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THE CALIBRATION AND FLIGHT TEST PERFORMANCE OF THE SPACE SHUTTLE ORBITER AIR DATA SYSTEM

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SUMMARY

The Space Shuttle air data system (ADS) is used by the guidance, navigation and control system (GN&C) to guide the vehicle to a safe landing. In addition, postflight aerodynamic analysis requires a precise knowledge of flight conditions. Since the orbiter is essentially an unpowered vehicle, the conventional methods of obtaining the ADS calibration were not available; therefore, the calibration was derived using a unique and extensive wind tunnel test program. This test program included subsonic tests with a 0.36-scale orbiter model, transonic and supersonic tests with a smaller 0.2-scale model, and numerous ADS probe-alone tests. The wind tunnel calibration was further refined with subsonic results from the approach and landing test (ALT) program, thus producing the ADS calibration for the orbital flight test (OFT) program.

The calibration of the Space Shuttle ADS and its performance during flight are discussed in this paper. A brief description of the system is followed by a discussion of the calibration methodology, and then by a review of the wind tunnel and flight test programs. Finally, the flight results are presented, including an evaluation of the system performance for on-board systems use and a description of the calibration refinements developed to provide the best possible air data for postflight analysis work.

INTRODUCTION

The Space Shuttle orbiter is a unique vehicle. Its primary mission is to deliver payloads to near-earth orbit and return, landing like a conventional aircraft. Upon entry, the orbiter must maintain its stability and control over an extensive flight regime. During a typical flight, the Mach number may vary from 27 at entry to 0.25 at landing, with the angle of attack ranging from 40 to 0 degrees. Since the vehicle is unpowered, accurate air data is crucial to enable it to make a safe landing.

In many ways, the Space Shuttle orbiter ADS is a typical ADS. It uses two fuselage-mounted probes to measure local flow conditions. Freestream conditions, such as Mach number, angle of attack, and altitude are computed using previously derived calibration algorithms. The freestream conditions are used by the GN&C system and are also displayed to the crew. In addition, air data is used extensively during postflight aerodynamic analysis of the Shuttle.

Since the orbiter is an unpowered air vehicle, the traditional ADS flight calibration methods, e.g., pacer aircraft and tower-fly-by are not possible; therefore, an extremely comprehensive wind tunnel test program was developed to obtain the necessary data to derive the calibration. The wind tunnel data were merged with data obtained during the ALT program to produce an on-board calibration for OFT and a more accurate calibration for postflight aerodynamic analysis. Results from the OFT program indicated that the on-board (general purpose computer [GPC]) calibration easily met the specified requirements. These results were also used in an extensive effort to refine the postflight calibration in order to provide the best possible data for postflight aerodynamic analysis.

ADS DESCRIPTION

A sketch of the orbiter ADS probes illustrating their location on the orbiter nose is shown in figure 1. There are two probes, one on either side of the vehicle. They are secured to rotating doors that allow them to be stowed (and thus protected) during ascent, orbit, and reentry. After reentry, the probes are deployed when the orbiter has slowed to approximately Mach 3.5. Each probe includes a semispherical head with three pressure ports, as seen in figure 1. The center port (P_C) gives an indication of total pressure and senses local total pressure when the probe is aligned with the local flow field. The upper and lower ports (P_U and P_L) are sensitive to local flow angle. In addition, several static pressure ports (P_M) are located aft on the probe shaft, and a total temperature sensor is located at the rear.

The probes are connected to four air data transducer assemblies (ADTA), redundant pairs per side, through pneumatic lines. The ADTA house sensitive pressure transducers that convert the probe-measured pressures to electrical signals. Using the ADS calibrations, the GPC processes the ADTA signals to provide the basic air data parameters: static pressure, total pressure, and angle of attack (also total temperature). From these basic parameters, Mach number, dynamic pressure, pressure altitude, equivalent airspeed, and true airspeed are computed.

ADS CALIBRATION DESCRIPTION

The ADS calibration relates a set of conditions that cannot be measured directly during flight (i.e., Mach number, angle of attack. and altitude) to a set of parameters that can be measured (i.e., probe total, static, upper and lower pressures, and total temperature). In the wind tunnel, specific freestream conditions (i.e., static and total pressure, angle of attack, and sideslip) are known to a relatively high degree of accuracy. During a wind tunnel test these conditions are held constant, while the probe pressures are carefully measured and recorded.

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The development of the ADS calibration involved deriving a set of calibration parameters that relate the freestream conditions to the probe-measured conditions, using the wind tunnel derived data base (later merged with flight results). From the freestream conditions, the various air data parameters (Mach number, altitude, etc.) can be computed using basic aerodynamic equations. A flow chart illustrating the ADS calibration and showing how the above freestream parameters are computed is presented in figure 2.

Since the probe measurements are affected by the presence of the orbiter, it is not possible to measure freestream static and total pressure (P_∞ and P_{T_∞}) directly. Thus the error, or decrement from the actual value, was put in non-dimensional form and designated CPSD and CPTD. Freestream angle of attack also cannot be measured directly; therefore, a pressure parameter (RAX) was developed to provide an indication of angle of attack. The equations describing these parameters are presented below with typical calibration curves shown in figure 3.

- Static pressure decrement

$$CPSD = \frac{P_M - P_\infty}{P_C - P_M}$$

- Total pressure decrement

$$CPTD = \frac{P_C - P_{T_\infty}}{P_C - P_M}$$

- Angle-of-attack parameter

$$RAX = \frac{P_L - P_U}{P_C - 1/2(P_L + P_U)}$$

Note that CPSD and CPTD relate freestream static and total pressure to P_M and P_C, respectively, while RAX has a fairly linear relationship with angle of attack and exhibits good sensitivity. The wind tunnel data were used to derive a set of polynomial equations of the type shown below, which describe angle of attack as a function of RAX, and CPSD and CPTD as functions of angle of attack.

$$Y(X) = A0 + A1(X) + A2(X)^2 + A3(X)^3 + A4(X)^4$$

where

$Y(X) = \alpha_{ORB}(RAX)$
$CPSD(\alpha_{ORB})$
$CPTD(\alpha_{ORB})$

These equations are at a constant Mach number with a linear interpolation used between Mach numbers. For the on-board calibration, software storage restrictions limited the equations to fourth order, with the entire calibration utilizing 196 coefficients. On the other hand, the postflight calibration had no restrictions and thus resulted in a more complex calibration with over 600 coefficients.

Using these equations, the freestream values of static and total pressure are computed. Finally, using P_∞ and P_{T_∞}, the various air data parameters are computed (i.e., Mach number, pressure altitude, dynamic pressure, and equivalent airspeed). Note that since the ADS calibration parameters (RAX, CPSD, and CPTD) are modeled as functions of Mach number it is necessary to make an initial guess at the Mach number and use the equations to converge on the actual value.

SYSTEM REQUIREMENTS

Since air data is used extensively in the orbiter GN&C system, the ADS requirements are based on the GN&C requirements. These are shown in table I. The orbiter flight control system divides the atmospheric portion of the Shuttle flight into three parts: entry, terminal area energy management (TAEM), and approach and landing (A/L). Each area has specific requirements for air data parameters such as Mach number, altitude, and angle of attack, as shown in table I. It should be noted that these are specified system requirements. Postflight analysis accuracy needs are more stringent; hence, much effort was expended to provide postflight air data that is as accurate as the system will allow.

WIND TUNNEL TEST PROGRAM

Most aircraft ADS's have the advantage of being calibrated during flight. Standard techniques involve flying the aircraft at a constant altitude past a known ground station or paced by another aircraft with a known ADS. Since these techniques were not available to the orbiter air vehicle, limited flight calibration must be supplemented by wind tunnel tests that cover flight envelope extremes not encompassed by the flight test program. Consequently, the orbiter ADS wind tunnel calibration program was necessarily comprehensive.

The wind tunnel program was divided into two distinct parts: tests with the probes mounted on an orbiter model to relate probe response to orbiter freestream conditions, and probe-alone tests to evaluate the probe response to local flow field conditions. The extent of the wind tunnel test program is shown in tables II and III.

The initial ADS calibration wind tunnel tests, with the probes mounted on the orbiter, were performed in order to derive an ADS calibration for Orbiter 101 for use during ALT. Since Orbiter 101 was unpowered, it would not exceed subsonic velocities; hence, the Orbiter 101 ADS calibration was limited to the Mach range of 0.25 to 0.7. Data at Mach 0.25 were obtained using a 0.36-scale orbiter model, complete with scaled air data probes. The model was large enough that the ADS side probes could be accurately simulated; however, because of its size, it could only be tested in the Ames Research Center (ARC) 40 by 80-Foot Wind Tunnel. Because of this, only low speed (Mach = 0.25) data could be obtained.

