at 200 m, but $T_{MTP5} - T_{RASS}$ is mostly negative and the values are more scattered.

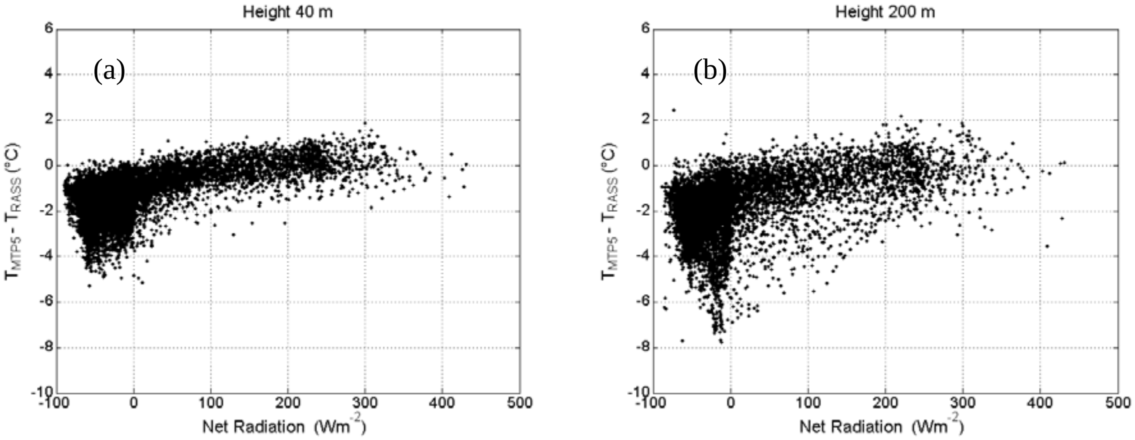

Figure 2. Scatter plot of $T_{MTP5} - T_{RASS}$ versus net radiation at 40 m (a) and 200 m (b) for the period 2 November, 2007– 7 February, 2008.

To study the height behaviour of $T_{MTP5} - T_{RASS}$ the probability distribution of the cases giving a certain $T_{MTP5} - T_{RASS}$ at a given height has been computed (Figures 3a,b). On the right side of the graph is also shown the behaviour of the percentage of data used at each level in computing the probability distribution. Considering the results of Figures 1 and 2 the diurnal (1000-1500 LT) (Figure 3a) and nocturnal (2200-0300 LT) (Figure 3b) periods have been analysed separately. During the day hours (Figure 3a) -below 150 m- the 50 % of cases shows a difference which varies between 0 and 1°C, this difference reduces to 0.5 °C above 150 m. A larger difference - even greater than 2 °C - but with a lower occurrence (10 % to 20 %) - is observed at all the heights. During the night the difference is greater. Only in the10 %- 20 % of the cases $T_{MTP5} - T_{RASS}$ is below 1 °C while in the 50 % of the cases is about 2 °C. In the 20 % to 30 % of the cases the difference may also reach 4 °C.

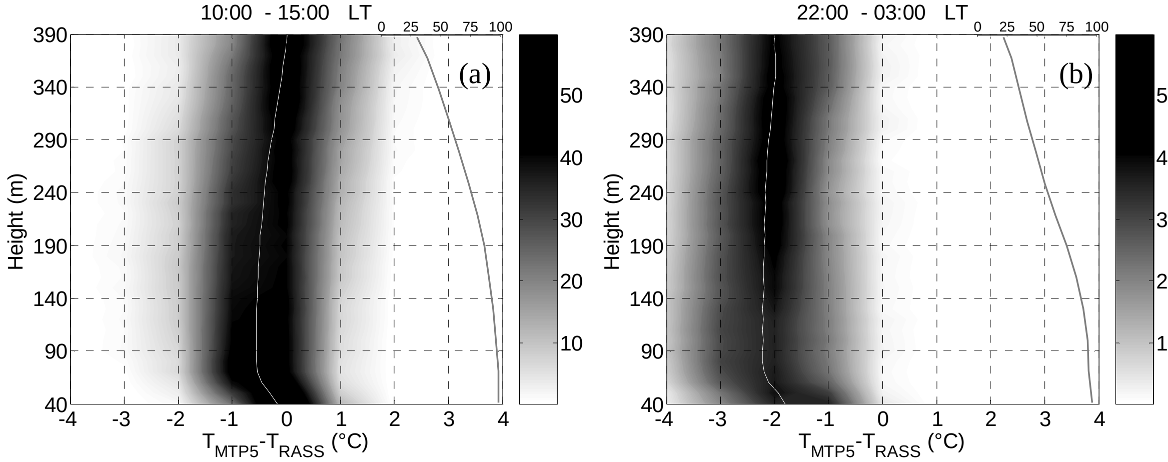

Figure 3. Probability distribution at 1000-1500 LT (a) and 2200-0300 LT (b) of temperature difference between MTP5-P and RASS data at different heights

