A HIGH-ALTITUDE RADIOSONDE HYPSOMETER

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ABSTRACT

Efforts to improve the basic design of a high-altitude radiosonde hypsometer have resulted in a working model consisting of a small vacuum flask filled with cotton which has been saturated with carbon-disulfide, and in which is immersed a bent-stem bead thermistor. In laboratory tests this device proved capable of measuring pressures within one per cent in the range 300 to five mb and within two per cent in the range five to two mb. Flight tests using only an aneroid capsule as the pressure "standard" have shown that this model functions with an accuracy of two to five per cent in the pressure range 30 to two mb.

1. Foreword

The development of meteorological balloons capable of reaching altitudes corresponding to pressures of two to five mb [1] has necessitated the development of a pressure-sensing device capable of accurately measuring the pressures in this region. A study [2] of the problem indicated that the device best suited for such measurements would be the hypsometer which operates on the principle that the pressure at the surface of a liquid determines in part the boiling point of the liquid. The objective of the investigation reported here was the development of a hypsometer satisfactory for research use.

2. Discussion

General Electric Company, in 1947, investigated the application of pressure phenomena to an instrument for a high-altitude radiosonde. This investigation resulted in the selection of a hypsometer as the most suitable instrument. One of the results of this General Electric study was the development of a full-range radiosonde hypsometer. After these Laboratories had made a study of this instrument, the decision was made to develop a new hypsometer using the G.E. model as a prototype. This new hypsometer was to be limited to measurement of pressures encountered at the higher altitudes attained by balloons. With this modification and others, described below, it was hoped to create a hypsometer that would approach its theoretical accuracy [2].

It was obvious that in order to design this hypsometer certain problems had to be solved. It had to be determined whether the vapor would be "superheated," causing incorrect measurements, or whether heat losses would be so great that the liquid would not boil. If so, how could a proper heat balance be effected? Would violent boiling occur? If so, how could it be controlled? Would the return paths of the vapor condensate be adequate? Would the condensate affect the measurements? Would there be a back pressure in the system, or would dilution by air of the vapor occur at very low pressures? Are the telemetering system and the "in flight" calibration methods sufficiently accurate? The uncertainty of the exact nature of the phenomena inside the hypsometer led to the belief that it was possible that the true vapor pressure was not being measured; therefore, it would be better to determine a "vapor pressure" *versus* temperature curve that is characteristic for this instrument.

In an attempt to solve some of these problems the General Electric model was modified as pictured in figs. 1 and 2. This final model[1] consisted of several parts:

a. A small (ten cc) vacuum flask.

b. A polyethylene cap which functions primarily as a support for the thermistor. A large hole in the cap allows access to the flask for inserting the hypsometric fluid. Polyethylene has been found to be sufficiently insoluble in the hypsometric fluid used here.

c. A glass-covered bead thermistor.[2] The thermistor stem is bent into an acute angle (about 45 deg) about one-quarter inch above the bead. This is done to prevent cold condensate on the stem from reaching the bead. The temperature-resistance characteristics of the thermistor are described in fig. 3.

d. Absorbent cotton that has been cleaned in carbon disulfide. After the fluid has been placed in the flask the cotton is wrapped around the bead and inserted in the flask. The cotton is used to provide adequate surface for evaporation; this minimizes the possibility of superheating and "bumping." The cotton also serves to keep the evaporating surface of the liquid in close proximity of the thermistor.

e. The hypsometric fluid which is carbon disulfide. Its vapor-pressure-versus-temperature characteristics are illustrated in fig. 4. For each test or flight the flask is filled with five or six cc of CS_2.

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[1] A discussion of some of these problems with K. C. Hickman of Eastman Kodak Company led to the final model.

[2] Western Electric Co. Model 14B was used throughout these tests. Victory Engineering Co. thermistor Model 32A1a has the same physical and electrical characteristics.