In order to obtain data at the higher Mach numbers, a much smaller model was used. It was determined that the 0.2 scale was the minimum practical probe size for valid simulation; however, this resulted in probe models that were too small to be completely simulated and an orbiter model that was too large for the available high speed facilities. Therefore, a compromise had to be made. It was decided to divide the four probe pressures between the left and right probe models. Thus, P_C and P_M were placed on one probe, with P_U and P_L on the other. The orbiter model size was reduced by eliminating the portion of the vehicle aft of fuselage station 670, and replacing it with a boattail fairing. The resulting model was still too large, so the scale was reduced to 0.1; hence, the high speed data (Mach > 0.25) were obtained using two 0.2-scale probe models on a 0.1-scale orbiter forebody-only model.

The validity of using a forebody-only model was substantiated by testing a complete orbiter 0.03-scale model with flush pressure taps bracketing the probe location. Wing-on and wing-off comparisons showed essentially no influence at these pressure ports.

For later verification tests, a 0.1-scale probe was developed with a single pressure tap for measuring static pressure; thus, to determine the static pressure parameter, this probe was tested in conjunction with a 0.2-scale probe that measured the total pressure.

ALT PROGRAM

The ALT program was conducted at the Dryden Flight Research Center, Edwards Air Force Base, in August, September, and October, 1977. The program consisted of five air launches from the Boeing 747 Shuttle carrier aircraft, three with a large tailcone fairing closing off the fuselage base and the last two without the fairing, thus simulating the operational configuration. The tailcone-on flights allowed about 5 minutes of free flight time. Less than half that time was available with the tailcone removed.

The ADS was calibrated during ALT using the flight test probe (FTP) as a reference. The FTP was a conventional noseboom, which was mounted on the orbiter nose. It measured stagnation pressure through a total pressure head, static pressure through pressure ports on the barrel of the probe, and both angles of attack and sideslip with vanes. During ALT, the air data from FTP were also used by the backup flight control system (BFCS). There was no FTP installed for the OFT program.

OFT PROGRAM

The OFT program consisted of four flights launched from the Kennedy Space Center in 1981 and 1982. These flights were designated as test flights and the orbiter carried a wide variety of instruments designed to accurately measure its performance. Much of the analysis performed on these flights, and the analysis of the data gathered by the flight test instrumentation, required an accurate source of air data; thus, the ADS provided air data for the on-board systems and air data for postflight analysis. The latter required air data parameters that were more accurate than those provided to the on-board systems.

During OFT, the accuracy of the ADS parameters was judged by comparison with alternate data sources. Since these alternate sources are also subject to errors, differences are not necessarily a measure of the ADS inaccuracy; however, if it is assumed that the alternate data errors are random, any consistent bias error would indicate an actual error in the ADS calibration. The alternate sources available for the OFT flight program include a best estimated trajectory (BET) generated by TRW, another BET generated by the Langley Research Center (LaRC), and a trajectory based on phototheodolite tracking, generated by the Air Force Flight Test Center (AFFTC). The primary cause of inaccuracy in these sources is that the parameters are corrected for measured (jimsphere) winds, which differ in time and location from the actual winds. Of course, the ADS experiences the actual winds.

The OFT program had two primary ADS test objectives: verification of the on-board GPC function, and refinement of the postflight ADS calibration for the generation of high quality air data parameter time histories for postflight aerodynamic analysis.

GPC RESULTS

The GPC air data parameters supplied to the on-board, flight control, guidance, and navigation systems differ from the postflight derived parameters in several regards. On-board (GPC) parameters are provided at 1 sample per second, whereas the postflight parameters are derived from transducer output pressures at 12 1/2 samples per second. The on-board calibration algorithms are simplified in order to conform to the software limitation of 196 calibration coefficients, as compared with approximately 600 coefficients used in the postflight calibration. In addition, the on-board system employs a rate limiting function to avoid air data discontinuities in the Mach jump regions (Mach 1.4 and again near 1.0). Each of these differences can contribute to loss of accuracy.

Another possible error source is the on-board mechanization of the calibration. The system begins with the previous Mach number (initially an assumed Mach number) to enter the calibration equations, but does not iterate with a corrected Mach number. Prior to STS-1, it was analytically shown that the rate of change of Mach number, and/or the calibration coefficients, was low enough to preclude a significant error. This analysis has been verified by flight results.

Results from STS-1 through STS-4 have shown that the GPC functioned satisfactorily and produced air data parameters well within the system accuracy requirements. Figures 4, 5, and 6 show the GPC output dynamic pressure, angle of attack, and Mach number for STS-4 compared with the ADS parameters. The latter have been refined, as described in the following section, and are considered the best source of air data. These figures show the flight region from approximately Mach 2.5 to landing gear deployment. The maximum difference in dynamic pressure (about 9 psf) is approximately 4 percent, while the system accuracy requirement is 10 percent. Similarly, the maximum difference in angle of attack is approximately 0.85 degree as compared to the requirement of ± 2.0 degrees, and the maximum difference in Mach number is -0.063 compared with a requirement of ± 0.15 (± 10 percent). The other air data parameters show similar differences. Comparisons using data from STS-4 are shown in the figures; however, results from the other flights are similar.

The maximum differences between the ADS parameters and the LaRC BET data are shown in table I along with the system accuracy requirements. Only those parameters that have a specified requirement are presented. The table shows that the accuracy achieved by the on-board GPC calibration is well within the system requirements.

SUBSONIC POSTFLIGHT CALIBRATION

The subsonic postflight calibration was based on ALT flight results because the FTP provided an accurate reference data source. Using limited data, initial analysis efforts showed that there were distinct differences between wind tunnel and flight-derived calibrations. The wind tunnel static pressure calibration coefficient (CPSD) was somewhat lower than that indicated by flight. The total pressure calibration coefficient (CPTD) showed differences at low angles of attack, and the angle-of-attack parameter (RAX) showed a bias of approximately 1/2 degree. These differences were applied to produce an initial flight calibration. Additional analysis indicated that this initial calibration could be refined further.

A multiple linear regression technique was adapted for the refinement effort. This is a least-squares technique used to derive a relation between one parameter and several independent variables. In addition to this sophisticated analysis tool, a computer program was developed that was capable of processing a very large quantity of data. The regression analysis was applied to angle-of-attack, static pressure, and total pressure.

The angle-of-attack analysis showed a dependence on α, α^2, and pitch rate. The derived correction took the following form.

$$\alpha_{CORR} = \alpha_{ADS} - \Delta\alpha$$

$$\Delta\alpha = 0.2476 - 0.5853(QTERM) - 0.1033\alpha_{ADS} + 0.00697\alpha_{ADS}^2$$

$$(QTERM) = qr/V_T$$

This correction reduced the three-sigma dispersion in angle of attack from about 3/4 degree to a little more than 1/2 degree. This is illustrated in figures 7 and 8, which show the ADS angle of attack with and without the correction plotted against the FTP-measured angle of attack. Figure 9 shows the correction (with zero pitch rate) plotted as a function of angle of attack. It should be noted that the practical limit for accuracy of flight test determined angle of attack is probably between 1/4 and 1/2 degree.

The static pressure analysis began with determining the dependence of the calibration parameter, CPSD, on angle of attack, Mach number, and pitch rate. The pitch rate dependence was shown to be insignificant, so the analysis continued using Mach number and various powers of angle of attack. The final correction was made consistent with the basic calibration equation, i.e., a polynomial equation with CPSD as a function of Mach number and a fourth order function of angle of attack, as follows:

$$CPSD_{CORR} = CPSD - \Delta CPSD$$

$$\Delta CPSD = -4.843 \times 10^{-2} + 5.293 \times 10^{-2} (M_{ADS}) + 7.612 \times 10^{-3} (\alpha_{ADS}) - 1.933 \times 10^{-3} (\alpha_{ADS})^2 + 1.758 \times 10^{-4} (\alpha_{ADS})^3 - 4.783 \times 10^{-6} (\alpha_{ADS})^4$$

This correction reduced the three-sigma dispersion in CPSD from ± 0.04947 to ± 0.0168. The significance in the equivalent airspeed uncertainty was to reduce the static pressure contribution to the uncertainty from about 4 knots to 1.4 knots. Figure 10 shows the ADS calibration coefficient with no corrections plotted against that derived from the FTP. Figure 11 shows the ADS coefficient with corrections applied.

