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DETERMINING PITOT-STATIC POSITION ERROR CORRECTIONS IN-GROUND EFFECT

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DECEMBER 2020

TECHNICAL INFORMATION HANDBOOK

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EDWARDS AIR FORCE BASE, CALIFORNIA
AIR FORCE MATERIEL COMMAND
UNITED STATES AIR FORCE

This technical report (412TW-TIH-19-02, *Determining Pitot-static Position Error Corrections In-ground Effect*) was submitted under job order number 99800000 by the Commander, 412th Test Wing, Edwards AFB, California 93524-6843.

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This handbook documents methods used to determine, via flight tests, the Pitot-static position errors for an aircraft in ground effect. Applicable Federal Aviation Administration and military requirements for the in-ground effect corrections are identified and summarized.

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INTRODUCTION

Flight testing to determine Pitot-static position errors has been performed for decades, since at least the mid-1920s. The flight test and analysis methods for out-of-ground effect testing are well established and documented in the open literature. Out-of-ground effect Pitot-static calibrations are an integral part of all aircraft performance programs and are performed frequently. In-ground effect Pitot-static calibrations, although not performed as frequently or on every program, have also been a required part of flight testing for many years. However, the flight test procedures for in-ground effect Pitot-static testing have not been well documented in the open literature of the aerospace industry even though they have been used for over 90 years. The lack of documentation forced engineers to “start from scratch” when planning in-ground effect testing and associated analyses, an inefficient use of time and resources. The purpose of this handbook is to provide the information and algorithms an engineer would need to plan, conduct, and analyze an in-ground-effect Pitot-static calibration test in one document. Accurate Pitot-static calibration data for the in-ground-effect environment is important for the determination of accurate takeoff and landing speeds. These speeds include:

- ground and air minimum control speeds,
- rotation speed,
- critical engine failure speed,
- brake energy speeds,
- takeoff speed, and
- initial climb out speed.

An additional purpose is to provide a historical perspective on in-ground-effect Pitot-static testing and flight test industry techniques, as well as the data analysis methods most commonly used today. First, the regulations and guidance on in-ground-effect Pitot-static testing from government documents are summarized. Then, the primary techniques used for in-ground-effect Pitot-static testing from early flight test through current testing are reviewed. Finally, the two techniques most commonly used with current instrumentation systems, the airspeed and altitude methods, are discussed in more detail. To assist the reader in data analysis, the pertinent algorithms for performing Pitot-static analyses are provided in appendix A in enough detail to make this handbook a stand-alone reference document for engineers performing in-ground-effect calibrations. Representative recent test results are presented appendices E and F.

This handbook does not address several aspects of Pitot-statics in-ground effect. These include determination of:

- Pitot-static system pneumatic lags. The pneumatic tube length between the Pitot and static pressure sources and the transducers that convert these pressures to an electronic signal is usually short in modern aircraft (small volume), therefore the pneumatic lag can be considered negligible, especially for takeoff and landing operations.
- Air data computer or central computer time delays.
- Cockpit display time lags or refresh rates.
- Total air pressure measurement errors in-ground effect. The assumption that the Pitot source has no position error is usually true for conventional airplanes at low angles of attack and sideslip. This may not be true for aircraft such as helicopters and those with short or vertical takeoff and landing capabilities. If in doubt, a good source might be the Pitot-static equipment manufacturer’s wind

tunnel test report to determine the effects of angles of attack and sideslip on the total air pressure measurement.

DOCUMENTATION REVIEW

A review of existing regulations, guidance and practices related to in-ground effect Pitot-static flight testing from National Aeronautics and Space Administration (NASA), Federal Aviation Administration (FAA), and military documents is summarized as follows:

- No National Advisory Committee for Aeronautics (NACA) or NASA published information on the subject was found.
- The FAA states the system error from the minimum value of 0.8V1 to the maximum value of V2 will be determined in-ground effect where V1 is defined as the takeoff decision speed and V2 is the first climb segment target climb speed. System error is the sum of any pneumatic lag error and the Pitot-static position error.
- North Atlantic Treaty Organization (NATO) AGARDOGRAPH NUMBER 300 (reference 1) discusses four possible flight test techniques for determining Pitot-static position error corrections. Three will be presented in this handbook. The fourth employs a flight test source (such as a boom ahead of the aircraft pressure field) to correct the production Pitot indicated pressure.
- Military Document: MIL-DTL-7700G *Detail Specification Flight Manuals*, *Air Refueling Procedures, and Abbreviated Checklists* (reference 2) clearly identifies a requirement to present ground effect position error correction data in flight manuals. Air Force Flight Test Center (AFFTC) documents are silent on the subject with the exception of AFFTC-TIH-81-5, *AFFTC Standard Airspeed Calibration Procedures* (reference 3) which discusses the altitude method which will be presented in this handbook.

For a partial list of documents reviewed see appendix B.

PITOT-STATIC OVERVIEW

The term “Pitot-static” refers to the total and static air pressures around an aircraft. The total air pressure is referred to as “Pitot pressure” for the French civil engineer, Henri Pitot, who also invented the Pitot tube. The measured static air pressure near the aircraft is normally not equal to the freestream ambient air pressure away from the local disturbances near the aircraft. The correction to be added to the measured static air pressure to equal the freestream ambient air pressure is the static air pressure position error correction. The static air pressure position *error* has the same magnitude as the static air pressure position error *correction* but has the opposite sign. These two terms and their signs can be confusing as it is the convention of some aircraft companies to subtract the position error vice adding the position error correction.

The measured total air pressure is normally accurate at low angles of attack and sideslip. This handbook only addresses the static air pressure position error corrections. Pressure altitude, calibrated airspeed, and Mach number can be calculated using only the measured total air pressure and the calculated freestream ambient air pressure. Ambient air temperature or total air temperature are not required. Calculating the true airspeed, however, requires either the measured total air temperature or a measured or calculated ambient air temperature.

The derivations of the equations for pressure altitude, calibrated airspeed, and Mach number can be found in AFFTC-TIH-10-01, *Subsonic Relationships Between Pressure Altitude, Calibrated Airspeed, and Mach Number* (reference 4). A review of the Pitot-static equations applicable to takeoff and landing evaluations is presented in appendix A.

The static air pressure position error corrections to be added can be represented by several dimensional and non-dimensional expressions. The three most common dimensional terms are:

- pressure altitude position error correction,
- airspeed position error correction, and
- static air pressure position error correction.

The three most common non-dimensional terms are:

- Mach number position error correction;
- static air pressure position error correction divided by the instrument-corrected, indicated static air pressure; and
- static air pressure position error correction divided by the difference between the instrument-corrected, indicated total air pressure and the instrument-corrected, indicated static air pressure.

Procedures to convert from one term to another are presented in appendix A.

The flow of the air around an aircraft is different when it is close to the ground compared to when the aircraft is at a height of more than one wingspan above the ground. (A definition using an aircraft height of one wingspan above the ground as the division between in- and out-of-ground effect is commonly used.)

The proximity of the ground will affect the aircraft's lift curve (lift coefficient as a function of angle of attack), the induced drag at a given lift coefficient, the pitching moment, and the static air pressure sensed at the aircraft flush static ports, dogleg probes, wing-mounted probe, or noseboom. This handbook addresses how to determine the position error correction in-ground effect. This correction is important for the flight test engineer analyzing takeoff performance, landing performance, ground minimum control speeds, and aircraft braking performance.

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FLIGHT TEST METHODS

Pitot-static position error corrections to be added have been determined for decades, at least since the mid-1920s. However, the flight test procedures for in-ground effect have not been as well documented as have the procedures for out-of-ground effect. Several flight test techniques will be discussed:

- A technique documented by Kelly Johnson of the Lockheed Corporation in 1939,
- Low flight over a relatively flat surface,
- The "trapped static" method,
- An airspeed method, and
- An altitude method.

The analysis algorithms presented in the following sections start with the values of instrument-corrected, indicated altitude ($H_{p_{ic}}$) and instrument-corrected, indicated airspeed (V_{ic}). These values may be available directly from the instrumentation system, or may require a correction by the engineer from recorded values of indicated altitude (H_i) and indicated airspeed (V_i) or from the static and total air pressures. These corrections are explained in detail in appendix A, and are common to all Pitot-static testing, not just to in-ground-effect testing.

Unless otherwise specified, the equations shown in this handbook may be used with any consistent set of units. Most flight test analyses use airspeed in knots (nautical air miles per hour), pressure in inches of mercury (in Hg), and distance in feet. The system of airspeed in feet per second, pressure in pounds per square foot, and distance in feet is also widely used. The constants and standard atmosphere values for each system are included in appendix A. Temperature must be expressed in an absolute scale of either Kelvin (K) or degrees Rankine (R).

CLARENCE "KELLY" JOHNSON'S 1939 TECHNIQUE

An early published article by Kelly Johnson of the Lockheed Corporation described a method of determining the liftoff speed or the landing speed using a swiveling Pitot probe. *A Simple Method of Measuring Landing and Take-off Speed* (reference 5) is the earliest reference to in-ground-effect Pitot-statics testing that the author has found. As such, it represents a starting point for this handbook.

The goal of Kelly Johnson's technique was to determine the takeoff (mainwheel liftoff) and the landing (mainwheel touchdown) airspeeds for a Lockheed model 14 airliner. It is important to note that he was not trying to determine position error corrections to be added. He published a two page summary of his technique in the Journal of the Aeronautical Sciences.

Prior to takeoff (or after landing) he recorded the static air pressure from the Pitot line with the aircraft stationary on the runway. If the runway was sloped, he recorded the static air pressure after the takeoff or after the landing with the aircraft positioned on the runway over the point of interest. This gave him an accurate value for the ambient air pressure at the point of interest.

At the time of liftoff or touchdown he recorded the total air pressure which was assumed to have no pneumatic lag or position error correction. The post-flight data processing was as simple as:

1. Apply an instrument correction to the static air pressure recorded from the flight test total air pressure gauge plumbed to the Pitot probe with the aircraft stationary on the runway.
2. Apply an instrument correction to the recorded total air pressure at takeoff or touchdown.

3. Calculate the calibrated airspeed. (Since Johnson was using the incompressible Bernoulli relationships at the time, equivalent airspeed would simply be equal to this calibrated airspeed.)

It was not clear in Johnson's paper if he was using a photopanel or hand recording the data for this technique. An advantage of this approach was that only the values from one gauge had to be recorded; before (or after) and during each event. During the event he recorded a total air pressure and before (or after) the event he recorded a static air pressure. The Pitot (total) pressure from the probe was manually recorded at either liftoff or touchdown for each test maneuver. The aircraft taxied back to the same point on the runway after the test point and the engineer recorded the static air pressure from the Pitot probe with the aircraft stationary. The difference between the two readings was used to calculate a differential pressure and the resulting calibrated and equivalent airspeeds.

Johnson also described a photo-based technique that he implied was in common use at the time. Ground speed was determined from the film and airspeed was determined from the ground speed using an assumed wind speed. This is essentially the airspeed method discussed later. His comments (reference 5) on the film-based technique included:

> "…involve the use of a fairly large ground crew and none of the camera methods can be more accurate than the measurement of the wind velocity and the atmospheric pressure and temperature, which are used to correct the speeds to sea level air density. The air temperature must be carefully obtained outside the airplane at wing height in a shaded location away from ground radiation and direct sunlight. Computing the results of a camera test is a tedious task and the results are not immediately obtainable. The cost of such testing is very high."

LOW FLIGHT OVER A RELATIVELY FLAT SURFACE

This test is intended to determine the Pitot-static position error corrections with the main gear off the ground but with the aircraft less than one wingspan above the ground. Testing at Edwards AFB has utilized this technique over several paths: over Rogers' dry lakebed (usually over the tower flyby line), over Rogers' dry lakebed along the line approaching Runway 22L and including runway 22L, and just over the main runway 22L. The segment of the flyby line over the lakebed is approximately 7 statute miles long with a very small change in elevation. The approach to runway 22L is also over the lakebed and is also approximately 7 statute miles in length. The runway is an additional 15,000 feet long with a smoothly increasing elevation (rise) of 21 feet along the 15,000 foot run. The variation in runway elevation with distance from the approach end of runway 22L (the North East end) is presented in appendix C.

Two techniques can be used. The test aircraft is in level flight throughout the maneuver when using the first technique, just as in an out-of-ground effect tower flyby test. The tower flyby line can be used for this technique. The second technique involves flying a gradual descent from a height of approximately two wingspans to touchdown or near touchdown. When performed at Edwards AFB, it is usually flown using runway 22L. The advantage of the second technique is that data can be collected at multiple heights above the ground on a single pass.

The aircraft height above ground level can be determined using an onboard radar altimeter, an inertial navigation system (INS), a Global Positioning System (GPS) receiver, or in the case of a tower flyby, a grid reading from the tower. The engineer must know the point on the aircraft that was used as a reference. The height of the reference must be adjusted to the height of the aircraft's air data computer or the static air pressure sensor.

The engineer also needs to know the elevation of the location at which the reference ambient air pressure was recorded. The engineer can then determine the difference in geometric (tapeline) height between the reference point and the height of the air data computer or the pressure sensor on the aircraft as a function of time. That height difference must then be adjusted to represent a change in pressure altitude.

Converting a Change in Geometric Height to a Change in Pressure Altitude:

The goal is to determine a “truth source” ambient air pressure or pressure altitude at the aircraft’s air data computer or the aircraft’s static air pressure sensor. The difference in a geometric height and the equivalent change in pressure altitude can be determined as shown in equations 1 through 3:

$$\Delta H_p = \Delta h_{MSL}\ (T_{STD}/T_{TEST}) \tag{1}$$

$$H_{p\ TRUTH\ SOURCE} = (\text{pressure altitude at the ground site}) + \Delta H_p \tag{2}$$

$$\Delta H_{pc} = (H_{p\ TRUTH\ SOURCE}) - (H_{p_{ic}}) \tag{3}$$

where: ΔH_p = change in pressure altitude relative to the ground site (feet)

Δh_{MSL} = change in height in geometric length between the ground site and the aircraft reference point (feet)

T_{STD} = ambient air temperature on a standard day at the pressure altitude half way vertically between the ground site and the aircraft (degrees R or K)

T_{TEST} = test day ambient air temperature half way vertically between the ground site and the aircraft (degrees R or K)

$H_{p\ TRUTH\ SOURCE}$ = true pressure altitude at the reference point on the aircraft (feet)

ΔH_{pc} = pressure altitude position error correction (feet)

$H_{p_{ic}}$ = instrument-corrected, indicated pressure altitude at the aircraft (feet)

The ambient air temperatures must be in consistent units and must be either degrees R or K. The standard day ambient air temperature in Kelvin can be calculated with equation 4.

$$T_{STD}\ (K) = [288.15\ (K)] - [(0.001\ 981\ 2)(K/ft)\ H_p\ (feet)] \tag{4}$$

Table 1 presents standard day ambient air temperatures for pressure altitudes between sea level and 8,000 feet. The values for K in the table were calculated using equation 4.

Table 1 Standard Day Ambient Air Temperatures[1]

Pressure Altitude (1,000 ft)	Temperature in Degrees		
	(K)	(C)	(F)
0	288.15	15.00	59.00
2	284.19	11.04	51.87
4	280.23	7.08	44.74
6	276.26	3.11	37.60
8	272.30	-0.85	30.47

Table 2 presents representative changes in pressure altitude corresponding to a change of 10 feet in geometric height for a range of pressure altitudes and ambient air temperatures. The data were calculated

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[1] Abbreviations and acronyms in all tables and figures are defined in appendix G.

using equation 1. The differences between incremental changes in geometric (tapeline) heights and changes in pressure altitudes are less than 20 percent at low altitudes and typical ambient air temperatures.

Table 2 Change in Pressure Altitude Corresponding to a Change of 10 Feet of Geometric Height

Pressure Altitude (1,000 ft)	Ambient Air Temperature (deg F)				
	-50	0	50	90	130
	Change in Pressure Altitude (ft)				
0	12.66	11.84	10.18	9.44	8.80
2	12.49	11.13	10.04	9.31	8.67
4	12.31	10.97	9.90	9.18	8.55
6	12.14	10.82	9.76	9.05	8.43
8	11.96	10.66	9.62	8.92	8.31

Summary:

The low approach flight test technique is used by large aircraft. The equivalent data for smaller aircraft are normally determined from the takeoff, climbout, and landing air phases. The technique for smaller aircraft will be discussed in the airspeed and altitude method sections. These other techniques can also be used with good results for large aircraft.

TRAPPED STATIC METHOD

The trapped static method for determining in-ground-effect Pitot-static data is used to aid the aircrew in real time and the engineer post-flight. The post-flight use is a logical extension of Kelly Johnson's 1939 approach.

Real Time Application:

The aircraft is modified with an airspeed indicator plumbed to a total air pressure line and to a static air pressure line attached to a bottle which can be vented to the ambient air pressure or isolated from later pressure changes via a valve. Prior to brake release for takeoff, the aircrew opens the valve to allow the pressure within the bottle to stabilize at the ambient pressure level. The valve is then closed prior to brake release, thereby maintaining the pressure in the bottle and in the static line equal to the pre-brake release ambient air pressure, hence, the name "trapped static." The airspeed indicator will display calibrated airspeed to the aircrew while doing takeoffs, ground minimum control speed tests, or braking tests. It should be noted that the airspeed indicator will only display calibrated airspeed (vice indicated airspeed) if the mechanical instrument error is zero. This technique only eliminates the need for a position error correction for the aircrew. This real time use also assumes that the runway has no slope.

Post-flight Application:

Historically, the trapped static method was associated with hand-recorded data or with photopanels. The engineer would have two indicated airspeeds from two different airspeed indicators. Both indicators would be plumbed to the same total air pressure source. One indicator would be plumbed to the trapped static bottle and the other to a production static air pressure source. The data processing to obtain the airspeed position error correction in-ground effect would be:

1. Correct the production airspeed indicator reading for the mechanical airspeed indicator instrument error.
2. Correct the test airspeed indicator reading (the one plumbed to the trapped static) for its mechanical airspeed indicator instrument error.
3. Solve for the airspeed position error correction to be added (ΔV_{pc}) using equation 5.

$$\Delta V_{pc} = [(V_{ic})_{\text{TRAPPED STATIC}}] - [(V_{ic})_{\text{PRODUCTION}}] \tag{5}$$

where: V_{ic} = instrumented-corrected, indicated airspeed

If modern, sensitive pressure sensors were used to record the trapped static pressure and the production static air pressure, then the pressure difference, $\Delta P = [(P_{\text{TRAPPED STATIC}}) - P_{s_{ic}}]$, could be calculated. The airspeed position error correction as well as all the other comparable corrections to be added could be calculated, assuming that there was no error in the measured total air pressure and no lags in the Pitot-static system.

Summary:

The trapped static method is popular for two reasons. The first reason is that the trapped static method is specifically documented in the FAA Flight Test Guides, *Flight Test Guide for Certification of Part 23 Airplanes,* and *Flight Test Guide for Certification of Transport Category Airplanes* (references 6 and 7). The second reason for the popularity of the trapped static method is that it provides the pilot with a more accurate airspeed indication for performance takeoffs and for ground minimum control airspeed tests.

AIRSPEED METHOD

This is the method most frequently used. It is also documented in the FAA Flight Test Guides, and since it is an airspeed method, it directly produces the desired airspeed position error correction. The airspeed method uses measured aircraft ground speed, ground track, and wind speed and direction to calculate true airspeed. True airspeed is then converted to calibrated airspeed, which is used as the reference truth source for computing the airspeed position error correction, ΔV_{pc}. The primary desired result of most in-ground-effect Pitot-static testing is generally the airspeed position error correction, due to the importance of knowing airspeed accurately for computing takeoff and landing performance parameters. The altitude position error correction, ΔH_{pc}, is of secondary importance, but can be calculated from ΔV_{pc} using the equations in appendix A for converting between the different forms of position error corrections. The equations in appendix A to convert ΔV_{pc} to ΔH_{pc} are valid only if there is no total air pressure error on the Pitot side.

In-ground-effect Pitot-static calibrations using the airspeed method are typically performed concurrently with takeoff tests. In-ground-effect data with the wheels on the ground are obtained during the takeoff roll, both before and during rotation. Typically, the maneuver is continued past liftoff into the initial climb to an altitude of at least 50 feet in order to collect data at various levels of ground effect (typically high enough past one wingspan to verify the phase-out of ground effects). Data may also be collected during landing tests, including the final approach through full stop. The analysis methods shown in this document address the takeoff; however, the same equations can be used for a landing, with the reference static air pressure being recorded at the end of the maneuver after the aircraft has come to a full stop. In-ground-effect Pitot-static data may also be obtained during ground minimum control speed (V_{mcg}) testing.

The primary disadvantage of the airspeed method is the need for calm, or non-varying winds and accurate determination of the winds. Inaccurate or changing wind speed~~s~~ and/or directions have a significant effect on the final results. In addition, ambient air temperature is required to determine the truth source calibrated airspeed. Inaccuracies in the ambient air temperature measurement can have a significant effect on the results.

Data Required:

Required and optional parameters for the airspeed method are summarized in table 3. The required onboard instrumented parameters are the instrument-corrected, indicated static and total air pressures or alternatively, the instrument-corrected, indicated pressure altitude and airspeed. Groundspeed, ground track, and inertial vertical velocity data can be obtained from an onboard INS, a GPS system, an embedded GPS and INS (EGI), or an external radar, laser tracker, or phototheodolite system. The wind speed and direction should be recorded as close as possible in distance to the runway. The ambient air temperature and pressure at the start of each maneuver should be recorded on the aircraft, and should also be measured as close as possible to the runway with portable devices for back-up. Pitch angle data would be provided from an inertial system or from a pitch gyro. As will be discussed, pitch angle and weight-on-wheels data are not required to determine position error corrections using the airspeed method; however, this data may be useful during the air phase to correlate the position errors with the height of the aircraft above the ground.

The most important factors affecting the accuracy of the airspeed method are the wind measurement and the ambient air temperature. Not only must winds be measured as close as possible to the runway, but the winds must be constant throughout each maneuver. Variations in wind magnitude and/or direction lead to large errors in the true airspeed calculated from the measured ground speed. The accuracy of the ambient air temperature and pressure readings is also important because of their use in converting true airspeed to equivalent airspeed using ambient air density. Several factors that can affect the accuracy of the airspeed method are discussed in the following sections.

Table 3 Parameters for the Airspeed Method

Requirement	Parameter
Required	ground speed and ground track or inertial velocities North, East, and vertical
	wind speed/wind direction (with respect to true North)
	ambient air pressure or pressure altitude
	ambient air temperature or total air temperature and Mach number
	indicated airspeed measured on the test aircraft (or static and total air pressures)
	indicated pressure altitude or indicated static air pressure measured on the test aircraft
Required After Rotation	inertial vertical velocity
	pitch angle
Optional	latitude and longitude
	aircraft heading
	weight-on-wheels or weight-off-wheels discretes for both rear main gear struts
	wheelspeed sensors for both main gear struts

Surface Winds.

The major source of error when using the airspeed method is the need to assume that the wind is known and is constant in both magnitude and direction for the duration of the takeoff, from brake release through the aircraft reaching approximately 50 feet above ground level (AGL). The wind speed and wind direction with respect to true North can be obtained from a portable wind kit positioned near the runway. Because it is not possible to measure the winds over the entire horizontal distance the aircraft will travel during a takeoff or landing maneuver, the wind kit should be positioned adjacent to the estimated takeoff liftoff point or landing touchdown point, since the takeoff and landing calibrated airspeeds are the most critical to determine.

Data from analyzing hundreds of takeoffs at Edwards AFB has shown that light surface winds (less than 10 knots) vary about 0.5 to 1.5 knots and winds of 10 to 20 knots vary by about 0.5 to 2 knots during the approximate 30 seconds of a takeoff. The ideal situation is to limit in-ground-effect Pitot-static flight testing to calm or nearly calm days (less than 2 knots), supplemented by wind kits adjacent to the runway.

The recorded wind direction is the direction the wind is coming FROM. Aviation surface winds, such as those reported by the control tower, are with respect to magnetic north, whereas flight test analysis requires winds with respect to true north. The wind kits can be set to indicate with respect to true north, but other wind data may need to be corrected from magnetic to true using the known magnetic deviation for the flight test locale.

Tables 4 and 5 present historical magnetic deviation (also known as magnetic declination) data for Edwards AFB. Table 4 was created using Department of Defense (DOD) data from DOD Flight Information Publication (FLIP) (Terminal), Low Altitude, Southern California, United States documents published by the National Geospatial – Intelligence Agency in St. Louis, Missouri. Table 5 was created using FAA National Aeronautical Navigation Services, Los Angeles Sectionals published in Silver Spring, Maryland. The magnetic deviation values from the Los Angeles Sectionals required an interpolation between two isogonic lines separated by 0.5 degree magnetic deviation. The two isogonic lines on the sectionals were approximately 12 inches apart. Both sets of data show that the magnetic deviation at Edwards AFB has been decreasing in magnitude during the last 25 years. These changes are the result of the magnetic north pole's movement to the northwest from its current location in northeastern Canada.

Based on the data in tables 4 and 5, a heading with respect to true north would be approximately 13 degrees more than one with respect to magnetic north.

Table 4 Magnetic Deviations at Edwards AFB from DOD Flight Information Publications (Terminal) Low Altitude, Southern California, Unites States

Effective Date	Magnetic Deviation		Annual Rate of Change (deg/year)
	(date)	(deg)	
30 March 1995	February 1995	13.9 E	0.0
1 November 2001	August 2000	13.8 E	0.0
27 December 2001	August 2000	13.8 E	0.0
5 July 2007	September 2005	13.3 E	0.1 W
20 December 2007	September 2005	13.3 E	0.1 W
25 September 2008	June 2008	13.0 E	0.1 W
7 May 2009	May 2009	12.9 E	0.1 W
22 October 2009	August 2009	12.9 E	0.2 W
17 December 2009	August 2009	12.9 E	0.2 W
11 February 2010	August 2009	12.9 E	0.2 W
3 June 2010	August 2009	12.9 E	0.2 W
26 August 2010	August 2009	12.9 E	0.2 W

Table 4 Magnetic Deviations at Edwards AFB from DOD Flight Information Publications (Terminal) Low Altitude, Southern California, Unites States(Concluded)

Effective Date	Magnetic Deviation		Annual Rate of Change (deg/year)
	(date)	(deg)	
15 December 2011	October 2011	12.6 E	0.1 W
31 May 2012	January 2012	12.6 E	0.1 W
10 January 2013	November 2012	12.6 E	0.1 W
10 December 2015	September 2014	12.4 E	0.1 W
19 July 2018	November 2016	12.2 E	0.1 W
8 November 2018	November 2016	12.2 E	0.1 W

Table 5 Magnetic Deviations at Edwards AFB from FAA Los Angeles Sectionals

Edition	Date		Magnetic Deviation (deg)
	Chart	Magnetic Model	
36	17 January 1985	1980	14.4 E
41	30 July 1987	1985	14.3 E
52	7 January 1993	1990	14.1 E
56	5 January 1995	1990	14.1 E
57	20 July 1995	1990	14.1 E
58	4 January 1996	1990	14.1 E
59	18 July 1996	1995	14.1 E
61	17 July 1997	1995	14.1 E
66	30 December 1999	1995	14.1 E
67	13 July 2000	1995	14.1 E
68	28 December 2000	1995	14.1 E
69	12 July 2001	1995	14.1 E
70	27 December 2001	2000	13.8 E
71	11 July 2002	2000	13.8 E
72	26 December 2002	2000	13.8 E
74	25 December 2003	2000	13.8 E
76	23 December 2004	2000	13.8 E
77	7 July 2005	2000	13.8 E
78	22 December 2005	2000	13.8 E
79	6 July 2006	2000	13.8 E
80	21 December 2006	2005	13.4 E
81	5 July 2007	2005	13.4 E
82	20 December 2007	2005	13.4 E
83	3 July 2008	2005	13.4 E
84	18 December 2008	2005	13.4 E
86	17 December 2009	2005	13.4 E
87	1 July 2010	2005	13.4 E
88	16 December 2010	2005	13.4 E
90	15 December 2011	2010	12.9 E
91	28 June 2012	2010	12.9 E
103	21 June 2018	2015	12.3 E
105	20 June 2019	2015	12.3 E

Many test programs at Edwards AFB and contractor test programs at other facilities have used wind speed and direction determined from onboard sensors (INS ground speed, ground track, and air data computer true airspeed). These results have proven to be more accurate than those measured by a wind kit, references 8 through 12.

