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RE-61

Final Report - Survey and Preliminary Evaluation of Barometric Altimetry Techniques

October, 2, 1969

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS
Measurement Systems Laboratory

CAMBRIDGE, MASSACHUSETTS 02139

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Final Report - Survey and Preliminary Evaluation of Barometric Altimetry Techniques

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Contract NAS 12-2016
Electronics Research Center, NASA
M.I.T. DSR Project 71191

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I Introduction

This report summarizes a brief survey of the state-of-the-art of barometric altimetry with emphasis on the problems concerning vertical separation of aircraft. Consideration of the terminal phase of flight is omitted because the future role of barometric altimetry during this phase is questionable. Research on landing aids is centered principally on automated radiation systems for use under low visibility conditions.

The quality of separation is affected by the position error for each aircraft, the altimeter error and the flight technical error. Position error results from incorrect sensing of static ports. The pressure error is approximately a fixed fraction of the ambient static pressure. Since small altitude errors are almost linearly related to the percentage pressure error $\frac{\Delta p}{p}$, position error is generally quoted directly as an altitude error. The altimeter error embodies all errors involved in transferring the measured pressure to an altitude display and includes both fixed and variable errors associated with the instrument. The inability of the pilot or autopilot to maintain the assigned flight level, indicated on the altimeter system display, is termed flight technical error. It is not a part of the altimeter system error and is discussed in this paper only in view of its relative importance to the total separation error.

Altimeter system error depends to a large degree upon calibration techniques and schedules. Therefore, pressure sensors, altimeters (or pressure transducers); and calibration methods and regulations are discussed separately.

In the chapter on altimeters, a new design concept for the instrument is introduced. Development of such an altimeter could provide either better performance at low cost or higher accuracy over an extended altitude range.

The influence of nonstandard atmospheric condition on vertical separation also is considered although it is not of major significance. Finally, the status of barometric altimetry is summarized and the areas requiring the greatest effort for its improvement are outlined.

The Federal Aviation Regulations governing aircraft separations specify acceptable flight levels for IFR and VFR operations. The following table summarizes these rules in concise form. Normal separations are 1000 feet at altitudes below 29,000 feet and 2000 feet above this level for VFR or IFR operations. However in mixed IFR/VFR traffic, separations can be 500 feet and 1000 feet below and above FL290 respectively.

	VFR flight levels		IFR flight levels	
Heading	0°-179°	180°-359°	0°-179°	180°-359°
Altitude ~ft. <18,000	odd thou. +500'	even thou. +500'	odd thou.	even thou.
18,000 to 29,000	odd FL+500'	even FL+ 500"	odd FL	even FL
>29,000	FL300,340, 380,...	FL320,360 400,...	FL290, 330,370...	FL 310, 350,390...

Table 1 FAR Flight Levels

II Static Pressure Sensors

Two types of sensors are common to static pressure installations. The most prevalent is the flush static port located on the side of the fuselage. These are generally the simplest and cheapest to install. A more accurate and somewhat more complex sensor is the static pressure probe which extends from the nose, wing or tail of the aircraft, or is mounted on a pylon along the fuselage, away from the local pressure field influenced by skin perturbations. Details of the various probes are considered in this chapter including aerodynamic compensation for the fuselage-induced pressure field in which the probe is located.

A. Flush Ports

The choice of location of flush static ports depends upon the pressure field distribution over the fuselage. In general the field varies both positively and negatively from the free stream static pressure as indicated by Figure 1 (extracted from ref 1). Points 2, 3 and 5 are commonly chosen as locations for flush ports. Efforts also are made to reduce the sensitivity to angle of attack. Points corresponding to 2, 3 and 5 and lying about 40° on either side of the bottom centerline serve to minimize the static pressure errors caused by variations of the pressure field with angle of attack. The exact position to be used is found experimentally.

The principal source for error stems from differences in skin contours between the calibrated aircraft and subsequent production models. The port location is generally determined in wind tunnel tests and verified on the prototype and perhaps one or two production models by calibration with ground tracking facilities or by a trailing cone system.(15) Manufacturing tolerances lead to small variations in fuselage shapes while aging effects and stress patterns established in flight tend to alter local skin contours.

