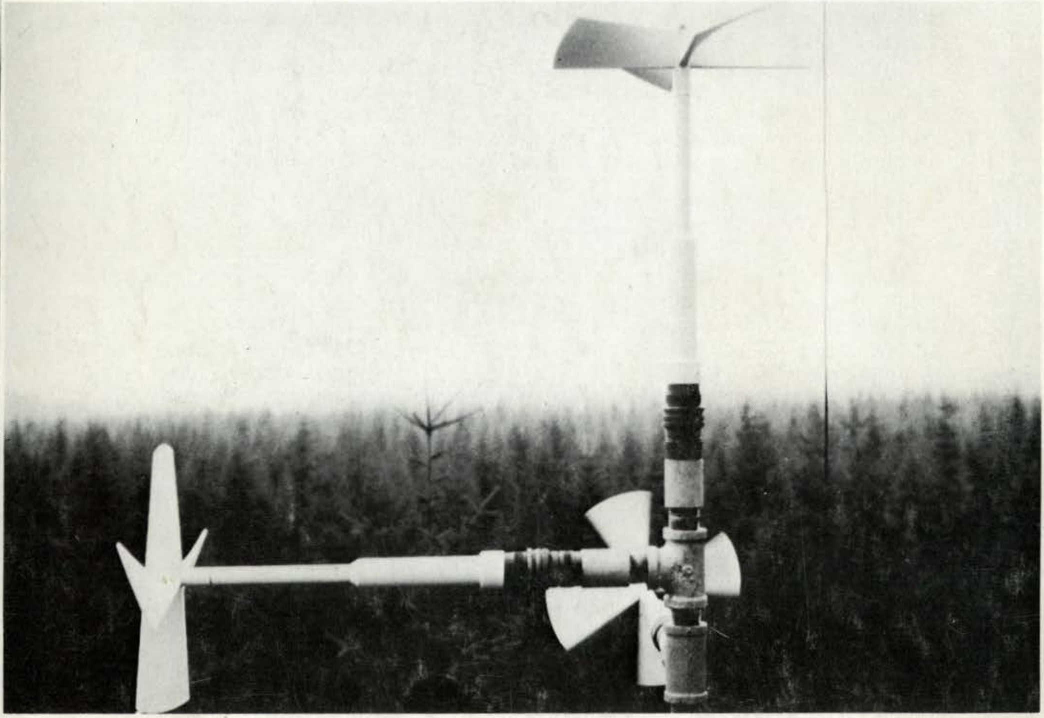
UNIVERSITY OF IDAHO
COLLEGE OF FORESTRY WILDLIFE AND RANGE SCIENCES

AN INSTRUMENT SYSTEM FOR ESTIMATION OF EVAPOTRANSPIRATION BY THE EDDY CORRELATION METHOD

By George H. Belt, Jack King, and Everett Bailey
University of Idaho



Forest, Wildlife and Range Experiment Station
Moscow, Idaho

Station Paper No. 19

December 1974

AN INSTRUMENT SYSTEM FOR ESTIMATION OF EVAPOTRANSPIRATION BY THE EDDY CORRELATION METHOD

George H. Belt, Jack King, and Everett Baily
University of Idaho

ABSTRACT

A fast response meteorological instrument system for measuring parameters used in calculating evapotranspiration above a forest stand is described. Comprised of Gill-type propeller anemometers, Brady-array humidity sensors, thermistor air-temperature sensors and a Metro-Data digital tape recorder, the system was designed to measure eddy fluctuations in the range from one to 0.005 cycles per second. Details of the shop-built signal conditioning circuitry for the Brady-array are presented along with a discussion of apparatus and techniques employed to calibrate the sensors as a part of the instrument system. Problems with electrical noise and condensation within instrument packages which occurred during field trials are also discussed.

INTRODUCTION

Measurement of evapotranspiration above a forest stand by the eddy correlation method requires an instrument system capable of responding to, and measuring rapid changes in, vertical wind velocity, W, and specific humidity, Q. These fluctuations, caused by the eddying motion of the air moving past the measurement point, have a nominal frequency range or spectrum of 0.005 to approximately 10 cycles per second, cps. The response of the system ideally must be sufficient to measure the full range of time-dependent fluctuations of the aforementioned quantities. In practice, when using less than perfect instruments, it is sufficient to measure that portion of the frequency spectrum where most of the fluctuations occur and to estimate error caused by the system's inability to accurately measure the higher frequency fluctuation. While information defining the range of frequencies to be expected above a forest stand is sparse, work by McBean (1968) suggests that the greater portion of the range lies between frequencies of 0.005 and 1.0 cps. This is in general agreement with studies made above other types of vegetative cover and was taken as a working assumption in the design of this system. For more detailed consideration of design requirements, refer to McBean (1972).

In measuring evapotranspiration, with eddy correlation methodology, the more difficult measurement is the specific humidity fluctuations Q', where $Q' = Q - \bar{Q}$ and Q is the instantaneous value of specific humidity, $\bar{Q}$ is the average value of Q over some specified period and Q' is the instantaneous deviation from the mean. Some earlier approaches to this problem have been the use of (1) the fine-wire wet-bulb in the evapotron by Dyer (1965), (2) the barium-floride sensor by Goltz et al. (1970) and (3) the Lyman-alpha humidiometer by Miyake et al. (1970). These sensors were rejected due to their difficulty of maintenance, difficulty of manufacture or cost, respectively. A new sensing element, the Brady-array, was chosen instead, principally because of its solid-state nature, 300 millisecond response, moderate cost, and the comparative ease with which it could be maintained in inaccessible locations. The Brady-array, described in more detail in a subsequent section, is manufactured by Thunder Scientific of Albuquerque, New Mexico.