Ambient Air Pressure and Temperature at the Surface.

The ambient air pressure at the reference starting point should be obtained just prior to brake release using the static air pressure or the pressure altitude from the aircraft instrumentation system. A portable pressure sensor carried by the wind kit operator should also be used to record ambient air pressure as a backup. The measured ambient air temperature is one of the top two sources of error for the airspeed method. The ambient air temperature can be obtained either from the airfield weather station, a wind kit, or various sources on the aircraft. Potential sources on the aircraft include: a flight test total air temperature probe, a production total air temperature probe, or a temperature probe in an engine inlet. Usually the most accurate source for ambient air temperature is the on-aircraft flight test total air temperature measurement. Ambient air temperature is calculated from the total air temperature and the aircraft Mach number in the area of rotation to 50 feet in the initial climb.

Analyses:

Determining the Ground Speed.

First, the ground speed must be determined as a function of time. The ground speed is a primary required parameter. Ground speed may be determined in several ways. External techniques such as an external radar, a laser tracker, or a phototheodolite system were used more extensively in the past, and are still occasionally used for some flight test programs. Ground speed is currently most commonly obtained using an onboard system such as an INS, GPS, EGI, or various other test-unique systems providing inertial data. In almost all cases, ground speed and vertical velocity are provided directly from the aircraft data bus. For other systems, the data are provided in the form of the north, east, and vertical inertial velocities. In this case, ground speed may be calculated using the north and east inertial velocities and equation 6.

$$V_{grd} = [(V_N)^2 + (V_E)^2]^{0.5} \tag{6}$$

where: V_{grd} = inertial ground speed
V_N = North component of inertial velocity
V_E = East component of inertial velocity

Determining the Truth Source True Airspeed.

The ground speed and measured wind are used to calculate the truth source true airspeed. Then the values of equivalent airspeed and calibrated airspeed are calculated from the true airspeed.

True airspeed for the pure headwind or tailwind case is simply, equation 7:

$$V_T = V_{grd} + HW \tag{7}$$

where: V_T = true airspeed
V_{grd} = inertial ground speed
HW = headwind component of wind, at the runway location (in same units as V_{grd} and V_T)

Note: A tailwind would result in a negative HW value.

It should be noted that equation 7 is based on the assumption of zero runway slope and zero sideslip. The inertial ground speed is calculated along the horizontal direction. The true airspeed is along the aircraft flight path, which in this case is along the runway. For the case of a runway with slope, the calculation for true airspeed becomes equation 8:

$$V_T = (V_{grd} + HW) / \cos(\theta_{rw}) \quad (8)$$

where: θ_{rw} = runway slope (radians or degrees)

In Pitot-static analysis, this correction is usually so small it is commonly ignored. However, for testing with very large runway slopes, the engineer should consider applying the runway slope correction, equation 8. This correction will not be addressed further in this handbook.

The calculation of true airspeed is more complicated for the case where a crosswind exists, equation 9:

$$V_T = \{(XW)^2 + [(V_{grd}) + (HW)]^2\}^{1/2} \quad (9)$$

where: XW = crosswind component of wind (in same units as V_T)

Table 6 compares the values of true airspeed calculated using equations 8 and 9. The data in the far right column in table 4 represent the results using equation 9 and are the most accurate.

Table 6 Determining the Truth Source True Airspeed for a Ground Speed of 100 Knots and a Wind of 10 Knots

Wind Angle Relative to the Runway Centerline (deg)	Headwind Component (kts)	Crosswind Component (kts)	Truth Source True Airspeed (kts)	
			KGS + HW (kts)	$(XW^2 + (KGS + HW)^2)^{1/2}$ (kts)
0	10.00	0.00	110.0	110.0
10	9.85	1.74	109.9	109.9
20	9.40	3.42	109.4	109.5
30	8.66	5.00	108.7	108.8
40	7.66	6.43	107.7	107.9
50	6.43	7.66	106.4	106.7
60	5.00	8.66	105.0	105.4
70	3.42	9.40	103.4	103.8
80	1.74	9.85	101.7	102.2
90	0.00	10.00	100.0	100.5

Notes: 1. Wind angle of zero degree is a pure headwind.
2. Wind angle of 90 degrees is a pure crosswind.

Determining the Truth Source Equivalent Airspeed.

The next step is to calculate the truth source equivalent airspeed. The equivalent airspeed is an intermediate step between true airspeed and calibrated airspeed. To make the conversion, the values of ambient air pressure ratio, δ; ambient air temperature ratio, θ; and ambient air density ratio, σ; are first calculated as shown in equations 10 through 12. As discussed previously, these calculations require accurate measurement of both ambient air pressure and ambient air temperature.

$$\delta = P_a/P_{SL} \quad (10)$$

$$\theta = T_a/T_{SL} \quad (11)$$

$$\sigma = \delta/\theta \quad (12)$$

where: δ = ambient air pressure ratio (n/d)
θ = ambient air temperature ratio (n/d)
σ = ambient air density ratio (n/d)
P_a = ambient air pressure
P_{SL} = ambient air pressure at sea level, standard day
T_a = ambient air temperature
T_{SL} = ambient air temperature at sea level, standard day

The ambient air pressures and ambient air temperatures must be in consistent units. Temperatures must be on an absolute scale, either degrees R or K. Sea level values for standard day atmospheric pressure and temperature may be found in appendix A. Equivalent airspeed, V_e, is then calculated as equation 13:

$$V_e = V_T (\sigma)^{0.5} \quad (13)$$

As can be seen in equations 10 through 13, converting a true airspeed to an equivalent airspeed requires the test day ambient air pressure and the test day ambient air temperature. The uncertainty in the test day ambient air pressure at brake release is probably no more than 0.002 inch of mercury, or approximately 2 feet of pressure altitude. Experience has shown the temperature measured 4 to 10 feet above a black asphalt surface can be 5 to 10 degrees F higher than the actual test day ambient air temperature and may be 5 degrees F or more higher than ambient above a painted white concrete surface. An example of the resulting sensitivity of equivalent airspeed due to a 10 degrees F difference in the test day ambient air temperature is shown in table 7. For this example, 100 knots true airspeed at 2,000 feet pressure altitude, the calculated equivalent airspeed changed by approximately 0.10 KEAS for each 1 degree F (0.18 KEAS for one degree C) change in the assumed ambient air temperature.

Table 7 Sensitivity in Equivalent Airspeed Due to an Uncertainty in Ambient Air Temperature for a True Airspeed of 100 knots at 2,000 Feet Pressure Altitude

Assumed Ambient Air Temperature (T) (deg F)	Calculated Ambient Air Temperature Ratio, θ (n/d)	Calculated Ambient Air Density Ratio, σ (n/d)	Calculated Equivalent Airspeed (V_e) (KEAS)
45	0.973 008	0.955 603	97.75
46	0.974 936	0.953 713	97.66
47	0.976 864	0.951 831	97.56
48	0.978 792	0.949 956	97.47
49	0.980 720	0.948 088	97.37
50	0.982 648	0.946 228	97.27
51	0.984 576	0.944 375	97.18
52	0.986 504	0.942 529	97.08
53	0.988 432	0.940 691	96.99
54	0.990 360	0.938 860	96.89
55	0.992 288	0.937 035	96.80

Notes: 1. The ambient air pressure ratio, δ, at 2,000 feet pressure altitude is 0.929 809.
2. $\theta = (T + 459.67)/ 518.67$ for the temperature in degrees Fahrenheit
3. $\sigma = \delta/\theta$
4. $V_e = V_T(\sigma)^{0.5}$

Determining the Truth Source Calibrated Airspeed.

Once the equivalent airspeed has been calculated, the truth source calibrated airspeed, V_c, can be determined. The algorithms used to calculate the airspeed compressibility correction, ΔV_c, may be found in appendix A. Representative tabular values may also be found in appendix A in tables A11 through A14. The tabular data show that ΔV_c is less than 0.2 knot at 2,000 feet pressure altitude and calibrated airspeeds less than 200 KCAS. Engineers frequently assume that calibrated and equivalent airspeeds are identical at relatively low airspeeds and pressure altitudes. However, the compressibility correction, ΔV_c, is easy to calculate and even though small, should always be applied in the interest of accuracy.

The compressibility correction is a correction to be added to calibrated airspeed to obtain equivalent airspeed, equations 14 and 15. Therefore:

$$V_e = V_c + \Delta V_c \tag{14}$$

$$V_c = V_e - \Delta V_c \tag{15}$$

NOTE: ΔV_c is zero at sea level for all ambient air temperatures.

Determining the Position Error Corrections.

The airspeed position error correction, ΔV_{pc}, is now simply the truth source calibrated airspeed, V_c, minus the aircraft instrument-corrected, indicated airspeed, V_{ic}, equation 16.

$$\Delta V_{pc} = V_c - V_{ic} \tag{16}$$

where: ΔV_{pc} = airspeed position error correction
V_{ic} = aircraft instrument-corrected, indicated airspeed

The altitude position error correction, ΔH_{pc}, and Mach number position error correction, ΔM_{pc}, may be calculated from the airspeed position error correction using equations in appendix A. The algorithms which convert between the different forms of the position error correction are based on the assumption of zero total pressure error in the Pitot system.

Calculating Ambient Air Temperature.

It was stated earlier that flight test experience has shown the ambient air temperature most representative of that an aircraft experiences during takeoff is derived from an aircraft total temperature probe and a Mach number near rotation, equations 17 and 18.

$$T_{T_{ic}} = T_a\,(1+0.2K_R M^2) \tag{17}$$

$$T_a = T_{T_{ic}} / (1+0.2K_R M^2) \tag{18}$$

where: $T_{T_{ic}}$ = total air temperature, K
T_a = ambient air temperature, K
M = Mach number
K_R = total air temperature probe recovery factor

The recovery factor for a typical production or flight test probe is between 0.98 and essentially 1.0, and is usually available from the probe manufacturer. The calculated ambient air temperature is relatively insensitive to small differences in the recovery factor for low Mach numbers, table 8. For example, for a Mach number of 0.20, the calculated ambient air temperature changes approximately 0.04 degrees F for a 0.01 difference in recovery factor. It can be observed that for typical takeoff and landing speeds an assumed value of 1.0 for temperature probe recovery factor will produce an ambient air temperature well within the uncertainties of the measuring systems.

Table 8 Variation in the Calculated Ambient Air Temperature with Changes in Assumed Total Air Temperature Probe Recovery Factor for a True Mach Number of 0.2000

Assumed Total Air Temperature Probe Recovery Factor (n/d)	Calculated Ambient Air Temperature (deg R)	Calculated Ambient Air Temperature (deg F)
0.90	508.34	48.67
0.95	508.14	48.47
0.96	508.10	48.43
0.97	508.06	48.39
0.98	508.02	48.35
0.99	507.98	48.31
1.00	507.94	48.27

Note: Instrument-corrected, indicated (measured) total air temperature of 512.00 degrees R.

Equation 18 is one equation with three unknowns: the two temperatures and the true Mach number. Note: This assumes that the total air temperature probe recovery factor was known to an acceptable level of uncertainty. It can be "solved" for the ambient air temperature by iteration. For the first iteration the instrument-corrected, measured total air temperature and the instrument-corrected Mach number, $M_{ic,}$ are used to calculate the first estimated ambient air temperature. Equation 9 calculates V_T; equation 13 calculates V_e; equation 15 calculates calibrated airspeed using the first estimated ambient air temperature, V_c; and equation 16 calculates ΔV_{pc} from which ΔM_{pc} can be calculated as explained in appendix A. For the next iteration using equation 18, the Mach number inserted would be $M = M_{ic} + \Delta M_{pc}$. The process would be repeated until the calculated ambient air temperatures converge with an acceptable difference.

Analysis for Rotation and Climb.

Theoretically, the airspeed method could continue to be used after liftoff and through the initial climb, as inertial or GPS ground speed data would be available regardless of the height above the ground. However, after liftoff, it would be more difficult to obtain an accurate true airspeed truth source due to the fact that the wind is varying as the aircraft climbs, and the exact wind speed and direction at any point would not be known. Typically, better results would be obtained by switching to the altitude method of data analysis after liftoff.

ALTITUDE METHOD

This method is often overlooked because the engineer is seeking an airspeed position error correction to be added. However appendix A clearly shows the conversion from ΔH_{pc} to ΔV_{pc} is relatively easy. Flight test results using this method are presented in appendices E and F.

Data Required:

The required instrumentation is essentially the same as for the airspeed method. The parameters were identified in table 3. The wind speed and wind direction are not required in the analyses, but they are convenient to have. The use of surveyed runway elevation profiles will result in more accurate results.

Analyses:

Determining Aircraft Height above the Starting Point as a Function of Time.

The starting reference point is determined by measuring the static air pressure or pressure altitude prior to brake release. Because the aircraft is stationary, the static air pressure position error is assumed to be zero.

The ground speed of the aircraft as a function of time is determined using the same equations as for the airspeed method. The ground speed is then integrated from brake release to calculate the horizontal distance along the runway as a function of time. Runway elevation profiles are typically published as a function of the distance from the start of the runway. Geometric height of the aircraft above the brake release point due to the runway slope, Δh, is equal to the look-up value of the runway elevation at any point of interest minus the look-up value of the runway elevation at brake release. Profiles for runway 04R/22L at Edwards AFB and runways 04/22 and 07/25 at Air Force Plant 42 in Palmdale, California are presented in appendices C and D. If runway elevation data are not available at the test location, vertical velocity from an onboard inertial navigation system may be integrated to produce the change in geometric height of the aircraft from the reference brake release point until the start of rotation.

After rotation, a second correction must be applied to the height of the aircraft from the reference brake release elevation. During rotation the aircraft air data sensor will move vertically as the aircraft pitches. The vertical movement due to rotation is equal to the sine of the change in pitch angle multiplied by the horizontal distance (change in fuselage station) between the sensor and the main landing gear wheels, equation 19.

$$\Delta h_{rot} = (x_{rot}) \sin (\theta_{rot}) \qquad (19)$$

where: Δh_{rot} = additional height correction during rotation
x_{rot} = longitudinal distance between the air data computer or the static air pressure sensor and the main landing gear
θ_{rot} = pitch angle change during rotation

Then, the total height of the air data sensor above the starting point, h_{adj}, will be equation 20:

$$h_{adj} = \Delta h + \Delta h_{rot} \qquad (20)$$

where: Δh = height of the landing gear wheels above the elevation of the starting point

The result of the calculations from equations 19 and 20 will be a time history of the aircraft change in geometric altitude from brake release through rotation to liftoff. During the initial climb after mainwheel liftoff, a third altitude adjustment is required, the height of the main gear above their liftoff point. This may be approximated using the integral of the vertical velocity after mainwheel liftoff.

Determining the Truth Source Pressure Altitude as a Function of Time.

The change in pressure altitude due to a change in geometric altitude may be calculated by using equation 1 to convert the time history of tapeline changes in geometric elevation to pressure altitude changes. The change in pressure altitude could be 18 percent more than the change in geometric (tapeline) altitude at sea level and 0 degrees F or 8 percent less at 4,000 feet pressure altitude and 90 degrees F, as shown in table 2. These differences would be small, but not insignificant before rotation. The differences during climbout would become progressively more significant. The adjustment to a change in pressure altitude from brake release should be made for both phases of the takeoff. The result will be a “truth source” time history of the pressure altitude of the aircraft throughout the maneuver.

Determining the Position Error Corrections.

The pressure altitude position error correction, ΔH_{pc}, is now simply the truth source pressure altitude, $H_{P,}$ minus the aircraft instrument-corrected, indicated pressure altitude, $H_{p_{ic}}$, as shown in equation 21.

$$\Delta H_{pc} = H_p - H_{p_{ic}} \tag{21}$$

where: ΔH_{pc} = pressure altitude position error correction
H_p = truth source pressure altitude
$H_{p_{ic}}$ = aircraft instrument-corrected, indicated pressure altitude

The airspeed position error correction, ΔV_{pc}, may then be computed from ΔH_{pc} using the algorithms in appendix A.

A check to verify the validity of the results is to correct the flight test data with the assumed corrections and then compare the true airspeeds from the position error corrected Pitot-static data to the true airspeeds from the inertial velocities and the assumed wind. Typically, the true airspeeds will agree within ±0.5 knot from brake release through liftoff if the takeoff was performed in light, less than 5 knots, wind conditions.

SUMMARY OF THE AIRSPEED AND ALTITUDE METHODS

The two key factors in determining ΔH_{pc} using the altitude method are the determination of the runway elevation beneath the aircraft as a function of time and the resolution of the aircraft instrument-corrected, indicated pressure altitude or the air data computer calculated pressure altitude. Unlike in the airspeed method, the determination of ΔH_{pc} is relatively insensitive to the wind magnitude or variations in its magnitude or direction. The test day ambient air temperature is used to convert a change in geometric height from brake release to a change in pressure altitude for a sloped runway. However, the test day ambient air temperature is not required to convert the truth source true airspeed into the truth source equivalent airspeed in the altitude method.

In a perfect world with constant winds of known magnitude and direction, no uncertainty in the test day ambient air temperature, and adequate resolution for the parameters of interest; the airspeed method would provide more consistent results than the altitude method. In the real world, the opposite is true. Most of the time, the altitude method yields better results.

TEST RESULTS

Test results for two different aircraft are presented in appendices E and F, a Northrop T-38C and a McDonnell Aircraft Company F-15, respectively. The T-38C data includes the takeoff rotation showing the effects of increasing pitch angle. The F-15 data shows the effects of external stores on the position error corrections. Both sets of results are corrections to be added to the outputs of the production air data computer and were obtained from production Pitot-static systems. The T-38C had a production noseboom while the F-15 had two F-15E production dogleg probes on the sides of the fuselage.

NORTHROP T-38C

The Pitot-static position error corrections in-ground effect were evaluated four times in the period of 2001 to 2010 using one T-38C aircraft. The results were very consistent with almost all of the data scatter less than ±4 feet (less than ±0.5 knot) for the pressure altitude position error correction prior to rotation using the altitude method previously described in this handbook.

The four Air Force Flight Test Center (AFFTC) Technical Reports (TRs) documenting the results were:

1. *T-38C Aircraft Performance Evaluation*, AFFTC-TR-03-18 (reference 8),
2. *T-38C Takeoff Flap Evaluation*, AFFTC-TR-07-10 (reference 9),
3. *T-38C/J85-GE-5S Synthetic Paraffinic Kerosene/JP-8 Fuel Blend (SJ-8) Aircraft Performance Testing*, AFFTC-TR-09-45 (reference 10), and
4. *T-38C Propulsion Modernization Program (PMP) Engine Bay Overheat Resolution Aircraft Performance Evaluation Data Package*, AFFTC-TR-10-52DP1 (reference 11).

See appendix E for additional details. In figures E2 and E8 note that the discontinuities in the T-38C data near 65 knots true airspeed, just less than 0.10 Mach number, are due to the production air data computer applying no corrections below that speed and applying out-of-ground-effect position error corrections above 0.10 Mach number.

MCDONNELL AIRCRAFT COMPANY F-15

The flight test F-15 had a production F-15E Pitot-static system. The production Pitot-static system was evaluated in-ground effect with a wide variety of air-to-air and air-to-ground stores. Most of the configurations were only evaluated from brake release to rotation. Two heavy-weight, high-drag, air-to-ground loadings were also evaluated during rotation, figure F15.

Most of the data scatter was within ±7 feet for a given loading using the altitude method. There were significant differences in the results for difference loadings; for example, ΔH_{pc} = 14 to 24 feet at 130 KCAS (approximately 1 to 2 knots ΔV_{pc}). The F-15 results were documented in AFFTC-TR-98-04, (reference 12).

SUMMARY

The purpose of this handbook is to document the flight test techniques, required instrumentation, and the data analysis options available to the flight test engineer for determining Pitot-static position error corrections in-ground effect. Emphasis is placed on the impact of instrumentation uncertainties on the data scatter and the validity of the calculated position error corrections. In conclusion, it is the author's belief that the altitude method will provide the most consistent results. It is recommended, however, that both the altitude and the airspeed methods be used to calculate the static air pressure source position error corrections in-ground effect and the results compared.

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APPENDIX A – PITOT-STATICS REVIEW

INTRODUCTION

This appendix is intended to be a quick review of Pitot-statics. There are many papers, textbooks and documents widely available which provide more complete discussions on the subject. Four of those documents are:

1. *Subsonic Relationships Between Pressure Altitude, Calibrated Airspeed, and Mach Number*, AFFTC-TIH-10-01 (reference 4).
2. *AFFTC Standard Airspeed Calibration Procedures*, AFFTC-TIH-81-5 (reference 3).
3. *Measurement of Aircraft Speed and Altitude*, NASA RP-1406 (reference 13).
4. *Calibration of Air Data Systems and Flow Direction Sensors*, AGARD AG-300, volume 1 (reference 1).

This appendix uses the 1976 U.S. Standard Atmosphere, *U.S. Standard Atmosphere, 1976,* NOAA-S/T 76-1562 (reference 14) and the ICAO Standard Atmosphere, *Manual of the ICAO International Standard Atmosphere (Extended to 80 Kilometers (262,500 Feet),* ICAO Document 7488 (reference 15).

The equations in this appendix are valid for subsonic Mach numbers in the troposphere, below 36,089 feet pressure altitude. They are presented using the units of feet, knots (nautical air miles per hour), and inches of mercury for the air pressures.

PRESSURE ALTITUDE AND AMBIENT AIR PRESSURE

Pressure altitude, H_p, and ambient air pressure, P, are related by equations A1 through A3:

$$H_p = (145{,}442.16)\,(1 - \delta^{\,0.190\,263\,1})\ \text{(feet)} \tag{A1}$$

$$\delta = \{1-[(6.875\,585\,7 \times 10^{-6})\,H_p]\}^{5.255\,880} \tag{A2}$$

$$P = (P_{SL})\,(\delta) \tag{A3}$$

where: H_p = pressure altitude
δ = ambient air pressure ratio
P = ambient air pressure
P_{SL} = ambient air pressure at sea level on a standard day

Values for P_{SL} are presented in table A1.

Table A1 Ambient Air Pressure at Sea Level on a Standard Day (P_{SL})

Units	Value
in H_g	29.921 252 4
lb/ft^2	2116.216 7
psia	14.695 95
millibars	1013.250

Equations A2 and A3 were used to create table A2 in the region of interest for takeoffs and landings. Note that the change in ambient air pressure for each change in pressure altitude is approximately equal to 1 inch of mercury for each 1,000 foot change in pressure altitude below 5,000 feet. This is consistent with the general aviation rule of thumb: one inch per 1,000 feet. The change is approximately 0.8 inch of mercury per 1,000 feet between 8,000 and 12,000 feet pressure altitude.

Table A2 Ambient Air Pressure and Ambient Air Pressure Ratio as a Function of Pressure Altitude

Pressure Altitude (1,000 ft)	Ambient Air Pressure (in Hg)	Ambient Air Pressure Ratio, δ (n/d)
-3	33.310 672	1.113 278
-2	32.148 028	1.074 421
-1	31.018 463	1.036 670
0	29.921 252	1.000 000
1	28.855 683	0.964 388
2	27.821 051	0.929 809
3	26.816 665	0.896 241
4	25.841 845	0.863 662
5	24.895 918	0.832 048
6	23.978 226	0.801 378
7	23.088 120	0.771 629
8	22.224 960	0.742 782
9	21.388 117	0.714 814
10	20.576 975	0.687 704
11	19.790 923	0.661 434
12	19.029 365	0.635 982
13	18.291 711	0.611 328
14	17.577 384	0.587 455
15	16.885 816	0.564 342
16	16.216 446	0.541 971

Notes: 1. $\delta = \{1 - [(6.875\,585\,7 \times 10^{-6})\, H_p]\}^{5.255\,880}$

2. The reference pressure for sea level on a standard day in inches of mercury is 29.921 252 4 (in Hg).

Table A3 was created using equations A1 and A3. It shows the change in pressure altitude corresponding to a change in ambient air pressure of 0.001 inch of mercury. This change in ambient air pressure is about an order of magnitude smaller than the current state of the art for inflight determination of ambient air pressure.

There are three sources of this limitation:

1. Pressure sensor technology,
2. Laboratory and inflight calibration limitations (accuracy of the truth source), and
3. Aircraft instrumentation resolution.

The static air pressure sensors can be limited by any of the three. Modern dead weight testers, the laboratory truth source, are typically guaranteed to ±0.002 inch of mercury. The truth sources for inflight calibrations to determine the ambient air pressure are typically accurate to ±10 to 20 feet of pressure altitude below 30,000 feet pressure altitude. It will be shown in appendices E and F that the typical data scatter for the Pitot-static position error corrections determined during takeoff were on the order of ±5 feet. These results were better (less data scatter) than the typical out-of-ground effect results as there was less uncertainty in the truth source.

Table A3 Change in Pressure Altitude Due to a Change in
Ambient Air Pressure of 0.001 Inch of Mercury

Pressure Altitude (1,000 ft)	Change in Pressure Altitude (ft)
0	0.92
1	0.95
2	0.98
3	1.01
4	1.04
5	1.07
6	1.11
7	1.14
8	1.18
9	1.21
10	1.25
11	1.29
12	1.33
13	1.38
14	1.42
15	1.47
16	1.52

The flight test instrumentation systems on modern aircraft use a pulse code modulation (PCM) system to record onboard and to telemeter the air data computer or the pressure sensor data for post-flight analyses. Most modern aircraft are usually not limited by the resolution of the instrumentation systems. Two words in the word and frame locations are frequently combined to create the equivalent of a 20-bit word from two 16-bit words. A 20-bit word spread over 65,000 feet results in approximately 10 bits per foot of altitude. A 20-bit word for 35 inches of mercury would have approximately 0.000 05 inch of mercury for a PCM count or 2 PCM counts for each 0.0001 inch of mercury. It must be noted that these are resolutions and not accuracies for the measurements. Table A4 lists the number of PCM counts as a function of the number of bits. Most modern aircraft have at least a 16-bit instrumentation system. They also have the ability to combine two 16-bit words to have the equivalent of a 20-bit word for pressure altitude. A 20-bit word, spread over 65,000 feet pressure altitude, would give a resolution (but not an accuracy) of approximately ±0.1 foot.

Table A4 Pulse Code Modulation (PCM) Counts

Number of Bits (n/d)	Number of PCM Counts (n/d)
0	1
1	2
2	4
3	8
4	16
5	32
6	64
7	128
8	256
9	512
10	1,024
11	2,048
12	4,096
13	8,192
14	16,384
15	32,768
16	65,536
17	131,072
18	262,144
19	324,288
20	648,576

Note: PCM counts = 2^n where n is the number of bits

CALIBRATED AIRSPEED AND DIFFERENTIAL PRESSURE

Calibrated airspeed, V_c, and differential pressure, q_c, are related by equations A4 and A5:

$$V_c = a_{SL} \left(5\left\{\left[\left(\frac{q_c}{P_{SL}}\right) +1\right]^{1/3.5} -1\right\}\right)^{0.5} \qquad \text{(A4)}$$

$$q_c = P_{SL}\left\{\left[1 + 0.2\left(\frac{V_c}{a_{SL}}\right)^{2}\right]^{3.5} -1\right\} \qquad \text{(A5)}$$

where: V_c = calibrated airspeed
a_{SL} = the speed of sound at sea level on a standard day
q_c = differential pressure
P_{SL} = pressure at sea level on a standard day

Note that q_c and P_{SL} must have the same units and that V_c and a_{SL} must have the same units. Values of a_{SL} are presented in table A5

Table A5 Speed of Sound at Sea Level on a Standard Day (a_{SL})

Units	Value
knots	661.478 617 7
ft/sec	1116.450 131
meters/sec	340.294

Equation A5 was used to create table A6. It shows the differential pressure equal to total minus static air pressure ($q_c = P_T - P_s$), as a function of calibrated airspeed.