Total pressure was found to be the largest contributor to the equivalent airspeed uncertainty. The total pressure analysis followed the same steps as the static pressure and culminated in a calibration parameter (CPTD) correction in the same format as the basic calibration equation.

$$CPTD_{CORR} = CPTD - \Delta CPTD$$

$$CPTD = 4.1242 \times 10^{-2} + 6.2598 \times 10^{-2} (M_{ADS}) - 8.3247 \times 10^{-3} (\alpha_{ADS}) - 1.5937 \times 10^{-3} (\alpha_{ADS})^2 + 2.4879 \times 10^{-4} (\alpha_{ADS})^3 - 8.0762 \times 10^{-6} (\alpha_{ADS})^4$$

This correction reduced the three-sigma dispersion in CPTD from ± 0.0652 to ± 0.01686. In terms of equivalent airspeed, it reduced the uncertainty from about 6 knots to about 1.5 knots. The ADS total pressure calibration coefficient is plotted against that derived from the FTP before corrections were applied, as shown in figure 12, and after corrections were applied, as shown in figure 13. The differences between the wind tunnel and flight-derived calibrations are shown in figures 14, 15, and 16. These figures show the ALT flight data with both the wind tunnel and flight-derived calibrations superimposed.

These corrections were applied to the STS flight data in the trajectory range from Mach 0.6 to landing gear deployment. Prior to correction, the maximum differences in equivalent airspeed were about 10 knots when compared to the LaRC BET and about [illegible] knots when compared to the AFFTC data. After the corrections were applied, these differences were reduced to about 6 knots for the LaRC BET and about 2 knots for the AFFTC data. Considering that the alternate sources are subject to wind uncertainties, the corrected ADS equivalent airspeed is considered the most accurate. Figures 17 and 18 show an example of these comparisons. Figure 17 compares the ADS equivalent airspeed with the LaRC BET before corrections, and figure 18 shows the same comparison after corrections.

TRANSONIC AND SUPERSONIC POSTFLIGHT CALIBRATIONS

The transonic and supersonic postflight calibrations were based entirely on wind tunnel results. This calibration proved to be adequate for on-board use, but in order to provide the best possible air data for postflight analysis, some improvement appeared appropriate.

In the transonic range, the measured static pressure experiences a rapid change at two points: Mach 1.4 and near Mach 1.0. The rapid fluctuations are shown in figure 19. This figure shows a time history of the ADS static pressure calibration coefficient compared with the coefficient derived using the freestream static pressure, as provided by the LaRC BET. This example is for STS-2 and is typical of all the flights. The results of the system not precisely following the rapid changes are discontinuities in the static pressure history. This is also reflected in other parameters. For example, figure 20 shows the effect on Mach number for STS-4. As a first approach to removing the discontinuities, a simple linear interpolation was used; however, other aerodynamic analysis results indicated that this method could be improved upon.

An attempt was made to derive a calibration correction from the three alternate sources of air data for all four flights; however, no consistent error pattern could be determined.

As used by the alternate data sources, the meterolcgical-measured static pressure (Rawinsonde) is considered an accurate measure of static pressure. In fact, it is considered more accurate than is possible with any conventional air vehicle ADS, particularly within the ADS altitude range. Consequently, it was a logical step to resolve the discontinuities in the ADS static pressure, by simply substituting the meteorological static pressure for the ADS-determined static pressure. This was done with the static pressure from the LaRC BET.

At higher Mach numbers (2.5 to 3.5), all four flights showed a consistent negative bias in static pressure when compared with either the LaRC BET or the TRW BET, although the magnitude differed between flights and between sources. An example from STS-4 is shown in figure 21. This bias was also resolved by substituting the static pressure from the LaRC BET.

CONCLUSIONS

The calibration of the Space Shuttle orbiter ADS was a unique program to derive an accurate system calibration without the benefit of an extensive flight calibration program. The bulk of the calibration was derived from an extensive wind tunnel test program and was combined with a limited amount of flight test results. From the comprehensive wind tunnel test program, angle of attack, static pressure, and total pressure calibrations were developed and proved to be sufficiently accurate to meet the specified requirements.

Further refinements were developed from the flight programs to produce the best possible air data parameters for postflight analysis work. From Mach 3.5 to Mach 0.6, the meterological static pressure was substituted for that derived by the ADS. From Mach 0.6 to landing gear deployment, corrections derived from a regression analysis technique were applied to angle of attack, static pressure, and total pressure. The entire ADS Mach number range is illustrated in figures 22 and 23, which show an example of Mach number from the refined ADS (STS-4), compared with that from the LaRC BET. The differences are small and cannot be considered a measure of accuracy since there is some uncertainty associated with the reference source.

To date, there has been no requirement to isolate the effects of ground proximity on the ADS parameters, although it is known that there is a significant effect, particularly in angle of attack. Current analysis work has shown that the angle of attack derived from the inertial measurement unit (IMU) has been adequate.

In general, the final air data parameters are considered an accurate representation of the actual trajectories flown and are suitable for use in postflight data analysis.

SYMBOLS AND ABBREVIATIONS

ADS	air data system
ADTA	air data transducer assembly
AFFTC	Air Force Flight Test Center
ALT	approach and landing test
ARC	Ames Research Center
A/L	approach and landing
BFCS	backup flight control system
CPSD	static pressure decrement coefficient
CPTD	total pressure decrement coefficient
FTP	flight test probe
GN&C	guidance, navigation, and control
GPC	general purpose computer
IMU	inertial measurement unit
LaRC	Langley Research Center
LeRC	Lewis Research Center
OFT	orbital flight test
P_C	probe center pressure
P_L	probe lower pressure

P_M	probe-measured static pressure
P_U	probe upper pressure
P_∞	freestream static pressure
P_{T_∞}	freestream total pressure
q	pitch rate (deg/sec)
r	distance from the center-of-gravity to the ADS probe (ft)
RAX	angle-of-attack parameter
TAEM	terminal area energy management
Ve	equivalent airspeed (knots)
V_T	true airspeed (ft/sec)

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TABLE I.-ADS PARAMETER PERFORMANCE

Air Data Parameter	Units	Flight Phase Utilization	System Requirement		Most Stringent Subsystem Requirement	Maximum Difference With LaRC BET
			Range	Accuracy (3σ)		
Altitude	ft	TAEM	10K to 100K	±10%	Navigation	±4%
Dynamic pressure	psf	(TAEM)/(A/L)	90 to 375	±10%	G&C	±7%
Mach number	dim	TAEM A/L	0.6 to 2.5 0.25 to 0.6	±10% ±5%	Guidance FCS	±6% ±3%
True airspeed	fps	TAEM A/L	600 to 2500 250 to 600	±10% ±5%	FCS Guidance	±6% ±3%
Equivalent airspeed	KTS	(TAEM)/(A/L)	160 to 335	±5%	Crew	±4%
Angle of attack	deg	(TAEM)/(A/L)	-4 to +20	±2°	G&C	±1°

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TABLE II.-WIND TUNNEL PROGRAM (AIR DATA PROBE CALIBRATION)
ORBITER MODEL TESTS

Test	Model Scale		Mach Range	Facility	Purpose
	Orbiter	Probe			
OA-22	0.03	None	0.6 → 1.5	ARC 11x11, 9x7	Pressure survey
OA-143	0.03	None	0.25	Rockwell NAAL	Pressure survey
OA-100	0.36	0.36*	0.25	ARC 40x80	Development
OA-164	0.36	0.36*	0.25	ARC 40x80	Development
OA-174	0.36	0.36	0.25	ARC 40x80	Verification
OA-161A,B C	0.03	None	0.6 → 3.5	ARC 11x11, 9x7, 8x7	Pressure and local survey
OA-220	0.10 (forebody)	0.20*	0.3 → 1.1	ARC 14x14	Transonic-scaled probes
OA-224	0.10 (forebody)	0.20	0.2 → 1.3	LaRC 16-ft transonic	Verification
OA-228	0.10 (forebody)	0.20	0.25	Rockwell NAAL	Static pressure comparison
OA-237	0.10 (forebody)	0.10, 0.20	0.25	ARC 40x80	Scale and blockage
OA-232	0.10 (forebody)	0.10, 0.20	0.2 → 1.3	AEDC 16T	Scale and blockage
OA-221B,C	0.10 (forebody)	0.20	1.5 → 3.5	ARC 9x7, 8x7	Development
OA-234	0.10 (forebody)	0.10, 0.20	2.0 → 3.5	LaRC 10x10	Verification
OA-238	0.10 (forebody)	0.10	0.25	Rockwell NAAL	Scaled probes
OA-251B,C	0.10 (forebody)	0.10, 0.20	1.5 → 3.5	ARC 9x7, 8x7	Verification
Other tests:					
OA-236	(ARC Rosemount NAAL tunnel calibration probes)		0.25	Rockwell NAAL	Facilities calibration comparison

