A NEW HIGH ACCURACY METEOROLOGICAL THERMOHYGROMETER FOR FIELD MEASUREMENTS OF AMBIENT AIR AND DEW POINT TEMPERATURES

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Present-day professional quality (i.e., ventilated and solar-shielded) meteorological ambient temperature monitoring systems capable of electronic data transmission typically offer accuracy in the order of ±0.2°C. In order to verify the performance of these systems in the field, a system offering an order-of-magnitude more precision is desirable, i.e., a system capable of ±0.02°C accuracy and NIST-traceable. An absolute accuracy of this degree is readily achieved in the laboratory, but achieving it in the presence of intense solar radiation, coupled with the wide and often rapid changes in environmental conditions experienced in the field, presents some special challenges to the instrument designer. This article describes the evolution of a state-of-the-art instrument to fill the need for checking the accuracy of operational meteorological thermometry systems in the field.

Target specifications

Early in the development program, a target specification for NIST-traceable absolute accuracy of ±0.02°C in ambient temperature measurement over the range of +50°C to -50°C was set. This dictated a minimum data resolution of 100 / 0.02, or one part in 5,000. Ambient air temperature measurement in the field environment is particularly challenging, because the measurement must be achieved in an adverse environment where solar radiation, conduction, and convection sources all contribute to errors. The central challenge lies in bringing the temperature-sensing element into thermal equilibrium with the true uncontaminated air temperature while, at the same time, physically suspending the sensing element from a structure that is both influenced by radiation and lagged from the true air temperature. In addition, because water plays such an important role in atmospheric heat transfer and dynamics, for many applications a precision measurement of dew point temperature provided by a true chilled mirror hygrometer was deemed highly desirable.

Calibrating Instruments with ± 0.02°C Accuracy

In order to calibrate an instrument that claims to have an absolute NIST-traceable accuracy of ±0.02°C, one would like to have a reference or standard with at least an order of magnitude better, i.e., ±0.002°C. An in-situ atmospheric thermometer with such a degree of accuracy is well beyond the current state-of-the-art. An approach to establishing the accuracy of an atmospheric thermometry system is to rely on the NIST-traceable Standard Platinum Resistance Thermometer (SPRT), using it is as a transfer standard to calibrate the platinum resistance thermometer(s) used in the field instrument. The problem that arises is that SPRT and subsequent thermometer calibrations are done in a stirred liquid bath and, although the calibrations can be precise to ±0.001°C or better, they are not representative of the environment in which the atmospheric thermometer must operate. The major errors in an atmospheric thermometry system are caused by stem conduction, solar radiation, and self-heating and are typically much larger in an air environment than in the stirred calibration bath.

Figure 1 demonstrates that in order to establish the accuracy of the atmospheric system, the best one can do is to accept the NIST-traceable calibration of the basic thermometer, and then conduct a careful worst-case error analysis of the system, factoring in all of the errors resulting from the

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unique installation. Finally, one must recognize that errors associated with the representativeness of the air sample under measurement can often dominate all of the other sources of error.

