TECHNICAL NOTE

D-463

MEASUREMENT OF THE ERRORS OF SERVICE ALTIMETER

INSTALLATIONS DURING LANDING-APPROACH

AND TAKE-OFF OPERATIONS

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

WASHINGTON   November 1960

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SUMMARY

The overall errors of the service altimeter installations of a variety of civil transport, military, and general-aviation airplanes have been experimentally determined during normal landing-approach and take-off operations. The average height above the runway at which the data were obtained was about 280 feet for the landings and about 440 feet for the take-offs.

An analysis of the data obtained from 196 airplanes during 415 landing approaches and from 70 airplanes during 152 take-offs showed that:

1. The overall error of the altimeter installations in the landing-approach condition had a probable value (50 percent probability) of ±36 feet and a maximum probable value (99.7 percent probability) of ±159 feet with a bias of +10 feet.

2. The overall error in the take-off condition had a probable value of ±47 feet and a maximum probable value of ±207 feet with a bias of -33 feet.

3. The overall errors of the military airplanes were generally larger than those of the civil transports in both the landing-approach and take-off conditions. In the landing-approach condition the probable error and the maximum probable error of the military airplanes were ±43 and ±189 feet, respectively, with a bias of +15 feet, whereas those for the civil transports were ±22 and ±96 feet, respectively, with a bias of +1 foot.

4. The bias values of the error distributions (+10 feet for the landings and -33 feet for the take-offs) appear to represent a measure of the hysteresis characteristics (aftereffect and recovery) and friction of the instrument and the pressure lag of the tubing-instrument system.

INTRODUCTION

In reference 1 the overall errors of airplane altimeter installations in the landing-approach condition were estimated from an assessment of the various individual errors (instrument, pressure, and operational) which contribute to the complete system error. In that analysis the allowable tolerances for each of the individual errors (taken for the most part from ref. 2) were assumed to represent maximum probable values; that is, values having a probability of 99.7 percent. The maximum probable values of the individual errors were then combined to produce an overall error having a probability of 99.7 percent; that is, an error that would not be exceeded in 997 cases out of 1,000.

The two individual errors having the largest values were the altimeter scale error and the static-pressure error. For the analysis in reference 1 the values of these two errors were assumed to equal the tolerances specified for altimeter systems in military airplanes prior to about 1954; that is, an altimeter scale error of ± 50 feet and a static-pressure error (based on an assumed approach speed of 150 knots) of ± 38 feet. The combination of these values with the values of the other instrument and operational errors given in reference 2 produced an overall error of ± 170 feet.

In view of the magnitude of this error and its serious implication for the safety of landing operations under low-visibility weather conditions, a test program has been conducted to determine experimentally the overall errors of the service altimeter systems of a variety of aircraft during routine landing operations. As an extension to this program, tests were also conducted to determine the altimetry errors during take-off operations. This report presents the altimetry errors as determined from 196 airplanes during 415 landing approaches and from 70 airplanes during 152 take-off operations.

SYMBOLS

h_g geometric height of wheels of airplane above runway, ft

h_p pressure altitude at height h_g, ft

h_i pressure altitude indicated by altimeter with barometric dial
set to current altimeter setting, ft

Δh overall error of altimeter installation, $h_i - h_p$, ft

T_s standard atmospheric temperature at elevation of runway, °F abs

T_a actual atmospheric temperature at elevation of runway, °F abs

APPARATUS AND TEST METHOD

The overall errors of the altimeter installations during landing-approach and take-off operations were determined from a comparison of (1) the altimeter indication as read by the pilot when the airplane was directly over a ground station and (2) the correct pressure altitude at the elevation of the airplane as determined from the geometric height of the aircraft above the ground station. Prior to each test run the pilot was asked to set the barometric adjustment on the altimeter to the current altimeter setting as reported by the airport control-tower operator.

The ground station was located near the middle marker of instrument landing system installations at two commercial airports serving civil transport, military, and general-aviation airplanes. For this investigation the average height of the aircraft over the runway plane was about 280 feet in the landing-approach and 440 feet in the take-off operations. These heights are noted to indicate that the airplanes were a sufficient height above the ground for the static-pressure systems to be unaffected by ground effect.

The geometric height of the airplane above the ground station was determined by photographing the airplane with a camera located at the station. The camera used for these measurements was a single-exposure, 5- by 5-inch aerial camera mounted on a tripod with its optic axis vertical. The camera was equipped with a simple sighting device by means of which the camera operator could determine when the airplane was alined with the optic axis. (See fig. 1.) In most of the test runs the speed of the airplane was sufficiently low for the operator to "center" the airplane in the film frame. The camera record and the pilot's reading of the altimeter were synchronized by means of a radio signal which was transmitted by the camera operator at the instant he photographed the airplane.

The geometric height was computed from the length of the wing span on the photographic film, the actual wing span, and the focal length of the lens. The focal length of the lens was calibrated prior to the test program by photographing vertical ground markers a known distance apart and a known distance from the camera. This calibration also provided the corrections to be applied to the film measurements for those cases in which the airplane image was offset from the center of the film frame.

