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CALIBRATION OF ALTIMETERS UNDER PRESSURE CONDITIONS SIMULATING DIVES AND CLIMBS

By Daniel P. Johnson

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SUMMARY

A method has been developed for the dynamic calibration of aneroid altimeters under conditions of rapidly changing pressures simulating pressure conditions in climbs and dives. It consists essentially in photographing, under stroboscopic lights, the altimeters and an especially designed liquid manometer, which measures the difference between the rapidly changing pressure to which the altimeters are subjected and an accurately known constant pressure. The probable accuracy of the method is about ±3 feet at low rates and ±10 feet at 30,000 feet per minute.

Tests were made of three types of sensitive altimeter and two types of precision aneroid barometer. The barometers were found to be suitable for use as secondary standards and have been used to calibrate electrical contacting altimeters. The altimeters were tested at room temperature in the cyclic state, in pressure cycles of ranges up to 30,000 feet. Observations were at simulated rates of climb and descent from about 1000 feet per minute to more than 30,000 feet per minute.

At rates of altitude change between 500 and 3000 feet per minute, the lag varied from 5 to 50 feet for various altimeters. At 30,000 feet per minute, the lag ranged from about 30 feet for the better sensitive altimeters to more than 100 feet in erratic instruments. The lag varied irregularly with altitude, but at any given rate and altimeter reading the reproducibility was about ±5 feet.

High correlations were found between the lags at low rates and those at high rates and between the lag and the Coulomb frictions measured by various methods. The forces involved in the decay of transient oscillations accounted for only a small part of the lag.

On the grounds of efficiency, production tests should be directed toward selecting instruments of relatively low lag rather than attempting detailed measurements of the lag in erratic instruments.

INTRODUCTION

The problem of obtaining the instantaneous value of the altitude of aircraft during a climb, dive, or other maneuver involving rapid changes in altitude is frequently encountered in flight testing and service. The determination of altitude by means of an aneroid altimeter under such conditions can be broken into three parts: (a) the transfer of the true static pressure from the atmosphere to the aircraft, which involves proper design and location of the static tube to reduce its installation error; (b) the relation of the pressure in the static tube to that at the inlet of the altimeter, which involves knowledge of the pressure drops in the connecting lines; and (c) the determination of the errors of the altimeter itself under the conditions of use.

The installation error of the static tube has not been determined directly. Apparently this must be obtained from a measurement of the total error in altitude by subtracting out the pressure drop and altimeter errors. The pressure drop in the connecting tubing has been studied experimentally and theoretically by a number of authors. (See references 1 to 4.)

Much work has been done on the various errors of the altimeter itself. In the case of the aneroid altimeters, procedures are well established for measuring the effects of temperature, acceleration, vibration, and so forth. Errors in the scale of the altimeters and errors caused by hysteresis and by drift are usually determined by applying a static pressure in a number of steps and comparing the altitude indicated by the altimeter with that given by a standard altimeter for each value of static pressure. The error caused by changing pressure with time, as in a climb or dive, has been estimated from observations of the oscillatory response of the altimeter to a sudden pressure change. (See reference 5.)

A more direct approach to the determination of the errors in climb and dive is to set up pressure standards suitable for calibrating altimeters under pressure conditions similar to those in which they are to be used. It should be possible to subject the altimeter to any pressure changes within its range, at rates of pressure change as great as can be encountered in service. An accuracy comparable with that of the ordinary scale calibration is desirable. It is the purpose of this paper to describe such a pressure standard, its use in calibrating altimeters, and particularly its use in studying the effect on the scale correction of rate of pressure change.

The author expresses his indebtedness to the members of the staff of the National Bureau of Standards for their assistance and advice, in particular, to E. O. Sperling, who designed the ball check valves used in the check-valve manometer; to F. Cordero, who made the check valves for the manometer used in these tests; to A. Wexler, who supplied the data on the calibration of the two contacting altimeters; to H. B. Henrickson, D. I. Steele, and V. H. Goerke, who assisted in the dynamic calibration runs; and to Marie de Novens, who did much of the laborious computations involved in the tests.

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DEFINITIONS

The direct determination of the scale corrections to be applied to altimeters under conditions of continuously changing pressure herein is called dynamic calibration to distinguish it from the static calibration in which pressures are held constant when readings are made. The results of a calibration may be expressed in terms of corrections obtained by subtracting the reading of an altimeter from the pressure altitude, that is, the altitude in the U. S. Standard Atmosphere corresponding to the true pressure. (See reference 6.) If the correction is obtained in a dynamic calibration it is termed a dynamic correction; if in a static calibration, a static correction. In general, the dynamic scale correction depends on the direction and rate of the pressure change at the time of reading, on the magnitude of the change in pressure just before the reading, and, to a lesser extent, on the history of the instrument before the pressure change. In the dynamic calibrations described, the pressures were changed so that the readings of the altimeters changed at a substantially constant rate and simulated a constant rate of climb or dive.

The lag is defined as the difference between a correction obtained in a dynamic calibration, with pressure changing, and the correction in a static calibration obtained at the same reading. Both observations should be made under similar conditions as regards previous history. The lag may depend on the rate of pressure change, on the reading of the instrument, on the conditions of vibration, and so forth.

In the present tests it was found that the reproducibility of a calibration at a simulated rate of altitude change of about 1000 feet per minute was somewhat better than the reproducibility of a static calibration. There was no significant variation of corrections in the range between 600 and 3000 feet per minute. Corrections obtained at rates in this range are termed slow dynamic corrections and may be used as a reference for corrections obtained at higher rates of altitude change. The dynamic lag is defined as the difference between slow dynamic corrections and the dynamic corrections obtained at a higher rate. The dynamic lag is therefore that part of the lag of an altimeter which depends on the rate of altitude change. The dynamic lag of an altimeter may be a function of the reading of the altimeter and the direction and rate of change of altitude. The value of the lag is positive when the correction at the higher rate is more positive in ascent or more negative in descent. With this definition of signs the hysteresis is greater at the higher rate if the lag is positive.

Altimeters are usually calibrated in the rested state, that is, after having been at or near atmospheric pressure for at least 16 hours before the test. This approximates the service condition in which the aircraft makes a single flight in a day.

If a cycle of pressure changes is repeated, the corrections in the second cycle will differ somewhat from those in the first. After a number of cycles, the corrections will have stabilized about new values, with little change in subsequent cycles. The altimeter is then said to be in the cyclic state with reference to pressure cycles of that range. Six pressure cycles may be considered sufficient to put an altimeter in the cyclic state. Calibrations in the cyclic state are valuable in the laboratory where an altimeter may be used in a large number of tests in a day. In service flights, the cyclic state may be approximated when a maneuver which involves an altitude change is executed repeatedly. In a pressure cycle covering the full range of an altimeter, the hysteresis observed when the altimeter is in the cyclic state is usually about 60 percent of that observed in the rested state.

PROCEDURE AND APPARATUS

The method of determining the dynamic corrections near any given test point consisted essentially in photographing, at definite short time intervals, the readings of the altimeters under test and the liquid levels in a manometer which measured the difference between the rapidly changing pressure to which the altimeters were subjected and the substantially constant pressure maintained in a large ballast tank. Rates of climb or descent were determined from the time interval and the change of reading between successive observations. The absolute pressure in the ballast volume was determined by readings on the standard mercurial barometer.

A schematic layout of the apparatus is shown in figure 1. The instruments under test were connected by a manifold to a ballast volume, the left leg of the check-valve manometer, and the control valve by which the rate of pressure change was controlled. The valve could be connected to a pressure line or suction line by means of a two-way stopcock. A sensitive altimeter, connected into the system near the control valve, was used as a monitor in controlling the pressure change. The right leg of the check-valve manometer was connected to a second ballast volume, to the standard barometer, and to control valves in the suction and pressure lines. The check-valve manometer, the instruments under test, a clock, and a thermometer were grouped in the field of a camera, illuminated by stroboscopic lights, and enclosed on all sides by black curtains.

In operation, the part of the system connected to the right leg of the check-valve manometer was stabilized at the pressure near which dynamic observations were desired and the standard mercurial barometer was adjusted for readings at that pressure. The instruments connected to the left leg of the manometer were carried through the desired sequence of pressure changes. The control valve was used to maintain the desired rate of pressure change, as determined by timing the pointer of the monitor altimeter.

When the difference between the pressures in the two sides of the system came within the desired range, as indicated by the check-valve manometer, photographic exposures were made recording a series of observations of the instruments. At the same time the mercurial barometer was read to determine the pressure on the right-hand side of the manometer.

The stroboscopic lights which illuminated the instruments were flashed at convenient time intervals. If the readings of the instruments changed between successive flashes, multiple images appeared on the negative. Since the pointers and graduations of all the altimeters were white on a black background, legible pictures could be obtained with as many as 10 such images on a single negative. In general, it was found that the number of useful images was limited by the difficulty of establishing which of the images of the various instruments were simultaneous. This was usually done by waiting until the check valves had opened and the tops of both liquid columns were visible, then opening the shutter for not more than 10 flashes with an altitude range well under 1000 feet. The fast pointer of a sensitive altimeter thus made less than one full revolution, so that there was no confusion from overlapping. The direction of the pressure change was recorded in the log of the tests. The initial image of all instruments was therefore identifiable and subsequent images could be located by counting.

The timing of the flashes was controlled by a relaxation oscillator which was locked in on the 60-cycle line frequency. For rates of climb or descent greater than about 12,000 feet per minute, the lamps were flashed five times per second. For lower rates they were flashed once per second. At rates less than about 3000 feet per minute the camera shutter was opened for occasional flashes. The number of seconds between pictures was indicated by the clock.

Satisfactory illumination of the meniscus of the manometer was obtained by the use of a light placed about 2 feet back of the manometer and just below the line of sight. Light was reflected into the camera from the air-liquid interface at the bottom of the meniscus and produced a short line on the negative. Light was also refracted into the camera by the wedge of liquid near the rim of the meniscus and produced a lighter line extending clear across the tube. Since the manometer was viewed against a dark background and there were no light sources at the same level, reflections from the cylindrical walls of the manometer are not confusing in the photographs. The other instruments were illuminated by a second light placed above the camera.

Five observations at a low rate of altitude change are recorded in figure 2. According to the clock, the first was at 1:53:09 and the last at 1:53:30. The pointer motion on all the aneroid instruments was clockwise, with the right arm of the manometer falling. The change in pressure altitude was about 387 feet in the 21-second interval, equivalent to a rate of climb of about 1100 feet per minute. In the images of the meniscus, the short line at the bottom and the long line at the top are visible.