INSTRUMENT SYSTEM

Components of the instrument system are indicated below.

Component	Measurement	Time Constant (sec)
1. Gill-type propeller anemometer	W, U, V	1*
2. Thunder Scientific sensor BR-101 consisting of:		
a. Brady-array for relative humidity measurement Q = f(relative humidity)	Q	0.3
b. VECO Thermistor for air temperature measurement	T	2†
c. Temperature compensated Brady-array		
3. Shop-built signal conditioning circuitry for excitation, and demodulation of relative humidity and temperature sensors, and scaling of analog output signals		
4. Metro-Data, 1.27cm (½ inch) digital tape recorder model 620		

*dependent upon wind velocity
†still-air time constant is five seconds; two seconds estimated for moving air

While fairly standard approaches to wind velocity and air temperature measurement were employed, measurement of specific humidity was accomplished using a relatively new sensor, the Brady-array. The following portion of this report provides a brief description of the wind instrument with more detailed explanation of electronic circuitry and calibration methods devised to utilize the Thunder Scientific sensor as a component in the instrument system.

Propeller Anemometers

Due to their comparative low cost and simplicity of operation, Gill-type propeller anemometers were selected over faster response hot-wire anemometers for vertical velocity measurement. Both commercial propeller anemometers (R. M. Young Co.) and shop-built propeller anemometers were utilized. The latter anemometers, constructed from a design supplied by L. J. Fritschen (1972, personal communication), have performance characteristics similar to those commercially available. Four-bladed, 23 cm (9-inch) diameter propellers supplied by the R. M. Young Co. were used on both commercial and shop-built units. These sensors, with distance constants of approximately one meter, provided nominal response time of approximately one second. Calibration of the anemometers was accomplished by driving the propeller shafts at known revolutions per minute, rpm, and by measuring the millivolt, mV, output of the sensor tachometers with the digital recording system.

Relative Humidity and Temperature Sensor

The Brady-array

The Brady-array consists of an array of crystals which form semi-conducting bodies. As water vapor penetrates the interstitial spaces of the crystal lattice, bonds are distorted, causing energy to be released to the free electrons in the structure. The element then conducts more readily, decreasing in resistance as more electrons enter the structure. The Brady-array is normally operated as one element of a voltage divider, across which is applied as AC excitation of approximately 5 volts root mean square, rms, at a frequency of one kilohertz, kHz. The voltage output of the circuit follows changes in relative humidity and in our circuit varies from approximately 0.10 volts rms at zero percent relative humidity up to approximately five volts rms at 100 percent relative humidity.

Electronic circuitry used with Brady-array

A complete circuit diagram for the electronic system designed for use with the Thunder Scientific Brady-array sensor is contained within the Appendix. The diagram includes circuits for both temperature and humidity sensors and is partitioned into three sections labeled sensor, remote, and master. Each section relates to a different physical location for the associated components.

The physical arrangement of the sensor and remote packages as used in the field is shown in Figure 1. White polyvinylchloride, PVC, tubing of 5.0 cm (2-inch) inner diameter provides a weather tight housing for the electronic circuitry housed in the remote package. Electronic components are mounted on a printed circuit, PC, card for ease of assembly. Placement of the remote circuitry in white PVC tubing reduces thermal stress due to solar radiation on the electrical components. This protection, coupled with the low offset voltage drift inherent in the operational amplifiers chosen, minimizes errors due to temperature variations. Further reduction of temperature related errors is accomplished by use of the full range of output voltage of the operational amplifiers which are employed in low gain circuit configurations.

A short length of cable routed through a section of 1.90 cm (nominal ¾ inch) galvanized pipe connects sensor and remote units. The pipe also serves as a duct to route air from the sensor shield inlet to an exhaust fan. Physical separation of the remote and sensor units permits the construction of a compact sensor radiation shield. This minimizes disturbance of air flow near the anemometers. Electronic "loading" of the Brady-array voltage divider circuit by the eight-foot connecting cable is avoided by including a voltage-follower amplifier (LM 302) in the sensor package.

The master unit electronics are housed within a chassis several hundred feet from the remote and sensor packages. In this unit, temperature and relative humidity signals are fed to a central terminal strip and to voltage level adjustment networks to which recording equipment can be easily attached. To facilitate field checking and the substitution of system components, the entire electronics assembly was constructed in modular form with generous use of electrical connectors.

