NCAR/TN-313+STR
NCAR TECHNICAL NOTE

July 1988

Position Error Calibration of a Pressure Survey Aircraft Using a Trailing Cone

Edward N. Brown

ATMOSPHERIC TECHNOLOGY DIVISION

NATIONAL CENTER FOR ATMOSPHERIC RESEARCH
BOULDER, COLORADO

TABLE OF CONTENTS

LIST OF FIGURE LEGENDS

ABSTRACT

A review is presented of the trailing cone development and testing, application procedures and the results of position error evaluation over a wide speed and altitude range.

The position error of the NCAR Sabreliner determined by the trailing cone method is different from the error determined from earlier tower flights. Independent comparisons with pacer aircraft confirm the static pressure differences between the two position error functions. D-values during deceleration maneuvers at the pressure survey altitudes indicate the coefficients of the dynamic pressure terms of either correction function are valid and the versatility of the trailing cone method provides sufficient data to indicate the position error has no significant Mach number sensitivity in the medium to high subsonic range.

The uncertainty or the largest expected error in the Sabreliner static pressure measurement after correction for position error is ±0.39 mb.

1. Introduction

The measurement of aircraft static pressure is required primarily for safety of flight for maintaining safe, vertical spacing between flight levels. Also when aircraft are used in pressure survey and meteorological research, the static pressure measurement takes on added importance since it plays an interactive role with other measured and computed variables. Static pressure is generally sensed by a pitot-static tube mounted on the aircraft or by flush or compensated pressure ports installed on the fuselage. In flight the flow field is distorted and in turn the local pressure may be in error at the static source; the magnitude of the error is related to the coefficient of lift (Cl) and is strongly affected as well by the location of the source on the aircraft. Figure 1 illustrates the static pressure distribution along a line on the fuselage of a typical aircraft (DeLeo and Hagen 1966). As is evident from the figure, the tip of the nose and the vicinity of the lifting and stabilizing surfaces are regions of large pressure gradients. The most desirable locations for static source location would clearly be in the general areas of minimum static error indicated by points 1-6. When requirements exist for precise static position corrections to reduce errors to the order of 0.3 mb (0.15 psf), flight test with a trailing cone and pre-flight static comparisons to a primary pressure standard, and dynamic flight evaluation and verification are necessary.

This paper describes the methodology by which the Research Aviation Facility (RAF) calibrated and verified the position error of a North American Sabreliner during the Vertical Separation Standards Program of the Federal Aviation Administration (FAA). A trailing cone assembly was installed on the aircraft periodically to establish a position error data base for survey altitudes up to 12,500 meters.

The trailing cone pressure calibration procedure is recommended by the Society of Automotive Engineers, Inc. (1971). The procedure is also established as an acceptable means of compliance by the International Civil Aviation Organization and has been adopted by major aircraft manufacturers as a flight test practice for certification purposes. Advantages of the trailing cone method have been discussed at length (1, 3, 10, 11), however, it is appropriate to reiterate that the accuracy of the cone calibration is much higher than other methods. The technique is often described as "errorless" as only small errors are associated with the device in wind tunnel evaluations. The technique can be used to provide position error data for the complete flight envelope of an aircraft; the RAF limited the position error flight test and analysis to straight and level coordinated flight in a clean configuration with all non-standard external stores removed.

2. Trailing Cone Development

In 1959, the Douglas Flight Test Group at Edwards Air Force Base developed a novel concept for obtaining a measurement of static pressure with small error for use on an aircraft in flight. Theoretical studies indicated the static pressure field surrounding an aircraft in flight reverts, for all practical purposes, to undisturbed atmospheric pressure within a few wing chord lengths behind an aircraft. It can also be shown that orifices in an infinite-length cylindrical tube at zero angle of attack transmit static pressure without bias; thus an entirely new method for pressure calibration could be made available if a relatively long length of tubing could be stabilized by the drag of a non-lifting body trailed behind the aircraft at a small angle of attack. (3)

Experimental devices incorporating these principles were designed and flight tested with very encouraging results by Douglas Aircraft Company (4), the Royal Aeronautical Establishment (2), the Naval Test Center (5), the Federal Aviation Agency (7), (8), and NASA (6). In the early tests by Douglas 1969 (4), trailing cone calibrations on an Aero Commander, A3, and A4 aircraft indicated the cone error is extremely small and constant over the Mach range of 0.14 to 0.82; the position error for the cone (C_p), shown in Figure 2, is essentially zero which indicates no Mach effect on the position error of the cone assembly. From this data, the cone system error is estimated to be only 0.2 mb at an altitude of 10,600 meters and Mach number 0.73. Barnes (1969) reports, from tower fly-by comparison of the Douglas trailing cone installed on a Meteor aircraft, the error at sea level to be less than ±3 meters for trail lengths greater than 16-18 meters; in further examination of the data the largest error measured at 18 meter extension is about 0.18 mb at 175 m/s.

The Douglas wind tunnel evaluation (10) of the cone position error utilized the "infinite probe" and pitot-static probe methods for relatively low speeds; over the range of 35-75 m/s and trail angles of 2-4 degrees the cone system position error was essentially zero. With tunnel static errors possibly larger than the overall error of the cone system it was recommended to use the more stable tower pressure reference or pacer method for measuring cone bias, and speed or Mach influences.

The RAF undertook a separate wind tunnel study of the angle of attack influences on the cone pressure error; with the cone referenced to a tunnel static the data show no systematic correlation with variations of ±0.05 mb for sleeve angles of ±4 degrees, Figure 3. Such tests provide only relative comparisons as tunnel static pressure errors depend on tunnel speed and are often larger than the errors of the test model. Regardless, the sleeve of the assembly showed no orderly pressure influence for angles of ±4 degrees at speeds of 63 and 102 m/s.