In figure 3, the conditions were similar to those in figure 2 except that the rate of climb was about 30,000 feet per minute. Flashes were at intervals of one-fifth of a second. The pointer of each altimeter moved about 100 feet in this time.

Check-Valve Manometer

Details of the check-valve manometer are shown in figure 4. The tubes are of precision-bore glass with an inside diameter of 0.554 inch. They are assembled into the brass base and top sections and clamped against gaskets. The flow of liquid is damped by a 40-mesh-per-inch screen in the base. Check valves in the top sections prevent the liquid from spilling over under large differential pressures. These valves consist of hollow glass balls about 7 millimeters in diameter which fit into glass seats. The balls are light enough to float in water and are so accurately ground and fitted to the seats that there is no observable leakage when they are pushed against the seat. The balls are prevented from dropping into the tubes by wire retainers. When the differential pressure is large, the check valves close and the liquid is retained in the manometer. When the differential pressure falls within the range of the manometer the check valves release and both liquid levels can be observed.

The heights in the two legs of the manometer were scaled on the negative. Correction for shrinkage of the film was determined by measuring a scale mounted between the legs of the manometer. The scale interval was determined by direct comparisons with the mercurial barometer and was found to check with that obtained from the nominal density of the liquid.

The readings of the manometer made when levels were changing at a constant rate were corrected for the pressure drop across the restriction required to maintain the flow of liquid from one side of the manometer to the other. The magnitude of this correction was determined by a continuous-flow experiment. The glass tubes of the manometer were replaced by tubes in which pressure taps were inserted and the ball check valves removed. Liquid in a continuous flow was forced through the manometer and the pressure drop between the two pressure taps measured as a head of the same liquid. Rates of flow corresponded to the highest and lowest encountered in the operation of the manometer. Liquids were used with kinematic viscosities ranging from 1 to 20 centistokes. All the observed pressure drops could be represented by the sum of two terms, one proportional to the kinematic viscosity and to the first power of the velocity and the second proportional to the square of the velocity. With normal butyl phthalate at 25° C, the correction was 0.4 millimeter of mercury when the reading of the manometer changed at a rate of 5 millimeters of mercury per second and was 1.92 millimeters of mercury at a rate of 20 millimeters of mercury per second.

The manometer was filled with normal butyl phthalate. This liquid was chosen because: (a) it is transparent so that illumination of the meniscus by internal reflection was possible; (b) its density (1.045) is low enough to obtain a sensitivity comparable with that of a water manometer yet high enough to float the glass balls in the check valves; (c) its viscosity (about 16 centistokes at room temperature) is such that the effect of drainage of liquid from the walls is not serious and yet viscous damping is obtainable; (d) its vapor pressure is low; (e) it is not corrosive; and (f) it wets the glass walls of the tube so that the meniscus is stable even after the manometer has been in use for a long time.

The theory governing the operation of the manometer is given in the appendix.

Friction

The friction without vibration was determined at the pressure corresponding to the approximate midpoints of the altitude ranges in which lag measurements were made. The pressure was first increased enough to cause the altitude reading to decrease by 200 to 300 feet, then decreased slowly to the original value and held constant while the altimeters and aneroid barometer were read before and after vibration. Similar readings were made after the pressure had been decreased and then increased slowly to the original value.

Free Period, Damping, and Coulomb Friction

The free periods were obtained by applying to the pressure inlets of the instruments a pressure which varied sinusoidally. As the frequency of the pressure fluctuation was varied, the amplitude and phase of the pointer fluctuations were observed. The ratio to critical damping and the Coulomb friction were calculated by the method of reference 5 from observations of the pointer oscillation following the sudden release of a small pressure applied to the inlets of the instruments. These observations were made at atmospheric pressure and room temperature with vibration comparable with that of the lag tests.

Viscous Damping Effect

The lag due to viscous damping L_t was calculated from the formula:

$$L_t = \lambda P r / \pi$$

where

λ ratio to critical damping

P free period

r rate of altitude change

PRIMARY DYNAMIC CALIBRATIONS

Dynamic calibrations were made simultaneously on eight sensitive aircraft altimeters and one precision aneroid barometer, using the check-valve manometer system as a primary standard. Separate calibrations were made of a Wallace & Tiernan precision aneroid barometer.

All the sensitive altimeters had $2\frac{3}{4}$-inch dials, graduated to 10 feet, with the main pointer making one revolution for 1000 feet. Altimeters 839 and 840 were Kollsman altimeters of 35,000-foot range, 5373, 5374, and 5375 were Kollsman altimeters of 50,000-foot range, and 5384, 5385, and 5386 were Pioneer altimeters of 35,000-foot range. Altimeter 840 was built in 1937 and the others, about 1942.

The 6-inch aneroid barometer shown in the lower right-hand corner of figures 2 and 3 was one of two built in 1934 by the Kollsman Instrument Company for use in the National Geographic Society and U. S. Army Air Corps Stratosphere Flight of 1935 (reference 7). This instrument had a range from 0 to 800 millimeters of mercury in eight revolutions of the main pointer, was graduated to 1 millimeter of mercury, and could be read easily to 0.1 millimeter of mercury. It was not temperature compensated and the corrections on both temperature and pressure scales were so large that corrections had to be applied even for rough readings. The calibration of this aneroid barometer has been remarkably stable. For example, at an indicated temperature of 17° C and a reading of 750 millimeters of mercury, the calibration of May 1934 gave a correction of 9.8 millimeters of mercury; in September 1935 the correction was 10.2 millimeters of mercury; in August 1938 it was 9.0 millimeters of mercury; in April 1945, 9.0 millimeters of mercury. The curves of the 1935 calibration (reference 7, p. 222) are used at present for interpolation between the relatively widely spaced points of recent calibrations. As shown by the tests described in the following discussion, this particular instrument is well adapted for use as a secondary standard because its dynamic lag is negligible.

The Wallace & Tiernan precision aneroid barometer covered a range from 20 to 1060 millibars in two revolutions of the pointer. The diameter of the graduated scale of the barometer is about $7\frac{1}{2}$ inches. The graduation interval is 1 millibar and the barometer can be read easily to 0.2 millibar. The barometer was temperature compensated. The scale errors were less than 2 millibars.

Both precision aneroid barometers have been used as secondary standards in tests of contacting altimeters. These were 50,000-foot sensitive altimeters in which electrical contacts have been inserted to close an electrical circuit at predetermined pressures.

In the dynamic calibrations all readings in a series were made while the aneroid instruments were being subjected repeatedly to cycles between fixed end-point pressures. Just before the runs of a given range, the instruments were placed in the cyclic state by subjecting them to at least six pressure cycles of the same range. This placed all readings in the series of cycles on the same basis, with regard to previous history.

Runs were made at slow rates, that is, at rates of ascent and descent between 600 and 3000 feet per minute and at faster rates ranging up to 30,000 feet per minute. Some attempts were made to get observations at 50,000 feet per minute, but satisfactory photographs were obtained in only a small percentage of these exposures.

Observations were made at points scattered over a range of several hundred feet and sufficiently removed from the end points of the pressure cycle to obtain substantially constant rates of climb or descent for several seconds before each observation. Readings were made at the same rate of change of altitude in an ascent and the following descent.

The pressure was held constant at the high and low pressure extremes of the cycle only for the time required to make preparations for the readings to follow. This time was usually less than 1 minute at the highest altitude and less than 5 minutes at the lowest altitude of a cycle.

All the tests were conducted at instrument temperatures of approximately 24° C.

The sensitive altimeters were subjected to vibration from a buzzer. The intensity was sufficient to make the pointers move smoothly during pressure changes but not sufficient to cause significant oscillations of the pointers. The large precision aneroid barometer was not vibrated.

Figures 5, 6, and 7 show in detail the results of observations made on three of the sensitive altimeters near the midpoint of a 9000-foot pressure cycle. Qualitatively the performance of all the altimeters tested was similar.

A quantitative summary of the test results is given in table I. In order to obtain these data, plots similar to those in figures 5, 6, and 7 were made for all instruments. Parallel smooth curves were drawn through the points for low rates of change of altitude (those with short tails in the figure). The separation of these curves gave the hysteresis under slow dynamic conditions. In table I are given the average and maximum values of the dynamic lag at a rate of 30,000 feet per minute for each test point.

In general, the dynamic lag for both directions of altitude change was such as to increase the hysteresis. The hysteresis at the high rate of change of altitude was therefore greater than that for low rates by an amount equal to double the dynamic lag. For comparison, there is given the static hysteresis based on observations in which the pressure had been held constant for about 1 minute before reading the standard barometer and photographing the altimeters. These observations were made during the same series of pressure cycles as the dynamic measurements, so that they are closely comparable with regard to the previous history of the altimeters.

Table I shows the results of the friction test, that is, the average of the changes due to vibration of each instrument obtained with increasing and decreasing pressures. The free period of the instruments as determined from pointer oscillations, the Coulomb friction, the ratio to internal damping, and the lag due to viscous damping are also given in table I for each instrument.

The Wallace & Tiernan aneroid barometer was given a separate dynamic calibration. The setup was essentially the same as that of figure 1, with the altimeters omitted, and the general conditions of operation were similar to those in the tests of the altimeters. The barometer was calibrated in the cyclic state, in a pressure cycle between atmospheric pressure and approximately 460 millibars (0 to 20,000 ft). It was also given tests at two rates of pressure change, equivalent to vertical speeds of 3000 and 20,000 feet per minute. Figure 8 is one of the photographs taken at the higher rate. A large number of observations were made at pressures between 540 and 940 millibars. Figure 9 shows the results of this calibration. The observed points fell so close together that many of the circles in the figure enclose the points representing two to four observations. The data indicate a dynamic hysteresis of about 1.5 millibars at the low rates and a dynamic lag of about 0.5 millibar, corresponding to a hysteresis of about 50 feet and a lag of about 15 feet. Data taken from figure 9 are included in table I for comparison.

The Wallace & Tiernan barometer was to be used to measure pressures in a bell jar several feet from it, and the calibration therefore was made with a length of tubing attached. In the final application of the barometer, the same piece of tubing was used. At least half of the dynamic lag could be ascribed to pressure drops in this tube. For the most part, the irregularities in the calibration curve could be reproduced in repeat runs; they were ascribed to local irregularities in the response of the pressure capsule.