Relative humidity circuit

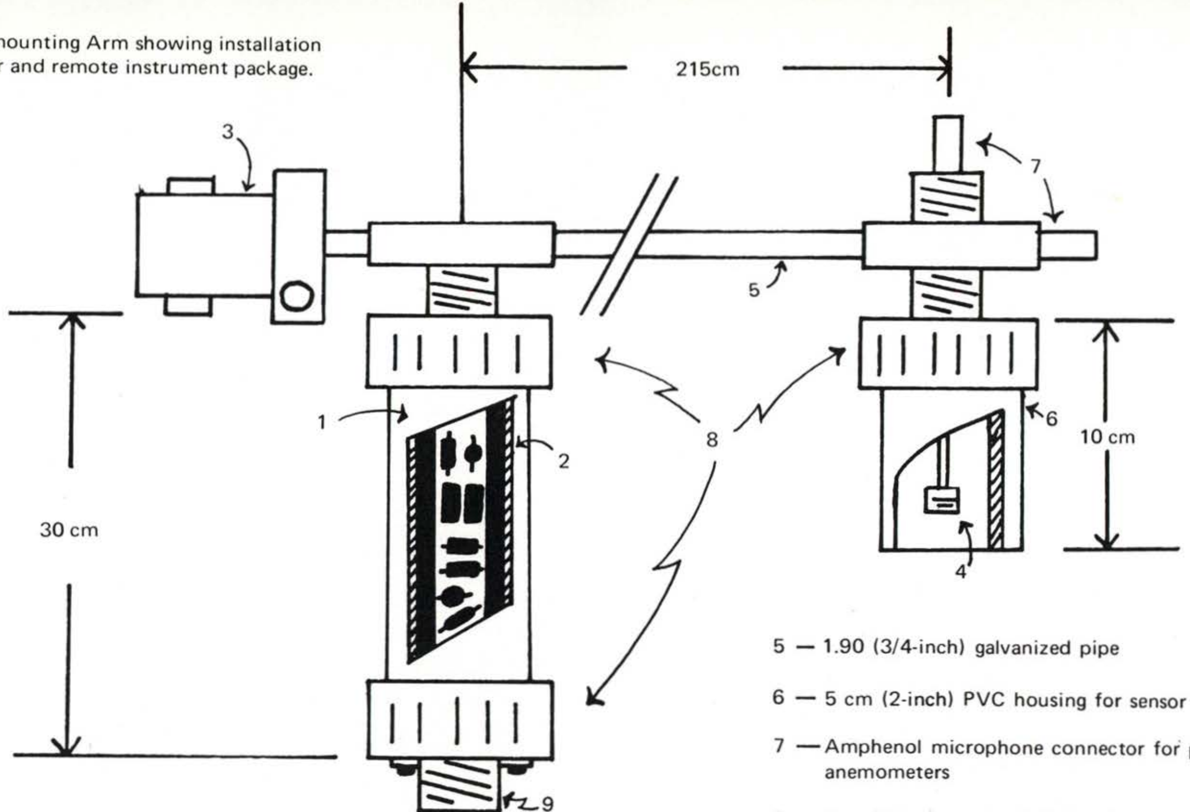
A block diagram of the relative humidity circuitry is shown in Figure 2. An oscillator provides a constant AC excitation to the Brady-array sensor network. Output from the sensor is fed to a voltage follower circuit and from there to a demodulator unit. The demodulator produces a DC, output signal proportional to relative humidity, which is adjusted by a voltage divider circuit and then recorded.

The circuit diagram of the excitation oscillator is shown in Figure 3a. It is a Wein bridge oscillator employing an operational amplifier as the active element. A zener diode-resistor network is used in the negative feedback path of the operational amplifier to stabilize the oscillation amplitude. When the voltage across the diode pair exceeds the zenor breakdown voltage, the diodes conduct to connect resistor R5 in parallel with resistor R4. This increases negative feedback in the circuit to limit the amplitude. The 1,000 ohm potentionmeter, P1, also affects the negative feedback and provides limited adjustment of the output amplitude. The oscillation frequency is determined by resistors, R1 and R2, and capacitors, C1 and C2. Transformer, T1, precludes any possibility of a DC voltage component at the output as required by the Brady-array elements.

The Brady-array sensor network to which the oscillator output is connected is shown in Figure 3b. The Brady-array constitutes one element of a voltage divider circuit. The other element of the circuit is a glass enclosed Brady-array sensor which is contained in the sensor package purchased from Thunder Scientific. The resistance of the glass enclosed sensor varies only with temperature and serves to compensate the circuit for temperature variations. Loading of the divider circuit is minimized by the voltage follower, A1, which has an input impedance in excess of 10^9 ohms. This unit also isolates the sensor circuit from any capacitance effects of the cable which connects it to the demodulator unit.

The demodulator circuit is shown in Figure 3c. It is a precision rectifier-filter circuit which produces a DC voltage output that is proportional to the amplitude of the AC voltage from the sensor. Capacitor, C4, is selected for the desired filtering action. A value of 0.82 microfarads is a compromise value which gives relatively fast response to

Figure 1
Sensor mounting Arm showing installation of sensor and remote instrument package.



