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TECHNICAL NOTE 4127

THE MEASUREMENT OF PRESSURE ALTITUDE ON AIRCRAFT

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THE MEASUREMENT OF PRESSURE ALTITUDE ON AIRCRAFT

By William Gracey

SUMMARY

The accuracy with which pressure altitude can be measured is determined by calculation of the errors in the measuring system, errors arising from operation of the system, and variations in atmospheric pressure. Available information on the magnitude of each of the errors is presented, and an indication of the means by which some of the errors can be reduced is given.

The overall errors in the measurement of altitude in a single aircraft are calculated for Mach numbers up to 1.0 and for altitudes up to 40,000 feet. The overall errors of the installations in two aircraft are then combined to show the minimum vertical separation which can be tolerated with present instrumentation and operating practices. Various systems of barometric reference for pressure altimetry are also discussed.

INTRODUCTION

From considerations of safety in flight, accurate measurements of altitude are required to insure clearance of terrain obstacles and vertical separation between aircraft. Terrain obstacles may be encountered either within terminal areas (during landing approach) or en route between areas (over mountainous regions). Similarly, vertical separation between aircraft must be assured in terminal areas and en route between areas. For each of these flight regimes the operating speeds and altitudes may be stated in general terms, as follows:

Terrain clearance (landing approach) . . .	Low speed, low altitude
Terrain clearance (en route)	High speed, moderate altitude
Vertical separation (terminal area) . . .	Low speed, moderate altitude
Vertical separation (en route)	High speed, high altitude

Inasmuch as the error in pressure-altitude measurement increases with both speed and altitude, the largest errors occur in providing vertical separation en route. This fact does not mean, however, that accurate altitude measurement in high-speed, high-altitude flight is the most critical aspect of the altitude measuring problem. Actually, the measurement of altitude during a landing approach can present a much more difficult problem, because the height errors which can be tolerated near the ground are much lower than those which can be tolerated at higher altitudes.

The accuracy with which pressure altitude can be measured is determined by calculation of the errors in the measuring system, errors arising from the operation of the system, and variations in atmospheric pressure. Available information on the magnitude of each of these errors is presented, and an indication of the means by which some of the errors can be reduced is given. Calculations are made of the overall accuracy of pressure altitude as measured in a single aircraft, and the overall errors of two aircraft are then combined to show the minimum vertical separation which can be tolerated with present instrumentation and operating practice. Various systems of barometric reference for pressure altimetry are also discussed.

ALTIMETRY ERRORS

Errors in Measuring System

The errors in the measuring system are determined from (1) errors in the static-pressure source, (2) errors in the instrument, (3) errors due to tubing lag, and (4) errors which may arise in service operation.

Static-pressure errors.- The static pressure which is sensed by the static-pressure source of an airspeed-altitude system, for the usual case, differs from the current ambient pressure because of errors of the sensor itself and errors due to the location of the sensor on the aircraft (ref. 1). The combined sensor and position error (static-pressure error) varies with Mach number and angle of attack and thus depends on the related variables: impact pressure, static pressure, aircraft weight, and normal acceleration. The static-pressure error may also vary with changes in configuration of the aircraft, such as flap deflection and landing-gear extension.

The magnitude and variation of the static-pressure error with Mach number and angle of attack must be determined by a flight calibration of the system. Calibrations of four typical installations (static-pressure tubes ahead of the fuselage nose, wing tip, and vertical fin and static-pressure vents on the fuselage) have been compiled in a study conducted by the Langley Laboratory. An evaluation of the four installations on the basis of the magnitude and variation of the error with Mach number indicated that a choice of the most suitable system for a given aircraft could be stated in terms of the speed range through which the aircraft was expected to operate. On this basis, it was concluded that

(1) For operation at supersonic speeds, the best installation would be a static-pressure tube ahead of the fuselage nose.

(2) For operation at speeds below sonic speeds, a static-pressure tube ahead of the wing tip may, for some aircraft configurations, be preferable.

(3) For operation at speeds below a Mach number of 0.8, a static-pressure tube ahead of the vertical fin or fuselage vents, properly located and installed, may produce a satisfactory installation.

These conclusions are, of course, generalized statements which are subject to qualification depending on the configuration of the aircraft and on the location of the static-pressure source on or near the aircraft. Furthermore, even an apparently optimum installation for a particular aircraft may produce undesirably large static-pressure errors in some ranges of Mach number or angle of attack. For example, fuselage-nose installations, considered optimum for supersonic aircraft because the static-pressure error is negligible at supersonic speeds, may have very large errors at subsonic and transonic speeds.

For any of the four general locations of the static-pressure source, the static-pressure error may be minimized by properly locating the source within the region considered. For example, for static-pressure-tube installations, the static-pressure error may be decreased by locating the static-pressure orifices a greater distance ahead of the fuselage nose, wing tip, or vertical fin.

For cases in which the static-pressure error of an installation is found to be higher than desired, the error may be decreased by the use of aerodynamic compensators located near the static-pressure orifices. Aerodynamic compensators for fuselage-vent installations have been used with some success at subsonic speeds. These compensators are usually developed by a trial-and-error procedure and, as a rule, are successful for only a limited range of Mach number and angle of attack. An aerodynamic compensator based on a more rational concept has been applied to a static-pressure tube located ahead of the fuselage nose (ref. 2). This compensator was designed to reduce the large static-pressure errors which are typical of the fuselage-nose installation in the subsonic- and transonic-speed ranges. Wind-tunnel tests of a model of this device showed that relatively good compensation could be attained over a fairly wide range of Mach number.

In the design of a service installation an attempt is made to locate the static-pressure source in a position where the static-pressure error will remain within specified limits throughout the operating range of the aircraft. The allowable tolerance of the error in altitude measurement as specified in reference 3 is 25 feet per 100 knots indicated airspeed corrected to sea-level conditions.

This specification is subject to different interpretations with regard to the magnitudes of the errors at altitudes other than sea level. If, on the one hand, the height increment of 25 feet is considered to apply at all altitudes, then the altitude errors for a given Mach number will decrease with altitude because the indicated airspeed at constant Mach number decreases with altitude. If, on the other hand, the pressure difference corresponding to a 25-foot height increment (at sea level) is considered to remain constant, the altitude errors at a given Mach number will increase with altitude because in this case the altitude errors at each altitude must be multiplied by the inverse of the density ratio at that altitude. The second interpretation is the one which is used in this report. For this case the altitude errors corresponding to an error of 25 feet per 100 knots indicated airspeed have been calculated for Mach numbers up to 1.0 and for altitudes up to 40,000 feet. The results of these calculations are presented in figure 1.