DYNAMIC CALIBRATION WITH SECONDARY STANDARDS

The procedure of the primary calibrations is too elaborate for use when the results of the calibration of large numbers of instruments must be known immediately, as in acceptance tests or field calibration of instruments. A precision aneroid barometer, for which the dynamic characteristics are known, has been found to be a satisfactory secondary standard. A photographic record of the standard and a number of instruments under test can be made while the pressure is changing as desired. The labor of obtaining the data as well as that of analyzing it can thereby be greatly reduced.

Both the Kollsman and the Wallace & Tiernan aneroid barometers have been used in the calibration of sensitive altimeters of the contacting type. The standard aneroid barometer was illuminated by a stroboscopic light which flashed when the electrical contacts in the altimeters were closed as the desired change was made in the pressure to which the contact altimeter and the standard barometer were subjected.

Data on the dynamic lag are given in table II for two 50,000-foot, contacting altimeters, one representative of the better instruments and the other of those with excessive lag. The pressure altitudes at the contacts were obtained from the average of three runs in which the average deviation from the mean was ±4 feet for both instruments.

SOURCES OF ERROR

Primary Calibrations

The level of the liquid in each leg in the check-valve manometer was read to about 0.002 inch on the negative, which corresponded to about 0.02 millimeter of mercury. The uncertainty in determining the conversion factor to millimeters of mercury is about 0.2 percent. The scale interval was checked within 0.5 percent by comparison of the check-valve manometer with a mercury column. The over-all error in reading small differential pressures on the manometer was estimated to be about 0.05 millimeter of mercury, or about 2 feet, at altitudes below 10,000 feet and 0.1 millimeter of mercury, or about 4 feet, in reading differential pressures above 5 millimeters of mercury. With regard to measurements of lag and hysteresis, this error is random.

The correction for the lag of the check-valve manometer was determined with an uncertainty of 5 percent in the continuous-flow measurements. The lag measurements were checked closely by measurements on the decay of large initial oscillations of the column. This correction may introduce an error in the lag of about 3 feet at 30,000 feet per minute and a negligible error at low rates.

Surface tension effects were made small by choosing tubes of large bore. The meniscus formed by normal butyl phthalate in glass remained symmetrical and well defined even after long use. The effects on the lag at 30,000 feet per minute of the change in shape of a falling meniscus and of the drainage of liquid from the walls of the tube are in the opposite direction, of the order of 1 foot, and therefore nearly cancel. At very rapid pressure changes, the change of capillary depression will predominate and increase the lag of the manometer.

The pressure in the constant-pressure side of the system was measured by a mercurial barometer which had a reproducibility of about 0.02 millimeter of mercury, or about 1 foot of altitude.

When the liquid moved from one leg of the manometer it displaced about 25 cubic centimeters. This caused a pressure change in the constant-pressure side of the system which was troublesome in the early measurements. By use of an 80-liter ballast volume in this side, the pressure change was reduced to the equivalent of about 10 feet. The absolute pressure at the midpoint of the range of the check-valve manometer could be determined with an uncertainty of a tenth to a fifth of this pressure change, or 1 to 2 feet.

During the rapid pressure changes there was an appreciable flow of air along the lines connecting the various instruments with the manifold on the changing-pressure side of the manometer. In addition, while the liquid was moving in the check-valve manometer there was a flow in the line to the ballast volume on the constant-pressure side. The pressure drop in the lines was kept small by making them short and of large diameter. The net effect on the lag at 30,000 feet per minute is probably not more than 2 feet.

The sudden flow in the lines leading to the manometer as the check valves opened produced transient oscillations in all the instruments of the system. The damping of the manometer reduced the oscillations in that instrument to negligible magnitude before the midpoint of its range was reached. On the other hand, the aneroids were undamped and oscillations may have persisted in some of them throughout the period of observation. In the first readings on a negative, errors of as much as 20 feet may result from such oscillations. After the midpoint of the manometer had been reached, the oscillations were usually less than 5 feet. In general, observations which showed indications of oscillation were discarded when other data were available. Errors from oscillations are of both signs and their principal effect is to increase the scatter of the results without great effect on the values of the lag. Inasmuch as these errors are in the instrument under test and not in the absolute standard, they should be charged to the method.

The estimate of errors is summarized in table III for dynamic calibrations made at pressure altitudes below 10,000 feet.

Secondary Calibrations

When a precision aneroid barometer or altimeter is used in calibration, the transient oscillations associated with the check-valve manometer are eliminated. For this reason the reproducibility of the data may be expected to be as good as or better than in the primary calibrations. When lag measurements are based on fast and slow calibrations made in close succession, the results may be almost as good as for the primary calibration. This would be particularly the case if readings were obtained in both directions in the same or successive pressure cycles. Hysteresis data so obtained should also be fairly reliable. Because of the possibility of shifts in calibration in aneroid instruments, less reliance can be placed on scale errors so obtained.

DISCUSSION

The following inferences can be drawn from the data plotted in figures 5, 6, and 7 and given in table I. These inferences are supported by the examination of the data on the other instruments and other test points, not given in full because of space limitations.

At low rates of altitude change in a given direction, observations could be reproduced with an average deviation of about ±3 feet. At a rate of 30,000 feet per minute, the reproducibility was about ±5 feet.

While the reproducibility was fairly good at any given reading and rate, the lag varied widely with reading. For example, observations made on altimeter 5385 (fig. 7), in the four fast runs all fell within 5 feet of smooth curves for both ascent and descent. With decreasing altitude the lag remained near 30 feet. On the other hand, with increasing altitude the lag varied from about 5 feet at a reading of 4800 feet to about 45 feet at a reading of 5100 feet. The irregular variation of lag with reading was abundantly confirmed in data obtained in the secondary calibrations. For example, in table II, altimeter 746, the largest and smallest lags were for adjacent test points, less than 300 feet apart.

Large lags are associated with irregular lags. The difference between maximum and average values of the lag at 30,000 feet per minute is a good measure of the variation of the lag. This difference and the average lag had the high correlation of 0.7. This was also confirmed in the secondary calibrations.

There is some slight indication of oscillations, with a period comparable with the free period of the altimeter, superimposed on the uniform motion due to the pressure change; for example, see figures 5 and 7 for the fast runs with increasing altitude.

The 50,000-foot altimeters tested had a somewhat larger lag than the 35,000-foot altimeters of either make. Of the eight sensitive altimeters, six had average lags at 30,000 feet per minute of less than 30 feet, with no individual lag observation as large as 50 feet. This probably represents the best that can be expected of sensitive altimeters of the 3-inch size in the present stage of development. One of the sensitive altimeters, 5374, had lags in excess of 100 feet at readings near 8700 feet. That this can be expected in a significant percentage of altimeters was indicated by tests in which a precision aneroid barometer was used as a secondary standard.

The performance of the 6-inch aneroid barometer is noteworthy. Its lag was zero with the average deviation of an individual observation about ±5 feet. This shows that it is possible to build instruments of small lag. This instrument is considerably larger than the sensitive altimeters, and its scale is covered by 8 revolutions of the fast pointer as compared with 50 for the 50,000-foot sensitive altimeter. Presumably, the use of a larger capsule combined with less gearing than used in the sensitive altimeters results in a lower lag for this instrument.

Relation of Lag to the Decay of Transient Oscillation

Attempts have been made to predict the lag from measurements of the decay of oscillations which occur after a step-function change of pressure. These measurements are in substantial agreement with values predicted on the assumption of a combination of retarding forces due to viscous damping and to Coulomb friction (reference 5). These same retarding forces will contribute to lag in the case of altitude change at a uniform rate.

The contribution to the lag due to the forces measured in the decay of transient oscillations is given in table I. The Coulomb force will contribute to the lag at low rates of change of altitude and the viscous damping force, which is proportional to the rate of altitude change, will contribute to the dynamic lag.

The lag at 1000 feet per minute ranged up to 29 feet, as compared with Coulomb frictions ranging up to 10 feet. The viscous damping forces would account for less than 10 feet of the dynamic lag, which ranged up to 75 feet. The coefficients of correlation between the Coulomb friction and the lag at 1000 feet per minute and between the viscous damping force and the dynamic lag were positive but of the same order as the probable error of the correlation coefficients. The small correlation and the discrepancy in magnitude indicated that the analysis referred to was not adequate for the prediction of lag.

The surprising high correlation of more than 0.8 was found between the dynamic lag and the Coulomb friction forces obtained from the analysis of transient response. This was directly contrary to expectation, since the Coulomb friction was assumed to be independent of the velocity while the dynamic lag is roughly proportional to the velocity. This correlation is comparable with that between measurements of Coulomb friction by various methods and even to that between runs by the same method in different portions of the range of the instruments. Consequently it appears that there is a close relation between the lag and Coulomb friction.

Causes of Lag

The lag of an aneroid barometer or altimeter seems to be a complex phenomenon with a number of contributing factors which vary in relative importance from instrument to instrument. The nature of certain of these factors is relatively well understood, and it may be possible to evaluate them by other experiments.

<u>Pneumatic effects</u>.- In many instruments the entrance connection to the case contains a restriction to the flow of air. The pressure drop through this restriction will increase with increase of rate of pressure change and may vary as the first, second, or some intermediate power of the rate. At a given rate of climb or descent this contribution to the lag will be a slowly varying function of altitude. Because of the similarity in nature it may be convenient to estimate the pressure drop and treat it as an increase in the effective length of the tubing. In the sensitive altimeters the pressure drop through the inlet restrictions

may account for 5 feet of the lag at 30,000 feet per minute, or about 20 percent of that observed in the better instruments.

Thermal effects.- When an altimeter or aneroid barometer is subjected to rapid increase in pressure, the air inside it is heated by compression; when the pressure is decreased, the air is cooled. If there were no thermal exchange between the air in the instrument and the metal parts, the air would be cooled approximately 90° C in the expansion from the pressure at sea level to that at 30,000 feet. The heat transfer to the metal parts of the instrument is quite rapid, so that the actual cooling is a small fraction of this. Since the elastic members (diaphragms and springs) have relatively small mass and large area, it is entirely possible for temperature gradients of several degrees to occur within the mechanism. Although the temperature-compensation means will correct for changes in temperature if all parts are at the same temperature, it is unlikely that complete compensation for temperature gradients is obtained. The resulting change in scale error may be in either direction, depending on the structure of the instrument. The error due to temperature gradients will be roughly proportional to the rate of altitude change.

