Engineering Report on a Dropsonde for Measuring Vertical Wind Velocity in Thunderstorms

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R. H. Bushnell
V. M. Glover
R. D. Chu
FOREWORD

This paper is an engineering report on the NCAR dropsonde design. Work started in 1962 when Dr. P. Squires laid plans for doing a most difficult thing, making measurements inside severe thunderstorms with primary effort on mapping the vertical wind field. This effort could be undertaken upon the creation of the National Center for Atmospheric Research to do atmospheric research that could not reasonably be conducted by the universities or government agencies.

Engineering work on the NCAR dropsonde was dominated by two things; the need for making many measurements simultaneously (the system handles 10 dropsondes at once) and the need for good pressure measurements. The pressure measurements are limited, not by the special environment of the sonde in a thunderstorm, but by the hysteresis of the metal capsules used in the pressure transducers. By using an additional capsule in a redundant arrangement we have more or less avoided this problem. The maximum distance at which the horizontal position measuring system can be used is barely adequate, as expected, in that the technology for making a small receiver is limited.

The dropsondes were first used in June 1966 in Northeast Colorado. A full series of measurements was made in 1967 when 55 dropsondes were dropped at 9 km from a propeller-driven airplane. In 1970 sixty and in 1972 fifty were dropped at 14 km from the NCAR Sabreliner jet airplane.

Recent improvements, including digitizing of the telemetered data, were made by Jack L. Fink.

Robert H. Bushnell
Boulder, Colorado

9 February 1973
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I. INTRODUCTION

This report describes a special dropsonde for measuring and mapping the vertical wind inside thunderstorms. The significance of the vertical wind is shown in the Thunderstorm Project description of thunderstorms [1, p. 682] in which the three stages of a thunderstorm's life are defined solely by the presence of updrafts and downdrafts. Battan [2] concludes "that those properties of the atmosphere which govern the characteristics of the updrafts are the ones which chiefly control the quantity of rainfall and lightning." Mason [3, p. 257] tells us "Hailstones are believed to occur in clouds containing particularly strong updraughts, . . ." 

The lack of measurements of this important wind is revealed in the literature. "If we knew the distribution of updraft velocity . . ." [4, p. 9], and ". . . we may expect that the updraft velocities inside the column . . ." [4, p. 13]. "Although direct observations are lacking, it is likely that in general the main updraft (whether continuous or considered as the "average" motion) in large storms is inclined in an upshear rather than a downshear direction" [5, p. 51], and ". . . the downdraft is drawn as continuous from cloud top to base for the sake of discussion, though there are inadequate observations . . ." [5, p. 52].

We can infer the speed of the vertical wind from the literature. Foster and Bates [6] assumed the "updraft velocity prevailing in the zone of hail formation is the velocity required to just sustain the fully grown hailstone." Ludlam [7, p. 697] says "In the more nearly adiabatic motion the buoyancy increases and updraft speeds of 20 m sec\(^{-1}\) and exceptionally, more than 40 m sec\(^{-1}\) are attained. These more intense cumulonimbus seem to depend upon the production of a downdraft chilled by the partial evaporation of rain . . ." Accordingly both up- and downdrafts of tens of meters per second can be expected.

The vertical wind in a thunderstorm is not easily measured. If an airplane is used it is limited to operations in smaller storms or in parts of severe storms where it is safe to fly. Small thunderstorms
have been measured this way [8]. Balloons have been used in the Soviet Union [9].

Doppler radar can give measurements over most of a storm, wherever there is rain, snow, or hail. Vertical speed is determined by observing the vertical speed of the reflecting precipitation particles and then applying a correction for the fall speed of these particles. Unfortunately, even if the smallest downward speed observed, which is from the particles with the smallest fall speed, is used there is still doubt about the amount of correction to make [10]. Thus the accuracy of doppler radar is limited.

Of the possible ways of measuring vertical wind, we have chosen to drop instruments from an airplane into the tops of thunderstorms. As these instruments fall, they measure static and dynamic pressures and radio the data to the ground. As many as ten can be dropped together from an airplane above a storm. These lightweight, rapidly falling instruments descend through a storm fast enough to give a moderately good map of the internal winds without being too much at the mercy of the storm. In addition to vertical wind mapping the design provides an instrument body which can carry other measurement devices into storms.

Based on published measurements [10] we set down the following requirements that must be met by this system to give a useful map of the winds inside a thunderstorm. The measurements should be spaced 100 to 500 m horizontally and 100 m vertically. The standard error of the vertical wind measure should be less than 0.5 m/s. There should be as many as ten sondes measuring simultaneously. The fall speed should average about 30 m/s. The systems should function for sondes as far as 50 km from the ground stations with provision for operation up to 100 km. Because ice will collect on the body its drag cannot be assumed and accordingly the airspeed of the sonde must be measured. The standard error of position measurement should be less than 10 m.
II. SYSTEM DESCRIPTION

A. FORM

In the system we have designed, the measurement of vertical wind is done as follows. From measured static (barometric) pressure, height is calculated by reference to a pressure and temperature sounding made outside the thunderstorm. This external sounding is made either by radiosonde or, after the drop, by the airplane which dropped the sondes. Geometric fall speed is found from the numerical time derivative of this height. Vertical airspeed is calculated from measured dynamic pressure. The vertical wind speed is calculated by subtracting the geometric fall speed from the airspeed. In this we assume that the pressure surfaces inside a storm deviate less than 10 m from their heights outside of the storm where they are measured from an airplane or radiosonde. This assumption of course, can be questioned [111] but now we can do nothing about it.

Accuracy is determined largely by the ability of the transducers to withstand aging, vibration, and acceleration.

Three pressure transducers measure static pressure p, dynamic pressure q, and rate of change of static pressure divided by static pressure. We name these p, q and p-dot respectively. The p-dot signal is used to calculate the fluctuating part of the vertical speed. This has better noise properties than have the values obtained from the numerical derivative of barometric pressure. The outputs from the pressure transducers along with temperatures and references are telemetered to the ground and recorded on magnetic tape. Following the flight the signals are digitized and put on another magnetic tape. Vertical wind is subsequently calculated by a computer which introduces the individual calibrations of each of the transducers.

Horizontal positions of all ten dropsondes are obtained simultaneously with a tracker which makes measurements by a transponder method using two ground stations. The measurements give slant distances from
the stations. These are converted to horizontal position with the use
of height previously calculated in finding vertical speed.

The dropsonde, shown in flight configuration in Fig. 1, has a
cylindrical body containing batteries, pressure transducers, a telemetering subcarrier oscillator, a telemetering transmitter, and a tracking receiver. The fully assembled dropsonde weighs 2400 g and is 112 cm long. All circuits use solid state devices. A heated pitot-static tube extends out the bottom. The body is controlled in flight by a drag device which limits the speed and which points the sonde into the relative wind. The speed is reduced for landing by a parachute so that safety is insured and damage to the dropsondes is small. The dropsondes are recovered, renovated and reused.

The master ground station (Fig. 2) has the antenna, receivers, demodulating circuits and tape recorder for collecting the telemetered data. The two units on the left are the main parts of the tracker.

B. PRESSURE MEASUREMENT

Following the requirements of Section I we have chosen the measuring method and telemeter design shown in the block diagram (Fig. 3). There are the three pressure transducers. One, connected to the pitot-static tube, senses static (barometric) pressure p. Another transducer, connected to the downward-pointing pitot tube, senses dynamic pressure q. The third transducer senses (dp/dt)/p.

The pressures are transduced into electrical signals by pressure capsules and linear variable differential transformers (LVDT). These signals are selected in sequence by a commutator and put on a subcarrier which in turn phase modulates a 403 MHz transmitter which sends them to a ground station. The signals telemetered to the ground are:

\[
\begin{align*}
\text{A low reference (zero)} & \quad Z \\
\text{A high reference (reference)} & \quad R \\
\text{Tracker received signal level} & \quad S \\
\text{Air temperature} & \quad T_a \\
\text{Temperature of the barometric pressure transducer} & \quad T_p
\end{align*}
\]
Temperature of the p-dot transducer $T_p$
Temperature of the q transducer $T_q$
Barometric pressure $p$
p-dot $\dot{p}$
Dynamic pressure $q$
Battery voltage $B$
A repetition of the low reference $Z$

The signals from as many as ten dropsondes, each on its own frequency near 403 MHz, are received simultaneously on the ground by one antenna and converter. They are separated, using 10 second-intermediate frequencies, and put on ten channels of magnetic tape. Later the tape is played to recover the signals. The subcarrier frequencies are then, each in turn, converted to dc voltages which are measured and digitized for computer use.

