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THE BOULDER LOW-LEVEL INTERCOMPARISON EXPERIMENT

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7. REMOTE ACOUSTIC ELECTRONIC SOUNDING (RACES)

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7.1 INTRODUCTION

The Remote Acoustic Electronic Sounding system (RACES) can measure in the lower layer of the atmosphere the vertical profile of the three-dimensional wind vector, the vertical profile of temperature, and the vertical profile of humidity. The version described here measures only the vertical profiles of vertical wind and temperature. As the measurements are made at the same time and in the same sampling volume, the system can calculate in time the vertical profile of the thermal coefficient of turbulent diffusivity K_h,

$$K_h = \frac{\overline{T'u_3'}}{\partial\bar{T}/\partial x_3} \tag{7.1}$$

where T is the aleatory variable of the temperature, and $T = \bar{T} + T'$, u_3 is the aleatory variable of the vertical component of the wind, and $u_3 = u_3 + u_3'$. $\bar{T}$ and $\bar{u}_3$ are the statistical averages, defined in terms of probability density functions $p(T)$ and $p(u_3)$:

$$\bar{T} = \int_{-273}^{\infty} T \cdot p(T)dT \tag{7.2}$$

and

$$\bar{u}_3 = \int_{-\infty}^{+\infty} u_3 \cdot p(u_3)du_3. \tag{7.3}$$

Since the RACES system measures time series, the ergodic assumption of the stationarity of the measured phenomenon must be made, to replace the statistical averages by time averages. The averaging time is a critical parameter which depends on atmospheric conditions and topography.

7.2 OPERATION

The RACES system is based on the physical properties of transmission and diffusion of sound in the atmosphere. Thus the basis of the instrument is an electro-acoustic device which transmits vertically in the atmosphere.

7.2.1 Sound Transmitter

The sound transmitter (Fig. 7.1) contains an oscillator, which produces a sinusoidal electric signal at a very stable frequency f = 1600 Hz, $\Delta f/f < 10^{-6}$. The signal is transmitted through a switch (which is electronically operated) to a power amplifier and then to the electro-acoustic transducer. There the electric signal is transformed to an acoustic wave. The efficiency of the transducer is low:

$$\eta = \frac{P_s}{P_e} \cong 20\% \,, \tag{7.4}$$

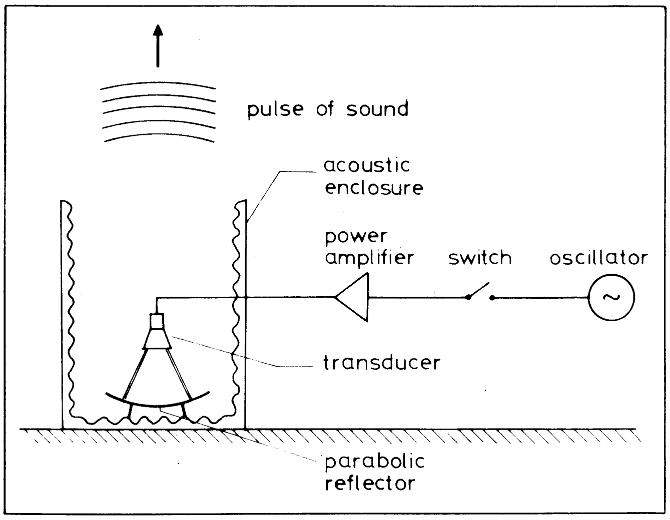


Figure 7.1. Diagram of sound transmitter.

where p_s = acoustic power, and p_e = electric power.

$$p_e = \frac{\overline{u^2}}{Z} \qquad (7.5)$$

where u is the instantaneous voltage applied to the transducer and Z is the electrical impedance of the transducer at the oscillator frequency (1,600 Hz). The relation between the effective (u_{eff}) and peak (u_p) values is given for a sinusoidal signal by

$$u_{eff}^2 = \overline{u^2} = \frac{1}{2} u_p^2 \; . \qquad (7.6)$$

In the low-power version used here p_e = 30 W, and the acoustic power is only 6 W.