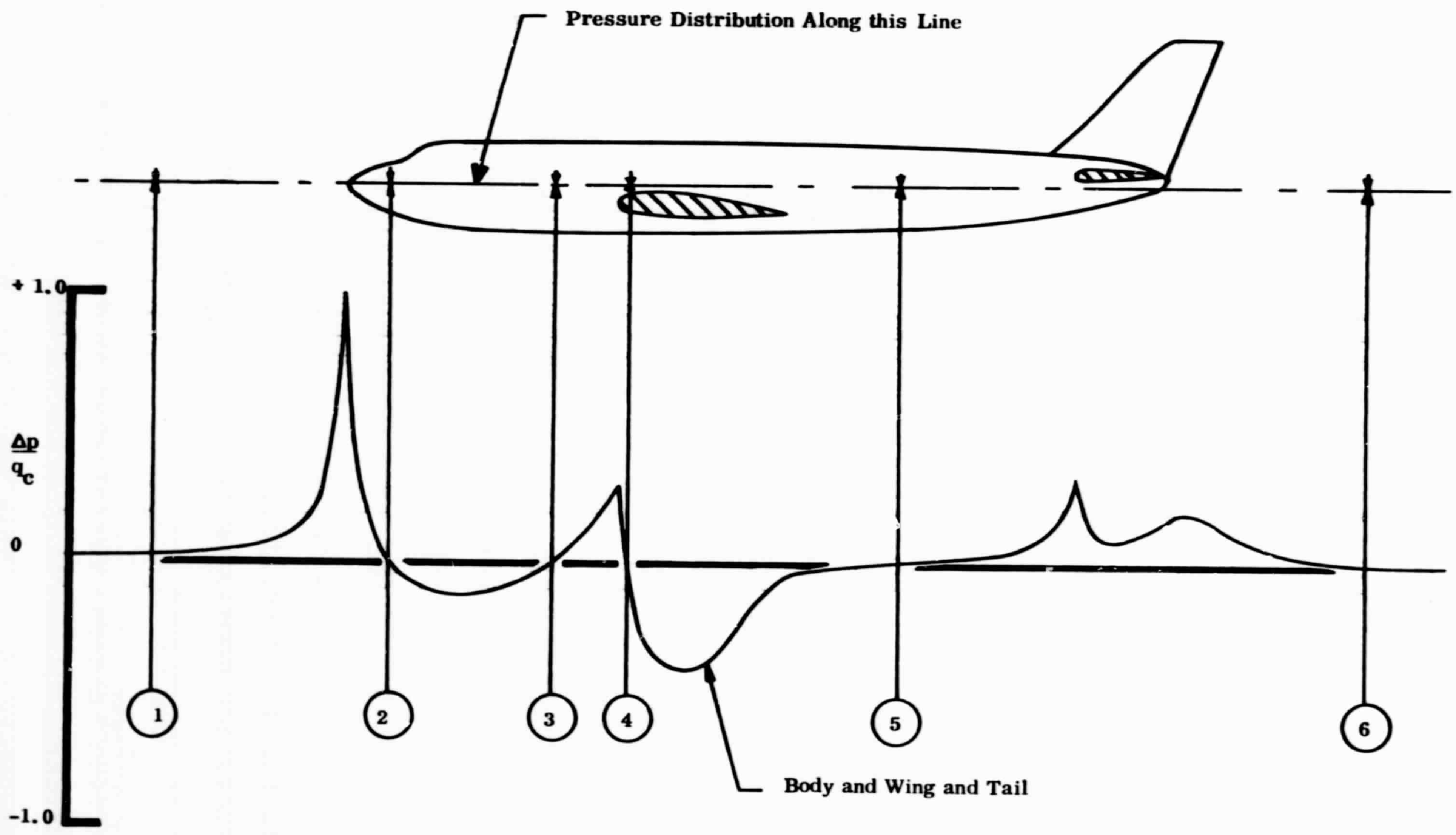

Figure 1 *

Typical Subsonic Static Pressure Distribution on Aircraft Fuselage

1 - 6 are points of minimum static pressure error

* From FAA SRDS Report RD-66-3 (Reference 1)

That flush-mounted pressure ports can lead to relatively large errors is clearly demonstrated in the literature. An analystic investigation performed at the Wright Air Development Center(2) predicted a standard deviation in height of 90 feet for thirteen B-47's and 96 feet for eleven B-52's at M = 0.8 and 40,000 feet. The analysis is generally an application of three-dimensional wavy-wall, small-perturbation theory using measured skin contours. Low level calibrations of sixteen transports, representing three types, showed errors ranging from - 40 to + 105 feet.(3) Scaling these to typical cruise conditions projects errors from 35 to 165 feet.

The small-perturbation theory suggests that a zone of controlled waviness is required in the region of the ports to assure adequate repeatability with this type of pressure vent. However, if the zone is limited to 0.0005 inches per inch, with waviness outside the region limited to 0.050 inches per inch, this zone must be at least 18 inches square for the B-47 and 43 inches square for the B-52 to assure errors below ± 60 feet.(2) Additional studies,(4) carried out by Rosemount Engineering Company show that if the static ports are located in the center of a skin ripple, the allowable depth (as a function of wavelength) for an error of 50 feet at sea level is approximately $\lambda/3000$. Although this is not in close agreement with the WADC report, it is clear that manufacturing tolerances would be prohibitively rigid if the errors resulting from skin irregularities are to be kept below a significant level.

Furthermore, only rough estimates of aging effects and contour changes under the stress of flight conditions can be made. The Rosemount work(4) showed skin contours of relatively new C-135 aircraft to be two to three times smoother than older C-118 aircraft. A more valid comparison, of course, would involve just one aircraft type; more information is needed on the extent to which skin contours can change during the service of an aircraft.

In general, flush static ports may be expected to measure static pressure with errors up to 250 feet.(3,7) This figure is also supported by members of the Royal Aircraft Establishment, Farnborough, England.(5,6) Manufacturing variations that occur between different aircraft of the same model number prevent accurate prediction; only individual calibration can reduce the spread. Even then, changing flight conditions may introduce large uncertainties. This constitutes the major difficulty in using flush ports to measure static pressure.

B. Probes

Static pressure probes avoid some of the problems encountered with flush ports by being removed from the influence of the local skin irregularities. A small displacement of the probes from the surface makes them relatively insensitive to these conditions. Two positions for static pressure probes are popular. Foremost is the nose where a short boom serves to place the static orifices in a relatively uniform pressure field. Although the pressure is generally higher than ambient static, due to the influence of the fuselage, the difference is easily calibrated and can be compensated either aerodynamically, through probe design, or in an air data computer. The alternate probe position is atop a short pylon mounted on the fuselage or wing. The position is not restricted to one of the zero static error points shown in Figure 1 if the measured pressure is compensated. Pylons on the order of five to eight inches are adequate to reduce the sensitivity to local skin ripple by nearly an order of magnitude for short wavelengths (<10') and by at least a factor of two for longer wavelengths which are less critical.

The minimization of the probe sensitivity to angle of attack is similar to the fuselage port positioning. For a cylinder, orifices located ± 37.5 degrees from the bottom centerline are essentially insensitive to angle of attack. The angle-of-attack optimized probes are generally restricted to fuselage mounting. Wing locations are impractical because of large induced updrafts ahead of the wing at even moderate angles of attack in the subsonic regions. The sensitivity to sideslip is not an independent function; the choice is made to minimize angle of attack effects since the sideslip angle can be kept small by crabbing into the wind.

The principal disadvantage of a pitot-static probe is its vulnerability. It can be damaged by mishandling during routine aircraft maintenance and cleaning; care must be exercized when working near the probe. The advantages of insensitivity to variations in fuselage skin contours and the possibility of incorporating aerodynamic compensation in the design may outweigh this inconvenience.

C. Aerodynamic Compensation

The pitot-static probes discussed above can be designed to compensate, in part, for the departure of the pressure field at the probe location from ambient static. In general the probe is placed in a positive pressure error region. Normally, the pressure error increases with Mach number to the supersonic region. The static orifices are placed on a curved section of the probe where the pressure error is negative and where it decreases with Mach number, thereby offsetting the positive pressure error induced by the fuselage.