C. POSITION MEASUREMENT

The horizontal position of the sondes is measured by an electronic tracker. The tracker must follow ten sondes at once when the sondes are inside the high water regions of a thunderstorm. Ordinary radar tracking of even one object cannot easily be done in such conditions, much less of ten at once. Therefore, we use a transponder method of distance measurement and operate at frequencies low enough not to be attenuated by the storm. The measurement of position by the use of direction of arrival of the radio signals is not used because of the large antenna required and because of the difficulty of moving it to keep track of ten sondes. Furthermore, angles may be distorted by refraction in the humidity changes near a storm.

The transponder method measures distance only. We use two transmitters on the ground to give two coordinates. Tracking is done (Fig. 4) with a short group of ten interrogation pulses with a 2-km wavelength, a frequency of 75 kHz, sent repeatedly from the ground 500 times per second on 1689 MHz. This pulsed signal is sent from the ground to all ten sondes and is returned by frequency modulation on the ten separate
telemetering radio frequencies near 403 MHz. All 20 of the tracking signals are subsequently tracked one at a time. Distance is calculated from the time delay of the ten-pulse group.

Figure 5 shows the two ground stations. The second station can be located up to 30 km from the master. It sends pulses the same as the master station but delayed so the pulses do not overlap in the receivers. The timing is controlled by receiving the pulses sent out by the master station. Pulses, received from both stations by the dropsondes, are returned to the master station. The time delays measured at the master station for the second-station signals represent the sums of the distances from the master to the second-station, from the second-station to the sondes, and from the sondes back to the master. From such a measurement an ellipsoidal position surface can be calculated. For the master pulses, of course, a spherical position surface is calculated. Introducing the height obtained from the pressure measurement there are two positions, to the right and to the left of the line between the stations, which satisfy the measurements. The ambiguity between these two is resolved by knowing generally where the sondes have been dropped. Accordingly sondes are not dropped close to the line where the ambiguity cannot be resolved. The tracking system is discussed in detail in Section VII.E.

D. ERROR TABLES

In the design of this dropsonde system it was necessary to consider the contributions to the measurement errors. The significant sources are listed in Tables 1 through 4 along with the values which meet the requirements given in Section I. The tables give the performance achieved except as noted below for Table 4. The values are based on measurements and calculations. They are, however, estimates in that spectral data were not available; spectra of the error contributors were not integrated to find the variances. In all of the error tables the contributions are added using the sum of the variances.
Table 1 shows the errors in measuring static pressure which is used in computing geometric speed \( z \) and in finding height.

Table 2 shows the errors in the p-dot measurement while Table 3 shows the errors in measuring air speed \( V \).

In Table 4 distributions are given for the errors in the tracker. The 10-m column shows the desired levels. The 50-m column shows the performance achieved. The large error due to signal level changes in the sonde receiver results from nonlinearities in the crystal-video receiver (see Section VI.B.). We have not yet been able to improve this performance in a receiver weighing only 200 g.
Table 1. Error Table for Static Pressure p
Contributors to the error in measuring p and the standard
error allowed in each.

Error allowed for speed $\dot{z}$: 0.4 m/s
Assume 30 m/s, points 2500 m apart.
$\sigma = 2500 \, \frac{0.4}{30} = 33 \, \text{m (1.6 mb)}$ allowed for the
effect of both end points.
$\sigma = \frac{33}{\sqrt{2}} = 23 \, \text{m (1.1 mb)}$ allowed for the
effect of one end point.

Error allowed for height: 20 m (1.0 mb)

<table>
<thead>
<tr>
<th>Item</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Port exposure</td>
<td>0.1 mb</td>
</tr>
<tr>
<td>2. Pipe lag</td>
<td>0.05</td>
</tr>
<tr>
<td>3. Transducer</td>
<td>0.8</td>
</tr>
<tr>
<td>4. Transducer acceleration</td>
<td>0.2</td>
</tr>
<tr>
<td>5. Subcarrier</td>
<td>0.2</td>
</tr>
<tr>
<td>6. Transmission noise</td>
<td>0.01</td>
</tr>
<tr>
<td>7. Tape recorder</td>
<td>0.01</td>
</tr>
<tr>
<td>8. Digitizing quantum</td>
<td>0.2</td>
</tr>
<tr>
<td>9. Calibration</td>
<td>0.4</td>
</tr>
</tbody>
</table>

$\sigma = 0.97 \, \text{mb}$
Table 2. p-dot Error Table

Contributors to the error in measuring $\dot{z}$ with the p-dot transducer and the standard errors allowed in each.

<table>
<thead>
<tr>
<th>Item</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Port exposure</td>
<td>$10 \times 10^{-6}$/s</td>
</tr>
<tr>
<td>2. Transducer temperature</td>
<td>12</td>
</tr>
<tr>
<td>3. Transducer hysteresis</td>
<td>24</td>
</tr>
<tr>
<td>4. Transducer acceleration</td>
<td>6</td>
</tr>
<tr>
<td>5. Subcarrier</td>
<td>10</td>
</tr>
<tr>
<td>6. Transmission noise</td>
<td>0.2</td>
</tr>
<tr>
<td>7. Tape recorder</td>
<td>0.2</td>
</tr>
<tr>
<td>8. Digitizing quantum</td>
<td>4</td>
</tr>
<tr>
<td>9. Calibration</td>
<td>20</td>
</tr>
<tr>
<td>10. Environmental temperature</td>
<td>15</td>
</tr>
</tbody>
</table>

$\sigma = 40 \times 10^{-6}$/s
Table 3. Error Table for Dynamic Pressure $q$
Contributors to the error in measuring air speed
and the standard error allowed in each.

\[ \rho = 0.5 \text{ kg/m}^3 \quad q = \frac{1}{2} \rho v^2 \]

\[ q_{\text{max}} = 6.20 \text{ mb} \]

\[ \frac{\partial q}{\partial v} = \rho v = 0.5 \frac{\text{kg}}{\text{m}^3} \times 30 \frac{\text{m}}{\text{s}} = 0.15 \frac{\text{mb}}{\text{m/s}} \]

Error allowed in $V$: 0.3 m/s

Error allowed in $q$: $0.15 \frac{\text{mb}}{\text{m/s}} \times 0.3 \text{ m/s} = 0.45 \mu \text{b}$

<table>
<thead>
<tr>
<th>Item</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Both port exposures</td>
<td>20 $\mu$</td>
</tr>
<tr>
<td>2. Pipe lag</td>
<td>1</td>
</tr>
<tr>
<td>3. Transducer temperature</td>
<td>14</td>
</tr>
<tr>
<td>4. Transducer hysteresis</td>
<td>10</td>
</tr>
<tr>
<td>5. Transducer acceleration</td>
<td>16</td>
</tr>
<tr>
<td>6. Transducer time stability</td>
<td>27</td>
</tr>
<tr>
<td>7. Subcarrier</td>
<td>10</td>
</tr>
<tr>
<td>8. Transmission noise</td>
<td>0.1</td>
</tr>
<tr>
<td>9. Tape recorder</td>
<td>0.1</td>
</tr>
<tr>
<td>10. Digitizing quantum</td>
<td>1.6</td>
</tr>
<tr>
<td>11. Calibration pressure reading</td>
<td>5</td>
</tr>
<tr>
<td>12. Calibration subcarrier</td>
<td>6</td>
</tr>
<tr>
<td>13. Calibration</td>
<td>10</td>
</tr>
</tbody>
</table>

\[ 45 \mu \text{b} \]
Table 4. Error Table for the Tracker
Contributors to the error in measuring position
and the standard error allowed in each for
two accuracy levels, 10 m and 50 m.

<table>
<thead>
<tr>
<th>Item</th>
<th>Desired σ</th>
<th>Achieved σ</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. 75 kHz frequency</td>
<td>1 m</td>
<td>1 m</td>
</tr>
<tr>
<td>2. Ground transmitter sync</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>3. 1689 MHz path refractive index</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>4. 403 MHz path refractive index</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>5. Sonde receiver noise</td>
<td>4.5</td>
<td>10</td>
</tr>
<tr>
<td>6. Sonde receiver delay stability, signal level</td>
<td>4.3</td>
<td>40</td>
</tr>
<tr>
<td>7. Sonde receiver delay stability, temperature</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>8. Sonde receiver delay stability, RFI</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>9. Sonde transmitter intermodulation</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>10. Ground receiver delay stability</td>
<td>1.7</td>
<td>4</td>
</tr>
<tr>
<td>11. Tape recorder</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>12. Phase tracker drift</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>13. Phase tracker signal level</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>14. Tracker velocity error</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>15. Tracker potentiometer</td>
<td>1.7</td>
<td>1.7</td>
</tr>
<tr>
<td>16. Digitizing quantum</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>17. Zero calibration</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>18. Sync delay stability</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>19. Sync path Δn = 30</td>
<td>1.5</td>
<td>1.5</td>
</tr>
</tbody>
</table>

σ = 10.0 m 49.3 m
III. AERODYNAMICS

In measurement flight the sonde must line up with the relative wind and fall without "lift," that is, with no aerodynamic forces perpendicular to the relative wind. It should not oscillate. We accomplish this stability by using a so-called disk-and-fins drag form made of cloth and fiber glass struts. The top is as flat as a cloth structure allows. Four triangular fins extend from four struts down to the body. This form has no oscillating responses to rotational or translational disturbances about any axis. Response time constants are on the order of 1.5 s. With a top area of 0.21 m$^2$ and a mass of 2.4 kg the mean fall speed is about 21 m/s. The fall time is accordingly 10 to 15 min. While the desired fall speed is higher we have not yet found it necessary to change from an early design of the top area.