1 — 5 cm (2-inch) I.D. PVC pipe housing containing remote PC board

2 — Cut-away view of remote PC board

3 — 28 volt DC exhaust blower

4 — TO-5 can containing Brady-array and air temperature thermistor

5 — 1.90 (3/4-inch) galvanized pipe

6 — 5 cm (2-inch) PVC housing for sensor

7 — Amphenol microphone connector for propeller anemometers

8 — 5cm (2-inch nominal) PVC pipe caps

9 — 10 conductor MS Amphenol connector for cable to master unit

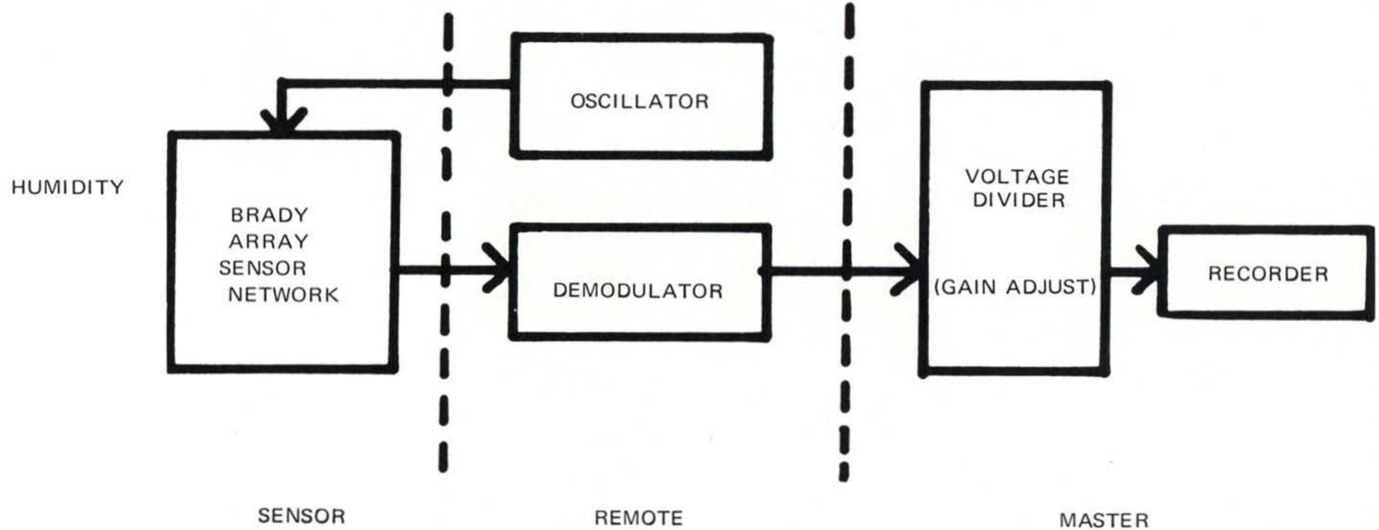


Figure 2
Block diagram of the relative humidity system.

changes in the amplitude of the sensor signal (16.2 millisecond circuit time constant) and still maintains a minimum of ripple in the DC output. Capacitor, C3, serves two purposes in coupling the sensor unit to the demodulator. It passes the AC sensor humidity signal to the demodulator and blocks any DC offset or drift voltage from the voltage follower amplifier. Capacitor, C5, suppresses high frequency oscillation which otherwise can occur at the demodulator output when it is connected to the 300-foot cable which links the demodulator to the gain adjust network.

The voltage divider network which is used for gain adjustment of the relative humidity signal is shown in Figure 3d. Resistors R18, R19, R20, and R21 provide the adjustment feature. Use of the parallel combination of R19 and R20 rather than a single resistance facilitates the hand selection of 5 percent tolerance resistors to achieve 1 percent tolerance gain adjustment. The network provides output ranges of zero to +1 volt and zero to +10 millivolts. Capacitors, C8 and C9, attenuate noise which appears on the 300-foot connecting cable.

Temperature circuit

A block diagram of the temperature sensing network is shown in Figure 4a. The temperature sensing element is a thermistor which is contained in the sensor package purchased from Thunder Scientific. This element is used in conjunction with a voltage divider and a voltage follower unit to produce a voltage signal which follows changes in temperature. An output amplifier adjusts the voltage signal for recording purposes.

Thermistor and voltage networks are shown in Figure 4b. The thermistor and the fixed resistor, R16, constitute a voltage divider network which generates the temperature signal. A negative 10 volt bias for this circuit is produced by a second voltage divider composed of resistors, R15 and R17. The voltage follower amplifier, A5, receives the temperature signal and its high input impedance minimizes loading of the thermistor circuit. Resistance of the thermistor varies from approximately 6 Megohms at 0 C to 470 Kilohms at 40 C to produce −3.2 volts to −7.8 volts, respectively, at the voltage follower output. Capacitors, C6 and C7, are necessary to shunt out 1 Kilohertz AC voltages which are unavoidably coupled into the circuit from the relative humidity network.

Shown in Figure 4c is the circuit diagram of the output amplifier. This amplifier serves two important functions. First, it adjusts the reference level of the temperature signal to center it at 0 volts. Under these conditions the temperature signal can produce both a positive and a negative voltage swing. The second function is that of amplification of the temperature signal to expand it over the entire positive and negative output ranges of the amplifier. This produces maximum resolution of the temperature signal and reduces errors which can result from offset or drift voltages in the operational amplifier units. For the temperature range of 0 C to 40 C an amplification factor of 4.2 is appropriate. Both the amplification and reference level adjust features can be easily changed to accommodate any temperature range of concern. The amplification factor is controlled by the resistors in the operational amplifier circuit and is given by

$$K_a = (1 + R_{23}/R_{22})\ [R_{26}/(R_{24} + R_{26})].$$

The DC voltage added to the temperature signal for reference level adjustment is equal to the breakdown voltage of zener diode, D5, multiplied by a gain factor whose expression is

$$K_r = (1 + R_{23}/R_{22})\ [R_{24}/(R_{24} + R_{26})].$$

This assumes that the zener diode, D5, is carrying enough current to operate in its breakdown region. Appropriate selection of the resistor, R28, establishes this mode of operation.

At the output of the amplifier a voltage divider network is used to establish precise signal voltage ranges for recording purposes. The divider consists of resistors R25, R27, and R29. These provide ranges of ±1 volt and ±10 millivolts. Capacitors C10, C11, and C12 have been added to the circuit for noise suppression. Compromise values have been used for these elements such that noise is greatly reduced while the response time of the network is not degraded beyond the time constant of the thermistor.

Power Supply

A dual output 15 volt DC power supply (R. O. Associates, Model 115) is used to power

FIGURE 3. COMPONENTS OF THE RELATIVE HUMIDITY SYSTEM

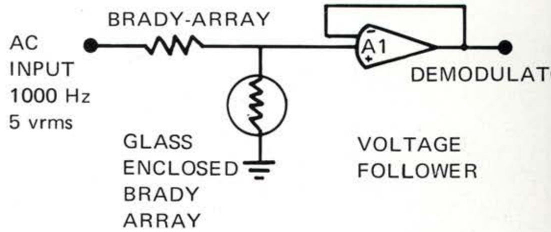


Figure 3b. Brady array circuit showing glass enclosed Brady array for temperature compensation