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The geometric height computed on the basis of the wing span represented the height of the wing-tip plane above the camera. The quantity needed for comparison with the altimeter readings, however, is the pressure altitude at the height of the wheels of the airplane above the runway. The basis of this statement is the fact that, when the barometric dial of an altimeter is set to the current altimeter setting, the altimeter should indicate the elevation of the runway when the airplane is at rest on the runway. For this reason, the geometric height of each airplane above the camera was corrected to the height of the wheels of the aircraft above the runway. (Actually, the altimeter setting is computed for an altimeter at a height of 10 feet above the runway surface; thus, an additional error will be present in the altimeter readings of those airplanes for which the height of the altimeter above the runway is different from the 10-foot standard.)

In the computation of the geometric height it was necessary to assume that the wings of the airplane were laterally level. From ground observations of the airplane over the camera station it appeared that in no case were the airplanes banked more than 5°. For an airplane with a wing span of 100 feet at a height of 300 feet above the camera, the error in geometric height introduced by a bank angle of 5° would be about 1 foot.

The geometric height of the wheels of the airplane above the runway was converted to the corresponding pressure altitude above the runway by means of the equation

$$h_p = h_g \frac{T_s}{T_a} \tag{1}$$

where h_p is the pressure altitude above the runway, h_g is the geometric height of the wheels above the runway, T_s is the standard absolute temperature for the elevation of the airport, and T_a is the actual absolute temperature at the runway. The elevation of the runway was then added to the pressure altitude h_p and this sum was used as the basis of comparison of the altimeter indications over the camera station. Strictly speaking, the temperatures given in equation (1) should be stated in terms of the mean temperatures (actual and standard) of the air column between the ground and the airplane. However, for the relatively low airplane heights (280 to 440 feet) and the small ground-temperature deviations from standard (-27° to +13° F), of the present tests, the error introduced by this approximation is negligible. Errors in height due to errors in the measurement of ground temperature were also small. For example, for an error of 1° F, the error in the computation of a height of 300 feet would be less than 1 foot.

The airplanes for which altimetry errors were determined in the landing program included 74 civil transport airplanes (operated by three scheduled airlines), 91 military airplanes (operated by various air force, army, coast guard, and navy squadrons), and 31 general-aviation airplanes (most of which were of the private-owner, as compared with the executive-transport, type). These airplanes represented 8 civil transport types, 13 military types, and 18 general-aviation types. The airplanes varied in size from small private-owner types to medium-size civil and military transports.

ALTIMETRY ERRORS IN LANDING-APPROACH AND TAKE-OFF OPERATIONS

For an airplane in the landing-approach or take-off condition, the difference between the altitude indicated by the altimeter and the true elevation of the airplane is determined by the error in the pressure measured by the static-pressure source, the mechanical errors of the altimeter, the errors due to a tubing lag or to leaks in the static-pressure system, errors in the measurement and reporting of the altimeter setting, errors in setting the barometric pressure scale and in reading the altimeter, and variations in pressure altitude due to deviations of the atmospheric temperature from standard. In this report the overall error Δh of an altimeter installation is defined as comprising all the above errors except that due to variations in atmospheric temperature.

The static-pressure error on a particular airplane should, for a given speed, pressure altitude, gross weight, and aircraft configuration, have a fixed value. However, since any or all of these quantities may be different during successive take-off or landing-approach operations, the static-pressure error may be expected to vary to some extent during repeated runs at the same elevation. These variations in static-pressure error, however, should not exceed the allowable tolerance specified for civil transport aircraft (-50 to 20 feet for the older aircraft, ref. 3, and ±30 feet per 100 knots at sea level for the more recent types, ref. 4) and for military aircraft (±25 feet per 100 knots at sea level, ref. 5). It may be noted that the static-pressure systems of private-owner airplanes in the general aircraft category are not required to meet any specified tolerance.

The mechanical errors of the altimeter include the scale error, which should be relatively invariant, and a number of smaller errors (temperature, friction, acceleration, and aftereffect and recovery - i.e., hysteresis and drift at the completion of a pressure cycle) which will generally vary in an indeterminate manner. (For the relatively constant rates of change of altitude of most landing-approach and take-off operations, however, the error due to friction would be expected to be always in a direction that would cause the indicated altitude to lag behind the sensed pressure altitude.) The scale-error tolerances at sea level for altimeters having the so-called "sensitive" mechanism is ±20 feet for the older civil transport airplanes (ref. 6) and ±50 feet

for the older military airplanes (ref. 7). The tolerance for altimeters
having the newer "precision" mechanism and which are being specified for
the newer aircraft is ±20 feet for civil airplanes (ref. 8) and ±30 feet
for military airplanes (ref. 9). Again, it may be noted that there are
no regulations governing the error tolerances of the altimeters installed
in private-owner types of airplanes. From a knowledge of the type and
age of the airplanes tested, it is believed that most of the altimeters
from which measurements were obtained were of the "sensitive" type.