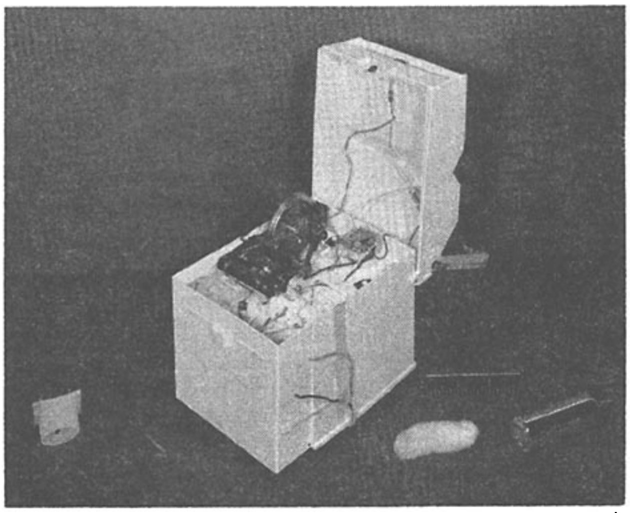

FIG. 1. High-altitude radiosonde hypsometer. Group view showing component parts: cap, bead thermistor, cotton, and vacuum flask. Complete unit shown attached in Radiosonde Modulator MD–210(XE–1)/AMT–4B.

The electric immersion heater used in the original model was eliminated as this is a nonessential feature which could introduce errors into the system. Without the heater the effective range of the hypsometer is limited to the lower pressures (*i.e.*, less than 400 mb). However, the greatest need for the hypsometer is in the 50 to one mb region where the reliability of the standard radiosonde capsule is most likely to be in doubt.[3] This model was given laboratory bench tests and was tested on radiosonde balloon flights.

3. Laboratory tests

Procedure.—In making a simulated flight with the hypsometer, a pressure system, as shown in fig. 5, was used.

The resistance of the thermistor was measured by means of an Anthony-pattern Wheatstone bridge using a d'Arsonval galvanometer. The current passing through the thermistor was limited to less than 40 microamps to prevent measurable heating effects.

In any simulated flight the following procedure was used: The hypsometer, using six cc of CS_2, was connected into the electrical circuit. The pressure was reduced at a fairly constant, predetermined rate. The bridge was set at specific resistances covering the range 4000 to 300,000 ohms and as the resistance of the thermistor passed through these values, the pressure was read. Since two persons worked at each run, and since the percentage change in pressure-per-unit time was small (ranging between approximately one to eight per cent per second), it is believed that very little error was introduced by taking dynamic readings.

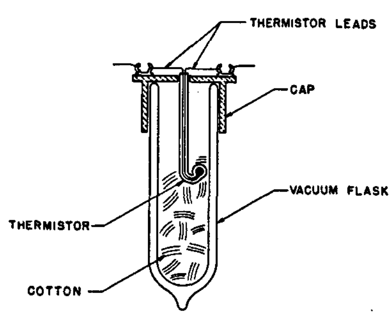

FIG. 2. High-altitude hypsometer.