Jordan and Ritchie (6) performed wind tunnel tests to investigate the pressure sensing characteristics of the trailing cone device with the pressure-tube orifices at several locations ahead of the cone. They show the pressure increased slightly but consistently as the distance between the cone and orifices was decreased. The RAF performed a similar evaluation on the Douglas 501 system and the results are similar to those of Jordan, et al., shown in Figure 4. The cone pressure referenced to a tunnel static is shown to be relatively flat when the separation is a maximum; the pressure difference, referenced to the wind tunnel, increases as the separation decreases and as the dynamic pressure increases; the increase with tunnel speed is related to a change in tunnel static pressure. The important feature is the relative flat nature of the curves at the 2 meter cone position; a cone calibration in a wind tunnel requires a special sting apparatus to keep the sleeve-line assembly in the same relative position when varying the angle and an extremely accurate tunnel static pressure reference; these references were not available but the results suggest the particular RAF cone and sleeve assembly, when separated 2 meters, probably operates with negligible bias.

An indication of the flight-to-flight repeatability of the trailing cone method was obtained during Douglas Aircraft flight development (Mabry and Brumby); five calibrations of a DC-9 aircraft are shown in Figure 5. At a typical flight condition of 0.8 Mach at 9,000 meters the repeatability of the cone method appears to be ±8 meters or about ±0.3 mb.

3. Trailing Cone Procedures

In normal use the trailing cone is assumed to be a zero error static pressure source since the cone and tubing assembly is relatively light in weight compared to the drag forces which serve to restrict the local angle of attack to small values. On the Douglas 501 system, in use at the Research Aviation Facility, a symmetrical pattern of pressure orifices are located about 2 meters ahead of the cone apex to avoid its positive pressure influence. It is recognized that in actual practice small errors may arise due to: (1) cone configuration and local angle of attack, (2) the trail distance of the cone assembly, (3) the degree of air turbulence perhaps enhanced by the jet engine wake and (4) the stability of the line and cone.

Due to its length, the trailing cone system has a slightly larger pressure lag than a normal aircraft static system. Unless the cone data is taken in stabilized flight, it is necessary to correct for system time lag which may be several seconds; the evidence from ascent, descent or pitching maneuvers indicates the lag may introduce dynamic errors of the order of ±2.5 mb.

The position calibration procedure, using the trailing cone or tower fly-by method, and practiced by the RAF is defined by several discrete steps:

1. All transducers are calibrated to a common primary pressure standard traceable to the National Bureau of Standards prior to an after a test program.

2. Daily pre-flight checks are referenced to a secondary standard to develop a transducer history.

3. When the cone method is used system leak tests are necessary with the line under a tension load of 50 lbs. Leak rates for 5 minutes are less than 0.1 mb/min for differential pressures of 350 mb.

4. The proper trail distance for the cone is established and repeated for all tests; for all flights, the aircraft test weight was maintained between 15,000-17,000 lbs.

5. Determine the aircraft position error throughout the altitude and speed envelope in stabilized flight.

6. Evaluate the validity of the bias term of the pressure correction by reference to tower fly-by data or pacer aircraft and verify the speed dependent terms with D-value deceleration maneuvers at the higher pressure survey altitudes.

7. Formation intercomparison with similarly calibrated aircraft.

8. Determine the uncertainty in measurement of static pressure from the aircraft using both the trailing cone and tower references.

4. Trail Position

The fixture for deploying the line was mounted on the bottom of the fuselage at station 330 about 6 meters ahead of the tail and extended 0.5 meters below the fuselage. While the tip of the vertical fin is generally considered the best attach point, the fuselage is usually acceptable for cruise flight testing. Verification data discussed later will illustrate the quality of the position error data collected with this installation.

The position of the sleeve and cone in the vertical plane was determined by in-flight photography; the assembly in tow is located just under the contrail formation hopefully in a position not influenced by the jet wake. Observations indicate the line and cone assembly is stable with no oscillation except that which occurs during extension and retraction when about 7-10 meters aft of the aircraft. The cone relative wind angles are small at speeds in excess of 50 m/s; the manufacturer estimates the angles to be less than 2 degrees from which we expect a small bias error.

Trail position behind the aircraft is that length determined when the flaps and gear are retracted, at constant Mach number, for straight and level flight where the pressure field disturbances diminish to zero; this condition occurs when the differential pressure between the aircraft static system and the cone assembly no longer changes as the trail length is increased. The trail length versus pressure measurements shown in Figure 6 where obtained when the assembly was extended between 9 to 48 meters aft of the tail at Mach number of 0.4 at 3,000 meters altitude. The criteria for a constant pressure error is satisfied at between 15 - 18 meters. It is interesting to note the ratio of trail length to wing span is about 1.27 which is consistent with the manufacturers recommended practice (11).

The trail length is important in terms of possible corrections for longitudinal accelerations of the air column enclosed by the tubing. The aircraft may be accelerated or decelerated to obtain position error verification data. A pressure change that will occur due to accelerations is given by:

$$P\ (\text{dynes/cm}^2) = (dv/dt)*0.34838(p/T)*L$$

where dv/dt is the acceleration rate, p and T correspond to the flight level conditions and L is the total line length. A particular case involved slowing from 145 to 70 m/s in 2.5 minutes at 7,000 meters (355 mb) followed by an acceleration; the computed compressional change due to the deceleration is only 0.055 mb which agrees well with the measured difference value of 0.1 mb for the complete maneuver. For the Sabreliner trail lengths a correction is not required for deceleration maneuvers referred to in section (f).

5. Sabreliner Position Error Calibration

The first position error tests on the NCAR Sabreliner were performed during 1969-70 using the tower fly-by method and are periodically checked by the same procedure; the position error so determined was limited to a Mach range of 0.35-0.5 and has been applied as a general solution for all speeds and altitudes through a dynamic pressure relationship, Figure 7. The tower derived function was based upon some 94 tower passes which closely grouped the data at three speeds corresponding to dynamic pressures of 34, 63 and 100 mb. The available statistics indicate the standard deviation of the position error measurements ranged between 0.54 and 0.86 mb suggesting scatter considerably larger than an acceptable value. In view of hardware compensation of the static orifices built into the aircraft, the magnitude of the remaining error is of major concern. A pressure survey at 12,000 meters and dynamic pressure of about 100 mb the uncorrected altitude error would be about 135 meters and a related airspeed error of +3 m/s. Clearly neither error is acceptable; a pressure survey aircraft requires the total pressure error to be less than 0.5 mb or an altitude accuracy of 15-20 meters at the high altitudes while a valid true airspeed is an equally demanding requirement for air motion research.