Errors due to the time lag in the transmission of the source pres-
sure to the altimeter depend on (1) the pressure and viscosity of the
air, (2) the rate of pressure change at the pressure source, (3) the
flow resistance characteristics of the tubing (which depend principally
on the length and bore of the tubing), and (4) the volume of the instru-
ments at the end of the static-pressure tubing. For the relatively low
rates of descent of the normal landing approach, the design of most
pressure systems is such that the lag error will be small. For example,
for a system of two altimeters, two airspeed indicators, and two rate-of-
climb indicators connected to a 50-foot length of 3/16-inch-bore tubing
and a rate of change of altitude of 600 feet per minute, the lag error
at sea level would correspond to an altitude error of about 3 feet.

Errors due to leaks in the pressure system depend on the size and
location of the leak in the system and on the pressure differential
across the leak. Although both civil and military agencies prescribe
maximum permissible leak rates for altimeter systems, these tolerances
may not truly reflect the leak rates of service installations. In the
test program reported in reference 10, for example, serious leaks were
found in about 20 percent of over 100 service airplanes on which leak
tests were performed. The effect of a leak can be most serious in pres-
surized aircraft if the leak occurs within the pressurized area. Although
a large number of the civil transport and military airplanes for which
data were obtained in this investigation were known to be pressurized,
the effect of this factor on the measured errors was impossible to deter-
mine because of a lack of knowledge of the leak condition of the systems
and of the degree of pressurization employed during the landing approach.

Errors in the measurement and reporting of the altimeter setting
by the tower were determined from measurements of the barometric pressure
at the camera stations at the two airports. The instrument used for the
measurement of barometric pressure was a barograph having an accuracy of
about ±0.01 inch mercury. For each day of operation, sample measurements
were selected from the barograph record for time periods when the pressure
was unchanging. These pressures were converted to altimeter settings,
which were then compared with the current reported setting. A comparison
of 65 measurements showed the reported settings to have a standard devia-
tion of 0.013 inch mercury (about 12 feet in altitude).

Errors due to the pilot's missetting of the barometric scale or
misreading of the altimeter in the present tests are, of course, impos-
sible to evaluate. However, an indication of the extent to which the

pilots attempted to provide accurate information may be gathered from the fact that in most cases the altimeter readings were reported to the nearest 10 feet and in many cases to the nearest 5 feet.

It is true that, if there were a time lag in the pilots' reading of the altimeters after receiving the signal from the camera operator, the error distribution would be biased. For a rate of altitude change of 600 feet per minute and a lag of 1 second in reading, the error due to lag in reading would amount to an altitude error of 10 feet. If errors due to this source did occur, the overall errors measured in the present tests would be biased in a negative direction for the landing-approach condition and in a positive direction for the take-off condition.

With the barometric dial set to the current altimeter setting, the deviation of the airplane from the true elevation due to a variation in the atmospheric temperature from standard is a function of the amount by which the actual temperature differs from standard and the height of the airplane above the runway. For a temperature deviation of 40° F from standard, the pressure altitude will differ from the actual height above the runway by about 10 percent of that height. Since, in the present tests, the height of the airplane above the runway was converted to the pressure altitude corresponding to the existing temperature, the overall errors as determined in this investigation will become more positive when the air temperature is below standard and more negative when the temperature is above standard. For a geometric height of 200 feet, for example, the effect of variations in atmospheric temperature (assuming no other errors) would cause the altimeter to indicate 220 feet at a temperature of 20° F and 180 feet at a temperature of 100° F.

RESULTS AND DISCUSSION

The range of the overall errors measured on each type of airplane in the landing-approach condition is tabulated in table I. Since the altimeter systems of the airplanes in the civil transport, military, and general-aviation categories are controlled by different specifications for the static-pressure and instrument errors, the data in table I have also been grouped according to aircraft category and to the operating agencies within each category. A large range of error for a given type of aircraft can result from differences in the instrument errors and from differences in static-pressure errors due to variations in the landing speed and aircraft configuration. Errors in excess of the applicable tolerances for a given aircraft category may reflect the degree to which the altimeter systems are maintained by the particular operating agency.

The overall errors of the altimeter installations of the various individual airplanes in the landing-approach condition are presented in figures 2 to 4. In these figures the errors have been grouped in 20-foot increments and plotted in terms of the number of errors in each class interval.

Figure 2 shows the distribution of 444 errors of 196 civil transport, military, and general-aviation airplanes as determined during 415 landing approaches. (The number of errors is greater than the number of landings because in a number of cases readings were reported for both the pilot's and copilot's altimeters.) The average value of these errors is +10 feet and the standard deviation is 53 feet. The probable error (50 percent probability) is, therefore, ±36 feet (0.675 times the standard deviation) and the maximum probable error (99.7 percent probability) is ±159 feet (3 times the standard deviation) with both errors having a bias of +10 feet.

In figures 3 and 4 the distributions of the errors for the civil transport and military airplanes are shown separately. (The number of test points obtained from general-aviation airplanes was too limited to form a valid statistical sample.) For the 161 measurements obtained from 74 civil transports in 154 landing approaches the probable error is ±22 feet and the maximum probable error is ±96 feet with a bias of +1 foot. For the 248 measurements of 91 military aircraft in 226 approaches the probable error is ±43 feet and the maximum probable error is ±189 feet with a bias of +15 feet. The larger error of the military airplanes appears consistent, at least in part, in view of the larger scale-error tolerance (±50 feet) for military airplanes as compared with that (±20 feet) for civil airplanes. It may also be noted that, as discussed previously, the military tolerances for the altimeter scale error and the static-pressure error were used in the estimation of the ±170-foot maximum probable error reported in reference 1; this estimated figure compares favorably with the ±189-foot value determined in the present tests for military airplanes.

