NASA Technical Memorandum 86733

(NASA-TM-86733) A CONSTANT ALTITUDE FLIGHT SURVEY METHOD FOR MAPPING ATMOSPHERIC AMBIENT PRESSURES AND SYSTEMATIC RADAR ERRORS (NASA) 11 p HC A02/MF A01 CSCL 01C G3/05

N85-29951

Unclas

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June 1985

National Aeronautics and
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A CONSTANT ALTITUDE FLIGHT SURVEY METHOD FOR MAPPING ATMOSPHERIC AMBIENT PRESSURES AND SYSTEMATIC RADAR ERRORS

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ABSTRACT

The flight test technique described uses controlled survey runs to determine horizontal atmospheric pressure variations and systematic altitude errors that result from space-positioning measurements. The survey data can be used not only for improved air-data calibrations, but also for studies of atmospheric structure and space-positioning accuracy performance. The examples presented cover a wide range of radar tracking conditions for both subsonic and supersonic flight to an altitude of 42,000 ft.

INTRODUCTION

A static-pressure position error method incorporates ground-based radar (or other space-positioning facilities) to determine geometric altitude and upper-air rawinsondes to independently measure the atmospheric static-pressure profile on the test day (Ref. 1). In many cases the rawinsonde pressure measurement may not be precisely representative of the ambient pressure because of spatial and temporal differences between the balloon and the aircraft measurements. In addition, significant instrument errors may exist in the rawinsonde measurements, and pressure discrepancies caused by horizontal pressure gradients in the atmosphere may be especially serious when large distances are used that result from accelerating and/or decelerating calibration runs at supersonic speeds.

To accommodate long calibration runs, upper-air meteorological analyses were performed using data from several rawinsonde stations to obtain representative ambient pressure values for supersonic calibration of the YF-12 aircraft (Ref. 2). This procedure produces more accurate data because it identifies horizontal gradients and inaccurate data from individual stations which do not fit the pattern of the multistation data. However, other systematic altitude errors resulting from radar tracking biases can also be experienced.

This paper describes an air data calibration technique that uses flight survey runs to determine horizontal pressure variations in the atmosphere and systematic space-positioning altitude errors. Surveys of this type can also be used for studies of atmospheric structure, refraction of radar waves, and space-positioning tracking performance. Examples are given of surveys at altitudes to 42,000 ft and of air data calibration applications extending to supersonic numbers obtained during flight test programs at the Dryden Flight Research Facility of NASA Ames Research Center.

SYMBOLS

E — elevation angle measured by radar, deg

h_p — pressure altitude, ft

M — Mach number

R — slant range measured by radar, ft

t — time, sec

z — geometric altitude, m (ft)

Δh_{p_s} — pressure altitude correction for variations of radar altitude error and geometric altitude from reference point along survey track, ft

$\left(\Delta h_{p_s}\right)_c$ — pressure altitude correction, Δh_{p_s}, corrected for position error changes caused by variations in Mach number and pressure altitude from the reference point, ft

ΔM_c — Mach number correction for static-pressure position error, based on correction $\left(\Delta h_{p_s}\right)_c$ determined from survey run

ΔM_u — Mach number correction for static-pressure position error, without benefit of correction determined from a survey run

Subscripts

i — indicated; determined from the aircraft measurements

m — measured

s a point during survey run

ref refers to a reference point or time

DESCRIPTION OF METHOD

Static-Pressure Position Error Calibration

In the basic space-position and pressure survey method, the aircraft is flown at constant values of indicated pressure altitude, indicated Mach number, and flightpath heading. The ground track is as close as possible to that used for the static-pressure calibration test run. The Mach number should be selected for adequate controllability of altitude, little sensitivity of static-pressure position error with Mach number, and fuel economy. The survey can be made by the same airplane as the one to be calibrated.