It is necessary to measure air speed for two reasons. The first reason is that the drag coefficient of the dropsonde is not dependably constant. The Reynolds number of the dropsonde is about 500,000 where changes of drag coefficient occur irregularly. Although in a test drop through clear air the drag coefficient changed less than 10% we have no assurance that this is the case under other conditions. The second reason is that the mass of the dropsonde changes as ice and water accumulate. Because this mass is unknown we have no choice but to measure the vertical air speed.

The airplane is traveling about 180 m/s when a sonde is released. If the sonde is not lined up with the relative wind the drag structure will break. Therefore the drag is folded and held closed for 4 s after release to allow the sonde to line up with the wind so that opening stresses are symmetrical and no damage is done.

When the sonde nears the ground a baroswitch electrically releases a parachute. The sonde falls sideways onto the ground at about 3 m/s which minimizes damage to the sonde.
IV. PITOT-STATIC TUBE DESIGN

The pitot-static tube must be kept free of ice and water because a small amount of ice or water near the tip will cause serious errors. Accordingly the tube is heated electrically to nearly 100°C. Only a small surface area can be heated because the energy supply in the sonde is small. The tube, as a result, must be small. We have made it 6.4 mm in diameter extending out 139 mm from the bottom of the sonde body. The six static holes, 1.2 mm in diameter, are large enough to keep water films from blocking them.

The heat lost by the pitot-static tube was estimated assuming typical cloud conditions for temperature, density, and liquid water content. More than 75% of the heat is lost in evaporating impinging water droplets and ice particles. The estimated value, 16 W, was used in the fabrication of a pitot-static tube for testing in a wind tunnel.

Wind tunnel tests of the heater design were made at 30 m/s, -10°C, and with a liquid water content of 6 g/m³. Figure 6 shows the vertical wind tunnel used. Water was sprayed in near the bottom to simulate clouds. Accumulation of 1 cm of ice on the body behind the tube changed the observed static pressure by about 0.01 mb, which is well below the value permitted (Table 1). The exterior of the pitot-static tube stayed free of water during all tests but the dynamic pressure line became obstructed with ice after 9 min of exposure to icing conditions. It is unlikely that prolonged severe conditions like those experienced in the wind tunnel will be encountered in actual clouds and obstruction of the pitot-static tube is unlikely. We accepted 16 W for the design.

The pressure field around the dropsonde is distorted by the motion of the dropsonde through the air and, because the pitot tube is short, the static ports must be located with care. The body increases the pressure along the pitot-static tube while the tube itself causes the pressure to decrease just behind the tip. A point was found rather near the tip, 16.7 mm from the end, where these positive and negative
pressures cancel to give a true static pressure. This position is distinctly closer to the end than for a simple pitot-static tube.

Because the dropsonde drag device provides good aerodynamic stability during a flight it was not necessary to minimize pitot-static tube yaw effects by the use of an elaborate tip shape. The tip design is therefore simple, having a straight taper of 30° for about 1.5 tube diameters and slightly rounded corners where the tapering meets the outside wall of the tube. The simplicity of the design makes it unnecessary to calibrate each pitot-static tube separately.

Figure 7 shows the angular response of such a shape [12] for the measurement of dynamic pressure. The response for static pressure smoothly changes with angle [12] and at 20° is 0.08 mb less than the actual static pressure. This small value at the large angle of 20° puts the standard error within the allowance of 0.10 mb for port exposure in Table 1.
V. TRANSDUCERS

The dropsonde has two types of transducers: pressure-sensing capsules and temperature-sensing thermistors. Both devices have electrical analog outputs. They are excited by a 17 kHz Wien-bridge oscillator of low output impedance. This oscillator drives all transducers and internal zero and reference circuits thus providing a common driving source for all measuring and internal calibration circuits.

A. TRANSDUCER FORM

1. Pressure Transducers

The three pressure transducers in the dropsonde; p, p-dot, and q (see II-B) function alike except for physical size and pressure source. A pressure-sensitive capsule is mounted in a rigid frame which also supports a miniature linear variable differential transformer (LVDT). The free end of the capsule carries the transformer core. The linear displacement of the core produces signals in the output windings of the LVDT.

The LVDT, which is identical in all three transducers, has a linear range of 1270 µm (0.050 in.) on each side of the null point. Motion is used on only one side of the null point. The capsules have a hysteresis specification of 0.25% of full scale. We typically find half that, probably because we exercise the capsules 100 times just before calibration.

2. p Transducer

This transducer uses an evacuated and sealed aneroid capsule manufactured by the Bristol Company (part number A1309-1) with maximum O.D. of 41.2 mm. It has a spring rate of 0.92 µm/mb and, for a design range of 850 mb, has a total travel of 780 µm. With the low-end-of-range set 180 µm from the LVDT null point, 1090 µm of range is available assuring linear operation. The support frame is milled from extruded 6063-T5 aluminum channel. Then it is heat treated at 190°C for 4 hr for dimensional stability.
The p transducer is in the lower of two leak-proof chambers and shares this chamber with the q transducer. A connection tube of 3.18 mm I.D. Tygon hose, 18 mm long, makes a low-restriction connection to the static line of the pitot tube. The Tygon tube connection is an effective mechanical decoupling which prevents stresses on the chambers and transducer support during handling and ground impact after flight.

3. q Transducer

The q and p-dot transducers have identical capsules and frame structures. The capsule (Bristol part A3458) has a maximum O.D. of 79.4 mm which determines the diameter of the whole sonde. With a spring rate of 25.4 μm/mb and a design range of 6.2 mb the total travel is 157 μm. The frame is milled from extruded aluminum channel and heat treated for dimensional stability.

Pitot dynamic pressure is applied to the inside of the q capsule and static pressure exists on the outside, the capsule being in the lower sealed chamber.

The time constant for the p and q transducers is 40 ms at 800 mb pressure.

4. p-dot Transducer

The p-dot transducer uses a capsule and frame identical to those of the q transducer. It is mounted in the upper sealed chamber which is connected to the lower chamber by a capillary tube 18.5 mm long, with a 403 μm I.D. which produces a viscous pressure drop. The inside of the capsule is connected to the static pressure of the lower chamber. Thus a differential pressure is applied across the capsule. As a pressure sensor this transducer has an operating range of -4.18 to +12.55 mb resulting in a core travel of 426 μm. The time constant is 2 s at 800 mb static pressure, 8 s at 200 mb.
5. Temperature Transducers

Four bead thermistors, one for each capsule and one for air temperature, are used to sense temperatures. Each is a VECO 31A2 glass-coated bead having a resistance of 1000 ohms ±20% at 25°C. The associated series and shunt resistors were selected so that the maximum sensitivity occurs at 9°C with asymptotes at the high and low extremes.

The thermistors for the p and p-dot transducers are mounted on the frames, near the LVDTs. However, they are situated at least 4 mm away from any surfaces and stand on their own leads. They sense chamber temperatures and provide data for p-dot corrections.

The thermistor of the q transducer is mounted on the frame near the LVDT and is encapsulated in epoxy. It senses structure temperature and provides the information necessary to correct for temperature in the LVDT, frame, and capsule.

The fourth thermistor, situated on the top plate of the dropsonde is exposed to the air directly below the drag structure. In this position, it does not accurately measure air temperature. Because any simple exposure will have serious trouble with supercooled cloud droplets, we have made no further effort at measuring air temperature.