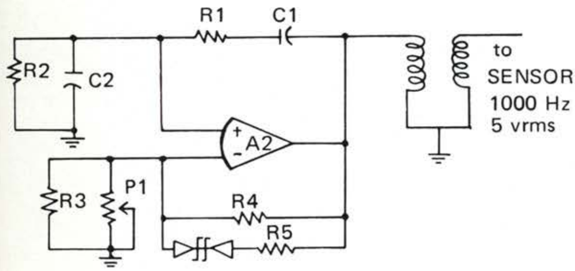


Figure 3a. The wien bridge excitation oscillator

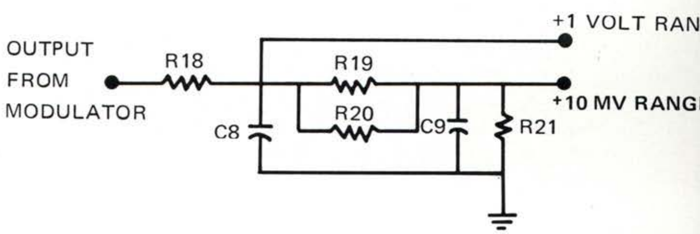


Figure 3d. Voltage divider network

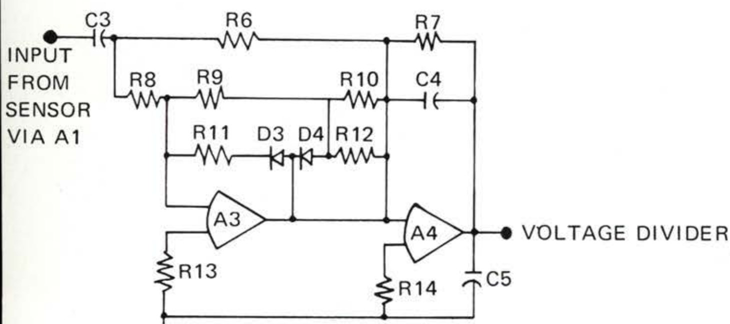


Figure 3c. Demodulator circuit

FIGURE 4. TEMPERATURE SENSOR NETWORK

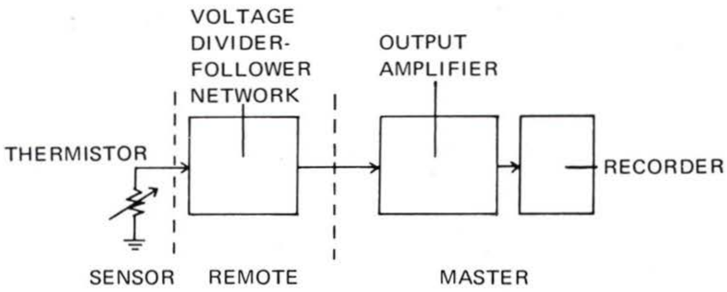


Figure 4a. Block diagram

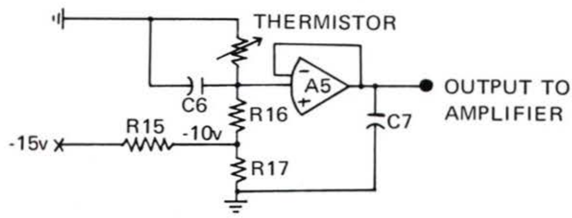


Figure 4b. Thermistor and voltage follower

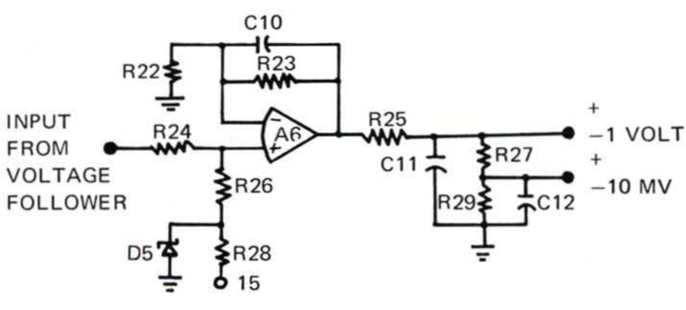


Figure 4c. Output amplifier

the electronic units. The power supply is housed in the master electronics package. Voltage is carried to the remote and sensor packages over the 96 meter and 3 meter connecting cables. The common terminal of the supply is connected to the 95 meter cable ground wire as shown in the Appendix and capacitors C15 and C16 are added from the +15 volt and −15 volt leads to ground in the remote package. These capacitors reduce the impedance from the voltage leads to ground to compensate for the resistance added to the power supply by the long lead lengths. Finally, resistance R34 is connected from the +15 volt lead to ground at the remote to balance the currents in the negative and positive wires. This reduces the ground wire current to zero to prevent the occurrence of a voltage drop in that wire.

CALIBRATION

The Brady-array sensors are calibrated by Thunder Scientific using a precision excitation source and synchronized demodulator. Since a new circuit design and component lay-out were developed for the sensors and because the output voltage of the sensors was to be scaled to the range of zero to ten millivolts, each sensor was recalibrated as a part of the total system before field use.

Saturated Salts

An initial attempt to calibrate the sensors was made using saturated salt solutions in equilibrium at standard temperatures. Several salt solutions were used to obtain reference points for a calibration curve plotting R.H. against voltage output. With this technique repeatable results were unobtainable. Apparently deposition of salts within the crystal lattice of the Brady-array changed the characteristic resistance of the sensor. After consulting with Thunder Scientific and noting their use of a split-flow calibration system monitored by a precision psychrometer, the use of a salt solution was abandoned.

Humidity Chamber

To obtain known relative humidity and temperature values, a method was developed wherein stable calibration points could be maintained through regulation of temperature and water vapor concentrations in a small, 865 cc, cylindrical chamber. Figure 5 shows the basic design of the apparatus.