If the altitude errors of an installation cannot be made to conform to the specified tolerance by suitable location of the static-pressure source or by the use of aerodynamic compensators, corrections for the errors may be applied either by means of an automatic computer or by the use of correction cards. Even when corrections for the static-pressure error are applied, however, the altitude measurement is known to an accuracy no greater than the precision of the flight-calibration method. For most of the calibration methods in use at the present time, the accuracy of the method is no better than ±1 percent of the impact pressure q_c. The altitude errors corresponding to a static-pressure error of ±1 percent q_c at Mach numbers up to 1.0 and altitudes up to 40,000 feet are given in figure 2.

Instrument errors.- The errors due to mechanical imperfection of the instrument include scale, friction, temperature, backlash, balance, coordination, instability, and zero setting. Definitions of each of these errors (from ref. 4) are given in appendix A. In addition to these errors, there are other errors associated with the elastic properties of the aneroid - hysteresis, drift, aftereffect, and recovery. These errors are taken into account in applying corrections for the scale error.

The maximum allowable limits of each of the mechanical errors have been taken from reference 4 and are listed in table I.

Although the scale error is the largest of any of the mechanical errors, the actual errors of a given instrument may differ considerably from the specified values. These errors can be determined by laboratory calibration of the instrument and corrections for the errors can be applied either by an automatic computing device or by the use of correction cards.

If corrections are applied for the scale error, it may be assumed that they will be applied on the basis of a mean curve through the hysteresis cycle of the calibration. In this case an error equal to one-half the hysteresis cycle remains after correction for the scale error. Estimates of this error have been based on the allowable limits for hysteresis, 150 feet at 20,000 and 25,000 feet, and for aftereffect, 60 feet at sea level (ref. 5). The deviations of the hysteresis cycle on either side of the mean curve, which may be called the "precision" of the scale error, have been assigned values of 30 feet at sea level, 60 feet at 10,000 feet, 75 feet at 20,000 feet, 75 feet at 30,000 feet, and 60 feet at 40,000 feet.

The tolerance for the friction error listed in table I applies when the instrument is vibrated with an amplitude of 0.04 millimeter and a frequency of 50 cycles per second. If the vibration to which an instrument is subjected when installed in an aircraft differs appreciably from these values, the friction error of the instrument may be considerably different. The fact that the frictional errors of altimeters in service operation can differ from the values determined by laboratory tests has been demonstrated by flight tests of a helicopter at the Langley Laboratory. In these tests it was found that, upon descending to the ground after a flight of short duration to an altitude of 1,000 feet, two standard 50,000-foot altimeters read high by about 100 feet. The greater part of these errors could be removed immediately by tapping the instrument. When friction tests of these altimeters were conducted in the laboratory, the friction error of both instruments was found to be within the allowable tolerance. In flight tests of a counter-pointer altimeter installed in a propeller-driven airplane (ref. 6), it was found that, with normal airplane vibration, the friction error at an altitude of 3,000 feet was about 50 feet. When vibration was applied to the instrument, the friction error was largely eliminated. From the results of these tests it would appear that, if the small values of the friction error listed in table I are to be realized in practice, some means of vibrating the instrument, particularly in jet aircraft, will be required.

Another error which should be taken into account in connection with the instrument errors is the error of the manometer used to calibrate the altimeter. This error has been assigned a value of 0.01 inch of mercury, with corresponding altitude errors varying from 10 feet at sea level to 38 feet at 40,000 feet.

Tubing-lag error.- When the altitude of an airplane is changing, an error in altimeter indication may develop as a result of pressure lag in the connecting tubing. The magnitude of this error will depend on the length and bore of the tubing connecting the altimeter and the static-pressure source, the volume of the instruments connected to the tubing, the rate at which the pressure at the static-pressure source is changing, and altitude (ref. 7). For most service installations and for the rates of pressure change normally encountered in routine service operation, the lag error will be comparatively small. For example, an installation consisting of 11 indicators connected to a 100-foot length of 3/16-inch-bore tubing and undergoing a rate of descent of 1,000 feet per minute at sea level will have a lag error of about 20 feet.

Service errors.- Errors in altitude measurement may develop if changes occur to the system during service operation. For example, variations in static-pressure error may occur because of changes to the static-pressure orifices or fuselage vents or as a result of structural changes in the vicinity of the orifices (for example, flaking of the plating on a static-pressure tube or the addition or removal of any protuberance near a fuselage vent). Errors may also be introduced into the system by leaks in the pressure tubing or in the altimeter case. Extreme variations in static pressure can occur as a result of the accretion of ice in the vicinity of the static-pressure source or the accumulation of water into the pressure tubing. Most of these errors can be eliminated or minimized by periodic inspection and proper maintenance of the system.

The importance of properly maintaining the measuring system was revealed during the course of a recent program in which the altimeter installations of over 100 aircraft were calibrated (ref. 8). Routine examination of the installation in each aircraft prior to the calibration flight disclosed leaks in the measuring systems in about 20 percent of the aircraft. Loose connections, faulty drains, and cracked lines accounted for most of the leaks. However, leaks were also discovered in the cases of the altimeters, and in two instances the leaks were so large that the instruments could not be calibrated. The seriousness of leaks in the system will, of course, vary, since the altitude error due to a leak depends on the size and location of the leak in the system and the pressure drop across the leak.

Operational Errors

Errors may be introduced into the altimeter indication as a result of the operation of the system; for example, errors in reading the barometric scale on the altimeter, errors in reading the altitude scale, and errors in determining the altimeter setting at the ground station may be present. Since the airplane may be allowed to deviate from its intended flight level, this random deviation may be considered as an operational error which in reference 4 was termed "flight technical error." Estimates of the magnitude of these errors (with the exception of the station altimeter error) have been taken from reference 4 and are given in table II.