The overall errors determined during take-off operations are presented in figure 5. This figure shows the distribution of 176 errors of 70 civil transport, military, and general-aviation airplanes as measured during 152 take-off operations. The probable error for this case is ±47 feet and the maximum probable error is ±207 feet with a -33-foot bias. The number of measurements obtained for each of the civil transport, military, and general-aviation categories was insufficient to permit a determination of the standard deviation for the separate aircraft groups. However, it may be noted that the errors of the military and general-aviation aircraft were generally larger than those of the civil transports.

For both the take-off and landing-approach condition the error distributions are biased in a direction that would result from hysteresis characteristics (aftereffect and recovery) and friction of the instrument and pressure lag of the tubing-instrument system. Supporting evidence that the bias values of the two error distributions are actually representative of lag in the altimeter systems was derived from the results of tests of 25 of the aircraft for which readings were obtained in both the landing and take-off conditions. The average difference between the errors measured with these aircraft in the two conditions was 40 feet; this is of the same order as the sum of the bias values (43 feet) of the error distributions for the landing and take-off conditions.

CONCLUDING REMARKS

From the results of tests of 196 civil transport, military, and general-aviation airplanes during 415 landing approaches (at an average height of 280 feet) and of 70 airplanes in 152 take-off operations (at an average height of 440 feet), it has been determined that:

1. The overall error of the altimeter installations in the landing-approach condition had a probable value (50 percent probability) of ±36 feet and a maximum probable value (99.7 percent probability) of ±159 feet with a bias of +10 feet.

2. The overall error in the take-off condition had a probable value of ±47 feet and a maximum probable value of ±207 feet with a bias of -33 feet.

3. The overall errors of the military airplanes were generally larger than those of the civil transports in both the landing-approach and take-off conditions. In the landing-approach condition the probable error and the maximum probable error of the military airplanes were ±43 and ±189 feet, respectively, with a bias of +15 feet, whereas those for the civil transports were ±22 and ±96 feet, respectively, with a bias of +1 foot.

4. The bias values of the error distributions (+10 feet for the landings and -33 feet for the take-offs) appear to represent a measure of the hysteresis characteristics (aftereffect and recovery) and friction of the instrument and the pressure lag of the tubing-instrument system.

Langley Research Center,
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TABLE I.- RANGE OF OVERALL ALTIMETRY ERRORS

OF THE VARIOUS TYPES OF AIRPLANES IN THE

LANDING-APPROACH CONDITION[1]

(a) Civil transport airplanes

Type of airplane	Number of airplanes	Range of errors, ft
Airline A		
Tm-1	8	-46 to +11
Tm-2	9	-23 to +40
Tm-3	2	-31 to +1
Tm-4	5	-65 to +6
Tm-5	20	-40 to +57
Airline B		
Tm-3	8	-12 to +58
Tm-6	11	-122 to +71
Tm-7	3	-60 to +43
Airline C		
Tm-1	1	-34
Tm-8	7	-99 to +68

[1]Airplane-type designations:

Pa	patrol, amphibious
POs	private-owner, small (2 to 3 passengers)
POm	private-owner, medium (4 to 5 passengers)
Tj	trainer, jet powered
Tp	trainer, propeller driven
Ts	transport, small (6 to 11 passengers)
Tm	transport, medium (21 to 52 passengers)

Numerals following an aircraft designation represent different types of airplanes within the class designation; for example, Pa-1 and Pa-2 are two different types of patrol, amphibious airplanes.

TABLE I.- RANGE OF OVERALL ALTIMETRY ERRORS

OF THE VARIOUS TYPES OF AIRPLANES IN THE

LANDING-APPROACH CONDITION - Continued[1]

(b) Military airplanes

| Type of airplane	Number of airplanes	Range of errors, ft
Service A		
Pa-1	4	-14 to +77
Tm-3	2	+103 to +184
Service B		
POm-3	6	-46 to +221
Ts-3	2	-19 to +46
Ts-4	7	-222 to +69
Service C		
POm-7	2	-18 to +192
Tj-1	9	+8 to +134
Tm-1	11	-82 to +125
Tm-3	7	-34 to +103
Tm-6	5	-22 to +128
Service D		
Pa-2	4	-62 to +116
Tp-1	2	-39 to +98
Ts-1	14	-269 to +156
Ts-5	6	-60 to +46
Tm-1	1	+21
Tm-3	3	-48 to +76
Tm-6	6	-66 to +163

[1]See footnote on first page of table.