In view of the magnitude of the error and the observed scatter in the tower data a trailing cone program was instituted to develop an independent data set.

Trailing cone test flights were conducted to develop the general solution to the pressure correction function under conditions which closely represent the research flight conditions and Mach numbers of a high altitude pressure survey program; we would like the function to apply over a wide weight range, although the test gross weight was in the range of 15,000-17,000 lbs, and as well for a wide speed range. Limiting conditions applied for all tests: (1) no flight below 70 m/s and, (2) the tests were limited to straight and level coordinated flight with gear and flaps retracted; perhaps the most basic case. To develop a more general correction function that would be applicable for maneuvering flight would require a more extensive program.

Constant speed, straight and level legs were flown at various altitudes for periods of 1-3 minutes and form the basis of the cone measured pressure error. During the period 1984-87, four sets were flown totaling 68 legs over a Mach range of 0.4-0.74 between altitudes of 4,500 and 12,000 meters. The position error derived by the cone, shown in Figure 7 is larger than the tower fly-by error by about 0.5-0.6 mb for the operational dynamic pressures; the expected scatter in cone data of 0.2 mb found by Mabry and Brumby is evident; however, there is no evidence of an orderly or systematic change in the cone derived position error based on the yearly test results to suggest a significant change in the error during the pressure survey period 1984-87.

6. Pressure Correction Verification

As argued earlier, most users of the cone for pressure calibration suggest the inherent errors of the method to be very small or non-existent; when properly handled and deployed behind the aircraft the trailing cone pressure has been shown to have an error of about 0.2 mb (9), (3), (2), and (11). Just how well do the pressure corrections perform on the Sabreliner and how does it compare with pacer aircraft? The RAF has developed several routines and independent evaluation procedures that provide a basis for judging the quality of the correction functions.

(1) Daily pre-flight pressure values are recorded during the test period which are referenced to a secondary pressure standard; this is necessary to insure transducer-recording system conformity.

(2) Pre- and post-program calibration of all transducers over the full dynamic range traceable to a secondary pressure standard. This step is extremely important to remove small biases that affect similar state-of-the art transducers differently.

(3) A small sample statistic for reviewing the correction functions is available from tower fly-by comparisons; during 1984 a positive cone bias of 0.3 mb was observed and a value of less than 0.1 mb in 1987 which are in close agreement with referenced accuracies. Similarly during 1986 and 1987 the original tower position error indicated undercorrection by 0.1-0.5 mb for dynamic pressures of 50-75 mb. Adjustments have not been made for these differences.

From the evidence it is concluded the two position error functions were properly derived within the RAF experimental measurement capability of each period in question. The tower fly-by data of the 1969-70 era was derived from a completely different hardware configuration than the Airborne Data System (ADS) in use presently with Rosemount 1501 and 1221 transducers and trailing cone assembly. Without an uncertainty analysis applicable to the 1969-70 era, significance cannot be attached to elemental errors that might explain the 0.5-0.6 mb difference between the two position error functions shown in Figure 7.

(4) General principles of measurement uncertainty analysis have been applied to objectively describe the error in the Sabreliner static pressure measurement with the current sensing and recording systems (APPENDIX A). The largest error expected using tower fly-by procedures is ±0.777 mb; using the trailing cone reference the uncertainty of the static pressure system is ±0.396 mb.

(5) A static pressure verification by formation intercomparison was limited to low speeds and altitudes with the RAF King Air

312D. Two levels were flown on separate days in close formation for two minute periods; the results clearly indicate the much used tower fly-by derived function for the Sabreliner under-corrects 0.5-0.7 mb.

TABLE 1
FORMATION INTERCOMPARISON
N307D/N312D

DATE	A/C	SN 1501	PSFDC	PSFD+DPSF
21/9/86	312D	36	695.74	695.90
	307D	29	695.03	695.68
DIFFERENCE (312D-307D)			0.71	0.22
25/9/86	312D	36	376.29	376.35
	307D	29	375.55	376.32
DIFFERENCE (312D-307D)			0.74	0.03

Pressure Units in Millibars

(PSFD is the mean measured fuselage pressure referenced to the RAF secondary pressure standard, PSFDC is the mean pressure after correction by the tower fly-by function for 307D while a cone derived function of angle of attack and Mach number was used for 312D data. DPSF is the position error simultaneously measured on each aircraft by a Douglas 501 trailing cone system.)

The data sets were reduced and independently corrected and of course calibrated to the same secondary pressure standard that is annually referenced to the National Bureau of Standards.

Knowlton (12) reports the measurement uncertainty of the King Air system to be ±0.39 mb, as noted earlier, an analysis yields the same calculated uncertainty values for the Sabreliner. The difference between the aircraft of 0.7 mb suggests that a bias error exists that is unaccounted for and which is not present in either uncertainty analyses. In view of the dedicated and extensive efforts to provide the best available pressure measurements and the quantity of data, some 4 minutes from two sorties, it is suggested the difference of 0.7 mb is significant and reflects a systematic distinction between the two position correction functions.

(6) The D-value (Dv) defined by the difference between the aircraft geometric and pressure altitudes provides a data set for evaluation of the coefficients of the dynamic pressure terms of the correction for all speeds and altitudes. Significance is

attached to the slope of this conservative parameter when radar altitude is held fairly constant during a deceleration maneuver performed in the upper levels of the troposphere where the Dv is characterized by relatively flat vertical and horizontal gradients. During the maneuver (Figure 8) the Dv horizontal gradients ranged 0.2-0.3 m/n mi while the vertical gradients were of the order of 0.05 m/m; under these conditions the slope of the Dv curve during the deceleration result from the aircraft position error influence. The meteorological gradients influence the Dv about 2-3 meters when the deceleration maneuver is flown in 60 seconds and transverses about 4 n mi; with a position error variation of several millibars, the slope of Dv/dt is largely determined by the aircraft systems and insignificantly by the meteorological gradients. The sensitivity of the test is given by the hydrostatic equation; at an altitude of 12,000 meters, d(Dv)/dp = 35m/mb.