The humidity chamber was made of stainless steel which permitted rapid temperature response within the chamber when a change in the water bath temperature was made. Brass fittings in the chamber wall permitted simultaneous calibration of four sensors.

Humidity conditions in the chamber were usually manipulated by varying the chamber air temperature; however, extreme values were regulated by passing the circulating air either through a column of desiccant to achieve humidities less than 15 percent, or through a saturated chamber to achieve humidities above 85 percent. The water bath allowed regulation of the temperature in the control chamber from room temperature up to 60°C. An auxiliary pump attached to the water bath transferred to cold water (0-2°C) from a separate source and mixed it with existing water to achieve temperatures below room temperature. When working in temperature ranges not near room temperature, there was an inherent 1°C difference between the chamber air temperature and the water bath temperature. This was caused by temperature changes in the air as it passed through the dewpoint hygrometer and other apparatus. Water loss was minimized by use of brass fittings and tubing of low absorptivity. By regulating temperature and water vapor concentrations, we were able to provide a range of humidities of approximately 6 to 95 percent. A Cambridge Systems dewpoint hygrometer, model 922-C1 with platinum resistance thermometer, continuously sampled chamber air and provided a millivolt signal linearly proportional to the dewpoint temperature. This signal was recorded on a strip-chart. Air temperature in the chamber was monitored using a 500 ohm platinum resistance thermometer connected to a manual precision resistance bridge. With this system we were able to measure R.H. to better than plus or minus two percent, and air temperature to ±0.15°C.

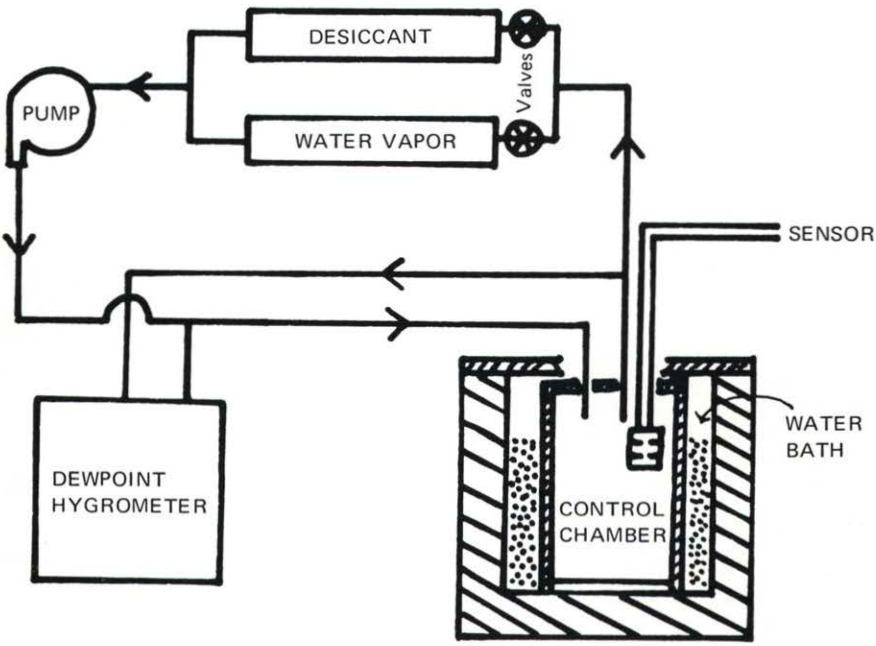


Figure 5
Apparatus used to calibrate RH and temperature sensors

Thunder Scientific reports a hysteresis in the Brady-array of one to two percent R.H. and a typical accuracy of plus or minus two percent. Using this calibration system, errors of four to six percent R.H. were observed of which part appeared to be hysteresis. Additional error may have been due to a lack of complete mixing in the TO-5 can enclosing the Brady-array. A flow of 472cc per second maintained in the chamber may not have completely purged the interstitial spaces of the crystalline Brady-array even though several minutes were provided to obtain equilibrium. To minimize this problem calibration runs were initiated by raising chamber air temperature to approximately 48°C and permitting air to flow through the desiccant column. This resulted in R.H. values of six to eight percent. Subsequently, chamber temperature was reduced and/or absolute vapor content of the chamber was increased so that R.H. increased to about 95 percent. At this point the procedure was reversed so that R.H. went from 95 to 6 percent. A typical curve, B, and data points obtained by this procedure are shown in Figure 6. Curve A is the calibration curve supplied by the manufacturer. Similarity of curve shapes is evident for this sensor, however all sensors did not produce this degree of similarity. The difference in voltage range of the two curves, as well as shape similarities (or differences) is a function of both the sensor and the electronics used in the measuring circuits. Sensors tested by the above procedures were connected to the recording system and electronic circuitry in the same manner that they were to be used in the field to minimize errors.

Temperature sensor calibration curves were typically linear over range from 3°C to 40°C providing a −10 to +10 m.v. output for this range.

FIELD TRIALS

The Cedar River watershed, an intensive study site, under the IBP Coniferous Biome program, is situated in the Douglas-fir, western hemlock forest near Issaquah, Washington. In August 1972, the instrument system was placed at this location to estimate evapotranspiration. The master unit was housed in a small trailer along with support equipment. Cables averaging 91 meters in length were run to each of three communications-type towers from the trailer. Remote and sensor packages were located on each of the three towers at heights of 30 meters.

