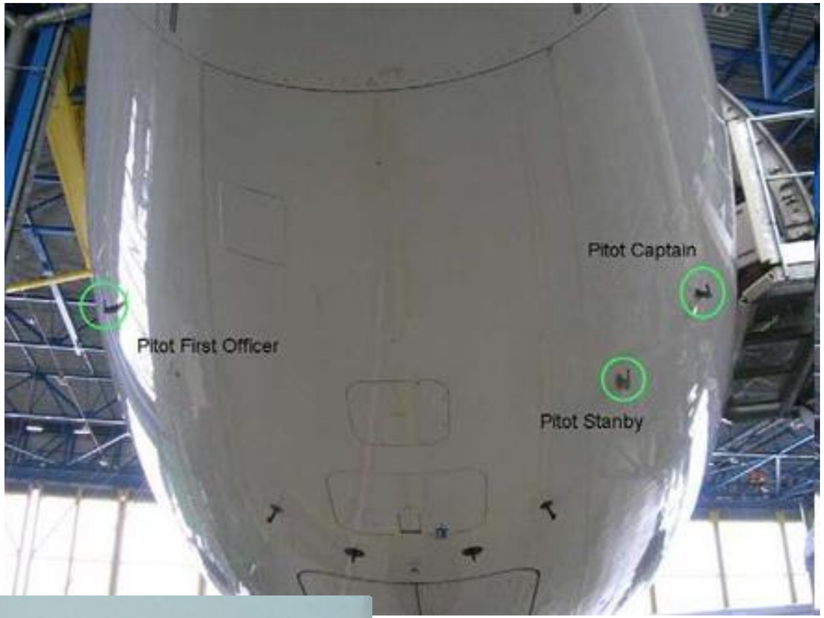
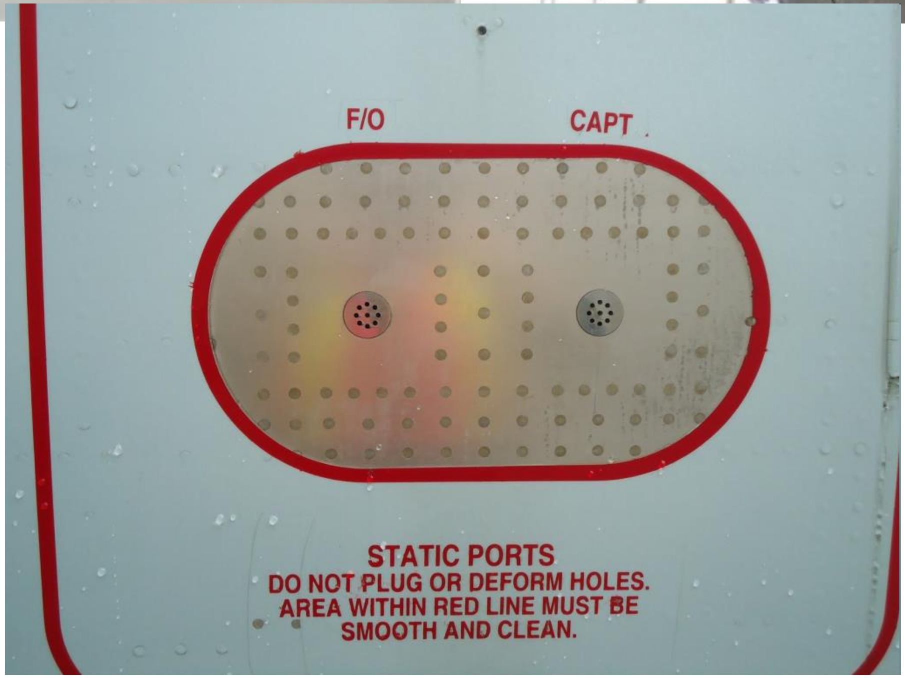
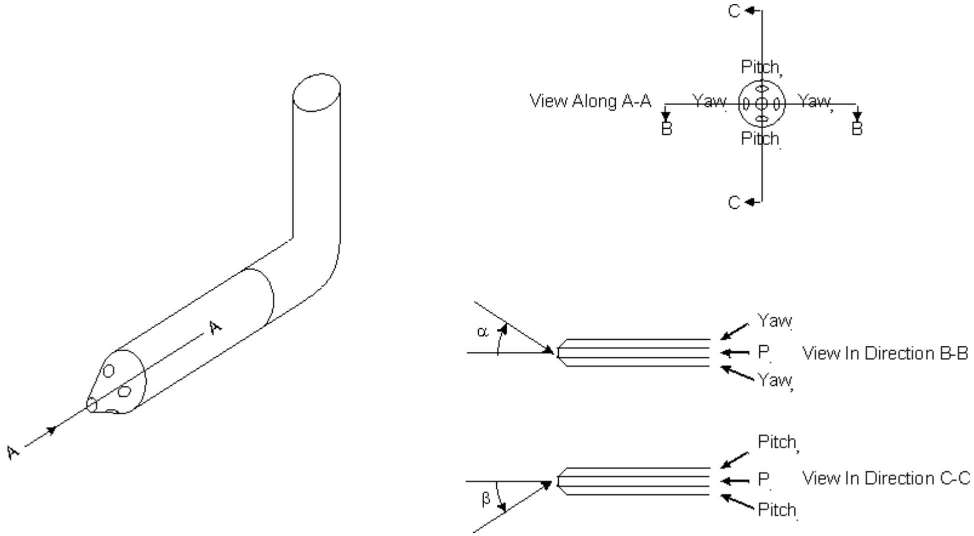
AE 242
Aerospace Measurements Laboratory