Table A6 Differential Pressure as a Function of Calibrated Airspeed

Calibrated Airspeed (KCAS)	Differential Pressure (in Hg)
10	0.004 787
20	0.019 152
30	0.043 103
40	0.076 659
50	0.119 841
60	0.172 680
70	0.235 211
80	0.307 478
90	0.389 529
100	0.481 422
110	0.583 219
120	0.694 991
130	0.816 812
140	0.948 769
150	1.090 949
160	1.243 452
170	1.406 382
180	1.579 850
190	1.763 976
200	1.958 885
210	2.164 711
220	2.381 595
230	2.609 687
240	2.849 141
250	3.100 123
260	3.362 804
270	3.367 364
280	3.923 992
290	4.222 883
300	4.534 243

Notes: 1. $q_c = P_{SL}\{[\ 1 + 0.2 \left(\frac{V_c}{a_{SL}}\right)^2]^{3.5} - 1\}$

2. P_{SL} = 29.921 252 4 (in Hg)

3. a_{SL} = 661.478 617 7 (knots)

4. The relationship between the subsonic calibrated airspeed and the differential pressure is independent of pressure altitude or ambient air temperature.

Table A7 was created using equations A4 and A5. It shows the changes in calibrated airspeeds corresponding to a change in differential pressure of 0.001 inch of mercury. A 0.001 inch of mercury change in the differential pressure results in less than a 0.10 knot change in calibrated airspeed for calibrated airspeeds faster than 100 knots and results in an approximate 0.2 knot change in calibrated airspeed at 50 knots. An error in differential pressure would most likely be due to an error in the sensed static air pressure. An error in static air pressure would result in errors in both the calculated pressure altitude and in the calculated calibrated airspeed.

Table A7 Change in Calibrated Airspeed due to a Change in Differential Pressure of 0.001 Inch of Mercury

Calibrated Airspeed (KCAS)	Change in Calibrated Airspeed (KCAS)
10	0.99
20	0.52
30	0.34
40	0.26
50	0.21
60	0.17
70	0.15
80	0.13
90	0.11
100	0.10
110	0.09
120	0.09
130	0.08
140	0.07
150	0.07
160	0.06
170	0.06
180	0.06
190	0.05
200	0.05
210	0.05
220	0.04
230	0.04
240	0.04
250	0.04
260	0.04
270	0.04
280	0.03
290	0.03
300	0.03

Table A8 shows the change in pressure altitude due to a change in static air pressure equivalent to a change in calibrated airspeed of one knot at sea level. Notice, the ratio of the pressure altitude error in feet to the calibrated airspeed error in knots divided by the calibrated airspeed in knots is approximately 0.09 [(foot)/(KCAS)^2] for airspeeds below 150 KCAS at sea level. Similar data for pressure altitudes from 2,000 to 10,000 feet are presented in table A9. Notice, the ratios of pressure altitude error in feet divided by the calibrated airspeed error in knots are approximately 0.10 [(foot)/(KCAS)^2] between 2,000 and 3,000 feet pressure altitude.

A rule of thumb for the ratios at ground level at Edwards AFB is the ratio of $\Delta H_{pc} / \Delta V_{pc}$ in feet/KCAS is approximately equal to the calibrated airspeed of interest in knots divided by 10.

Table A8 Change in Pressure Altitude Corresponding to the Ambient Air Pressure Change Equivalent to a One Knot Change in Calibrated Airspeed at Sea Level

Calibrated Airspeed (KCAS)	Change in Differential Pressure (in Hg)	Change in Pressure Altitude (ft)
10	0.000 910	0.84
20	0.001 963	1.82
30	0.002 924	2.70
40	0.003 885	3.59
50	0.004 849	4.48
60	0.005 816	5.38
70	0.006 788	6.28
80	0.007 764	7.18
90	0.008 746	8.09
100	0.009 733	9.00
110	0.010 727	9.92
120	0.011 728	10.85
130	0.012 739	11.78
140	0.013 756	12.72
150	0.014 785	13.68
160	0.015 822	14.64
170	0.016 871	15.61
180	0.017 931	16.59
190	0.019 003	17.58
200	0.020 089	18.58
210	0.021 188	19.60
220	0.022 303	20.63
230	0.023 431	21.68
240	0.024 577	22.74
250	0.025 739	23.81
260	0.026 918	24.90
270	0.028 117	26.01
280	0.029 334	27.14
290	0.030 572	28.29
300	0.031 829	29.45

Table A9 Change in Pressure Altitude Corresponding to the Ambient Air Pressure Change Equivalent to a One Knot Change in Calibrated Airspeed at Several Pressure Altitudes

Calibrated Airspeed (KCAS)	Pressure Altitude – (1,000 ft)				
	2	4	6	8	10
	Change in Pressure Altitude – (ft)				
10	0.89	0.95	1.01	1.07	1.14
20	1.93	2.04	2.17	2.31	2.46
30	2.87	3.05	3.24	3.44	3.66
40	3.81	4.05	4.30	4.57	4.87
50	4.76	5.05	5.37	5.71	6.07
60	5.71	6.06	6.44	6.84	7.28
70	6.66	7.07	7.51	7.99	8.50
80	7.62	8.09	8.59	9.14	9.72
90	8.58	9.11	9.68	10.29	10.96
100	9.55	10.14	10.77	11.45	12.19
110	10.52	11.17	11.87	12.62	13.44
120	11.51	12.22	12.98	13.80	14.69
130	12.50	13.27	14.10	14.99	15.96
140	13.50	14.33	15.22	16.19	17.23
150	14.51	15.40	16.36	17.40	18.52
160	15.52	16.48	17.51	18.62	19.82
170	16.55	17.57	18.67	19.86	21.14
180	17.59	18.68	19.85	21.10	22.46
190	18.65	19.80	21.03	22.37	23.81
200	19.71	20.93	22.24	23.65	25.17
210	20.79	22.07	23.45	24.94	26.55
220	21.89	23.23	24.69	26.25	27.94
230	22.99	24.41	25.94	27.58	29.36
240	24.12	25.60	27.21	28.93	30.79
250	25.26	26.81	28.49	30.30	32.25
260	26.42	28.04	29.80	31.69	33.73
270	27.59	29.29	31.13	33.10	35.23
280	28.79	30.56	32.47	34.53	36.76
290	30.00	31.85	33.84	35.99	38.31
300	31.24	33.16	35.24	37.47	39.89

MACH NUMBER

There are three primary methods which could be used to calculate Mach number, M.

First, equation A6

$$M = \{5[\left(\frac{P_T}{P_a}\right)^{1/3.5} - 1]\}^{0.5} \qquad \text{(A6)}$$

where: P_T = is the total air pressure
P_a = the ambient air pressure

If P_a is replaced by $P_{s_{ic}}$, the instrument-corrected, indicated static air pressure; then M_{ic}, the instrument-corrected, indicated Mach number, is calculated.

Second, equations A2 and A7.

$$\delta = \{1 - [(6.875\,585\,7 \text{ x } 10^{-6})\ H_p]\}^{5.255\,880} \qquad \text{(A2)}$$

$$M = \{5\ [(\left(\frac{1}{\delta}\right)\{[1 + 0.2\left(\frac{V_c}{a_{SL}}\right)\ ^2]^{3.5} - 1\} + 1)^{1/3.5} - 1]\}^{0.5} \qquad \text{(A7)}$$

Third, equations A8 through A12.

$$M = V_T\ /a \qquad \text{(A8)}$$

$$V_T = (\ V_i + \Delta V_{ic} + \Delta V_{pc} + \Delta V_c)\ /\sqrt{\sigma} \qquad \text{(A9)}$$

$$\sigma = \delta/\Theta \qquad \text{(A10)}$$

$$\Theta = T_a\ /\ T_{SL} \qquad \text{(A11)}$$

$$a = a_{SL}\ \sqrt{\ \Theta} \qquad \text{(A12)}$$

where: δ = P_a/P_{sl}
H_p = pressure altitude
V_c = calibrated airspeed
V_T = true airspeed
V_i = indicated airspeed
V_{ic} = correction for mechanical errors in a mechanical airspeed indicator (the instrument correction)
ΔV_{pc} = position error correction
ΔV_c = “compressibility” correction
σ = ratio of the local air density to the air density at sea level on a standard day
Θ = ratio of the local ambient air temperature to the ambient air temperature at sea level on a standard day.
T_a = local ambient air temperature
T_{SL} = ambient air temperature at sea level on a standard day
a = local speed of sound

Potential values for T_{SL} are presented in table A10.

Table A10 Ambient Air Temperature at Sea Level on a Standard day (T_{SL})

Units	Value
Degrees R	518.67
Degrees K	288.15

PITOT-STATIC SUBSCRIPTS

The subscripts used for Pitot-statics are a carryover from the use of mechanical altimeters and airspeed indicators. This section will introduce the subscripts assuming that we are talking about correcting data manually read from mechanical instruments. This section will end with a short description of how they are used with data from air data computers and pressure sensors.

Instrument Reading (i):

The subscript "i" is used to identify data manually recorded from the face of a mechanical altimeter, H_{p_i}, or an airspeed indicator, V_i. The subscript "p" refers to pressure altitude and assumes that the altimeter setting in the Kollsman window was 29.92 inches of mercury; the sea level, standard day value. The capital H vice a lower case h identifies the altitude as a geopotential altitude, vice a geometric (or tapeline) altitude.[2]

Instrument-corrected (ic):

The first correction to the indicated data is to correct for mechanical errors in the mechanical instruments. The errors could be due to manufacturing errors or due to wear on the mechanical components of the instruments, equations A13 and A14.

$$H_{p_{ic}} = H_{p_i} + \Delta H_{p_{ic}} \tag{A13}$$

$$V_{ic} = V_i + \Delta V_{ic} \tag{A14}$$

The terms $H_{p_{ic}}$ and V_{ic} are referred to as instrument-corrected, indicated pressure altitude and instrument-corrected, indicated airspeed because the indicated values have been corrected for mechanical errors in the instruments.[3]

These two "corrections to be added", $\Delta H_{p_{ic}}$ and ΔV_{ic}, are normally determined in an instrumentation lab using calibrated air pressures to drive the instruments. A similar calibration can be performed with the instruments installed in the aircraft using a Pitot-static test set like a military TTU-205. The TTU-205 provides a static and a total air pressure that correspond to a pressure altitude and to a calibrated airspeed. The position error corrections are assumed to be zero for this ground test with the TTU-205 because (unlike inflight) there is no airflow around the probes.

Position Error Correction (pc):

The second correction for airspeed and the final correction for pressure altitude accounts for a difference between the sensed static air pressure at the probe or the flush static port on the fuselage and the freestream ambient air pressure away from the influences of the aircraft. The word "position" in the title implies that the pressure difference existed because the designers placed the probe or the flush static port at the wrong location on the aircraft. The logic assumes that, if only they had selected the right position; then the

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[2] Some aircraft companies do not use the capital H. Their h_P is interchangeable with H_P. In their view, the subscript p denotes pressure altitude, a geopotential altitude, and does not require a capital H. They feel that geometric and geopotential altitudes need to be uniquely identified. However, since the subscript p denotes the altitude as a geopotential altitude, H_P or h_P could be used for pressure altitude. This handbook uses H_P for pressure altitude.

[3] Some companies use the term V_I for instrument-corrected, indicated airspeed vice the more common V_{ic}.

measured static air pressure and the actual ambient air pressure would be identical and the two corrections, ΔH_{pc} and ΔV_{pc}, to be added would be exactly zero, equations A15 and A16.

Calibrated (c):

$$H_p = H_{p_{ic}} + \Delta H_{pc} \tag{A15}$$

$$V_c = V_{ic} + \Delta V_{pc} \tag{A16}$$

The terms H_p and V_c are referred to as "calibrated" because the indicated values have been corrected for both the mechanical errors in the instruments and for the errors in trying to measure the ambient air pressure. The purpose of this handbook is to identify procedures for determining ΔH_{pc} and ΔV_{pc} with the aircraft in-ground effect.

Airspeed Compressibility Correction (ΔV_c)

The three equations (A17, A18, and A19) for the compressible case are:

$$V_c = (7\left(\frac{P_{SL}}{\rho_{SL}}\right)\{[\left(\frac{q_c}{P_{SL}}\right) + 1]^{1/3.5} - 1\})^{0.5} \tag{A17}$$

$$V_e = (7\left(\frac{P_a}{\rho_{SL}}\right)\{[(\frac{q_c}{P_a}) + 1]^{1/3.5} - 1\})^{0.5} \tag{A18}$$

$$V_T = (7\left(\frac{P_a}{\rho_a}\right)\{[(\frac{q_c}{P_a}) + 1]^{1/3.5} - 1\})^{0.5} \tag{A19}$$

Notice that the differences between the equation for true airspeed, A19, and for equivalent airspeed, A18, are the terms (P_a / ρ_a) in the true airspeed equation and (P_a / ρ_{SL}) in the equivalent airspeed equation. The ratio of $(P_a / \rho_a) / (P_a / \rho_{SL})$ is (ρ_{SL} / ρ_a) or $(1/\sigma)$.

Another form of the equation for calibrated airspeed is equation A4.

$$V_c = a_{SL}\,(5\{[\left(\frac{q_c}{P_{SL}}\right) + 1]^{1/3.5} - 1\})^{0.5} \tag{A4}$$

Notice that the difference between equation A18 for equivalent airspeed and equation A17 for calibrated airspeed is that P_{SL} has been substituted for P_a in two places in the equation for calibrated airspeed. Equation A4 or equation A17 for calibrated airspeed both have one input, q_c, and one output, V_c. Either equation could be solved with a mechanical airspeed indicator. The airspeed compressibility correction, ΔV_c, is normally obtained from a graph. However, it can be relatively easily calculated. The following equations are valid for subsonic Mach numbers, $M < 1$, in the troposphere, below 11 kilometers (approximately 36,089 feet) pressure altitude:

For a given pressure altitude and Mach number, equation A2, A20 through A23:

$$\delta = \{1-[(6.875\,585\,7 \times 10^{-6})\,H_p]\}^{5.255\,880} \tag{A2}$$

$$V_c = a_{SL}\,[\,5\,(\{[(1 + 0.2\,M^2)^{3.5} - 1]\,\delta + 1\}^{1/3.5} - 1)]^{0.5} \tag{A20}$$

$$V_e = a_{SL}\,M\delta^{0.5} \tag{A21}$$

$$V_e = V_c + \Delta V_c \tag{A22}$$

$$\Delta V_c = V_e - V_c \qquad \text{(A23)}$$

Table A11 presents the airspeed compressibility correction, ΔV_c, as a function of pressure altitude and Mach number for pressure altitudes of sea level through 15,000 feet and Mach numbers up through 0.50 Mach number. The airspeed compressibility correction is exactly zero for all airspeeds and Mach numbers at sea level and for all pressure altitudes at an airspeed or Mach number of zero.

Or, for a given pressure altitude and calibrated airspeed, equations A2, A7, A21, and A23:

$$\delta = \{1-[(6.875\,585\,7 \times 10^{-6})\, H_p]\}^{5.255\,880} \qquad \text{(A2)}$$

$$M = \{5[(\left(\frac{1}{\delta}\right)\{[1 + 0.2 \left(\frac{V_c}{a_{SL}}\right)^2]^{3.5} - 1\} + 1)^{1/3.5} - 1]\}^{0.5} \qquad \text{(A7)}$$

$$V_e = a_{SL}\, M\, \delta^{\,0.5} \qquad \text{(A21)}$$

$$\Delta V_c = V_e - V_c \qquad \text{(A23)}$$

Note, this handbook uses the convention that ΔV_c is a correction to be added. The magnitude of the correction is less than zero, negative, for all pressure altitudes above sea level. Equivalent airspeed is always less than calibrated airspeed for pressure altitudes above sea level. Some companies define ΔV_c as ($V_c - V_e$) and then use the equation $V_e = V_c - \Delta V_c$ to calculate V_e by subtracting a positive number instead of adding a negative number.

Table A11 Airspeed Compressibility Correction, ΔV_c, As a Function of Pressure Altitude and Mach Number

Pressure Altitude (1,000 ft)	Airspeed Compressibility Correction (correction to be added), ΔV_c, (kts)									
	Mach Number (n/d)									
	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1	-0.00	-0.00	-0.01	-0.02	-0.04	-0.08	-0.12	-0.18	-0.25	-0.34
2	-0.00	-0.01	-0.02	-0.05	-0.09	-0.15	-0.23	-0.34	-0.48	-0.65
3	-0.00	-0.01	-0.03	-0.06	-0.12	-0.21	-0.34	-0.50	-0.70	-0.95
4	-0.00	-0.01	-0.04	-0.08	-0.16	-0.28	-0.44	-0.64	-0.91	-1.23
5	-0.00	-0.01	-0.04	-0.10	-0.20	-0.33	-0.53	-0.78	-1.10	-1.49
6	-0.00	-0.01	-0.05	-0.12	-0.23	-0.39	-0.61	-0.91	-1.28	-1.74
7	-0.00	-0.02	-0.06	-0.13	-0.26	-0.44	-0.69	-1.02	-1.45	-1.96
8	-0.00	-0.02	-0.06	-0.15	-0.28	-0.49	-0.77	-1.13	-1.60	-2.17
9	-0.00	-0.02	-0.07	-0.16	-0.31	-0.53	-0.83	-1.24	-1.74	-2.37
10	-0.00	-0.02	-0.07	-0.17	-0.33	-0.57	-0.90	-1.33	-1.88	-2.55
11	-0.00	-0.02	-0.08	-0.18	-0.35	-0.60	-0.95	-1.41	-2.00	-2.72
12	-0.00	-0.02	-0.08	-0.19	-0.37	-0.64	-1.01	-1.49	-2.11	-2.87
13	-0.00	-0.03	-0.08	-0.20	-0.39	-0.67	-1.06	-1.57	-2.21	-3.01
14	-0.00	-0.03	-0.09	-0.21	-0.40	-0.70	-1.10	-1.63	-2.31	-3.14
15	-0.00	-0.03	-0.09	-0.22	-0.42	-0.72	-1.14	-1.69	-2.39	-3.26

Note: $V_e = V_c + \Delta V_c$

The airspeed compressibility correction is normally wanted as a function of pressure altitude and calibrated airspeed. Tables A12 and A13 present the corrections for 2,000 and for 10,000 feet pressure altitude respectively. At 2,000 feet pressure altitude, the corrections are less than 0.10 knot for calibrated airspeeds less than approximately 170 KCAS. The corrections at 2,000 feet pressure altitude do not exceed 0.20 knot for calibrated airspeeds less than approximately 210 KCAS. The comparable airspeeds at 10,000 feet pressure altitude are 90 KCAS for $\Delta V_c < 0.10$ knot and 115 KCAS for $\Delta V_c < 0.20$ knot.

Table A12 Airspeed Compressibility Correction, ΔV_c, as a Function of Calibrated Airspeed at 2,000 Feet Pressure Altitude

Calibrated Airspeed (KCAS)	Mach Number (n/d)	Airspeed Compressibility Correction (Correction to be Added), ΔV_c (kts)
50	0.078 385	-0.00
60	0.094 060	-0.00
70	0.109 734	-0.00
80	0.125 406	-0.01
90	0.141 076	-0.02
100	0.156 745	-0.02
110	0.172 412	-0.03
120	0.188 077	-0.04
130	0.203 739	-0.05
140	0.219 399	-0.06
150	0.235 056	-0.07
160	0.250 710	-0.09
170	0.266 361	-0.10
180	0.282 009	-0.12
190	0.297 654	-0.14
200	0.313 295	-0.17
210	0.328 932	-0.19
220	0.344 566	-0.22
230	0.360 195	-0.25
240	0.375 821	-0.29
250	0.391 442	-0.32

Notes: 1. $V_e = V_c + \Delta V_c$
2. $\delta = 0.929\ 809$ for 2,000 feet pressure altitude
3. $a_{SL} = 661.478\ 617\ 7$ knots

Table A13 Airspeed Compressibility Correction, ΔV_c, as a function of Calibrated Airspeed at 10,000 Feet Pressure Altitude

Calibrated Airspeed (KCAS)	Mach Number (n/d)	Airspeed Compressibility Correction (Correction to be Added), ΔV_c (kts)
50	0.091 120	-0.02
60	0.109 328	-0.03
70	0.127 528	-0.04
80	0.145 719	-0.07
90	0.163 898	-0.09
100	0.182 065	-0.13
110	0.200 218	-0.17
120	0.218 356	-0.22
130	0.236 478	-0.28
140	0.254 582	-0.35
150	0.272 668	-0.43
160	0.290 734	-0.52
170	0.308 779	-0.62
180	0.326 803	-0.73
190	0.344 804	-0.86
200	0.362 780	-1.00
210	0.380 732	-1.15
220	0.398 659	-1.32
230	0.416 558	-1.50
240	0.434 431	-1.69
250	0.452 275	-1.90

Notes:
1. $V_e = V_c + \Delta V_c$
2. $\delta = 0.687\ 704$ for 10,000 feet pressure altitude
3. $a_{SL} = 661.478\ 617$ knots

Table A14 shows the variations of the airspeed compressibility correction for 100 KCAS between sea level and 16,000 feet pressure altitude.

Table A14 Airspeed Compressibility Correction, ΔV_c, as a Function of Pressure Altitude For 100 Knots Calibrated Airspeed

Pressure Altitude (1,000 ft)	Mach Number (n/d)	Airspeed Compressibility Correction (Correction to be Added), ΔV_c (kts)
0	0.151 176	0.00
1	0.153 926	-0.01
2	0.156 745	-0.02
3	0.159 635	-0.03
4	0.162 599	-0.04
5	0.165 639	-0.06
6	0.168 757	-0.07
7	0.171 955	-0.08
8	0.175 238	-0.10
9	0.178 607	-0.11
10	0.182 065	-0.13
11	0.185 615	-0.14
12	0.189 260	-0.16
13	0.193 042	-0.18
14	0.196 850	-0.20
15	0.200 801	-0.22
16	0.204 861	-0.24

Equivalent Airspeed (e):

Equivalent airspeed is an intermediate step between calibrated and true airspeed. It can be calculated directly with either equation A18 or A21. Equation A18 requires ambient air pressure and differential pressure, $(P_T - P_a)$ or q_c. Equation A21 requires Mach number and the ambient air pressure ratio, δ. A third option is equation A24:

$$V_e = \left(7\left(\frac{P_a}{\rho_{SL}}\right)\left\{\left[\left(\frac{q_c}{P_a}\right)+1\right]^{1/3.5}-1\right\}\right)^{0.5} \tag{A18}$$

$$V_e = a_{SL}\,M\delta^{0.5} \tag{A21}$$

$$V_e = V_i + \Delta V_{ic} + \Delta V_{pc} + \Delta V_c \tag{A24}$$

True Airspeed (T):

True airspeed is the speed of the aircraft with respect to the local air mass. For the special case of horizontal flight with no vertical wind component, true airspeed may be calculated if the aircraft motion with respect to the ground (ground speed and ground track) is known, and the wind speed (wind magnitude and direction) with respect to the ground is known.

Alternatively, true airspeed can be calculated if ambient and total air pressure are known, and the ambient air density is known. The ambient air density is normally calculated using the ambient air pressure and the ambient air temperature, equation A25.

$$V_T = V_e / (\sigma)^{0.5} \tag{A25}$$

Air Data Computers and Pressure Sensors:

Much of the preceding section for Pitot-static subscripts assumed that the data came from either hand-recorded records from a knee pad or from photopanels using mechanical altimeters and airspeed indicators. The recorded data were in the form of indicated airspeeds and indicated pressure altitudes.

On most modern test aircraft, the Pitot-static data are recorded digitally onto magnetic tapes or other devices like compact discs (CDs). The parameters vary from aircraft to aircraft, but the most common are summarized in table A15. Two key factors should be noted in table A15: (1) two pressures or pressure altitude and calibrated airspeed are required, and (2) one air temperature is required (if true airspeed and/or air density or air density ratio, σ, is required).

The outputs of an air data computer (ADC) can cause problems with the names and subscripts of the parameters. If the air data computer has an input of static air pressure, applies a position error correction to the input, converts it into a pressure altitude, and outputs data labeled as pressure altitude or calibrated airspeed; how should the ADC output be labeled if the flight test engineer then applies an additional correction to account for a residual position error correction unique to that test aircraft?

One solution that has been used at Edwards AFB (formerly the Air Force Flight Test Center and now part of the Air Force Test Center) is to use the ADC pressure altitude as an instrument-corrected, indicated pressure altitude and the ADC calibrated airspeed as an instrument-corrected, indicated airspeed. The airspeed and pressure altitude can then be corrected using a position error correction determined during the flight test program for that unique aircraft. The "real" position error corrections would be equal to those in the air data computer plus the flight test-determined residual corrections.

CONVERTING THE FORMS OF POSITION ERROR CORRECTIONS

The initial form of the position error correction is normally a pressure altitude correction to be added, ΔH_{pc}, or an airspeed correction to be added, ΔV_{pc}. The engineer will frequently want the correction in a different form. Some of the potential forms are presented in table A16. Note: this section assumes that there is no error in the measured total air pressure.

Normally ΔH_{pc} and ΔV_{pc} are used at or near the pressure altitude at which they were determined. The other non-dimensional forms of the position error corrections are used to extrapolate the correction to other pressure altitudes.

Table A15 Pitot-static Data Set Options

	Option (n/d)			
Parameter	1	2	3	4
Static Air Pressure (in H_g)	X	X	---	---
Total Air Pressure (in H_g)	X	---	---	---
Differential Air Pressure (in H_g)	---	X	---	---
Indicated Total Air Temperature (deg C)	X	X	---	---
ADC Calibrated Airspeed (knots)	---	---	X	X

Table A15 Pitot-static Data Set Options (Concluded)

Parameter (n/d)	Option (n/d)			
	1	2	3	4
ADC Pressure Altitude (ft)	---	---	X	X
ADC Total Air Temperature (deg C)	---	---	X	---
ADC Ambient Air Temperature (deg C)	---	---	---	X

Table A16 Forms of the Position Error Correction

Symbol	Position Error Correction
ΔH_{pc}	pressure altitude
ΔV_{pc}	airspeed
ΔM_{pc}	Mach number
$\Delta P/P_{s_{ic}}$	pressure ratio
$\Delta P/q_{c_{ic}}$	pressure ratio

Notes: 1. ΔH_{pc} and ΔV_{pc} are not dimensionless.

2. ΔM_{pc}, $\Delta P/P_{s_{ic}}$, and $\Delta P/q_{c_{ic}}$ are dimensionless.

3. The measured total (or Pitot) air pressure is usually assumed to be accurate except when the aircraft is at high angles of attack or at high sideslip angles.