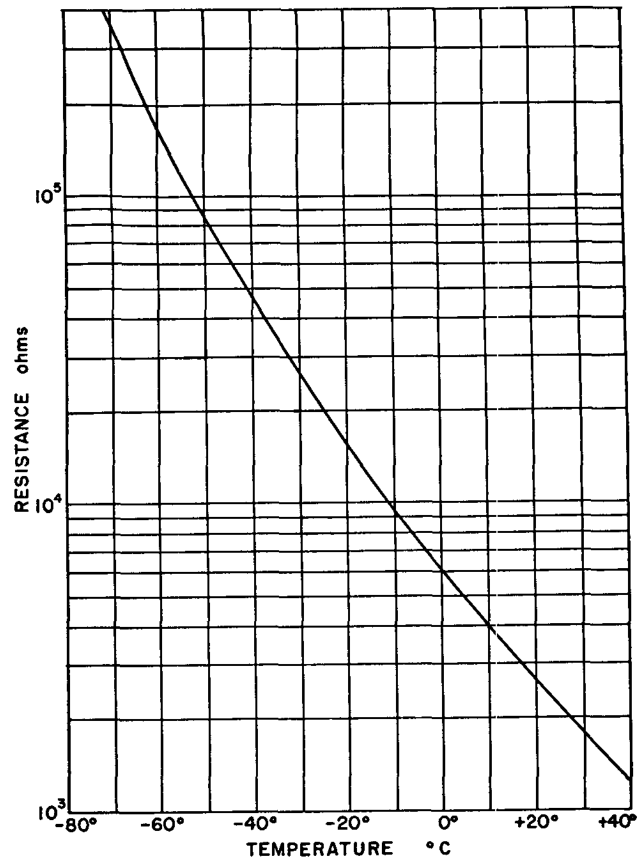

FIG. 3. Resistance *versus* temperature of average thermistor.

The thermistors were carefully and thoroughly calibrated over the temperature range −60C to +20C before they were put into use, the Anthony-pattern bridge being used for this purpose also. When the thermistor is properly used and the current through it is limited to 40 microamps, there is little question as to its reliability.

The aneroid's reproducibility after calibration was considered adequate for pressure measurements above 25 mb. The oil manometer had been checked against a McLeod gage. Its back pressure was measured during each run so it was a reasonably reliable instrument. The oil manometer was used as the standard in the range from 25 to one mb.

Seven tests were made as described above. Table 1

[3] Models of the hypsometer which work over the full range of atmospheric pressure are presently under development at these laboratories.

TABLE 1. Summary of data obtained from seven tests.

	Calibration of hypsometer		
$\bar{P}$ mb	X	S	N
263.5	.2	.5	7
177.5	.1	.4	6
114.0	.1	.2	6
70.0	−.2	.6	5
41.3	−.1	.6	6
21.7	−.1	.6	5
19.1	−.1	.5	6
13.1	.3	.8	5
10.16	.1	.8	4
6.92	.2	.4	6
4.96	.2	.7	5
3.52	−.3	1.2	6
3.13	.1	2.0	6
2.65	.3	1.5	6
2.20	.8	1.2	4
1.89	−.9	1.3	4
1.70	.4	3.3	5
1.41	−.4	3.3	5

$\bar{P}$—the mean of the pressure readings for each group of runs.
S—the standard deviation from the mean error X, given by $[\Sigma(X_i - \bar{X})^2/(N-1)]^{\frac{1}{2}}$ where $X = 100(P - \bar{P})/\bar{P}$.
N—the number of readings used in computing $\bar{P}$ and $\bar{X}$.

presents a summary of the data obtained from these tests.

Other tests were made on the hypsometer. To determine if ambient temperature affected the instrument's accuracy, it was calibrated at temperatures around −30C and compared to the calibrations made at room temperature (+20C). Since the hypsometer is meant to measure atmospheric pressures during a radiosonde balloon flight, a "system" calibration was made. That is, hypsometer measurements were transmitted through a radiosonde modulator, transmitter, receiver, and recorder at the time the hypsometer was being calibrated. The record was evaluated and the pressure measurements thus obtained were compared to those of the pressure standards. Figs. 6 and 7 are graphs summarizing the data obtained from the low-temperature tests and the system tests.

Test results.—Tests on this hypsometer have indicated that as a laboratory instrument it is capable of repeating its measurements to one per cent down to five mb, and to two per cent from five to two mb. Below two millibars the repeatability is around four per cent (see table 1). These errors are so small that there may be some doubt as to whether the scatter is the result of inaccuracies in the hypsometer or inaccuracies in the testing system.

In a number of these tests the rate of evacuation was varied in a manner equivalent to balloon rates of ascent of 500 to 2000 ft per min. These varying rates of ascent had no observable effect on the hypsometer's reliability.