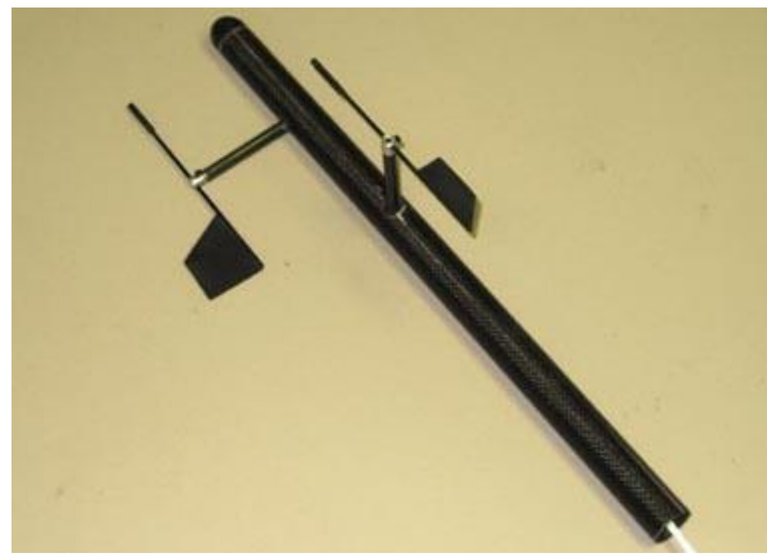
Air data and air data systems





Air data probes - Tejas





Air Angle measurement

Air data and air data systems

Information on : pressure altitude, vertical speed, calibrated airspeed, true airspeed, Mach number, static air temperature and air density ratio.

Information essential for key avionics system

Air data and air data systems

Information on : pressure, altitude, vertical speed, calibrated airspeed, true airspeed, Mach number, static air temperature and air density ratio.

Information essential for key avionics system

Three measurements are done:

1) Total (or pitot) pressure
2) Static pressure
3) Total (or indicated) air temperature

Frome these measurements above quantities are obtained.

Air data and air data systems

Information on : pressure, altitude, vertical speed, calibrated airspeed, true airspeed, Mach number, static air temperature and air density ratio.