*Also nose probe

TABLE III.-WIND TUNNEL PROGRAM (PROBE-ALONE TESTS)

Test	Probe Scale	Mach Range	Facility	Purpose
OA-501	Full	0.2 → 0.95	Rosemount	Preliminary development
OA-502	Full	1.5 → 3.50	AEDC D	Preliminary development
OA-503*	0.36	0.15 → 0.30	Rosemount	Scale development
OA-504	Full	0.20 → 0.95	Rosemount	Development
OA-505	Full	0.80 → 1.50	AEDC IT	Development
OA-506	Full	1.50 → 3.50	AEDC D	Development
OA-507	0.36	0.20 → 0.95	Rosemount	Scale development
OA-508	0.36 & full	0.20 → 0.95	Rosemount	Verification
OA-509	0.20	0.20 → 0.95	Rosemount	Scale development
OA-510	0.20	0.80 → 1.50	AEDC IT	Scale development
OA-511	Full	0.20 → 0.95	Rosemount	Verification
OA-512	Full	1.50 → 3.50	AEDC D	Verification
OA-513	Full	0.80 → 1.50	AEDC IT	Development
OA-514	Full	1.50 → 3.50	AEDC D	Development
OA-515	0.20	1.50 → 3.50	AEDC D	Scale
OA-516	Full	1.50 → 3.50	AEDC D	Verification
OA-517	Full	0.20 → 0.95	Rosemount	Verification (qualification)
OA-518	0.10	0.20 → 0.95	Rosemount	Verification
OA-519	0.10	0.80 → 1.50	AEDC IT	Verification
OA-520*	0.36 noseboom	0.20 → 0.95	Rosemount	Verification

*Includes noseboom tests.

Note: Not in chronological order.

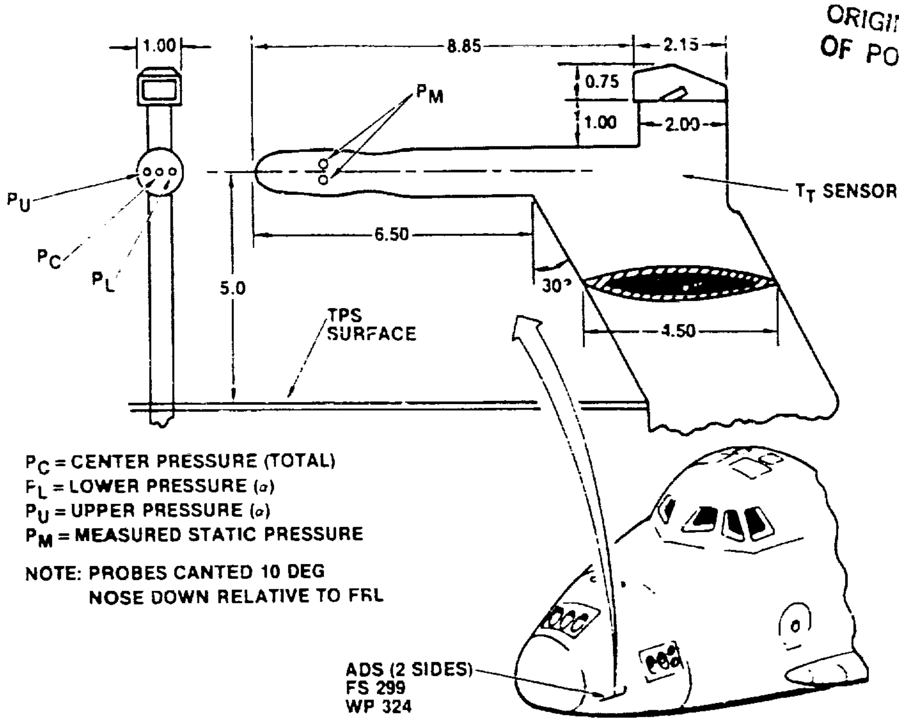

Figure 1.- ADS probe.

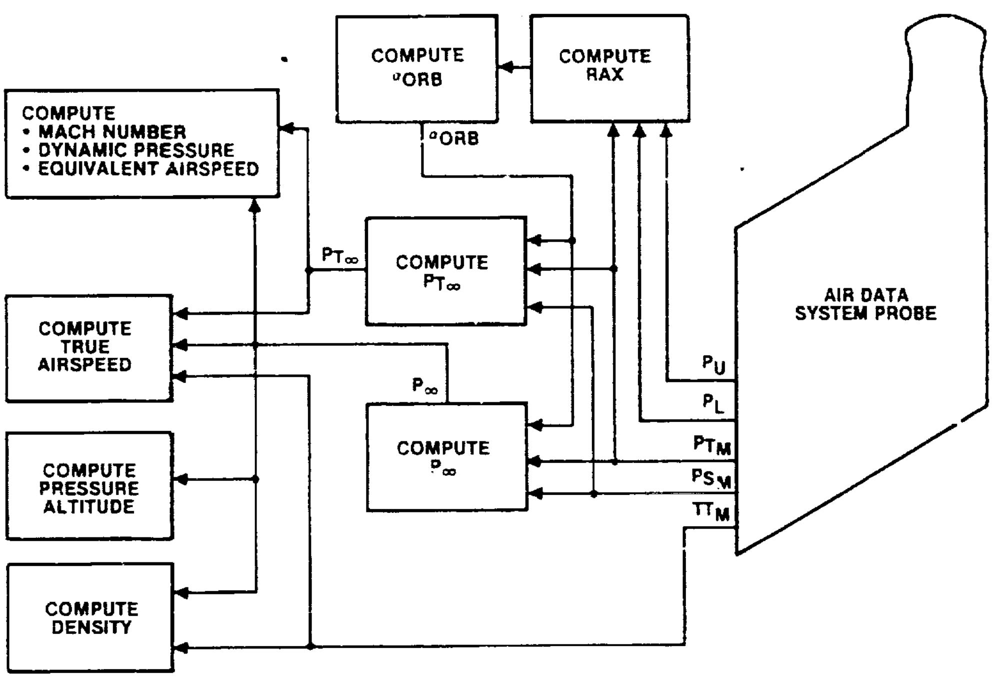

Figure 2.- ADS logic program.

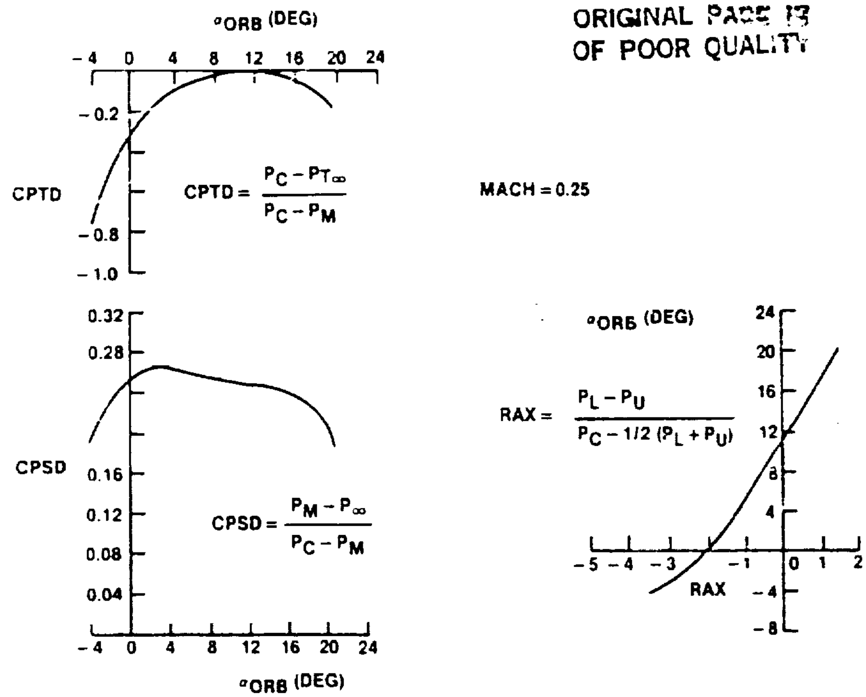

Figure 3.- Typical ADS calibration curves.