Results of fourteen of these laboratory tests were combined to form a mean vapor-pressure curve for carbon disulfide[4] (fig. 4). This is the curve that would

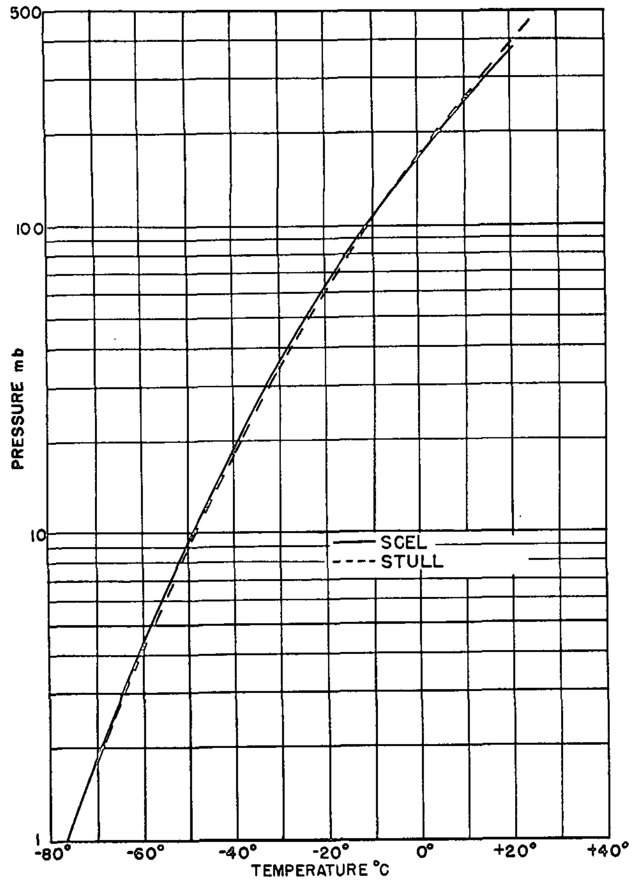

FIG. 4. Vapor-pressure *versus* temperature of CS_2.

be applicable for use with a hypsometer that had only a thermistor calibration (no pressure calibration of the unit). Preceding the construction of this vapor-pressure curve, the curve used for reference was that of D. R. Stull [3]. This curve is also plotted in fig. 4. It is interesting to note that the curve evolved from these tests runs only two and one-half per cent higher in pressure than the Stull curve in the range from 60 to six mb, while outside this range it approaches the Stull curve.

The low-temperature tests (fig. 6) show that the hypsometer is definitely affected in the higher pressure range by low ambient temperatures. From these tests and from measurements of the rate of cooling of a liquid in the hypsometer, it appears that heat is lost through the walls of the flask when the ambient tem-

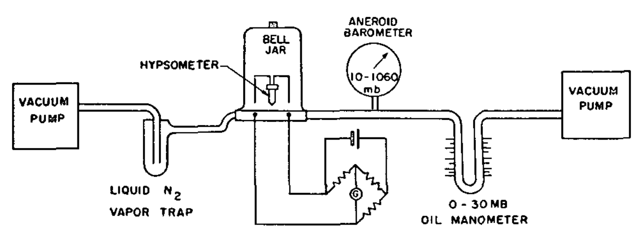

FIG. 5. Pressure-measuring equipment for hypsometer tests.

[4] Reagent Carbon Disulfide Merck, Merck and Co., Inc.

perature is below the boiling point of the liquid. This delays the onset of boiling until lower pressures are reached. For this reason care must be exercised when hypsometer flight data are evaluated to assure that the liquid is boiling; otherwise, pressure values will be obtained which are lower than the true pressure. Errors of this sort cannot arise at very high altitudes because there the boiling temperature will always be lower than ambient.

Fig. 7 is a graph summarizing three laboratory tests in which the pressure calibration of each hypsometer is compared to the same pressure calibration as computed from a meteorological record. One may see from this graph that the resistance (temperature)-frequency sensitivity of the recorder is such that at pressures lower than 60 mb the computed hypsometer pressures are for the most part accurate to around two or three per cent. At pressures higher than 60 mb (above 85 recorder divisions) the sensitivity of the radiosonde telemetering system is too low for accurate pressure measurements.

4. Flight tests

Procedure.—It was felt that the best way to test the hypsometer in flight, since there is no really accurate pressure standard, would be to fly two hypsometers and one radiosonde together.