7.2.2 Sampling Volume

The sampling probe is the sound pulse itself. The sizes of the sampling volume are identical to the sizes of the sound pulse. The pulse duration is t_p = 50 ms. The length of the sampling volume is given by

$$\ell = C_s \cdot t_p \; . \qquad (7.7)$$

C_s is the speed of sound in the air, and varies slightly with the temperature according to the law

$$C_s = 20.05 \sqrt{T} \; , \qquad (7.8)$$

where T = temperature (K). At 20°C, ℓ = 17 m.

The acoustic antenna is circular, which gives the pulse of sound a cylindrical form whose diameter varies with the altitude according to the law of diffraction of a circular opening.

$$\theta = 1.22 \frac{\lambda}{d} \; , \qquad (7.9)$$

where λ = wavelength of the sound (m), and d = diameter of the antenna.

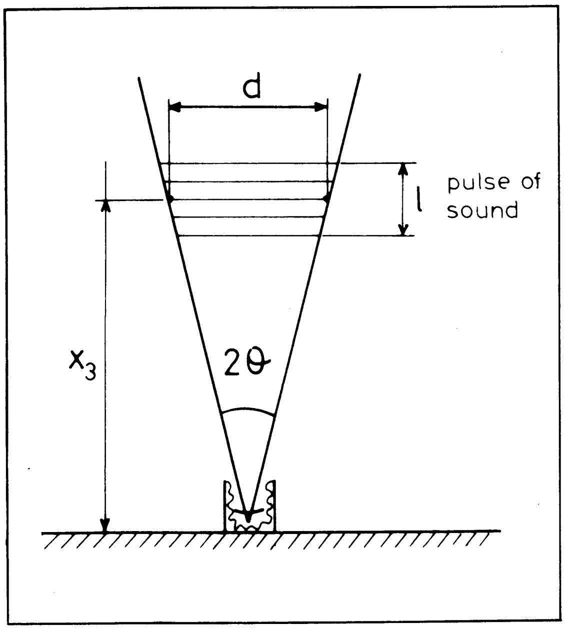


Figure 7.2. Sound propagation from acoustic antenna.

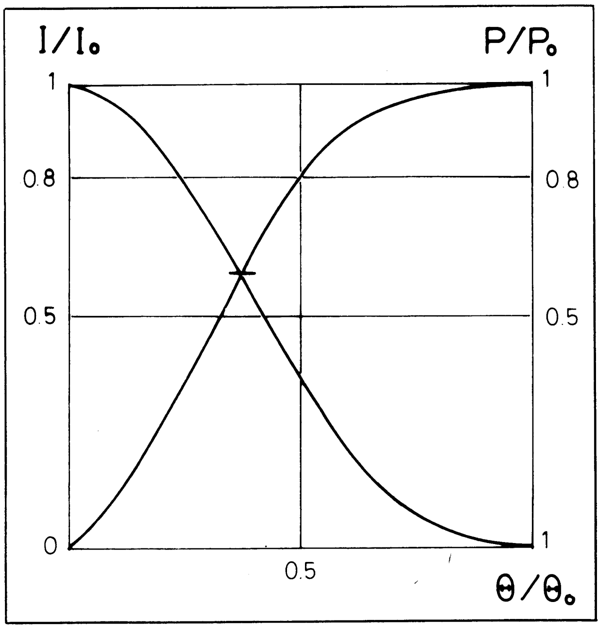


Figure 7.3. Acoustic intensity and power as a function of angle.

$$\lambda = \frac{C_s}{f} \; . \tag{7.10}$$

For the 1600-Hz signal at 20°C,

$$\lambda = 0.21 \text{ m.}$$

For the present low-power version, the diameter of the antenna is 1.31 m. It is therefore possible to calculate at which altitude the diameter and the length of the pulse of sound will have the same value (Fig. 7.2):

$$x_3 = \frac{\ell}{2 \sin(1.22 \frac{\lambda}{d})} = 44 \text{ m} \; . \tag{7.11}$$

The intensity of the sound is, however, not constant in the sampling volume. It varies according to the law

$$I = I_o \frac{2 J_1(\frac{d}{2} k \sin \theta)^2}{\frac{d}{2} k \sin \theta} \; , \tag{7.12}$$

where I_0 = intensity at the center, J_1 = first-order Bessel function, k = wave number = $2\pi/\lambda$.