B. TRANSDUCER ALGEBRA

1. Ratio, Linearity, Temperature

The dropsonde transducers and their associated circuits are subject to deviations which must be removed by compensation techniques or corrected algebraically. Effects which result from changes in transducer excitation voltage or changes in the transfer characteristics of the telemetering circuits are compensated by using reference signals from fixed resistors in a divider excited by 17 kHz from the excitation oscillator (see Fig. 8). If we let X be the rectifier output (see Fig. 3) when the commutator has selected one of the pressure transducers, R be the rectifier output when the reference has been selected, and Z
be its output when zero has been selected, we can write the following expressions:

\[ X = EgnC \]

\[ R = \frac{Eg(R_4 + R_5)}{(R_3 + R_4 + R_5)} = Egk_1 \]

\[ Z = \frac{EgR_5}{(R_3 + R_4 + R_5)} = Egk_2 \]

where \( E \) is the excitation oscillator output voltage, \( g \) is the rectifier scale factor, \( n \) is the LVDT scale factor, \( C \) is the LVDT core position, and \( R_3, R_4 \) and \( R_5 \) are the values of the fixed resistors in the divider. Now if we define a quantity

\[ \text{Ratio} = \frac{X-Z}{R-Z} \]

and substitute for \( X, R, \) and \( Z \), the following expression is obtained:

\[ \text{Ratio} = \frac{EgnC - Egk_2}{Egk_1 - Egk_2} = \frac{nC - k_2}{k_1 - k_2} \]

We now have a quantity, \( \text{Ratio} \), which is independent of transducer excitation voltage and rectifier scale factor and dependent only upon LVDT scale factor \( n \) and core position \( C \). The core position of course is dependent upon the transducer capsule deflection.

\( \text{Ratio} \) is not a linear function of transducer input. Deviations from linearity exist because transducer capsule deflection is not a linear function of differential pressure and because rectifier output is not a linear function of LVDT core position. Because of these nonlinear relationships it is helpful to fit a nonlinear curve between calibration points. We have selected a spline function technique which fits a cubic function between adjacent calibration points with the requirement that the first and second derivatives of adjacent cubic expressions be identical. The spline gives better results than a straight-line point-to-point interpolation and avoids discontinuities which might result from fitting higher order curves to several groups of points.
In the discussion below the notation \( f(\text{Ratio}) \) refers to the spline functions.

The temperature sensitivity of the pressure transducers and their associated circuits has been studied in the laboratory under constant and time-varying temperatures. From these experiments we determined static temperature coefficients for each of the three transducers and relationships between the indicated temperature of the transducer temperature sensor and the actual transducer temperature. Signal offsets which result because the transducer temperature differs from the temperature at which it was calibrated are described by a pressure \( \Delta p = K\Delta T \) where \( \Delta p \) is the pressure offset in millibars for the p and q transducers and \( \Delta T \) is the pressure offset per second for the p-dot transducer, \( \Delta T \) is the difference in degrees Celsius between the transducer temperature and its temperature at the time of calibration, and \( K \) is a constant which is dimensionally proper for each of the transducers. When the transducer temperature is not constant the temperature of the temperature sensor differs from the transducer temperature and further algebraic correction is necessary. If we let \( T' \) represent the indicated transducer temperature, \( T \) the actual transducer temperature, and \( \lambda \) the lag coefficient between \( T \) and \( T' \) then we can write the relationship

\[
T' = T + \lambda \frac{dT}{dt}.
\]

\( \lambda \) has a value of 200 s. Because \( T' \) is not a simple function of time numerical integration is used to find \( T \).

In addition to the transducer signal offsets due to structural and circuit temperature changes the p-dot transducer has an offset resulting from air temperature changes within its chamber. Accordingly, the chamber air temperature must be found. It is derived from the same sensor used to find the p-dot transducer temperature. The temperature of the sensor lags that of the chamber air whereas it leads the transducer temperature. The expression which relates the chamber air temperature
The lag coefficient, \( \tau \), has a value of 250 s.

2. p. Transducer

The p transducer is corrected for temperature. The expression for \( p \) is

\[
p = f_p(\text{Ratio}_p) + K_p \Delta T_p
\]

The quantity \( f_p(\text{Ratio}_p) \) is the spline function, \( K_p \) is the p transducer temperature coefficient (-0.56 mb/°C), and \( \Delta T_p \) is the difference, in degrees Celsius, between the transducer temperature and the temperature at which it was calibrated.

3. p-dot Transducer

The p-dot transducer uses the viscous pressure drop across a capillary tube to produce a differential pressure across its capsule. If the flow through the capillary tube is assumed to be laminar, the differential pressure is related to \( \dot{p}/p \) by the following expression [13].

\[
\frac{\dot{p}}{p} = \frac{1}{p} \frac{dp}{dt} = \left(1 - \frac{\Delta p}{p}\right) \left(\frac{\pi r^4 \Delta p}{8 \mu V_c L} + \frac{1}{p - \Delta p} \frac{d\Delta p}{dt} - \frac{1}{V_c} \frac{dV}{dt} + \frac{1}{T_c} \frac{dT}{dt}\right)
\]

where \( p \) is atmospheric pressure, \( \Delta p \) is the pressure across the capillary (and the transducer capsule), \( r \) is the inside radius of the capillary, \( L \) is the length of the capillary, \( \mu \) is the dynamic viscosity of the air, \( V_c \) is the volume of the transducer chamber, and \( T_c \) is the temperature of the air inside the transducer chamber.

The volume of the transducer chamber changes slightly with changes in \( \Delta p \). While this volume change is small and can be ignored in the first term of the right-hand factor its time derivative produces a significant
correction to $\dot{p}/p$. Accordingly the term $-(dV_c/dt)/V_c$ is replaced by $K_s \Delta p/dt$ where $K_s = 0.000413$.

The quantities $r$, $V_c$, and $L$ are not known for each p-dot transducer and in addition $\Delta p$ and $\mu$ are air temperature dependent. Calibration of the p-dot transducer eliminates the need for measuring $r$, $V_c$, and $L$ by defining $f_p(Ratio_p)$ in terms of these quantities. Thus

$$\frac{\pi r^4 \Delta p}{8\mu V_c L} = f_p(Ratio_p) .$$

Here $\mu_o$ is the air viscosity at the time of calibration. The relationship must be modified to be useful at temperatures different from the calibration temperature. If we multiply both sides of the definition above by $\mu_o/\mu$ and replace $\mu$ on the right hand side by $\mu_o (1+\alpha \Delta T)$ where $\alpha$ is the viscosity temperature coefficient and $\Delta T$ is the difference in degrees Celsius, between the transducer chamber air temperature and the air temperature at the time of calibration we get

$$\frac{\pi r^4 \Delta p}{8\mu V_c L} = \frac{1}{1+\alpha \Delta T} f_p(Ratio_p) .$$

When the transducer temperature correction is applied to this relationship we get

$$\frac{\pi r^4 \Delta p}{8\mu V_c L} = \frac{1}{1+\alpha \Delta T} f_p(Ratio_p) + K_p \Delta T,$$

where $\alpha$ has a value of $2.56 \times 10^{-3}$ deg$^{-1}$, $K_p$ is $5.2 \times 10^{-6}$ s$^{-1}$ deg$^{-1}$ and $\Delta T_p$ is the difference, in degrees Celsius, between the transducer temperature and the temperature at which it was calibrated. The final expression for $\dot{p}/p$ is

$$\dot{\frac{p}{p}} = \left(1 - \frac{\Delta p}{p}\right) \left(\frac{f_p(Ratio_p)}{1+\alpha \Delta T_p} + K_p \Delta T_p + \left(\frac{1}{p - \Delta p}\right) \frac{d\Delta p}{dp} + \frac{1}{T_p} \frac{dT_p}{dt}\right).$$
In addition to Ratio, the variable $\Delta p$ appears. Because the influence of $\Delta p$ is small and because the capsule deflection is approximately proportional to $\Delta p$, it is calculated from the crude pressure calibration made at the time of manufacture. No temperature correction is made. In fact, the worst case exists for small $p$ and then the error in $p/p$ is only a few parts per thousand.

4. q Transducer

The only offset for which the q transducer is corrected is that caused by transducer temperature changes. The q transducer temperature coefficient is $K_q = 0.0047 \text{ mb/°C}$. The complete expression for q is

$$q = f(Ratio_q) + K_q \Delta T_q$$

where $\Delta T_q$ is the difference, in degrees Celsius, between the temperature of the transducer and the temperature at which it was calibrated.

5. Temperature Transducers

The dropsonde has four identical thermistor circuits, each having a shunt and a series resistor. These two resistors modify the temperature response so that it is nearly linear in the primary range of interest and compressed at the high and low extremes (Fig. 9).