Converting ΔH_{pc} to ΔV_{pc}:

Given instrument-corrected, indicated pressure altitude, ($H_{p_{ic}}$), instrument-corrected, indicated airspeed, (V_{ic}), and the pressure altitude position error correction, (ΔH_{pc}); ΔV_{pc} can be solved for using the following equations (A26, A27, A15, A2, A28 through A33):

$$\delta_{ic} = \{1-[(6.875\,585\,7 \times 10^{-6})\, H_{p_{ic}}]\}^{5.255\,880} \tag{A26}$$

$$P_{s_{ic}} = P_{SL}\, \delta_{ic} \tag{A27}$$

$$H_p = H_{p_{ic}} + \Delta H_{pc} \tag{A15}$$

$$\delta = \{1-[(6.875\,585\,7 \times 10^{-6})\, H_p]\}^{5.255\,880} \tag{A2}$$

$$P_s = P_{SL}\, \delta \tag{A28}$$

$$\Delta P = P_s - P_{s_{ic}} \tag{A29}$$

$$q_{c_{ic}} = (P_T - P_{s_{ic}}) \tag{A30}$$

$$q_c = (P_T - P_s) \tag{A31}$$

$$(q_c - q_{c_{ic}}) = (P_T - P_s) - (P_T - P_{s_{ic}}) \tag{A32}$$

$$\Delta q_{c_{pc}} = (P_{s_{ic}} - P_s) \tag{A33}$$

By comparison of equations A29 and A33, use equations A34 through A36, A4, and A37:

$$\Delta q_{c_{pc}} = -\Delta P \tag{A34}$$

$$q_{c_{ic}} = P_{SL}\{[\ 1 + 0.2 \left(\frac{V_{ic}}{a_{SL}}\right)^2]^{3.5} -1\} \tag{A35}$$

$$q_c = q_{c_{ic}} + \Delta q_{c_{pc}} \tag{A36}$$

$$V_c = a_{SL}\ (5\{[\left(\frac{q_c}{P_{SL}}\right)+1]^{1/3.5} -1\})^{0.5} \tag{A4}$$

$$\Delta V_{pc} = V_c - V_{ic} \tag{A37}$$

Converting ΔV_{pc} to ΔH_{pc}:

Given instrument-corrected, indicated pressure altitude, ($H_{p_{ic}}$), instrument-corrected, indicated airspeed, (V_{ic}), and the airspeed position error correction, (ΔV_{pc}); ΔH_{pc} can be solved for using equations A26, A27, A35, A16, A5, A36, A37, A34, A38, A39, A40, A1, and A41 as follows:

$$\delta_{ic} = \{1-[(6.875\ 585\ 7 \times 10^{-6})\ H_{p_{ic}}]\}^{5.255\ 880} \tag{A26}$$

$$P_{s_{ic}} = P_{SL}\ \delta_{ic} \tag{A27}$$

$$q_{c_{ic}} = P_{SL}\{[\ 1 + 0.2 \left(\frac{V_{ic}}{a_{SL}}\right)^2]^{3.5} -1\} \tag{A35}$$

$$V_c = V_{ic} + \Delta V_{pc} \tag{A16}$$

$$q_c = P_{SL}\{[\ 1 + 0.2\left(\frac{V_c}{a_{SL}}\right)^2]^{3.5} -1\} \tag{A5}$$

$$q_c = q_{c_{ic}} + \Delta q_{c_{pc}} \tag{A36}$$

$$\Delta q_{c_{pc}} = q_c - q_{c_{ic}} \tag{A37}$$

$$\Delta q_{c_{pc}} = -\Delta P \tag{A34}$$

$$\Delta P = P_s - P_{s_{ic}} \tag{A38}$$

$$P_s = P_{s_{ic}} + \Delta P \tag{A39}$$

$$\delta = P_s / P_{SL} \tag{A40}$$

$$H_p = (145{,}442.16)(1- \delta^{0.190\ 263\ 1}) \tag{A1}$$

$$\Delta H_{pc} = H_p - H_{p_{ic}} \tag{A41}$$

Converting ΔH_{pc} to ΔM_{pc}:

Given instrument-corrected, indicated pressure altitude, ($H_{p_{ic}}$), instrument-corrected, indicated airspeed, (V_{ic}), and the pressure altitude correction, (ΔH_{pc}); ΔM_{pc} can be solved using equations A26, A27, A15, A2, A3, A24, A35, A30, A42 through A45, as follows:

$$\delta_{ic} = \{1-[(6.875\,585\,7 \text{ x } 10^{-6})\, H_{p_{ic}}]\}^{5.255\,880} \tag{A26}$$

$$P_{s_{ic}} = P_{SL}\, \delta_{ic} \tag{A27}$$

$$H_p = H_{p_{ic}} + \Delta H_{pc} \tag{A15}$$

$$\delta = \{1-[(6.875\,585\,7 \text{ x } 10^{-6})\, H_p]\}^{5.255\,880} \tag{A2}$$

$$P_s = P_{SL}\, \delta \tag{A3}$$

$$\Delta P = P_s - P_{s_{ic}} \tag{A24}$$

$$q_{c_{ic}} = P_{SL}\{[\ 1 + 0.2 \left(\frac{V_{ic}}{a_{SL}}\right)^2]^{3.5} -1\} \tag{A35}$$

$$q_{c_{ic}} = (P_T - P_{s_{ic}}) \tag{A30}$$

$$P_T = P_{s_{ic}} + q_{c_{ic}} \tag{A42}$$

$$M_{ic} = \{5[\left(\frac{P_T}{P_{s_{ic}}}\right)^{1/3.5} - 1]\}^{0.5} \tag{A43}$$

$$M_c = \{5[\left(\frac{P_T}{P_{sa}}\right)^{1/3.5} - 1]\}^{0.5} \tag{A44}$$

$$\Delta M_{pc} = M_c - M_{ic} \tag{A45}$$

Converting ΔH_{pc} to $\Delta P/Ps_{ic}$:

Given instrument-corrected, indicated pressure altitude, ($H_{p_{ic}}$), and the pressure altitude position error correction, (ΔH_{pc}); $\Delta P/P_{s_{ic}}$ can be solved for using equations A26, A27, A15, A2, A3, and A29 as follows:

$$\delta_{ic} = \{1-[(6.875\,585\,7 \text{ x } 10 -6)\, H_{p_{ic}}]\}^{5.255\,880} \tag{A26}$$

$$P_{s_{ic}} = P_{SL}\, \delta_{ic} \tag{A27}$$

$$H_p = H_{p_{ic}} + \Delta H_{pc} \tag{A15}$$

$$\delta = \{1-[(6.875\,585\,7 \text{ x } 10^{-6})\, H_p]\}^{5.255\,880} \tag{A2}$$

$$P_s = P_{SL}\, \delta \tag{A3}$$

$$\Delta P = P_s - P_{s_{ic}} \qquad \text{(A29)}$$

The correction $\Delta P/P_{s_{ic}}$ can then be calculated using the results from equations A46.

$$\Delta P/P_{s_{ic}} = P_{SL}\{[\ 1 + 0.2 \left(\frac{V_{ic}}{a_{SL}}\right)^2]^{3.5} -1\} \qquad \text{(A46)}$$

Converting ΔH_{pc} to $\Delta P/q_{cic}$:

Given instrument-corrected, indicated pressure altitude, ($\Delta H_{p_{ic}}$), instrument-corrected, indicated airspeed, (V_{ic}), and the pressure altitude position error correction, (ΔH_{pc}); $\Delta P/q_{c_{ic}}$ can be solved for using equations A26, A27, A15, A2, A3, A29 and A35 as follows:

$$\delta_{ic} = \{1-[(6.875\ 585\ 7 \times 10^{-6})\ H_{p_{ic}}]\}^{5.255\ 880} \qquad \text{(A26)}$$

$$P_{s_{ic}} = P_{SL}\ \delta_{ic} \qquad \text{(A27)}$$

$$H_p = H_{p_{ic}} + \Delta H_{pc} \qquad \text{(A15)}$$

$$\delta = \{1-[(6.875\ 585\ 7 \times 10^{-6})\ H_p]\}^{5.255\ 880} \qquad \text{(A2)}$$

$$P_s = P_{SL}\ \delta \qquad \text{(A3)}$$

$$\Delta P = P_s - P_{s_{ic}} \qquad \text{(A29)}$$

$$q_{c_{ic}} = P_{SL}\{[\ 1 + 0.2 \left(\frac{V_{ic}}{a_{SL}}\right)^2]^{3.5} -1\} \qquad \text{(A35)}$$

The correction $\Delta P/q_{c_{ic}}$ can then be calculated using the results from equations A47.

$$\Delta P/q_{c_{ic}} = (P_s - P_{s_{ic}})/(\ P_{SL}\{[\ 1 + 0.2 \left(\frac{V_{ic}}{a_{SL}}\right)^2]^{3.5} -1\} \qquad \text{(A47)}$$

Pressure Altitude Range of Applicability:

The field elevations of runways around the world range from approximately 1,300 feet below sea level to approximately 14,500 feet above sea level. The range of pressure altitudes at these airports during non-standard day atmospheric conditions would be approximately 3,000 feet below sea level to approximately 16,000 feet above sea level. Examples of low and high field elevation airports can be found in *Determining Conventional Aircraft Takeoff Performance and Adjusting the Results to a Reference Set of Conditions*, 412TW-TIH-19-03 (reference 16).

Most military flight manuals and civilian pilot operating handbooks present predicted takeoff performance for sea level through 8,000 feet pressure altitude. Some manuals and handbooks have predictions for pressure or density altitudes above 10,000 feet. The sea level predictions are normally used for pressure or density altitudes below sea level, as the sea level performance data are conservative for lower altitudes.

The flight test determined position error corrections to be added, the pressure altitude and the airspeed corrections in-ground effect, must be applicable over a wide range of pressure altitudes.

These corrections vary with pressure altitude. They can be changed to a non-dimensional form: either Mach number correction to be added (ΔM_{pc}), or a pressure ratio ($\Delta P/q_{c_{ic}}$ or $\Delta P/P_{s_{ic}}$) which should be independent of pressure altitude. These non-dimensional corrections to be added can then be corrected back to pressure altitude or airspeed corrections to be added at the required pressure altitudes for inclusion in the flight manual. The equations for making these conversions are described in this appendix.

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APPENDIX B – DOCUMENTATION REVIEW

The regulations, guidance, and practices related to in-ground effect Pitot-static flight testing in government and contractor documents are discussed below. This documentation search in some cases reveals the rather limited specific guidance available to the flight test community.

NACA AND NASA

Although surprising, a documentation search revealed that neither the National Advisory Committee for Aeronautics (NACA) nor the National Aeronautics and Space Administration (NASA) has ever published a paper or a document on determining Pitot-static position error corrections in-ground effect.

FAA DOCUMENTS

There are four applicable Federal Aviation Administration (FAA) documents: Federal Aviation Regulation FAR Part 23, *Airworthiness Standards: Normal, Utility, Acrobatic, and Commuter Category Airplanes*,[4] (reference 17); FAA Advisory Circular 23-8C, *Flight Test Guide for Certification of Part 23 Airplanes*, (reference 6); FAR Part 25[5], *Airworthiness Standards: Transport Category Airplanes*, (reference 18); and FAA Advisory Circular 25-7C, *Flight Test Guide for Certification of Transport Category Airplanes*, (reference 7).

FAR Part 23:

The applicable part of FAR Part 23 is § (section) 23.1323 Airspeed Indicating System, subpart (e). In the FARs, V_1 is defined as the takeoff decision speed. At V_1 the pilot can continue the takeoff using the available runway to accelerate or abort the takeoff and come to a stop using the available runway. The target climbout speed for the first climb segment, V_2, is between mainwheel liftoff (takeoff) and the start of the landing gear retraction cycle.

> (e) In addition, for normal, utility, and acrobatic category multiengine jets of more than 6,000 pounds maximum weight and commuter category airplanes, each system must be calibrated to determine the system error during the accelerate-takeoff ground run. The ground run calibration must be determined -
>
> (1) From 0.8 of the minimum value of V_1 to the maximum value of V_2, considering the approved ranges of altitude and weight; and
>
> (2) The ground run calibration must be determined assuming an engine failure at the minimum value of V_1.

The significance of FAR 23 subpart (e) (2) is the need to consider pressure lags in the static and in the total pressure lines. For a given aircraft gross weight, airport pressure altitude, and ambient air temperature, the aircraft acceleration down the runway will be reduced following an engine failure.

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[4] Throughout this document, “FAR 23” refers to 14 Code of Federal Regulations (CFR) Part 23.

[5] Throughout this document, “FAR 25” refers to 14 Code of Federal Regulations (CFR) Part 25.

FAA Advisory Circular 23-8C:

Advisory circular 23-8C presents guidance on acceptable techniques which may be used to show compliance with the FAR Part 23 requirements. The advisory circular is very clear that it is not intended for the procedures in the advisory circular to be the only acceptable ones.

1. **Purpose.**
   - **a.** This advisory circular (AC) sets forth an acceptable means, but not the only means, of showing compliance with Title 14 of the Code of Federal Regulations (14 CFR) part 23 concerning flight tests and pilot judgements. Material in this AC is neither mandatory nor regulatory in nature and does not constitute a regulation.
   - **b.** This AC is one method being utilized to achieve national standardization in normal, utility, acrobatic, and commuter category airplanes.
   - **c.** This material is intended as a ready reference for part 23 airplane manufacturers, modifiers, Federal Aviation Administration (FAA) design evaluation engineers, flight test engineers, and engineering flight test pilots, including Organization Delegation Option (DOA).
2. **Applicability.**
   - **a.** The methods and procedures contained in this AC are available for use during all normal, utility, acrobatic, and commuter category airplane flight test certification activities. This material does not have any legal status and must be treated accordingly. The procedures set forth are one acceptable means of compliance with applicable sections of part 23.
   - **b.** Like all AC material, these guidelines are not mandatory and do not constitute a regulation. They came from previous FAA experience in finding compliance with the airworthiness requirements. They represent the methods and procedures found acceptable by that experience. Since these methods and procedures are only one acceptable means of compliance, individuals should be guided by the intent of the methods provided in this AC.

Appendix 9 of the advisory circular presents information on two acceptable techniques: (1) a trapped static source method and (2) a distance measuring unit (DMU) technique. Both are discussed in this handbook.

FAA FAR Part 25:

The applicable sections of FAR 25 are §25.107 and §25.1323. Throughout §25.107 the required speeds are identified as calibrated airspeeds versus indicated airspeeds. The test organization must therefore determine Pitot-static position error corrections in order to calculate the calibrated airspeeds that meet the requirements. §25.1323 is presented below in its entirety. In this excerpt, indicated airspeed is abbreviated as IAS, and calibrated airspeed as CAS.

§25.1323 Airspeed Indicating System.

For each airspeed indicating system, the following apply:

(a) Each airspeed indicating instrument must be approved and must be calibrated to indicate true air speed (at sea level with a standard atmosphere) with a minimum practicable instrument calibration error when the corresponding pitot and static pressures are applied.

(b) Each system must be calibrated to determine the system error (that is, the relation between IAS and CAS) in flight and during the accelerated takeoff ground run. The ground run calibration must be determined -

(1) From 0.8 of the minimum value of V_1 to the maximum value of V_2, considering the approved ranges of altitude and weight; and

(2) With the flaps and power settings corresponding to the values determined in the establishment of the takeoff path under § 25.111 assuming that the critical engine fails at the minimum value of V_1.

(c) The airspeed error of the installation, excluding the airspeed indicator instrument calibration error, may not exceed three percent or five knots, whichever is greater, throughout the speed range, from -

(1) V_{MO}[6] to 1.23 V_{SR1}[7] , with flaps retracted; and

(2) 1.23 V_{SR0}[8]to V_{FE}[9]with flaps in the landing position.

(d) From 1.23 V_{SR}[10] to the speed at which stall warning begins, the IAS must change perceptibly with CAS and in the same sense, and at speeds below stall warning speed the IAS must not change in an incorrect sense.

(e) From V_{MO}[6] to V_{MO}[6] + 2/3 (V_{DF}[11] – V_{MO}[6]), the IAS must change perceptibly with CAS and in the same sense, and at higher speeds up to V_{DF}[6] the IAS must not change in an incorrect sense.

(f) There must be no indication of airspeed that would cause undue difficulty to the pilot during the takeoff between the initiation of rotation and the achievement of a steady climbing condition.

(g) The effects of airspeed indicating system lag may not introduce significant takeoff indicated airspeed bias, or significant errors in takeoff or accelerate-stop distances.

(h) Each system must be arranged, so far as practicable, to prevent malfunction or serious error due to the entry of moisture, dirt, or other substances.

(i) Each system must have a heated pitot tube or an equivalent means of preventing malfunction due to icing.

Where duplicate airspeed indicators are required, their respective pitot tubes must be far enough apart to avoid damage to both tubes in a collision with a bird.

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[5] V_{MO} is the maximum operating limit speed.

[7] V_{SR1} is the reference stall speed in a specific configuration.

[8] V_{SR0} is the stall speed in the landing configuration.

[9] V_{FE} is the maximum flap extended speed

[10] V_{SR} is the reference stall speed.

[11] V_{DF} is the demonstrated dive speed.

FAA Advisory Circular 25-7C:

Advisory Circular 25-7C was issued in October 2012, and replaced the previous Advisory Circular 25-7B. The text below was unchanged in the new version, with the exception of paragraph number. The applicable guidance in the advisory circular is in Chapter 6, Section 2, paragraph 177b(4) and 177b(5):

> 4. (4) The procedures presented in this paragraph pertain to the calibration of the airspeed indicating system during takeoff ground acceleration. In particular, airplanes with electronic instruments in the cockpit must account for the airspeed lag at the cockpit display associated with data processing and filtering as required by § 25.1323 (g). The airspeed indicating system should not have a lag in excess of 3 knots at the V_1 speed during any takeoff condition. Furthermore, if airspeed lag causes an increase of more than 100 ft. in takeoff or accelerate-stop distances, a lag correction should be applied to the airspeed indicating system. Airspeed lag should be determined by one of the following methods:
>
> (a) Conduct ground acceleration tests for a range of airplane gross weights to calibrate IAS at the cockpit display against the reference CAS. Determine airspeed lag from the calibration data by comparing the cockpit displayed airspeed with the reference calibration speed for a given gross weight and V_1 speed.
>
> (b) Determine airspeed lag by analysis using a computer program suitable for AFM development. Compute takeoffs for a range of gross weights to determine the acceleration at V_1. Calculate airspeed lag at V_1 for a corresponding acceleration and a known time lag due to data processing and filtering. The analysis should also consider other sources of airspeed lag as appropriate, such as the pneumatic lag in the pressure lines for the pitot and static sources.
>
> (5) Having established the calibration data, one acceptable method of adjusting for airspeed lag is to apply corrections directly in the ADC data processing to result in a lag-corrected airspeed at the cockpit display. Another would be to include an airspeed lag correction in the takeoff ground speed calibration of IAS vs. CAS in the AFM. A single airspeed lag increment can be developed as the correction for the range of gross weights and corresponding accelerations at V_1. This increment, when applied to the calibration, should result in no more than a 100 foot increase in takeoff or accelerate-stop distances due to airspeed lag for any takeoff condition. A more accurate correction would result from presenting airspeed lag as a function of airplane acceleration based on the calibration data. If acceleration data are available in the ADC, a real time correction for lag during the takeoff can be applied in the data processing.

Except for the emphasis on determining the Pitot-static lag, the in-ground effect calibration requirements for Part 25 aircraft are similar to those for Part 23 aircraft. Determining the Pitot-static lag in-ground effect is not addressed in this handbook.

NATO AGARDOGRAPH NUMBER 300

The North Atlantic Treaty Organization (NATO) AGARDOgraph series was created and maintained by its member nations to assist in the flight testing of their military aircraft. Volume 1 of the series AGARD Flight Test Techniques (reference 1), has a half page devoted to Pitot-statics in-ground effect on page 22, paragraph 4.9, of the document:

> 4.9 Calibration in-ground Effect
>
> Pressure error in-ground effect is in general relevant only for aircraft in the takeoff or landing configuration, in which flight close to the ground may not be unduly hazardous, or possibly for terrain-following aircraft which may operate sufficiently close to the ground in other configurations for ground effect to be significant and which will require a control system which makes such operation acceptable for a pressure calibration trial. Calibration is made using the tower flypast method in the required conditions. The necessary accurate measurement of ground clearance may be obtained from the photographic record used in the usual height determination of the flypast method, since the height of the local surface relative to the observation point can be readily measured; alternatively a kinetheodolite tracking method may be used and this, if the surface height profile is included in the calculation program, can give height above surface throughout the length of a run which, if synchronized with the air data system, can give multiple data points from a single run; a high quality radio altimeter can be similarly used. The data required are the air data pressure, the reference point ambient pressure, the height of the aircraft relative to the surface, and the height relative to the reference pressure point; since ground effect trials will if at all possible to be made above a level surface, the latter height will usually be obtainable with sufficient accuracy by inference from the former if, for example when a radio altimeter is used, it is not explicitly measured.
>
> Pressure error calibration data may be acquired during takeoffs and landings, and in particular during measured takeoff and landing trials in which the aircraft path is recorded by kinetheodolites or other method, so that the height relative to an ambient pressure datum position may be obtained; the data can then be processed as for a fly-past calibration. If aircraft groundspeed is obtained, as usually it will be during such trials, and if the windspeed is accurately recorded, a true airspeed is obtained and hence a stagnation pressure which can be used to check the calibration of the pitot system, and a calibrated airspeed may be obtained for comparison with that of the air data system; the accuracy of knowledge of windspeed at the aircraft will not usually be sufficient for this true airspeed data to be used as a primary calibration method.
>
> Calibration of the pitot system by venturi or swiveling pitot is a trial self-contained within the aircraft which can equally well be made in-ground effect if necessary; in the flight conditions occurring in-ground effect a pitot calibration error should not exist in any well designed system, and a ground effect on such error should be improbable.

The AGARDOgraph identifies four possible flight test techniques:

1. Data collected during low approaches (or flypasts) with the data processed like a conventional tower flyby: An altitude technique.
2. Data collected during takeoffs and landings with the data processed along lines similar to a conventional tower flyby: An altitude technique.
3. Data collected during takeoffs and landings with the data processed using an assumed wind magnitude and direction plus an assumed ambient air temperature: An airspeed technique.
4. Data collected by measuring Pitot total air pressure using a flight test device and the production Pitot probe. The measured error in Pitot pressure is then the difference between the pressure from the flight test device and from the production probe. (It is important to understand that this technique only addresses an error on the Pitot side and has limited applicability. The airspeed error is normally due to an error on the static pressure side.)

The first three techniques were each addressed in this the handbook.

MILITARY DOCUMENTS

MIL-C-5011A AND MIL-C-005011B:

These military specifications were primarily used to define the requirements for the USAF Standard Aircraft Characteristics Charts (the SAC charts). Neither MIL-C-5011A nor its replacement MIL-C-005011B, Military Specification Charts; *Standard Aircraft Characteristics and Performance, Piloted Aircraft (Fixed Wing)* (reference 19) clearly specified a requirement to determine and correct for Pitot-static position errors in-ground effect.

MIL-DTL-7700G:

Detail Specification Flight Manuals, Air Refueling Procedures, and Abbreviated Checklists, MIL-DTL-7700G (reference 2), clearly identified a requirement to determine the Pitot-static position error corrections in-ground effect:

> 5. 3.4.10.1.1.4.3 Pitot-static installation correction. If correction is more than ±2 knots airspeed or ±100 feet pressure altitude, the following charts for the installation correction shall be furnished. (Corrections up to a magnitude of ±2 knots airspeed or ±100 feet pressure altitude may be shown in tabulations.)
>
> a. The chart for airspeed installation correction shall plot equivalent airspeed (EAS) versus CAS [IAS corrected for instrument error] or IAS versus correction to EAS. For high speed flights, the airspeed correction may be a plot of mach position correction versus indicated mach. Parameters shall be included for normal operating weights and for all normal configurations such as full flaps and gear down, and flaps and gear up, for both in-ground effect (IGE) and out of ground effect (OGE). Text shall include an explanation of the conversion from IAS to TAS and the statement: "Where the symbol IAS is used on performance charts, mechanical error is assumed to be zero.
>
> b. The chart for altimeter correction shall be a plot of altimeter position error correction to be added to pressure altitude versus CAS/IAS with pressure altitude parameters, from sea level to service ceiling and gross weight parameters, for all normal

> configurations such as full flaps and gear down. For aircraft whose airspeed correction data is in terms of Mach number, the altitude position correction shall be a chart showing altitude or altitude correction versus mach number. The data shall include ground effects and the curves shall be similar to those for airspeed corrections.

Previous versions of MIL-DTL-7700G, including MIL-M-7700C, MIL-M-7700D, and MIL-PRF-7700F, had similar wording for the requirement. Note that the document requires both a correction for airspeed and for pressure altitude in-ground effect.

MIL-STD-1793:

Military Standard Flight Performance, Air Vehicle, MIL-STD-1793 (reference 20) did not clearly specify a requirement to determine and correct for Pitot-static position errors in-ground effect.

MIL-STD-3013:

Department of Defense Standard Practice Glossary of Definitions, Ground Rules, and Mission Profiles to Define Air Vehicle Performance Capability, MIL-STD-3013 (reference 21) superseded MIL-C-5011A. Like MIL-C-5011A, MIL-STD-3013 does not clearly specify a requirement to determine and correct for Pitot-static position errors in-ground effect.

AF TECHNICAL REPORT NUMBER 6273 (“HERRINGTON”):

Flight Test Engineering Handbook, Air Force Technical Report (AFTR) 6273 (reference 22), known informally as “Herrington” for its author, has 69 pages of advice for determining out-of-ground effect Pitot-static position error corrections. It does not mention the existence of, nor the need to correct for, errors in-ground effect.

AFFTC-TIH-99-01:

Aircraft Performance Flight Testing, AFFTC-TIH-99-01 (reference 23), intentionally concentrated on aircraft performance flight test improvements developed after the *Flight Test Engineering Handbook* (reference 22) was published. As noted in the preface of AFFTC-TIH-99-01, airspeed calibration in-ground effect was not included in the final document.

AFFTC-TIH-81-5:

The *AFFTC Standard Airspeed Calibration Procedures*, AFFTC-TIH-81-5 (reference 3) identifies an altitude method for determining the Pitot-static position error corrections in-ground effect with the aircraft on the ground during the takeoff roll. The following is quoted from page 87 in reference 3.

6. Airspeed Calibration in-ground Effect:

Definition of the position error in-ground effect is important in determining airplane performance during the ground roll phase of takeoffs or landings.

The calibration of the airspeed system in-ground effect may be obtained from the difference between the altimeter reading prior to brake release and altimeter readings obtained at various speeds during the takeoff ground roll. Test results are plotted in a form of ΔH_{pc} versus indicated airspeed, then a line is faired through the test data which will be representative of the ΔH_{pc} calibration. Values from this faired line, not the test points, are then converted to values of ΔV_{pc} and plotted versus indicated airspeed. It will be noted that the use of this method assumes no total pressure lag during the ground roll, and, as a result, must be applied judiciously.

A ground slope correction must also be applied if a runway slope exists.

The method described in this reference (the altitude method) is the author’s preferred method and was discussed in detail in this handbook.

APPENDIX C – RUNWAY PROFILE FOR EDWARDS AFB RUNWAY 04R/22L

Table C1 Variation of Runway Elevation with Distance for Edwards AFB Runway 04R/22L

Distance from the East End (1,000 ft)	Orthometric Elevation (EGM 96) (ft)
0	2281.9
1	2283.3
2	2284.7
3	2286.1
4	2287.5
5	2288.9
6	2290.2
7	2291.6
8	2293.0
9	2294.4
10	2295.8
11	2297.2
12	2298.5
13	2299.9
14	2301.3
15	2302.7
15,024	2302.7

Note: The average slope over the entire 15,024 feet is 0.001382 (ft/ft), 0.0793 (deg), or 20.8 feet of elevation change in 15,024 feet.

APPENDIX D – RUNWAY PROFILES FOR USAF PLANT 42

Table D1 Variation of Runway Elevation with Distance for Plant 42 Runway 04/22

Station Name	Latitude (WGS 84) (DD MM SS.SSSSS)	Longitude (WGS 84) (DDD MM SS.SSSSS)	Ellipsoid Elevation (WGS 84) (ft)	Orthometric Elevation (EGM 96) (ft)	Slope Distance (ft)
RW 04	N 34 37 00.87310	W118 05 29.85183	2,437.19	2,543.75	0.00
R0401	N 34 37 06.99111	W118 05 20.45211	2,430.95	2,537.51	1,000.03
R0402	N 34 37 13.10748	W118 05 11.05120	2,424.70	2,531.25	2,000.02
R0403	N 34 37 19.22426	W118 05 01.64990	2,419.13	2,525.67	3,000.04
R0404	N 34 37 25.34035	W118 04 52.24815	2,413.79	2,520.31	4,000.04
R0405	N 34 37 31.45530	W118 04 42.84493	2,407.77	2,514.28	5,000.05
R0406	N 34 37 37.57119	W118 04 33.44390	2,401.61	2,508.11	5,999.97
R0407	N 34 37 43.68695	W118 04 24.04083	2,397.30	2,503.79	6,999.99
R0408	N 34 37 49.80185	W118 04 14.63659	2,394.56	2,501.04	8,000.01
R0409	N 34 37 55.91673	W118 04 05.23168	2,392.26	2,498.73	9,000.06
R0410	N 34 38 02.03310	W118 03 55.82748	2,389.90	2,496.36	10,000.14
R0411	N 34 38 08.14646	W118 03 46.42421	2,387.60	2,494.04	10,999.97
RW 22	N 34 38 14.18069	W118 03 37.13936	2,385.38	2,491.82	11,987.05

Table D2 Variation of Runway Elevation with Distance for Plant 42 Runway 07/25

Station Name	Latitude (WGS 84) (DD MM SS.SSSSS)	Longitude (WGS 84) (DDD MM SS.SSSSS)	Ellipsoid (WGS 84) Elevation (ft)	Orthometric (EGM 96) Elevation (ft)	Slope Distance (ft)
RW 07	N 34 37 50.13195	W118 06 47.06392	2,434.77	2,541.28	0.00
R0701	N 34 37 50.79103	W118 06 35.12627	2,429.81	2,536.32	999.97
R0702	N 34 37 51.44861	W118 06 23.18545	2,424.92	2,531.42	2,000.16
R0703	N 34 37 52.10607	W118 06 11.24848	2,420.06	2,526.55	3,000.04
R0704	N 34 37 52.76309	W118 05 59.31006	2,415.15	2,521.64	4,000.02
R0705	N 34 37 53.42029	W118 05 47.37123	2,410.20	2,516.69	5,000.05
R0706	N 34 37 54.07761	W118 05 35.43160	2,405.75	2,512.24	6,000.13
R0707	N 34 37 54.73311	W118 05 23.49337	2,403.10	2,509.59	7,000.07
R0708	N 34 37 55.39014	W118 05 11.55504	2,400.41	2,506.89	8,000.03
R0709	N 34 37 56.04519	W118 04 59.61557	2,397.63	2,504.11	9,000.08
R0710	N 34 37 56.70128	W118 04 47.67600	2,396.15	2,502.63	10,000.12
R0711	N 34 37 57.35650	W118 04 35.73733	2,394.69	2,501.16	11,000.09
RW 25	N 34 37 58.00895	W118 04 23.81560	2,393.08	2,499.55	11,998.63

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APPENDIX E – TEST RESULTS FOR NORTHROP T-38C

The test results in this appendix were obtained for the production Pitot-static system of a T-38C aircraft. The production system had a noseboom that was approximately 4.6 feet above the ground and extended approximately 2.8 feet ahead of the nose of the aircraft. The height of the wingtips, for reference, was approximately 4.0 feet above the ground prior to rotation. The results are pressure altitude position error corrections to be added to the pressure altitudes calculated by the aircraft's production air data computer. The results were documented in references 8 through 11.