The survey-run true geometric altitudes generally differ substantially from the true pressure altitudes because of deviations between conditions on the actual test day and the pressure altitude relationship defined by the U.S. Standard Atmosphere (Ref. 3). At a given altitude the difference measured between geometric altitude (z) and pressure altitude (h_p) may also be variable in time and space along the survey track because of (1) pressure gradients on the test day, (2) errors affecting the tracking radar, and (3) changing pressure measurement errors on the airplane (Fig. 1). By minimizing pressure altitude and Mach number excursions during the survey, effects of the airplane instrument errors and previous air data calibration inaccuracies are essentially held to a fixed bias throughout the run. For the example in Fig. 1, small varying differences are illustrated between the indicated and the true pressure altitude, which may be caused by instrument errors and position error changes with Mach number variations. The true pressure altitude (h_p) and true geometric altitude (z) differ because of horizontal pressure gradients and deviations from the standard day. Similarly, any errors in the radar altitude measurement (z_m) will cause it to differ from the true geometric altitude. Thus changes in the difference between radar altitude and the airplane indicated pressure altitude ($z_m - h_{p_i}$) establish the measurement variations caused by pressure gradients, atmospheric refraction of the radar beam, or other radar elevation angle or range errors.

When the true values are known for radar altitude and pressure altitude at any given point in the run, a reference point can be established from which the true time histories can be calculated, as is shown subsequently.

The best estimates of true geometric altitude are obtained at high radar elevation angle where atmospheric refraction and other radar errors are minimal. True pressure altitude at such points can be estimated by use of a flight Mach number that has been previously calibrated on the test airplane or by use of a calibrated pacer airplane. When measurements are not available for good estimates of either the true geometric altitude or the true pressure altitude, the value of $z - h_p$ based on the meteorological analysis can be used with the value available to obtain the missing altitude quantity (z or h_p) at the reference point. When both are available, the meteorological estimate of $z - h_p$ is an effective, independent basis for judging the accuracy of the airplane and radar data.

Measurements available for the survey run establish the altitude relationships at the reference point which equate true pressure altitude to the sum of the measured geometric altitude and the difference between pressure altitude and geometric altitude ($z - h_p$).

$$h_{p_{ref}} = z_{ref} + (h_p - z)_{ref}$$

Once the true pressure altitude is determined for a reference point, the true pressure altitude at any point, s, in the survey space can be obtained from on-board pressure altitude and radar altitude measurements by the equation

$$h_{p_s} = z_m + (h_p - z)_{ref} + \Delta h_{p_s}$$

This equation is identical to the previous equation except an adjustment term, Δh_{p_s}, is included that accounts for the horizontal pressure variations and systematic geometric altitude error variations from the reference point. This quantity is given by

$$\Delta h_{p_s} = \left(h_{p_{i,s}} - h_{p_{i_{ref}}}\right) - \left(z_{m_s} - z_{m_{ref}}\right)$$

or equivalently,

$$\Delta h_{p_s} = \left(z_m - h_{p_i}\right)_{ref} - \left(z_m - h_{p_i}\right)_s$$

In order for this equation to be valid, the static-pressure position error should not vary from the reference point, which means that the indicated pressure altitude and indicated Mach number should not be allowed to significantly vary from the reference point.

Figure 2 illustrates the variation Δh_{p_s} with range or elevation angle for a hypothetical survey run. From such a plot, Δh_{p_s} can be directly applied to a calibration run as a function of location in order to determine true pressure altitude. The rationale for using Δh_{p_s} for the calibration run is that it is assumed that the bias errors in the radar measurements are time-invarient functions of radar range and elevation angle, and that the horizontal ambient pressure variation is also temporally invarient.

Once the true pressure altitude is determined, the pressure altitude position error is then given by the differences between h_{p_s} and h_{p_i} for the calibration run. Mach number and static-pressure position error corrections are subsequently determined.

Application of Radar-Pressure Survey

Application of a survey to static-pressure calibration purposes is especially needed when the test runs require significantly long flight distances. In such cases horizontal pressure gradients associated with strong winds can cause large differences from the pressure values at the reference point. Figure 3 shows the geostrophic approximation (Ref. 2) for the pressure gradient as a function of windspeed in straight balanced flow at two values of latitude. With a 75-knot wind, the geometric height of a constant pressure altitude value will slope approximately 2 ft/nmi in a direction perpendicular to wind heading. A greater slope may be experienced when there is curvature in the wind field.

Altitude errors that increase with distance can also result from imperfect corrections for atmospheric refraction as well as from radar pedestal mislevel or other elevation angle biases. For example, an elevation angle error as small as 0.1 mil causes an increasing altitude error with range which becomes approximately 35 ft at 60 nmi for typical flight test altitudes. At this range atmospheric refraction effects are greater than 600 ft and errors resulting from imperfect refraction corrections can be significant.