The high altitude APN-159 radar altimeter used in these tests operates within ±18 degrees of pitch and is characterized by short term signal variation (fine synchro variation) of only ±1.87 meters (13); the overall system accuracy of 3 meters is not a factor since we are concerned with relative measurements. The estimated error in Dv determined with this system is ±6 meters; at 12,000 meters this is equivalent to ±0.16 mb.

During the maneuver the position error is imposed upon the static pressure measurement; to illustrate the effect, two computations of Dv are shown in Figure 8, DVALU with the cone derived position correction and DVALUF without any correction. In evaluating the pressure correction polynomial, the coefficients are valid when Dv is constant during the maneuver as is true with the DVALU curve where the variation is ±4 meters; the variation of pressure error with speed provides a DVALUF curve with end points separated by 46 meters. The Mach range of the test was 0.59-0.75 which spans the operational speed envelope at 12,800 meters.

Often fuselage source errors vary in the same general way as errors of a static pressure tube installation in the high subsonic speed range by exhibiting a Mach number sensitivity. Examining the Mach number sensitivity in detail, data points were selected for a dynamic pressure range of 84-89 mb and altitude range of 5,800-12,000 meters; this data shown in Figure 9 clearly demonstrates the error is insensitive to the static pressure level or Mach number between 0.48-0.74. This evidence is consistent and supportive of the results of the Dv deceleration maneuver.

7. Conclusions

1. There is strong evidence from the small variability of the trailing cone data to suggest the aircraft position error did not significantly change over the period 1984-87.

2. The formation intercomparison of 312D/307D at relatively low speeds indicates the tower fly-by function undercorrects position error about 0.5-0.6 mb.

3. An uncertainty analysis is not available for the 1969-70 era, therefore speculation is not offered relative to the 0.5-0.6 mb difference between the two methods of determining the position error.

4. The uncertainty, or the largest expected error, in the Sabreliner static pressure measurement after correction with the trailing cone function is ±0.408 mb.

5. The Dv maneuver indicates the coefficients or speed terms in either position error are valid for the speed range flown; also, Mach number sensitivity of the Sabreliner position error is insignificant up to 0.74.

6. A number of citations refer to the quality of trailing cone measurements when it is used properly; a typical error is ±0.2 mb and this analysis presents no clear evidence to suggest the error is larger.

7. In view of the quality of the verification tests of the trailing cone data it is recommended this function be utilized for correction purposes and the cone become the standard method for position error studies in the future.

8. Acknowledgments

The Research Aviation Facility is indebted to Mr. Brian Colamosca of the Federal Aviation Administration Technical Center for providing the Sabreliner flight hours and funding for the evaluation tests; the general advice of Mr. Dennis Knowlton in the wind tunnel testing was extremely practical and his interest in the project highly regarded. As well, I appreciate the punctual efforts of the Instrumentation Group, in particular Mr. M.N. Zrubek, for his timely efforts in preparation of the aircraft.

9. References

DeLeo, R.V., and F.W. Hagen, 1966: Flight calibration of aircraft static pressure systems. Armed Services Technical Information Agency Publication AD 650146, 200 pp.

Barnes, C.S., 1969: Flight assessment of a Douglas trailing cone static pressure probe at subsonic speeds. Royal Aircraft Establishment, Technical Report 69139.

Ikhtiari, P.A., and V.G. Marth, 1964: Trailing cone static pressure measurement device. Journal of Aircraft, Vol.1, No.3 March 1964.

Cook, J.L., 1969: FAA Certification Test Results of the DC-8 Production Trailing Cone Kit, Douglas Aircraft Company. Development Report 67, 5 May 1969.

Mickle, D.A and J.L. Holcomb, 1965: Trailing Cone Method of Measuring Static Source Position Error (F-4B Airplanes), Naval Air Test Center. AD 462821L.

Jordan F.L. and V.S. Ritchie, 1973: Subsonic Wind-Tunnel Tests of a Trailing Cone Device for Calibrating Aircraft Static Pressure Systems. NASA TN 83217.

Russell, W.M. 1966: Trailing Cone Tests in Large Turbojet. Federal Aviation Agency, Report No. 66-58-15.

Schrager, J.J., 1964: Test of Trail Cone System to Calibrate Static Ports for Barometric Altimeters, Federal Aviation Agency Atlantic City, New Jersey Report No. RD-64-156.

Flight Test Procedure for Static Pressure Systems Installed in Subsonic Transport Aircraft. S.A.E. Aerospace Recommended Practice 921. Issued July 15, 1971.

Douglas Trailing Cone System-Low Speed Wind Tunnel Calibration, Douglas Aircraft Co. Inc. Technical Memorandum GEN-4199, August 1967.

Trailing Cone Systems Applications, Douglas Aircraft Company Flight Development. TM-GEN-4158, 1967.

Knowlton, Dennis, 1987: Measurement Uncertainty Analysis. Sixth Symposium of Meteorological Observations and Instrumentation, pp. 368-371, Jan. 12-16 1987, New Orleans La.

Brown, E.N., M.A. Shapiro, P.J. Kennedy and C.A. Friehe, 1981: The Application of Airborne Radar Altimetry to the

Measurement of Height and Slope of Isobaric Surfaces. Journal of Applied Meteorology, Vol.20,No.9,pg.1070-1075.

Mabry, G.C. and R.E. Brumby, 1968: DC-8 Airspeed Static Position Error Repeatability, Douglas Paper 5517, Douglas Aircraft Co.

Abernathy, R.B., et. al., Instrument Society of America Measurement Uncertainty Handbook, ISBN: 87664-483 Revised 1980.