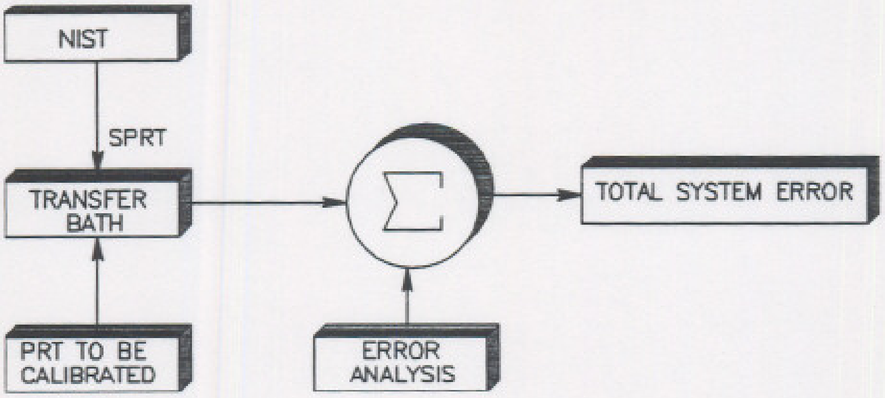

Figure 1. Calibration traceability of an atmospheric temperature sensor

SOURCES OF ERROR

The design approach taken uses platinum resistance thermometers (PRTs) due to their inherent long-term stability. A PRT probe was designed that uses many of the features of the SPRT construction, specifically strain-free mounting of the platinum element, a four-wire connection, and minimization of thermal conduction through the stem by using a low thermal conduction stem design and low thermal conductivity connecting wires in the stem. To take advantage of commercially available bridge completion circuitry, a 100 Ohm PRT element is used. The International Temperature Scale of 1990 defines platinum resistance thermometers as the standard interpolation instruments for realizing the temperature scale from -259.34 °C to +961.78 °C. (or 13.81 °K to 1234.93 °K) and a SPRT has been defined for this temperature span. Commercially available, miniature wire wound ceramic platinum elements are not capable of achieving the stability and precision of the SPRT, but they offer an acceptable alternative for this application when properly calibrated against a NIST reference. This compromise is due, in part, to the very narrow temperature regime of -50°C to +50°C over which one must operate vs. the SPRT that operates over a much wider temperature span. A cross-section of the PRT thermometer is shown in Figure 2.

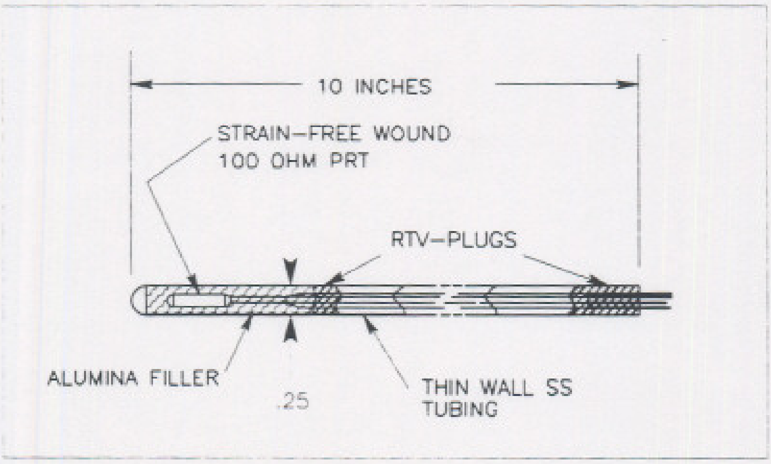

Figure 2. Cross-section of a low strain, four-wire PRT with minimal stem conduction

Solar Radiation Errors

The major source of error in atmospheric temperature measurement is from solar radiation heating of the PRT element. The maximum level of solar radiation experienced at the surface of the Earth is in the order of 1400 W/m^2. An extensive research program was carried out to develop an optimized solar shielding system that would reduce the solar radiation errors and stem conduction errors to a minimum. The errors due to solar heating and stem conduction in a properly designed triple-walled shielded enclosure aspirated at 450 fpm can be shown to be less than 0.0016°C, significantly less than the uncertainty target of ±0.02°C. A typical design is shown in Figure 3.