Figure 7.3 shows that 80% of the power is emitted in an angle

$$\theta \cong 0.5 \; \theta_0 \; .$$

For the RACES system, the length and the diameter of the sound pulse reach the same size at an altitude of ~90 m.

Table 7.1. Corrections for relative humidity

Temp.	100% H	0% H
0°C	-0.23	+0.23
10°C	-0.48	+0.48
20°C	-0.93	+0.93
30°C	-1.78	+1.78

7.2.3 Time Constant

The time constant in the RACES system is the time that the sound takes to propagate along a distance equal to the length of the sound pulse. This is obviously the time duration of the pulse (50 ms). The RACES system is therefore capable of measuring the instantaneous value of the spatial average of the parameters T and u_3 in the sampling volume.

$$T_{ev} = \frac{1}{V} \iiint^{V} T \, dV \tag{7.13}$$

$$u_{3ev} = \frac{1}{V} \iiint^{V} u_3 \, dV \quad . \tag{7.14}$$

7.3 MEASUREMENT OF THE TEMPERATURE PROFILE

The speed of sound propagation in air is directly connected to the thermodynamical properties of the atmosphere. Because of this the RACES system measures directly the absolute value of the temperature.

7.3.1 Theory

The speed of sound in the air depends solely on the temperature. This can be deduced from the equation of the mechanics of fluids and the thermodynamic equations of the adiabatic processes,

$$C_s = \sqrt{\frac{\gamma R T}{\mu}} \quad , \tag{7.15}$$

where C_s = speed of sound (m/s), γ = ratio of the isobaric and isochoic specific heats, R = gas constant (J mole^{-1} K^{-1}), μ = molecular weight (mole^{-1}), and T = absolute temperature (K).

In a dry atmosphere the proportions of the main gases, Ar, N_2, and O_2, are constant. In this case μ is also constant. γ does not vary with atmospheric pressure but does, very slightly, with temperature. However, the effect is negligible within a 10°C temperature variation.

7.3.2 Effect of the Air Moisture

Unfortunately the effect of the water vapor in the atmosphere is too strong to be negligible, especially at high temperatures. Because this version of the RACES system does not measure the vertical profile of humidity, the assumption of a constant 50% humidity profile was made. As seen in Table 7.1, the influence of moisture decreases rapidly with temperature. Table 7.1 gives the corrections for 100% and 0% relative humidity compared with 50% relative humidity, at different temperatures.