Initial use of the system uncovered two problems: (1) high frequency noise, i.e., greater than 10 cps, in the connecting cables which resulted in unwanted noise in the recorded digital signal and (2) condensation which occurred in the PVC remote containers causing failure or frequent erroneous readings. The first of these problems had been anticipated because of the use of unshielded cable and was largely eliminated by the use of 150 microfarad capacitors between the positive side of the signal input to the recorder and common ground. This solution was suggested by the Metro-Data Corporation and did not significantly change the system's performance. The second problem, not sufficiently appreciated in advance and not completely resolved, was the result of frequent rainfall, high humidity and temperature fluctuations sufficient to cause daily condensation on electronic components in the remote housing. These difficulties were temporarily overcome by periodic drying of components, additional use of potting compounds on connectors and insertion of larger amounts of desiccant in the PVC housings. The problem of condensation severely hampered our field effort and reduced the amount of usable data.

Data obtained during initial field trials were insufficient to fully evaluate the system or to draw conclusions regarding the meteorological processes under study. Reduction in support monies by NSF and priorities established in the Coniferous Biome Program resulted in loss of financial support to conclude the field portion of this project. This loss of support did not constitute dissatisfaction with the work described herein or that proposed, but rather the ebb and flow of grant funding.

Work reported in this paper was supported in part by National Science Foundation Grant No. GB-20963 to the Coniferous Forest Biome, U.S. Analysis of Ecosystems, I.B.P.

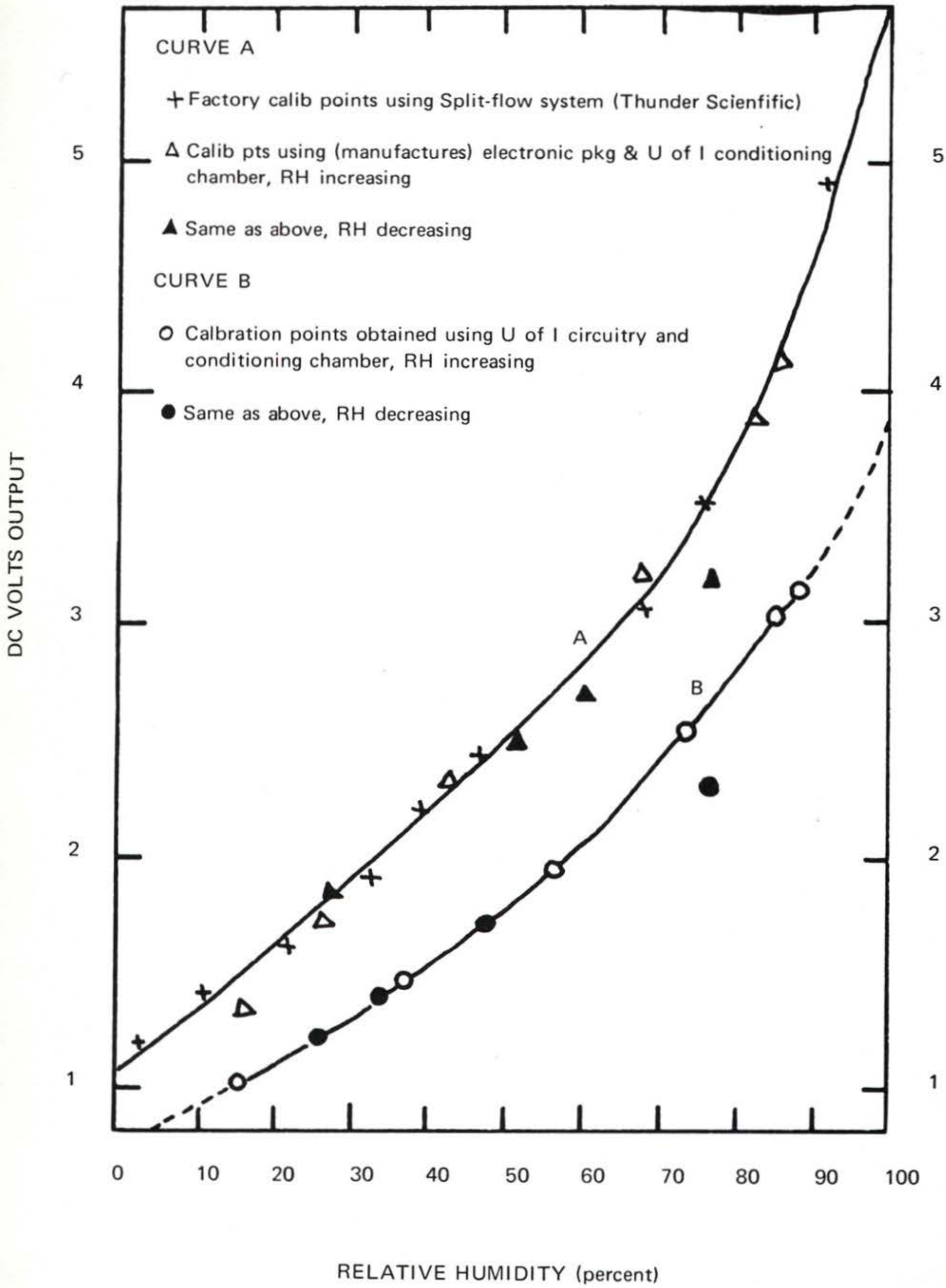


Figure 6
Calibration curves obtained for a typical Brady-array under controlled laboratory conditions.

REFERENCES

Dyer, A. J., and F. J. Maher. 1965. Automatic eddy-flux measurement with the evapotron. J. Appl. Meteorol. 4:622-625.

Goltz, S. M., C. B. Tanner, and G. W. Thurtell. 1970. Evaporation measurements by the eddy correlation method. Water Resources Res. 6:440-446.

McBean, G. A. 1972. Instrument requirements for eddy correlation measurements. J. Appl. Meteorol. 11:1078-1084.

McBean, G. A. 1968. An investigation of turbulence within the forest. J. Appl. Meteorol. 7:410-416.