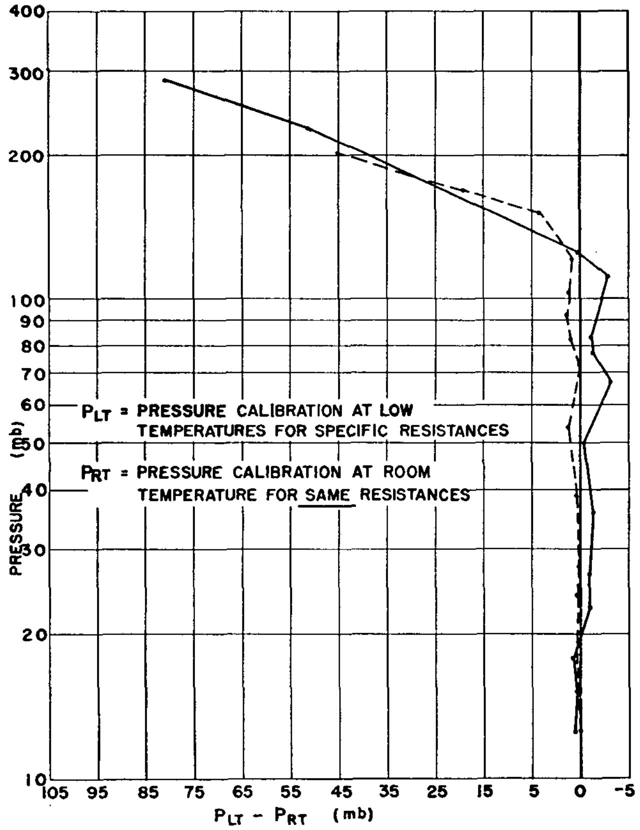

FIG. 6. Errors in two low-temperature (−30C) hypsometer calibrations.

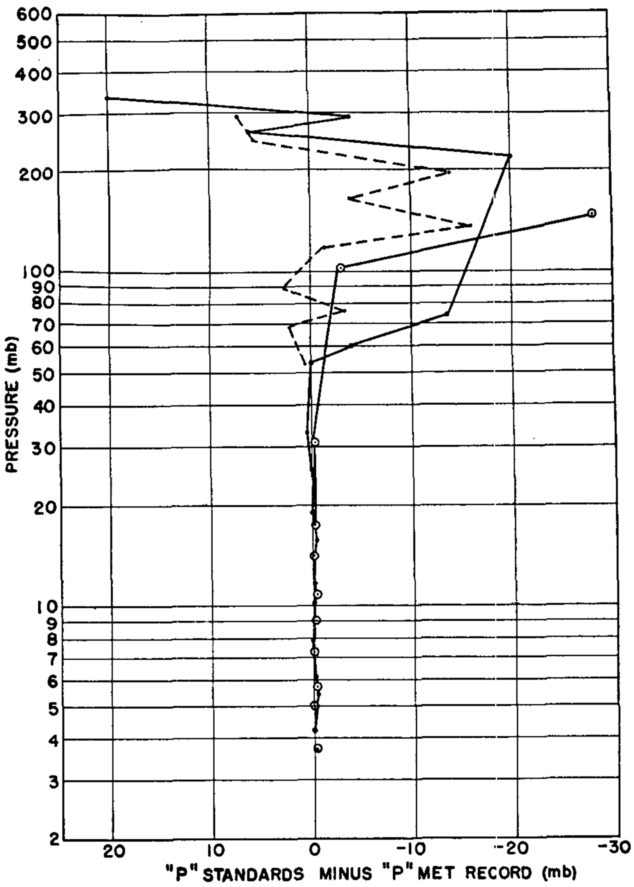

FIG. 7. Error in pressure as computed from a radiosonde record. Three runs.