Information essential for key avionics system

Three measurements are done:

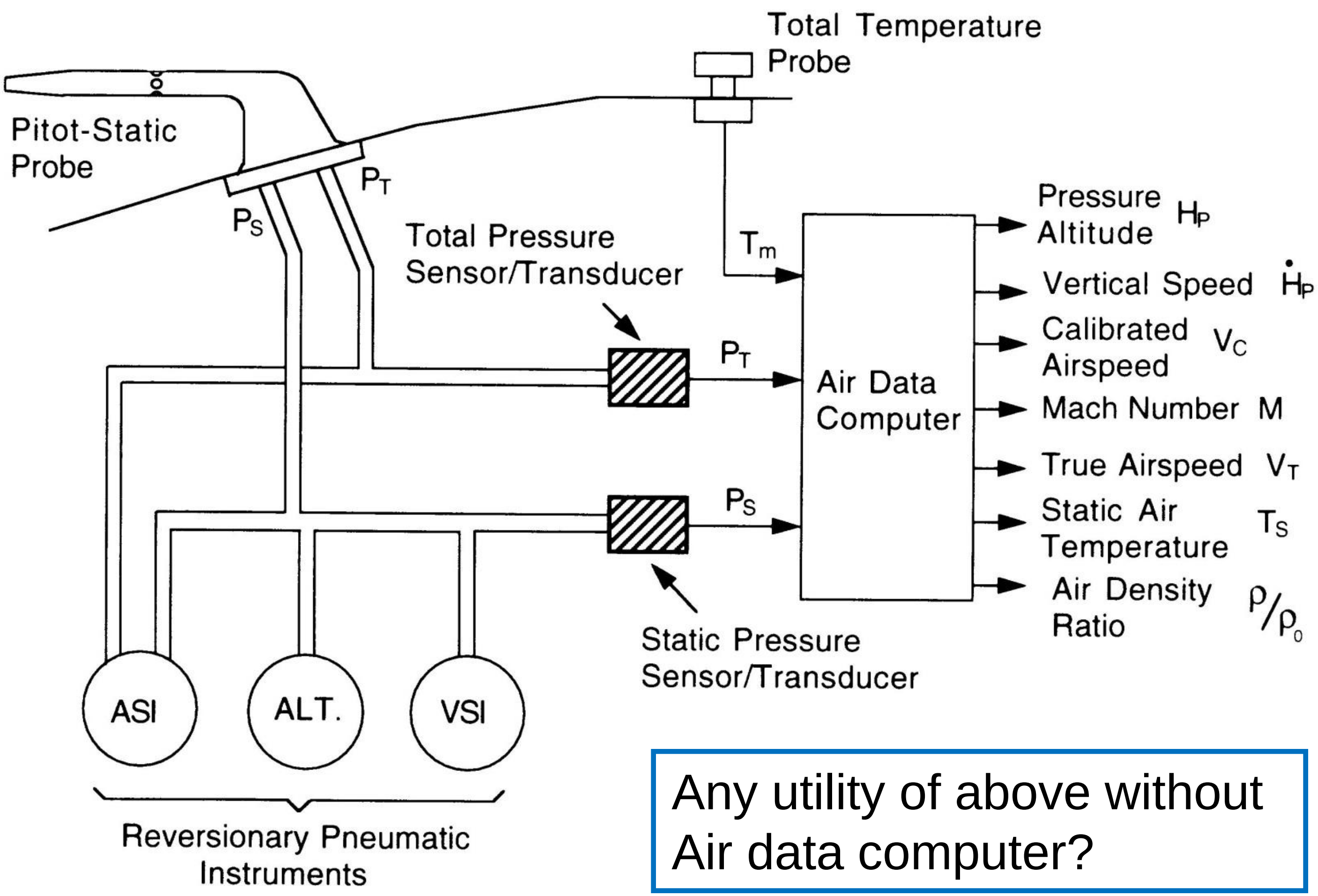
1) Total (or pitot) pressure
2) Static pressure
3) Total (or indicated) air temperature

Total pressure : P_T is measured by absolute pressure sensor. This measures the pressure exerted to bring down air stream to rest plus the static pressure of the free stream.