Miyake, M. and G. McBean. 1970. On the measurement of vertical humidity transport over land. Boundary-Layer Meteorol. 1:88-101.

APPENDIX

PARTS LIST

Capacitors

	H^F	Type
C1	.02	Mica
C2	.02	Mica
C3	.82	Mylar
C4	.82	Mylar
C5	.1	Mica
C6	.022	Mica
C7	.1	Mica
C8	10	Electrolytic
C9	75	Electrolytic
C10	.82	Mylar
C11	.68	Mica
C12	75	Non Polarized
C13, 14	250	Electrolytic
C15	10	Electrolytic
C16	10	Electrolytic

Diodes

D1	1N749A	Zener Diode
D2	1N749A	Zener Diode
D3	1N457	Rectifier Diode
D4	1N457	Rectifier Diode
D5	1N754A	Zener Diode

Operational Amplifiers

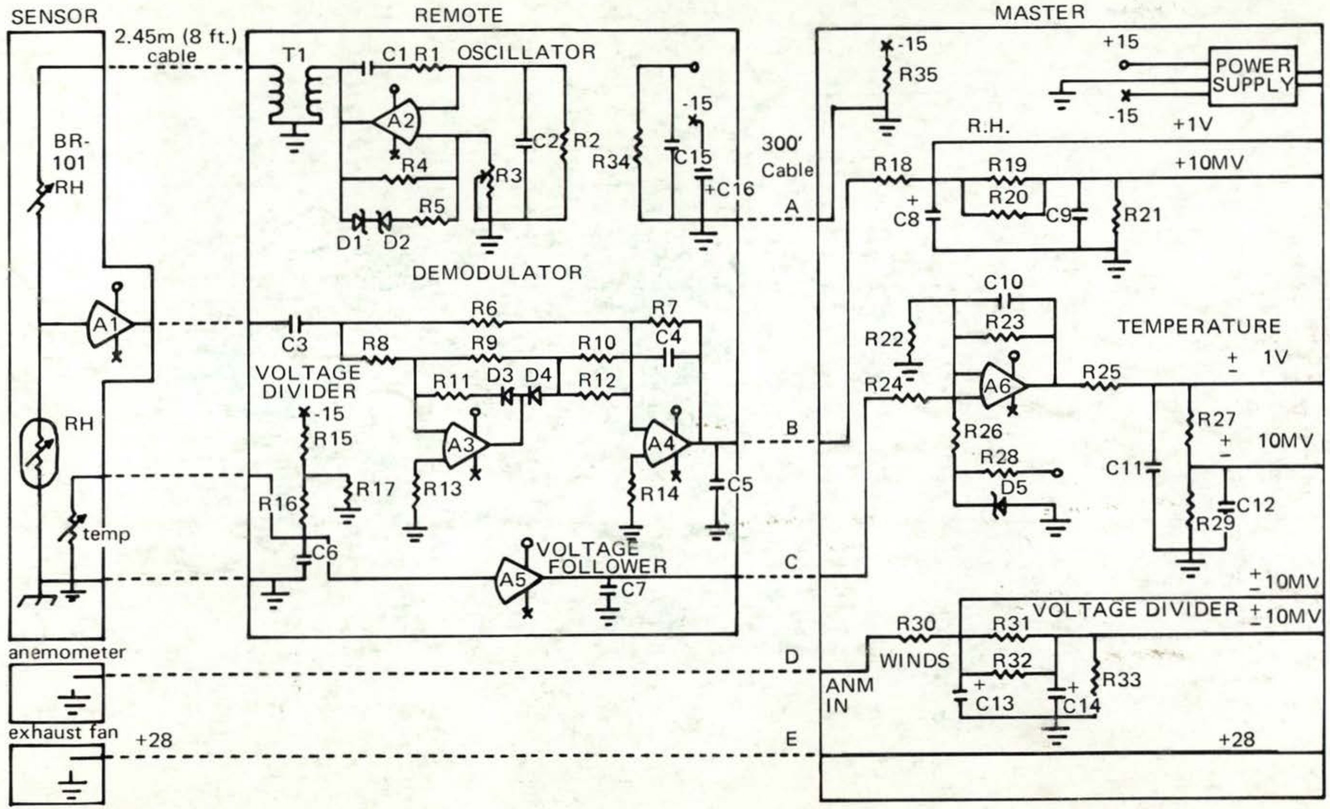
A1	LM302
A2	A741C
A3	A741C
A4	A741C
A5	LM302
A6	A741C

Transformer

T1	UTC DO - T36 1 to 1 transistor transformer

Resistors

	ohms	%	Watts
R1	8.2K	5	¼
R2	8.2K	5	¼
R3	select	for	5 vrms out 400-500 ohms
R4	1K	5	¼
R5	.7	5	¼
R6	19.8K	1	¼
R7	19.8K	1	¼
R8	19.8K	1	¼
R9	19.8K	1	¼
R10	19.8K	1	¼
R11	19.8K	1	¼
R12	19.8K	1	¼
R13	10K	1	¼
R14	10K	1	¼
R15	1K	5	¼
R16	1M	5	¼
R17	2K	5	¼
R18	10K	1	¼
R19	2.55K	1	¼
R20	82K	5	¼
R21	25	1	¼
R22	3.3K	1	¼
R23	21.5K	1	¼
R24	15K	1	¼
R25	22.6K	1	¼
R26	19.8K	1	¼
R27	2.43K	1	¼
R28	350	1	½
R29	25	1	¼
R30	2.37K	1	¼
R31	75	1	¼
R32	75	1	¼
R33	50	1	¼
R34	3K	5	½ balance current
R35	630	1	½ balance current



Electronic circuitry used with Brady-array.