9.6 **STANDARDS FOR EVALUATING RADIOSONDE MEASUREMENTS**

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Abstract

Radiosonde measurement errors occur for various reasons: calibration, mishandling of sensors, poor software, radiation, etc. It is important that these errors be found and corrected, or at the least, corrections determined that might be sensibly applied. Radiation errors apparently are the most serious since the lack of radiative equilibrium between the thermistor and its surrounding environment can not be corrected for just a single thermistor without serious intervention. However, errors may be determined using the Accurate Temperature Measuring (ATM) radiosonde. The ATM radiosonde development was initiated in the mid-1980's using three thermistors; five thermistors are presently incorporated in the ATM radiosonde. Test flights at a number of locations proved that the radiative effect on the thermistor varies because each location's environment is different. When comparisons between different thermistors (radiosondes) are required the ATM is a valuable tool.

Investigation of relative humidity measurements is an ongoing issue because of the large discrepancies in the observed data. The first chilled mirror (SNOW WHITE) radiosonde was flown from Wallops Flight Facility in 1997. Tests and analyses show the chilled mirror radiosonde present very acceptable data to the tropopause and in some measurements, to 100 hPA. Improvement and better interpretation of the measurements is important.

Discussion concentrates on new aspects of the ATM radiosonde application and the utility of the chilled mirror radiosonde.

1. Introduction

In this day of improved radiosonde instrumentation technology there remains the question: has upper air instrument measurements (accuracy) really improved? Data quality requires that measurements be checked thoroughly and errors corrected or the offending measurement removed. NASA emphasizes instrument and measurement quality for all its satellite data, including *in situ* validation data. Considerable resources are expended for measurement validation of different disciplines. Nevertheless, questions about measurement accuracy, precision, and reproducibility continue to be raised. This is especially true for temperature and relative humidity measurements. Not only is NASA concerned about measurement quality but also, so are other laboratories and agencies that also expend a considerable part of their budgets to obtain good data. In particular, the National Weather Service, Department of Energy, US Air Force, and others have in place programs to evaluate radiosonde temperature and relative humidity measurement accuracy and quality. Recognizing the need to insure that operational radiosondes provide accurate data, and that suitable standards do not really exist by which temperature measurement accuracy can be verified, NASA introduced the Accurate Temperature Measuring ATM radiosonde (Schmidlin et al, 1986). The ATM radiosonde uses multiple thermistors of different colors to obtained true ambient temperatures and has a demonstrated accuracy of 0.2ºC-0.3ºC.

The importance of water in the atmosphere prompted development of a new instrument utilizing the well-known chilled-mirror hygrometer technique to obtain better relative humidity measurements. The balloon-borne chilled-mirror dew point hygrometer, developed by Meteolabor, located in Switzerland, uses the trade name 'Snow White'. This instrument, so far, is capable of providing high-quality humidity profiles to the altitude of the tropopause (Wang et al, 2002) and in some instances somewhat higher. The chilled mirror system is helping the science community achieve a better understanding of the limitations of routine radiosonde humidity sensor performance.

2. ATM Radiosonde

It is known from WMO radiosonde intercomparisons (Yagi et al, 1996) and from experience using the ATM radiosonde, that thermistor measurement accuracy is affected by long- and short-wave radiation. As a result, the temperature of a thermistor continually tries to reach equilibrium with its surroundings; consequently, the ambient temperature is not reported. The sources of radiation impinging upon the thermistor are from direct and scattered solar radiation and infrared radiation absorption and emission. To overcome error due to these radiative influences and other influences (conduction and lag errors), corrections should be applied.

The heat balance equation

$$-HA(\Delta T) + \varepsilon R + \alpha S - \varepsilon\sigma A T^4 = 0, \qquad [1]$$

is used to determine the radiative error of a single thermistor, where

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H	=	convective heat transfer coefficient
A	=	thermistor surface area
ΔT	=	($T - T_{air}$), or thermistor error (K)
ε	=	emissivity of thermistor coating
R	=	long-wave radiation impinging thermistor
α	=	absorptivity of thermistor coating
S	=	short-wave radiation impinging thermistor
σ	=	Stefan-Boltzmann constant
T	=	sensor temperature (K)
T_{air}	=	ambient temperature (K).