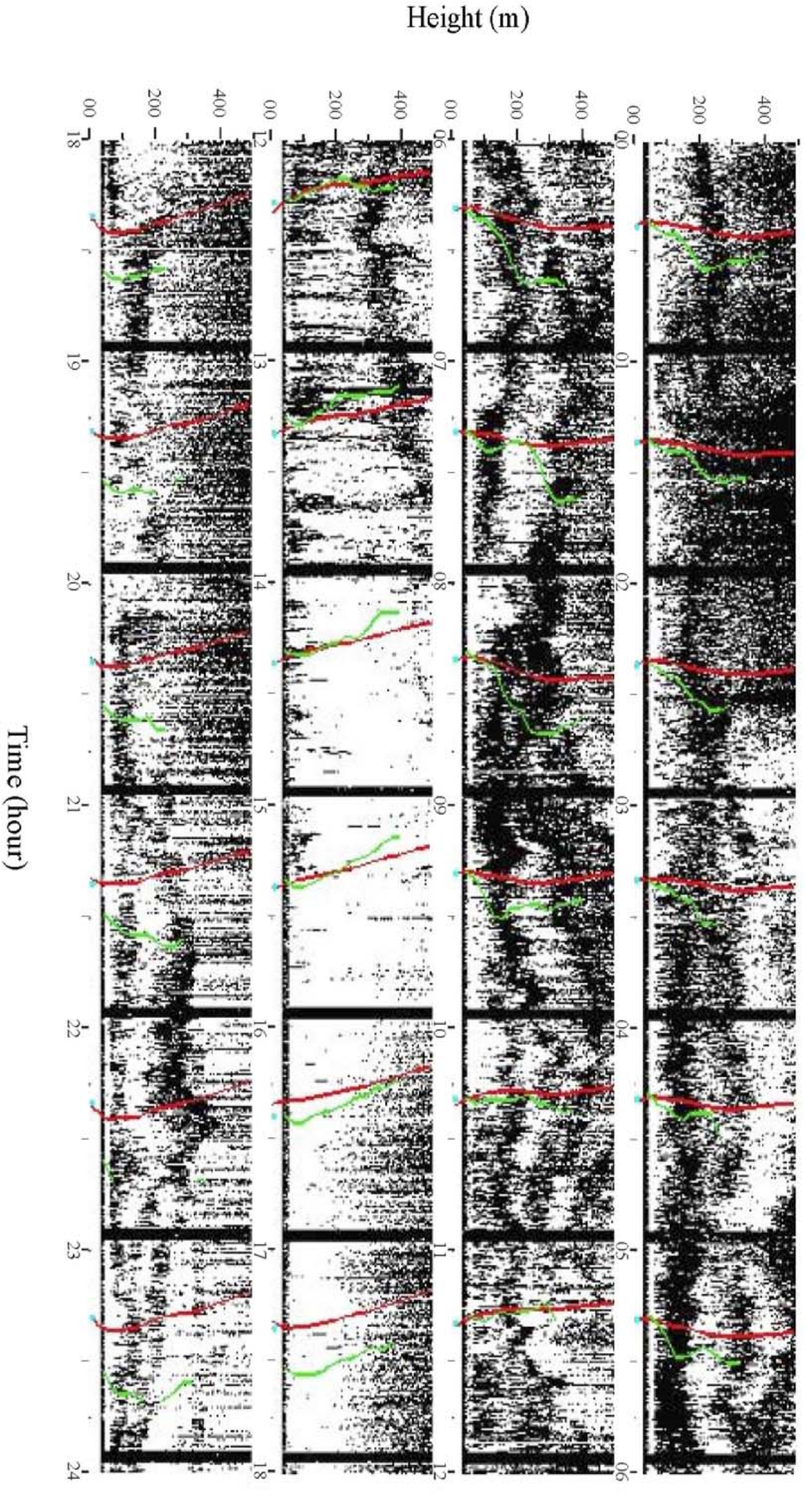

Figure 4. Facsimile representation for 30 November 2007 given by ISAC SODAR with superimposed MTP5-P (red) and RASS (green) profiles.

3.2 Vertical structure of the temperature field

It is well known that the layer structure of the temperature fluctuation field under stable stratification detected by the SODAR indicate the presence of strong temperature gradients located in narrow layers with a thickness of a few ten meters. The correlation of such thermal structure pattern with the gradients of the relevant meteorological parameters was studied by Gossard et al. [18].

Figure 4 shows the thermal structure of the atmosphere for 30 November, 2007 given by the Doppler SODAR, the level of grey in the figure is proportional to the intensity of the backscattered signal. At each hour, starting from 0030 LT in the morning, we superimpose the instantaneous temperature profiles. Red and green lines represent the MTP5-P and RASS profiles respectively reported on the same scale (we do not give values for keeping the figure more clear). The vertical scale is the same of the SODAR echogram. In general the RASS gives a better representation of the thermal structure of the atmosphere than the MTP-5P although the RASS vertical range is always lower than the theoretical range of sounding (400 m). In most of the cases the MTP5-P it is not able to catch the strong gradients occurring in a narrow range. This may explain in part the reason for the strong negative differences observed during the night.