In addition to changes in air temperature there may be thermoelastic effects in the stressed materials themselves (reference 8). For beryllium copper, the value of Young's modulus under adiabatic stressing is greater than that under isothermal stressing by about 1 part in 300. There is little change in the shear modulus. If bending or compression stresses predominate, a lag of 50 feet would occur at the midpoint of a very fast altitude change of 30,000 feet.

Thermal effects could easily account for lags of the order of 20 feet observed in the better instruments tested. Such lags would be expected to be proportional to the rate of altitude change and be quite regular in behavior.

Friction effects.- There are significantly high correlations between the lag at all rates and the Coulomb friction observed in the decay of transient oscillations and between the lag and the friction without vibration observed in the ordinary friction test. It is also significant that the maximum lags observed in the various instruments are of the same order as the maximum values of the friction without vibration. The lag at 1000 feet per minute (where Coulomb friction is presumed to dominate) was found to have a high correlation with the dynamic lag (presumed to result from viscous drag).

These facts indicate a close connection between the lag and friction despite the apparent dependence of the lag on the rate of change of altitude. The following is set forth as a hypothesis as to the relation between the friction and the lag.

If an altimeter is subjected to a slow pressure change without vibration, the motion of the pointer is held back by friction and a lag is observed. This lag will not change much with rate. If vibration is present, the pointer will be dislodged from time to time and will move up toward the position it would have in the absence of friction. After a short jump it will catch and stop until dislodged again by the vibration. If the pressure change is slow, the releases from the vibration will come so frequently that the pointer will not drop back much between releases, and the lag will be small; if the pressure change is rapid, the pointer may drop back by the full amount of the friction before being released, and the lag will be of the order of the maximum friction. Therefore the lag will increase with increase of rate of pressure change, even though the forces involved do not depend on the rate.

The increase of lag with rate is similar to the effect of a viscous retarding force much larger than that required to account for the decay of transient oscillations. In the mechanism of the sensitive altimeter it is difficult to find any explanation for large viscous forces, since pivots are frequently not lubricated, and the drag due to windage and gaseous flows is small. It seems more reasonable to assume that the intermittent action of the friction forces gives rise to a quasi-viscous drag. While it may be convenient mathematically to treat such forces as truly viscous, their true nature should not be overlooked. In particular, caution should be exercised in applying the results of one type of experiment (for example, oscillatory decay) to very different phenomena (for example, lag at substantially constant rate of pressure or altitude change).

The friction varies irregularly with reading, although at any particular reading it may have a definite reproducible value. For example, a rough spot on the tooth of a gear will cause increased friction, when that particular tooth is engaged, always at the same reading. Furthermore, at a given reading the friction may be large in one direction and small in the other. These characteristics are reflected in the irregular, but reproducible, variation of lag with reading and direction.

The lag observations show some evidence of oscillations with a period comparable with the free period of the mechanism of the altimeters. This may be expected with irregular friction. Suppose the pointer has been arrested at a point of high friction, then breaks free (or is jarred free by the vibration) and moves into a region of lower uniform friction. A plot of lag against time would show an oscillation about the constant value of the lag corresponding to the uniform friction. The initial displacement of the oscillation will equal the amount by which the pointer was held back at the point of arrest, and the initial velocity will equal the average rate of change of reading. A plot of lag against pressure altitude will be similar to that of lag against time if the pressure altitude is changing at a uniform rate.

A plot of lag against reading will resemble a cycloid with a cusp at the point of arrest. One full cycle later there will be another cusp, at which the pointer motion will be relatively slow and the conditions favorable for another arrest. The progress of the pointer may then take place in a succession of jumps, each occupying a time equal to the period of free-pointer oscillation, with intervals of arrest during which the pointer is stationary. The excess of starting friction over sliding friction will suffice to maintain the oscillations once started, even in the absence of large irregularities. This type of progress is easily observed when the pressure is changing slowly and the instruments are not vibrated. With more rapid pressure changes and with vibration the arrests are occasional and only partial and the pointer motion appears more uniform.

Relation of Dynamic Lag and Drift

The difference between static corrections and dynamic corrections is identical with the drift during the period of 1 to 5 minutes spent at constant pressure before the reading for the static calibration is made. The causes enumerated for the lag may therefore be expected to contribute components to the drift. Thus, the lag due to friction will be reduced to zero during the period at constant pressure if the instrument is tapped, and the effects of temperature changes will disappear as the inequalities of temperature decay. The components of drift associated with the lag may be expected to be effective over relatively short times. The long time components of drift, which change little over a period of hours or days, will persist over the whole of a rapid pressure change and contribute little to the lag. However, the long time components of drift may cause a shift of the static and dynamic calibrations of a sensitive altimeter by as much as 50 feet in the first ascent after a long time on the ground or in the first descent after a number of hours at high altitude. Thus, for an altimeter that has not been flown for a long time and then is taken on an extended flight at high altitude, the instrument may be expected to read low in the ascent and high in the descent so that the width of the hysteresis loop is increased.

Only very scanty data on these phenomena are available and quantitative information must await a later investigation.

CONCLUSIONS

With the aid of the check-valve manometer and a photographic technique it is possible to make dynamic calibrations of altimeters and aneroid barometers at simulated rates of altitude change up to 30,000 feet per minute. The accuracy of such dynamic calibrations compares favorably with that of the conventional static calibration; and at low rates, 3000 feet per minute or less, the dynamic calibrations may be even more reliable.

Dynamic calibrations against an absolute standard are extremely laborious, and it has been found convenient to replace the check-valve manometer with a large precision aneroid barometer of a design which makes for negligible lag. With reasonable precautions the labor of a dynamic calibration can be reduced tremendously with small loss of accuracy.

When the highest accuracy is desired in the calibration of an altimeter, it should be tested under the exact conditions of use, as regards previous history, direction and rate of approach to important readings, and so forth. This will most probably take the form of a history test and is possible only in exceptional circumstances.

Usually it will be acceptable to make a determination of average lag for the altimeter in question, under the conditions of use, and to apply the corresponding corrections to all readings under conditions of use. The bulk of the tests can then be under the more familiar static conditions. If an average value of the lag is to be used, it is imperative that the altimeter be selected for low and, which is more important, uniform lag.

The tests described in this report indicate that large and irregular lags are associated with large values of pointer friction. In this regard, the best of the 35,000-foot altimeters will probably have a lag of the order of 5 to 10 feet at low rates and 20 to 30 feet at 30,000 feet per minute, while the sensitive altimeters of 50,000-foot range will probably show somewhat greater and more erratic lags.

A practical comparison test could be set up on the following lines: As many altimeters as can be photographed conveniently are placed in a test chamber with suitable buzzers and subjected to pressures changing at any desired rate. Readings can be photographed by a motion-picture camera or by a still camera with stroboscopic light. At any test point observations should be made with pressures increasing and decreasing at the same rate. Instruments with large hysteresis or those exhibiting irregularities in pointer motion should be rejected. A precision aneroid barometer could be used as a standard or the mean of several of the better altimeters could be used as a reference.

A simple friction test or observations on the decay of oscillations may be used for elimination of instruments which will probably have unsatisfactory lag characteristics.

In designing an altimeter for low dynamic lag, the friction should be made as small as possible by good workmanship and by using a simple mechanism. Restrictions to air flow should be reduced to a minimum. The lag in the elastic response should be considered in the choice of materials. Cautious use might be made of thermal phenomena to introduce lag compensation.

National Bureau of Standards
Washington, D. C., February 20, 1946

APPENDIX

THEORY OF CHECK-VALVE MANOMETER

For a manometer of uniform bore with viscous damping, the following differential equation can be shown to apply

$$\frac{L}{2g}\frac{d^2h}{dt^2} + D\frac{dh}{dt} + h = p \qquad (1)$$

where

h	height or difference in level between liquid surfaces in manometer
p	differential pressure
t	time
L	total length of liquid column, including both legs and allowance for the bend
g	acceleration due to gravity
D	damping coefficient

Any convenient units can be used for h and p, provided that they are the same. The units for t, L, g, and D (which has the dimensions of time) must be consistent with each other, but not necessarily with those for h and p.

Once the coefficients in the differential equation have been determined the differential pressure can be calculated from the observed values of h and its two derivatives. At least three observations at time intervals which are short in relation to the period of oscillation of the manometer are required to determine the derivatives. In practice, even an approximate determination of the second derivative requires observations not more than 0.05 second apart. This is somewhat too short a time interval for most work. It has been found preferable to use only observations made when the rate of change of h is substantially constant.

If the value of h is observed to be changing at a uniform rate, the first (acceleration) term in the differential equation drops out and the pressure is given by:

$$D \frac{dh}{dt} + h = p \tag{2}$$

Then the pressure can be determined from the observed height and its derivative if the damping coefficient is known.

In general, when a changing level is first observed in the manometer, oscillations are superimposed on the uniform motion. In a properly designed manometer the oscillations decay rapidly and may become negligible before the level has moved out of the range of observation.