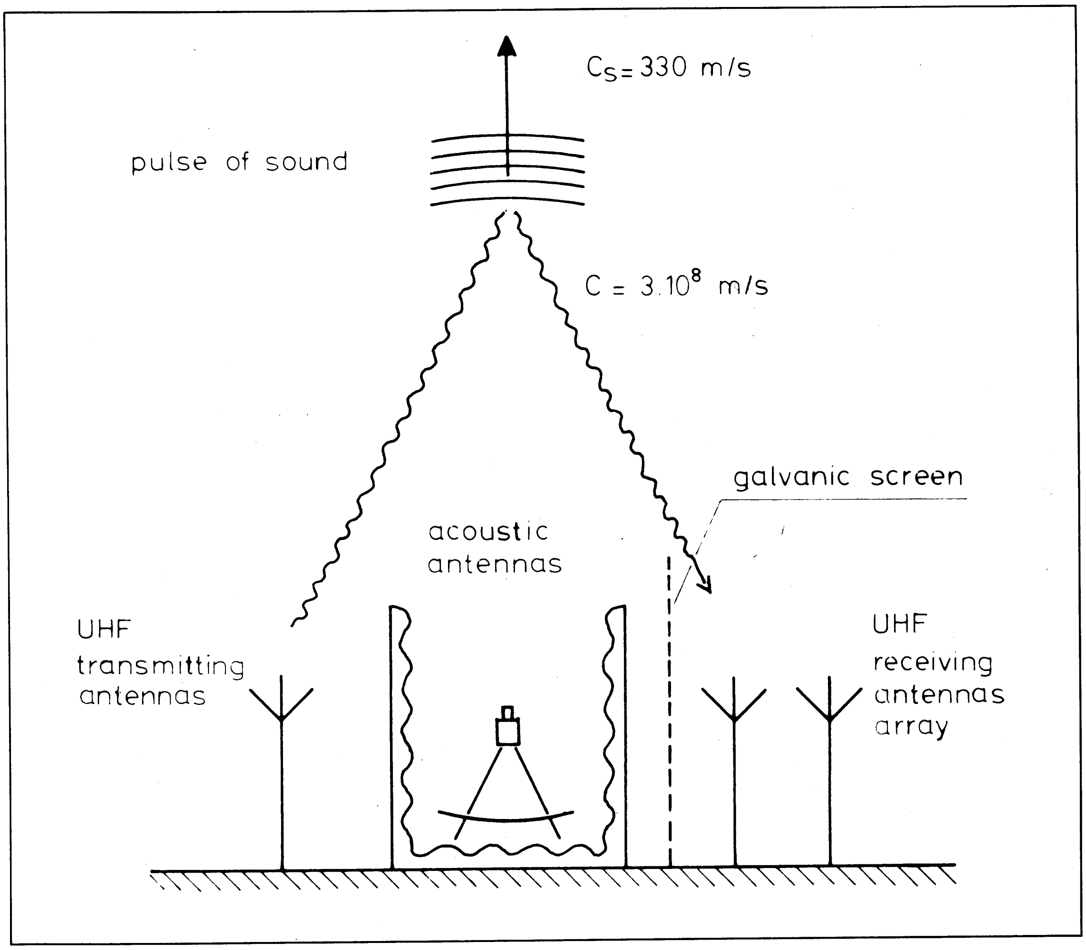


Figure 7.4. Measurement of speed of sound propagation in the atmosphere.

7.3.3 Effect of the Vertical Wind

The measured speed of sound is the sum of the effective speed of the sound and the vertical wind. Since the vertical wind is measured at the same time and in the same sampling volume, the computer can calculate this correction.

$$C_s = 20.05 \sqrt{T} + u_3. \tag{7.16}$$

7.3.4 Temperature Measurement

Since the speed of sound in the atmosphere depends mainly on the temperature, the propagation speed of the sound pulse is directly measured with a CW Doppler radar. The principle is illustrated in Fig. 7.4.

The wavelength of the radar must be exactly twice the wavelength of the sound pulse (which varies with the temperature). In order to improve the range, a feedback device was patented which corrects the frequency of the CW Doppler radar according to the frequency deviation of the return Doppler signal. The circuit used in this version is a phase-locked loop (PLL).

At the point of equilibrium the Doppler signal must have the same frequency as that of the sound pulse. Because of this, the same oscillator was used to produce the sound pulse and the reference signal for the feedback device. The relationship between the speed of sound and the radar frequency is given by the Doppler-Fizeau law:

$$\frac{\Delta\nu}{2\nu} = \frac{C_S}{C} \quad , \tag{7.17}$$

where $\Delta\nu$ = received Doppler-Fizeau frequency, ν = frequency of the emitter, C_S = speed of sound, and C = speed of the electromagnetic wave in the atmosphere. Since C is about 10^6 times faster than C_S, the speed of sound measurements made by RACES are essentially instantaneous.

The time interval between the starting of the sound pulse and the time of measurement gives the height of the measurement:

$$h = \int_{t_o}^{t} C_s \, dt \ . \tag{7.18}$$

The system measures the ratio $\Delta\nu/\nu$ directly and is therefore independent of the phase effect introduced by the low-pass filter of the PLL.