The compensation up to the transonic region (M = .9 to 1.1) is quite complete(8,9); residual errors below 0.5 percent of the ambient static pressure are realized. (This is equivalent to about 100 feet altitude error) Of course, the design analysis requires a good knowledge of the pressure field in the region of the probe location. Designs which are relatively insensitive to small changes in the probe curvatures have been evolved to permit easy tailoring to specific aircraft. Full-scale wind-tunnel testing of the probe-nose combination can be used to verify the probe design and indicate any final changes to be made.

When passing through the transonic region, compensation is impractical. The shock wave is forming and passing over the static orifices, while the pressure error increases rapidly. Above Mach 1.1, the static pressure error goes to zero for the nose probe since the fuselage-indiced pressure field is not transmitted upstream of the shock wave. In the low supersonic regime (M = 1.1 to 2.2), the pressure error remains zero and is essentially independent of the probe design.

At higher supersonic speeds, the pressure error increases rapidly. Little work has been performed to assess these errors or the possibility of compensation. Tests of the X-15(10) showed pressure errors corresponding to about 2200 feet at M = 3.3. However, the data are smoothly behaved, suggesting that compensation to some degree is possible. Ruetenik et al (11) predict similar altitude uncertainties in static pressure measurement for the Mach 3.5 SST by assuming the error is characterized by a constant pressure coefficient calibration error (δC_p) and scaling the error by Mach number using the definition of the pressure coefficient $\left(\frac{\Delta p}{\frac{\rho}{2} V^2}\right)$. The approximate formula becomes

$$\varepsilon = 14,500\ M^2 \delta C_p$$

Using values of 50 feet for fixed static pressure error and 105 feet for variable error, extracted from Gracey's 1965 paper(12), δCp's of .005 and .01 respectively are found for M = .8 at 40,000 feet. These lead to estimates of altitude errors of 950 and 2000 feet. The statistical sum becomes 2200 feet. Aerodynamic compensation techniques are not considered; the work is referenced here only to substantiate the magnitude of errors encountered in the high supersonic region.

Aerodynamic compensation techniques applicable at high supersonic speeds must be developed through knowledge of the influence of the fuselage nose and its shock wave together with the generation of secondary shocksfrom various parts of the probe. If aerodynamic compensation is impractical, perhaps the character of probes can be assessed adequately to specify compensation functions useable in an air data computer.

III Altimeters

The pressure transducers which provide altitude indication can be divided into two broad classes: high strain and low strain devices. The traditional instrument is a member of the first class; an expandable bellows is linked mechanically to the indicator needle. Although the stress levels do not approach the yield point, they are sufficient to cause considerable hysteresis and recovery effect. The low strain designs are quite new and represent applications of relatively modern instrumentation techniques. In general they call upon electrical signal sensing and remote repeater indication techniques to take the place of large strain displacements. Currently, very few of these units are in service, although Honeywell has their Digital Air Data System on the production line.(24) This system incorporates a solid-state pressure transducer, described in section B below.

A. The Traditional Approach

The earliest altimeters were similar to aneroid barometers, with a single capsule which could drive a pointer one or two revolutions. While this was satisfactory to about 20,000 feet, the scale became unacceptably cramped for extended ranges. Prior to World War II, Paul Kollsman developed an altimeter incorporating a stack of capsules. Termed the sensitive altimeter, current models are outgrowths of this design; the altitude limit has been extended to about 60,000 feet. At the higher altitudes the mechanical power available to move the indicators is barely adequate to overcome friction. Built in vibrators are often used to overcome static friction and achieve satisfactory performance in this region. Recent efforts to circumvent this problem have included the use of servo driven altitude indicators which do not draw upon mechanical power (e.g. capacitive or inductive pickoffs).

In a study for establishing vertical separation standards, the IATA[21] has separated altimeters into three performance classes, one of which is further divided according to ceiling capability. The sensitive altimeter is designated as type I. Type IA has a ceiling of 50,000 feet; type IB has a ceiling of 30,000 feet. Type II is similar in construction to Type I instruments, but exhibits better performance and is termed the precision pressure altimeter. Type III is the same altimeter as type II but is included as part of an air data system which automatically corrects part of the diaphragm and static pressure system errors. Not categorized by ICAO are the fully servoed altimeters discussed above. Since the fully servoed instruments demonstrate better performance than type III, they were placed in this category for the study.

It is difficult to find in the literature any reference to the actual capabilities of any of these instruments consistent, in the sense of error breakdown, with either the SAE instrument specifications or the FAA calibration specifications, described in the next chapter. One must assume the generally more stringent SAE specifications tend to be representative of these altimeters. In a different evaluation approach, IATA has adopted a set of error limits tolerable for assigned flight level separations of 1000 feet. These are presented in Table 2 to illustrate the relative magnitudes of the various errors. The dominant error sources are the combination of diaphragm, hysteresis, and drift errors associated with the characteristics of the aneroid capsule materials. The range between types, for any one altitude, can be as much as 540 feet; the largest ratio is 7.5 for these errors. However, it is clear from the FAA calibration specifications that either type IA is considerably better than Table 2 purports or it is not acceptable at its rated ceiling, the former being more likely. Nevertheless, the significant differences between altimeter types are the characteristics of the aneroid capsules. Type IA capsule errors are two to three times as large as those for type II. Comparing types II and III indicates that half the error can be compensated by the air data computer.