TABLE I.- RANGE OF OVERALL ALTIMETRY ERRORS

OF THE VARIOUS TYPES OF AIRPLANES IN THE

LANDING-APPROACH CONDITION - Concluded[1]

(c) General aviation airplanes

Type of airplane	Number of airplanes	Range of errors, ft
Executive transports		
Ts-1	1	-56
Ts-2	2	+52 to +111
Tm-1	1	-63
Tm-9	2	+1 to +30
Private-owner		
POs-1	1	-12
POs-2	1	+36
POs-3	4	-12 to +44
POs-4	3	+8 to +50
POs-5	1	+44
POs-6	1	+9
POs-7	2	-40 to +19
POs-8	3	-35 to +17
POm-1	3	-88 to +86
POm-2	2	+54 to +59
POm-3	1	-86
POm-4	1	-8
POm-5	1	+38
POm-6	1	+22

[1]See footnote on first page of table.
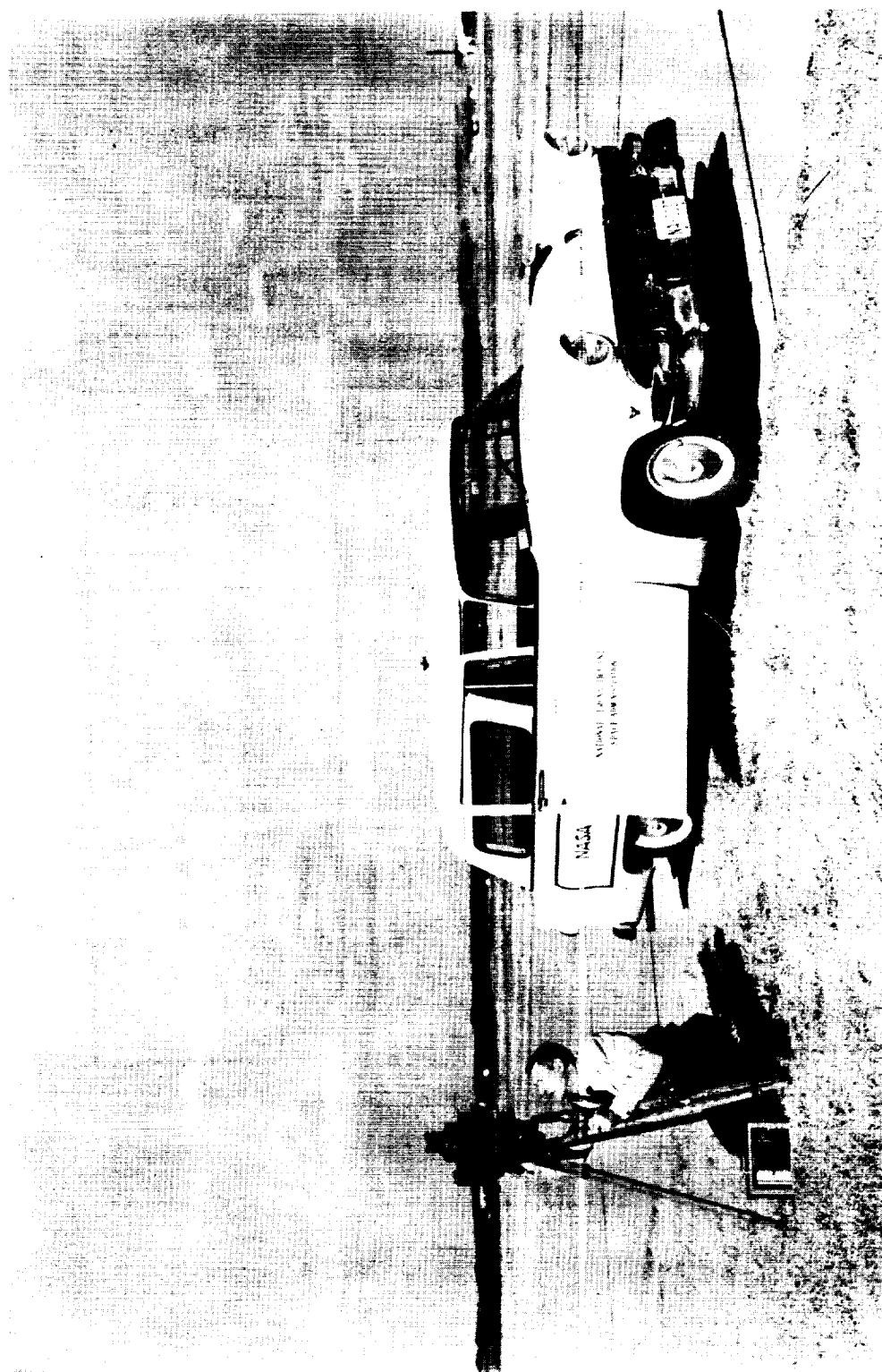
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Figure 1.- Aerial camera used to measure geometric height of airplanes in landing-approach and take-off operations.
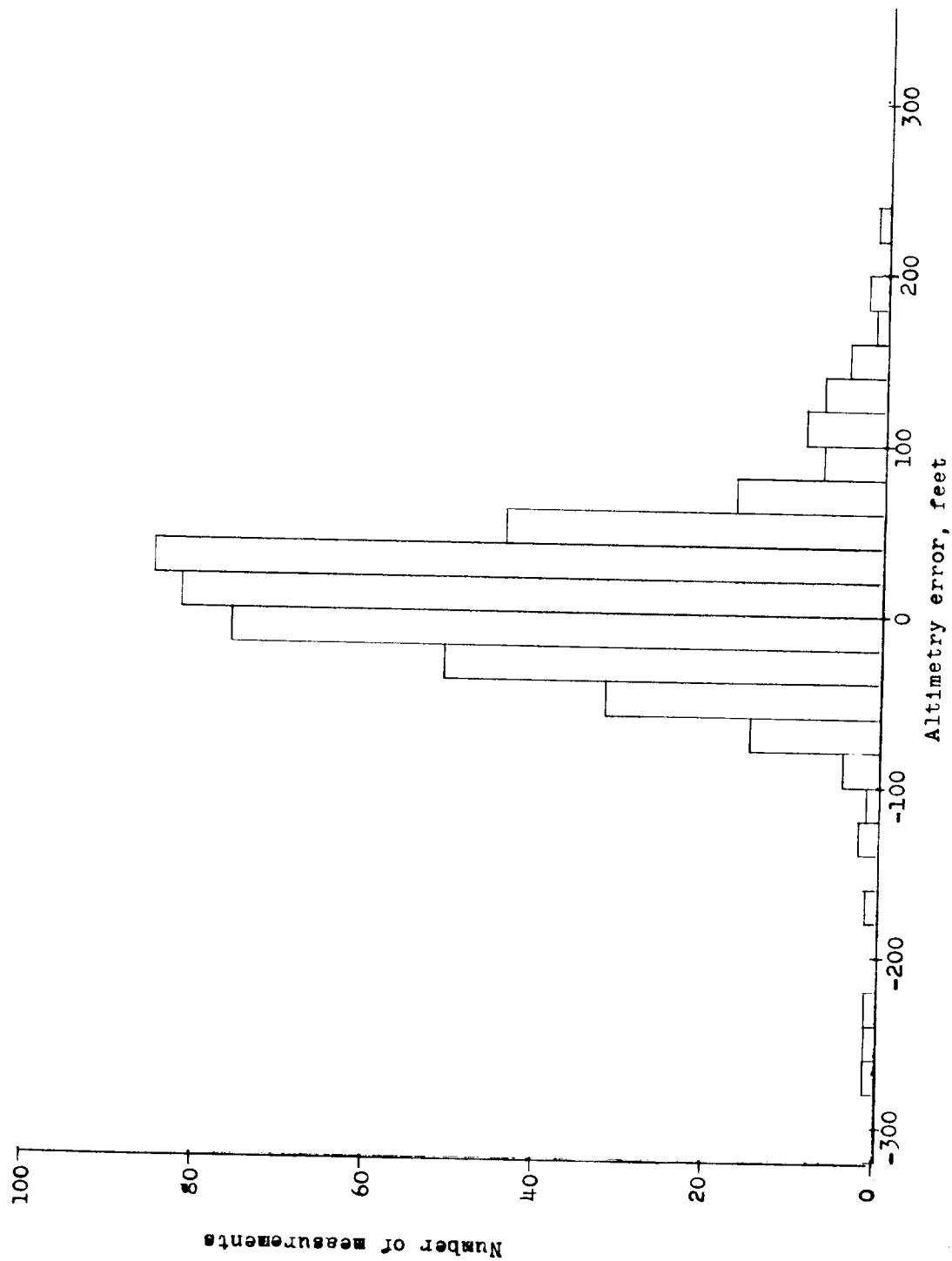
Figure 2.- Distribution of 444 altimetry errors of 196 civil transport, military and
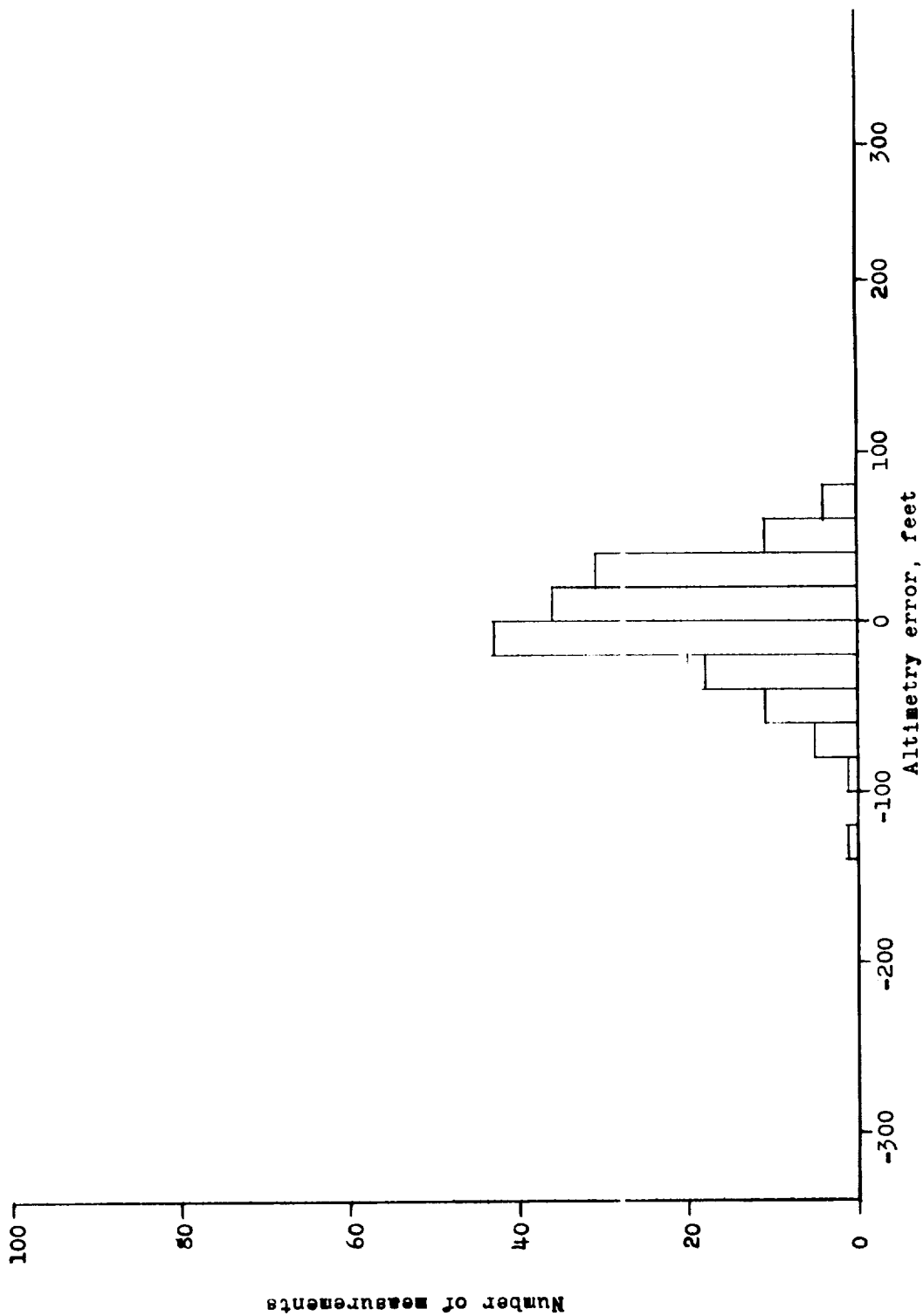general-aviation airplanes as measured during 415 landing approaches.