The thermistor has a temperature response given by Becker et al. [14].

$$R = kT^{-s}e^{\beta/T}$$

where $R$ is the thermistor resistance at absolute temperature $T$. The quantities $\beta$ and $s$ are constants which are determined from data supplied by the thermistor manufacturer. The other constant $k$ is found by a measurement on the thermistor at room temperature. The most commonly used thermistor equation does not have $T^s$ in the denominator and is useful over small temperature ranges. However for the ranges over which the dropsonde is expected to measure we must account for an additional small
temperature dependence by including $T^s$ in the expression. The values of $s$ and $\beta$ are 1.6 and 2820 respectively.

In Fig. 8 a typical thermistor circuit is shown along with the reference and zero divider. The algebra for the circuit in Fig. 8 yields the following expression for Ratio as a function of temperature:

$$\text{Ratio} = \frac{R_2(R_3+R_4+R_5)k}{R_4(R_1R_2)k+R_1R_2R_4T e^{-\beta/T}} - \frac{R_5}{R_4}.$$

This expression is used to find $k$ when Ratio is measured at room temperature. During data reduction an iteration technique is used to find $T$ for a given Ratio.
VI. DROPSONDE CIRCUITS

A. SUBCARRIER OSCILLATOR CIRCUITS

An excitation oscillator (see Fig. 3), running at 17 kHz, provides a driving source to all measuring and internal calibration circuits. Its output voltage is maintained at 5 V rms by an 18-V dc electronically regulated supply. The output stage is a complementary emitter follower of low impedance. A precision resistor divider connected to this output provides two internal calibration voltages, 40 mV peak-to-peak (p-p) for zero and 200 mV p-p for reference. The p, p-dot, and q transducers and the temperature-sensing thermistor circuits all produce signals in the range of 40 to 250 mV p-p.

All the telemetered signals are brought to individual segments of a commutator. The commutator steps every 0.4 s through 12 segments. Thus each data or calibration point is read once every 4.8 s or, on the average, every 100 m of flight. The commutator is stepped by a motor driven by complementary pulses produced by an astable multivibrator circuit. Before assembly of parts, a gold dip 0.2 to 0.5 μm thick, is put over the commutator circuit boards to improve contact reliability and reduce corrosion.

Commutated signals are changed to dc by an ideal rectifier. This is an integrated operational amplifier with rectifiers included in its feedback path. This circuit has a nominal voltage gain of 30 and reads negative peaks of the input waveform. The output dc, filtered by a capacitor, ranges from 0.60 to 3.75 V.

The dc from the ideal rectifier is applied to a voltage-controlled subcarrier oscillator (SCO). With its input ranging from 0.60 to 3.75 V, this oscillator produces 7.6 to 13.5 kHz triangular waves. This signal is fed into a filter (a two-section π-network low-pass filter) which has a sharp cut-off characteristic (-3 dB at 12.7 kHz, -10 dB at 15 kHz) primarily to reject second harmonics. The output is a low-distortion sine wave which is applied to the modulation terminal of the transmitter.
To protect these circuits from radio frequency interference from the transmitter the outer fiber glass shell is painted with conducting paint and many by-pass capacitors and ferrite filter beads are used in the circuit.

B. TRACKING RECEIVER

The functions of the 1689 MHz tracking receiver in the dropsonde are to receive the rf signals picked up by a quarter-wave-length antenna from the tracking transmitter on the ground, detect the tracking pulses and add them to the sonde transmitter modulation. The receiver is a crystal-video type weighing 200 g with a solid state 1689 MHz preamplifier, preselection filter, diode detector, and band-pass amplifier. The preselection filter reduces interference from the sonde transmitter, in particular its fourth harmonic near 1620 MHz. This filter consists of two high-Q helical resonators critically coupled which provide more than 80 dB attenuation for the unwanted interference.

The detector is an HP 2350 hot-carrier diode. The measured noise level of the whole receiver is -65 dBm. We can track at this level out to 35 km using a 500-W transmitter, 10-dB gain at the transmitter antenna, and minus 2 dB gain at the receiving antenna in the sonde. Beyond this distance intermittent tracking is achieved.

The receiver also produces an automatic gain control (AGC) voltage which is applied to the diode as back bias. The tracking signal level as controlled by the AGC is shown in Fig. 10. The AGC circuit has a time constant of 1 s and a dynamic range of 40 dB. The AGC voltage is brought out to a commutator segment and sent to the ground where it is used later to correct for tracking shifts caused by changes of signal strength.

Figure 10 also shows the effect of signal strength, as represented by the telemetered signal strength Ratio, on the track position signal.
C. TRANSMITTER AND ANTENNA

Each dropsonde transmitter operates on one of ten frequencies in the range 401.0 to 405.5 MHz, 0.5 MHz apart. During a drop sequence, no two sondes have the same frequency.

The transmitters are crystal controlled to assure that they do not drift off frequency enough to cause interference with signals in adjacent channels. We integrate the signal before applying it to the phase modulator to make the frequency proportional to the signal. This is done by the SCO filter as part of its function by the inclusion of a 6 dB per octave attenuation starting at 7.6 kHz, reducing all higher frequencies. We keep the modulation amplitude below the level where the harmonics produced by the nonlinear character of the modulation diode would interfere with the tracking signals at 75 kHz.

The oscillator operates near 34 MHz at one-twelfth of the channel center frequency. Its output is phase modulated by a voltage-variable-capacitance diode. From the modulator the signals pass through two doubler stages, one amplifier, and then are tripled by a step-recovery diode stage. The power in this third harmonic is used without further amplification. The modulation index for 75 kHz modulating signals is 0.5 and for 10 kHz it is 3.0. The rf power output is 250 mW. RF power is connected to the antenna through a ferrite circulator.

The transmitter is enclosed in a removable box made of double-sided tin-dipped circuit boards. Its dimensions are 80 × 55 × 40 mm. Including the circulator it weighs 244 g.

The antenna is a half-wave dipole made of metalized copper adhesive tape. Figure 11 shows a typical pattern. It is symmetrical about the vertical axis with a slight shift to below the horizon and with nulls on the vertical axis.

D. BATTERY

The dropsonde battery is an assembly of four stacks of rechargeable nickel-cadmium cells. To improve stability of the sonde in flight, i.e.,
to acquire the lowest center of gravity, the battery is placed in the lowest position in the sonde. It is accordingly convenient to mount the pitot tube on the battery assembly. The umbilical connector and baroswitch are also on this assembly, which puts all the power circuits together. The combined weight of the battery, baroswitch, umbilical connector, pitot tube, and heater is 730 g.

Each stack, General Electric type GB50, consists of five cells in series. With all 20 1.2-V cells connected in series the terminal voltage is 24 V. Peak performance of the batteries occurs at 10 to 40°C. Accordingly, a 20-W electrical heater is wrapped around the batteries and is energized by 28-V dc aircraft power for 20 to 30 min before ejection. No power is applied to the battery heater during sonde flight.

In flight the pitot tube heater is continuously energized and draws 690 mA current. The total for all sonde circuits is 880 mA. A 12-min flight results in a drain of 176 mAh. At 880 mA the cell capacity of 500 mAh is derated to 270 mAh. Accordingly, a margin of 94 mAh is available in reserve for longer flights in strong updrafts and for additional sensors for future experiments. We use the recommended recharge rate of 50 mA for 14 h.
VII. GROUND STATION CIRCUITS

A. TRACKING TRANSMITTER

The tracking transmitter on the ground is an externally modulated pulse source having a radio frequency of 1689 MHz and a peak power output of 500 W. We use an Applied Microwave Laboratory, Inc., model PG1K with a 1706 H rf head.

The antenna, a Helicone [17], is an eight-turn helix with a 60° conical horn to reduce side and backlobes. Its beam width is 35° and the gain is 12 dB. Its 140-ohm impedance is transformed to 50 ohms by a double-stub tuner.

B. GROUND RECEIVER AND ANTENNA

For receiving on 403 MHz we use a corner reflector antenna with a vertically polarized half-wave dipole feed designed for 50 ohms impedance. Its gain is 8.5 dB above that of an isotropic radiator and the measured beam width is 46°.

A converter performs rf amplification and mixing with a 373.0 MHz local oscillator. It converts 401.0-405.5 MHz signals received at the antenna to 28.0-32.5 MHz intermediate frequencies. Thus all ten channels of the dropsonde-transmitted frequencies are processed by one converter. The conversion gain is 36 dB, the noise figure is 6.5 dB and the bandwidth is 10 MHz.