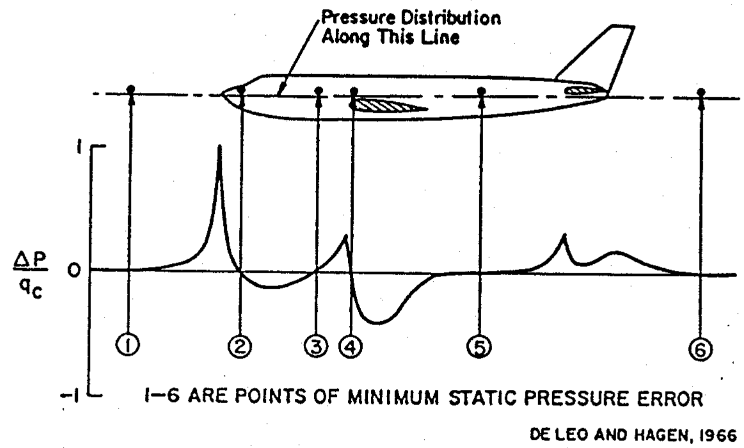

Fig. 1. Typical subsonic static pressure distribution on an aircraft fuselage. Numbers 1 through 6 indicate points of minimum static pressure error. The position error is the ratio of the static error to the dynamic pressure.

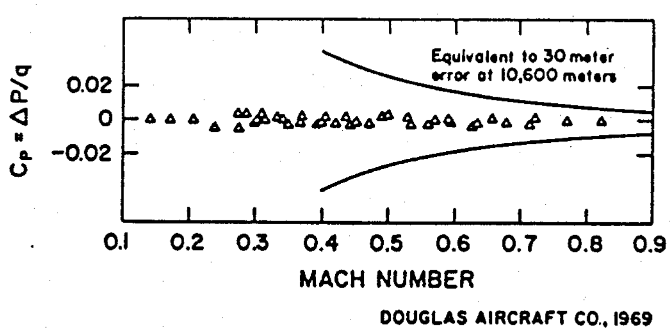

Fig. 2. Trailing cone position error based upon the Douglas Aircraft Company tower tests.

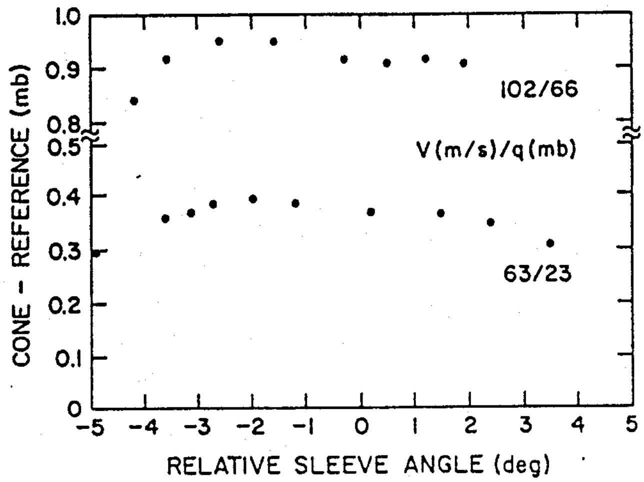

Fig. 3. Trailing cone static referenced to tunnel static versus sleeve angle relative to the tunnel.

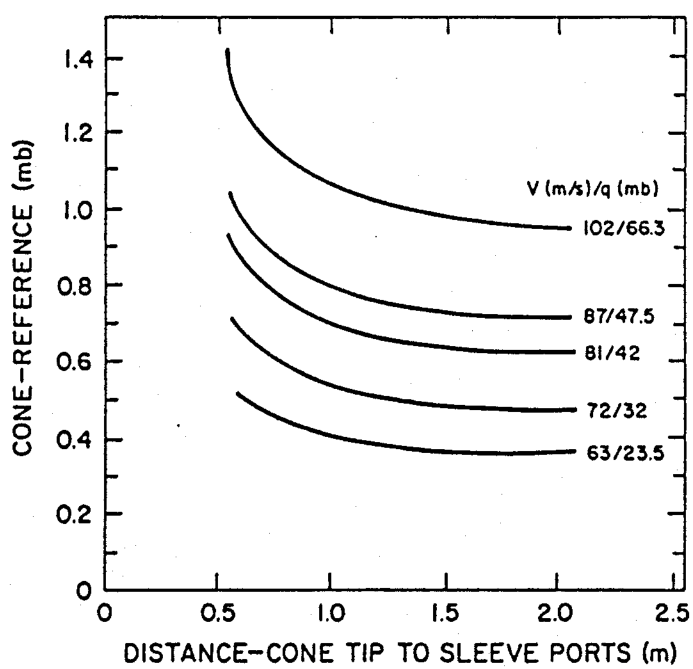

Fig. 4. Trailing cone static referenced to the tunnel static versus the distance between the sleeve and the cone for 5 speeds.

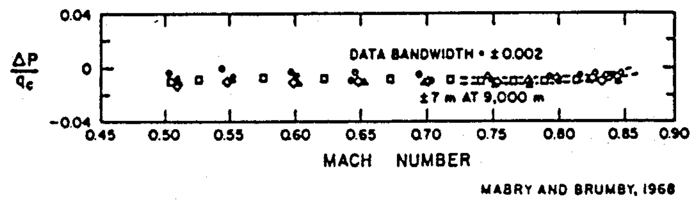

Fig. 5. Repeatability of the trailing cone calibration method as determined by multiple calibrations of the same aircraft (DC-9).