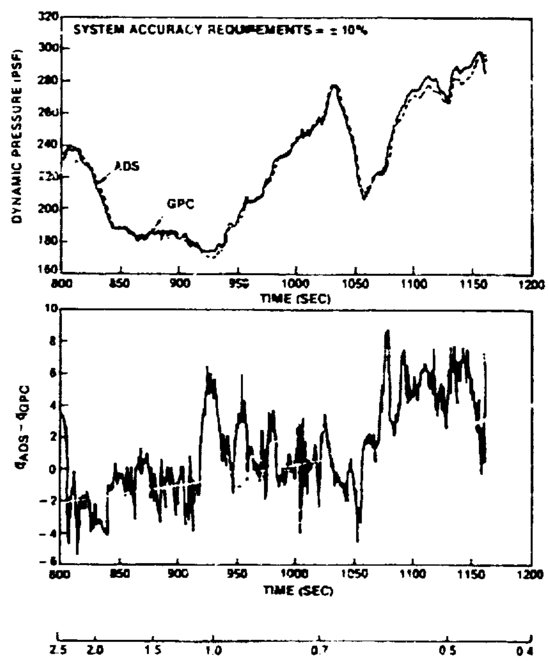

Figure 4.- STS-4 dynamic pressure comparison -
GPC and refined ADS calibration.

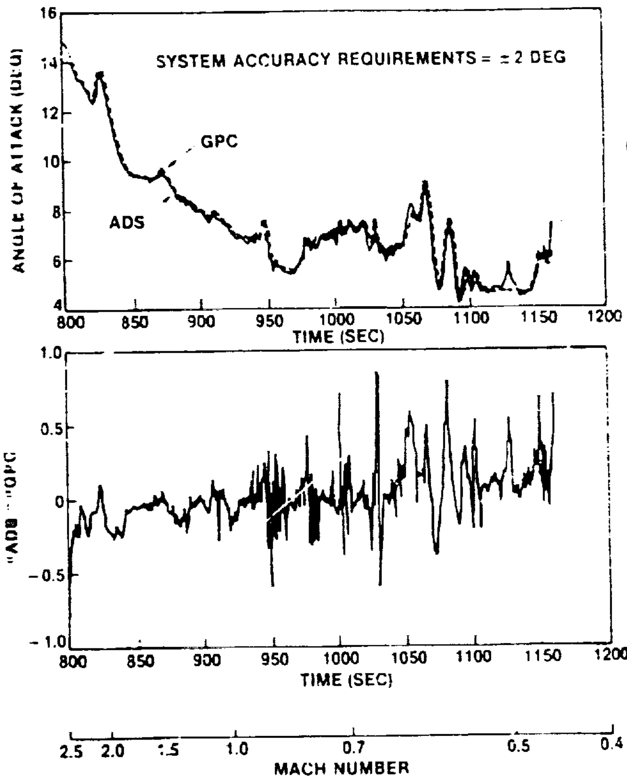

Figure 5.- STS-4 angle-of-attack comparison - GPC and refined ADS calibration.

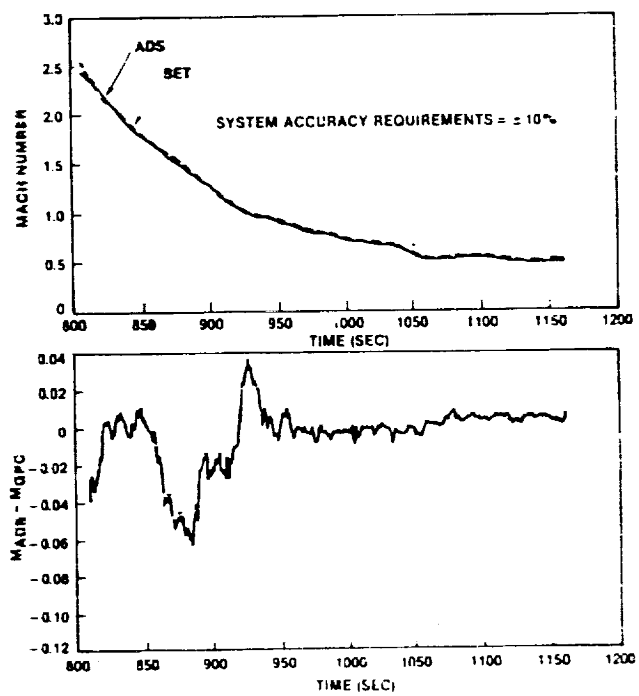

Figure 6.- STS-4 Mach number comparison - GPC and refined ADS calibration.

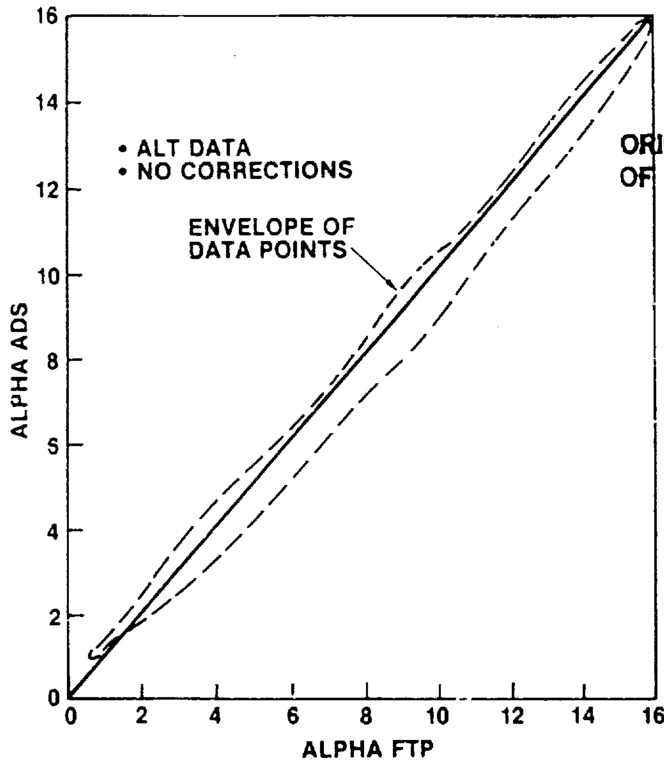

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Figure 7.- Angle-of-attack comparison - ADS and FTP (no corrections).

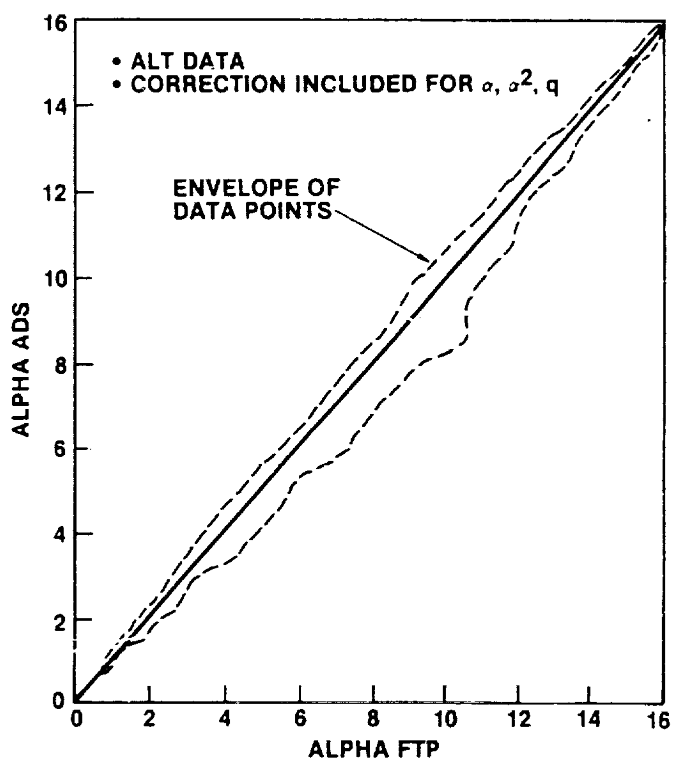

Figure 8.- Angle-of-attack comparison - ADS and FTP (corrections included).

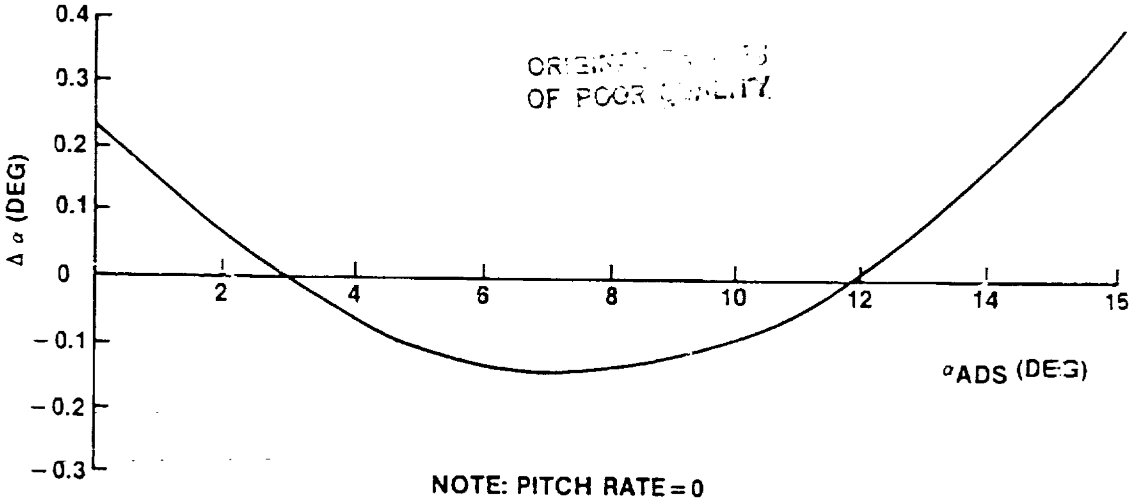

Figure 9.- Subsonic angle-of-attack correction.