Measurements of ε and α are made in the laboratory, but it is extremely difficult, if possible, to make *a priori* an accurate estimate of R and S. These latter depend on albedo; earth's surface (skin) temperature; visible and infrared emission from the earth's surface; cloud amount; cloud emissivity; atmospheric absorption and transmissivity; and, brightness temperature of the atmosphere. Thus, a dynamic correction cannot be applied to a single thermistor. However, radiosonde manufacturers have supplied corrections for their thermistor. These corrections (a function of pressure and solar angle) are a mean correction that simply shifts the measured temperature profile, with its error, to some other incorrect value.

The ATM radiosonde obtains the true atmospheric temperature T_{air} using three thermistors of different color (white, aluminum, and black) that have different values of ε and α. Simultaneous solution of three heat balance equations,

$$-HA(\Delta T_w) + \varepsilon R + \alpha S - \varepsilon\sigma A_w T_w^4 = 0 \qquad [2a]$$

$$-HA(\Delta T_a) + \varepsilon R + \alpha S - \varepsilon\sigma A_a T_a^4 = 0 \qquad [2b]$$

$$-HA(\Delta T_b) + \varepsilon R + \alpha S - \varepsilon\sigma A_b T_b^4 = 0, \qquad [2c]$$

provide T_{air}, and/or ΔT. Subscripts w, a, and b represent the white, aluminum, and black thermistors, respectively. Successful solution of the radiative error depends on knowledge of T, ε, and α of each thermistor, the thermistors' thermal characteristics and its physical dimensions. Each thermistor's ε and α must be appreciably different from each other to prevent ill-conditioned solution of the heat balance equations (Schmidlin, et al 1986; Luers, 1990). The white, aluminum, and black coatings satisfy this requirement. Additional error from conduction along the electrical leads supporting the thermistor and from thermistor thermal lag (Huovila and Tuominen, 1990), while important, are not discussed although these are included in the NASA ATM radiosonde processing.

An example of ATM radiosonde application is given in Figure 1. In this figure, comparisons between temperature measurements with the ATM radiosonde and a typical operational radiosonde (in this case Vaisala RS80) are illustrated. The RS80 applies corrections to the thermistor measurement. The profiles shown in Figure 1 were obtained during February 1992 in the United Kingdom and during February 1993 in Japan. Although obtained one year apart, the measurements were obtained at approximately the same time of day. The analysis considered various reasons why the measurements did not appear similar, such as they were obtained in different years and at different geographical sites. The analysis using the ATM radiosonde as a standard indicated that environmental conditions were the basic cause of the differences. Figure 1 characterizes the effect of the presence of a large amount of moisture and very saturated cloud layers on the RS80 thermistor accuracy. Although the RS80 temperatures were corrected, the radiation due to the very moist environment suggested that a larger correction should be applied. The ATM radiosonde's thermistors all responded similarly to the environmental conditions allowing calculation of the true temperature. On the other hand, moisture and cloud tops did not affect the measurements obtained in Japan, since these were absent.

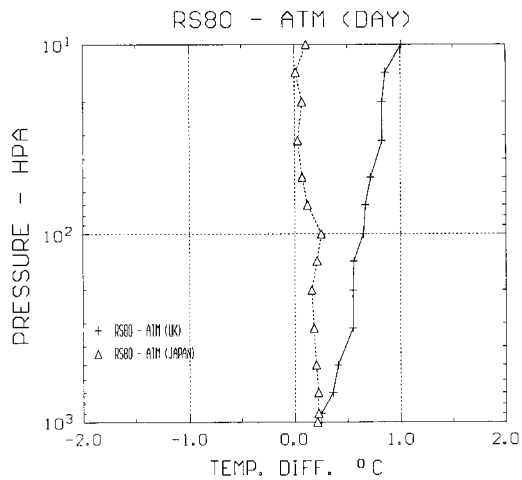

Figure 1. Daytime flights of the RS80 vs the ATM radiosondes during daytime. The differences should typically be about the same, however, the measurements made in the UK show the effect of large amounts of moisture and clouds on the RS80 thermistor performance.