3.3 Comparison of MTP5-P, RASS and tethersonde profiles

Due to logistic problems only a few tethersonde soundings could be done. The result of the comparison of these sounding with MPT5-P and the RASS profiles are shown in the Figures 5a,b,c, for 13 February 2007 at 1100 LT, 13 February 2007 at 1210 LT, and 14 February 2007 at 0910 LT respectively. Temperature at 1.6 m a.g.l. (star) is also plotted in the same graph. The three profiles of Figure 5a are in good agreement. However about one hour later (Figure 5b) the MTP5-P and the tethersonde profiles have mostly the same behaviour while the RASS seems to overestimate the tethersonde data of about 1.0 °C to 1.5 °C (depending on the height).

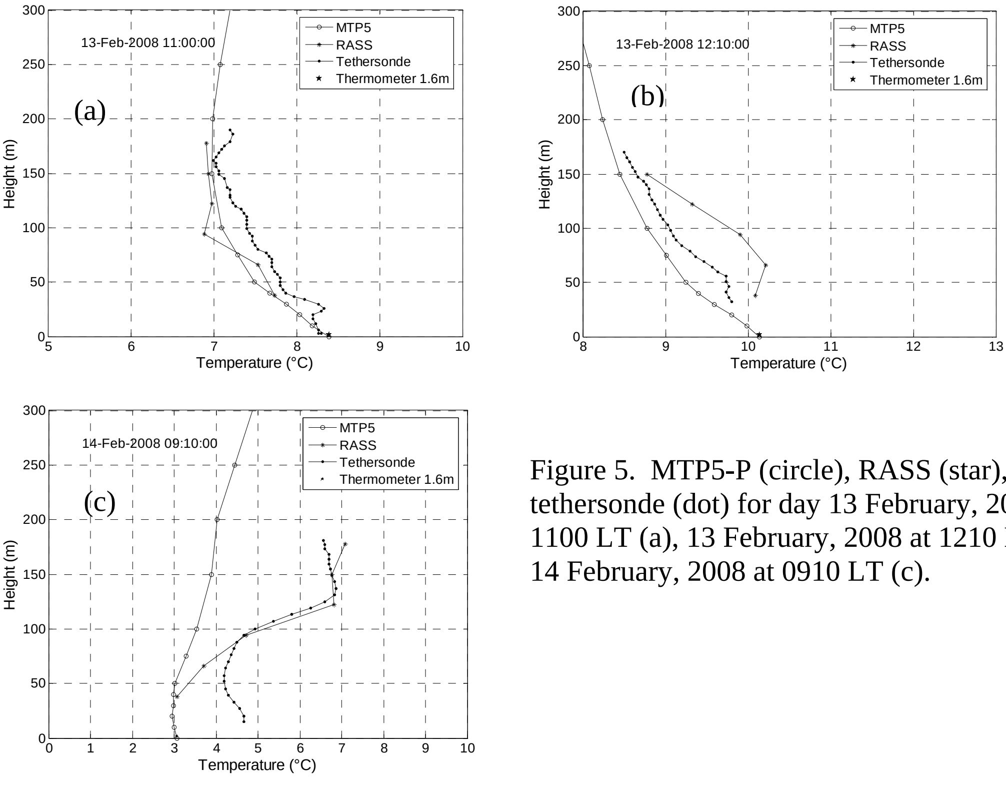

Figure 5. MTP5-P (circle), RASS (star), tethersonde (dot) for day 13 February, 2008 at 1100 LT (a), 13 February, 2008 at 1210 LT (b), 14 February, 2008 at 0910 LT (c).

Figure 5c shows that the RASS follows properly the strong temperature jump observed by the tethersonde (the temperature decreases more than 2 °C in about 50 m) while the radiometer temperature only evidences a weak tendency to decrease. The conclusion which can be given from the observation of these three cases is that both the MTP5-P and RASS have some limitations, limitations which occurs in different circumstances. A larger data set, obtained in different meteorological conditions, is then needed to fully understand which are the parameters influencing more the

Conclusions and future work

A difference greater than 1°C has been observed between the SODAR/RASS and MTP5-P temperature data. We can summarize the main results as follows:

(1) The bias between the temperature data at 40 m is -1.2 ± 1.0 while at 200 m is -1.8 ± 1.3.
(2) The profiles reach a better level of agreement in the warmest hours of the day
(3) The vertical range of the SODAR/RASS was limited in most of the cases at the first 200-meters.
(4) The RASS seems to better represent the multi-layer thermal structure of the atmosphere, the radiometer data being too smoothed
(5) The comparison with the tethersonde profiles did not help in giving a definite conclusion due to the limited number of profiles available for comparisons.

A definitive assessment of the profile data quality was not achieved because we could not include in our study a sufficient number of tethersonde profiles covering a wide range of meteorological conditions. In the next future we plan to make systematic, and all weather conditions measurements with the tethersonde, in order to achieve a full understanding on the RASS and MTP5 profiles data quality.

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