A resistive divider carries the IF signals to ten identical receivers. Using one of ten different crystals at 0.5 MHz intervals from 21.0 to 25.5 MHz, each receiver selects one of the ten frequencies. A multi-pole band-pass filter, the main selectivity component in each receiver (300 kHz wide centered at 7 MHz) sharply rejects the other nine channels. Subsequently a limiter and discriminator recover the subcarrier and tracking signals from that channel.
The telemetering performance with this receiver depends on the following: 250 mW transmitter power, -2 dB gain in the transmitting antenna, a distance of 50 km, 8.5 dB receiving antenna gain, a receiver noise figure of 6.5 dB and a bandwidth of 300 kHz. Accordingly the received power is -87 dBm and the receiver noise level is -112 dBm giving a signal-to-noise ratio of 25 dB. This results in a margin of about 15 dB for the demodulated telemetered signals.

C. TAPE RECORDER

Each of the ten outputs is recorded on magnetic tape. The magnetic tape recorder collects the telemetered data and tracking position signals for all ten channels. In each channel the telemetered band is 7 to 15 kHz while the tracking signals appear from 50 to 100 kHz. Many tape recorder models can handle this. However the tracking signals need to be measured from the tape to find the time delays. The error table allows 4 m of error from the tape recorder, which amounts to 27 ns for a spherical position surface and perhaps half as much for an elliptical surface. Tape recorders are not available with this small a stability specification, 250 ns being more usual. Furthermore one tape track is not time-stable with respect to another tape track.

However, the stability needed for tracking is for short times, namely, up to 2000 \( \mu \)s. Manufacturers do not specify this for tape recorders. Therefore we selected a tape recorder by testing with simulated tracking signals. Many recorders have servos which closely control the tape speed for average and low frequency fluctuations. These servos unfortunately must have an error signal in order to operate. This generates a tape motion spectrum at a frequency which would interfere with our tracking circuits. Accordingly we do not use a tape speed servo. We use a tuning fork type of tape drive with flywheels. Of the recorder models that showed good stability in our tests, we chose an FR 1200 made by Ampex, an old design for which manufacturing problems such as bearing noise are not expected. We use 1-inch tape with 14 tracks, 14-inch precision reels and run at 1.524 m/s (60 ips). Each reel holds
2200 m and runs 1440 s (24 min). The longest drop time expected is about 1200 s (20 min).

D. TELEMETERED DATA PROCESSING CIRCUITS

The telemetered measurements are read from the tape, one dropsonde at a time, passed through a low-pass filter and a frequency-to-dc converter, digitized into 12-bit binary numbers at 12-ms intervals and put on computer tape. A time code, read from another track of the data tape, is multiplexed on the computer tape along with the data.

For checking and synchronizing with other dropsonde records in the same drop we put the output of the frequency-to-dc converter on a graphic recorder. We use an Esterline-Angus Model E1101S Speed-servo recorder which has a slew rate of 3 m/s, fast enough to record signals which last only 400 ms.

E. TRACKING CIRCUITS

In section II. C. the transponder method of position measurement, which we use, was outlined. The design was developed from the following considerations.

Because of the low radio frequencies (403 and 1689 MHz) used to avoid attenuation in rain and because ten radio channels are needed, only a rather narrow modulation band is available for each tracking signal. Because this narrow bandwidth prevents the use of simple sharp-edged radar-like pulses, we use the repeated ten pulses to give a combination of narrow-band phase tracking and crude pulse tracking. We use 75 kHz for the phase tracking because it can be transmitted to the ground in the band width available and it gives a convenient 2000 m distance for 360° phase shift. The use of 10 pulses in each group results from a compromise between the need for many pulses for accuracy and for few pulses to prevent overlap of pulses from the two stations. The beginning of the ten-pulse group is used in the crude pulse tracking to discriminate among the several null points of the 75 kHz pulses.
By choosing the proper frequency the ten pulses in each group sent from the ground are spaced 4 km apart such that movement of a sonde over a 2-km distance causes a complete 360° shift in phase of the received pulses. This gives a convenient scale in the tracking circuits where a phase change representing a distance as small as 2 m can be observed. The frequency for 4 km spacing is

\[ f = \frac{c}{\mu d} = \frac{299792.5 \text{ km/sec}}{1.0002 \times 4 \text{ km}} = 74933.14 \text{ Hz} \]

where we have assumed \( \mu \), the refractive index of air, is 1.0002 for the air near Colorado thunderstorms. This frequency, provided by a crystal oscillator, is used to synchronize all of the pulses and measurements in the tracker. We have been referring to it as 75 kHz.

To prevent overlap of signals the ten-pulse group is not started again until all possible signals are received. For a 100-km distance this time is near 700 \( \mu \)s. To provide for this distance and the reception of the second-station signals the next pulse does not come until much later, at 2001 \( \mu \)s, the actual value being determined by a 150:1 countdown from the 75 kHz oscillator.

As shown in Fig. 4, the 75 kHz oscillator drives a divider which counts down 150 times and puts out a master synchronizing pulse about 500 times a second (2001 \( \mu \)s). This pulse controls a gate which opens for 134 \( \mu \)s and passes ten cycles of the 75 kHz frequency to the tracking transmitter. This pulse also starts the timing circuit which measures the delay of the received signal. A synchronizing pulse is recorded on each channel of the magnetic tape as well as is a 150-kHz CW reference.

In the tracker a delay circuit starts another 134-\( \mu \)s gate which selects ten pulses of the 75-kHz wave. These delayed pulses are used as the reference in a phase discriminator. The received tracking signal (the telemeter subcarrier has been filtered out) is connected to this phase discriminator. The output voltage, proportional to the phase error between the reference and the received signal, drives a mechanical
servo which changes the time of the reference to match the time of the received signal. For this circuit to function the phase of the reference must change continuously to match any received phase. This is done by a four-quadrant phase shift capacitor exactly as was devised in World War II for precision tracking circuits [15, p. 142]. The position of this capacitor is recorded by a printing digital voltmeter connected to a continuous one-turn potentiometer geared 1-to-1 to it. The printed digits represent one meter increments of position.

There are 20 signals, two per channel, to be tracked in a ten-sonde drop using two ground stations. The ten channels are recorded on magnetic tape along with reference signals. Then using only the one tracking circuit each of the 20 signals is tracked separately, one after another. The signals can be tracked as many times as necessary to recover the records from noise. When the tape is being read, the 75-kHz oscillator is disconnected and the 150-kHz signal from the tape is used instead.

The phase discriminator should, in principle, cross-correlate the received signal and the reference and identify the time delay for maximum correlation. We accomplish this by the usual method of multiplying the received signal by the rectangular reference in a discriminator. Recognizing that identifying a maximum is difficult we note that position information is all contained in the derivative of the signal [16, p. 18]. If we differentiate the received pulses we get a symmetrical positive and negative signal. This, when put through the discriminator, gives a position response negative and positive about the correct point. For rectangular pulses received there would be a wide zero-output region around the correct value. This is avoided not only by differentiating but also by filtering the tracking signal, rejecting all frequencies above 100 kHz and below 50 kHz. This filtering is done by a combination of a filter in the dropsonde, which conveniently limits the bandwidth to be transmitted to the ground, and a filter in the tracker. The resulting signal has the appearance of a sine wave taking one cycle to reach full amplitude and one cycle to turn off at the end of ten cycles. Because of numerous phase shifts and circuit delays there is
a large zero displacement. Its value is found by tracking a sonde on the ground at some known position, and calculating a zero correction from this.
VIII. OPERATIONS

A. INSPECTION

Each dropsonde is given a complete inspection by the manufacturer and by NCAR. Items tested are: weight, pitot and battery heater resistance, 17-kHz oscillator output frequency and voltage, transmitter deviation, radio frequency and rf power, the pattern of radiated power, SCO frequencies, linearity, scale and hysteresis of the three transducers and the effect of gravity on them. For the receiver the following are measured: sensitivity, band width, AGC action, antenna VSWR.

After a dropsonde has passed inspection and before its transducers are calibrated the pitot-static tube and pressure transducer chambers are tested for leaks. Leaks are of concern in maintaining the accuracy of the p-dot transducer. If the transducer capillary were bypassed by a leak it would be possible to calibrate the transducer but the calibration would not be reliable. After the dropsonde has passed the leak tests the time constant of the p-dot transducer is measured to determine whether the capillary tube is obstructed. The time constant of the p-dot transducer is measured by subjecting the dropsonde to a sudden pressure change and measuring the time required for the p-dot transducer output to return to zero. If there are no leaks the time constant will be about 2 s at 800 mb.