3. Snow White Chilled Mirror

Improvement of relative humidity (RH) sensor performance has been a goal of the meteorological community for many decades (Gaffen, 1993). Response, sensitivity, and accuracy of routine operational radiosonde RH sensors, in general, are mediocre and need considerable improvement (Wade, 1994; Carlson and Cole, 1999; Miloshivich, et al, 2001). Tests of a simple to use off-the-shelf radiosonde-adaptable chilled mirror dew point hygrometer revealed its ability to capture vertical moisture structure. Tests have shown that the chilled mirror is an improvement over the operational sensors, although questions about its accuracy and response in the upper troposphere and lower stratosphere are raised.

Meteolabor AG of Switzerland originally developed the chilled mirror sensor for use with the Swiss SRS 400 radiosonde. In 1997, the manufacturer adapted the chilled mirror to Sippican, Inc. MK-2 radiosonde. The MK-2 transmits the chilled mirror temperature as well as the standard radiosonde information. Although more costly than the typical radiosonde, the chilled mirror is relatively inexpensive compared with the cost of other *in situ* water vapor research instruments, such as those operated from aircraft, or from very large balloons.

UAIRP has released a number of instruments from Wallops Flight Facility, Virginia, Andros Island, The Bahamas, from the National Weather Service test site located at Sterling, Virginia, and from the Department of Energy's Cloud and Radiation Test sites located at Lamont, OK, and Alaska's North Slope. In brief, the analyses of these observations show: that measurements made in clear air or between cloud layers are more reliable than measurements within clouds; that careful interpretation of the measurements enables reliable detection of cloud bases and tops; and, that improved measurements are possible at pressure levels where the standard MK-2 radiosonde hygristor no longer performs well. Sensor reliability tests are continuing at Wallops Island in order to enhance our knowledge about its performance.

The chilled mirror dew point hygrometer is located in a duct where ambient air is brought into contact with the mirror's surface. A reflective mirror, thermoelectric heat pump (peltier element), light source, copper-constantan thermocouple, and a photocell detector make up the major components. The heat pump cools the mirror until a mist, or thin ice coating forms on its surface. Illumination of the mirror allows the photocell to optically detect and monitor the intensity of the scattered reflected light. The photocell detector output controls the current of the heat pump, allowing the condensate on the mirror to be constantly maintained. Heat generated by the thermoelectric heat pump, if not adequately eliminated, may bias the measurement and affect the mirror's response time. A metal radiator-type cooling system exposed to ambient air aids in the removal of the heat. The thermocouple imbedded in the mirror samples the mirror's temperature every few seconds enabling continual measurement. The mirror temperature is representative of the dew point temperature. An independent RH calibration of the chilled mirror is unnecessary since a well-calibrated, good quality thermocouple imbedded in the mirror gives a direct measurement relative to dew or frost of $T_{d/f}$. Nonetheless, calibration is performed at *in situ* pressure and temperature conditions existing in the laboratory, and have indicated the chilled mirror is accurate to 0.1°C. Calibration at lower pressures and temperatures need to be established, however.

An example of a chilled mirror measurement is given in Figure 2. During August and September 1998 a series of chilled mirror radiosondes were flown from Andros Island, The Bahamas (24.7N; 77.8W) as part of NASA's Third Convection and Moisture Experiment (CAMEX-3). These provided unique RH profiles near the tropopause. Andros Island is located approximately 280 km southeast of Miami, Florida. The chilled mirror observation of September 14, 1998, exhibits a moisture layer just above the tropopause that appears related to a cirrus cloud. In tropical and sub-tropical regions cirrus is not uncommon at this height. (Heymsfield et al, 1998; McFarquhar et al 2000).

Heat applied in the chilled mirror duct to remove excess water and/or ice caused $T_{d/f}$ to exceed the ambient temperature. Rapid increase of $T_{d/f}$ from –74ºC to –64ºC at 111 hPa (approximately 16000 meters) points out that the heat process to clear the mirror probably was initiated at this point. Determining the height of the cloud top is more difficult. A sharp moisture cutoff that might have been used to define the top is absent, however, we believe that heating of the mirror ceased at approximately 94 hPa or 17080 meters. If this analysis is correct, then the cirrus cloud thickness is slightly greater than 1 km.