In preparation for a flight the thermistors were calibrated and the hypsometers were calibrated with a "systems" check. The pressure standard that was used for the flights was an experimental radiosonde modulator designed for high accuracy at low pressures. The unit consists of a small metallic bellow for the higher-pressure region down to about 60 mb and a tandemly connected large bellows (three inches in diameter) that is operative in the pressure range from 100 mb to one mb. They jointly move a contact arm over a commutator bar. The "baroswitches" used in the flights were calibrated in the pressure range from 25 mb to one mb, and on another day were recalibrated. In general, these calibrations agreed to within one or two tenths of a millibar. The instruments were calibrated at a low temperature to determine the change in calibration caused by changes in temperature. When the baroswitch was flown its temperature was measured and the proper correction was applied to the calibration. The measurement of baroswitch temperature, ambient temperature, hypsometer liquid temperature, *etc.*, was accomplished by inserting in the

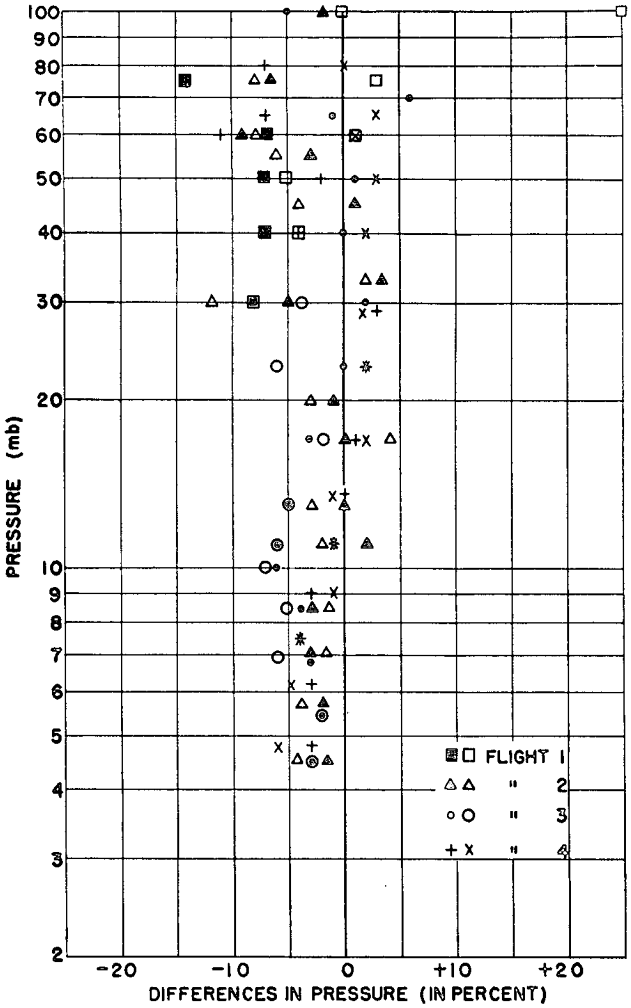

FIG. 8. Differences in pressure between baroswitch and hypsometer under flight conditions. The baroswitch is the pressure standard: represented by the zero per cent line. Each flight has two hypsometers.

radiosonde circuit a six-point switch driven by a one-rpm motor.

Altogether, eight daytime flights were made using this procedure. Only four of the balloons reached a high-enough altitude to provide sufficient data for these tests. The data from these flights are summarized in fig. 8, in which the hypsometer pressure indications at intervals in each flight are compared to the pressure indications of the baroswitch for the same points. The capsule measurements, however, have been modified —a smooth curve was drawn through the capsule pressure indications as they were plotted on a time-pressure graph. This curve represents the rate-of-ascent curve for the balloon flight. Those points which did not fall on the curve were corrected to it as it is more probable that the points displaced from the curve are in error rather than that the displacement was caused by an erratic rate of ascent (vertical gusts). The hypsometer readings were then compared to the corrected capsule readings.

Fig. 8a is of a flight in which an accurate baroswitch was not included; however, the flight is presented here because the extreme bursting altitude of the balloon affords a comparison of hypsometers at some lower pressures.