Height	5,000				10,000				15,000				20,000			
Error \ Type	IA	IB	II	III	IA	1B	II	III	IA	IB	II	III	1A	IB	II	III
1. Diaphragm 2. Hysteresis 3. Drift	100	60	55	20	150	100	80	30	225	150	105	40	320	200	130	50
4. Friction	10	10	10	10	10	10	10	10	15	15	15	15	15	15	15	15
5. Temperature	15	15	15	15	15	15	15	15	20	20	15	15	25	25	15	15
6. Instability	30	30	15	15	35	35	15	15	40	40	20	20	50	50	25	25
7. Backlash	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
8. Readability																
a. Height	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
b. Pressure	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15

	25,000				30,000				35,000			40,000			45,000		50,000	
	IA	IB	II	III	IA	IB	II	III	IA	II	III	I	II	III	II	III	II	III
1. 2. 3.	415	250	155	60	510	300	180	70	600	205	80	650	230	90	255	100	280	110
4.	20	20	20	20	20	20	20	20	25	25	25	25	25	25	30	30	30	30
5.	30	30	30	30	35	35	35	35	45	45	45	55	55	55	70	70	85	85
6.	60	60	30	30	75	75	35	35	90	45	45	110	55	55	70	70	85	85
7.	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10
8.																		
a.	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
b.	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15	15

Table 2

Maximum Altitude Tolerances

Extracted from "Altimetry and the Vertical Separation of Aircraft" IATA Jan. 1960 (reference 21)

The diaphragm error incorporates the nonlinear strain behavior of the aneroid under pressure induced stress. Since a part of this error is corrected in type III instruments, presumably in the other types it includes the nominal nonlinearity as well as the variations between individual instruments. Hysteresis is the variation in behavior with changes in altitude depending upon whether pressure is increasing or decreasing. The drift error comes about from the imperfectly elastic properties of the aneroid resulting in a change of indication with time after being subjected to a fixed altitude change. The friction error is the result of inadequate mechanical power in the aneroid to overcome friction in the indicator linkages. The temperature error depends upon the thermal characteristics of the instrument and the deviation of its temperature from the design temperature. Instability error is the change in the indication of a given altitude as a function of the history of pressure-altitude cycling. Finally, readability error is attributed to parallax when reading the altitude and pressure datum scales. There are a few additional errors associated with altimeters when set for a barometric pressure datum other than 29.92 in Hg; however, their effect on the root-sum-square error is small.

B. Modern Pressure Transducers and the Future

No exhaustive survey has been undertaken to identify current trends in altimeter designs. Only two sources are discussed here; the approaches taken by these manufacturers obviously make use of modern instrumentation techniques. The improved performance over even type III instruments demonstrates the obsolescence of the traditional altimeter.

The first step taken to overcome the problems of the aneroid type altimeter was the mechanical decoupling of the pressure transducer from the indicator mechanism. The latter became servo controlled through an electronic position sensor on the aneroid, thereby eliminating the friction and backlash associated with the earlier instruments. An important adjunct was the extension of the instrument's range, for no longer was the mechanical power of the aneroid a limiting factor.

The next step, in order to avoid the problems of hysteresis and recovery, common to the aneroid device, incorporated a low strain diaphragm along with remote indication techniques. This essentially represents the current state of the art. There are a variety of signal generating techniques used, the most "exotic" of which might be that of the Honeywell DADS wherein the diaphragm is a silicon disc onto which are diffused piezoresistive elements.(24) These are coupled into R-C oscillators. Pressure strains of the disc result in changes of oscillator frequencies which are then interpreted as altitude changes. The pressure-resistance characteristics depend upon the orientation of the resistive elements with respect to the crystalographic axes of the disc. In addition, there is a significant temperature sensitivity. However, by monitoring an oscillator whose element is oriented to be insensitive to pressure changes, temperature compensation can be effected. The net result is a very accurate alimeter used as part of an air data system as a whole. For pressure altitude, they are: $<\pm$ 10 ft at sea level, $<\pm$ 55 ft at 50,000 ft, $<\pm$ 200 ft at 80,000 ft. These correspond to an uncertainty of about 0.01 in Hg which is considerably better than even the type III altimeter discussed in the previous section. These figures would of course account only for the instrument package, (including readout) and not for position error of any aircraft. Reliability is claimed to be a factor of five better than analog devices; the MTBF is estimated to be 15,000 hours. Compensation for position error-static probe characteristics is accomplished through a diode matrix within the airborne computer. The complete system is fairly complex and naturally has a high price. Although no firm quote was given, a figure on the order of $10,000 was estimated by a Honeywell sales representative.

Another transducer which exemplifies the current trend of low strain pressure measurement is the Rosemount Engineering Company's capacitive pressure sensor.[22] The mechanism is a relatively stiff diaphragm which forms part of a capacitive pickoff circuit. While stated linearity is only 0.5 percent of full scale, the claimed accuracy is 0.05 percent (0.015 in Hg) and stability is 0.1 percent per six months. While this accuracy does not represent a great improvement over the type III altimeter, the figures on repeatability and hysteresis (0.01 and 0.015 percent respectively) show the advantages of the low strain devices. Cost of this sensor is on the order of 500 dollars in quantity; the indicating system is not included. Output is a dc voltage proportional to input pressure.

It is clear that modern instrumentation methods have found their way into the field of barometric altimetry. However, this has come about at considerable expense with the result that these instruments are generally installed in only the larger commercial air carriers. More emphasis needs to be placed on altimeters used in the general aviation field with a view towards either obtaining better accuracy from existing units (i.e. through periodic calibration) or developing a modern instrument with an acceptable price tag.

A design concept which could provide better accuracy at reasonable cost has come to light during the period of this altimetry survey. In fact, it offers two possible design approaches; a low cost, acceptably accurate instrument, or a more sophisticated instrument demonstrating high accuracy over an extended range.

Despite the use of low strain diaphragms in the two instruments described above, some strain phenomena (e.g. hysteresis and recovery) are still present. If, however, a force-feedback device is used to maintain the diaphragm at a null, unstressed position, and the force exerted is monitored to indicate static pressure, none of these nonlinear characteristics would affect the indication. This feedback concept, commonly used in inertial grade accelerometers and modern measurement and control systems, inherently extends the measurement range several orders of magnitude over the open loop sensor. Because of this, an altimeter might be devised which is more accurate than a type IA or IB instrument for comparable cost.

A highly accurate extended altitude range would be useful either for the SST or for high altitude experiments. The range extending capabilities of the feedback loop could provide this combination of range and accuracy. Its development would involve application of fairly classical techniques common to precision electronics, and relatively less emphasis on mechanical aspects. The ease of computation with modern electronics could help simplify the mechanical parts and achieve better compensation. It is hoped that the opportunity for development of prototypes will be forthcoming.