It will be convenient in the discussion of transient oscillations to substitute in equation (1):

$$\omega^2 = \frac{2g}{L} \tag{3}$$

and

$$\begin{aligned} \cos \delta &= \frac{\omega D}{2} \\ &= D\sqrt{\frac{g}{2L}} \end{aligned} \tag{4}$$

where $\cos \delta$ is equal to the ratio of the damping coefficient to that required for critical damping. Equation (1) becomes:

$$\frac{1}{\omega^2} \frac{d^2h}{dt^2} + \frac{2 \cos \delta}{\omega} \frac{dh}{dt} + h = p \tag{5}$$

Assume the manometer to be subjected to a differential pressure given by:

$$p = p_0 + \dot{p}\, t \tag{6}$$

where p_0 is the pressure at which the check valve opens and $\dot{p}$ is the rate of increase (assumed constant) of pressure with time. Until the check valve opens at time $t = 0$, the liquid in the manometer will remain stationary at a height h_0 corresponding to p_0. After the check valve opens, the differential equation (5) applies. That the following equations form a solution of this differential equation can be verified by substitution:

$$h = p_0 + \dot{p}\,t - \dot{p}\,\frac{2\cos\delta}{\omega} + \dot{p}\,\frac{\sin(2\delta + \omega t \sin\delta)}{\omega\sin\delta}\,e^{-\omega t\cos\delta} \qquad (7)$$

$$\frac{dh}{dt} = \dot{p} - \dot{p}\,\frac{\sin(\delta + \omega t\sin\delta)}{\sin\delta}\,e^{-\omega t\cos\delta} \qquad (8)$$

$$\frac{d^2h}{dt^2} = \dot{p}\,\frac{\omega\sin(\omega t\sin\delta)}{\sin\delta}\,e^{-\omega t\cos\delta} \qquad (9)$$

The initial conditions are satisfied since for $t = 0$, the expressions for h and its first derivative reduce to:

$$\begin{aligned} h &= p_0 - \dot{p}\,\frac{2\cos\delta}{\omega} + \dot{p}\,\frac{\sin 2\delta}{\omega\sin\delta} \\ &= p_0 \qquad (10) \end{aligned}$$

$$\begin{aligned} \frac{dh}{dt} &= \dot{p} - \dot{p}\,\frac{\sin\delta}{\sin\delta} \\ &= 0 \qquad (11) \end{aligned}$$

The transient oscillations, represented by the last term of equation (7), decay exponentially and eventually become negligible. Equations (7) and (8) then reduce to:

$$h = p_0 + \dot{p}\,t - \dot{p}\,\frac{2\cos\delta}{\omega} \qquad (12)$$

and

$$\frac{dh}{dt} = \dot{p}$$

By use of equations (4) and (6), equation (12) can be reduced to equation (2). The rate of decay of the transient oscillations is determined by the exponent:

$$-\omega t \cos \delta = -\frac{\omega^2 Dt}{2}$$

$$= \frac{g\ Dt}{L} \qquad (13)$$

If, as a first approximation, D and L are considered to be independent, the rate of decay is decreased by increase of L, and increased by increase of D. On the other hand, the amplitude of the oscillation term involves $\sin \delta$ in the denominator and becomes large as δ approaches zero and $\cos \delta$ approaches unity. Therefore the damping should be chosen so that $\cos \delta$ is somewhat less than 1. In practice the optimum value of $\cos \delta$ is about 0.8, but satisfactory use of the manometer can be made with $\cos \delta$ between 0.4 and 0.9.

The rate of decay of transients decreases with increase of L. Also, the amplitude increases with increase of L because of the appearance of ω in the denominator. For these reasons, it is desirable to make L as small as feasible when quick response to sudden pressure changes is desired. With a manometer for which L is less than about 50 centimeters, it is possible to have a period of oscillation less than 1 second. With optimum damping, the transient oscillations may be neglected after a time of the order of a half the period of oscillation. With a small manometer it is therefore possible to obtain accurate observations on rapid pressure changes, provided that the rate can be held constant for more than a half second. The upper limit for the rate of pressure change is set by the requirement that the range of the manometer is not covered in less than the period of oscillation.

For photographic observation a manometer liquid of density comparable with that of water is desirable, and consequently the manometer can cover only a limited pressure range. When the manometer is to be used for measurements over part of a large pressure change, check valves are essential to prevent the liquid from spilling over.

At the beginning of the theoretical discussion, the simplifying assumptions of uniform bore and viscous damping were made. Neither of these holds for a real manometer. In general, to obtain satisfactory damping it is necessary to constrict the tube at the bend or to interpose some other restriction to the flow. When the cross section of a tube is reduced, the effective length is increased. Therefore the contribution of the bend to the length L is much increased. The effective value of L was obtained from measurements on photographs of the manometer at intervals of 1/30 second, after a large differential pressure had been released. By calculation of h and its first and second derivatives at various times and substitution in equation (1), approximate values of L and D could be obtained. This was checked by a determination of ω by timing oscillations in the manometer when it was filled with a liquid of low viscosity. By both methods, the value of ω^2 was found to be about 75, and the effective value of L was therefore about 26 centimeters. The measured length of the liquid column was 20 centimeters, so the increase due to the restriction was 6 centimeters.

The damping in a real manometer departs significantly from viscous damping because of losses proportional to the square of the velocity of the liquid. Therefore, the damping coefficient D in equations (1) and (2) is not a constant but is a linear function of the absolute magnitude $\left|\frac{dh}{dt}\right|$ of the rate of change of height; that is,

$$D = D_0 + D_1\left|\frac{dh}{dt}\right| \tag{14}$$

The lag correction $p - h = D\frac{dh}{dt}$ to be applied to the readings of the manometer becomes a quadratic function of the rate of change of height,

$$p - h = D_0\frac{dh}{dt} + D_1\left|\frac{dh}{dt}\right|\frac{dh}{dt} \tag{15}$$

in which the squared term always has the same sign as the linear term.

With significant departure from viscous damping, the mathematical analysis becomes more difficult and a general equation for the transient oscillations could not be obtained in a form suitable for practical use. Approximate solutions in certain special cases indicate a qualitative similarity, provided that the damping ratio $\cos\delta$ is given a suitable average value, which increases with increase of the rate of change of height $\left|\frac{dh}{dt}\right|$. The choice of the effective values of L and $\cos\delta$ in the presence of nonlinear damping follows the same general considerations as those outlined for linear damping. But the method of evaluating $\cos\delta$ and L from the decay of a transient oscillation and obtaining D from equation (4) is not applicable.

When the height is increasing at a constant rate, the lag correction $p - h$ may be assumed to be equal to the pressure Δp required to force the liquid through the restriction from the falling to the rising side of the manometer. If the volume flow through the bend is V and the area of the tubes is a, the level rises in one side at a rate V/a and falls in the other at the same rate. The difference in level changes at a rate

$$\frac{dh}{dt} = \frac{2V}{a} \tag{16}$$

Equation (15) then becomes:

$$\begin{aligned}\Delta p &= p - h \\ &= D_0 \frac{2V}{a} + D_1\left(\frac{2V}{a}\right)^2 \qquad (17)\end{aligned}$$

when h is increasing. (When h is decreasing the terms in V and V^2 are both negative.)

Assuming laminar flow and including end and bend losses, the loss of head Δh across a restriction is given by:

$$\rho g \, \Delta h = \mu \alpha V + k\rho\left(\frac{V}{a}\right)^2$$

or

$$\Delta h = \frac{\mu\alpha}{\rho g} V + \frac{k}{g}\left(\frac{V}{a}\right)^2 \qquad (18)$$

where μ is the absolute viscosity, ρ is the density of the liquid, and k and α are constants.

Comparing equations (17) and (18) it is seen that

$$\left.\begin{aligned} D_0 &= \frac{\mu\alpha}{\rho g}\frac{a}{2} \\ \text{and} \qquad & \\ D_1 &= \frac{k}{4g} \end{aligned}\right\} \qquad (19)$$

Measurements were made on liquids for which the values of μ/ρ were between 1 and 20 centistokes and with range of flow which extended to higher rates than were expected to be used in the manometer. All the data could be represented by equation (18) within the accuracy of the measurement. For normal butyl phthalate at 25° C $\left(\frac{\mu}{\rho} = 15.6 \text{ centistokes}\right)$ the value of D_0 was 0.078 ± 0.003 second and that of D_1 was 0.0009 ± 0.0001 second^2 per millimeter of mercury.

The effective value of $\cos \delta$ corresponding to this damping is between 0.35 and 0.40, when the oscillations are superimposed on slowly changing readings, and rises as the rate of pressure change increases. Optimum damping (cos δ about 0.8) is reached at rates of pressure change in excess of 50 millimeters of mercury per second, corresponding to a rate of climb or descent of more than 200,000 feet per minute.

The determination of the lag coefficient by the continuous-flow method is subject to some uncertainty because of the possibility of energy losses at the tops of the liquid column. The losses between the two pressure taps, located in the center of lengths of straight pipe, with a continuous stream of liquid, might differ from the losses between two liquid surfaces.

Observations of the oscillations of the manometer liquid, after the sudden release of a pressure of about 10 millimeters of mercury, provided a check on the value of D at a rate of pressure change of the order of 40 millimeters of mercury per second, about double the highest encountered in the dynamic calibration. Agreement with the continuous-flow tests was within about 0.005 second, corresponding to an uncertainty in the lag measurement of less than 3 feet of altitude for rate of ascent or descent up to 30,000 feet per minute.

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TABLE I

SUMMARY OF TEST RESULTS

[Static hysteresis from calibration with constant pressure during readings; dynamic hysteresis from calibration at approximate rate of change of altitude indicated. Lag, change between calibration at indicated rate of change of altitude and static calibration; dynamic lag, change between calibrations at 30,000 ft/min and at 1000 ft/min.]

Instrument (a)	Hysteresis			Lag				
	Static (ft)	Dynamic, at 1000 ft/min (ft)	Dynamic, at 30,000 ft/min (ft)	Average, at 1000 ft/min (ft)	Average dynamic (ft)	Average, at 30,000 ft/min (ft)	Maximum, at 30,000 ft/min (ft)	Friction, no vibration (ft)
Readings between 4200 and 5200 feet in 9000-foot cycle								
Altimeter 839	39	41	76	1	18	19	35	32
Altimeter 840	40	43	124	2	40	42	82	39
Altimeter 5373	66	86	133	10	24	34	58	50
Altimeter 5374	74	72	222	-1	75	74	98	59
Altimeter 5375	36	54	103	9	24	33	46	95
Altimeter 5384	43	45	69	1	12	13	29	37
Altimeter 5385	32	40	98	4	29	33	51	29
Altimeter 5386	35	45	91	5	23	28	43	37
6-inch aneroid	35	35	38	0	1	1	12	12
Wallace & Tiernan aneroid	--	---	---	--	--	--	---	--
Readings between 4200 and 5200 feet in 18,500-foot cycle								
Altimeter 839	46	68	98	11	15	26	37	32
Altimeter 840	23	55	103	16	24	40	67	39
Altimeter 5373	53	105	144	26	20	46	74	49
Altimeter 5374	77	134	219	29	42	71	102	59
Altimeter 5375	50	65	129	8	32	40	53	96
Altimeter 5384	27	40	77	7	18	25	37	37
Altimeter 5385	26	50	93	12	22	34	51	29
Altimeter 5386	27	55	87	14	16	30	50	37
6-inch aneroid	31	39	43	4	2	6	28	11
Wallace & Tiernan aneroid	32	39	[b]64	4	[b]12	[b]16	[b]26	--
Readings between 8200 and 9200 feet in 18,500-foot cycle								
Altimeter 839	46	76	105	15	14	29	39	34
Altimeter 840	16	50	133	17	42	59	80	40
Altimeter 5373	64	115	172	26	28	54	71	60
Altimeter 5374	93	130	257	18	64	82	124	63
Altimeter 5375	53	65	121	6	28	30	45	90
Altimeter 5384	28	47	92	10	22	32	40	36
Altimeter 5385	23	51	93	14	21	35	43	31
Altimeter 5386	29	55	112	13	28	41	58	34
6-inch aneroid	35	51	58	8	4	12	19	14
Wallace & Tiernan aneroid	40	54	[b]80	7	[b]13	[b]20	[b]22	--

Instrument (a)	Transient response characteristics at atmospheric pressure			
	Free period (sec)	Ratio to critical damping	Coulomb friction (ft)	Dynamic lag due to viscous damping (ft)
Altimeter 839	0.36	0.07	3	4
Altimeter 840	.35	.24	1	13
Altimeter 5373	.44	.12	5	8
Altimeter 5374	.40	.05	10	3
Altimeter 5375	.36	.15	8	9
Altimeter 5384	.32	.10	6	5
Altimeter 5385	.31	.09	6	4
Altimeter 5386	.29	.11	5	5
6-inch aneroid	.34	.05	0	3
Wallace & Tiernan aneroid	.17	.05	0	1

[a] Altimeters 839, 840, 5384, 5385, and 5386 were of 35,000-ft range; altimeters 5373, 5374, and 5375 were of 50,000-ft range.
[b] Rate of change of altitude, 20,000 ft/min.

