

INTRODUCTION TO AIR DATA SYSTEM PARAMETERS, ERRORS AND CALIBRATION LAWS

1. NOTATION*, UNITS, CONSTANTS AND CONVERSION FACTORS

1.1 Notation and Units (see also Table 7.1)

		<i>SI</i>	<i>British</i>
a	speed of sound	m/s, kn	kn
H	geopotential height, see Section 4.3	km, m	ft
H_p	pressure height, see Section 4.3	km, m	ft
M	Mach number, see Section 4.4		
M'	Mach number based on p_p' and p_s , see Section 3.1		
p_a	ambient static pressure*	N/m ² , mb	lbf/ft ²
p_p	pitot pressure*, see Section 4.1	N/m ² , mb	lbf/ft ²
p_p'	sensed pitot pressure* in steady-level-flight conditions (alternatively, value obtained after correction for any effect of non-steady flight, see Reference 12)	N/m ² , mb	lbf/ft ²
p_{p_i}	registered (indicated) value of pitot pressure* (note, for steady level flight, $p_{p_i} = p_p'$, see Section 3.1)	N/m ² , mb	lbf/ft ²
p_s	sensed static pressure* in static system in steady-level-flight conditions	N/m ² , mb	lbf/ft ²
p_{s_i}	registered (indicated) value of static pressure* (note, for steady level flight, $p_{s_i} = p_s$, see Section 3.1)	N/m ² , mb	lbf/ft ²
p_t	total pressure*, see Section 4.1	N/m ² , mb	lbf/ft ²
q_c	impact pressure ($q_c = p_p - p_a$, see Section 4.1)	N/m ² , mb	lbf/ft ²
q_c'	impact pressure for steady-level-flight conditions ($q_c' = p_p' - p_s$)	N/m ² , mb	lbf/ft ²
R	gas constant for air	N m/kg K	lbf ft/slug K
r, r'	recovery factors for total temperature probe, see Section 5.4		

* Note that these pressures marked with asterisks are absolute.

T_a	ambient temperature	K	K
T_r	temperature registered by an ideal total temperature probe (recovery temperature), see Section 4.2	K	K
T_t	total air temperature, see Section 4.2	K	K
t	time	s	s
V	true airspeed	m/s, kn	ft/s, kn
V_c	calibrated airspeed, see Section 4.4	m/s, kn	ft/s, kn
V_e	equivalent airspeed, see Section 4.4	m/s, kn	ft/s, kn
V_i	indicated airspeed, see Section 4.4	m/s, kn	ft/s, kn
Z	geometric height, see Section 4.3	km, m	ft
α	angle of attack, see Section 4.5	degree	deg
β	angle of sideslip, see Section 4.5	degree	deg
γ	ratio of specific heat capacities of air (for $T_t < 400$ K, approximately, the value may be taken as $\gamma = 1.4$)		
δp_p	contribution to pressure error in pitot pressure system	N/m ² , mb	lbf/ft ²
δp_s	contribution to pressure error in static pressure system	N/m ² , mb	lbf/ft ²
δT_r	contribution to error in temperature registered by total temperature probe	K	K
ρ	ambient air density	kg/m ³	slug/ft ³
Σ	summation of errors for pressure or temperature system		

Subscripts

i	initial value of a parameter, usually a registered value, that is subject to corrections to arrive at a true value
ns	denotes non-steady-flight conditions
sf	denotes steady-level-flight conditions
TOT	denotes total of a number of individual pressure errors
xmh	denotes extreme conditions of Mach number or height
0	denotes conditions at sea-level in International Standard Atmosphere, ISA

1.2 Constants and Conversion Factors

Constants

a_0	340.294 m/s,	1116.45 ft/s,	661.479 kn
p_{a_0}	101 325 N/m ²	1013.25 mb,	2116.22 lbf/ft ²
R	287.052 87 N m/kg K		3089.8114 ft lbf/slug K
T_{a_0}	288.15 K		

Exact conversion factors implied

$$1 \text{ ft} = 0.3048 \text{ m}, 1 \text{ n.mile} = 1852 \text{ m}, 1 \text{ bar} = 10^5 \text{ N/m}^2, 1 \text{ Pa} = 1 \text{ N/m}^2$$

$$(T_a \text{ or } T_r \text{ or } T_t \text{ } ^\circ\text{C}) = (T_a \text{ or } T_r \text{ or } T_t \text{ K}) - 273.15$$

2. INTRODUCTION

A basic aircraft air data system is composed of the following.

- (i) A total pressure sensor*, termed variously “pitot probe”, “pitot tube” or “total pressure head” (see Reference 14).
- (ii) An ambient pressure sensor* in the form of a “static plate” or a “static probe” (see Reference 14).
- (iii) An altimeter, the transducer for which registers static pressure, p_{s_i} , from (ii).
- (iv) An airspeed indicator, the transducer for which registers the pressure difference ($p_{p_i} - p_{s_i}$), obtained from the pressures supplied by (i) and (ii).
- (v) A vertical speed indicator, the transducer for which registers the time rate of change of static pressure, dp_{s_i}/dt .
- (vi) A total air temperature sensor, usually termed “total air temperature probe” or “total air temperature head” (see Reference 11).
- (vii) A total air temperature indicator, whose transducer registers the temperature, T_{r_i} , from signals supplied by (vi). Alternatively, if automatic computing is available, ambient temperature, T_a , may be indicated.

For many aircraft the “basic” system of items (i) to (vii) cannot provide all the information required for all in-flight purposes so the air data system may include, in addition, items (viii) to (xi).

- (viii) A Machmeter, whose transducer registers the pressure ratio, p_{p_i}/p_{s_i} , from pressures supplied by (i) and (ii).