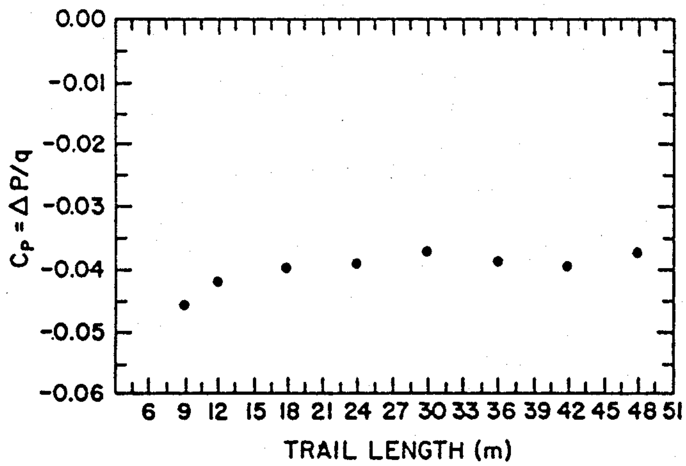

Fig. 6. The Sabreliner research static pressure referenced to the cone assembly as a function of trail length.

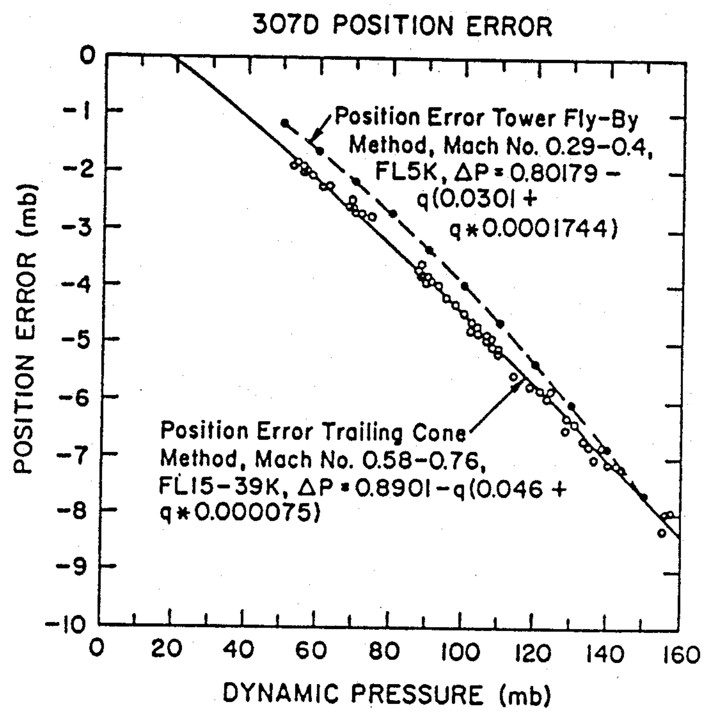

Fig. 7. The Sabreliner position error in millibars as a function of uncorrected dynamic pressure (QCF) determined by the tower fly-by (94 passes) and trailing cone methods. The plotted cone data are mean values from 68 periods 1-3 minutes duration taken over a Mach number range of 0.4-0.74 during the 1984-87 time period while the plotted tower points are computed values.

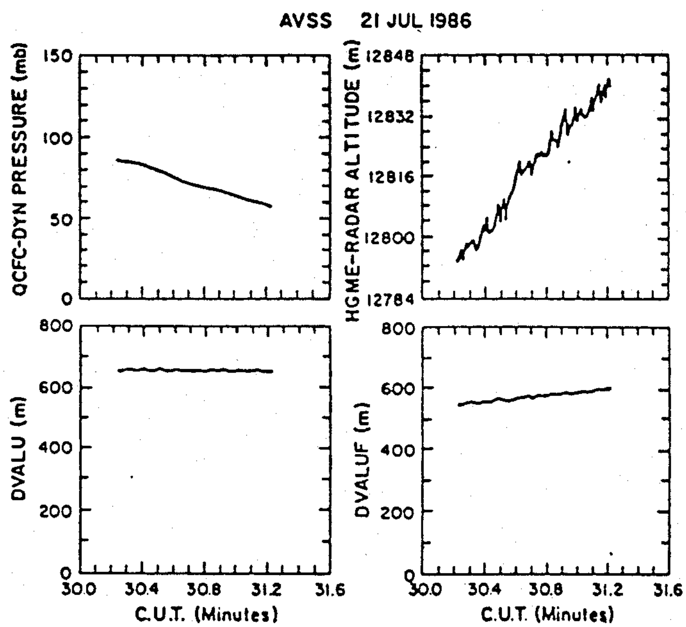

Fig. 8. The Dv Maneuver data from 21 July 1985 performed at 11,280 meters (40,000 feet). The top plots show the dynamic pressure (QCFC) and the radar altitude (HGME). The plot labeled DVALUR shows Dv computed with no pressure correction, while in the DVALU plot the pressure correction shown in Figure 6 was applied to static pressure used in the computation of pressure altitude.

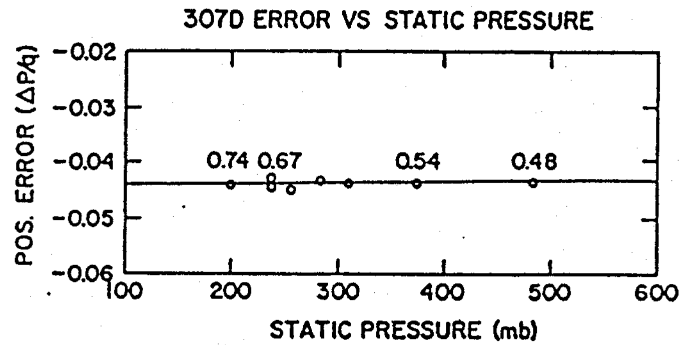

Fig. 9. Sabreliner error (mb) versus flight level static pressure (mb) for a limited dynamic pressure range of 84-89 mb. The Mach number is noted for several of the points. (Each point represents the average value from 60 measurements.)