Surveys can also be used for investigating systematic radar errors and the accuracy of estimating pressure gradients under various atmospheric conditions. Certain procedures used in conducting the surveys for these purposes are worth describing. For example, for studies of radar performance, it is useful to have the end points of the survey at nearly equal distances from the radar in order to provide two sets of elevation angles. If bias errors exist in the elevation angle measurement, independent of azimuth, then the $z_m - h_{p_i}$ differences should be identical at pairs of points for which elevation angles are the same. The minimum separation distance from the radar should be chosen to maximize elevation angle—hence, minimize altitude errors caused by elevation angle error—and yet assure that the slew rate of the antenna is not so excessive as to degrade accuracy. Cross-pattern surveys are useful for radar and meteorological evaluation. One survey is flown parallel to the wind to minimize horizontal pressure variations, and the other is flown normal to the wind to maximize the variations. The quantity Δh_{p_s} for the second survey, flown normal to the winds, would additionally reflect ambient pressure variations. Therefore, by flying such patterns, it is possible to distinguish the two components of Δh_{p_s}.

The atmospheric component of Δh_{p_s} (that is, the deviation of pressure altitude along the survey run caused by pressure gradient) can be compared with values obtained from meteorological analyses (Ref. 2). Such comparisons can define accuracies of these analyses, which, of course, is important for their application to static-pressure calibrations. For example, preliminary experience with flight test survey data on several days suggests that accuracies of the meteorological analyses are typically within 0.3 ft/nmi for the slope of the constant pressure altitude surfaces. Similarly, the analyzed $z - h_p$ values are typically accurate to 30 to 80 ft. These values are also representative of the accuracy of the meteorological data analyses for the test days discussed in this paper. Values of $z - h_p$ resulting from the meteorological analysis of the flights reported in this paper are shown in Fig. 4.

EXPERIMENTAL EXAMPLES

Test Aircraft and Instrumentation

Test data were obtained from F-104 and F-15 fighter aircraft (Refs. 4 and 5) for supersonic and subsonic survey runs as well as for acceleration-deceleration calibration runs. Each airplane was equipped with accurate flight test instrumentation. Data were encoded digitally by pulse code modulation (PCM) for recording on board and also for telemetry to the the ground station. Radar altitude was uplinked to the airplane and displayed to the pilot for one of the F-104 flights (Ref. 4).

Pressures were sensed for each aircraft by pitot-static probes attached to flight test nose booms. Indicated pressure altitudes for both aircraft were determined to resolutions of less than 1 ft and were repeatable to within 20 ft. Similarly, the indicated Mach numbers were determined to resolutions of less than 0.001 and were repeatable to within this value.

A precision ground-based C-band FPS-16 radar tracked the aircraft. Slant range was measured to a resolution of approximately 6 ft, and elevation and azimuth angles were measured to a raw resolution of 0.05 mils. Both aircraft carried radar beacon transponders, and the beacon tracking mode was used for the data in the following section. Raw data were corrected for refraction by the method in Ref. 6.

Test Samples

The F-104 airplane flew a supersonic survey using telemetry to uplink radar altitude data for display to the pilot. With the uplink display the pilot was able to maintain altitude excursions of 30 ft or less. During the first minute of the survey run, the Mach number increased from approximately 1.2 to 1.4, where it remained for the rest of the run. Although this acceleration was a significant change in Mach number, it was included in the survey because the position error is small and very constant in magnitude over this range of Mach numbers. No corrections were required for deviations in either pressure altitude or geometric altitude in this survey run. Thus the quality of data on this run improved with the use of uplink to minimize altitude excursions, and with the use of Mach numbers where the position error was relatively small and constant.

The $z_m - h_{p_i}$ variation shown for this survey in Fig. 5 was substantial (150 ft), becoming especially pronounced at an elevation angle below 20°. Meteorological analysis of the pressure gradient indicated that this survey was nearly parallel with the wind and that the $z_m - h_{p_i}$ value should be expected to increase only approximately 25 ft during the run. This contrasts with the radar and airplane measurements of $z_m - h_{p_i}$, which have changes reaching a 150 ft decrease over the course of the run. Evidently, the radar altitude errors were much larger than the pressure gradient effect.

