Radio Acoustic Sounding System (RASS) Applications and Limitations

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INTRODUCTION

Radio acoustic sounding systems (RASS) measure (virtual) temperature remotely, usually looking vertically from the ground. RASS have been under development since the 1970s but came into regular use only in the 1990s. An introduction to RASS techniques and history is given in this volume [1]. Briefly, RASS use a radar to measure the speed of propagation of an acoustic disturbance and derive therefrom the virtual temperature. Virtual temperature is the temperature of dry air at the same density as the moist ambient air, and is the appropriate measure for air density. It is up to a few degrees larger than (kinetic) temperature in very humid (tropical) conditions. RASS are now commercially available and are commonly deployed as attachments to lower troposphere wind profilers in a variety of routine monitoring situations as well as research applications.

Historically, temperature in the atmosphere has been measured by radiosondes, consisting of in-situ sensors carried on by a small balloon. Remote sensing instruments such as RASS have substantial advantages over radiosondes. RASS measurements can be made continuously at high time resolution (minutes) if desired, whereas launching radiosondes even hourly is very expensive and labor-intensive. Furthermore, RASS measurements are inherently averaged over a spatial domain of order 10^6 m^3, giving a more reliable estimate of the temperature than the essentially 1-dimensional radiosonde measurement.

In addition to their obvious uses, RASS, like any instrument, have limitations. This presentation concentrates on RASS applications in the lower troposphere for basic planetary boundary layer research and air quality applications. It also includes discussion of accuracy and precision and the ongoing quest for understanding of and corrections to the bias problem.

RASS APPLICATIONS

Probably the most common application for RASS is in field measurements for air quality studies. Approximately 30 to 50 wind profiler systems with RASS capability are in use throughout the world for these applications. Many of these are deployed on a campaign basis, while others are at fixed locations such as power plants. Important parameters measured by RASS in air quality applications are mean temperature, temperature profiles, and mixing depth.

The most common wind profiler/RASS, operating at UHF frequencies of approximately 915 MHZ (North America) or 1290 MHZ (Europe and Asia) can measure virtual temperature from approximately 150 m above ground level (AGL) to 800-1000 m AGL with 60 m resolution. The height coverage is limited by the attenuation of the acoustic signal, which at these acoustic frequencies (2-3 KHz) can be as much as 20 dB km^{-1}, and by the advection of the acoustic signal out of the radar beam by the wind. The coverage therefore depends on temperature, humidity, and wind speed.

The temperature affects the rates of chemical reactions determining air quality. The vertical profile of temperature can also aid in diagnosis of air transport and other meteorological phenomena affecting air quality.

In [2] and [3] we have used mean boundary layer temperatures measured by RASS in a calculation of the heat budget of the atmospheric boundary layer (the lowest 100-3000 m of the atmosphere, affected by the surface on time scales of about 1 hour). The budget was used to find the heat flux and thereby the amount of entrainment of air at the boundary layer top. Entrainment is quite difficult to measure but has an important influence on the thermodynamic structure and chemical composition of the air near the ground. It mixes in air from above the boundary layer that has different thermodynamic and chemical properties. For example, in the southeastern

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United States, biogenic hydrocarbons from rural areas are combined with nitrogen oxides from urban sources to produce ozone smog, and entrainment plays a key role in the mixing. For these budget calculations, the RASS provides a temperature representative of the appropriate temporal and spatial scales, which otherwise would be difficult to measure with in-situ instruments such as radiosondes.

RASS have also been used to measure the turbulent heat flux in the boundary layer [4,5]. Flux measurements are most commonly made a few meters above the surface by sonic anemometers, and suffer from scaling and representativeness problems if the surface is at all heterogenous, as most interesting surfaces are. By measuring flux profiles through at least the lower part of the boundary layer, the RASS has a much larger "footprint" and therefore represents an average over a larger area. However, there are significant uncertainties both instrumental and atmospheric that make determining how well RASS flux measurements perform difficult.

The mixing depth or height of the boundary layer is a key quantity in any air pollution measurement, model, or forecast, since it has a first-order effect on all chemical concentrations. Mixing depths in the daytime convective boundary layer are easily found from the radar reflectivity patterns of wind profilers [6,7]. However, nocturnal or other shallow boundary layers are not easily resolved by the reflectivity. In some cases RASS temperatures in conjunction with surface temperatures can be used to estimate the depth of such layers [8].

Microwave radiometers are another promising technology for remote sensing of temperature. It has been shown that RASS measurements can improve the precision and resolution of radiometer retrievals of temperature and humidity [9].

Wind profilers operating at or near 50 MHz and 400 MHz have also been equipped with RASS and used for research purposes. Eight of the NOAA 404 MHz network profilers have RASS.

ACCURACY AND PRECISION

There is no reference standard for temperature measurements in the atmosphere. Radiosonde temperature sensors have inherent accuracy and precision of a few tenths of a Kelvin, while humidity sensors (required for the calculation of virtual temperature) are not as precise. However, the spatial and temporal differences in sampling and the inherent variability of the atmosphere make comparisons much less precise. Comparisons have also been done with sensors on towers [10,11], which are continuous in time but usually only at one height. All radiosonde comparisons (for example [12,13,14]) show standard deviations of differences of 1 K or less, implying that the true instrumental precision of RASS is considerably better than 1 K. More troubling, however, is the presence of a systematic, height-dependent bias. This bias shows up in all RASS-radiosonde comparisons and its height dependence scales with the wavelength (and therefore the height range and antenna size) of the RASS. The height dependence of the bias makes calculation of stability parameters, one of the most desirable uses of temperature profiles, quite problematic.

Over the years, a number of researchers have worked on understanding the reasons for this bias [15,16,17]. A large number of hypotheses have been advanced, both from theoretical and empirical considerations. The outcome remains in some doubt, but the most recent results [18] show that the most important contribution is a "range error." Initially described in [12], the range error occurs because the RASS temperature measured within a single radar range gate is an average weighted by the reflectivity, which is a range-dependent function of the acoustic attenuation, advection, and effective overlap of the acoustic and radar beams. Thus the temperature in a particular range gate is not an average centered at the center of the gate, but at some other height. If the effective reflectivity is decreasing with height, the temperature is effectively measured at a lower height than expected, and vice versa if the reflectivity increases with height. In higher range gates, the reflectivity often decreases rapidly with height because of acoustic attenuation and advection, so the RASS tends to report a higher temperature (lower height). In lower range gates, the reflectivity increases with height because the acoustic beam may not fully overlap the radar beam (the sources are necessarily separated by some distance) and because the radar may still be recovering from the transmit pulse, and so the RASS reports a lower temperature (higher height).

Another issue for ongoing research is the use of vertical velocity correction. The vertical velocity of the air in the sampling volume enters the RASS temperature retrieval at first order, and if it can be measured correctly should certainly be removed [14,15]. This is particularly important in turbulent boundary layers, where the vertical velocity may be 2-3 m s^{-1}, leading to temperature errors of 1-2 K. However, the profiler does not always measure the velocity correctly [19]. This is clearly a problem in the presence of contaminants such as rain, but subtle errors are also present at many sites in clear conditions, and their cause is not understood. Some means to determine whether the vertical velocity is correct before using it to correct the RASS velocity must be found.

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