7.3.5 Description of the System

7.3.5.1 UHF transmitter

The UHF transmitter (Fig. 7.5) consists of a low-noise voltage-controlled oscillator (0.66 - 0.78 GHz) followed by a power amplifier (1 W) and a four-Yagi, 26-element, wide-band antenna system. The opening angle of the antenna is about 20°.

7.3.5.2 UHF receiver

The UHF receiver consists of an array of five 26-element (15.5-dB Yagi) antennas, electronically connected to the receiver. The purpose of the array is to compensate for the effect of sound pulse displacement by the horizontal wind. The antennas are followed by a 54-dB low-noise UHF preamplifier and the Doppler mixer. For practical reasons only one antenna was used for the Boulder comparisons.

7.3.5.3 LF receiver and converter

The low-frequency receiver consists of a low-noise preamplifier, a gyrator filter with adjustable Q factor from 0 to 1,000, a linear amplifier (0 - 40 dB), a log-amplifier, and a signal shaper circuit. The signal is then transmitted to an adjustable digital divider and to a UHF ratiometer with IEC-Bus interface. The measurement time is 12.5 ms. The measurement interval is 70 ms. This is because it takes about 35 ms to transmit the information to the computer through the IEC-Bus. Consequently, the temperature is measured every 20 m only.

7.4 MEASUREMENT OF THE VERTICAL WIND PROFILE

7.4.1 Theory

The sound pulse propagating vertically in the atmosphere is diffused by the small inhomogeneities of the air. The coefficient of diffusion σ_ϕ depends on the angle of diffusion of the thermal and wind turbulence according to the following expression:

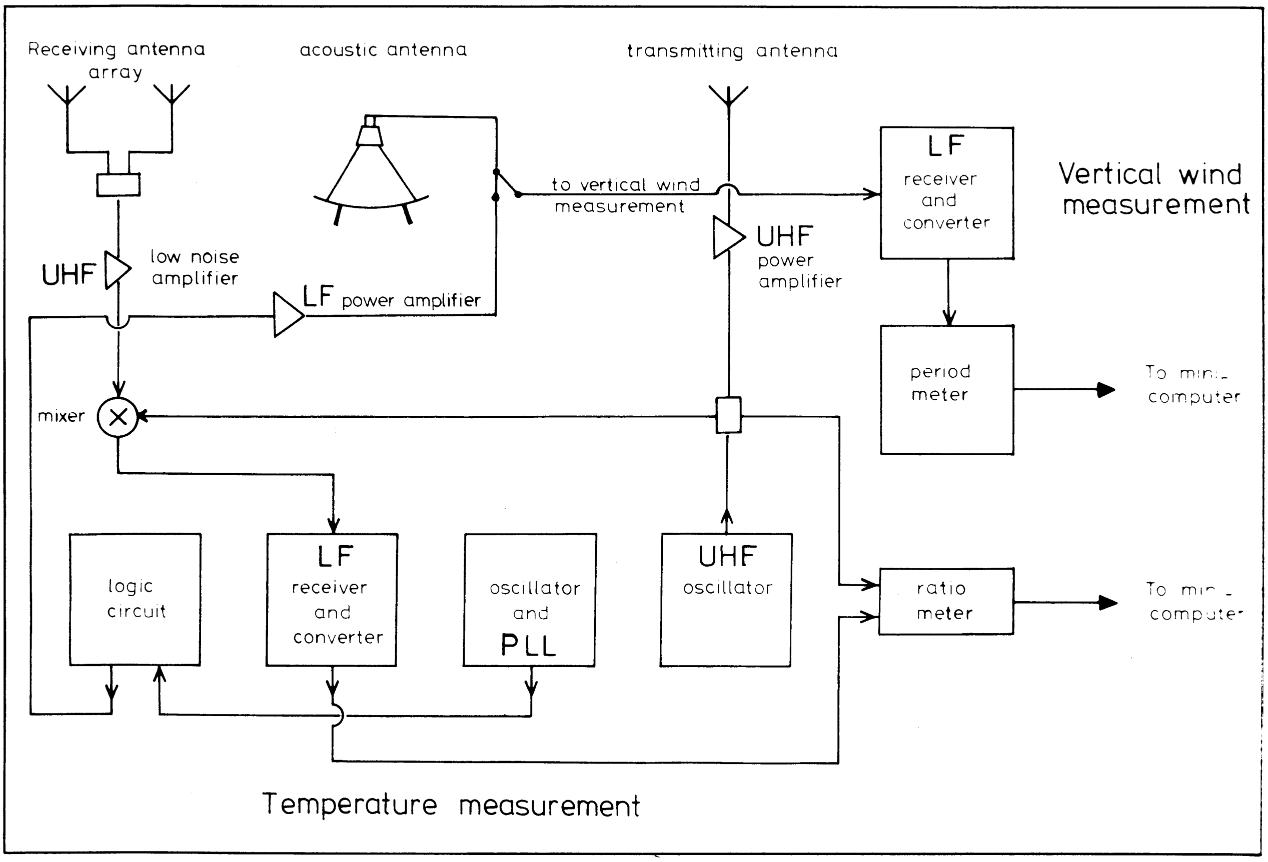


Figure 7.5. Block diagram of RACES system.

$$\sigma_\phi = 0.03\ k^{1/3} \cos^2 \phi \left(\frac{C_v^2}{v^2} \cos^2 \frac{\phi}{2} + 0.13 \frac{C_T^2}{T^2}\right) \left(\sin \frac{\phi}{2}\right)^{-11/3} , \qquad (7.19)$$

where k = wave number of the sound, ϕ = diffusion angle, C_v = wind turbulence parameter, v = wind speed, C_T = thermal turbulence parameter, and T = temperature.

This law assumes that the wind turbulence and the thermal turbulence have a Kolmogorov's spectrum. A small part of the sound is back-scattered and reaches the acoustic antenna.

For $\phi = \pi$,

$$\sigma_\phi = 0.0039\ k^{1/3} \frac{C_T^2}{T^2} .$$

The sound is back-scattered only by the thermal inhomogeneities of the atmosphere.

7.4.2 Principle of the Wind Measurement

The small-scale thermal inhomogeneities in the atmosphere have an average general movement u_3 in relation to the receiver's antenna. In this case, according to the Doppler law, the back-scattered sound that reaches the acoustic antennas has a frequency slightly different from that of the emitting antenna.

$$\frac{\Delta f}{2f} = \frac{u_3}{C_s} , \qquad (7.20)$$

where Δf = Doppler frequency, f = frequency of the pulse of sound, u_3 = vertical wind, and C_s = speed of the sound in the atmosphere. C_s is measured by the temperature-measuring part of the RACES system.

Because the Fourier transform needs a stationary signal, the frequency measurement of the received signal was not made with a spectrum analyzer. Instead the average period of the signal was directly measured with a zero-crossing technique. The average is taken on 20 periods of the signal.

7.4.3 LF Receiver and Converter

The acoustic antenna signal is switched (a few milliseconds after the emission of the sound pulse) to a low-noise preamplifier, a gyrator filter with adjustable Q factor from 0 to 1000, a linear amplifier (0 - 40 dB), a log amplifier, and a signal shaper circuit. The signal is then transmitted to an adjustable digital divider and to a periodmeter (interval timer) with an IEC-Bus interface. The minimum time interval of the periodmeter is 0.1 μs. The timing considerations are exactly the same as in the temperature measurements. Consequently the vertical wind is measured approximately every 10 m.