The values of flight technical error given in table II were derived from a large number of flight observations in a number of aircraft operated by manual control (ref. 4). These values can be reduced considerably if the airplane is flown by an autopilot having automatic height control.

Atmospheric Reference and Winds

Errors in altitude measurement may arise because of the use of an incorrect barometric dial setting on the altimeter and the effects of winds in mountainous regions.

Atmospheric reference.- The setting of the barometric dial of the altimeter (altimeter setting) may be incorrect because of variations in the atmospheric pressure following adjustments of the barometric dial or because of the use of different altimeter settings by two aircraft flying in the same vicinity (for example, between two stations, each reporting a different altimeter setting). The magnitude of the error will depend on the distance between the stations reporting altimeter settings and on the change in atmospheric pressure with time. In reference 4 this error was assigned a value of 200 feet, which is based on an atmospheric-pressure variation of 4 millibars per hour, a distance between reporting stations of 130 nautical miles, a geostrophic wind of 30 knots (producing a pressure gradient of 1 millibar per 26 nautical miles), and the assumption that the reported value of altimeter setting will not be older than one-half hour. It was noted in reference 4 that for some regions a value of 200 feet can be too conservative. In Europe, for example, height differences of 300 to 500 feet have been frequently reported at the boundaries between altimeter setting areas.

Effect of winds.- High-velocity winds over a mountain range will produce an appreciable reduction in the atmospheric pressure over and in the vicinity of the ridges. This pressure reduction increases as the square of the velocity of the wind across the flat approach to the mountain. An indication of the magnitude of the pressure reduction may be obtained theoretically by considering the mountain as a semicircular cylinder. In this case a 50-mile-per-hour wind normal to the ridge will induce a 100-mile-per-hour wind over the peak and an altitude error of about 250 feet at the surface of the peak. At 20 percent of the mountain height above the peak, the altitude error would be 160 feet.

CALCULATIONS OF THE OVERALL ERRORS OF ALTIMETER INSTALLATIONS

The errors in the measuring system, the operational errors, and the errors due to atmospheric reference have been combined in accordance with a computational method reported in reference 4. The overall error as determined by this method has a probability of 99.7 percent - that is, an error which would not be exceeded in 997 cases out of 1,000. A numerical example of the method for combining the errors is given in appendix B.

The calculation of the overall errors in this paper differs from that in reference 4 in a number of respects. In reference 4, for example, the altimeter-scale error and static-pressure error were included in the calculations. In the present paper two sets of calculations are presented: in the first, the altimeter-scale and static-pressure errors are included in the computations; in the second, these two errors are excluded on the assumption that corrections for both errors can be applied. The present calculations also include the error of the calibration method used to determine the static-pressure error, the "precision" of the altimeter-scale error (when corrections for this error are applied), the error of the manometer used to calibrate the altimeter, and the error of the station barometer.

Another difference between the calculations of reference 4 and those of the present paper concerns an "error" due to variations in air density. Reference 4 stated that a decrease in air temperature of 25° C below standard would decrease the vertical distance between two flight levels by 10 percent. An error, equal to 10 percent of the nominal separation of two flight levels (1,000, 1,500, or 2,000 feet), was therefore included in the calculations of the "effective" separation between two aircraft. The effective separation was defined as the nominal separation minus the sum of all of the altimetry errors, including the density error, plus an allowance of 75 feet for the physical dimensions of the aircraft. In the present paper the variations of air density are considered to have no effect on the vertical separation required for collision avoidance, except for the negligible effect (10 percent of 75 feet) on the allowance for the aircraft size. This statement is based on the premise that the altimetry errors represent height increments in the standard atmosphere and, as such, will expand and contract with density variations in the same proportion as the nominal separation of the flight levels.

The assignment of a maximum value for the static-pressure error is very difficult because of the wide variety of aircraft configurations and types of installations employed. In reference 4 the static-pressure error of an aircraft was estimated to vary from 125 feet at an altitude of 5,000 feet to 165 feet at an altitude of 40,000 feet. It was noted, however, that these figures do not represent extreme cases, for errors ranging from 50 feet to -600 feet are known to exist in the installations of some civil aircraft. In reference 8, calibrations of more than 100 airplanes, both civil and military, indicated that, although the static-pressure errors of most of the installations were within about ±200 feet (at an altitude of 15,000 feet and speeds up to 450 knots), the static-pressure errors of some of the installations were as much as 1,000 feet and -1,600 feet. Because of the difficulty of arriving at a realistic value for the static-pressure error which would apply to all aircraft, the static-pressure error in the present calculations has been assigned values specified in the currently applicable military specification: 25 feet per 100 knots at sea level (ref. 3 and fig. 1). The overall altimetry errors as determined by the present calculations would be valid, therefore, only when the static-pressure error is within a tolerance considered acceptable by present-day standards.

With the differences noted in the previous paragraphs, the computational method of reference 4 has been used to calculate the overall altimetry errors of the installations in a single aircraft for Mach numbers up to 1.0 and for altitudes up to 40,000 feet. The results of the calculations for the case in which the altimeter-scale error is within the tolerance given in table I and the static-pressure error is within the tolerance given in figure 1 are presented in figure 3(a). The overall errors for the case in which corrections are applied for the altimeter-scale and static-pressure errors are presented in figure 3(b). These figures show that the overall altimetry error increases with both Mach number and altitude. For the ranges of Mach number and altitude considered, the increase in overall error with altitude is much greater than with Mach number. These altimetry errors of a single installation are of primary interest in determining the allowances which must be made to provide adequate terrain clearance.

The combined overall errors of the installations in two aircraft have also been calculated for Mach numbers up to 1.0 and altitudes up to 40,000 feet. Inasmuch as the instrument and static-pressure errors of an installation may be either positive or negative, calculations of the vertical separation between two aircraft must be made on the assumption that the errors of the two installations have opposite signs. These calculations also include an allowance of 75 feet to account for the vertical airspace occupied by the aircraft (ref. 4). The combined overall errors of two aircraft for the case in which the altimeter-scale and static-pressure errors are within the allowable tolerances (table I and fig. 1, respectively) are presented in figure 4(a). The combined errors for the case in which corrections are applied to the altimeter-scale and static-pressure errors are presented in figure 4(b). These overall errors represent the vertical separation required to provide safe vertical clearance between the two aircraft.