In addition to the test described above the pressure transducer capsules are exercised to reduce capsule hysteresis. The exercising is accomplished by subjecting the individual capsules to pressures which cause nearly full-scale deflections and then relaxing them. The process of expansion and relaxation is repeated 100 times. Capsule exercising is done no more than three weeks before transducer calibration and no more than eight weeks before the dropsondes are used.
B. CALIBRATION

Each of the dropsonde's pressure transducers is calibrated. A Texas Instruments model 142 precision quartz pressure gage is used for calibrating \( p \) and \( p \)-dot transducers. Our calibration with a precision mercury barometer indicates an accuracy of 0.2 mb. A Meriam model 34 FB2 differential manometer is used for calibrating the \( q \) transducer. Its accuracy is specified as 0.003 mb.

Read-out of transducer signals is made with an Anadex model PL-408 frequency-to-voltage converter, a Hewlett-Packard model 3460A digital voltmeter, and a Hewlett-Packard model 561 digital printer. We equipped the Texas Instruments pressure gage with a pulse-generating circuit which provides a trigger for digital voltmeter reading and printing at each 10-mb increment during \( p \) and \( p \)-dot calibrations. Figure 12 shows a block diagram of the calibration system. During calibrations for \( p \) and \( p \)-dot, the dropsonde is placed in a vacuum chamber and connected to a regulated supply of 24.00-V dc.

The \( p \) transducer is calibrated by slowly decreasing the pressure inside the vacuum chamber and reading the dropsonde output at predetermined pressures up to a turn-around point of 100 mb. After reaching 100 mb the pressure is slowly increased to 800 mb with readings being taken at predetermined points in between. Immediately after reading the SCO output at each pressure point, the zero and reference signals are read. This technique makes telemetering-scale changes unimportant to the calibration. The data thus generated are used for finding the \( p \) transducer scale factor and hysteresis, for calibration of the \( p \)-dot transducer, and subsequently for reduction of dropsonde flight data.

A typical calibration for a \( p \) transducer is shown in Fig. 13. In this illustration a straight line connecting the first calibration point and the calibration point which has the highest Ratio has been subtracted from all points to allow a convenient drawing of hysteresis and deviation from linearity. For the example, in Fig. 13 the pressure span is 700 mb, the deviation from linearity is 0.31% of full scale, and the maximum hysteresis is 0.07% of full scale. The pressure sequence in this
calibration simulates that which the transducer experiences in being carried aloft by the airplane and falling to the ground in the dropsonde. Because the pressure sequences are approximately the same, one would expect the transducer response to be the same and a reduction in the effect of hysteresis should result from using that half of the calibration which corresponds to increasing pressures.

The q transducer calibration is similar to that for the p transducer except that the pressure readings are not controlled automatically. The dropsonde is removed from the vacuum chamber and parallel pressure lines are connected to the pitot-static tube and the differential manometer. Pressure is applied to the dynamic line and varied from 0 to 6 mb and back to 0 mb while readings of transducer output, zero, and reference are taken at several points in between. Scale factor and hysteresis are determined and the calibration is later used in dropsonde flight data reduction.

A typical q calibration is shown in Fig. 14. The range of this calibration is 0 mb (Ratio_q = 0.11) to 5.58 mb (Ratio_q = 0.93). The deviation from linearity is 6.8% of full scale and the hysteresis at Ratio = 0.52 is 0.16% of full scale.

The most difficult calibration is that for the p-dot transducer because the transducer is sensitive to \( \dot{p}/p \), that is, to both pressure and time rate of change of pressure. The difficulty is further increased because readings of the p-dot transducer output and of the time required for the vacuum chamber pressure to change 10 mb must be made rapidly. To facilitate the p-dot calibration, a semiautomatic technique has been developed (see Fig. 13). With the commutator on the p-dot position the time-interval meter receives start-stop pulses from the pulse generator attached to the Texas Instruments pressure gage. After a manual reset, the first pulse to enter the time interval meter starts the charging of a capacitor from a constant-current source. The capacitor and constant-current source produce a voltage across the capacitor which varies linearly with time and which has been calibrated against a time reference. The next pulse to enter the time interval meter stops the capacitor
charging, causes the capacitor voltage to be read and printed, and
switches the digital voltmeter input to the output of the frequency-to-
voltage converter. As soon as the switching function is performed the
output of the p-dot transducer is read and printed. Next the commutator
is stepped to the p transducer position and, at the next 10 mb point,
the p transducer output is read and printed. The 10-mb offset is removed
during data reduction.

With the dropsonde in a vacuum chamber the pressure is slowly de-
creased and the rate varied until a specified output from the p-dot
transducer is reached. The time-interval meter is reset to await a 10-mb
increment to start the timer. After the p-dot transducer output is
printed p transducer output, zero, and reference are printed. This pro-
cedure is repeated at several points for \( \dot{p}/p < 0 \). Later the pressure
is increased and several readings taken for \( \dot{p}/p > 0 \). Figure 15 shows
a typical calibration. The range covered is \(-0.0033 \text{ s}^{-1}\) (Ratio, \( \dot{p}/p = 0.02 \))
to \(+0.0082 \text{ s}^{-1}\) (Ratio, \( \dot{p}/p = 0.97 \)). From the calibration it is possible
to determine the transducer's scale factor but not its hysteresis. In
fact, no suitable method has been found for measuring hysteresis after
the transducer has been assembled.

Although erroneous calibration points may occur for the p, p-dot,
and q transducers these are obvious when the calibrations are plotted.
Such points are removed.

In addition to the three calibrations described above the parachute
release baroswitch is adjusted to close between 800 and 820 mb, appro-
priate for landing on terrain as high as 1750 m.

The value of the tracking zero is measured for each sonde.

C. PACKING

Packing for flight starts with these items: checking battery charge
condition, cleaning of the commutator, lacing internal wire groups,
connecting the commutator motor lead, connecting the power lead and
putting on the shell. The landing parachute is fastened to a tie-point
on the nose cone. Its shroud lines are gathered and run up one side of
the body to a nylon bag situated just above the body. The parachute is first stretched out in the direction of its shroud lines and then gathered in one hand using an accordion fold, with the last turn of the shroud lines making a complete turn across all the folds. It is then pushed into the bag. A 64-mm wide nylon shroud line cover is secured with the eyelets on the bag and strung through with a small nylon fishing line on a fuse. The other end of the fuse is secured to a bolt on the top plate. The cover is then wrapped over the shroud lines. One end of a spring made of 60 cm of 6-mm diameter surgical rubber tubing is secured to the bag and the other end is brought up through the top of the drag and then down to the body to maintain this assembly under tension. Finally the four horizontal struts are folded down to the center stick of the drag. They are held together by a 6-mm-wide clock spring steel band which is attached to a small expendable clockwork timer. The timer is set to release the spring band 4 s after launch. The timer and band are thrown clear of the sonde and are lost.

D. POD

A simple dispenser chute was adequate for releasing sondes from NCAR's Queen Air airplane, which has an altitude limit of about 9 km. For the Sabreliner, however, it was necessary to design an externally mounted pod, since the pressure-sensitive dropsondes would not tolerate sudden ejection from the airplane's pressurized interior. The pod has electrical power leads to each sonde for warmup of sensors and electronics prior to ejection, heating blankets around the dispenser tubes to maintain sondes at temperatures between 10 and 25°C, and an ejection mechanism that subjects sondes to accelerations less than 10 g.

The 1625 x 648 x 295 mm pod is constructed of aluminum with an aluminum foam-insulated cover and a front aerodynamic fairing of fiber glass. The pod is attached by a pylon to a reinforced skid between the wings on the plane's underside.

The pod holds ten dropsondes, arranged in two horizontal rows. Pilot-operated switches eject the sondes to the rear by releasing coiled
springs in the dispenser tubes. The separate switches controlling each tube allow the sondes to be released in any order and at any rate. The pilot's control box has switches for the electrical power leads to each sonde as well as temperature indicator lights for the heating blankets. Actual control of the heating blankets is by automatic thermostats within the pod.

E. DROP

A weather radar on the ground is used in a dropsonde operation. A watch is kept on echoes developing to the west of the drop area in northeastern Colorado. When echo motion shows that a suitable storm is likely to appear in the drop area the airplane is called. While the airplane takes off less than 10 min after being called it takes another 40 min for it to reach the drop altitude of 14 km. During this time storms can change considerably. Accordingly the decision to call for the airplane must be carefully made. As the airplane approaches the storm it is directed from the ground. The radar operator calls the drop and gives notice so that the recorder on the ground can be started. Ten sondes are dropped 2.5 s apart which puts them into the top of the storm about 400 m apart.

F. SEARCH

A search is made to locate precisely the landing point of each dropsonde and to recover the dropsondes for inspection, repair, and reuse. Immediately following a drop, search personnel are dispatched into the field. The initial guess at the landing point is derived from the aircraft drop point and wind estimates. In addition, the tracking equipment is used during a drop to track one sonde to within 300 m of the ground.