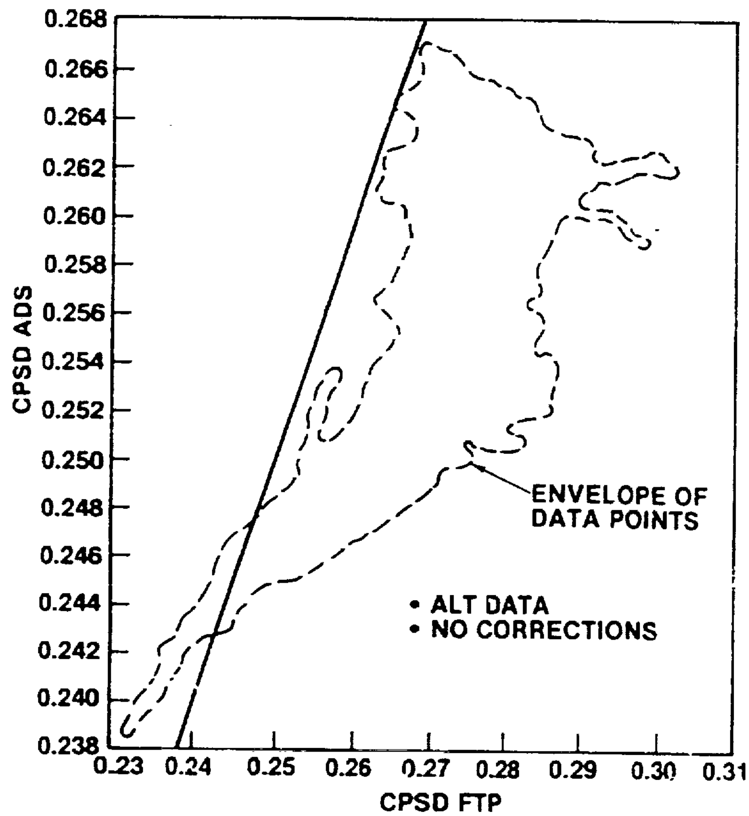

Figure 10.- Static pressure calibration coefficient comparison - ADS and FTP (no corrections).

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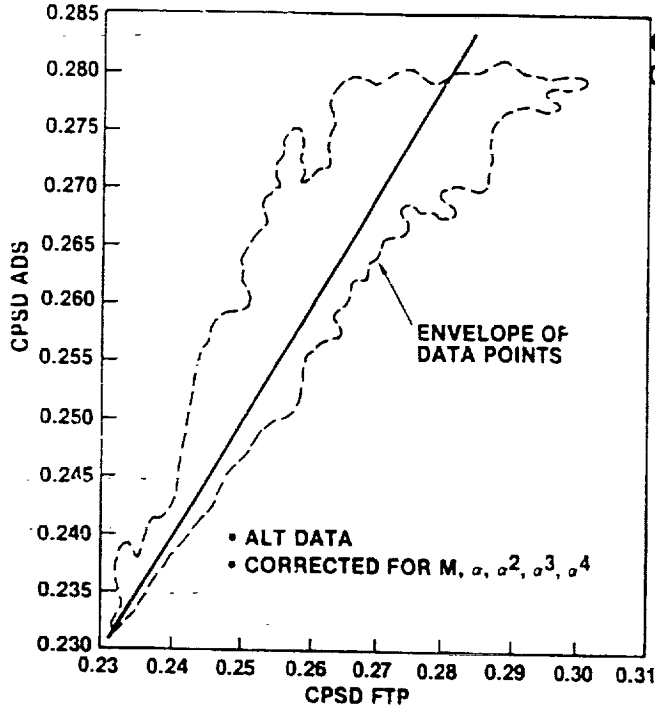

Figure 11.- Static pressure calibration coefficient comparison - ADS and FTP (including corrections).

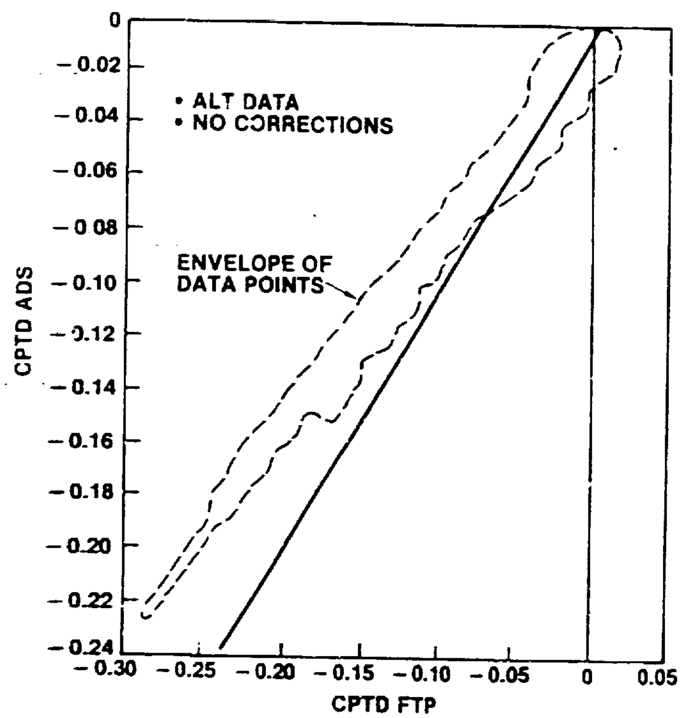

Figure 12.- Total pressure calibration coefficient comparison - ADS and FTP (no corrections).

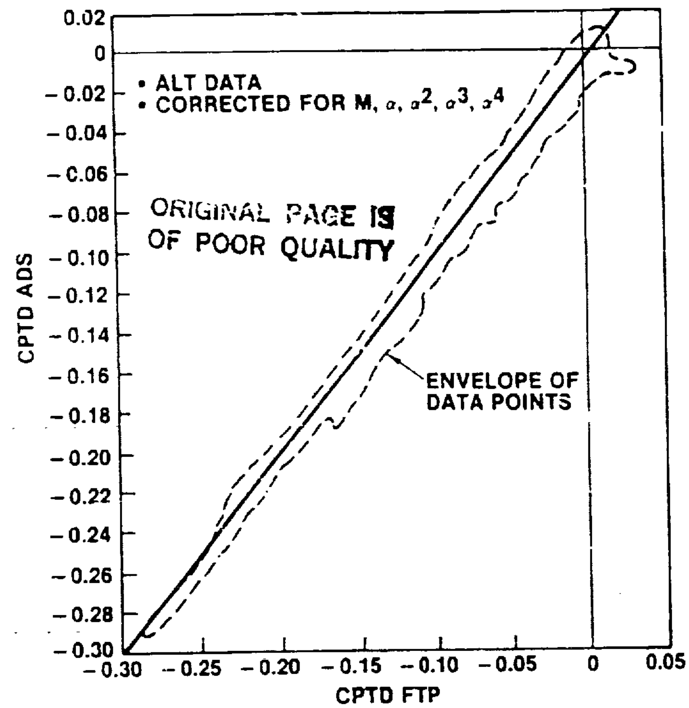

Figure 13.- Total pressure calibration coefficient comparison - ADS and FTP (including corrections).