The overall errors presented in figures 3 and 4 should be considered conservative, because the static-pressure error, atmospheric-reference error, and friction error may all be greater than the values used in these calculations. In addition, changes which may occur in the measuring system during its service life may cause the overall errors to increase considerably.

BAROMETRIC REFERENCE SYSTEMS

The overall altimetry errors presented in the preceding section are based on a barometric reference system requiring adjustment of the barometric dial of the altimeter to the current altimeter setting. If other barometric reference systems are used, the overall altimetry errors will be modified to some extent. Three barometric reference systems which have been considered at one time or another are

(1) Altimeter settings used in all areas

(2) Fixed setting of 29.92 used in all areas

(3) Fixed setting of 29.92 used outside of terminal areas and altimeter settings used within terminal areas

The system of using the altimeter settings in all areas (the system in use at the present time) has proved to be satisfactory in providing vertical separation in terminal areas and in providing reasonably correct measurements for terrain clearance en route. Safety of operation in regard to vertical separation en route, however, is questionable, because the use of this system imposes an obligation on the pilots in all aircraft to maintain barometric dial settings on the latest reported altimeter setting. Safety for en route operation also presupposes that the reporting ground stations will be spaced at frequent intervals (less than 100 miles apart).

The system of using a fixed setting of 29.92 by all aircraft in all areas has been proposed as a more positive means of separating flight levels and thus insuring vertical separation en route with a greater degree of safety. This system is used over certain ocean areas at the present time. The use of this system over land areas, however, would present a problem in providing adequate clearance over mountainous regions. It has been suggested that this problem could be solved by

(1) Establishing a network of barometric stations on mountain peaks to transmit local values of pressure altitude

(2) Calculating the maximum pressure altitude which could be expected over the mountains on the basis of the latest values of barometric pressure and temperature at the closest ground station

(3) Calculating the maximum pressure altitude over the mountains from the most adverse pressure, temperature, and wind data which might be encountered at these levels

The fixed-setting system includes the additional disadvantage that some loss of airspace would occur at the lower altitudes when the atmospheric pressure is lower than standard.

The system of using altimeter settings within terminal areas and a fixed setting of 29.92 en route has been proposed as a means of realizing the advantages of both the altimeter-setting system and the fixed-setting system. This combination of the two systems, however, may present a safety problem near the boundaries of terminal areas because of the possibility of different settings being used by aircraft operating in the same vicinity.

The use of a fixed barometric dial setting would reduce the overall altimetry error by eliminating the errors due to atmospheric reference, balance, coordination, zero setting, and station barometer.

COMPARISON OF ALTIMETRY ERRORS OF TWO AIRCRAFT WITH ALTITUDE SEPARATION MINIMUMS

The combined overall errors of the altimeter installations in two aircraft at a Mach number of 0.8 have been calculated for three cases:

(1) Altimeter-scale and static-pressure errors within tolerances given in table I and figure 1; altimeter settings used for barometric reference

(2) Corrections applied for altimeter-scale and static-pressure errors; altimeter settings used for barometric reference

(3) Corrections applied for altimeter-scale and static-pressure errors; fixed setting used for barometric reference

The results of these calculations, together with present altitude separate minimums (1,000-foot intervals from sea level to 29,000 feet and 2,000-foot intervals above 29,000 feet (ref. 9)), are presented in figure 5.

It is apparent from this figure that, when the altimeter-scale and static-pressure errors are within the specified tolerance and altimeter settings are used for barometric reference, the combined errors of two aircraft exceed present altitude-separation minimums at all altitudes. When corrections are applied for the altimeter-scale and static-pressure errors and altimeter settings are used for barometric reference, the combined errors are within the present minimums at altitudes up to 18,000 feet and between 31,000 and 40,000 feet. When corrections are applied to the altimeter-scale and static-pressure errors and a fixed setting is used for barometric reference, the combined errors are within the separation minimums at altitudes up to 24,500 feet and between 31,000 and 40,000 feet.

The three error curves shown in figure 5 are based on values for the flight technical error which would be experienced when the airplanes are operated by manual control. If the airplanes are flown by autopilots having automatic height control and if, in addition, the altimeter-scale and static-pressure errors are corrected and a fixed barometric setting is used, the combined errors could probably be reduced sufficiently to be within the separation minimums for all altitudes up to 40,000 feet.

In view of the magnitudes of the altimetry errors shown in figure 5, it would appear that, if present altitude separation minimums are to be retained, corrections should be applied to the altimeter-scale and static-pressure errors and a fixed setting should be used for barometric reference. In addition, aircraft in cruise operation (particularly at high altitude) should be flown by autopilots having automatic height control. Alternatively, if reduction in the altimetry errors cannot be accomplished, then the present altitude separation minimums should be increased to correspond more closely to the errors known to exist in present-day installations.

ALTIMETRY ERRORS DURING LANDING APPROACH

In the landing-approach condition, the overall error of an installation will be considerably lower than the values for en route operation given in figure 3 because two large errors, atmospheric-reference and flight technical errors, can be largely eliminated. The atmospheric-reference error should be negligible because of the short time lapse after adjustment of the barometric dial prior to the landing. The flight technical error should be small because of the increased concentration by the pilot in adhering to a prescribed altitude or flight path.

On the assumption that both the atmospheric-reference error and the flight technical error can be neglected, the overall error of an installation at a speed of 150 knots at sea level has been calculated for the same two cases considered for en route operation. When the altimeter-scale and static-pressure errors are within the specified tolerances (table I and fig. 1, respectively), the overall error is 170 feet. If corrections are applied to the altimeter-scale and static-pressure errors, the overall error becomes 112 feet. Inasmuch as a large part (82 feet) of this error is the accumulation of the many small instrument errors caused by imperfections in the instrument mechanism, any significant reduction in the overall error would appear to entail a difficult and, presumably, long-term instrument development program. Although the mechanical errors of the instrument are of primary importance for low-speed, low-altitude operation, they make up only a relatively small part of the overall errors of an installation operating at high speed and high altitude.