The T-38C production air data computer does not apply a Pitot-static position error correction for indicated Mach numbers less than approximately 0.09 Mach number, approximately 60 knots indicated airspeed. Figure E1 and table E1 show the corrections applied by the T-38C production air data computer at higher indicated Mach numbers. This is the cause of the discontinuity seen in figure E2 near an air data computer calibrated airspeed of 60 knots.

Table E1 Static Pressure Corrections for the Production T-38C Air Data Computer

Coefficients	$[(P_{tic}/P_{sic})$ -1] Breakpoints (n/d)				
(n/d)	0.00 to 0.20	0.20 to 0.85	0.85 to 0.90	0.90 to 1.04	1.04 to 1.70
C_1	-0.000606	-0.000420	13.190100	-2.091500	0.157070
C_2	-0.015450	-0.006640	-35.590000	6.744400	-0.169250
C_3	0.076620	0.032380	29.960000	-7.514800	0.052510
C_4	0.000000	-0.016670	-7.454000	2.882200	-0.001440

Notes: 1. (n/d) = non-dimensional

2. P_{tic} = total pressure corrected for instrument error
3. P_{sic} = static pressure corrected for instrument error
4. ΔP_{pc} = position error correction to be added to instrument-corrected static pressure
5. P_{tic}/P_{sic} - 1 = air-data computer position error correction abscissa
6. $\Delta P_{pc}/P_{sic}$ = air-data computer position error correction ordinate
7. Air-data computer static pressure correction equation:

$$\Delta P_{pc}/P_{sic} = C_1 + C_2(P_{tic}/P_{sic}-1) + C_3(P_{tic}/P_{sic}-1)^2 + C_4(P_{tic}/P_{sic}-1)^3$$

The information in table E1 were used to solve for the pressure altitude position error corrections added by the T-38C air data computer at an indicated pressure altitude of 2,300 feet, and indicated static pressure of 27.516591 inches of mercury. The results are summarized in table E2.

Table E2 Production T-38C Air Data Computer Pressure Altitude Corrections to be Added at a Pressure Altitude of 2,300 Feet

Indicated Mach Number (n/d)	ΔP_{pc} (in Hg)	ΔH_{pc} (ft)	$[(P_{tic}/P_{sic}) - 1]$ (n/d)
0.085	-0.018 776	18.6	0.005 07
0.090	-0.019 022	18.8	0.005 68
0.095	-0.019 282	19.1	0.006 33
0.100	-0.019 556	19.4	0.007 02

Notes: 1. (n/d) = non-dimensional
2. P_{tic} = total pressure corrected for instrument error
3. P_{sic} = static pressure corrected for instrument error
4. ΔP_{pc} = position error correction to be added to instrument-corrected, indicated static pressure
5. P_{tic}/P_{sic} - 1 = air-data computer position error correction abscissa
6. ΔH_{pc} = position error correction to be added to instrument-corrected, indicated altitude

The flight test data for the lower airspeeds are summarized in figure E2. Below approximately 60 knots, the production air data computer did not apply a correction and the flight test data shows that a positive correction of approximately 0 to 2 feet is required. At air data computer calibrated airspeeds above 60 knots, the air data computer applied a positive correction of 18 to 20 feet. The flight test results, figure E2, show a need to reduce the air data computer pressure altitudes by 16 to 22 feet, effectively removing the corrections applied by the production air data computer.

Figures E2 through E7 show the pressure altitude corrections to be added as a function of the T-38C air data computer calibrated airspeeds and the aircraft pitch angle. The data are summarized in figure E8.

Typical rotation speeds and mainwheel liftoff (takeoff) speeds for the T-38C are 145 KCAS and 165 KCAS, respectively. Figure E-2 for a pitch angle of 1 degree nose-up and a speed of 145 KCAS shows an altitude correction to be added of approximately -18 feet. This corresponds to an airspeed correction to be added of -1.2 knots. For a takeoff at 165 KCAS and a pitch angle of 5 degrees nose-up, figure E-6 shows and altitude correction to be added of approximately -9 feet. This corresponds to an airspeed correction to be added of -0.5 knot. Neither of these airspeed corrections is operationally significant to the pilot.

These T-38C flight test data were obtained at pressure altitudes of 1,800 to 2,500 feet at Edwards AFB. Data obtained at Marine Corps Air Station (MCAS) Yuma, Naval Air Station (NAS) Lemoore and at Holloman AFB matched the data obtained at Edwards AFB.

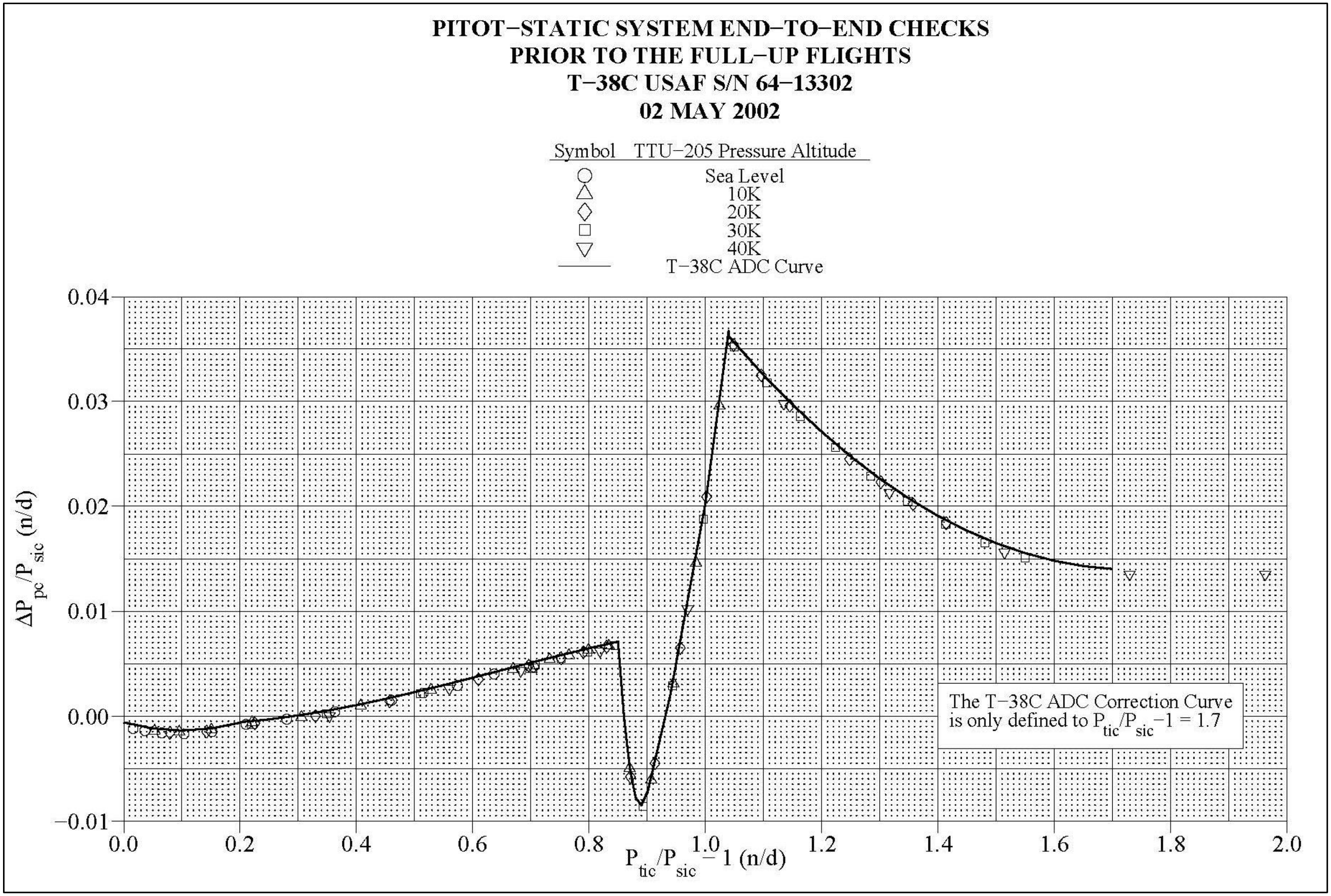


Figure E1 Pitot-static System End-to-End Checks Prior to the Full-up Flights

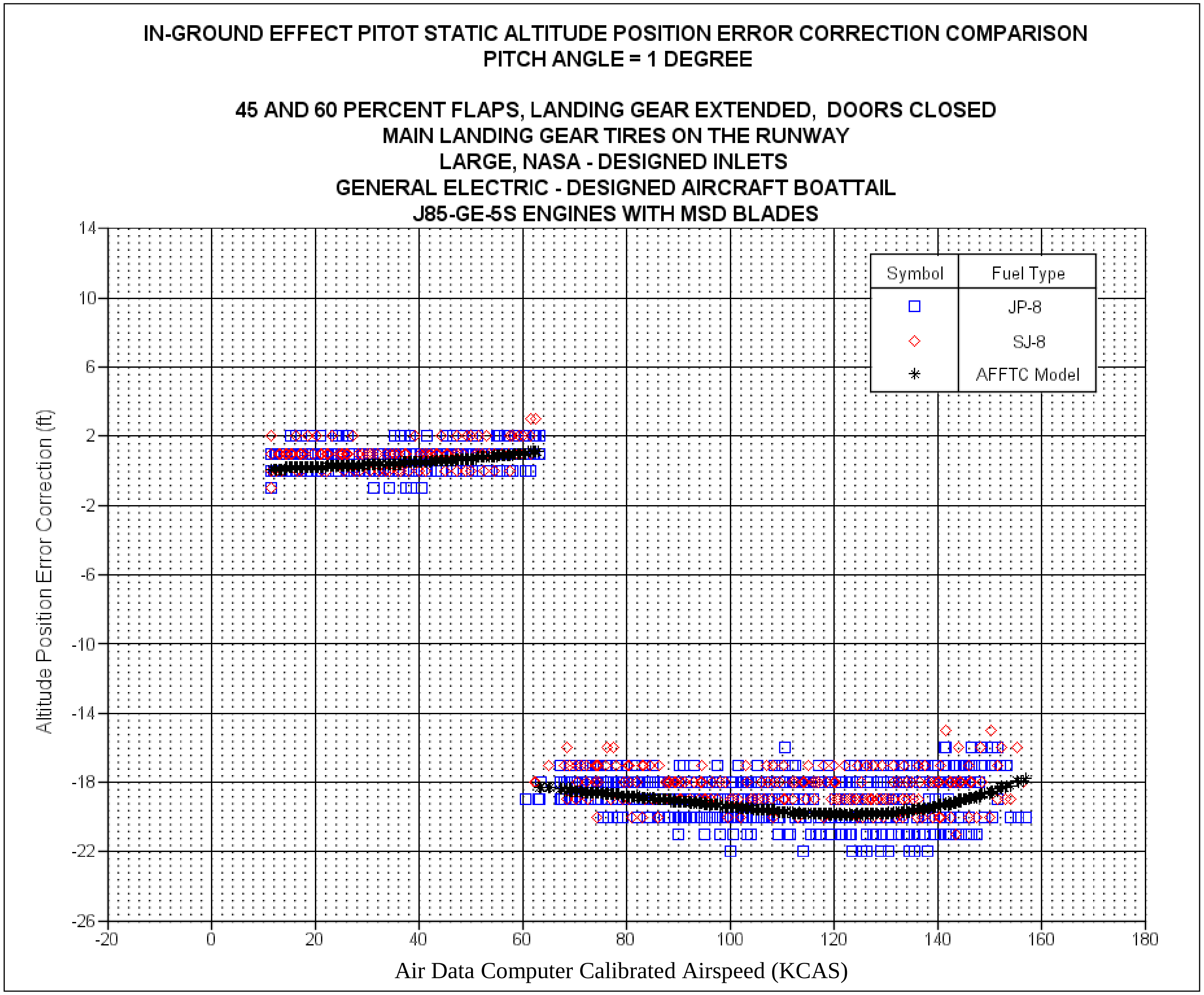


Figure E2 T-38C In-Ground Effect Pitot-Static Altitude Position Error Correction Comparison – Pitch Angle at 1 Degree

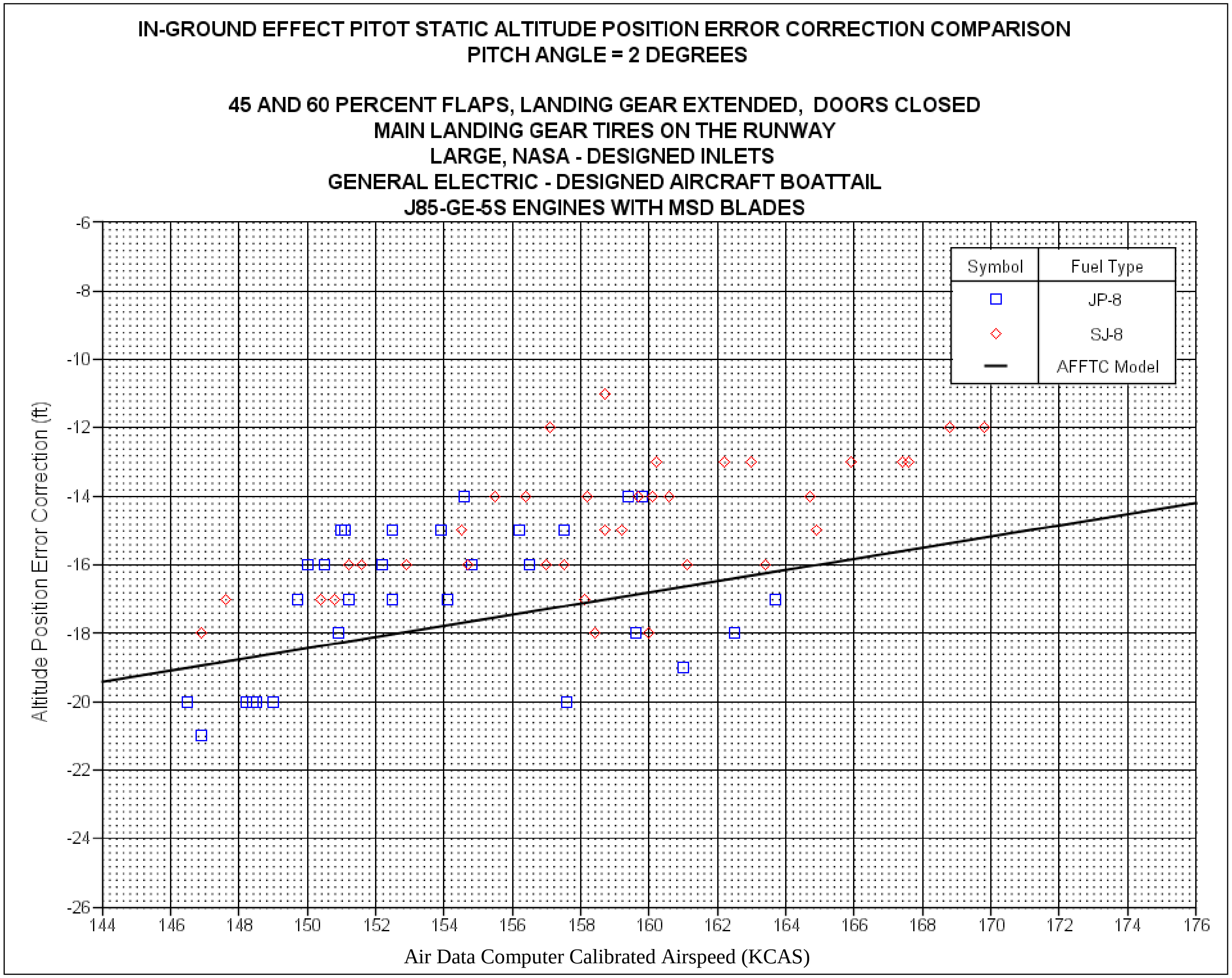


Figure E3 T-38C In-Ground Effect Pitot-Static Altitude Position Error Correction Comparison – Pitch Angle at 2 degrees

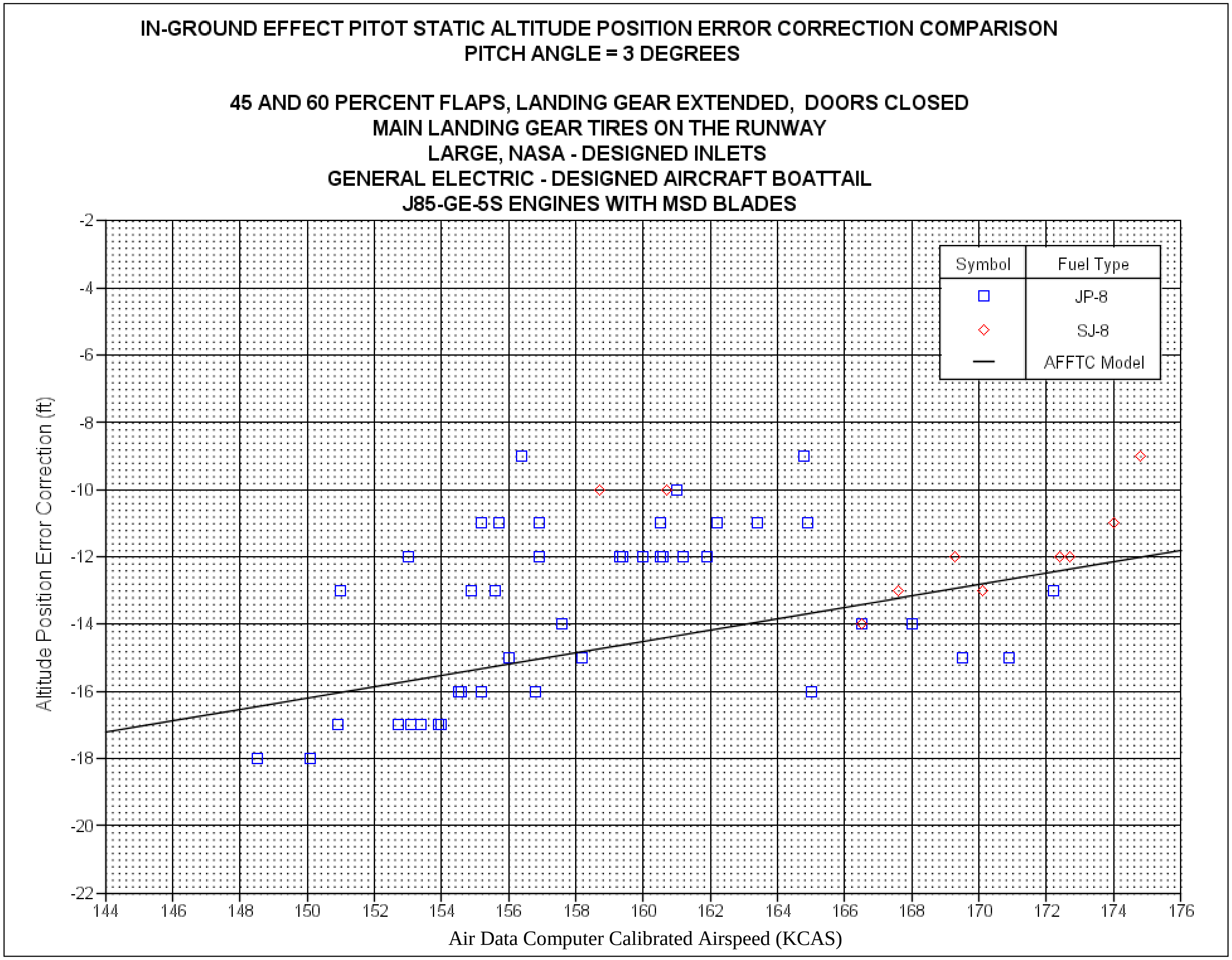


Figure E4 T-38C In-Ground Effect Pitot-Static Altitude Position Error Correction Comparison – Pitch Angle at 3 degrees

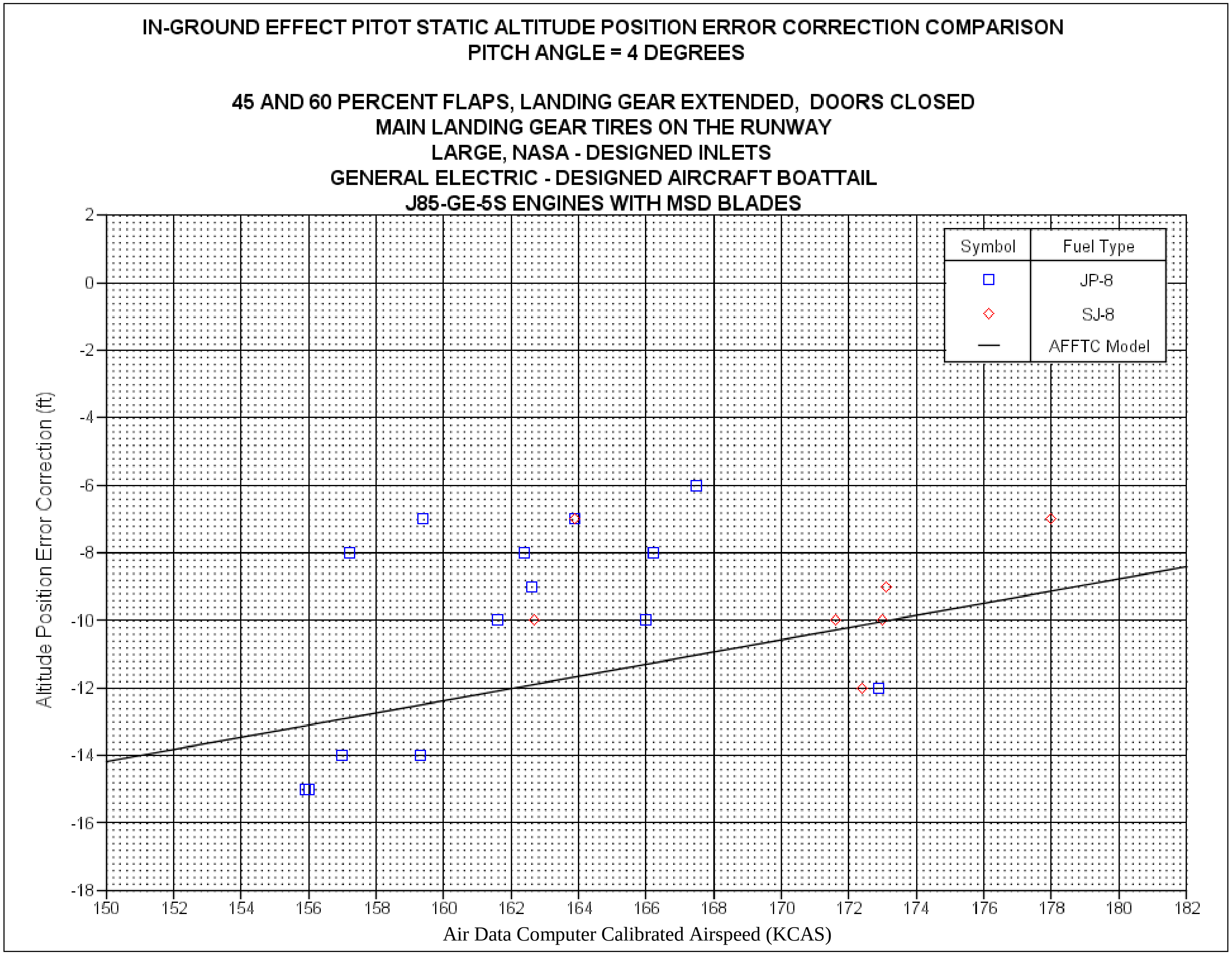


Figure E5 T-38C In-Ground Effect Pitot-Static Altitude Position Error Correction Comparison – Pitch Angle at 4 degrees

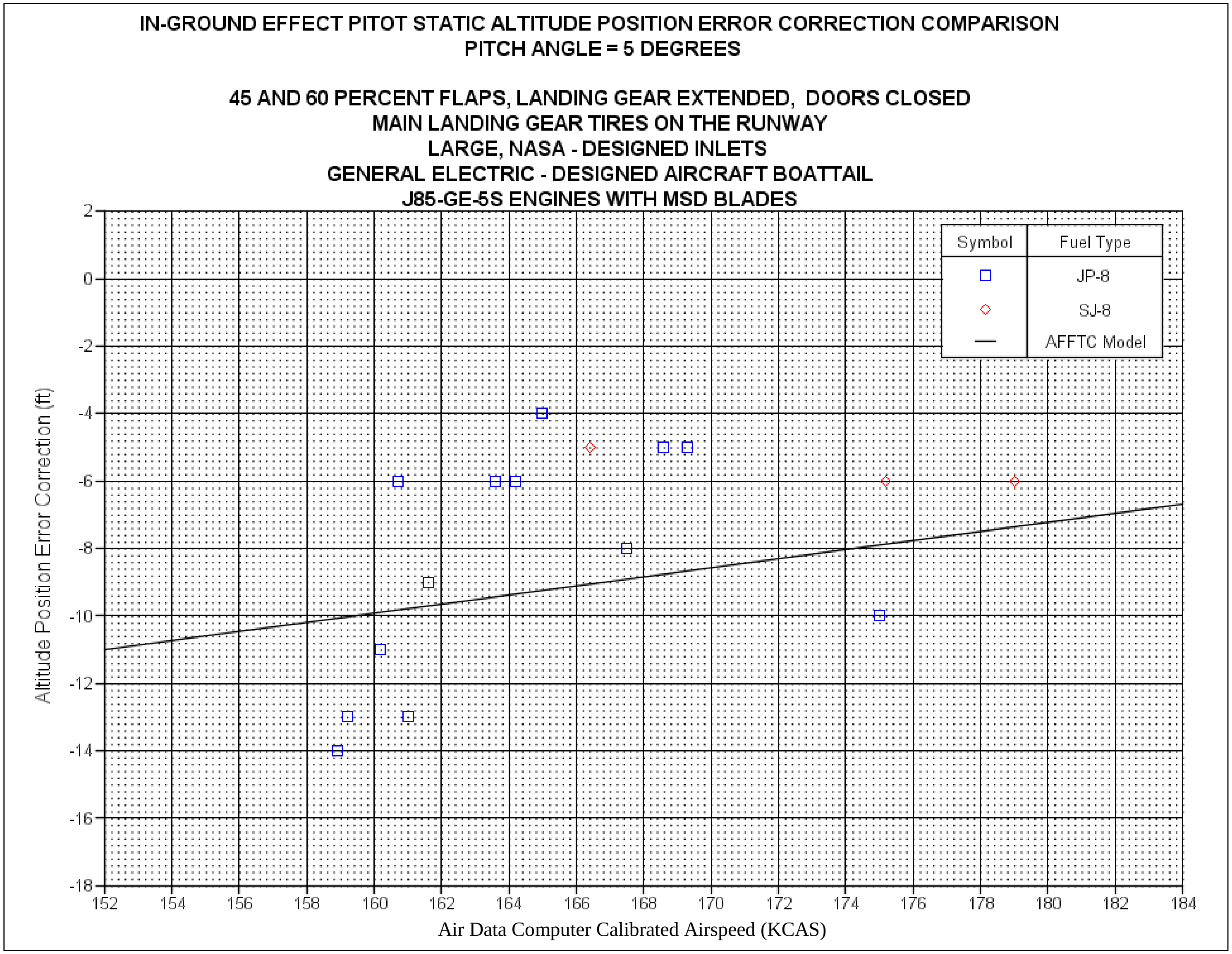


Figure E6 T-38C In-Ground Effect Pitot-Static Altitude Position Error Correction Comparison – Pitch Angle at 5 degrees