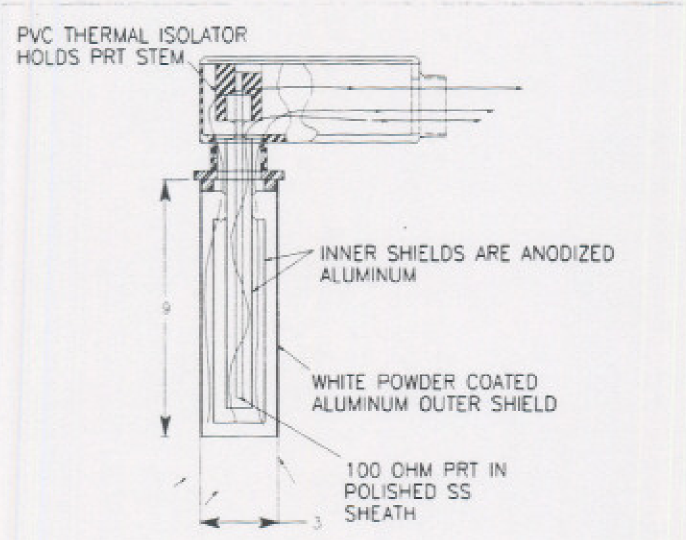

Figure 3. A Triple-walled Aspirated Solar Radiation Shield for PRTs

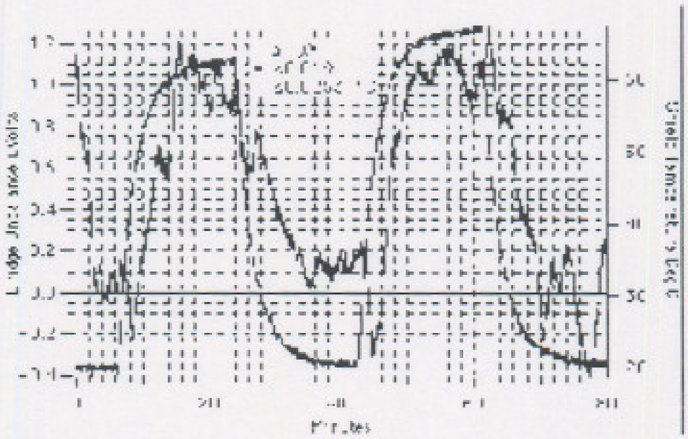

Figure 4. Effect of radiation heating errors under equivalent of "five suns" on the PRT

Self-Heating Errors

All PRT-based thermometers suffer from the effects of self-heating. This error occurs because the only way to determine the resistance of the platinum probe is to pass a current through it, which allows the measurement of a voltage across the device. The amount of self-heating depends upon the magnitude of the current used to determine the resistance as well as the physical construction, materials, and the convection-driven cooling rate of the mechanical aspiration. It is important to not that this error is a *bias error*, as it always results in a measurement higher than actual. In order to minimize this error, it is desirable to minimize the magnitude of the current used to measure the PRT's resistance. Figure 5 shows an implementation of the measurement. It consists of a half-bridge, utilizing AC excitation of 400 µA, based upon competing requirements of signal-to-noise ratio and drift. This design allows for self heating in the range of 0.0016°C. This is determined by operating the device at several hundred times its normal operating power dissipation (power dissipated is proportional to I^2), and measuring the temperature rise due to self heating. One can then predict the self-heating at the lower currents.

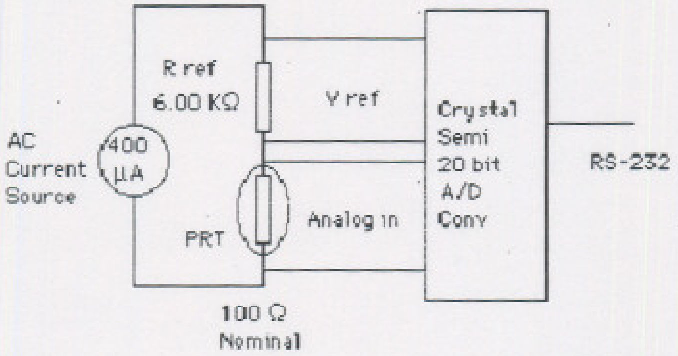

Figure 5. Bridge and Digitizer Circuit

In order to determine the actual magnitude of self-heating, measurement of the PRT resistance was performed with an excitation current of 10 mA. A large current such as this produced heating sufficient to heat the PRT probe just over 1°C. The heating reached steady state at about six minutes after application of the 10 mA current, as shown in Figure 6. Since heating power is proportional to the current squared, by reducing the heating current to a more realistic 400 µA, we expect a maximum steady state heating of:

$$[\,(400^{-6}) / (10^{-3})\,]^{2} \bullet 1°\mathrm{C} = 0.0016\ °\mathrm{C}$$

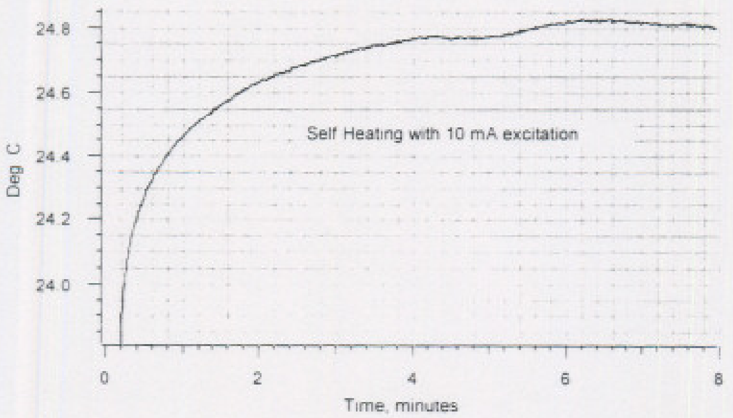

Figure 6. PRT self-heating error shown at 25 times normal bridge current

Bridge Resistor Tolerance and Drift Errors

In practice, precise electrical measurements of PRTs are typically made using ratiometric methods. In order to eliminate the need for an absolutely stable current or voltage source (which is difficult to build), PRT measurements are made relative to the voltage across a resistor being sourced by the same current as the PRT. It is necessary only for the resistor to be stable and accurate. All resistors exhibit some drift with time and temperature. This design uses a Vishay series-H, oil-filled and hermetically sealed unit. The Vishay specification guarantees a maximum $\Delta R/R$ of ±0.002% after 2000 operating hours at 0.1 W at 60 °C (Vishay Inc. catalog). The converter's output represents:

$$\Omega = 120 \bullet (6000 / R_{ref})$$

And thus R_{ref} 's specified maximum drift becomes:

$$6000 \bullet \pm 0.002\ \% = \pm 0.12 \text{ Ohms.}$$

The converter then returns a reading 120 ± 0.0024 Ohms. Using a typical PRT coefficient of 0.395 Ohms/°C, this results in an error of ± 0.00607 °C.

Amplifier Gain Errors

To measure the µV changes produced by the PRT a precision amplifier stage is required. Over operating temperatures found in field measurements, differences will exist between the intended design gain and the actual gain of the amplifier. The design we settled on uses a 20-bit delta-sigma A/D converter (Crystal Semiconductor, 1996) with a built-in programmable gain amplifier with gains of 25, 50, 100, and 200. The gain error is less than 24 PPM, after self-calibration and at constant temperature.

The design uses a nominal programmed gain of 50. Referring to Figure 5, a gain of 50 provides a full scale output with an input impedance of 120 ohm, given that the top resistor in the half bridge is 6000 ohms.

Gain variation, from 50 (nominal) is $50 \pm 2.4 \bullet 10^{-5}$ (Crystal Semi spec)

Measured resistance = gain • input resistance • 120 / 6000

Substituting gain into the above we have:

Measured resistance = $50 \pm 2.4 \bullet 10^{-5} \bullet$ input resistance • 120 / 6000

At a design full scale input of 120 ohms (at approximately 50°C), we have:

Measured resistance = $50 \pm 2.4 \bullet 10^{-5} \bullet 120 \bullet 1 / 50$

Measured resistance = $120 \pm 5.8 \bullet 10^{-5}$ ohms

Given the nominal PRT slope of 0.395 Ohms/°C this error, in °C, becomes:

$$\pm 5.8 \bullet 10^{-5}\ /\ 0.395 = \pm 0.000146°\text{C}$$

Linearity Error

Linearity error is the deviation of the converter's code from a straight line that extends between two fixed points on the A/D converter transfer function, generally specified as the point 1/2 LSB above a count of zero and the point 1/2 LSB above full scale. The linearity error is specified at ±0.0015% of full scale. The converter, as configured, is scaled to -250 °C to +50°C. So the linearity error is:

$$1.5^{-5} \bullet 300 = \pm 0.0045°\text{C}$$

Offset Drift

All amplifiers exhibit drift in the input offset voltage. This voltage is the input voltage required drive the output of the amplifier to zero when both inputs are connected together. Put another way, it is as if a battery was inserted in series with one of the amplifier inputs, and it exhibited a temperature dependence. The drift specification for the A/D converter is 0.005 μV°/C. Using AC excitation for the bridge eliminates this component of error as it only applies to DC-excited measurements.

Total Error Components

The worst case error is calculated as follows:

E_{meas} = stem error + resistor drift + amplifier gain + linearity

$= 0.00003 + 0.00607 + 0.000146 + 0.0045$

$= 0.0107$

$E = \pm E_{meas} + E_{heating} + E_{sol}$

$= \pm 0.0107 + 0.0016 + 0.005$

$= +0.0173, -0.0041$

FIELD TESTS OF THE THERMOMETRY SYSTEM

Comparative field tests were performed against a shielded, non-aspirated RM Young thermometer. The temperature of the outer shield was also measured to determine the effectiveness of the shielding and aspiration, with results shown in Figures 7 and 8. As was expected, the non-aspirated thermometer indicated higher ambient temperatures under the influence of solar radiation.

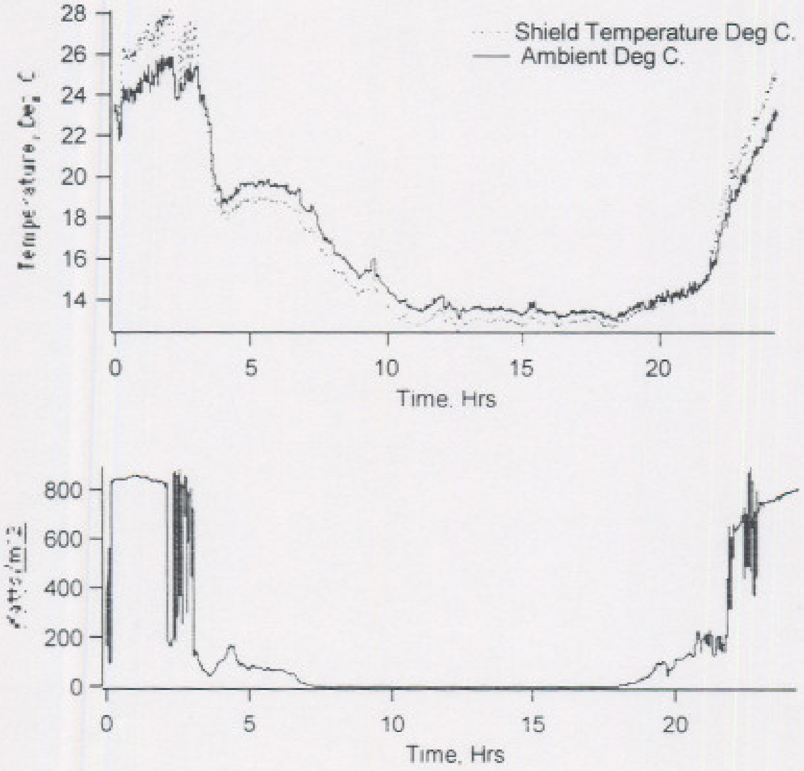

Figure 7. Test data for one day.