The F-104 subsonic survey shown in Fig. 6 was flown nearly perpendicular to the wind (that is, nearly along the gradient) and illustrated the radar error and pressure gradient effects more vividly. This survey was made at an indicated Mach number near 0.82 and without an uplink display. The indicated pressure altitude varied by 610 ft, and the indicated Mach number varied by almost 0.05. Such variations are larger than desirable for a survey run, but may be unavoidable depending on such variables as the altitude, aircraft handling characteristics, and limitations of the cockpit display. Effects of these variations are apparent in the scatter exhibited by the values of Δh_{p_s} shown in the center of Fig. 6. This scatter was reduced by correcting the pressure altitude data for position error changes caused by variations in Mach number and pressure altitude during the run. The reduced scatter in the resulting $(\Delta h_{p_s})_c$ values, shown in the lower portion of Fig. 6, indicates the effectiveness of the position error corrections.

For this run the differences between corrected pressure altitude and radar altitude vary by approximately 150 ft and correlate with radar elevation angle shown at the top of Fig. 6. The minimum difference in $(\Delta h_{p_s})_c$ occurs near the maximum elevation angle. These results demonstrate the usefulness of the radar-pressure survey. The maximum indicated correction of 150 ft pressure altitude is equivalent to a 0.007 correction in Mach number. The dashed line, which depicts the ambient pressure gradient determined from an upper-air analysis, shows the expected variation of $z_m - h_{p_i}$ caused by this gradient from a reference point taken at time 0. Good agreement is evidenced between the pressure gradient line and the data at the end of the run. For comparison, $z_m - h_{p_i}$ gradients were calculated from radar and airplane data pairs taken at equal elevation angles near the beginning and end of the run. These radar-airplane values for the gradient were between 0.76 and 1.18 ft/nmi and compare favorably to the value of 0.87 ft/nmi obtained from the upper-air analysis. This indicates that the analyzed pressure gradient is a good approximation since it is likely that the radar altitude errors at the beginning and end of the run are approximately equal because the elevation angles and the ranges at these points are nearly the same. However, application of only a pressure gradient correction to a position error calibration run over this flight track without the benefit of a survey run would result in significant altitude errors, as large as 100 ft.

Data from F-15 airplane survey and calibration runs are used for the last example (Figs. 7 and 8). During the survey, the F-15 Mach number was maintained between 0.718 and 0.745, and the indicated pressure altitude was maintained between 30,320 and 30,860 ft. High values of Δh_{p_s}, varying up to 175 ft, correlated strongly with elevation angle, as shown in Fig. 7(b).

For the calibration run, the data were first used without applying the results of the survey run. The static-pressure position error correction without benefit of the survey, shown in Fig. 8, indicates nominal differences of approximately 0.003 between increasing and decreasing Mach number points. On the other hand, in Fig. 8 the ΔM_c values for the corrected data are less scattered and are as much as 0.005 less than the uncorrected data values. These results are a clear illustration that the survey technique can substantially increase the accuracy of position error calibrations using conventional radar and rawinsonde measurements.

CONCLUSIONS

A flight test technique that uses flight survey runs for determining horizontal pressure variations in the atmosphere and systematic radar altitude errors has been developed and demonstrated to altitudes of approximately 42,000 ft and to supersonic Mach numbers. The data from these surveys indicate that the technique can provide increased accuracy in static-pressure position error calibration using radar and rawinsonde pressure measurements. In addition, these survey techniques can be useful in studies of pressure gradients, atmospheric refraction, and radar tracking performance.

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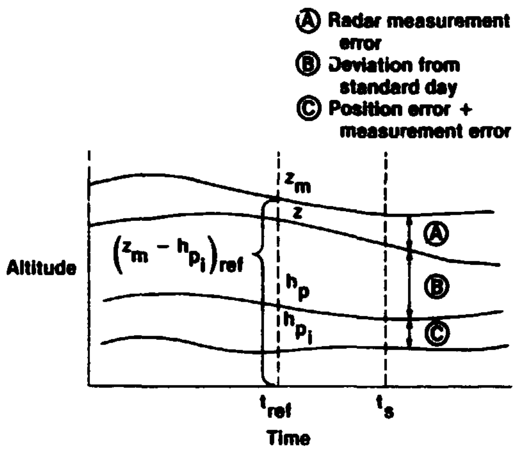


Fig. 1 Illustrative altitude time history during a radar-pressure survey run.