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TABLE II

DYNAMIC LAG OF CONTACTING ALTIMETERS USING ANEROID-BAROMETER STANDARD

[Decreasing altitude only.]

Average pressure altitude (ft) at contact for altimeter 746 at descent of -		Dynamic lag for altimeter 746 (ft) (1)	Average pressure altitude (ft) at contact for altimeter 742 at descent of -		Dynamic lag for altimeter 742 (ft) (2)
20,000 ft/min	1000 ft/min		20,000 ft/min	1000 ft/min	
10,245	10,275	30	10,260	10,297	37
8,544	8,574	30	8,568	8,662	94
7,091	7,104	13	7,122	7,202	80
5,878	5,904	25	5,942	6,012	70
4,893	4,911	18	4,951	4,972	21
4,080	4,097	17	4,096	4,137	41
3,419	3,427	8	3,425	3,460	35
2,830	2,857	27	2,877	2,898	21
2,346	2,361	15	2,373	2,417	44
1,938	1,954	16	1,979	2,012	33
1,622	1,623	1	1,658	1,695	37
1,309	1,346	37	1,356	1,386	30

[1] Mean lag, 20; average deviation, ±8.
[2] Mean lag, 45; average deviation, ±18.

TABLE III

ESTIMATE OF ERRORS IN PRIMARY DYNAMIC CALIBRATIONS AT PRESSURE ALTITUDES BELOW 10,000 FEET

Source	Error (ft) at rates of -	
	1000 ft/min	30,000 ft/min
Mercurial barometer	1	1
Reading of check-valve manometer	2	4
Surges in ballast volume	1	2
Lag of manometer	0	3
Pressure drop in lines	0	2
Surface tension effects	1	2
Transient oscillations	0	5
Maximum error	5	20
Probable error	3	10

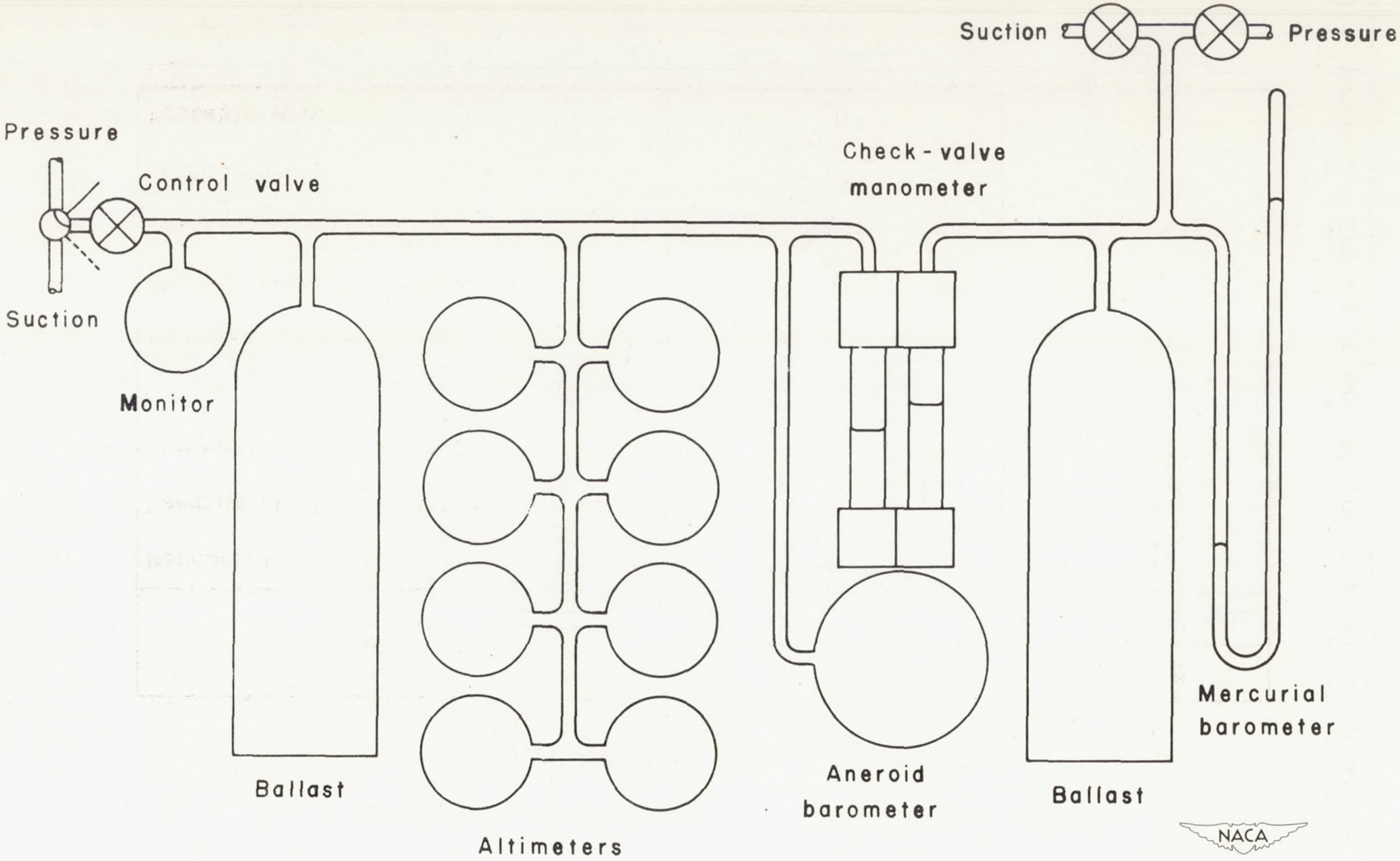

Figure 1.- Schematic diagram of apparatus for absolute dynamic calibration.

Figure 2.- Photographic observations in primary dynamic calibration. Rate of ascent, 1100 feet per minute.

Figure 3.- Photographic observations in primary dynamic calibration. Rate of ascent, 30,000 feet per minute.

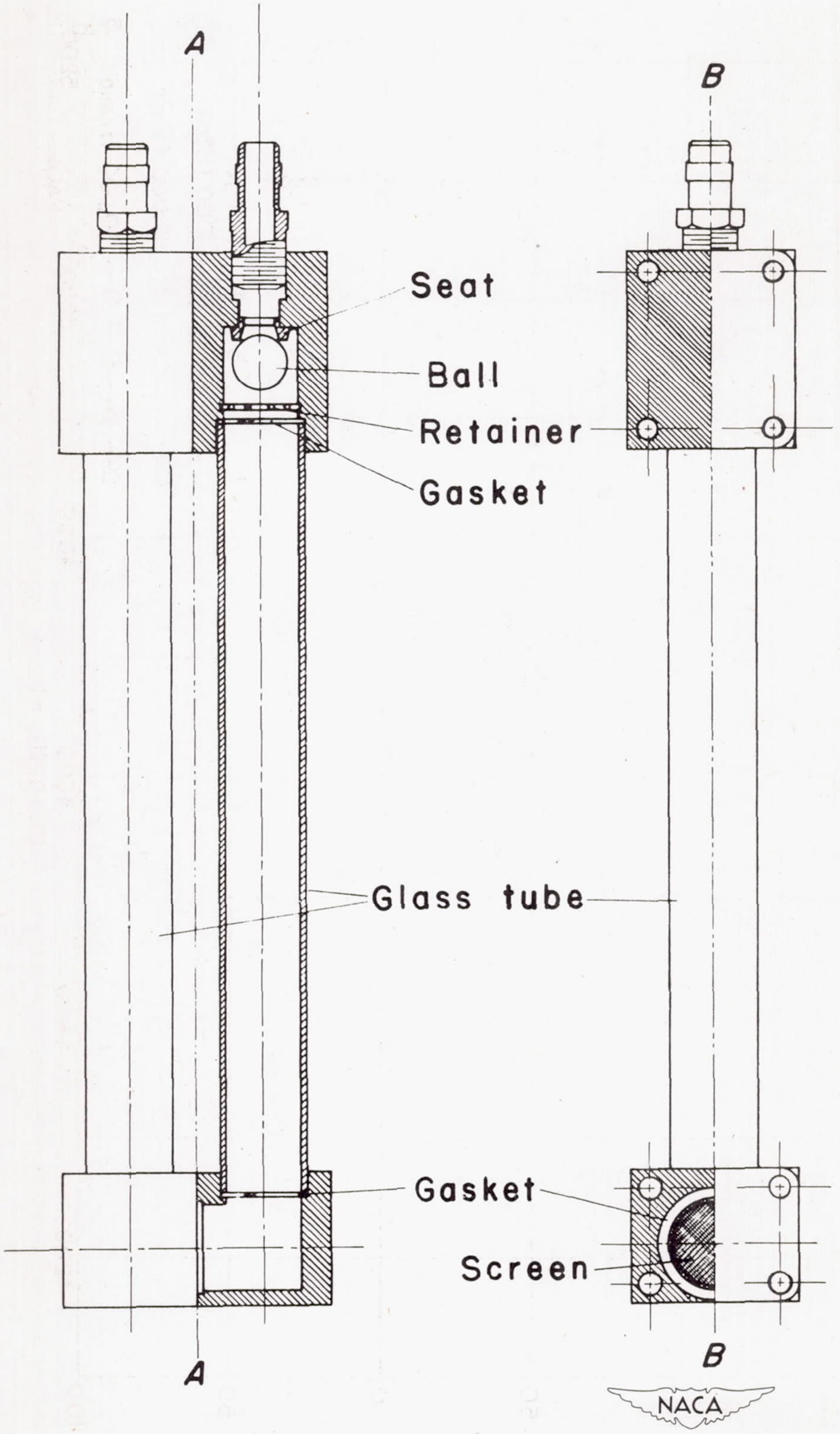

Figure 4.- Check-valve manometer.