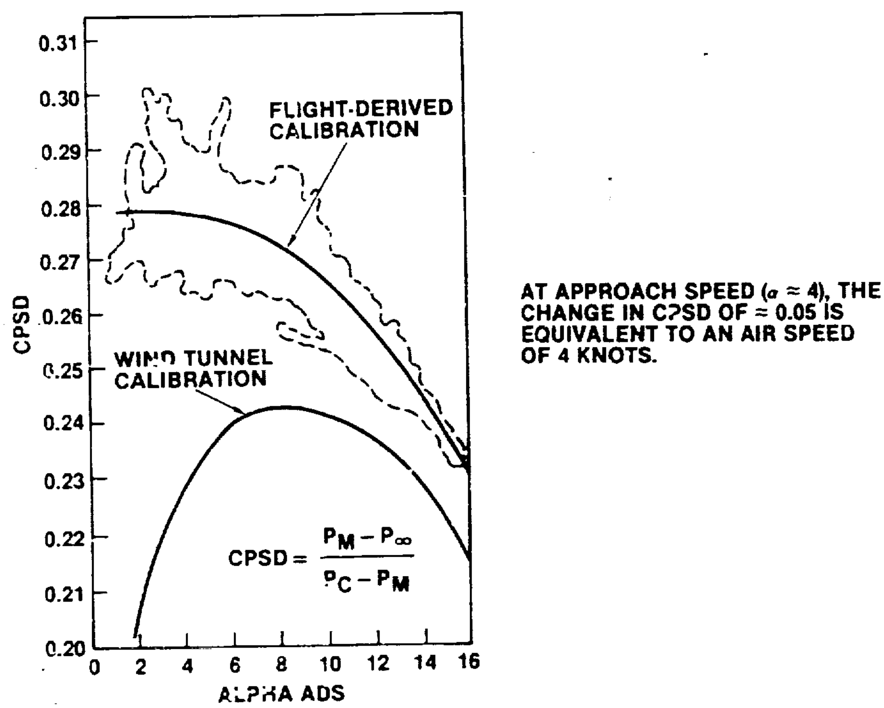

Figure 14.- Comparison of wind-tunnel and flight-derived static pressure calibrations (ALT flight data).

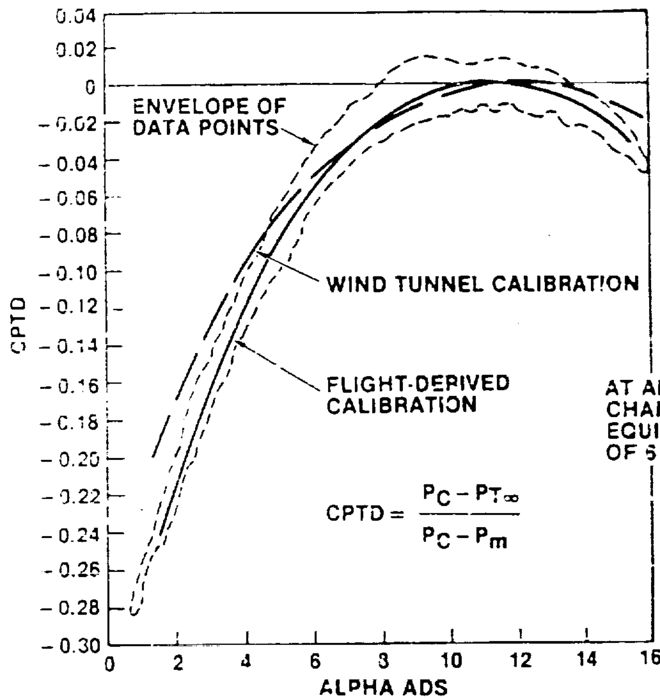

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Figure 15.- Comparison of wind-tunnel and flight-derived total pressure calibration (ALT flight data).

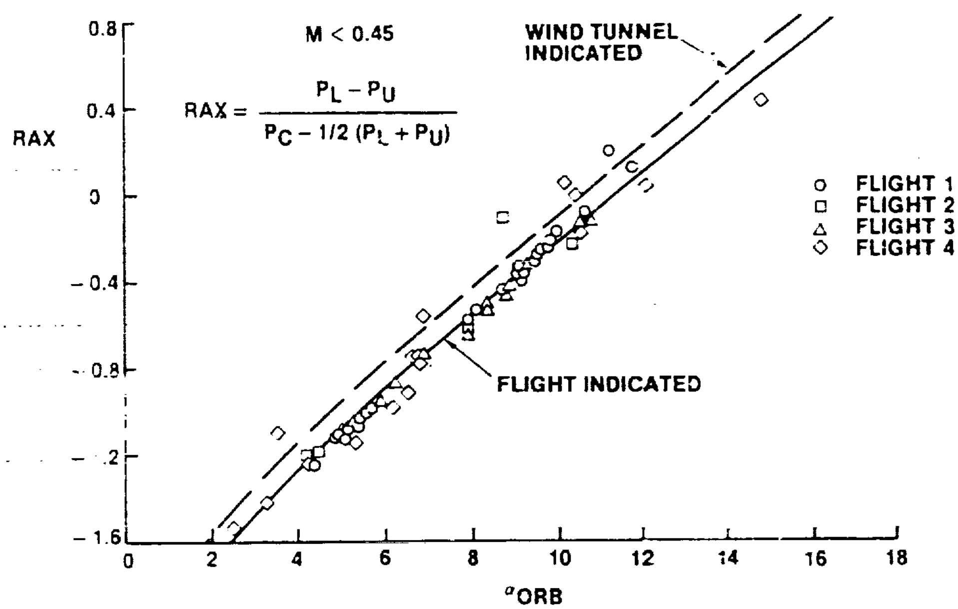

Figure 16.- Comparison of the angle-of-attack calibration and ALT results.

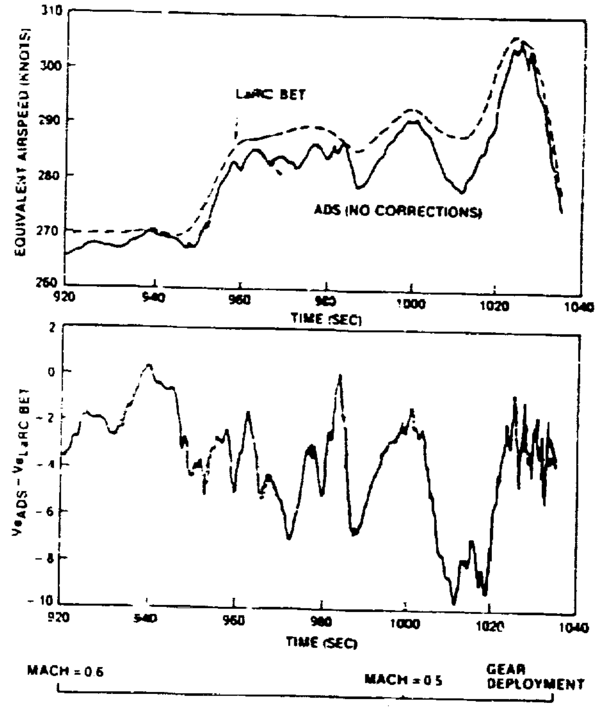

Figure 17.- STS-1 equivalent airspeed comparison - ADS and LaRC BET (no corrections).

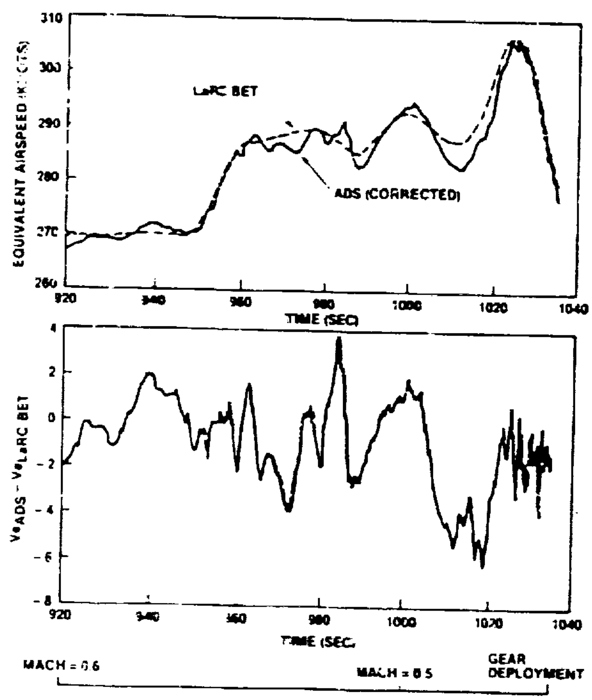

Figure 18.- STS-1 equivalent airspeed comparison - ADS and LaRC BET (including corrections).