IV Calibration and Maintenance of Altimeters and Static Pressure Systems

In discussing calibration and maintenance, the complete range of error contributors must be considered, starting with those associated with the calibration equipment and ending with those which inherently elude particular calibration processes. Furthermore, one must keep in mind what systems are required to be calibrated and what are not. The calibration standards specified in FAR Part 43 do not distinguish between altimeter types.

A. Instruments

1. Instrument shop calibration standards

A variety of barometers are used as calibration standards in altimeter repair shops; accuracies are correspondingly varied. One FAA study[13] in 1963 demonstrated the almost total lack of calibration equipment standards. Using portable standard barometers as references, the survey of 65 weather station instrument readings and 28 repair station instrument readings produced standard deviations of 0.012 in Hg and 0.016 in Hg respectively. In 1964 the FAA assessed the minimum acceptable standards needed in conjunction with Category II Instrument Approach Operations.[14] Appendix IV of this reference describes the minimum acceptable standards for altimeter calibration equipment, including operation and maintenance procedures. The barometer accuracy specified is 0.005 in Hg over the entire range of operation. This was followed in 1965 by FAA Advisory Circular 43-2 describing minimum barometry for calibration and test of atmospheric pressure instruments. The 0.005 in Hg specification is repeated.

Szymkowicz, in an AIAA paper[15], states the Weather Bureau has provided Category II stations with reference barometers of 0.005 in Hg or better accuracy. However, Mr. Wesley Irwin* of the Data Acquisition Division, ESSA indicated no new equipment had been supplied and that the secondary standards are of the 1/4 inch bore Fortin type. The best performance to be expected of these instruments is ± 0.01 in Hg; readability below that level is difficult. They are calibrated with a reference standard every one or two years. Although the Weather Bureau is improving quality control, Irwin feels that an instrument having an accuracy of 0.005 in Hg is of laboratory caliber and requires very careful handling to achieve such precision. In general, one reading takes fifteen minutes. The best available instrument demonstrates an accuracy of 0.002 in Hg.

In contrast to the weather bureau's outlook, De Leo et al[4] discuss thirteen barometers which could be used as working standards, i.e., those having greater flexibility and ease of operation while possibly sacrificing some absolute accuracy. Manufacturers' claims for accuracy range from about 0.016 in Hg down to 0.0003 in Hg. The latter is for an Ideal-Aerosmith mercurial manometer having one fixed cistern and one movable cistern interconnected by flexible tubing. The mercury level within the cisterns is sensed by capacitive pickoffs and is rebalanced by moving one cistern. Readout is by means of a lead screw. This is a standard modern technique of null seeking systems. Although no thorough investigation of current instruments was undertaken during the present contract, it is noted that at least partially automated operation of barometers is evolving throughout the industry. Further application of automation and less dependence on manual operation could help achieve the high standards prescribed by the FAA advisory circular.

2. Altimeter calibration

The FAA has established only calibration schedules and standards which an altimeter must meet in order to qualify for Category II IFR service, as described in FAR Part 43 Appendix E, and supplemented by Advisory Circular 43-203A. No periodic calibration schedules are provided for aircraft operating under visual rules only.

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* personal communication

Altimeters are calibrated for scale error, hysteresis, after effect, friction, case leak, and barometric scale error. Tolerances in feet are prescribed for these tests; Table 3 is an abbreviated set for the scale error and includes the corresponding pressure errors. A similar set of tolerances for

Altitude	Tolerance	Pressure Error
0 feet	± 20 feet	0.022 in Hg
10,000	80	0.065
20,000	130	0.076
30,000	180	0.074
40,000	230	0.062

Table 3 FAA Category II Scale Error Tolerances

friction-induced errors is given by FAA, with tolerances of ± 70, ± 80, ± 100, ± 140, and ± 180 feet for altitudes of 1, 10, 20, 30, and 40 thousand feet respectively. Hysteresis can account for 75 feet of error and after effect for 30 feet. The case leak test measures a leak rate, not to exceed one hundred feet per minute when subjected to a pressure differential equivalent to 18,000 feet altitude. It is somewhat difficult to relate this to an altimeter error, although estimates suggest such errors are negligible in view of the other system errors. Anderson postulates the error to be less than the altimeter resolution.[17]. Finally, the barometric scale error involves comparison of indicated altitude and specified indications at a variety of barometer scale settings. The differences must not exceed 25 feet.

Although these FAA specifications apply only to testing and calibration of altimeters, the Federal Aviation Regulations specify compliance with the SAE Aeronautical Standard AS-392C in order to be approved for civil aircraft. This is a much more detailed standard providing instrument performance criteria for a wide variety of operational and environmental conditions. In addition, a proposed standard for altimeters and air data systems capble of operation up to 80,000 feet has been devised by the SAE A-4 panel. This covers all types of altimeters and provides for four instrument ceilings: 20, 30, 50 and 80 thousand feet. The scale error tolerances for the 50,000 foot ceiling altimeter are about half those given in Table 3. The friction error tolerances are much lower if the instrument is provided with an integral vibrator, eq. 40 feet at an altitude of 35,000 feet. The proposed SAE standard is in line with generally accepted instrument accuracies. A representative[16] of S. Smith and Sons, Ltd. states that the instruments are capable of accuracies of 0.1 percent of the full-scale range, or 1 millibar which is equivalent to 111 feet at 40,000 feet. It is to be noted, however these standards do not concern periodic maintenance and calibration.

3. Altimeter setting to local conditions

The 1964 FAA assessment of minimum barometry standards[14] includes specifications for altimeter setting indicator equipment. Recommended is that indicator settings in control towers shall be within 0.010 in Hg of the latest transmitted setting from the associated weather station and that indicators in weather stations be within 0.010 in Hg of the computed setting derived from the mercurial barometer reading. The mercurial barometer reading at ambient pressure is to be within ± 0.005 in Hg of a portable mercurial transfer standard; this standard is to have an error not exceeding ± 0.003 in Hg. The mercurial barometers are to be calibrated with the portable standard every two months.