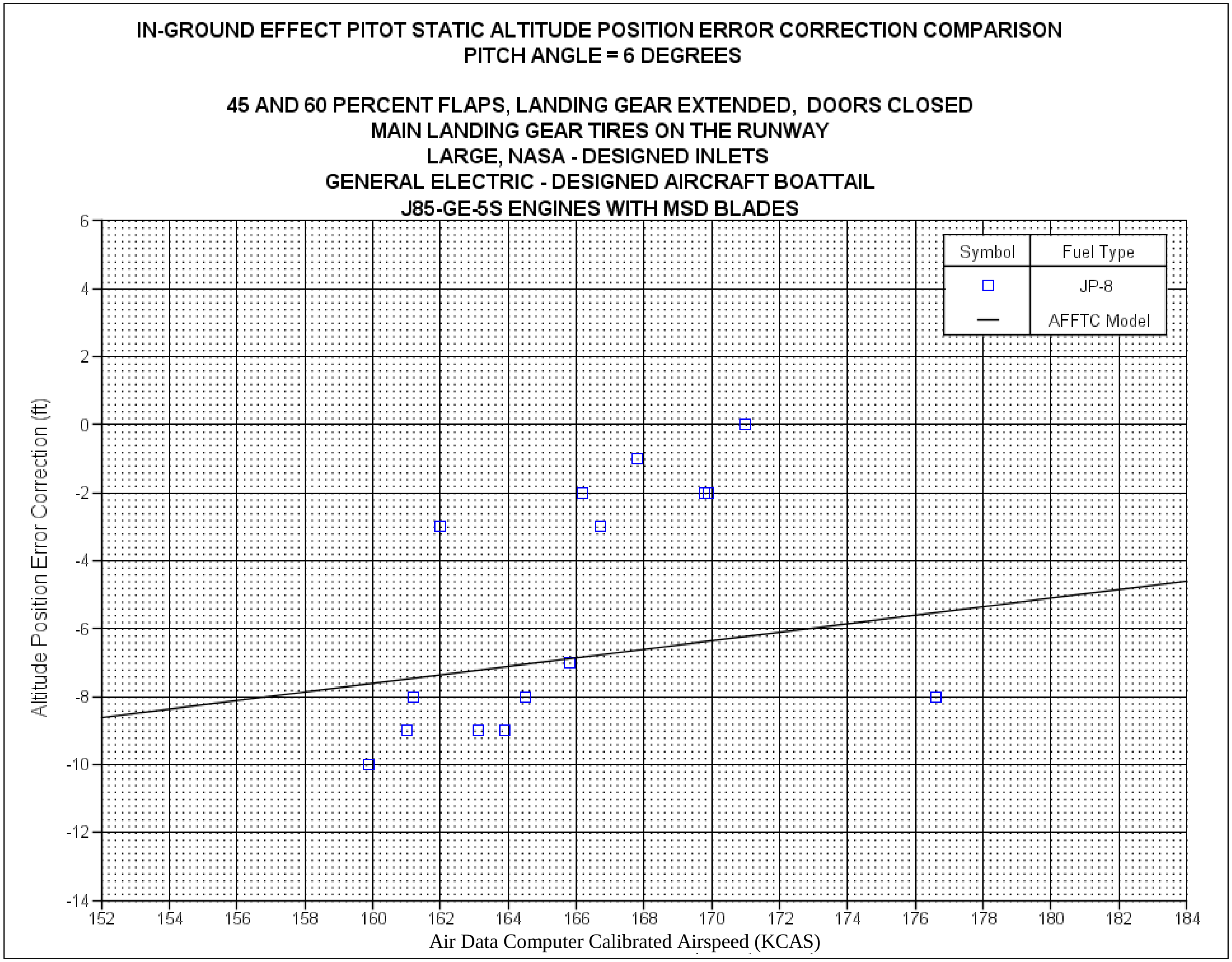


Figure E7 T-38C In-Ground Effect Pitot-Static Altitude Position Error Correction Comparison – Pitch Angle at 6 degrees

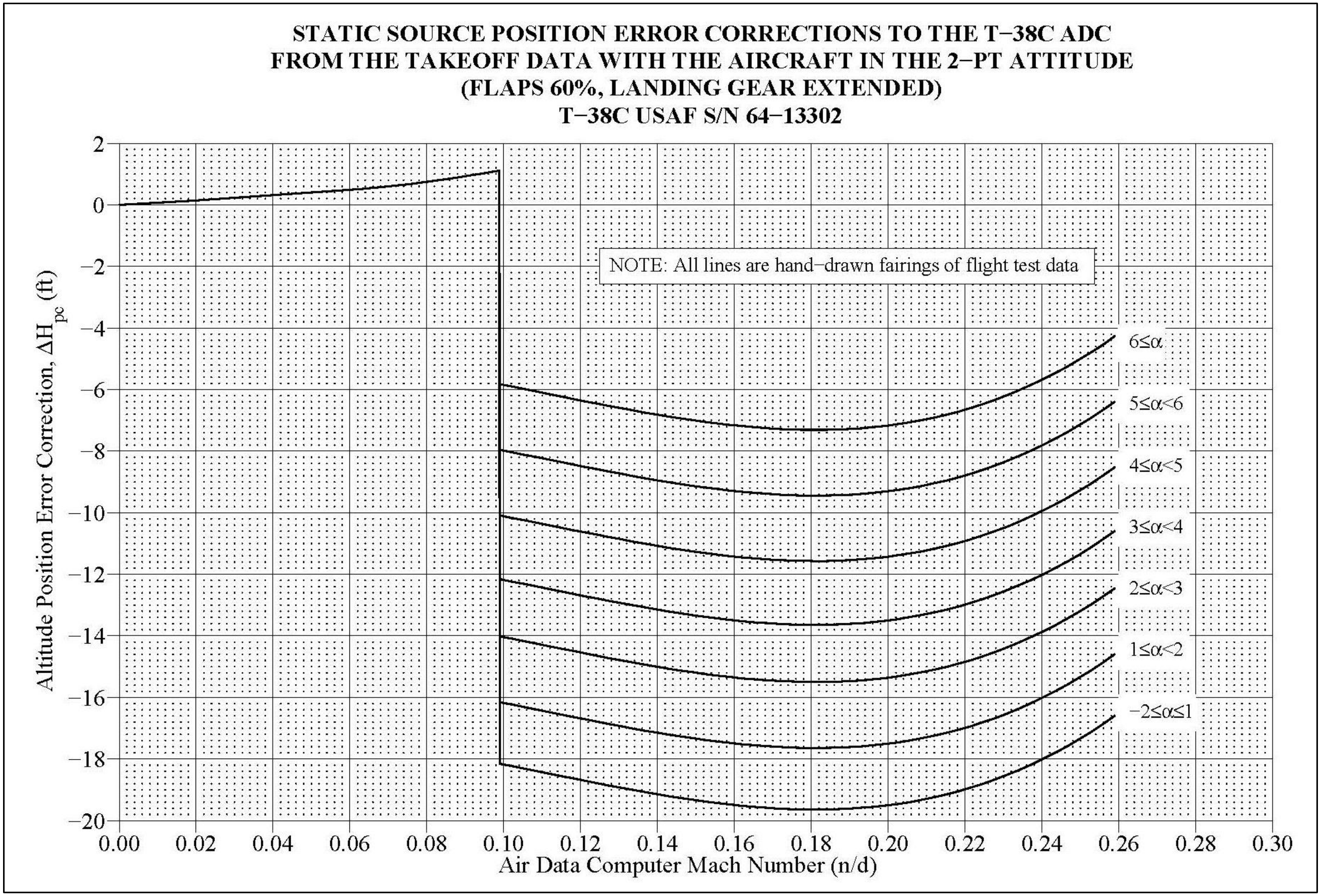


Figure E8 In-ground-Effect Static Position Error Corrections to the T-38C ADC with the Aircraft in the Two-point Attitude in the Takeoff Configuration

APPENDIX F – TEST RESULTS FOR MCDONNELL DOUGLAS AIRCRAFT COMPANY F-15

The test results presented in this appendix were obtained from a flight test F-15 that had a production F-15E Pitot-static system. Results are presented for 13 external store loadings with the aircraft in a 3 point attitude, prior to rotation. For the purposes of this handbook, the F-15E and the flight test F-15 are similar and the results are applicable to an F-15E. The results are the pressure altitude position error corrections to be added to the pressure altitudes calculated by the aircraft's production air data computer. The results were documented in AFFTC-TR-98-04 (reference 12).

The production dogleg probes for both Pitot (total) and for static pressure were on both sides of the fuselage with their static pressures manifolded together (left and right) to minimize the effects of sideslip. They were down and forward of the aircraft windscreen, approximately 10.3 feet aft of the tip of the nose of the aircraft and approximately 6.2 feet above the ground prior to rotation. The wingtip height, for reference, was approximately 7.8 feet above the ground.

The heavy-weight F-15 rotated at approximately 180 KCAS. The flight test-determined pressure altitude position error correction to be added was approximately 57 feet (180 KCAS and zero pitch angle). At mainwheel liftoff (takeoff) at 210 KCAS and 10 degrees nose-up pitch angle, the correction to be added was approximately 57 feet. The corresponding airspeed corrections to be added were 3.2 knots at rotation and 4.0 knots at takeoff.

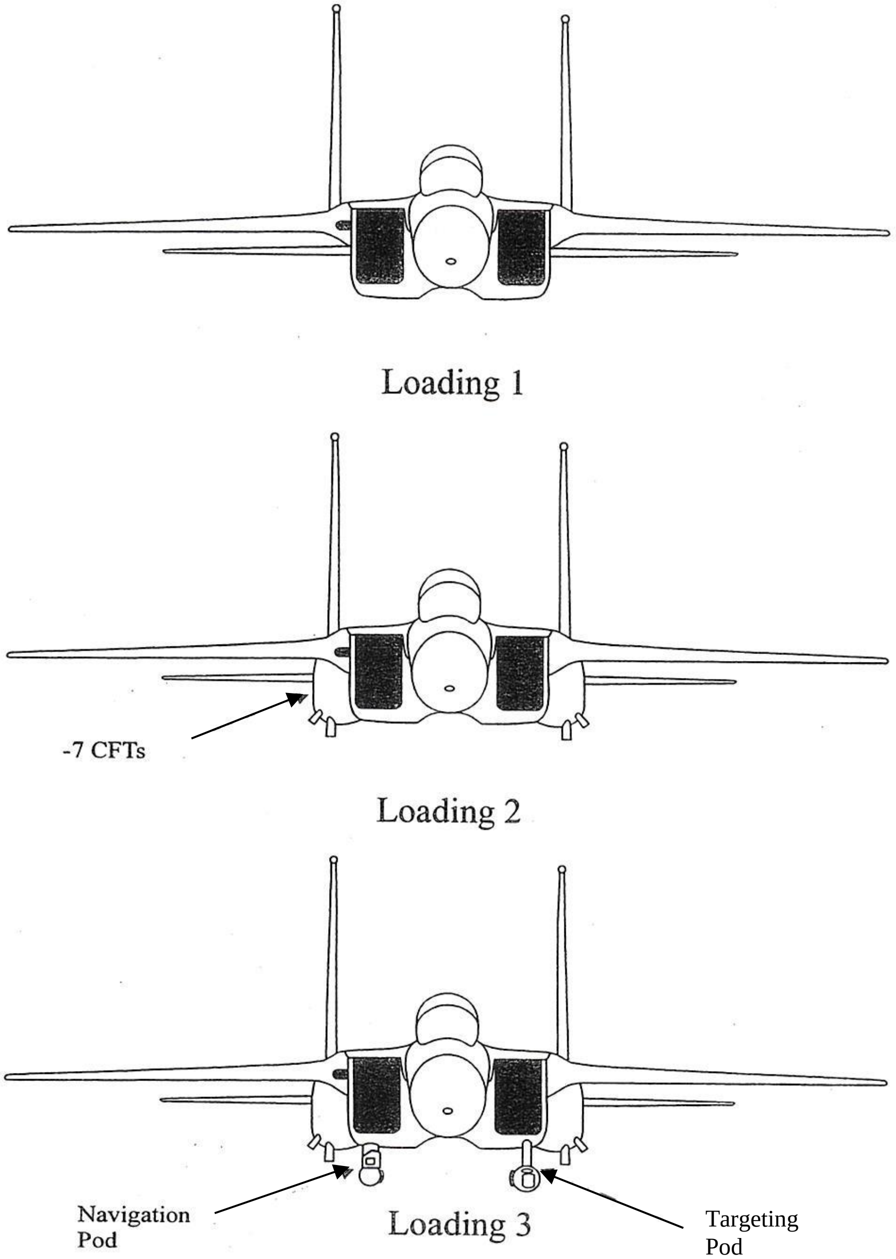


Figure F1 Head-On Views of the F-15 Test Loadings (Sheet 1 of 5)

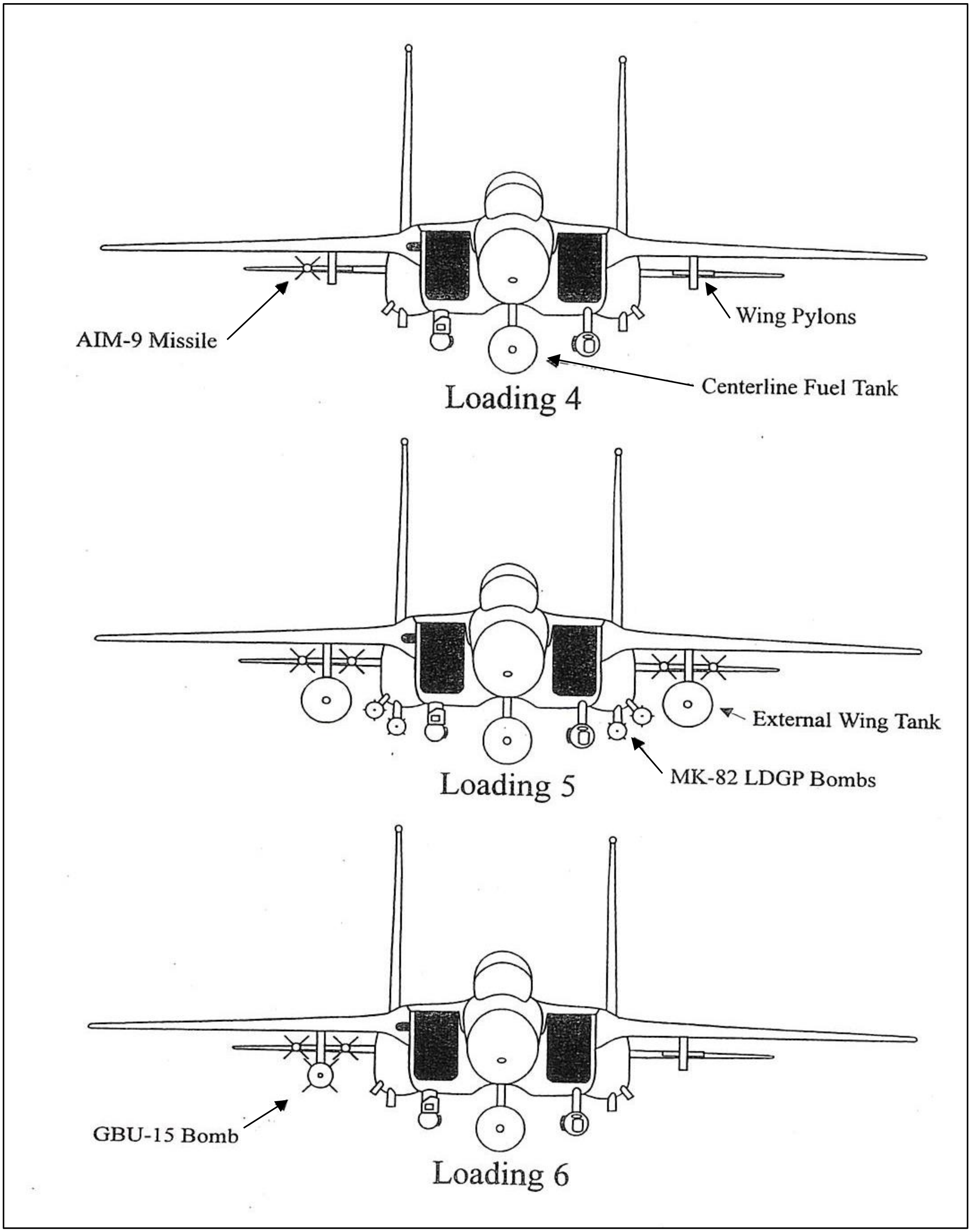


Figure F1 Head-On Views of the F-15 Test Loadings (Sheet 2 of 5)

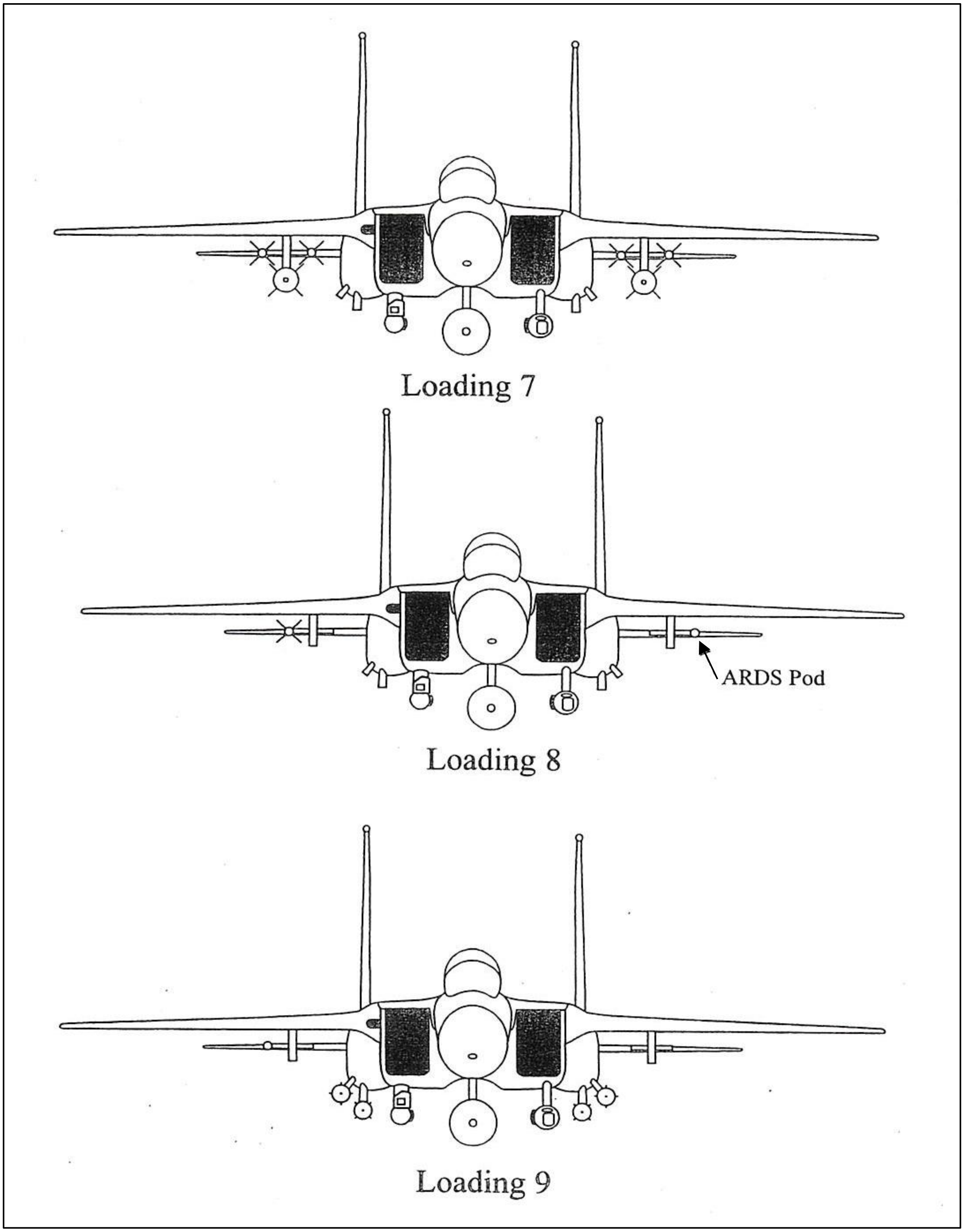
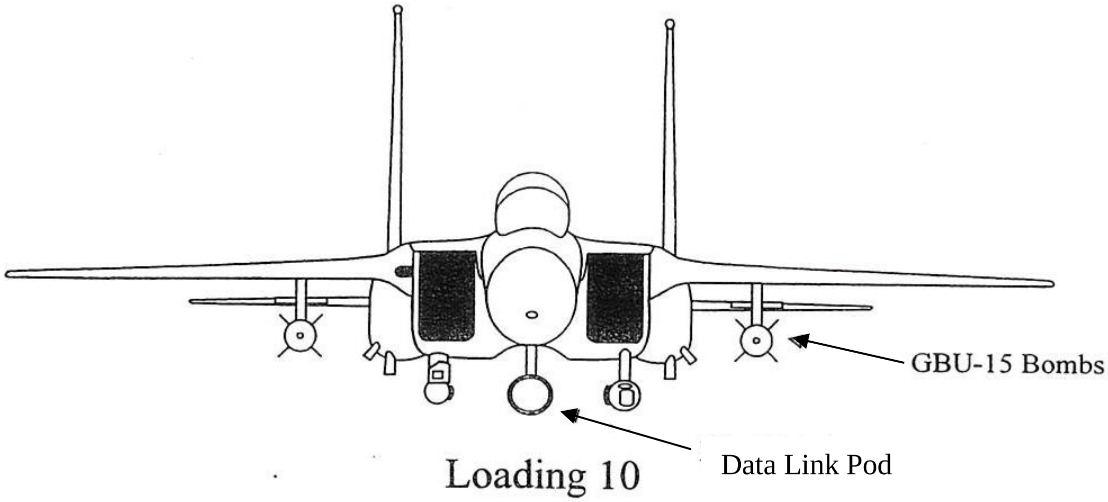


Figure F1 Head-On Views of the F-15 Test Loadings (Sheet 3of 5)



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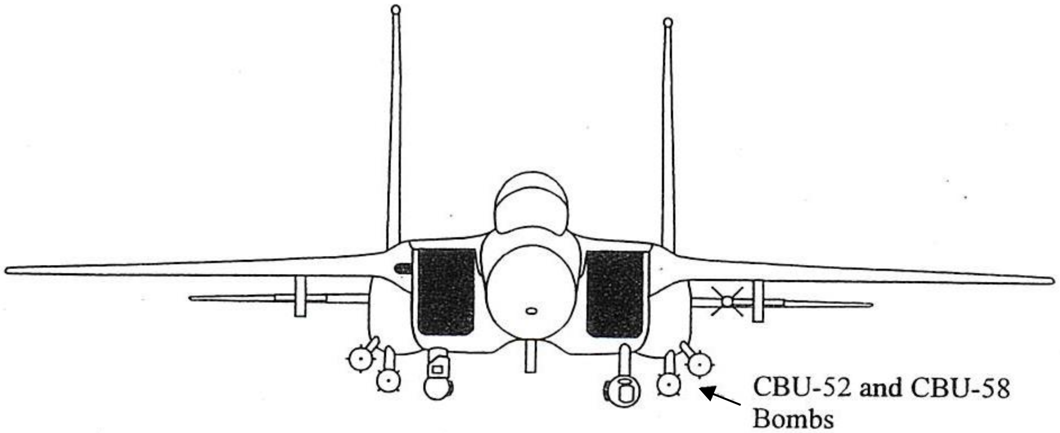

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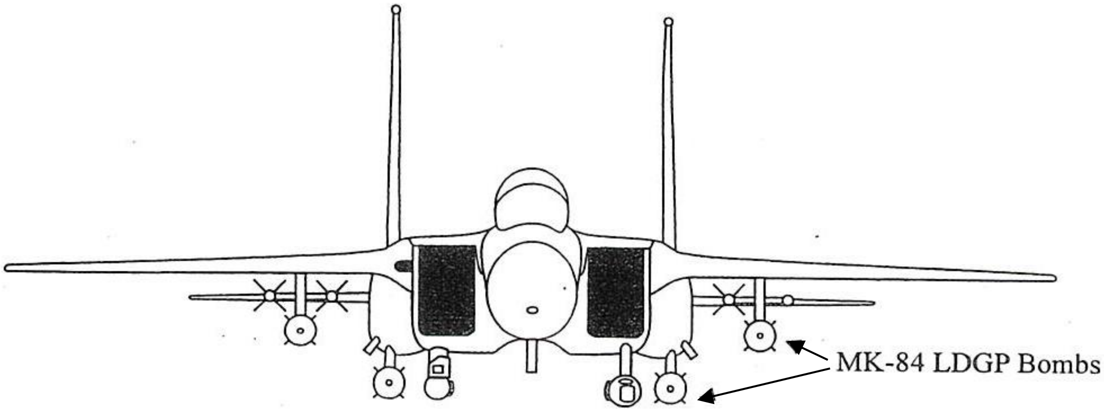

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Figure F1 Head-On Views of the F-15 Test Loadings (Sheet 4 of 5)

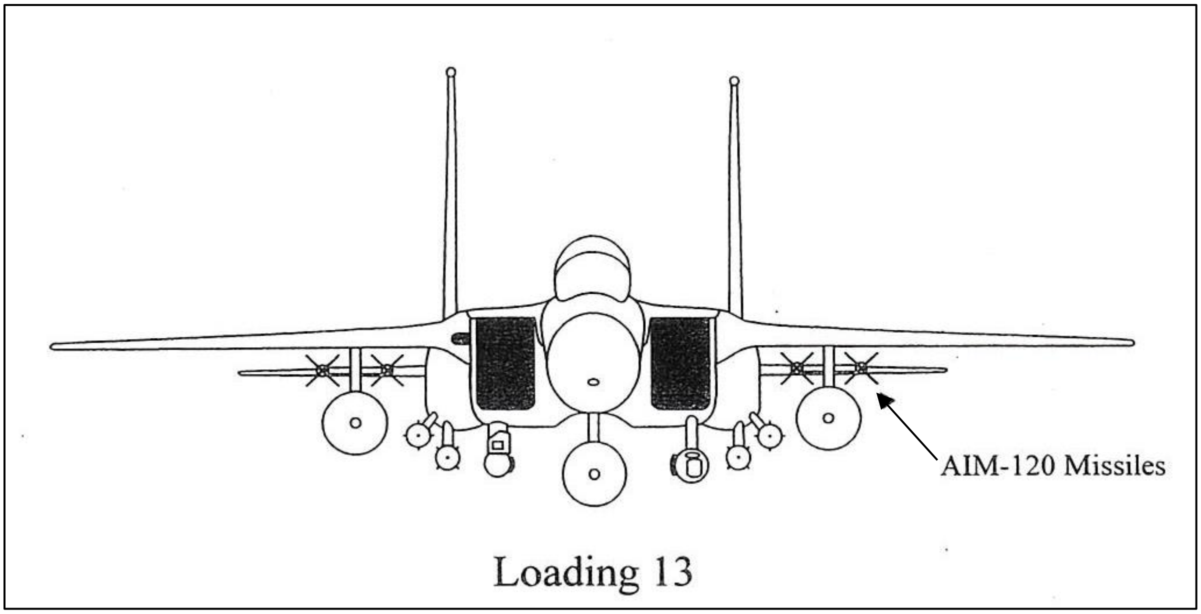

Figure F1 Head-On Views of the F-15 Test Loadings (Sheet 5 of 5)