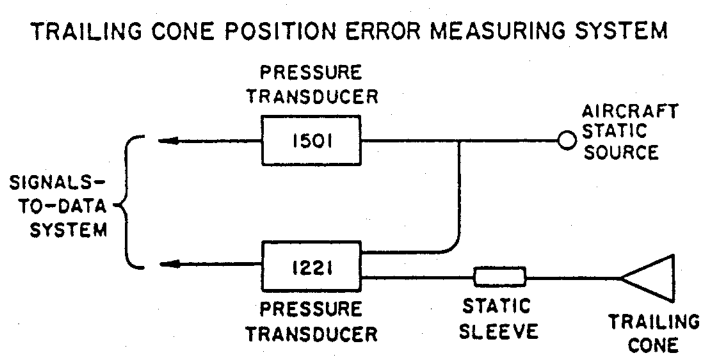

Fig. 10. Schematic of the trailing cone position error system.

APPENDIX A

STATIC PRESSURE UNCERTAINTY ANALYSIS FOR THE NCAR SABRELINER

An uncertainty analysis using the methodology of Abernathy et. al. (15) documents the elemental bias (B) and precision (S) errors at the 95% confidence level of the calibration, data acquisition and data reduction variables that are related to determining the uncertainty of the static pressure measurement of the Sabreliner using a trailing cone (B) and also by referencing the absolute pressure to a tower standard (APPENDIX C).

The sensor elemental errors follow closely the manufacturer's published specifications; the elemental error pertaining to the trailing cone is traceable to the experiential results described earlier while the tower uncertainty is a separate analysis of the errors as they are now understood. The uncertainty value is clearly dependent on present hardware and test procedures; as better estimates become available they will be integrated into the following formats. (N=sample size)

Pressure Calibration	B	2S	N
1. Accuracy of dead weight standard	.1	.1	>30
2. Dead weight standard resolution		.01	>30
3. 1501MD2 static accuracy	.1	.1	>30
4. 1501MD2 dynamic accuracy		.01	>30
5. 1501MD2 stability		.09	
6. 1501MD2 resolution		.03	>30
7. 1501MD2 height uncertainty	.015		
8. A/C 1501 static accuracy	.1	.1	>30
9. A/C 1501 dynamic accuracy		.01	>30
10. A/C 1501 stability		.09	
11. A/C 1501 resolution		.03	>30
12. A/C 1501 height uncertainty	.04		
13. A/C calibration setup		.1	
14. A/C data system			neg.

(Errors 3-7 refer to the transfer standard)

Aircraft Data Acquisition	B	2S	N
15. A/C 1501 dynamic accuracy		.1	>30
16. A/C 1501 data system digital channel		neg.	
17. Pressure leaks in cabin		neg.	

Data Processing

18.	Truncation		neg.	
19.	Trailing cone method uncertainty	.18	.158	>30
20.	Tower fly-by method uncertainty	0.26	.289	>30
21.	Function errors due dynamic pressure		neg.	

Uncertainty of Sabreliner pressure measurements:

Trailing cone method: B=0.253, 2S=0.305

$$U_{95} = (B^2 + 2S^2)^{1/2} = 0.396 \text{ mb}$$

Tower fly-by method : B=0.464, 2S=0.399

$$U_{95} = 0.777 \text{ mb}$$

APPENDIX B

UNCERTAINTY ANALYSIS OF

AIRCRAFT POSITION ERROR USING A TRAILING CONE

Elemental errors associated with the calibration, data acquisition and data processing of trailing cone measurements. Elemental bias (B), precision errors (S) and sample size (N). Figure 10 illustrates the trailing cone system.

	Pressure Calibration	B	2S	N
1.	Accuracy of the dead weight standard	.1	.1	>30
2.	Dead weight standard resolution		.01	>30
3.	A/C calibration setup	.1		
4.	A/C data system		neg.	
5.	Rosemount 1221 static accuracy		.008	>30
6.	" 1221 resolution		neg.	
7.	" 1221 stability		.03	>30
8.	" 1221 linearity		.02	>30
9.	" 1221 repeatability		.004	>30
10.	Power supply variation		.06	>30
	Acquisition of Test Data			
11.	Dynamic effects of cone	.1		
12.	Dynamic effects of angle of attack	.05		
13.	Compressional change due to acceleration		neg.	
14.	Pressure leaks in cabin		neg.	
15.	Rosemount 1221 dynamic accuracy		.08	>30
16.	" 1221 (dT/dt)		.02	>30
17.	" 1221 acceleration		.002	>30
18.	" 1221 electrical noise		.002	>30
19.	" 1221 data system analog channel	.002	.002	>30
	Data Processing			
20.	Truncation		neg.	

B=0.180, 2S=0.158

Uncertainty of differential pressure measurements between the aircraft system and trailing cone reference, i.e., the uncertainty of the aircraft position error.

$$U_{95} = (B^2 + 2S^2)^{.5} = (.0325 + .02829)^{.5} = 0.24 \text{ mb}$$

The uncertainty of ±0.24 mb applies to coordinated, straight and level flight at constant speed. The analysis is a general solution for all Research Aviation Facility trailing cone applications beginning in 1984 and will remain valid until a major elemental change occurs with either the calibration or acquisition systems.

APPENDIX C

UNCERTAINTY ANALYSIS OF THE POSITION ERROR BY THE TOWER METHOD

Calibration

		B	2S	N
1.	Dead weight standard accuracy	.1	.1	>30
2.	Dead weight resolution		.01	>30
3.	Calibration set up leaks		neg.	
4.	Calibration height uncertainty	.015		
5.	A/C 1501 static accuracy	.1	.1	>30
6.	A/C 1501 dynamic accuracy (laboratory)		.01	>30
7.	A/C 1501 stability		.09	>30
8.	A/C 1501 resolution		.03	>30
9.	A/C 1501 height uncertainty	.04		
10.	A/C calibration setup		.1	
11.	A/C data system			neg.
12.	Tower 1501 static accuracy		.1	
13.	Tower 1501 dynamic accuracy		.01	>30
14.	Tower 1501 stability		.09	>30
15.	Tower 1501 resolution		.03	>30
16.	Tower 1501 calibration setup	.015		

Data Acquisition

17.	Static defect of the tower conditions	.1		
18.	Aircraft height uncertainty	.16	.16	>30
19.	Pressure spatial variability		neg.	
20.	Tower operator error		neg.	
21.	Time lag	.1		

Data Processing

22.	Truncation		neg.	

B=0.260, 2S=0.289

Tower position error uncertainty, $U_{95} = (B^2 + 2S^2)^{.5} = 0.389$ mb.