7.5 DATA ACQUISITION AND PROCESSING

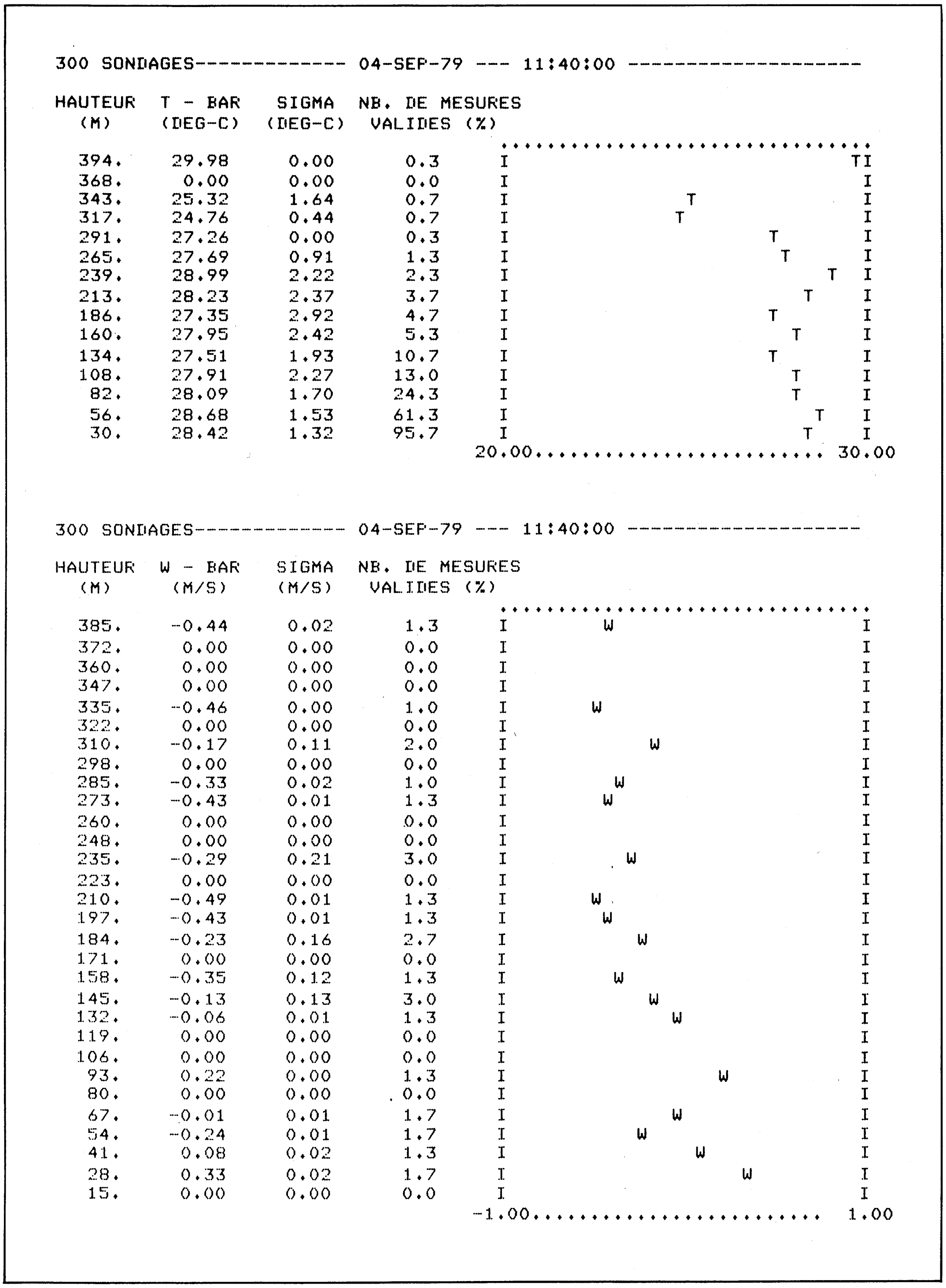
The RACES system uses a PDP11-03 16-bit minicomputer with 32-k-word RAM memory, display, an LA 35 printer, and an RX02 floppy disk driver with two single-side, double-density disk drivers.

The operator can choose the time interval from 0 (immediate) to 60 minutes, the number of soundings for averages from 0 to 400, and whether to print all the data, the selected data, or the statistical data, or to keep the data on file in a second floppy disk. A sample of the output is shown in Fig. 7.6.