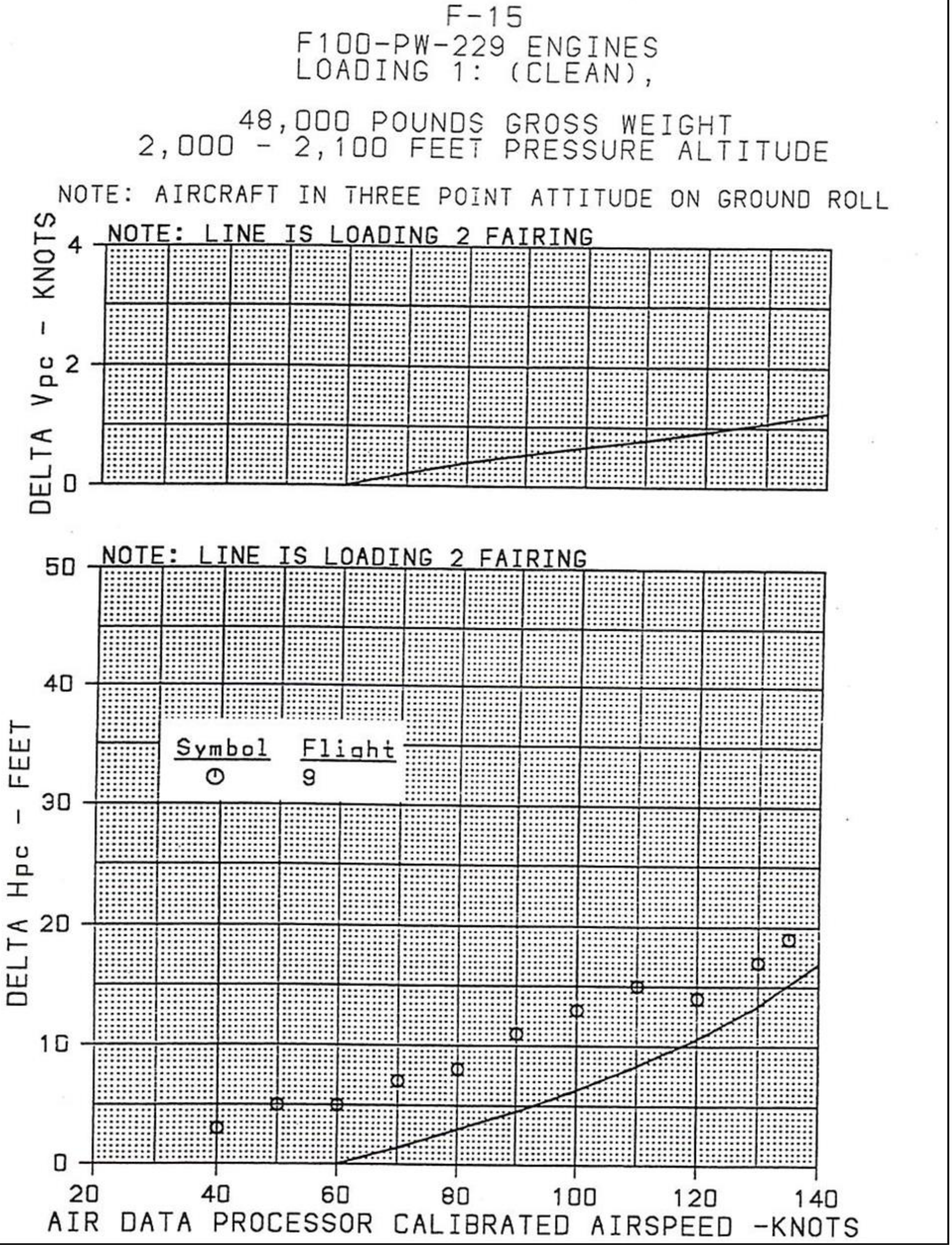

Figure F2 Position Error Corrections in a Three-Point Attitude on the Takeoff Ground Roll for Loading 1

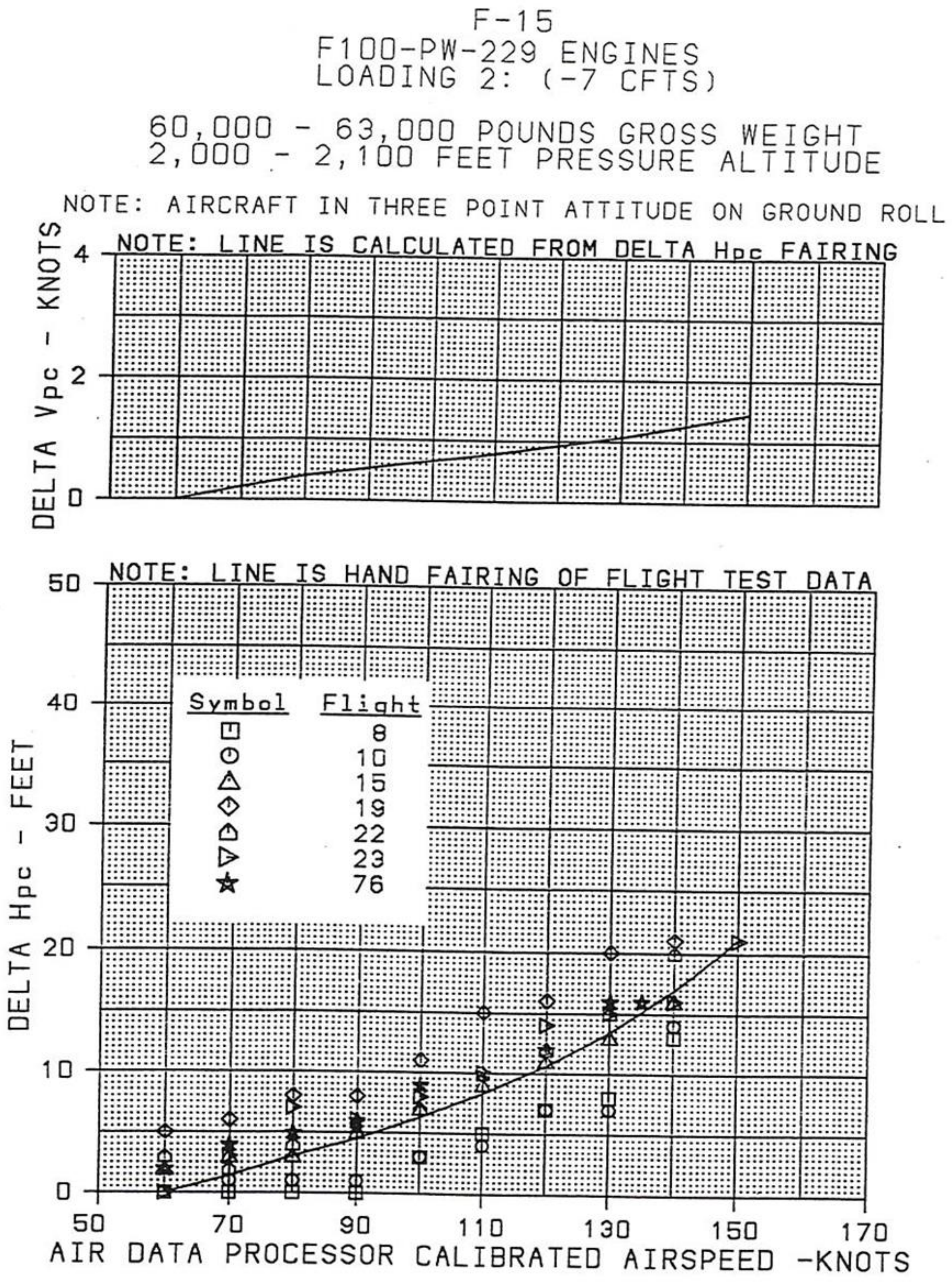

Figure F3 Position Error Corrections in a Three-Point Attitude on the Takeoff Ground Roll for Loading 2

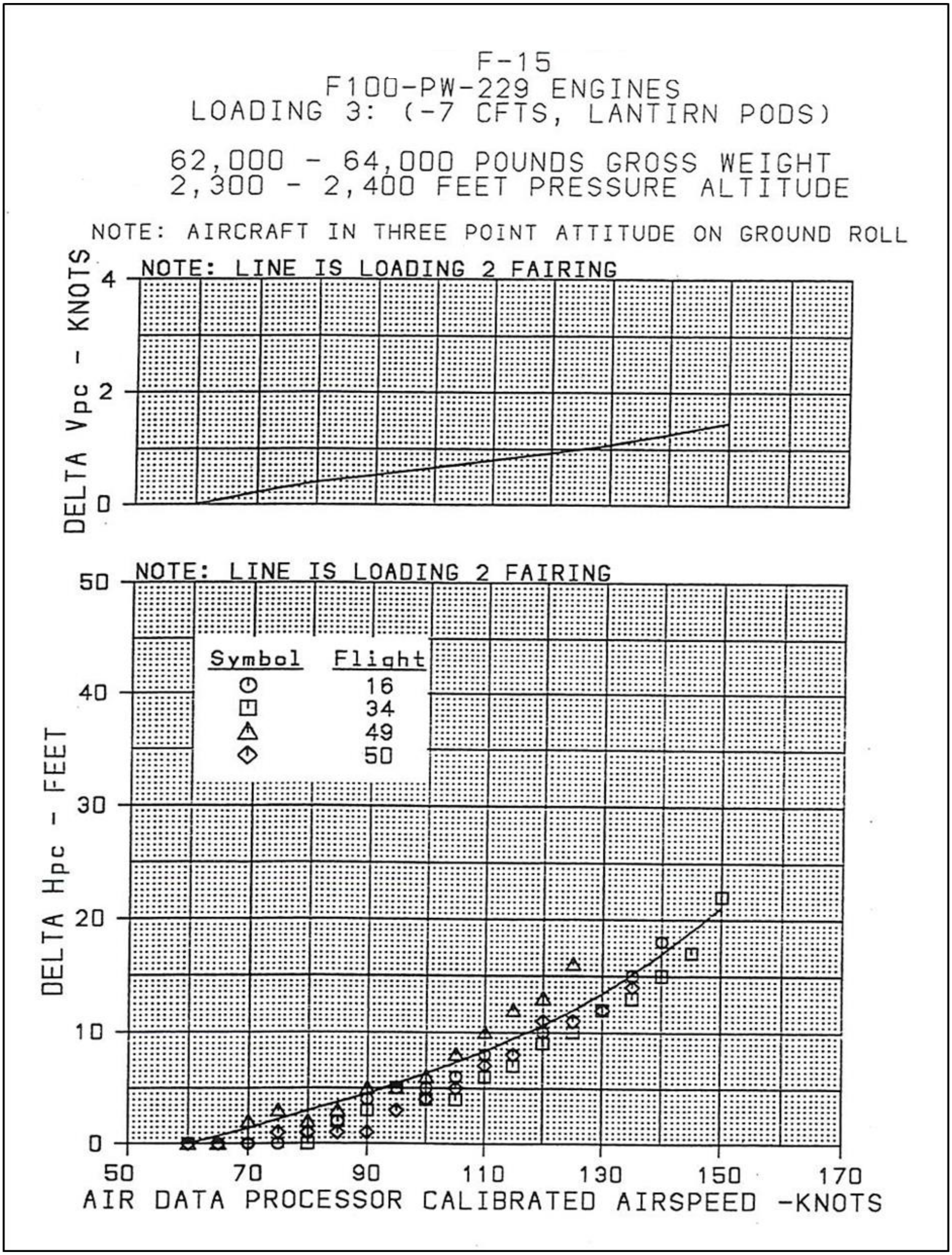

Figure F4 Position Error Corrections in a Three-Point Attitude on the Takeoff Ground Roll for Loading 3

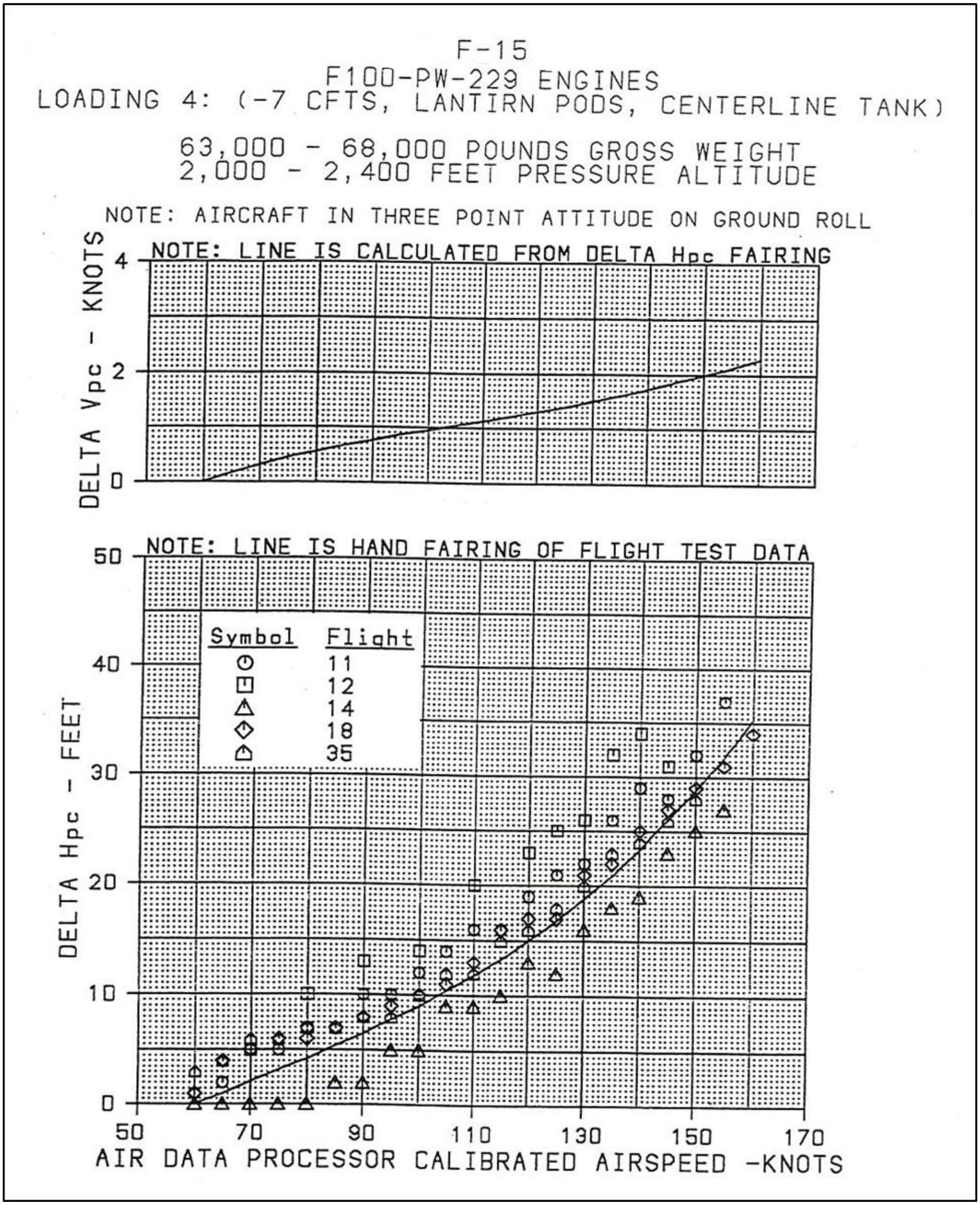

Figure F5 Position Error Corrections in a Three-Point Attitude on the Takeoff Ground Roll for Loading 4

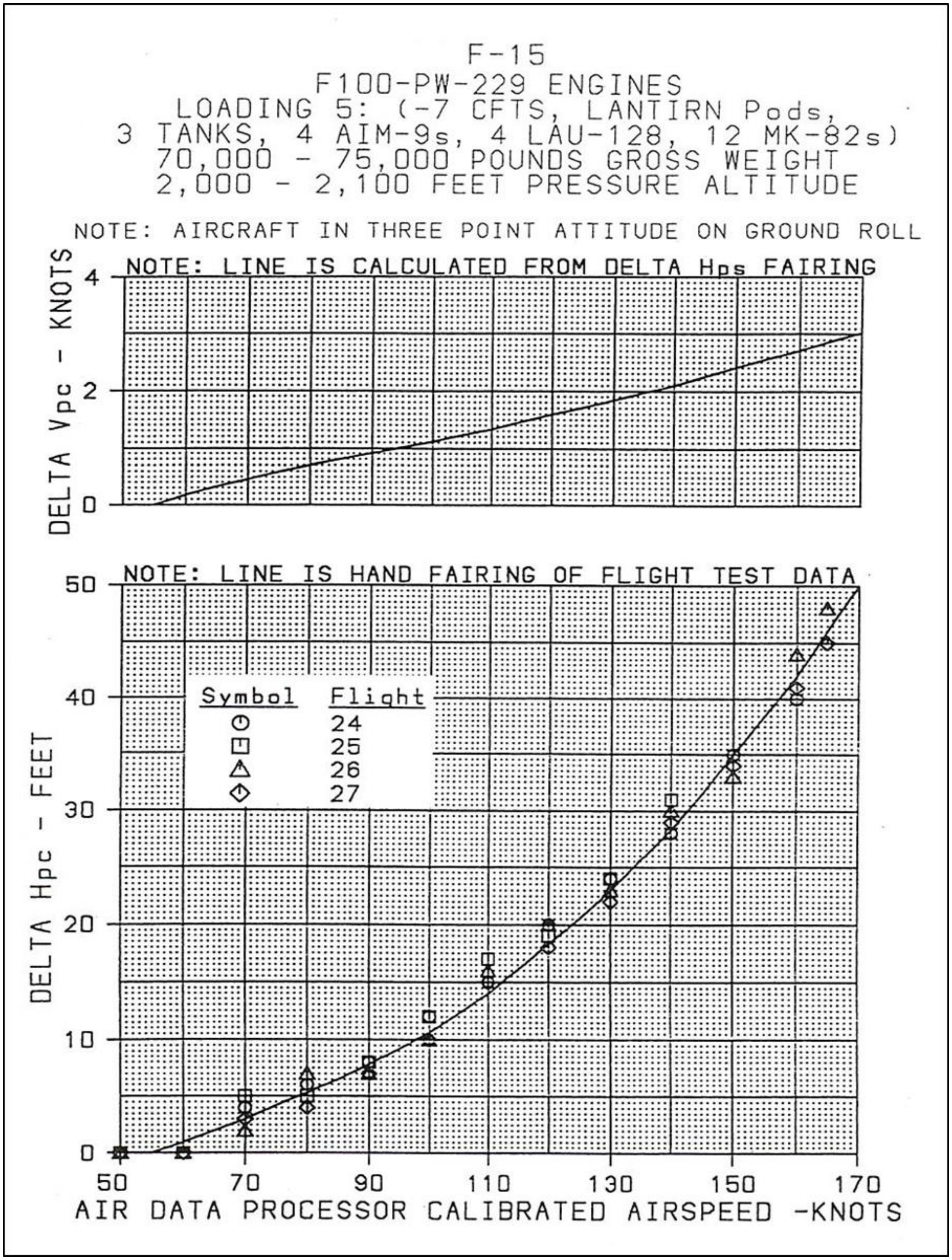

Figure F6 Position Error Corrections in a Three-Point Attitude on the Take-off Ground Roll for Loading 5

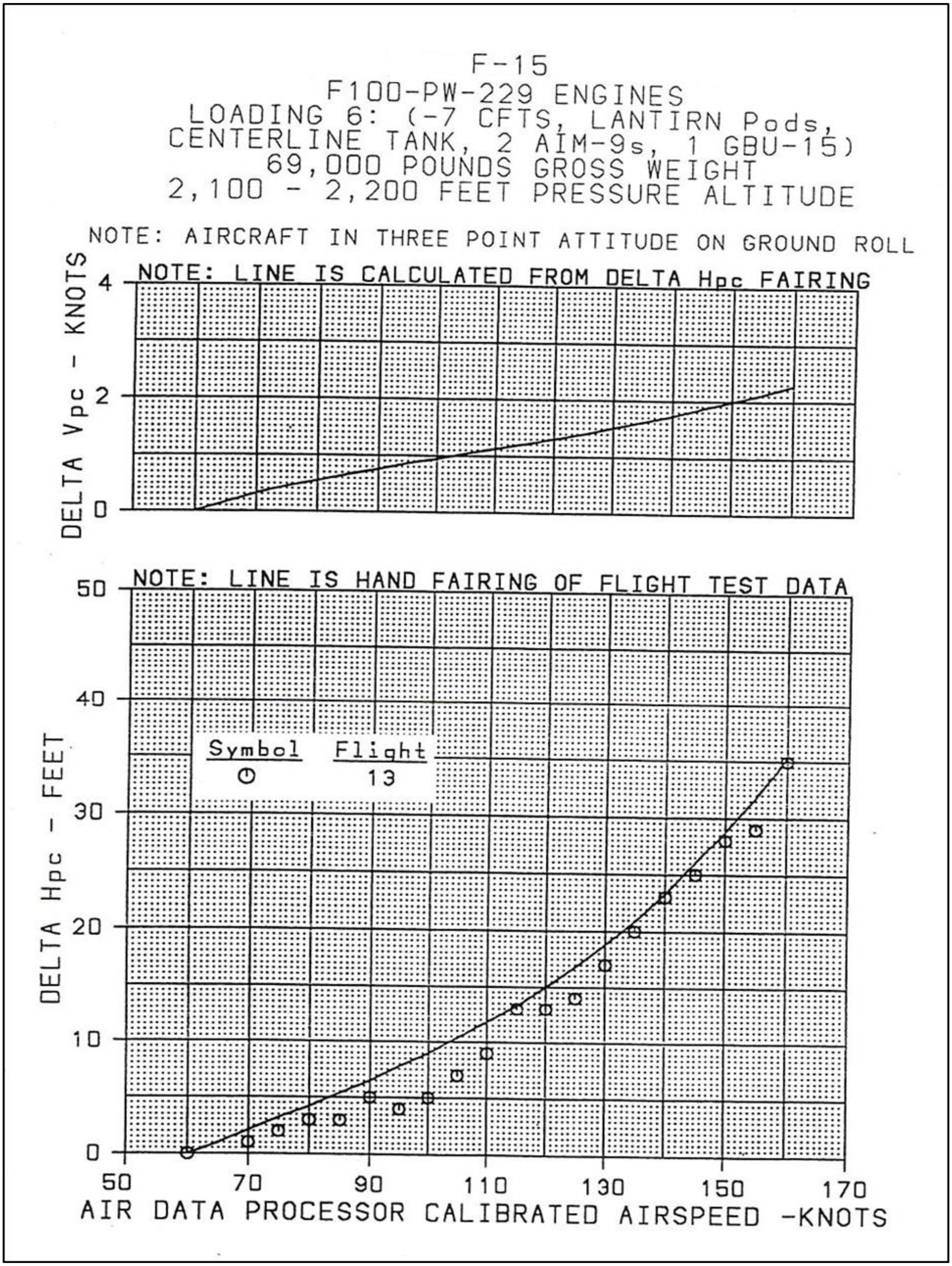

Figure F7 Position Error Corrections in a Three-Point Attitude on the Takeoff Ground Roll for Loading 6

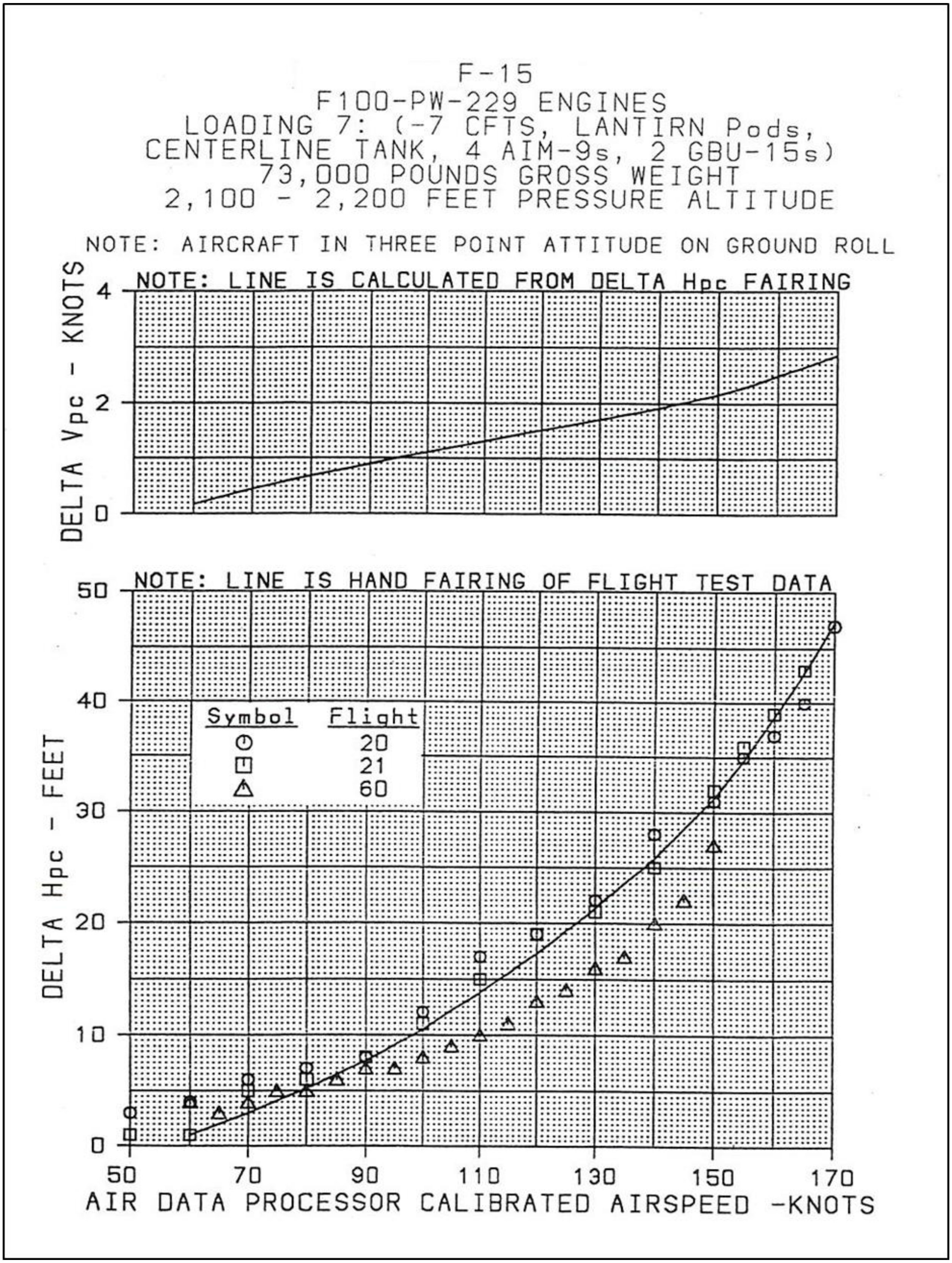

Figure F8 Position Error Corrections in a Three-Point Attitude on the Takeoff Ground Roll for Loading 7