Even an error as low as 112 feet (representing the lowest error that can be achieved with present instrumentation at low speeds and low altitudes) is higher than can be tolerated for instrument landings with minimum permissible breakout heights less than 200 feet. It is believed, therefore, that the solution to the problem of providing height measurements of sufficient accuracy to permit the use of breakout minimums of 200 feet or lower will not be found in pressure altimetry but instead will come from the development of a low-altitude height-measuring system based on radar or similar instrumentation.

CONCLUDING REMARKS

For high-speed, high-altitude operation of aircraft, significant reductions in the overall altimetry errors can apparently be achieved by the application of present knowledge of the magnitude and nature of the various errors. Means by which the more serious errors in an altimeter system can be reduced are listed as follows:

(1) Altimeter-scale error: This error may be eliminated by applying corrections for the calibrated error either by an automatic computer or by the use of correction cards.

(2) Static-pressure error: This error may be reduced by determining the magnitude of the error by flight calibration and by applying corrections for the error by means of automatic computers or correction cards.

(3) Atmospheric-reference error: This error may be eliminated by changing the barometric reference system from the present system of altimeter settings to a system based on a fixed barometric dial setting for all aircraft.

(4) Flight technical error: This error may be reduced by the use of an autopilot having automatic height control to maintain assigned flight levels, particularly at high altitudes.

(5) Friction error: This error may be largely eliminated by properly vibrating the instrument.

(6) Service errors: These errors can be minimized by frequent inspection and proper maintenance of the airspeed-altitude system.

If steps are taken to reduce the overall errors as outlined, then present instrumentation may be considered to be adequate for operation within present altitude separation minimums. If, on the other hand, the altimetry errors are not reduced, the present separation minimums should be increased to correspond more closely to the errors which may exist in present-day installations.

For operation in the landing-approach condition, height measurements of sufficient accuracy apparently cannot be obtained with present altimeter systems but must come from the development of a low-altitude height-measuring system based on radar or similar instrumentation.

Langley Aëronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., August 1, 1957.

APPENDIX A

DEFINITIONS OF MECHANICAL ERRORS OF ALTIMETERS

Definitions of the mechanical errors of altimeters have been taken from reference 4 and are listed as follows:

Scale (or diaphragm) error: Error due to the physical properties and the construction of the aneroid and linkage. Because of these properties, the diaphragm deflection will not be linear but will differ for the same given change of atmospheric pressure at different heights.

Friction error: Error due to friction in the altimeter mechanism transmitting the diaphragm movement to the pointers (which can be partially eliminated by vibration) plus friction in the temperature compensating pins (which cannot be eliminated by vibration).

Temperature error: Error due to the inability of the instrument, which is designed to compensate for effects of temperature over a considerable range, to eliminate all temperature effects.

Backlash error: Error which may arise because of lost motion in the gear transmission between the pressure scale and the height scale and in the idler gear of the instrument.

Balance error: Error due to the impossibility of coordinating the state of balance of all moving parts of the altimeter to such a degree that the instrument will be entirely independent of its position in relation to its calibration position (29.92 inches).

Coordination error: Error due to the inability to obtain complete correspondence between the pressure-scale graduation and the height scale of the altimeter.

Instability error: Error due to different reaction of the instrument during two consecutive climbs or descents.

Zero-setting error: Error due to the shape of the tolerance curve with height. Because of this characteristic, the tolerance at certain heights is different if a zero setting other than 29.92 inches is used.

APPENDIX B

SAMPLE CALCULATIONS OF OVERALL ERRORS OF ALTIMETER INSTALLATIONS

The method of combining the individual altimetry errors as given in reference 4 requires as a preliminary step that each error be examined to determine the nature of its distribution. Errors which have a random distribution (normal, rectangular, or limit) are then added statistically, and those that have no distribution are added in their entirety.

In the statistical summation of the random errors the numerical values given in the text are considered to be "maximum errors" (ref. 10). Thus, the standard deviation of each error can be determined by dividing the maximum errors by an appropriate factor which depends on the type of distribution (3 for normal, $\sqrt{3}$ for rectangular, and 1 for limit). The standard deviations of the various errors are then added statistically, and the sum is multiplied by 3. The result represents the maximum value for the random errors of a single installation and, as such, has a probability of 99.7 percent (that is, an error which will not be exceeded in 997 cases out of 1,000). When the random errors of two installations are to be combined, the maximum error of one installation must be multiplied by $\sqrt{2}$.

The maximum value for the random errors is then added to the full values of those errors having no distribution. This summation yields an overall error which, in the case of two aircraft, represents the altitude separation which will provide safe vertical clearance in 997 cases out of 1,000.

A numerical example of the method of combining the individual altimetry errors is given for two aircraft operating at $M = 0.8$ at an altitude of 20,000 feet. The overall altimetry error is calculated for two cases: in the first, the altimeter-scale error is assumed to equal the tolerance listed in table I, and the static-pressure error, the tolerance given in figure 1; in the second, it is assumed that corrections for these two errors can be applied.

Case I

In case I, the altimeter-scale error is assumed to equal the tolerance listed in table I, and the static-pressure error, the tolerance given in figure 1. The random errors, together with their type of distribution and the numerical values of their standard deviations, for $M = 0.8$ and an altitude of 20,000 feet, are listed as follows:

Error	Standard deviation, ft
Normal distribution	
Friction	50/3
Temperature	10/3
Flight technical	440/3
Instability	55/3
Coordination	25/3
Balance	20/3
Station barometer	25/3
Manometer	17/3
Precision (static-pressure error)	125/3
Rectangular distribution	
Readability (altitude)	$20/\sqrt{3}$
Readability (pressure)	$15/\sqrt{3}$
Limit distribution	
Backlash	10

The statistical sum σ of the standard deviations of the random errors is calculated as follows:

$$\sigma = \sqrt{\left(\frac{50}{3}\right)^2 + \left(\frac{10}{3}\right)^2 + \left(\frac{440}{3}\right)^2 + \left(\frac{55}{3}\right)^2 + \left(\frac{25}{3}\right)^2 + \left(\frac{20}{3}\right)^2 + \left(\frac{25}{3}\right)^2 + \left(\frac{17}{3}\right)^2 + \left(\frac{125}{3}\right)^2 + \left(\frac{20}{\sqrt{3}}\right)^2 + \left(\frac{15}{\sqrt{3}}\right)^2 + (10)^2}$$

$$\sigma = 157 \text{ feet}$$

The maximum value of the random errors of a single installation is 3σ or 471 feet. For two aircraft the maximum value is $471\sqrt{2}$ or 666 feet. To this value the errors having no distribution are added as follows:

Maximum value of random errors, ft	666
Zero setting (30 × 2), ft	60
Atmospheric reference (200 × 1), ft	200
Altimeter-scale error (320 × 2), ft	640
Static-pressure error (93 × 2), ft	186
Size of aircraft (75 × 1), ft	75
Total, ft	1,827

Case II

In case II, corrections are applied for the altimeter-scale error and the static-pressure error. When these corrections are applied, the "precision" of the altimeter-scale error should be included in the statistical summation of the other random errors. The "precision" of the altimeter-scale error is considered to be a limit error. For an altitude of 20,000 feet this error has been assigned a value of 75 feet (one-half the hysteresis at this altitude). The statistical addition of this error to the random errors considered in case I yields a value of σ of 174 feet. The maximum error of a single installation becomes 174×3 or 522 feet, and the combined error of two installations becomes $522\sqrt{2}$ or 738 feet. This error is added to the errors having no distribution as follows:

Maximum value of random errors, ft	738
Zero setting (30 × 2), ft	60
Pressure datum (200 × 1), ft	200
Size of aircraft (75 × 1), ft	75
Total, ft	1,073

Thus, the required altitude separation for two aircraft operating at $M = 0.8$ and an altitude of 20,000 feet is 1,827 feet when no corrections are applied for the altimeter-scale and static-pressure errors and 1,073 feet when corrections for these two errors are applied.

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TABLE I

MAXIMUM ALLOWABLE LIMITS OF MECHANICAL ERRORS FOR STANDARD 50,000-FOOT AIRCRAFT ALTIMETER

Type of error	Altitude error, ft, at altitude, ft, of -				
	5,000	10,000	20,000	30,000	40,000
Scale	100	150	320	510	650
Friction	30	30	50	75	100
Temperature	10	10	10	10	10
Backlash	10	10	10	10	10
Balance	20	20	20	20	20
Coordination	25	25	25	25	25
Instability	32	40	55	75	100
Zero setting	15	15	30	30	20

TABLE II

ESTIMATED MAGNITUDE OF OPERATIONAL ERRORS

Type of error	Altitude error, ft, at altitude, ft, of -				
	5,000	10,000	20,000	30,000	40,000
Readability (barometric scale)	15	15	15	15	15
Readability (altimeter scale)	20	20	20	20	20
Station altimeter	25	25	25	25	25
Flight technical	175	175	440	750	1,000

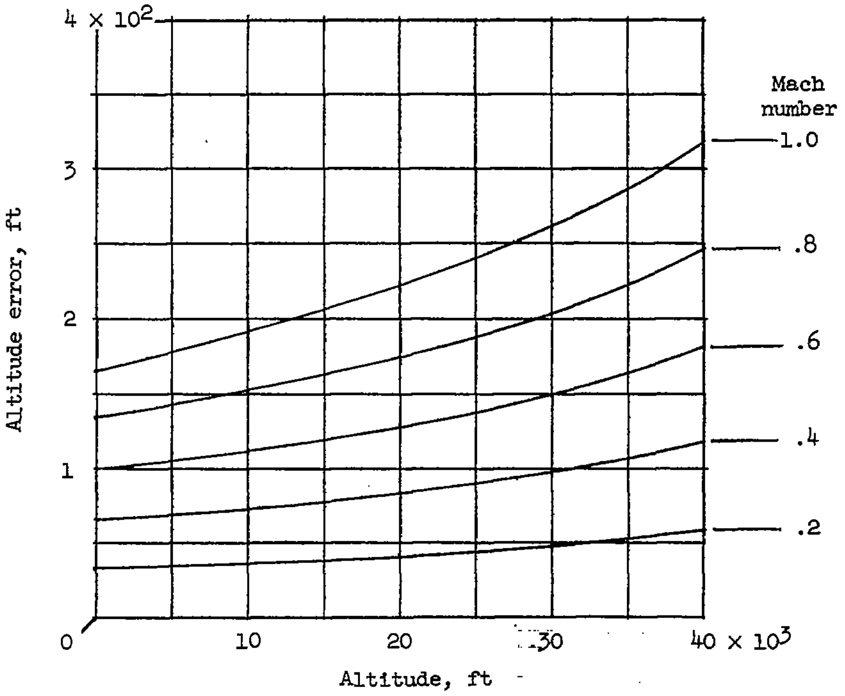


Figure 1.- Altitude errors corresponding to tolerance of 25 feet per 100 knots indicated airspeed at sea level as specified in reference 3.