7.6 PURPOSE OF THE COMPARISONS

Our purpose in BLIE will be to compare the measurements made by the RACES system with those made by the conventional tower instruments and by other remote sensing systems. It must, however, be considered that the RACES system has a sampling volume much larger and a sampling time much shorter than those of conventional instruments on the tower.

The range of the RACES system used will be rather low (∿150 m) because the high-level version is too bulky and too heavy to be transported easily overseas. Another reason for the low range will be that we will have only one UHF receiving antenna instead of five.



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300 SONDAGES------------- 04-SEP-79 --- 11:40:00 --------------------

HAUTEUR  T - BAR   SIGMA  NB. DE MESURES
  (M)    (DEG-C)  (DEG-C)  VALIDES (%)
                                      ................................
  394.    29.98     0.00      0.3     I                             TI
  368.     0.00     0.00      0.0     I                              I
  343.    25.32     1.64      0.7     I               T              I
  317.    24.76     0.44      0.7     I              T               I
  291.    27.26     0.00      0.3     I                      T       I
  265.    27.69     0.91      1.3     I                       T      I
  239.    28.99     2.22      2.3     I                           T  I
  213.    28.23     2.37      3.7     I                         T    I
  186.    27.35     2.92      4.7     I                      T       I
  160.    27.95     2.42      5.3     I                        T     I
  134.    27.51     1.93     10.7     I                      T       I
  108.    27.91     2.27     13.0     I                       T      I
   82.    28.09     1.70     24.3     I                        T     I
   56.    28.68     1.53     61.3     I                          T   I
   30.    28.42     1.32     95.7     I                         T    I
                                   20.00.......................... 30.00


300 SONDAGES------------- 04-SEP-79 --- 11:40:00 --------------------

HAUTEUR  W - BAR   SIGMA  NB. DE MESURES
  (M)      (M/S)     (M/S)   VALIDES (%)
                                      ................................
  385.    -0.44     0.02      1.3     I        W                     I
  372.     0.00     0.00      0.0     I                              I
  360.     0.00     0.00      0.0     I                              I
  347.     0.00     0.00      0.0     I                              I
  335.    -0.46     0.00      1.0     I       W                      I
  322.     0.00     0.00      0.0     I                              I
  310.    -0.17     0.11      2.0     I            W                 I
  298.     0.00     0.00      0.0     I                              I
  285.    -0.33     0.02      1.0     I         W                    I
  273.    -0.43     0.01      1.3     I        W                     I
  260.     0.00     0.00      0.0     I                              I
  248.     0.00     0.00      0.0     I                              I
  235.    -0.29     0.21      3.0     I          W                   I
  223.     0.00     0.00      0.0     I                              I
  210.    -0.49     0.01      1.3     I       W                      I
  197.    -0.43     0.01      1.3     I        W                     I
  184.    -0.23     0.16      2.7     I           W                  I
  171.     0.00     0.00      0.0     I                              I
  158.    -0.35     0.12      1.3     I         W                    I
  145.    -0.13     0.13      3.0     I            W                 I
  132.    -0.06     0.01      1.3     I              W               I
  119.     0.00     0.00      0.0     I                              I
  106.     0.00     0.00      0.0     I                              I
   93.     0.22     0.00      1.3     I                  W           I
   80.     0.00     0.00      0.0     I                              I
   67.    -0.01     0.01      1.7     I              W               I
   54.    -0.24     0.01      1.7     I           W                  I
   41.     0.08     0.02      1.3     I                W             I
   28.     0.33     0.02      1.7     I                    W         I
   15.     0.00     0.00      0.0     I                              I
                                   -1.00..........................  1.00
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Figure 7.6. Sample output sheet.

Commentaire de l'auteur non publié: ces résultats montrent clairement l'inversion de température qui culmine vers 240m. Cette inversion a aussi été mesurée par d'autres participants à l'expérimentation.