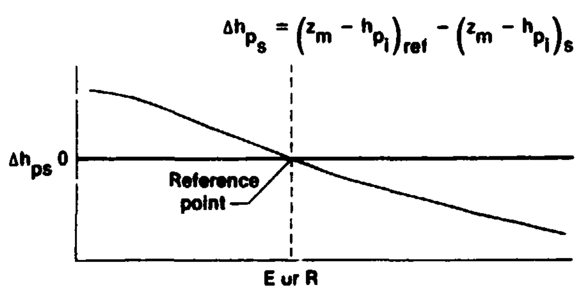


Fig. 2 Illustrative example of pressure altitude correction for radar altitude error and horizontal pressure variation.

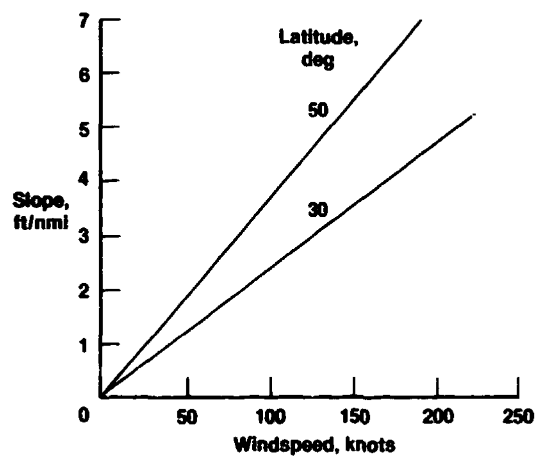


Fig. 3 Slope of a constant pressure altitude surface normal to the wind direction as a function of windspeed, as given by the geostrophic equation.

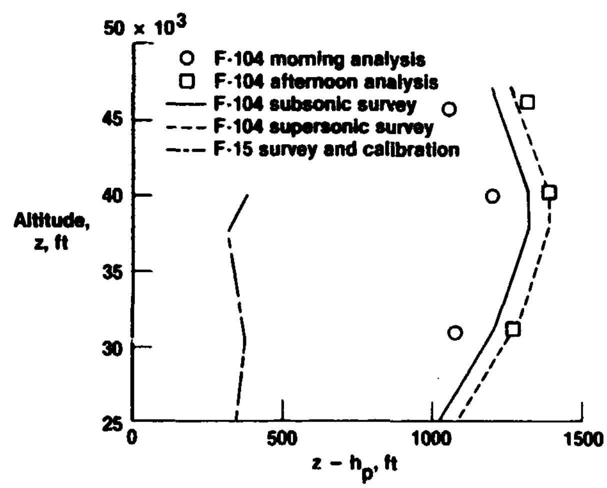


Fig. 4 Variation of difference between geometric and pressure altitude with geometric altitude based on meteorological analysis.

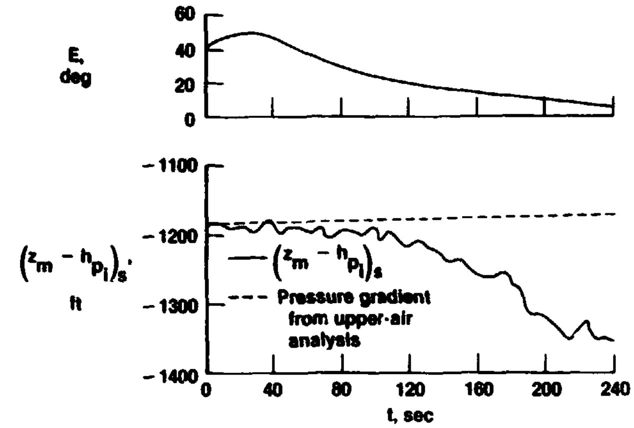


Fig. 5 Time history of F-104 survey run quantities for study of altitude measuring performance of radar. h_{p_i} = 39,980 ft to 40,040 ft; M_i = 1.200 to 1.408.