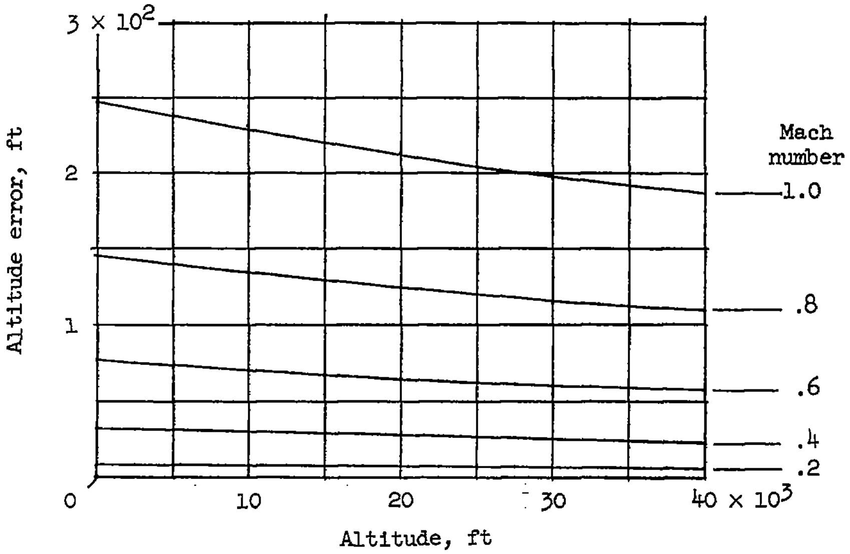
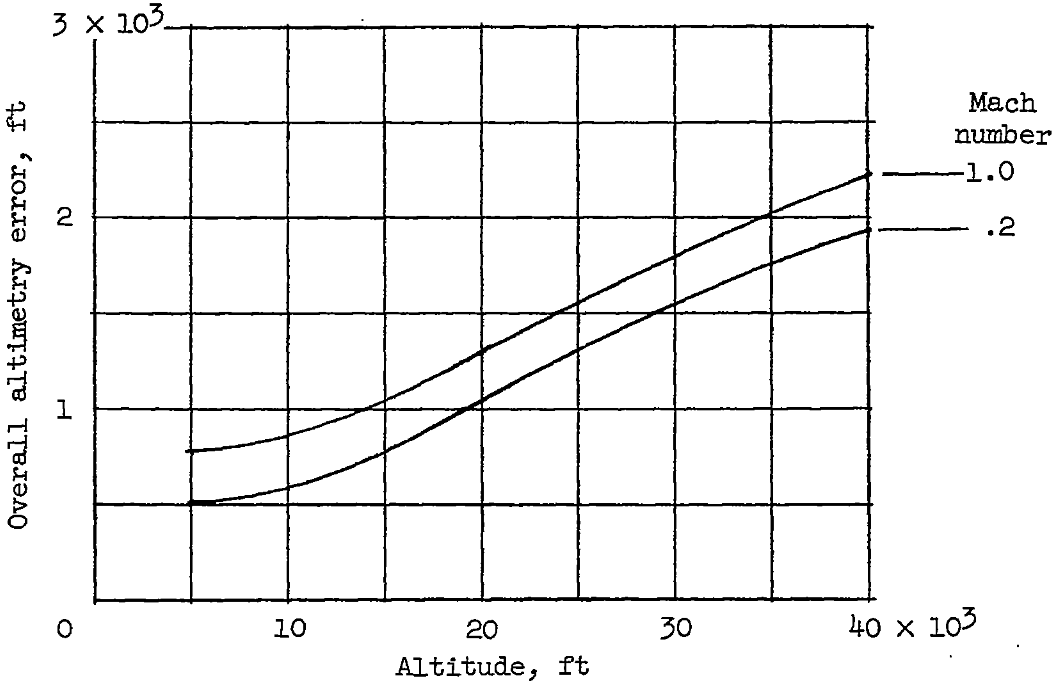
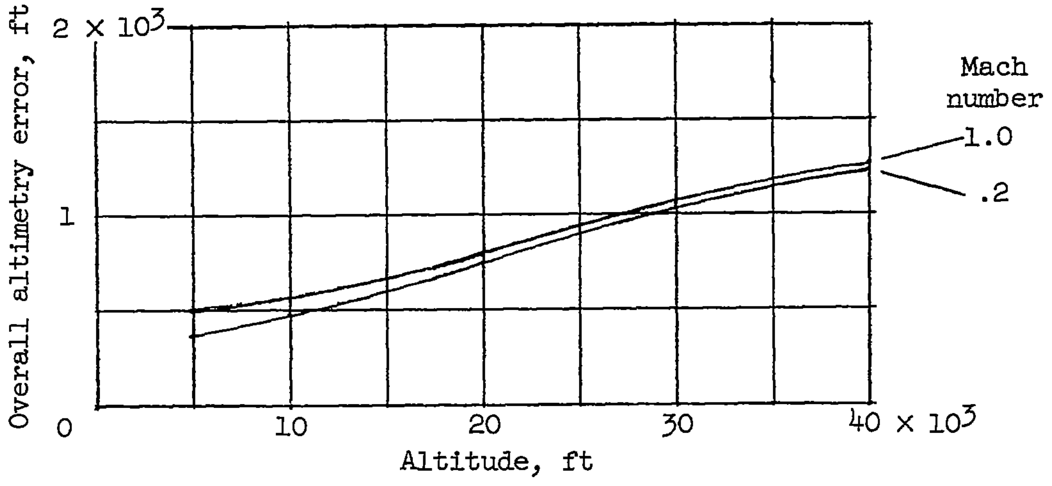


Figure 2.- Altitude errors equivalent to static-pressure error of 1 percent of impact pressure.

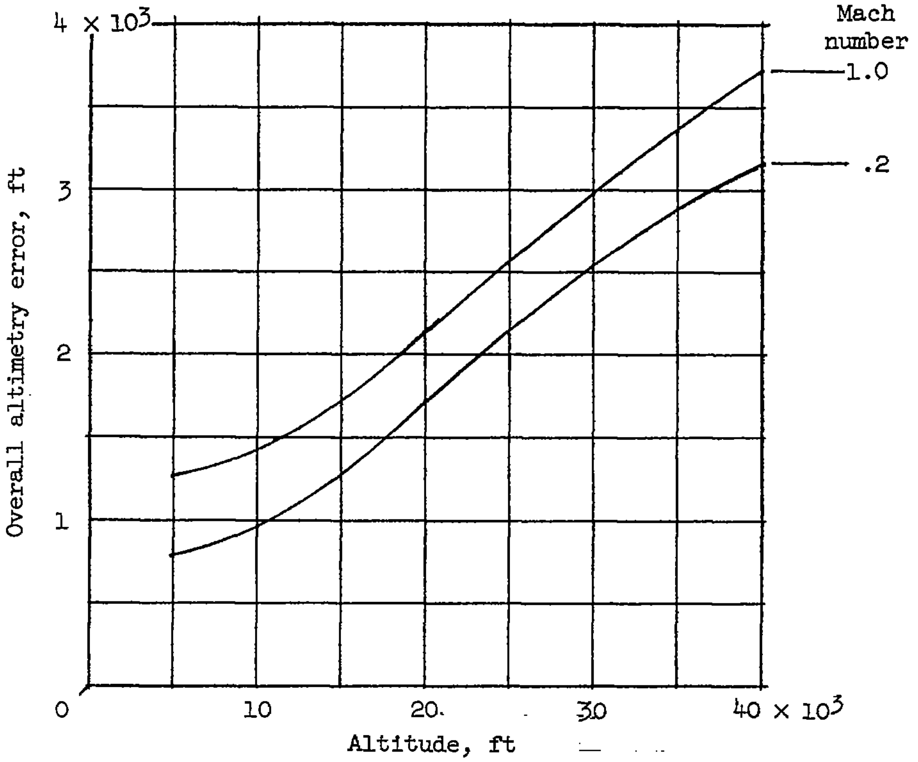


(a) Altimeter-scale error within tolerance given in table I and static-pressure error within tolerance presented in figure 1.