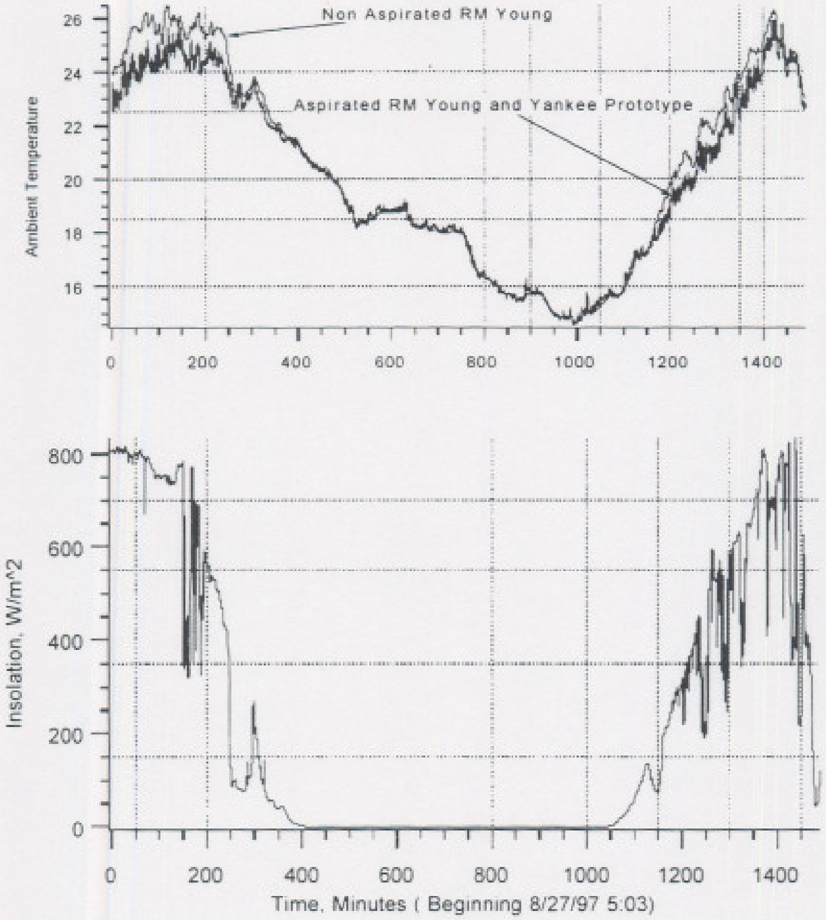

Figure 8. A typical clear day data set.

Chilled Mirror Hygrometer

The exhaust from the thermometer aspirated system is passed through a chilled mirror dew point hygrometer (CMH). Additional support electronics were developed for mirror control and measurement system. It was especially important to be able to re-establish the set point for the condensation layer at a regular interval. This required the addition of a real-time clock, so that the user can set the desired number of balance cycles per day and the time that they occur.