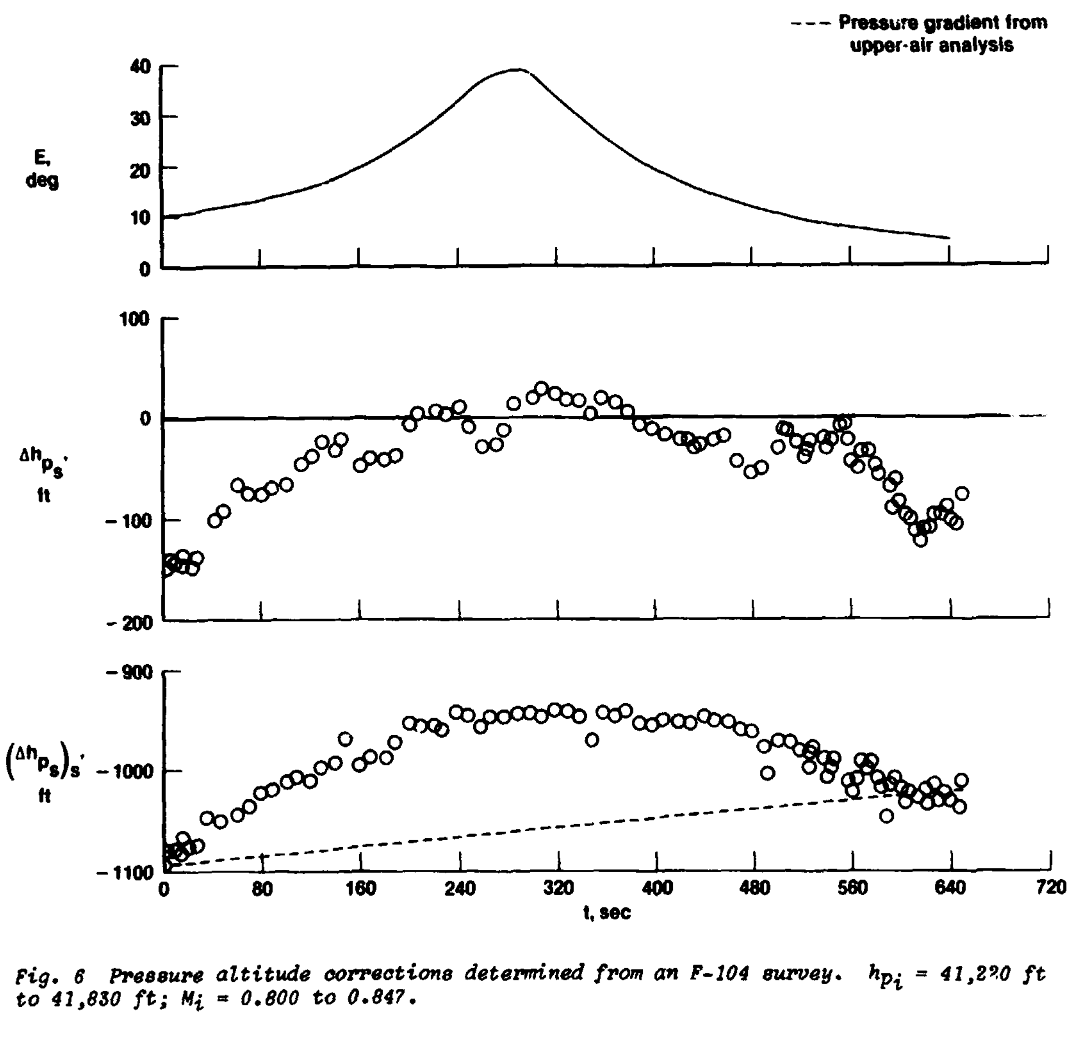
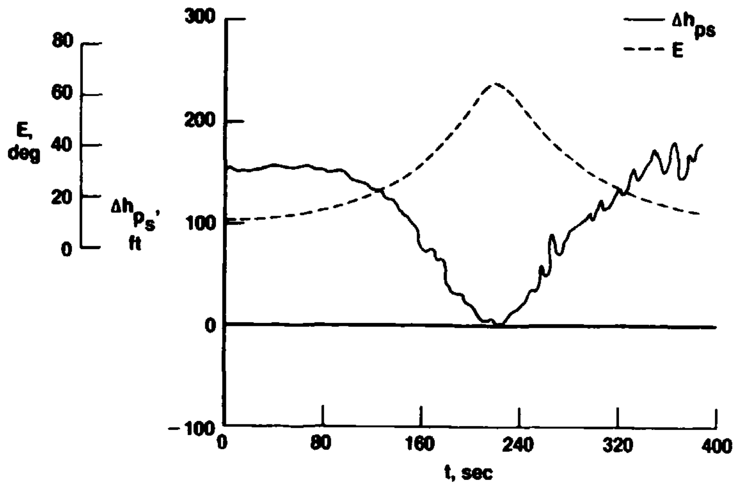
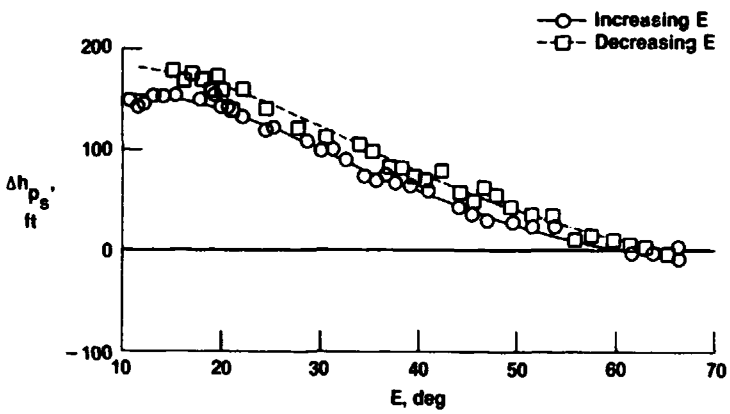