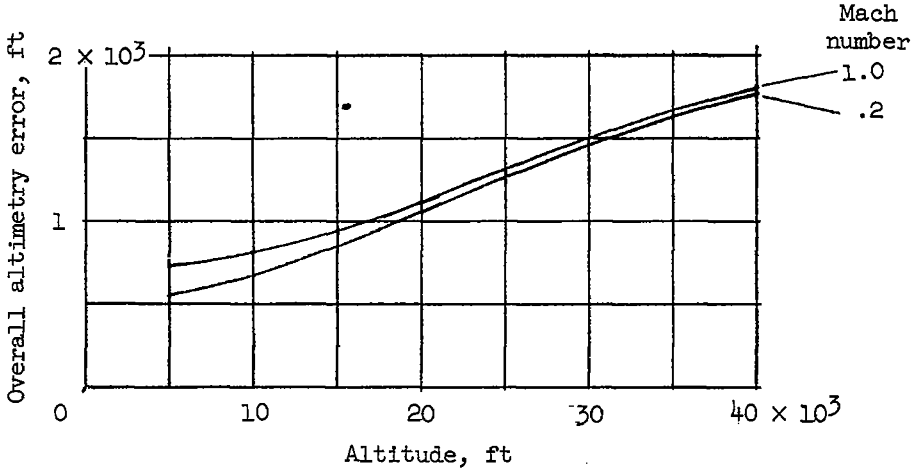


(b) Corrections applied to altimeter-scale and static-pressure errors.

Figure 3.- Overall altimetry error of installation in single aircraft. Probability of errors is 99.7 percent.



(a) Altimeter-scale error within tolerance given in table I and static-pressure error within tolerance presented in figure 1.



(b) Corrections applied to altimeter-scale and static-pressure errors.

Figure 4.- Combined overall altimetry errors of installations in two aircraft. Probability of errors is 99.7 percent.

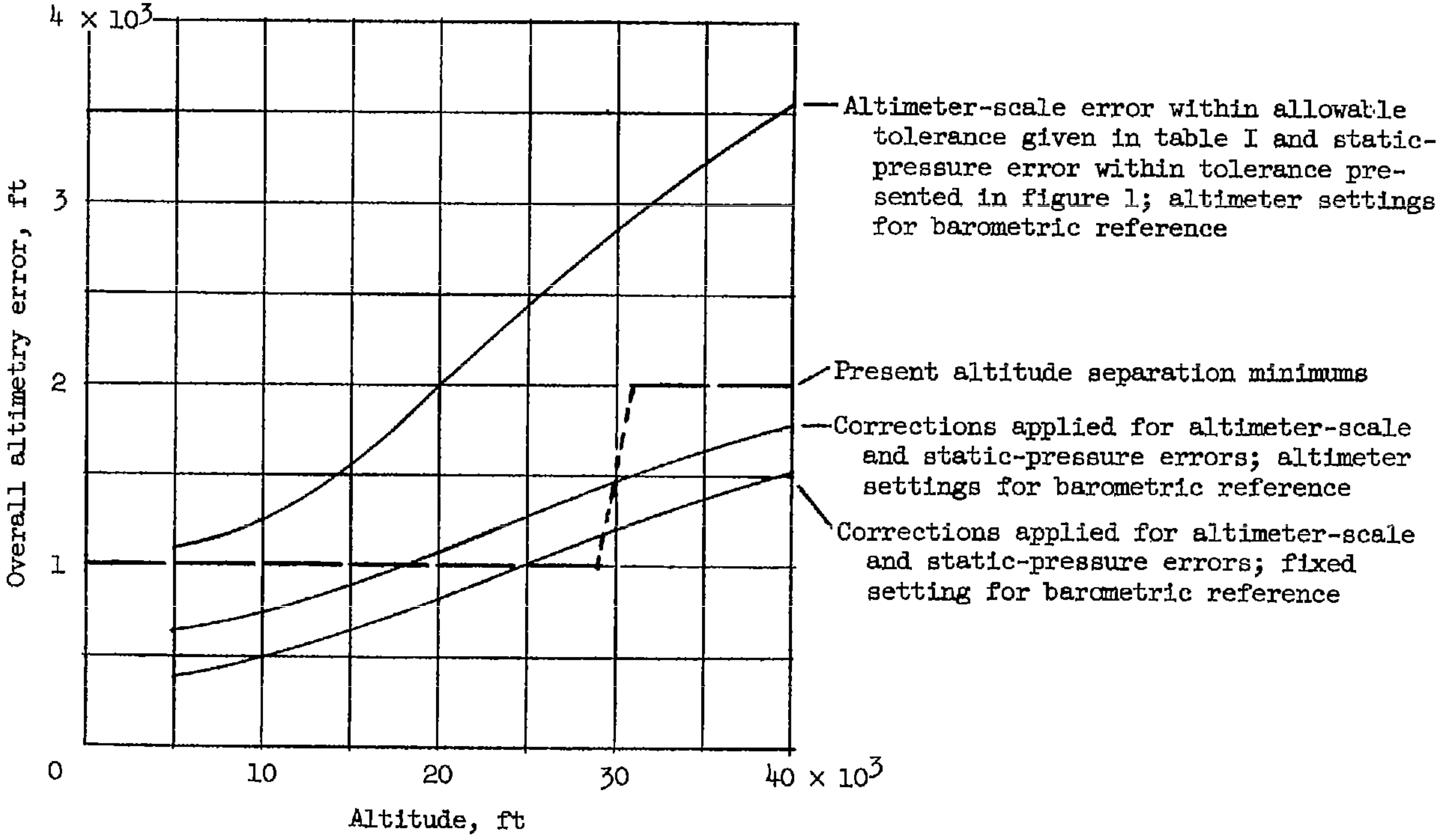


Figure 5.- Combined overall altimetry errors of installations in two aircraft at Mach number of 0.8. Probability of errors is 99.7 percent.