Test results.—It was seen from these and many other flights that the hypsometric fluid does cool off during the beginning of the flight, and for this reason the hypsometer does not start working until the balloon reaches an altitude corresponding to pressures between 100 and 30 mb.

Generally, the hypsometers measured pressures within 2 to 5 per cent of the pressure indicated by the baroswitch; however, the hypsometer pressures are almost invariably lower. If the baroswitch is assumed

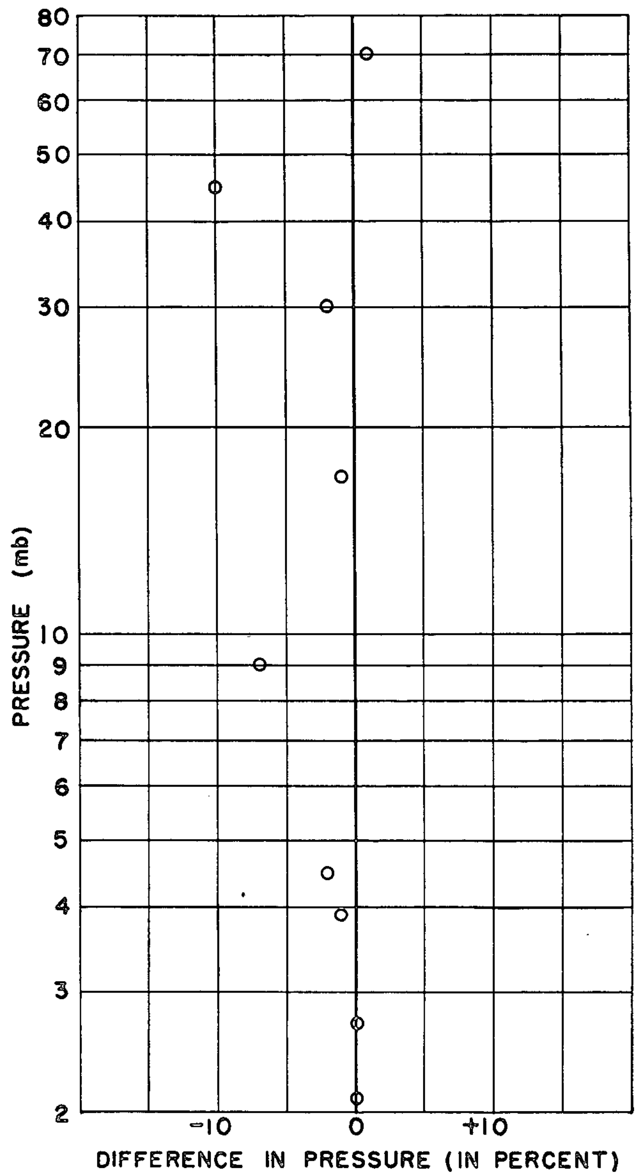

FIG. 8a. Comparison of two hypsometers on one flight. Baroswitch as standard is not represented here. Measurements made up to 2 mb; an altitude of approximately 140,000 ft.

to be accurate, some reason must be found why the hypsometer reads too low a pressure. At pressures in the vicinity of 100 mb it could perhaps be argued that heat losses from the hypsometer to the atmosphere caused the temperature of the thermistor to be too low; however, at pressures lower than 30 mb the atmosphere is normally at a higher temperature than the boiling CS_2 so there are no undesirable heat losses. No reasonable explanation has been found which might account for an erroneously low hypsometer temperature.

5. Conclusions

The purpose at the beginning of this investigation was to develop a radiosonde pressure-sensing element of good accuracy at the higher altitudes which balloons are capable of reaching. During the tests it was soon found that the hypsometer seemed to be outstripping the pressure standards used. The scattering of measurements could just as easily be attributed to errors in the standards as in the hypsometer. Under flight conditions there is no really good pressure standard with which to compare the hypsometer; furthermore, the variations between hypsometers on the same flight seem to be of the same magnitude as errors found in the telemetering system. More work can be done on this instrument to discover its ultimate capabilities, but as it now stands its accuracy of measurement seems dependent only on the accuracy of the telemetering system.

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