After each of the drops in 1967, the NCAR Queen Air descended outside of the storm for vertical soundings. When fuel and daylight conditions permitted, the aircraft made a low-level search for sondes. When the Queen Air was not used, a light airplane was flown as needed within a few days of the drop. Aircraft spotings are referred to a ground crew
for recovery. The location of sondes is marked on a county map with distances paced to the nearest section lines. The sondes are painted international orange. The drag nylon is also orange except for the top square sheet, which is white. These colors stand out well against the predominantly dead-grass color of northeastern Colorado. A label on the sonde states that the sonde is not dangerous and gives a telephone number and address, requesting its return to NCAR.
IX. DATA PROCESSING

The dropsonde signals which are recorded on magnetic tape during flight, are read automatically as described in Section VII. D. The resulting computer tape is processed by the NCAR computer using a program which finds the first transition between zero and reference and uses this for starting the synchronizing of subsequent signals.

The computer calculates $p$, $\dot{p}/p$, and $q$ using their calibrations and calculates temperatures by means of the thermistor equation given in Section V. B. 5. Intermediate to pressure and temperature computation, the ratios of signal minus zero to reference minus zero are printed out for inspection. Tracking receiver signal strength data are left in ratio form.

A sounding of pressure and virtual temperature made by airplane or radiosonde near the storm through which the drop sondes were launched is part of the computer input data and from this the program computes a table of height and virtual temperature versus pressure.

The vertical wind is computed in two ways, giving values called $w_1$ and $w_2$. $w_1$ is derived from the $p$-dot and $q$ transducers while $w_2$ is derived from the $p$ and $q$ transducers. The algebra used in this is:

\[
q = \frac{1}{2} \rho V^2 = \frac{p}{2RT} V^2
\]

from which

\[
V = \left(\frac{2RTq}{p}\right)^{\frac{1}{2}}
\]

\[
\frac{dp}{dt} = -\rho g \frac{dz_1}{dt} = -\frac{pg}{RT} \frac{dz_1}{dt}
\]

from which

\[
\dot{z}_1 = \frac{dz_1}{dt} = -\frac{RT}{g} \frac{\dot{p}}{p}
\]

\[
\dot{z}_2 = \frac{\Delta z_2}{\Delta t}
\]
\[ w_1 = V - (-z_1) = V + \dot{z}_1 \]

Similarly
\[ w_2 = V + \dot{z}_2 \]

where \( \rho \) is the air density, \( V \) is the speed of the dropsonde relative to the air, \( R \) is the gas constant for dry air, \( T_v \) is the virtual temperature, \( p \) is atmospheric pressure (measured by the \( p \) transducer), \( g \) is the gravitational acceleration, \( z_1 \) and \( z_2 \) are the heights of the dropsonde above mean sea level, \( \dot{z}_1 \) and \( \dot{z}_2 \) are the speeds of the dropsonde relative to the ground, and \( \Delta t \) is the time increment between telemetered points. \( z_2 \) is obtained by reading pressure from the \( p \) transducer and interpolating in the pressure-height table.

The final output, vertical wind speed \( w \), is a combination of \( w_1 \) and \( w_2 \) found by applying complementary numerical filters to remove high frequencies from \( w_2 \) and to remove low frequencies from \( w_1 \). This combination takes advantage of the better error characteristics of the \( p \) transducer for dc and low frequencies and of the \( p \)-dot transducer for high frequencies. Graphs of \( w \) vs height are plotted by the computer.

The position signals on the tape are followed by the tracker which produces a digital printed paper tape. On this are entered coarse position and starting time. The data are then punched on cards for computer solution and plotting. The positions of the ground stations are entered from survey measurements with respect to nearby geodetic stations. Height is entered from an output of the vertical computations. Signal strength is entered by using the ratios from the telemetered data. The computer draws a graph of position in north and east coordinates and prints out a table of positions.
X. FLIGHT TESTS

The most recent and complete tests of the vertical-wind-measuring function were made in April of 1972. A comparison was made of the measurement of airspeed and geometric speed. Weather was chosen to give a minimum of vertical wind to allow the speed comparison to be made. An instrumented Schweizer 2-32 sailplane, *The Explorer*, N9929J, made measurements at the same time to give an independent measure of the vertical wind. Four dropsondes were dropped at 06:30 MDT on April 21, 1972. Four more were dropped at 06:15 MDT on April 25. They were launched by hand from the NCAR Queen Air N304D, the jet, a Sabreliner, not being available.

The weather for these drops is shown in Figs. 16 through 19. On each day the drop was made near sunrise to preclude convection caused by surface heating. On April 21st the 500-mb pattern shows the drop point to have been near a trough in the pressure pattern. This point was chosen to minimize the westerly component of winds aloft which might produce mountain lee waves. At the morning drop time the trough was to the east giving winds at lower levels largely from the north. On April 25th the drop was made near a pressure ridge which was east of the drop point. Although winds were stronger than desired, April 25th was the last day the Queen Air was available for these tests so the day was used.

The sailplane, released 15 min before the drop, flew a rectangular pattern around the drop area, moved to the south as the dropsondes fell by, and then returned to the rectangular pattern. There being no lift the sailplane measurements were made in continuous glides which lasted half an hour each day.

The vertical wind soundings are shown in Figs. 20 and 21, with the sailplane data on the left, plotted by the computer.

The comparison of the airspeed and the geometric speed is shown here:
The numbers in this table are $\bar{U} - \frac{\Delta z}{\Delta t}$ where $\bar{U}$ is the average vertical airspeed measured using the pitot tube dynamic pressure and $\Delta z/\Delta t$ is the average geometric vertical speed determined from the pitot static pressure (with the sign changed because $z$ is positive upward). These numbers show the deviation of the measured vertical wind from the assumed zero vertical wind. The expectation is that the dropsondes will measure vertical wind within 1 m/s. One measurement exceeded this.

The sailplane measurements give a mean vertical speed of -0.2 m/s on the 21st and 0 m/s on the 25th. The sailplane has a standard error estimated at 0.5 m/s giving a combined value (square root of the sum of the squares) of 0.6 m/s for the standard error of the difference between the sailplane and the dropsonde measurements. Three of the dropsonde measurements exceeded this difference, as might be expected. In addition the sailplane and the dropsondes took different time and space measurements in the region used. This allows the possibility that different vertical wind speeds were the cause of the differences in the measurements.
Fig. 1 Dropsonde for measuring vertical wind as it would appear in flight. The length is 112 cm.
Fig. 2 Ground station equipment. From left to right: tracking transmitter, tracking circuit, receivers, tape recorder.
Fig. 3 Block diagram of the telemeter.
One of 1689MHz DROPSONDE 10 Freq. Near 403MHz
RD 7.
Crystal-Video
Receiver Transmitter
250mW
FM
SCO
1689MHz GROUND STATION
Converter Tracking 10 FM
Transmitter Receivers
10 Cycles
-2001,sec _ Magnetic
Tape
75kHz Play
Osc.
Tracker Gate
Divider Recorder
500Hz

Fig. 4 Block diagram of the tracker.

Fig. 5 Arrangement of two-station tracking.
Fig. 6 Vertical wind tunnel used for testing ice accumulation.
Fig. 7 Angular response of Pitot-static tube.
17kHz Excitation

Fig. 8 Excitation circuit.

Fig. 9 Thermistor signal curve.
Fig. 10 AGC response (top), tracking shift (bottom).
Fig. 11 403-MHz transmitter antenna pattern.
Fig. 12 Pressure calibration system.

Fig. 13 Typical calibration curve for the p transducer. Dropsonde No. 100 \( \Delta p = p + 699.50 \) Ratio - 874.32.
Fig. 14 Typical calibration curve for the q transducer. Dropsonde No. 100 $\Delta q = q - 6.802 \text{ Ratio} + 0.737$.

Fig. 15 Typical calibration curve for the p-dot transducer. Dropsonde No. 100 $\Delta(\dot{p}/p) = (\dot{p}/p) - 0.01216 \text{ Ratio} + 0.00361$. 
Fig. 16 Surface analysis (top), 500-mb analysis (bottom), Test 1, April 21, 1972.
Fig. 17 Surface analysis (top), 500-mb analysis (bottom), Test 2, April 25, 1972.
Fig. 18 Temperature sounding, Denver Test 1, April 21, 1972.

Fig. 19 Temperature sounding, Denver Test 2, April 25, 1972.
Fig. 20 Test 1, vertical wind in m/s, April 21, 1972. Ordinate is height above mean sea level.

Fig. 21 Test 2, vertical wind in m/s, April 25, 1972. Ordinate is height above mean sea level.
REFERENCES