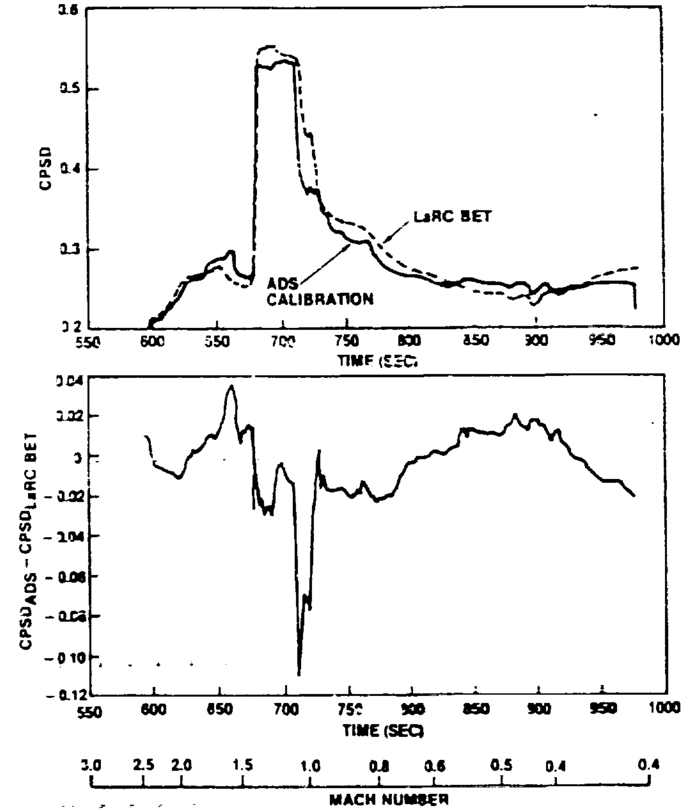

Figure 19.- STS-2 transonic static pressure calibration coefficient comparison - ADS and LaRC BET.

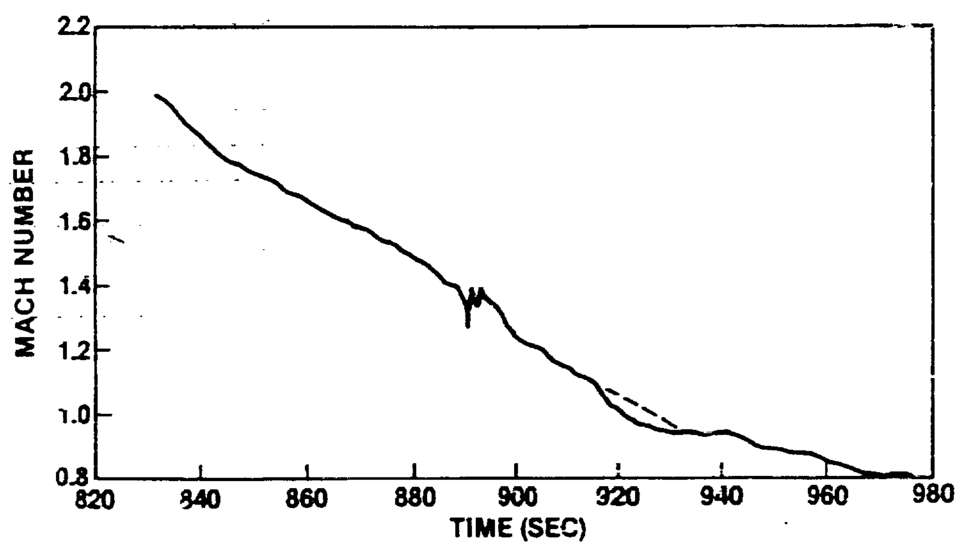

Figure 20.- STS-4 transonic ADS Mach number showing discontinuities.

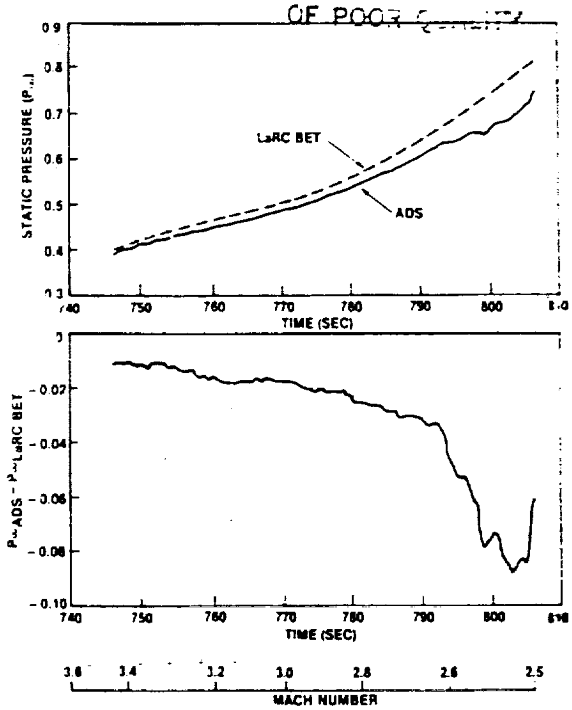

Figure 21.- STS-4 supersonic static pressure comparison - ADS and LaRC BET.

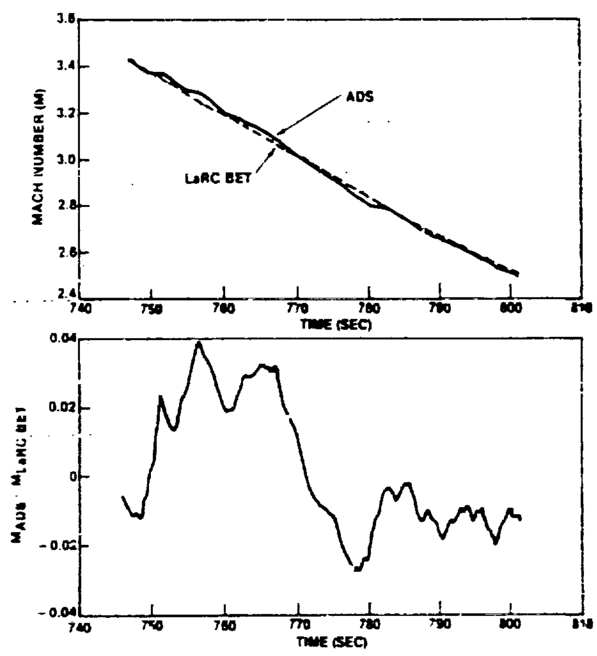

Figure 22.- STS-4 supersonic Mach number comparison - refined ADS and LaRC BET.

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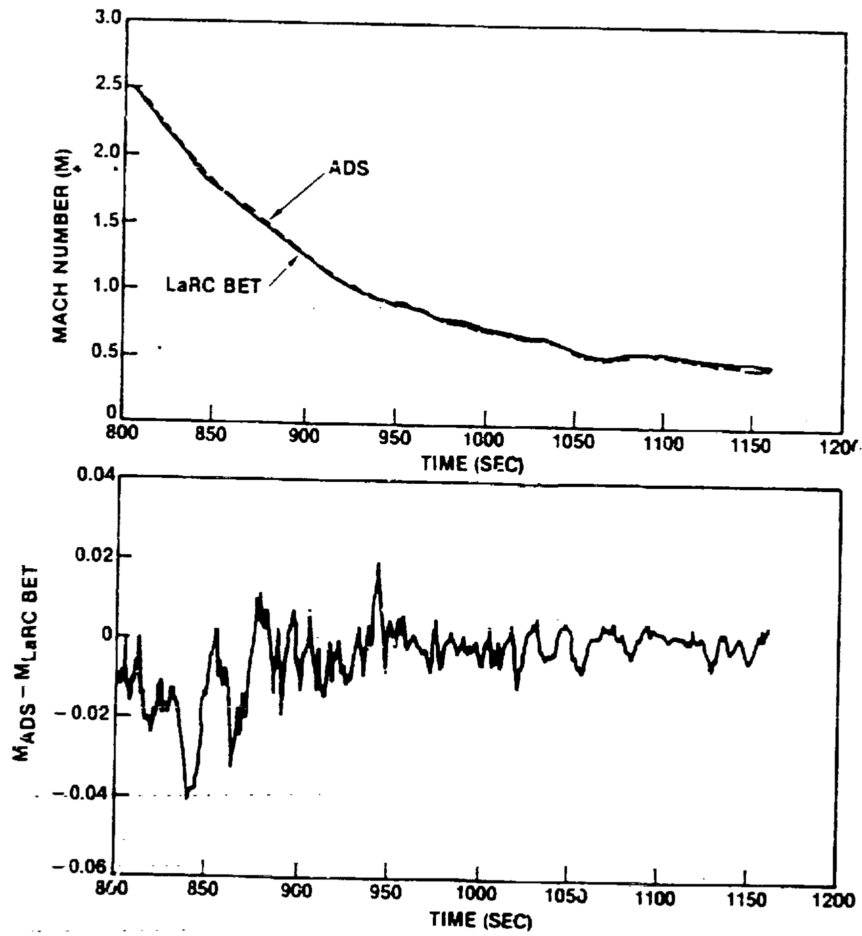

Figure 23.- STS-4 transonic and supersonic Mach number comparison - refined ADS and LaRC BET.