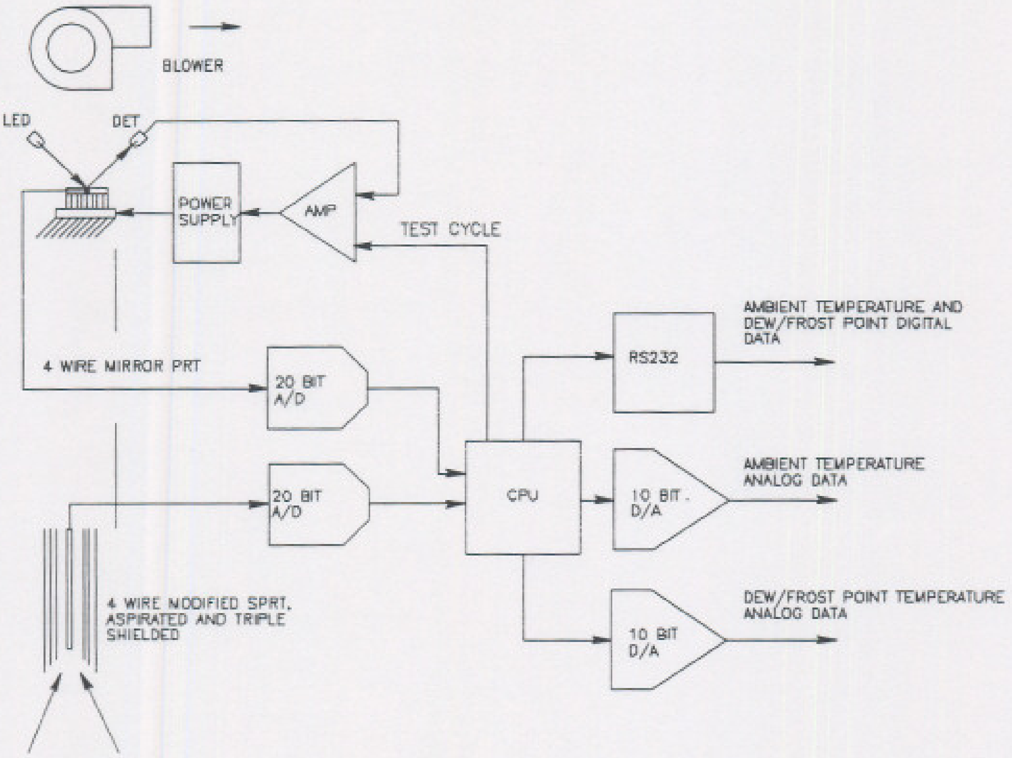

Figure 9 System block diagram

Figure 9 shows an electrical block diagram of the instrument, and outlines the major electronic control subsystems. A precision A/D converter is used for ambient temperature and dew point measurement and a Motorola microcontroller oversees operation. The system includes both analog and digital user signal interfaces, and automatically detects aspiration failure and dirty mirror conditions that require maintenance. Figure 10 shows a view of the CMH thermoelectric module and optics, that include an LED-photodetector pair for measurement of the dew layer scattering and a reference pair to compensate for changes in LED efficiency over temperature.

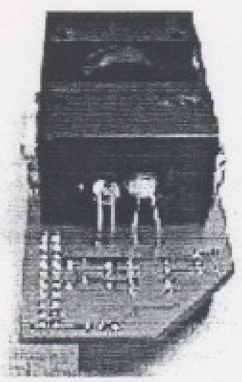

Figure 10. CMH thermoelectric module and optics

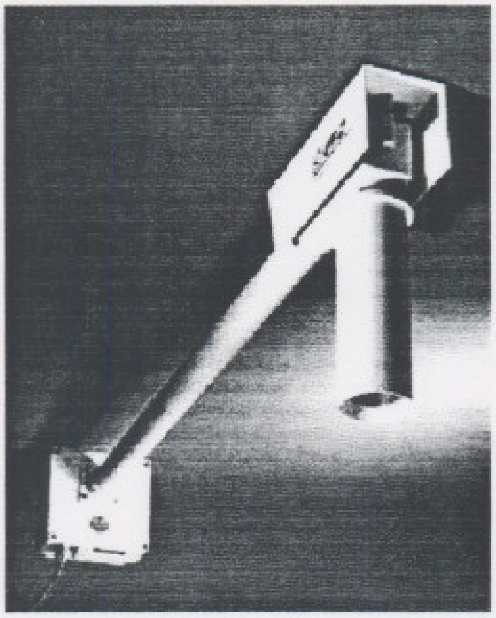

Figure 11. Yankee Environmental Systems Model MET-2010

CONCLUSION

Figure 11 shows the commercial realization of the research effort, the YES Model MET-2010. We feel that the system described represents the current state-of-the-art in making high accuracy measurements of ambient air temperature and humidity in the field. Testing in the US and Europe is ongoing and has verified system performance at national laboratories. The authors wish to thank the USDA's SBIR program office for financial support of this R&D program, as well as Mr. Boris Taubvurtzel of the U.S. National Weather Service office in Sterling, VA for his help in field-testing initial prototypes of the system.