In support of the above analysis each elemental source is discussed for reference even if the error is declared negligible. Many errors repeat in the three appendices, for brevity the discussions follow in order.

APPENDIX A

ELEMENTAL ERROR DISCUSSION

Calibration

1. Dead weight standard accuracy is noted by Bell and Howell to be ±.015% of reading, at 1,000 mb 3σ=.15 mb therefore 2S =.1 mb. Experience with the unit, recertification every five years and intercomparison with other standards suggest a bias of 0.1 mb is appropriate.

2. Dead weight resolution is certified by the weight resolution of .002% of reading or .01 mb.

3. The tower and laboratory transfer standard is a Rosemount 1501MD2; the specified accuracy is a 3 σ value of .026% full scale and includes linearity, hysteresis, temperature and calibration influences. In the laboratory, and to a lesser degree with tower use, a limited temperature range is encountered; also with extended comparison to the standard, the manufacturer's uncertainty of 0.26 mb is reduced to a bias of 0.1 mb and a precision of 0.1 mb.

4. Transfer standard dynamic accuracy includes vibration, acceleration, over pressure and power supply variation. The specified 3 σ value is 0.2 mb. The dynamic influences are expected to be small in our laboratory application; therefore an assumed error of 10% of the specified is .01 mb.

5. Stability is specified to be .025% full scale/year. Frequent calibration prior to and after test programs verifies confidence in a bias of .09 mb.

6. Transfer standard resolution is .03 mb.

7. Height variations of less than 0.2 meters between the standard and transfer unit yield a maximum bias error of .015 mb.

8-11. The Rosemount 1501 installed on the aircraft has similar errors noted above in 3-6.

12. Aircraft height uncertainty of approximately .5 meters is a systematic error of .04 mb.

13. Aircraft setup; a line 35 meters in length connects the two units for calibration and requires 0.1 seconds for pressure stabilization to 99%. Settling periods are part of the procedure but the line bias uncertainty is estimated to about 0.1 mb.

14. Reference to the Aircraft Data System (ADS) specifications indicates negligible uncertainty.

Data Acquisition

15. The aircraft 1501 dynamic accuracy is specified as 0.14 mb for the 2 σ confidence level.

16. ADS specifications indicate no significant uncertainty for digital channels.

17. Cabin pressure leaks are maintained below 1 mb per 5 minutes at a differential of 350 mb and as such have no significant effect.

Data Processing

18. Calculations are made on 32 bit floating point computers so round-off errors are negligible compared to 14 bit encoding.

19. Position error uncertainty references APPENDIX B when using the trailing cone method. This cone system repeatability determined from flight test procedures of Mabry and Brumby indicate a typical value of 0.3 mb; these results are excellent in view of the different transducers and data systems in use.

20. Position error uncertainty using the tower results references APPENDIX C.

21. The position correction has the form:

$$PCOR = a_0 = a_1*q + a_2*q^2$$

where q may range between 60-100 mb; dynamic pressure errors of the order of the uncertainties noted will influence the correction equal to the product $U*a_1$; as a_1 is typically .03-.04 the systematic contribution is considered negligible.

APPENDIX B

ELEMENTAL ERROR DISCUSSION

Calibration

1-2. Refer to 1 and 2, APPENDIX A
3. Refer to 13, APPENDIX A
4. Refer to 14, APPENDIX A
5-10. Rosemount 1221 static accuracy, resolution, stability, linearity, repeatability and power supply variation uncertainties are manufacturers specifications. Data Sheet 2442.

Data Acquisition

11-12. Wind tunnel tests of the cone position relative to the pressure sensing sleeve suggest a bias error of 0.1 mb; tests for angle of attack bias suggest a value of .05 mb for angles ±4 degrees which are not exceeded in straight and level flight.

13. Compressional effects in the tubing of the trailing cone are calculated to be negligible for small accelerations encountered in straight and level flight.

5-18. Rosemount dynamic accuracy is specified in data sheet 2305.

19. ADS analog channel uncertainty B = .012% full scale = .002 mb, 2S = .011% full scale = .002 mb.

Data Processing

20. Refer to 12-18, APPENDIX A

APPENDIX C

ELEMENTAL ERROR DISCUSSION

Calibration

1-2. Refer to 1 and 2, APPENDIX A

3. Leaks are considered to have negligible effects since the calibration range is typically 50 mb.

4. Refer to 2, APPENDIX A

5. Refer to 8, APPENDIX A

6. Refer to 9, APPENDIX A

7. Refer to 10, APPENDIX A

8. Refer to 11, APPENDIX A

9. Refer to 12, APPENDIX A

10. Refer to 13, APPENDIX A

11. Refer to 14, APPENDIX A

12. Refer to 8, APPENDIX A

13. Refer to 9, APPENDIX A

14. Refer to 10, APPENDIX A

15. Refer to 11, APPENDIX A

16. Refer to 7, APPENDIX A

Data Acquisition

17. The influence of calm to light wind conditions on the tower is entirely a judgement with a bias value of 0.1 mb; we recognize that without a quality static source this error may be judged to be larger in light wind fields.

18. Aircraft height is estimated for each pass although photographic verification indicates the estimates are valid to ± 1.5 meters. This is interpreted as both a systematic and a precision error of value 0.16 mb.

19. The aircraft separation with the tower is variable and may be as large as several hundred meters; horizontal atmospheric pressure gradients therefore have no significant error influence.

20. We assume the tower data logging by the observer is without error in recording digital by hand.

21. Time lag is important if the aircraft is changing altitude as it approaches the tower, a height change of 1.5 meters corresponds to 0.16 mb. An estimate dictates a bias of at least 0.1 mb and when altitude is changing rapidly the data set is not used.

Data Processing

22. Refer to 18, APPENDIX A