In the discussion with Irwin of ESSA, it became apparent that the precision aneroid barometers from which the altimeter settings are derived demonstrate accuracies of ± 0.02 in Hg. These instruments are calibrated with the 1/4 inch bore Fortin type barometers twice per week. Efforts are being made to improve accuracy in this area, but more than a factor of two is doubted. Since the ceiling for operation under local setting conditions is 24,000 feet, an error of 0.01 in Hg would produce a maximum of 21 feet altimeter error due to incorrect setting.

B. Static Pressure Systems

Numerous system calibration techniques have been evolved throughout the history of pressure altimetry. Some, such as radar tracking, require rather complex ground installations. Few are simple and self-contained. If periodic calibration of instrument systems is desirable, the means must be both accurate and economical. The one technique currently available which appears to offer these advantages involves the trailing cone. Rather than calibrate the pressure system against an independent altitude measure, the trailing cone is used to compare measured static pressure with something closely approaching the free stream static pressure. Although the "system" calibration is not complete, standard instrument shop checks of the altimeters can be used to find the instrument's contribution to the altimetry error.

The trailing cone method consists of measuring the free stream static pressure by placing a probe outside the aircraft's pressure field. The pressure ports are located in a long tube near a lightweight drag cone. By trailing it far enough behind the aircraft, and out of jet wakes, the sensed pressure is essentially ambient static. For jetliners, a distance of 100 to 200 feet is typical. The light weight of the complete apparatus permits the line to remain horizontal; errors due to angle of attack of the port section are negligible.

The trailing cone has undergone extensive development and testing, primarily by its originator Douglas Aircraft Company.[18] The ICAO[19] has issued a Provisional Acceptable Means of Compliance for calibrating the static pressure system which describes the trailing cone apparatus and a testing program for the purpose of certificating an aircraft. The stated accuracy requirements are ± 75 feet over an altitude range up to 50,000 feet. Only the subsonic regime is considered. The PAMC specifically designates the Douglas configuration in view of the extensive development by this vendor.

DeLeo and Hagen[1] attempt to evaluate the probable accuracy of a method where the trailing cone installation is calibrated in the first of an aircraft type by a reference pacer aircraft. Thus, the uncertainties of the pacer system are included in the estimate. At 30,000 feet, the trailing cone method is expected to yield an accuracy of ± 29 feet; at 50,000 feet it should be good to ± 42 feet.

Four other calibration techniques in use[1] are the pacer aircraft method, the radar tracking method, the camera fly-over method, and the tower fly-by method. The last two restrict the operating altitudes of the aircraft to very low levels and consequently limit the upper speed ranges for the calibration. Accuracy is predictable only to about 20,000 feet for these methods where it is 10 feet for each when a static port calibrator is used to calibrate position error. There are no altitude restrictions for the other techniques. The accuracy of position error calibration is expected to be ± 26 feet at 20,000 feet and ± 40 feet at 50,000 feet for the pacer method and ± 20 feet and ± 28 feet using radar tracking at these same altitudes. The principal disadvantages of these methods are the length of time needed to complete a calibration and the poor economy, especially for the pacer technique which requires two aircraft. The other three methods use ground-based equipment which may limit the number of calibration stations available. Time for a thirty point calibration range from 115 to 260 minutes for the four methods whereas only 80 minutes are required with the trailing cone.

C. Maintenance

The current FAA requirements for altimeter system maintenance are extremely limited, primarily due to a lack of personnel and facilities to support a more widespread program. Only aircraft flying in controlled airspace under IFP must have periodic calibration of the altimeter system. The period is two years; the standards are set forth in Appendix E of FAR Part 43. In short, the only system procedures are checks of freedom from entrapped moisture or restrictions, determination of leak rates (not to exceed 100 feet per minute under a pressure differential of 1 inch of mercury or the maximum cabin differential pressure, whichever is applicable), and checks of static port heater operation, if installed. The rest of the procedure concerns the altimeter alone and was discussed in section A above. Perhaps the most serious fault of the maintenance procedure is the lack of any position error calibration. Although the Air Transport Association of America[20] draws the conclusion that aging effects are statistically small, the method used in reaching this leaves much to be desired. The tests used trailing cone probes to measure pressure differentials between the probe and the pilot and co-pilot static systems. The airframe manufacturers' published static port corrections were then applied and the net differentials were interpreted as position errors. The difficulty in assessing aging effects lies in the fact the data were taken for each aircraft only once. Data from old and new aircraft were compared; no trend showed with age and the conclusion was drawn. However, the history of position error for any one aircraft is not available in this data; it would have been better to state that position error appears to remain within specific bounds, regardless of age.

More important, however, is the demonstrated spread in this data and in some collected by FAA.[7] Errors in the range of ± 200 feet are typical; only a few exceed this in the ATAA data. The FAA data does not distinguish position error from total system error and also uses a pacer aircraft for calibration which introduces additional errors. The range of this data is -275 feet to + 400 feet.

It is clear that a maintenance and calibration program to measure position error periodically would eliminate a major source of altimetry error. Such a program could be instituted, using trailing cone probes, on a fairly large scale until the real aging effects could be shown to be negligible. Thereafter, initial calibration of every aircraft might suffice. However, such a calibration system would be quite useful for a periodic check on the position error to update any otherwise unnoticeable shifts in the calibration. The moderate cost of a trailing cone system makes such a program especially attractive.

Despite the rules for periodic calibration for aircraft flying IFR, the great majority of aircraft, under the title of general aviation, fly VFR and are not required to perform such maintenance. Although the ceilings are low for most of these, such that altimeter system errors may not be very great, some of the business jets have cruise altitudes comparable to the largest air carriers. Some program to check at least the static pressure system and altimeter, if not the position error as well, should be adopted. If one hundred maintenance centers across the country were to service the 140,000 general aviation aircraft, only 14 per week would be calibrated in each shop if the interval were two years.