Fig. 6 Pressure altitude corrections determined from an F-104 survey. h_{p_i} = 41,230 ft to 41,830 ft; M_i = 0.800 to 0.847.



(a) Time history of Δh_{p_s} and E. h_{p_i} = 30,320 ft to 30,860 ft; M_i = 0.718 to 0.745.



(b) Δh_{p_s} as a function of E.

Fig. 7 F-15 survey quantities for application to static-pressure calibration run.

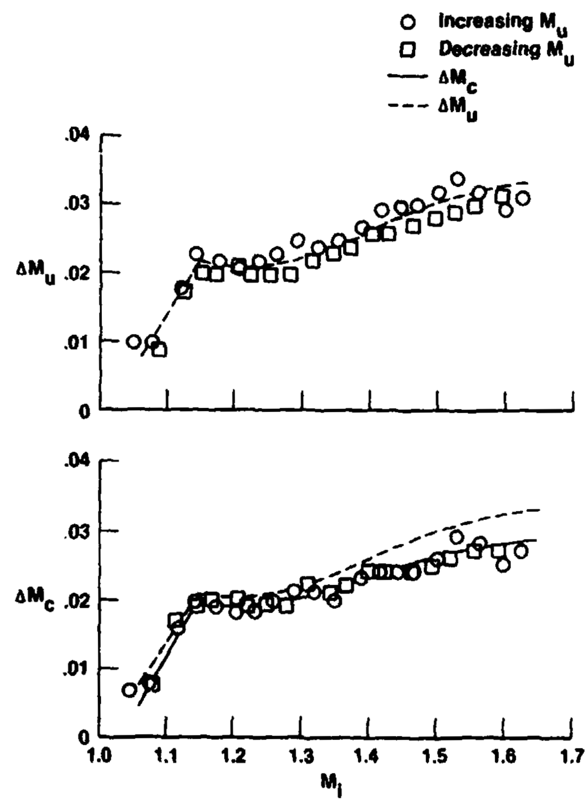


Fig. 8 Mach number corrections for F-15 test probe static-pressure position error with and without benefit of survey run.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-86733		

4. Title and Subtitle A Constant Altitude Flight Survey Method for Mapping Atmospheric Ambient Pressures and Systematic Radar Errors	5. Report Date June 1985
	6. Performing Organization Code
7. Author(s) Terry J. Larson and L.J. Ehernberger	8. Performing Organization Report No. H-1304
9. Performing Organization Name and Address NASA Ames Research Center Dryden Flight Research Facility P.O. Box 273 Edwards, CA 93523	10. Work Unit No.
	11. Contract or Grant No.
	13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546	14. Sponsoring Agency Code RTOP 505-31-21

15. Supplementary Notes

Prepared for presentation at IEEE National Aerospace and Electronics Conference, Dayton, Ohio, May 20-24, 1985.

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17. Key Words (Suggested by Author(s))	18. Distribution Statement
Air data calibration Altitude measurements Radar Measurements Static pressure position error	Unclassified — Unlimited STAR category 05

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	9	A02

*For sale by the National Technical Information Service, Springfield, Virginia 22161.