* Sensors (i) and (ii) may be combined in a “pitot-static probe”, “pressure” or “airspeed” head.

- (ix) Flow direction sensors, which may be in the form of vanes, or in the form of a multi-hole pressure probe, for angle of attack and sideslip sensing.
- (x) Indicators of angles of attack and sideslip, α_i and β_i , whose transducers register pressures in the case of multi-hole sensors. Where vanes are used, the transducer at each airflow-angle indicator registers the signal supplied by a vane-driven transducer registering angular position.
- (xi) An air data computer, whose inputs are provided by transducers which register the quantities from (i), (ii), (vi) and (ix), can provide calculated values (including, if required, relevant corrections) of heights, airspeeds, Mach numbers, temperatures and airflow angles. Outputs provided to flight-deck displays, whether partially or fully corrected, must be consistent with scheduled operational data.

The sensors referred to in (i), (ii), (vi) and (ix) above, in general do not **sense** true values of total or ambient pressures, total air temperature or flow direction. The differences between “sensed” and true values are termed “sensing errors”, see References 10, 11 and 14. Errors in **transmission** of the sensed air data quantities also may occur before they are registered by transducers described in (iii), (iv), (vii), (viii), (x) and (xi) above, see References 10, 11 and 12.

The series of Data Items (References 10 to 14), to which the present Item is an introduction, provides procedures by which all identified errors are corrected within an overall flight-test analysis method, such as Reference 10, so that true values of pressure height, calibrated airspeed, Mach number and ambient air temperature can be derived. An index to the procedures is given in Table 7.2. For extreme values of Mach number or height ($M > 4$, $H_p > 120\,000$ ft, approx.) different methods of data analysis are required. These are given in Reference 15.

The matters dealt with in this Item are as follows:

Section 3 gives an outline of the notation conventions used.

Section 4 gives general definitions of pressures, temperatures, heights, airspeeds and airflow angles.

Section 5 gives calibration laws for the altimeter, airspeed indicator, Machmeter and ambient air temperature indicator. These laws are required to transform registered quantities into indicated values.

3. NOTATION CONVENTIONS

3.1 “Registered” or “Indicated” Quantities

The subscript “*i*” is applied to notation of air-data-system parameters where values are “registered” (“indicated”) by transducers (instruments), for example p_{p_i} , p_{s_i} , T_{r_i} , M_i , H_{p_i} , V_i , α_i etc. The transducers are assumed free of any calibration or other inherent error and, in the case of pressure transducers, are responding to the registered or output pressure(s) of the static and/or pitot-pressure system(s). Similar assumptions are made for the temperature system. A schematic description of these quantities is as follows.

SYSTEM PART	sensor	transducer/instrument
STATE OF PARAMETER VALUE	“sensed”	“registered”/“indicated”

Where corrections are made for errors introduced by non-steady flight, see References 11 and 12, (the values so corrected being termed “equivalent steady-level-flight” values) the subscript “*i*” is dropped and

replaced by the superscript “’”. For example, “ p_{p_i} ” becomes “ p_p' ” and “ M_i ” becomes* “ M' ”. For steady level flight, the values p_{p_i} , M_i , etc. are identical to p_p' , M' , etc. True values are then derived by making the steady-level-flight corrections (see Section 3.3). The set of parameter notations used here is displayed in Table 7.1 for comparison with those of other authoritative sources.

3.2 True Values of Parameters

A “true” value is obtained when a registered or indicated quantity is corrected for all the errors considered in this series of Data Items. The parameters are then identified by notation without primes or subscript “ i ”, for example, p_p , $p_a^\dagger$, T_r , M , H_p , V_c , V , V_e , α .

3.3 Groupings of Error Summations

Within this series of Data Items it is convenient to group and sum the various errors for identification and calculation procedures. The notation used is as follows.

Flight conditions	Data Item References	Notation for error summations for		
		Pitot pressure	Static pressure	Temperature
Non-steady flight	10, 12, 13	$\Sigma(\delta p_p)_{ns}$	$\Sigma(\delta p_s)_{ns}$	—
Steady level flight	10, 13, 14	$\Sigma(\delta p_p)_{sf}$	$\Sigma(\delta p_s)_{sf}$	—

Calculation procedures in References 10 and 11 do not, in general, require that the temperature errors should be grouped. Note also that in Reference 13, which is not intended for use with extreme values of M or H_p , the following notation is introduced for summations of pressure errors,

$$(\delta p_p)_{TOT} = \Sigma(\delta p_p)_{ns} + \Sigma(\delta p_p)_{sf} \quad (3.1)$$

$$(\delta p_s)_{TOT} = \Sigma(\delta p_s)_{ns} + \Sigma(\delta p_s)_{sf}. \quad (3.2)$$

4. GENERAL DEFINITIONS

4.1 Pressures

Ambient pressure, p_a

Pressure of undisturbed air.

Pitot pressure, p_p

Stagnation pressure sensed by a pitot tube not subject to any sensing errors. In subsonic flow this pressure is equal to total pressure, p_t . In supersonic flow it is the stagnation pressure behind a normal shock, given by the “normal-shock” relationship.

$$p_p = p_a \left[\frac{(\gamma + 1)}{2} M^2 \right]^{\gamma/(\gamma - 1)} \left/ \left[1 + \frac{2\gamma}{(\gamma + 1)} (M^2 - 1) \right]^{1/(\gamma - 1)} \right. \quad (4.1)$$

* By established practice the static pressure in steady level flight is denoted by p_s and not by p_s' . In this case p_{s_i} is identical with p_s for steady level flight.

† The full correction to p_{s_i} takes account of aerodynamic errors due to the aircraft flow-field at the sensor and, on occasions, due also to the sensor orientation, see Reference 14, so that the pressure derived is ambient pressure, p_a .