V The Atmosphere

With the emphasis on the aircraft separation problem in altimetry, interest centers not on absolute altitude deviations due to nonstandard atmosphere characteristics, but rather on the reduction in separation resulting from these. Assuming that two aircraft fly at their assigned pressure levels (i.e. those pressures of the standard atmosphere corresponding to the assigned flight levels), the actual separation depends upon the temperature of the atmosphere. The governing equation is called the hypsometric equation.

$$\Delta h = 221.1\ T \log\frac{P_1}{P_2}$$

where T is the mean temperature between the levels in degrees Kelvin, and Δh is measured in feet. This equation can also be expressed in terms of the differential pressure between the levels. The first-order expansion is

$$\Delta h = 96.02\ T\ \frac{\Delta P}{P_2}$$

This is essentially a differential form of the standard atmosphere model. The temperature model has been derived from measurements and represents an average at any one altitude. It is deviations from the average which are of concern here. A ten-year collection of temperature data[23] from thirteen points in North America, ranging from Swan Island in the West Indies to Barrow, Alaska, was analyzed to assess temperature deviation statistics. The results show that the northern regions exhibit the lowest temperatures. Expressed as aircraft separation when flying at pressure levels nominally 1000 feet apart, the minimum separation would have been 849 feet at about 5000 feet over Caribou, Maine in February. However, the average temperature at this altitude is 25°K greater than the minimum (corresponding to a 938 foot separation) and the standard deviation is 7.7°K(28 feet). Standard deviations for all areas covered ranged from two to nine degrees K. The minimum average temperature ranged from -31.6°K below to +0.3°K above the standard atmosphere temperatures at the corresponding pressure altitudes. The range of separations for these average temperatures is 891 to 1065 feet.

In summary, one might expect normal regional temperature fluctuations to result in diminished aircraft separation of less than ten percent. An extreme figure of fifteen percent, might occur in northern regions in winter.

VI Summary

The technological tools to improve altimetry for the most part already are at hand. The principal problems are attaining widespread distribution of high quality equipment and adequate periodic inspection and calibration of the equipment. In view of the cost of an aircraft, it would not seem unreasonable to expect that some of the better altimeter systems be universally adopted. This is not to imply that complete air data systems be required hardware; rather it suggests discontinuing the use of the outmoded instrumentation often found in the smaller general aviation aircraft. Barometric altimetry is summarized here in two sections. First, estimated maximum errors are compared to the capabilities cited for some of the better equipment. Then the areas requiring the most concentrated effort are outlined along with some broader range research and development topics.

A. Status of Altimetry

Flush parts are subject to widely varying pressure patterns because of local skin contours arising from normal manufacturing tolerances, variable stress patterns at altitude and aging or cycling effects. Position errors for one type of aircraft may range up to several hundred feet. To avoid such variability, static pressure probes can be moved out of the zone of surface influence which may be only a few inches from the skin. These probes need not be located at a zero static pressure error position along the fuselage; their shape can be computed to compensate for pressure differences due to location. Residual errors can be kept below 0.5 percent of the static pressure for the entire subsonic region. This corresponds to about 100 feet of altitude error. Sensitivity to angle of attack and sideslip can be minimized by proper port location on the probe.

The four types of altimeters classified by ICAO demonstrate a wide range of accuracy. The worst performance, by the type IA instrument, with a range of 50,000 feet, is estimated to have a standard deviation not in excess of 110 feet at 20,000 feet and 221 feet at 40,000 feet. The best of those classed by ICAO is the type III servo-compensated altimeter with a standard deviation not exceeding 27 feet at 20,000 feet, 44 feet at 40,000 feet, or 58 feet at 50,000 feet. While this is markedly better than the type IA, it is interesting to note that both instruments are certificated for operation to at least 50,000 feet. The only regulation overriding this factor is that for use in IFR controlled airspace, the instrument accuracy (3σ) must be calibrated every two years at altitude steps throughout their range. As an example, they must be accurate to about 380 feet at 50,000 feet. In contrast to these figures, the stated accuracy of the Honeywell Digital Air Data System is 55 ft at 50,000 feet and only 200 feet at 80,000 feet. The pressure transducer in this altimeter represents a sharp break with tradition of these instruments; the sensing diaphragm is relatively stiff and flexes over a very small range. The readout device incorporates stress-dependent components attached to the diaphragm to provide signals with frequencies proportional to the static pressure. Thus the need for mechanical power, the nemesis of the aneroid instrument, is at a minimum. This is but one example of the application of modern instrumentation techniques. The direct result of improved performance is obvious.

To achieve the best performance from any instrument it must be properly handled and calibrated on a periodic basis. This would seem especially pertinent to the lower quality altimeters which are inherently less consistent than their more expensive counterparts. Yet, unless they are used under IFR conditions, no calibration is ever required by the FAA. Not even an inspection to check for foreign matter in the static ports or the condition of these ports is required.

For those instruments which are calibrated, the quality of the tests is of prime interest. Whereas the accuracy claimed by Honeywell for their DADS corresponds to about 0.01 in Hg over the entire pressure range, the transfer standards in instrument shops are generally Fortin type mercurial barometers which demonstrate an accuracy of about 0.01 in Hg. It is accepted practice to limit test equipment uncertainty to ten or twenty percent of the instrument uncertainty if at all possible. The state of the art of altimeters calls for considerably better calibration standards than are presently used. The best available is claimed to be accurate to 0.0003 in Hg, with several manufacturers citing repeatability of 0.001 in Hg. A relatively important consideration for shop calibration is the ease and speed with which the measurements can be taken. If the best standards require excessive care and time, they lose their practicality for this application.

Periodic calibration requirements do not extend, for the most part, to the entire static pressure system. Only a leak test, check of port heater operation, and ensurance of freedom from trapped water or other restrictions is prescribed. The absence of testing position error could be one of the most serious limitations of barometric altimetry.

B. Areas For Concentrated Effort

The lack of any uniform, broadbased program for periodically calibrating each component which contributes significantly to the total error appears to be the principal accuracy limitation in barometric altimetry. Not only must the barometers used in altimeter repair shops and instrument setting stations meet the standards recommended by the FAA in 1964, but also a precise method, such as the trailing cone technique, should be implemented to ascertain position errors. In each of these areas, the number of altimeter systems calibrated should encompass all aircraft capable of high altitude cruise, where small static pressure errors transform into large altitude errors.