Figure 3.- Distribution of 161 altimetry errors of 74 civil transports as measured in 154 landing approaches.
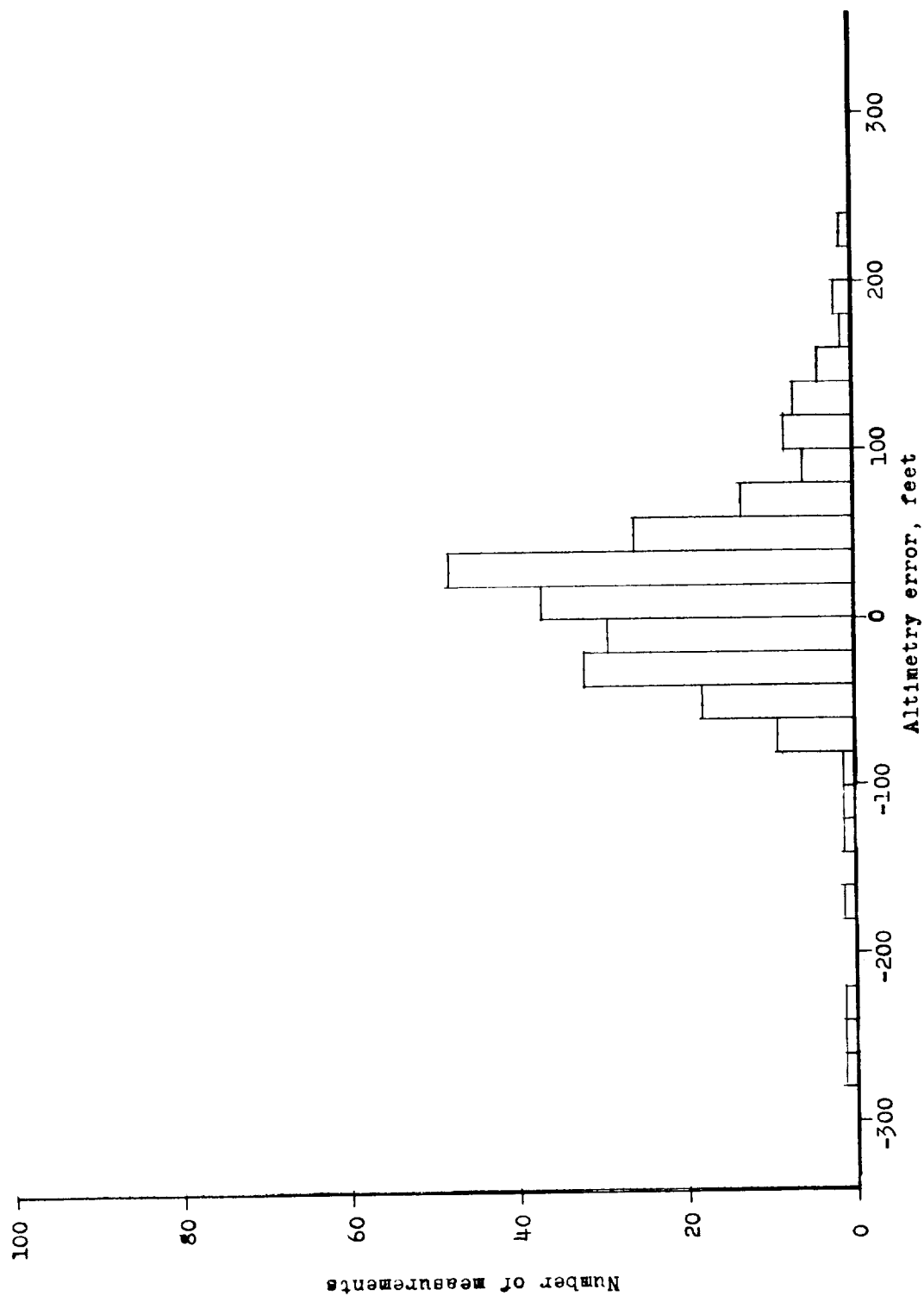
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Figure 4.- Distribution of 248 altimetry errors of 91 military airplanes