The extremely sharp RH signature is a certain indication that a cloud base was observed; the RH below the base is more diffuse. During the instrument's ascent the slowly increasing RH suggests that ice may be precipitating from the cloud. This type of RH profile has been observed with other chilled mirror observations. The RH in the moisture layer near 300 hPa is also unique. The RH increased significantly but did not reach saturation. Closer examination showed that $T_{d/f}$ increased near 340 hPa and also might be

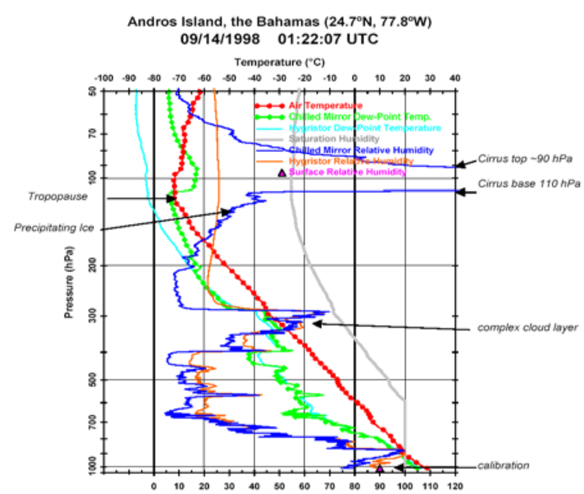

Figure 2. Example of Chilled mirror measurement at Andros Island, Bahamas. Comparison of RH from hygristor and chilled mirror is reasonable to 300 hPa.

related to the mirror's heating function. Although the rapid rise in $T_{d/f}$ corresponds to the increase in RH, Figure 2 also suggests that the rise might be affected by lag of the mirror. Similarly, at the top of the layer, RH may have responded to a decrease of the applied heating. A qualitative estimate of lag is difficult, and although the lag at 300 hPa is less than that at 100 hPa it is reasonable to expect the lag to increase with lower pressure and temperature.

4. Discussion and Summary

The multi-thermistor ATM radiosonde provides accurate temperatures that should be used to qualify operational radiosondes and possibly to quantify the error of their thermistor measurements. The ATM radiosonde also provides an acceptable reference method for validating remotely measured temperatures, in fact, any temperature measurement.

The thermistor error in different localities, clearly illustrated in Figure 2, varies with the earth's skin temperature, cloud type and amount, albedo, and vertical temperature structure. Direct measurements from the ATM radiosonde, rather than a mean correction, would better serve the meteorological community.

A serious deficit associated with the chilled mirror is the uncertainty associated when measurements are made in a cloud. Excessive moisture (liquid or ice) accumulates on the mirror's surface. Heating the mirror forces $T_{d/f}$ to be higher than T. In spite of super saturated RH and the attendant measurement uncertainty when in a cloud, the chilled mirror gives a reasonable indication of the height of a cloud base, and with suitable analysis also the height of their tops.

Adding the chilled mirror technology to the operational MK-2 radiosonde has given new insight into the capability of the carbon hygristor measurement. Because of the slow response at low temperatures, the hygristor has difficulty detecting ice clouds. The slightly elevated RH measured by the hygristor near 100 hPa, such as seen at Andros Island in Figure 2, does not reveal cloud boundaries, such as shown by the chilled mirror measurement. Because of the lack of a balloon-borne RH reference standard it is not possible to make an absolute comparison of RH sensors in situ, especially needed in the upper troposphere. Nevertheless, the Andros Island profile discussed above showed poor hygristor response at low temperatures.

In summary, the Chilled mirror's performance is similar to the hygristor's performance at high temperatures (i.e., lower troposphere) but its performance must be reviewed carefully at low temperatures (i.e., upper troposphere and lower stratosphere). Test flights showed that the dew point hygrometer and routine hygristor performance are comparable at temperatures above -35C, whereas the chilled mirror showed better sensitivity and responsiveness to RH perturbations at lower temperatures, to at least tropopause heights
It is important that the chilled mirror not be operated in precipitation; and, when clouds are encountered all measurements should be reviewed carefully.

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