From the standpoint of aircraft separation, flight technical error is of major importance. While not related to barometric altimeter performance, it is emphasized here because current estimates of these errors are of the same magnitude as altimetry system errors. Relatively few studies have been made to determine the causes of flight technical error which might lead to the means for their reduction. The studies which do exist point out the value of autopilot systems incorporating altitude hold modes. There are many factors, ranging from cockpit displays to high gusts, which can affect flight technical error and must be assessed before assigning lower flight separation standards.

To help achieve higher altimetry system performance, the use of static pressure probes should be encouraged in order to circumvent the possibility of shifts in position error resulting from skin contour changes. A program for assessing the temporal behavior of flush static port position error should be performed in order to determine the extent to which the use of probes might be an FAA requirement. The use of trailing cones over a considerable portion of the service life of a variety of aircraft could provide this position error data.

If lower separation standards are to be a part of future regulations, some thorough studies identifying altimetry errors must be undertaken. A complete statistical and physical assessment of each error source is needed before even a basis for assigning flight level separations should be established. For example, some groups propose that separation standards be based on fixed pressure differences, rather than on altitude since they would be more consistent with the error characteristics of a barometric altimeter system. Even the more extreme, but rare, errors may be significant factors in determining the standards.

One of the most interesting prospects for development is an advanced pressure transducer incorporating force-feedback. Two approaches are possible: first the development of an accurate broad range (e.g. to 100,000 feet) altimeter using modern instrumentation techniques. Such an instrument could be used in high altitude experiments, or by the commercial aviation industry in the SST. The second avenue of development could take advantage of the broad range characteristics inherent in null-seeking feedback devices and attempt the production of a low cost instrument demonstrating relatively high accuracy. Use of this altimeter would be intended for the general aviation industry. If sufficient reliability could be domonstrated, the periodic calibration proposed above might be simplified to a significant degree. This type of instrument would be particularly attractive in view of the trend toward highly complex air data systems. By circumventing the typical nonlinear characteristics of the bellows-type unit with gear-coupled readout, the need for altimeter servo compensation may be eliminated.

Finally, the altitude display should be examined. While the display is more critical during the landing phase, misreadings have led to numerous near-misses. The trend toward redundancy as with the counter-drum-pointer altimeter, represents an attempt to dissolve the ambiguity present in digital, odometer-type counters when passing through the thousand foot levels. An integrated approach to the complete cockpit display appears badly needed. With the advent of electronic measuring equipment using digital readouts, the technology for providing legible indications is probably developed to the stage where direct application is feasible. Certainly, the three-pointer instrument which has the worst history of misreading should be eliminated.

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References

1. De Leo, Richard V., and Hagen, Floyd W. "Flight Calibration of Aircraft Static Pressure Systems" FAA SRDS Report No. RD-66-3, February 1966.

2. Weiner, F.D. and Teigen, M.J. "An Investigation of the Effect of Random Fuselage Wall Irregularities on Flush Static Ports," W.A.D.C. Tech Report No. 57365, April 1957.

3. Silsby, N.S. and Stickle, J.W. "Flight Calibrations of Fuselage Static Pressure Vent Installations on Three Types of Transport," NASA Tech Note D-1356, May 1962.

4. De Leo, R.V. et al "Evaluation of Factors Affecting The Calibration Accuracy of Aircraft Static Pressure Systems," Wright-Patterson AFB, Technical Report SEG-TR-65-35, July 1965.

5. Bone, A.G. in "Height Measurement in Supersonic Aircraft", Journal of the Institute of Navigation, Jan 66 pp 56-77.

6. Anderson, R.G. "Survey of the Errors of Pressure Measuring Instruments in Relation to Air Traffic Separation Standards", RAE TEchnical Report No. 65262, Dec. 1965.

7. Shrager, J.J. "Limited Survey of Commercial Jet Aircraft Altimeter System Position Error By Pacer With Trailing Cone", FAA Report No. RD-64-157, December 1964.

8. Ritchie, V.S. "Several Methods for Aerodynamic Reduction of Static-Pressure Sensing Errors for Aircraft at Subsonic, Near-Sonic, and Low Supersonic Speeds", NASA Technical Report R-18, 1959.

9. Rosemount Engineering Bulletin 2661, October 1966, and Bulletin 116010.

10. Larsen, T.J. and Webb, L.D. "Calibrations and Comparisons of Pressure-Type Airspeed-Altitude Systems of the X-15 Airplane from Subsonic to High Supersonic Speeds," NASA TN-D-1724, February 1963.

11. Ruetenik, J.R., Barry, J.M., and Ives, D.C. "Survey of Avionics Instrumentation Needs for Advanced Supersonic Transports", Kaman Avidyne TR-43, April 1967.

References (cont'd)

12. Gracey, W. "Recent Developments in Pressure Altimetry", AIAA Journal of Aircraft, May-June 1965.

13. Albin, L. "Barometric Pressure Standard Survey and Calibration", FAA Contract FA-WA-4170, the Bendix Corporation, July 1963.

14. Russell, W.M. "Pressure Measurement for Pressure Altimetry", FAA Report No. RD-64-119, August 1964.

15. Szymkowicz, J.S. "Altimetry", AIAA Meeting on Collision Avoidance, AIAA paper A68-13211 Feb. 1967.

16. Cape, B. "Some Aspects of Pressure Measurement Techniques:, in Height Measurement in Supersonic Aircraft", Journal of the Institute of Navigation Vol 19 no 1 Jan. 1966.

17. Anderson, R.G. "Survey of the Errors of Pressure Measuring Instruments in Relation to Air Traffic Separation Standards," RAE Technical Report No. 65262, Dec. 1965.

18. Technical Memorandum TM-GEN-4158, Douglas Aircraft Co. August 1967.

19. "Uniform Method of Calibration of Position Error", ICAO PAMC, Circular 81-AN/68 1967.

20. "Performance Report on Static Air Source on Air Carrier Turbojet Aircraft", Air Transport Association of America, October 1966.

21. "Altimetry and the Vertical Separation of Aircraft", International Air Transport Association, January 1960.

22. Rosemount Engineering Bulletin 7662.

23. Hilsenrod, A. "Deviations From Standard Altitude Separations Due to Atmospheric Temperature Variations," FAA Report No. RD-65-12 July 1966.

24. Honeywell Digital Air Data Systems Brochure ADC 299 September 1967.