as measured in 226 landing approaches.
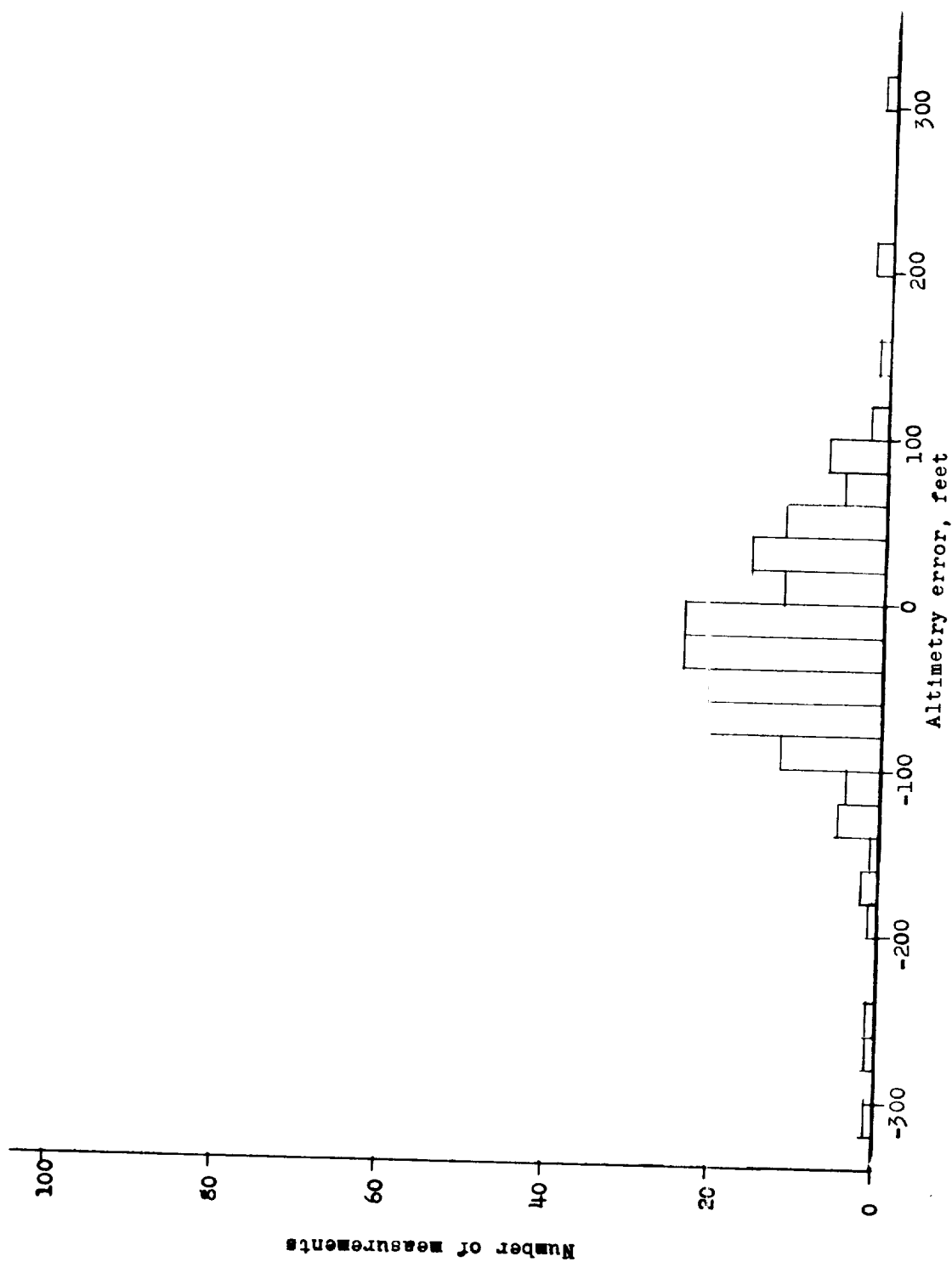
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Figure 5.- Distribution of 176 altimetry errors of 70 civil transport, military, and general-aviation airplanes in 152 take-off operations.