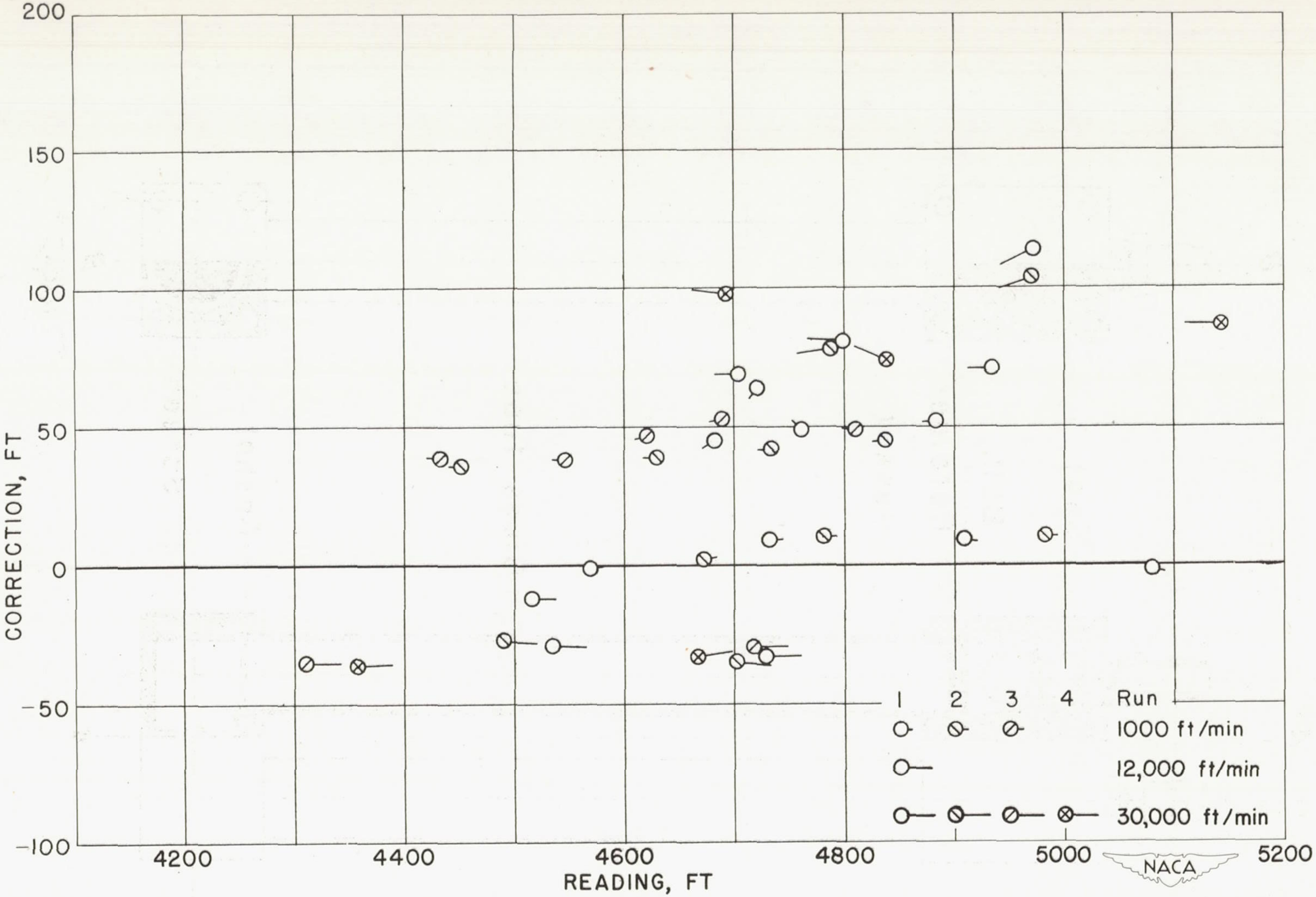

Figure 5.- Dynamic scale corrections. Altimeter 840 in cycles between 0 and 9000 feet. Tails point toward preceding reading in point of time. Rate of change of altitude indicated by length of tail. Four symbols with similar tails indicate four nominally identical runs.

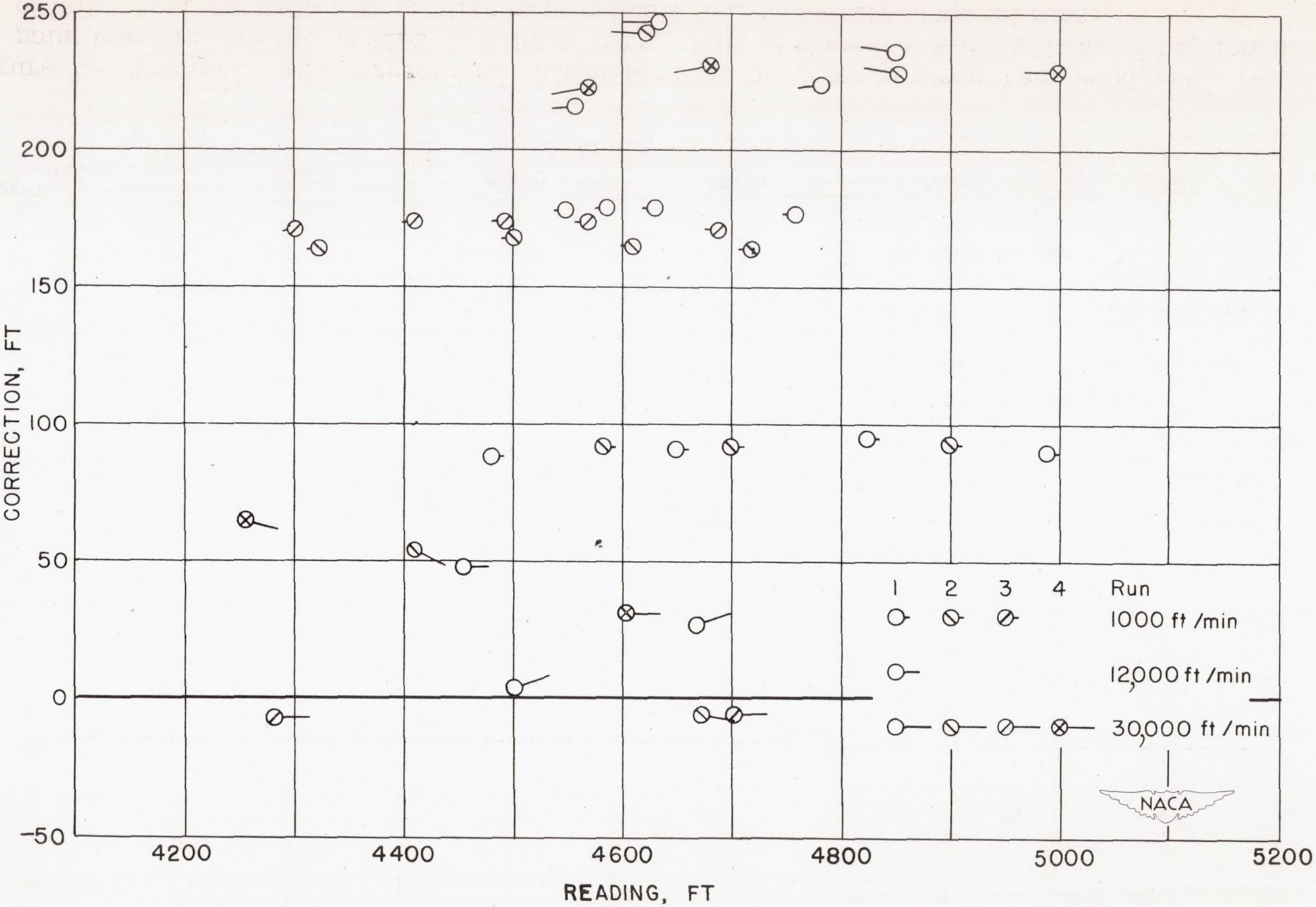

Figure 6.- Dynamic scale corrections. Altimeter 5374 in cycles between 0 and 9000 feet. Tails point toward preceding reading in point of time. Rate of change of altitude indicated by length of tail. Four symbols with similar tails indicate four nominally identical runs.