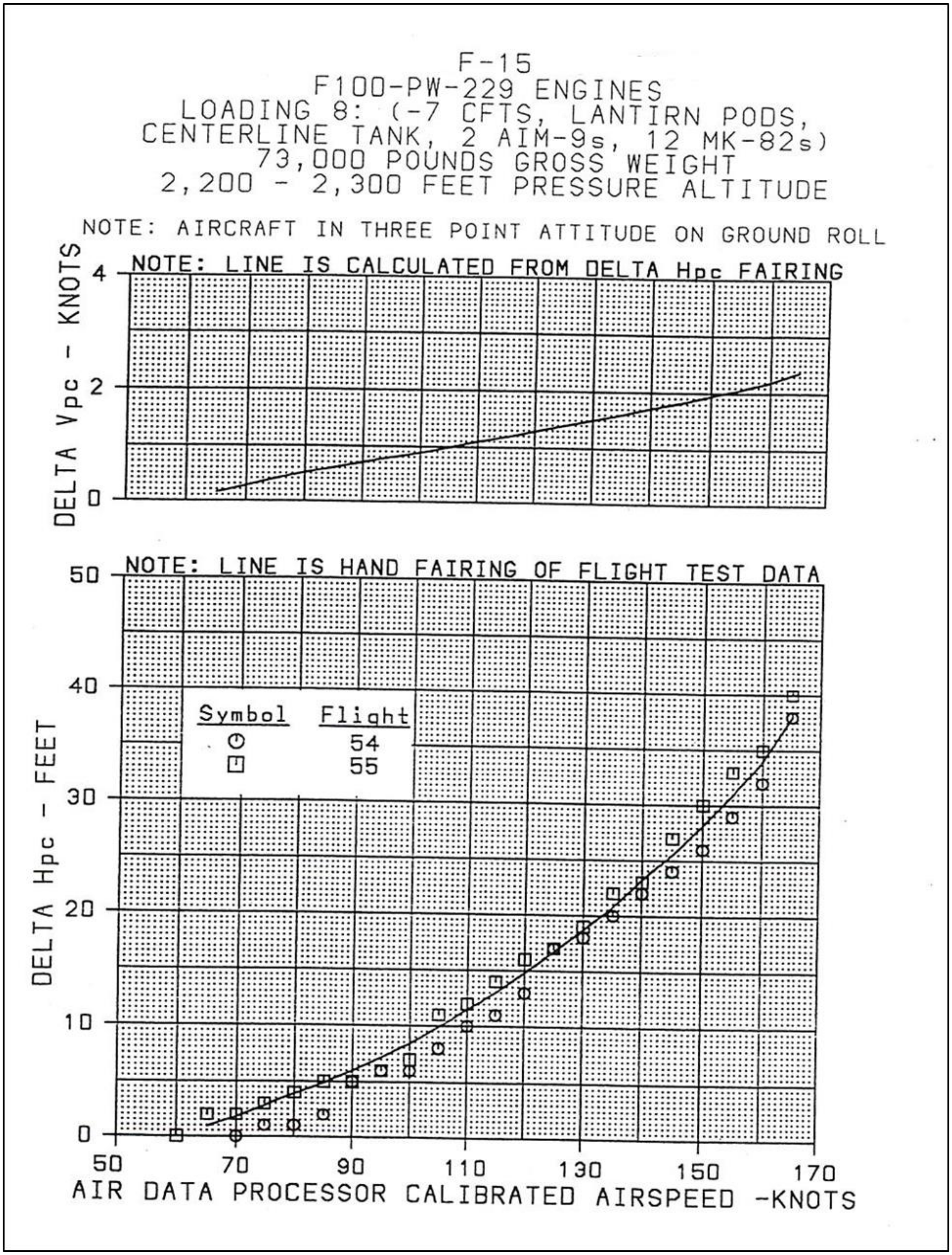

Figure F9 Position Error Corrections in a Three-Point Attitude on the Takeoff Ground Roll for Loading 8

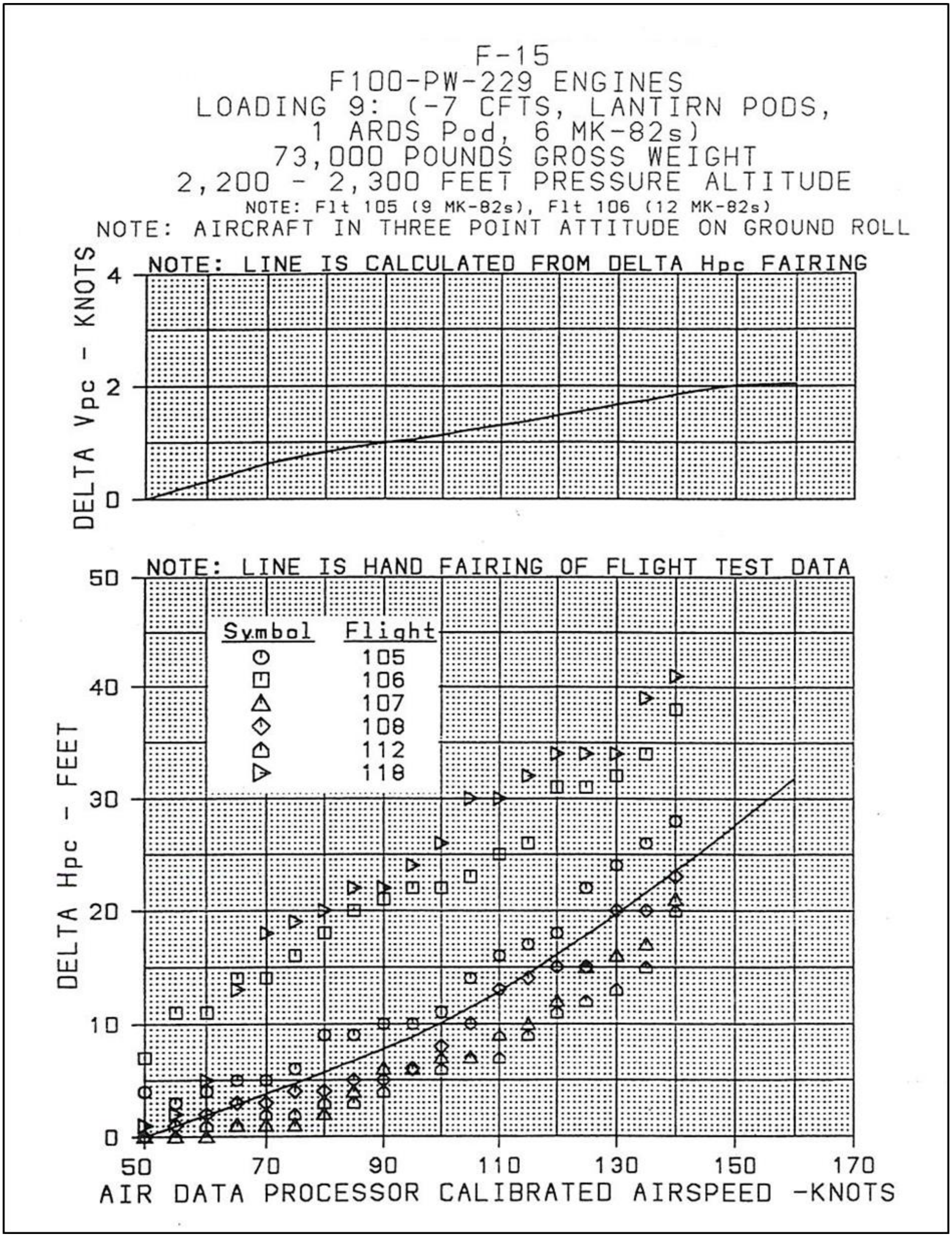

Figure F10 Position Error Corrections in a Three-Point Attitude on the Takeoff Ground Roll for Loading 9

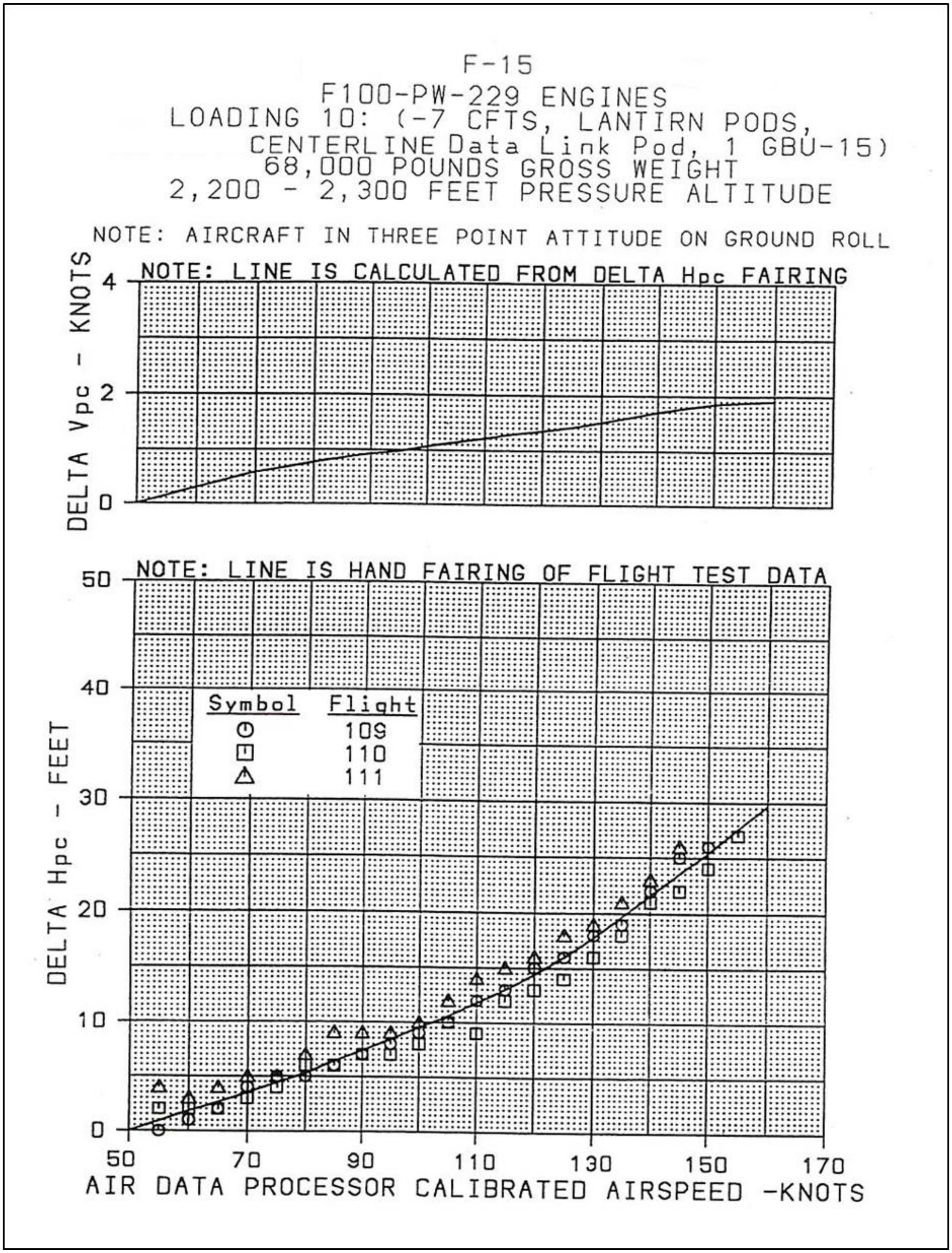

Figure F11 Position Error Corrections in a Three-Point Attitude on the Takeoff Ground Roll for Loading 10

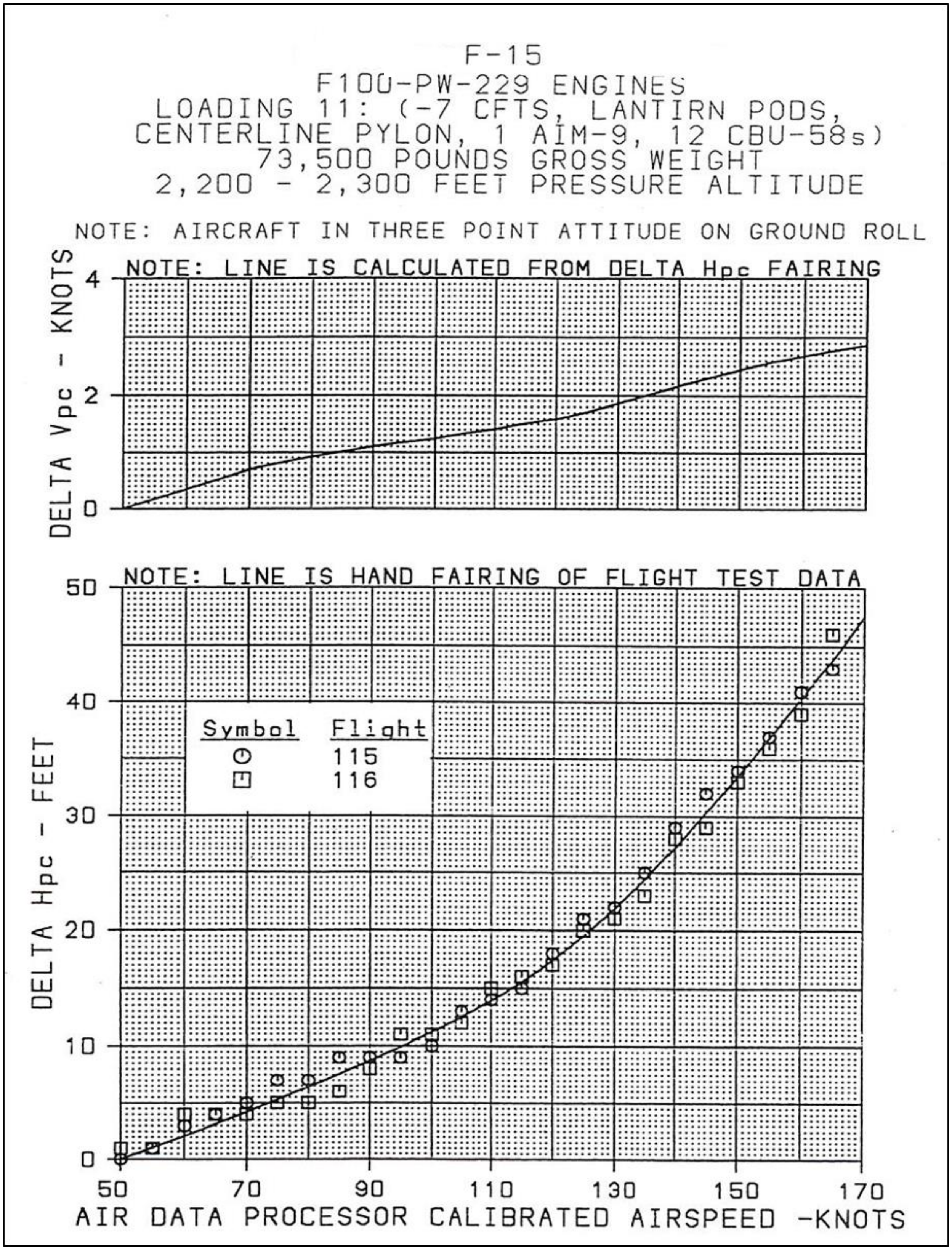

Figure F12 Position Error Corrections in a Three-Point Attitude on the Takeoff Ground Roll for Loading 11

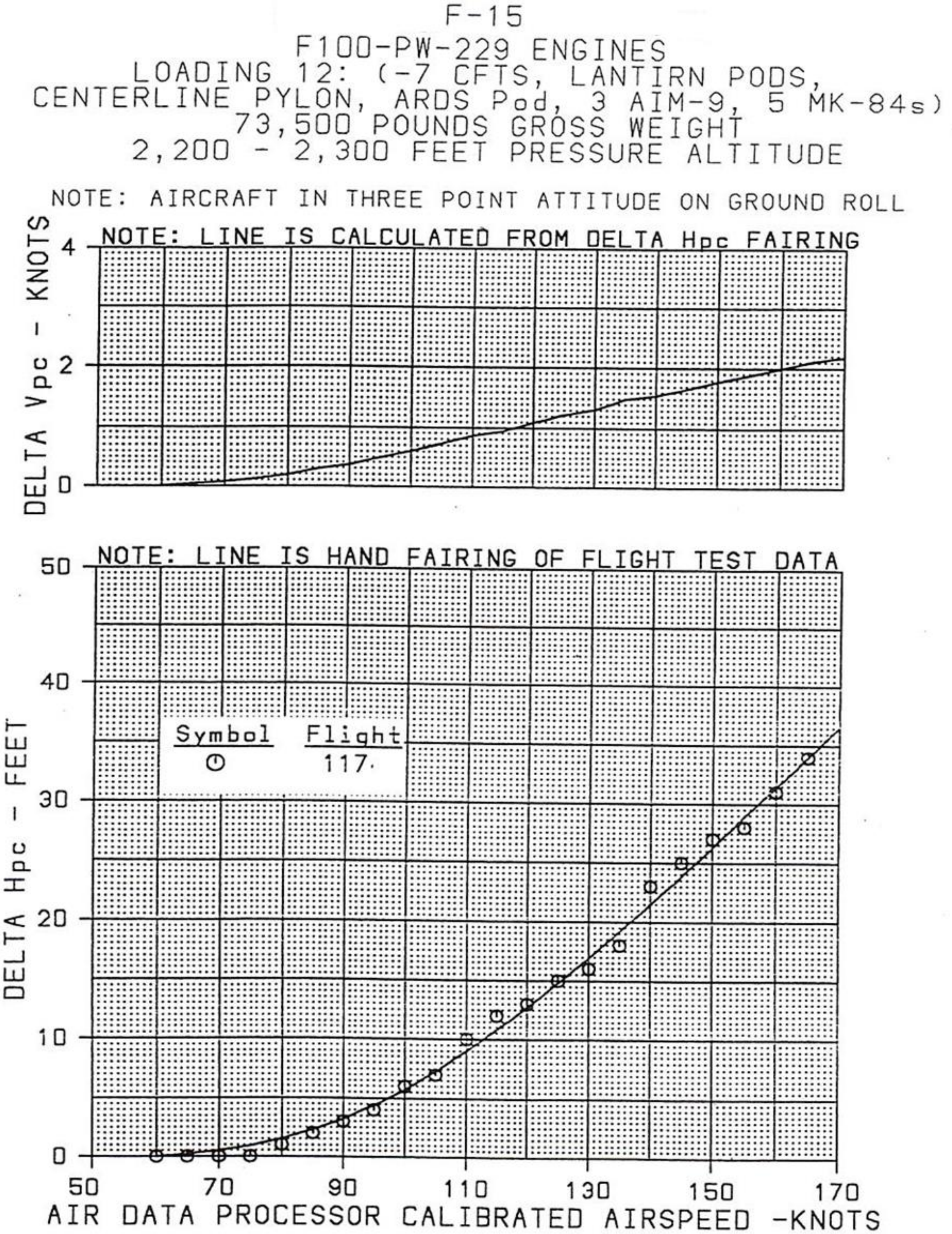

Figure F13 Position Error Corrections in a Three-Point Attitude on the Takeoff Ground Roll for Loading 12

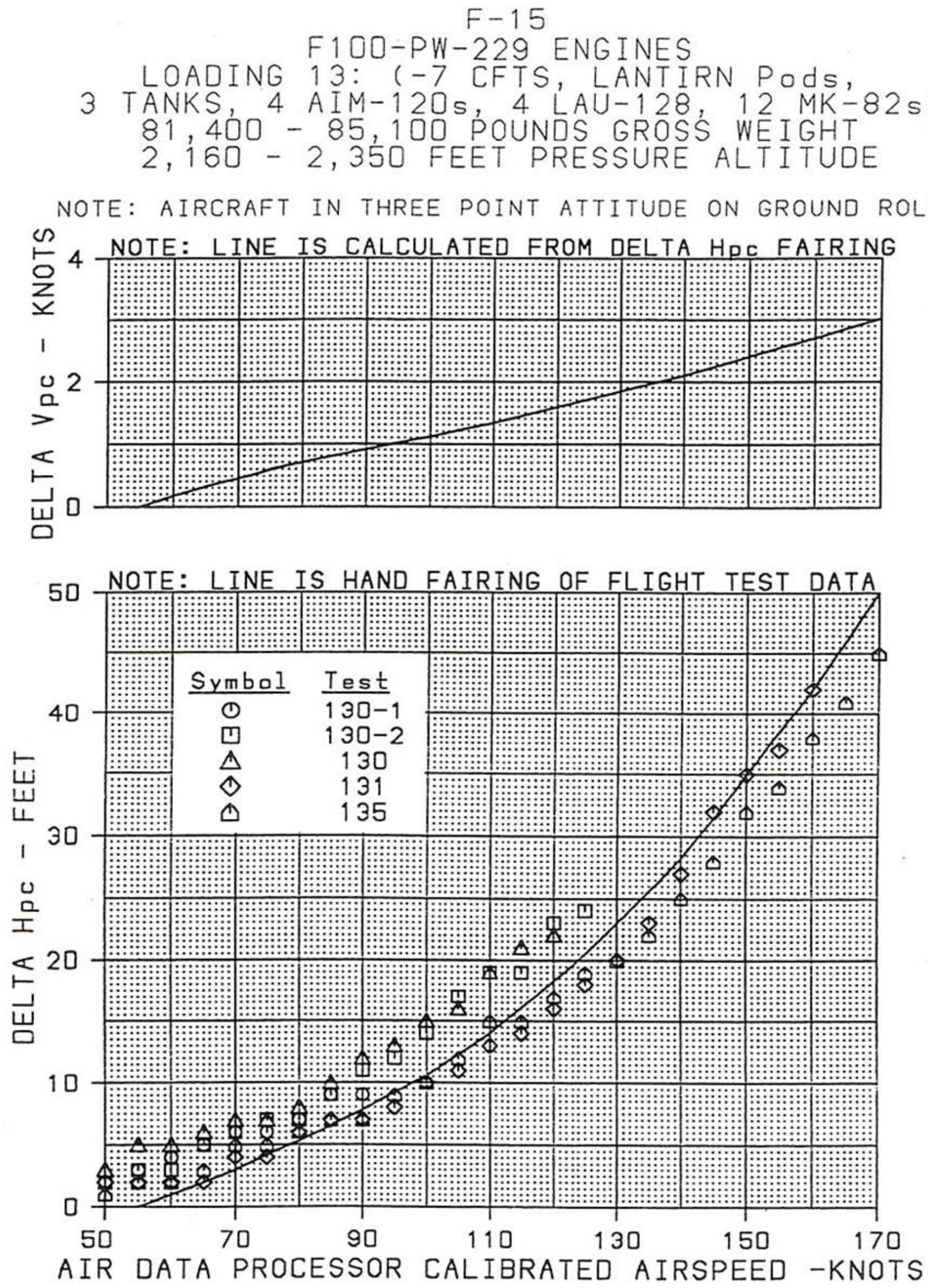

Figure F14 Position Error Corrections in a Three-Point Attitude on the Takeoff Ground Roll for Loading 13

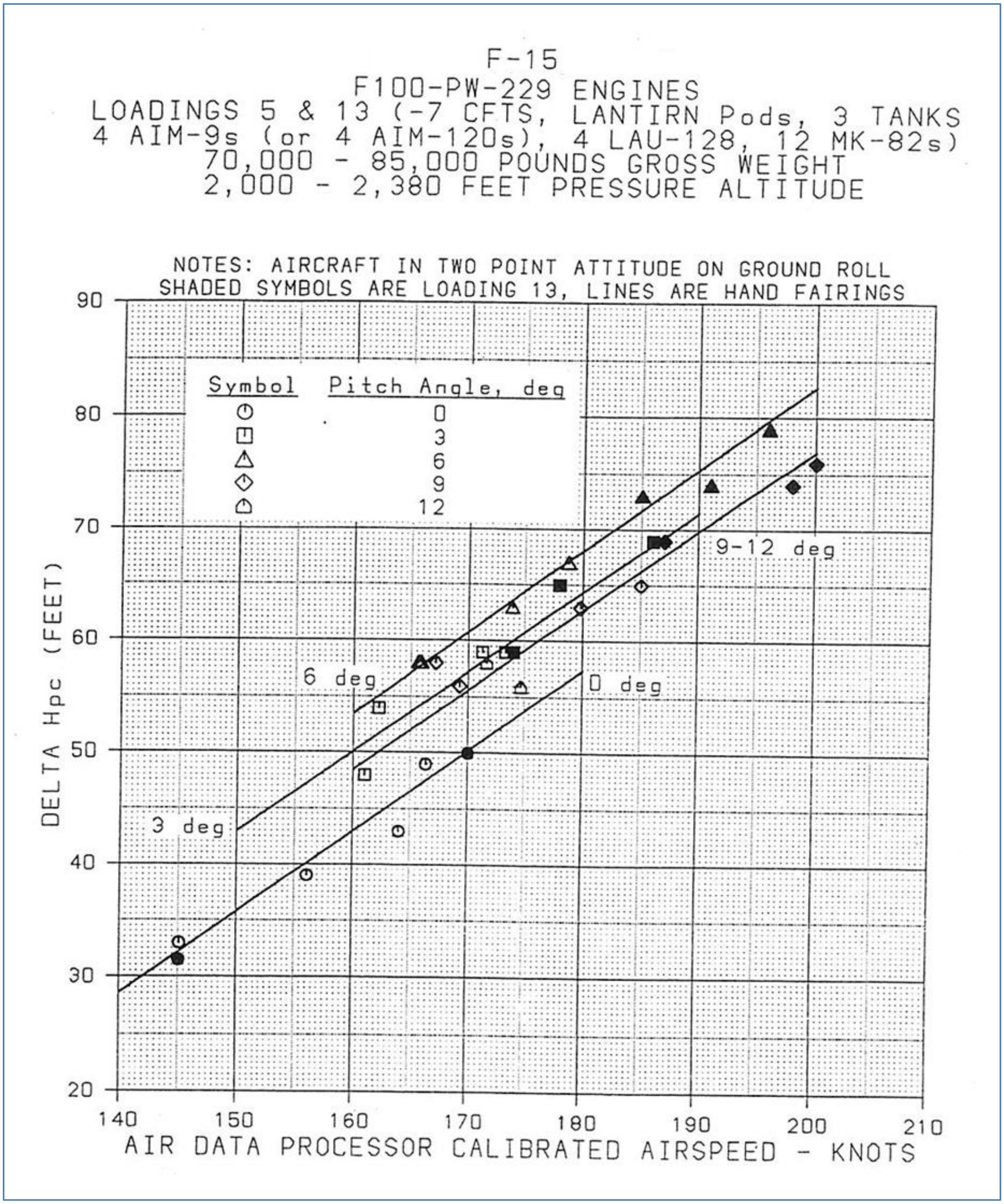

Figure F15 Position Error Corrections in a Two-Point Attitude on the Takeoff Ground Roll for Loadings 5 and 13

APPENDIX G – ABBREVIATIONS, ACRONYMS, AND SYMBOLS

Abbreviation	Definition
AC	advisory circular
ADC	air data computer
AFB	Air Force Base
AFFTC	Air Force Flight Test Center
AFM	airplane flight manual
AFTR	Air Force Technical Report
AGARD	Advisory Group for Aeronautical Research and Development
AGL	above ground level
AIM	air intercept missile
ARDS	advanced range data system
C	Celsius
CAS	calibrated airspeed
CBU	cluster bomb unit
CFR	Code of Federal Regulations
CFTs	conformal fuel tanks
CD	compact disk
DD MM SS.SSSSS	degrees minute seconds, latitude
DDD MM SS.SSSSS	degrees minute seconds, longitude
deg	degree
deg C	degree Celsius
deg F	degree Fahrenheit
deg R	degree Rankine
DL	data link
DMU	distance measuring unit
DOA	Organization Delegation Option
DOD	Department of Defense
DTIC	Defense Technical Information Center
DTL	detail specification
E	East
EAS	equivalent airspeed
EGI	Embedded GPS and INS
EGM	Earth Gravitational Model

Abbreviation	Definition
F	Fahrenheit
FAA	Federal Aviation Administration
FAR	Federal Aviation Regulation
FLIP	Flight Information Publication
ft	international foot or feet, length exactly equal to 0.3048 of a meter
GBU	guided bomb unit
GPS	global positioning system
Hg	mercury
HW	headwind
IAS	indicated airspeed
ICAO	International Civil Aviation Organization
IGE	in-ground effect
in	inch, inches
INS	inertial navigation system
JP	jet propellant
K	Kelvin, a unit of temperature, formerly a degree Kelvin
KCAS	knots calibrated airspeed
KEAS	knots equivalent airspeed
KGS	knots ground speed
kts	knots
LANTIRN	low navigation and targeting infrared for night
lb	pound
lb/ft^2	pounds per square foot
LDGP	low-drag general purpose
M	Mach number
MCAS	Marine Corps Air Station
MIL	military
MK	mark
N	North
N/A	not applicable or not assigned
NACA	National Advisory Committee for Aeronautics
NAS	Naval Air Station
NASA	National Aeronautics and Space Administration

Abbreviation	Definition
NATO	North Atlantic Treaty Organization
n/d	non-dimensional
NOAA	National Oceanic and Atmospheric Administration, part of the U.S. Department of Commerce
OGE	out of ground effect
PCM	pulse code modulation
PMP	Propulsion Modernization Program
psia	pounds force per square inch absolute
PW	Pratt Whitney
R	Rankine or specific gas constant
SAC	standard aircraft characteristics
sec	second
S/N	serial number
TAS	true airspeed
TIH	technical information handbook
TR	technical report
U.S.	United States
USAF	United States Air Force
W	West
WGS	World Geodetic System

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