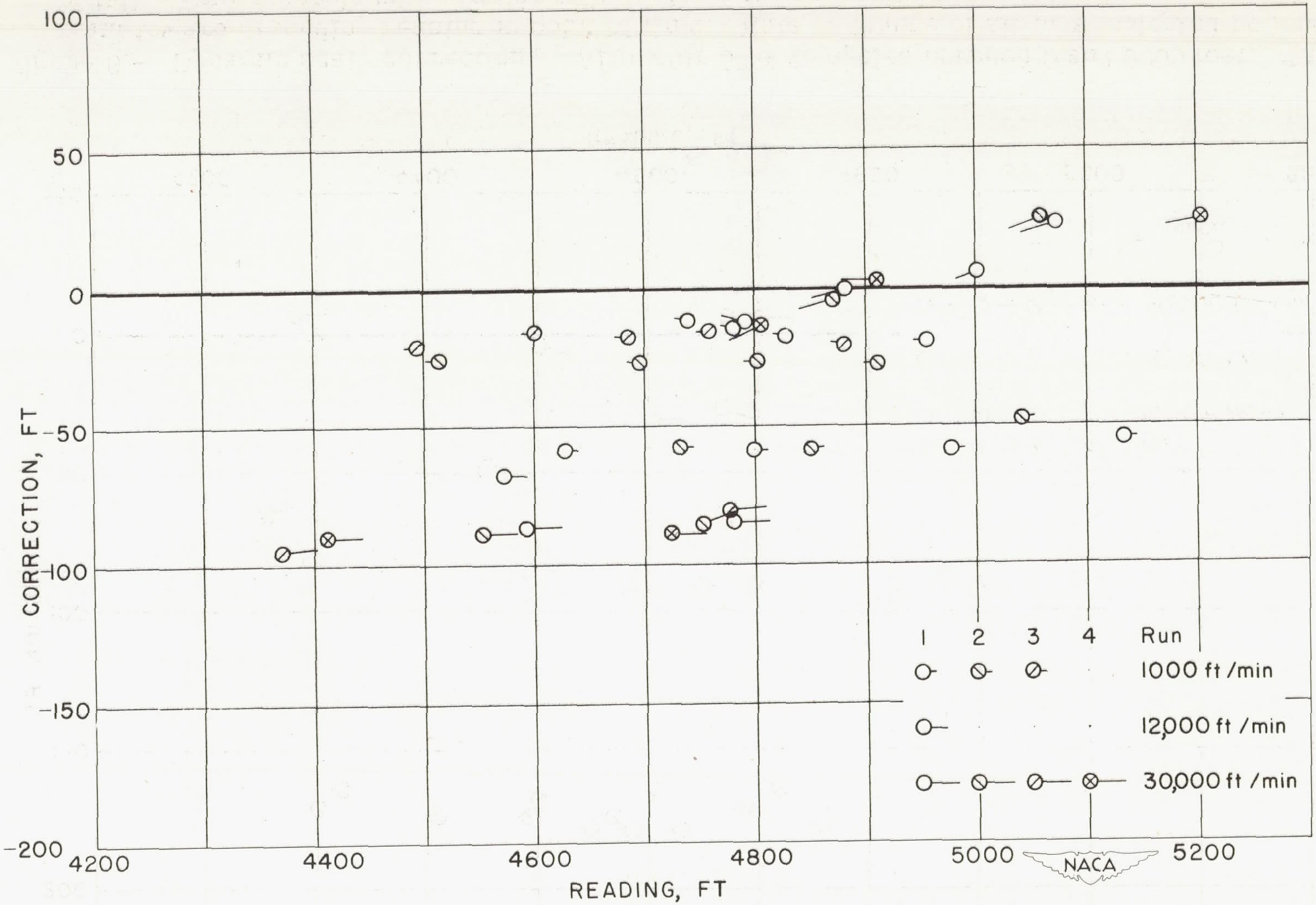

Figure 7.- Dynamic scale corrections. Altimeter 5385 in cycles between 0 and 9000 feet. Tails point toward preceding reading in point of time. Rate of change of altitude indicated by length of tail. Four symbols with similar tails indicate four nominally identical runs.

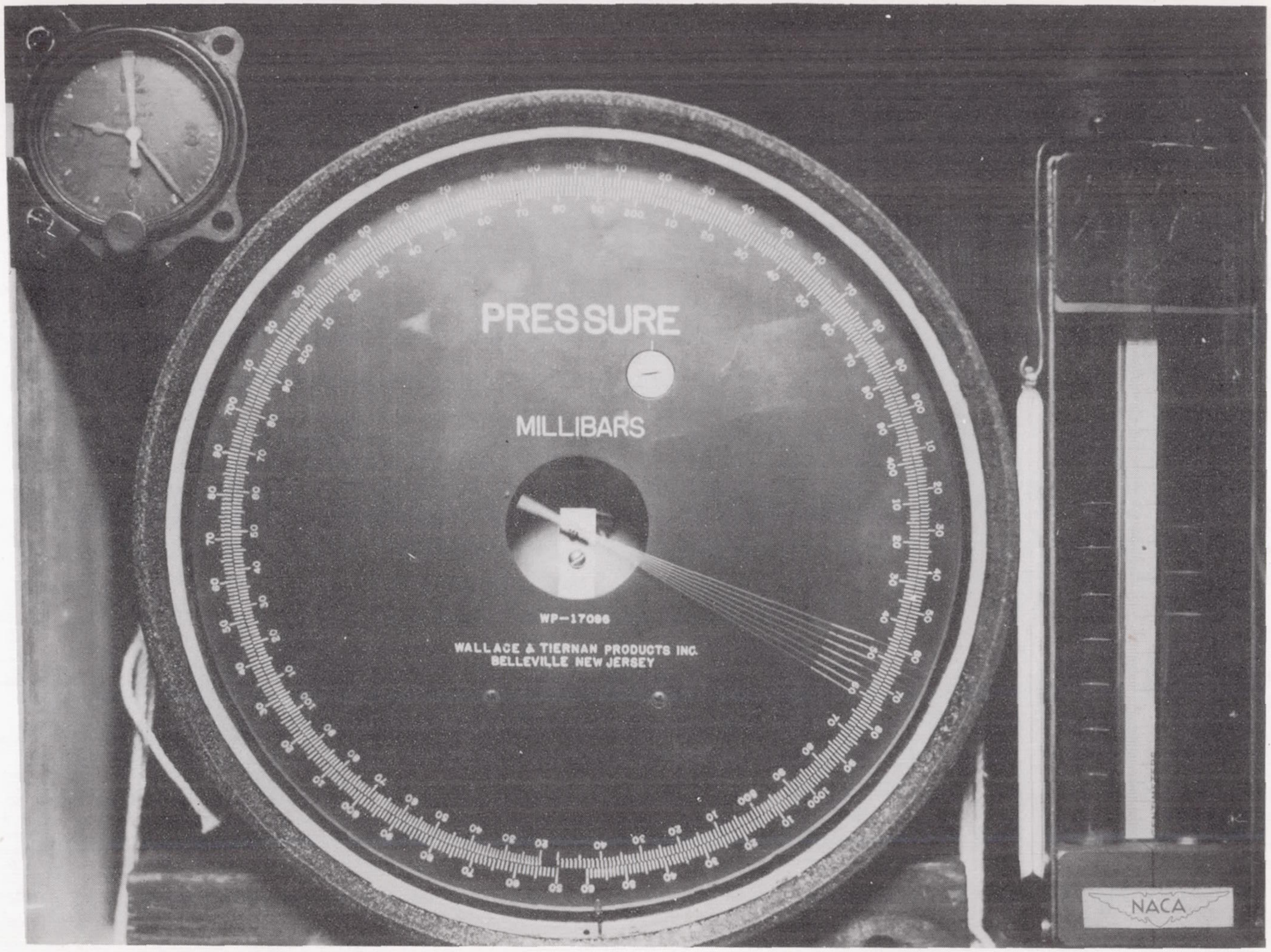

Figure 8.- Photographic observation in primary dynamic calibration. Rate of descent, 20,000 feet per minute.

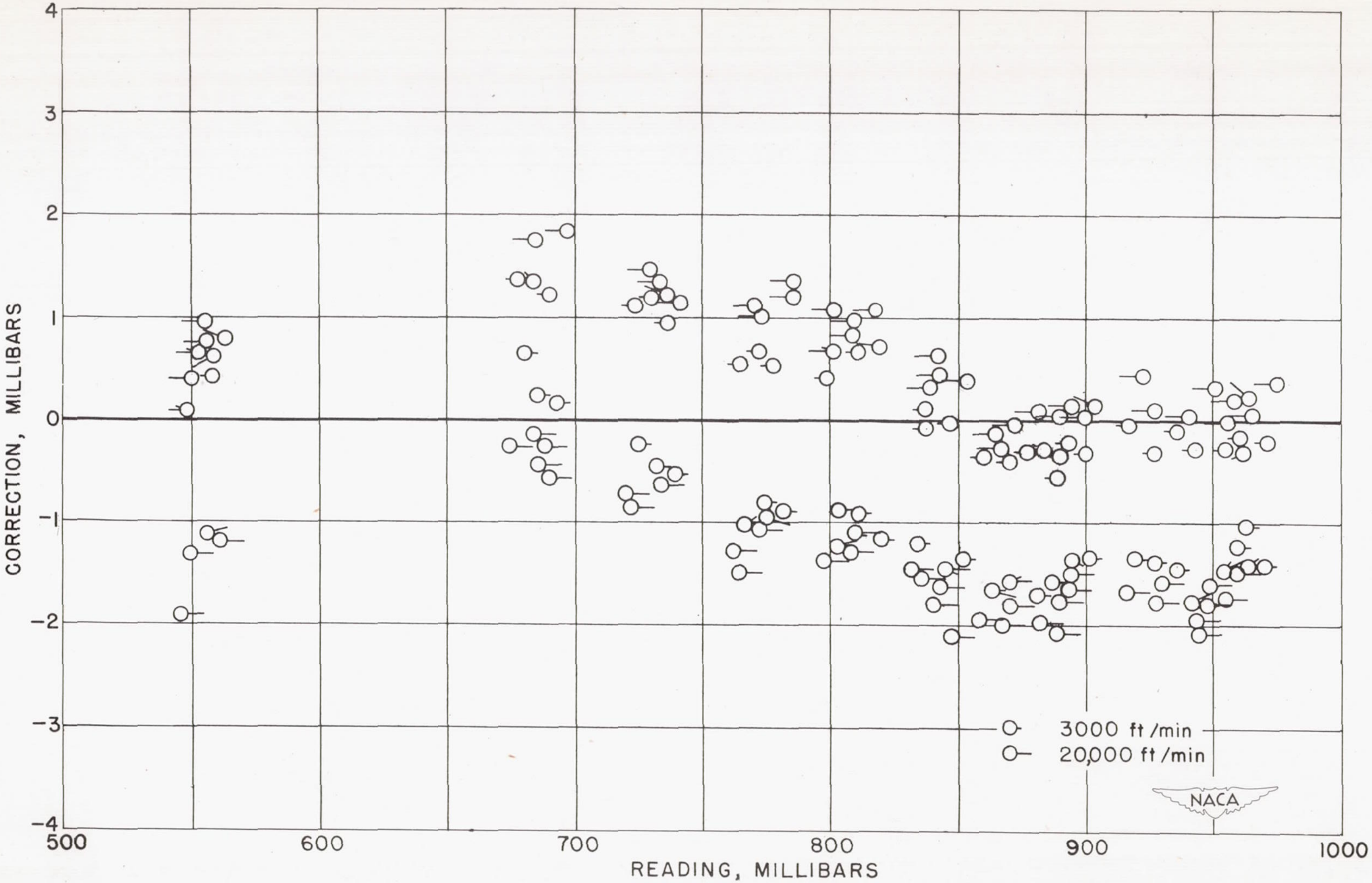

Figure 9.- Dynamic scale corrections. Wallace and Tiernan precision aneroid barometer in cycles between 0 and 20,000 feet. Tails point toward preceding reading in point of time. Rate of change of pressure indicated by length of tail.