Static pressure : P_S is measured by an absolute pressure sensor connected to an orifice located where the surface pressure is nearly the same as the pressure of the surrounding pressure.

Air data and air data systems

Airspeed indicator, pressure altitude and vertical speed indicator are directly connected to Pitot and static pressure tapings. For glider, only these measurements are available.



Any utility of above without Air data computer?

Air data and air data systems

From the measurement of static pressure and total pressure following quantities can be derived:

1) Pressure altitude, H_P this is derived from the static pressure by assuming a standard atmosphere.
2) Vertical speed derived by differentiating pressure altitude
3) Calibrated airspeed, V_c Directly from the impact pressure
4) Mach number, M. Ratio of true speed V_T to local speed of sound A. Directly derived from the ratio of total pressure to static pressure

Air data and air data systems

Measured or indicated temperature T_m. It is a measure of free stream air stream temperature. T_s plus the kinetic rise in temperature due to the air being brought partly or wholly to rest relative to temperature sensing probe. When the air brought to totally rest (recovery ratio 1), it is known as total air temperature T_T. Measurement of static temperature can be used for Mach number calculation

Air data quantities and their importance

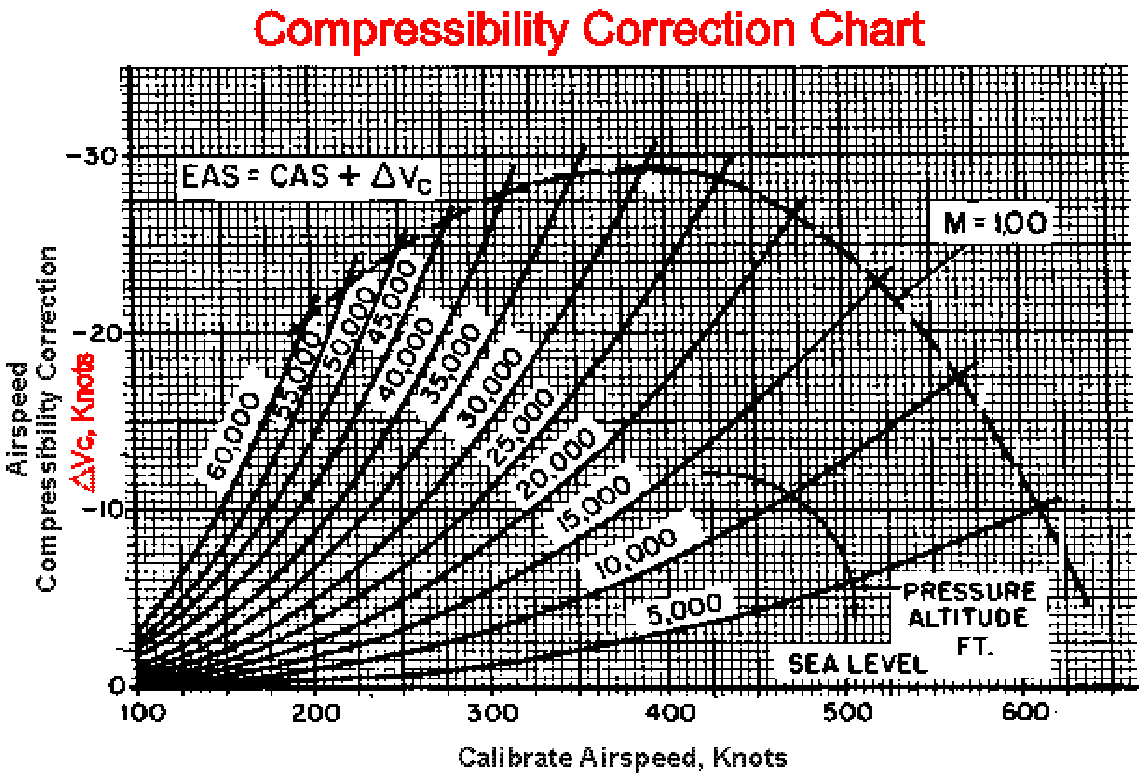
Indicated air speed has three sources of error:

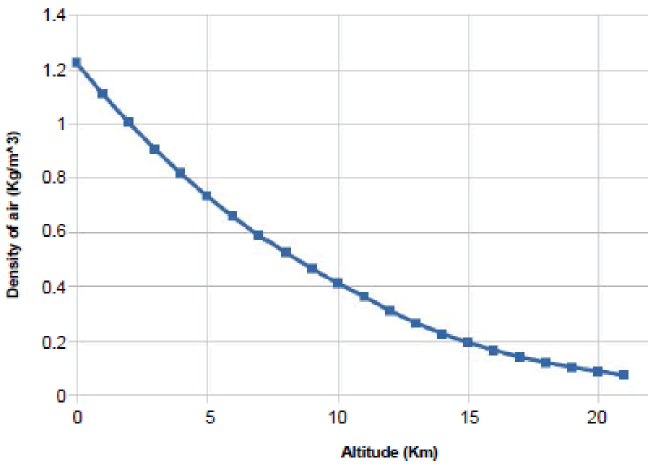
1) Calibration error (position)
2) Compressibility error
3) Density error

1) Calibration error (position) : Pitot tube should be away from any flow distortion, fuselage, wing etc. Static probe should measure actual static pressure and it depends on the location. The error is due to position of pitot and static probes and dependent on flight speed. These errors are minimum for a normal flight speed and maximum for low and high speeds. This error is particular to a aircraft. For static pressure measurement, two or three locations are used, sides of the fuselage, un-pressurised chamber etc.

Air data quantities and their importance

2) Compressibility error (position) :





3) Density error : Density varies (reduces) with altitude. Airspeed indicator is calibrated at sea level and at other altitudes, correction is required. For a same aircraft speed, dynamic pressure is less at higher altitude compared to sea level. At high altitude indicated airspeed will be less compared to true air speed.

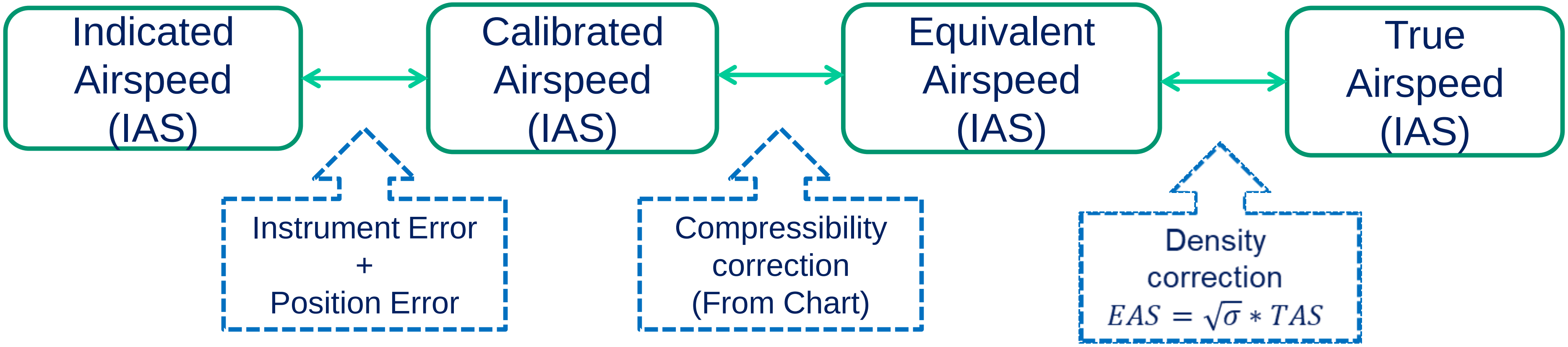
Air data quantities and their importance

Indicated airspeed: Speed as indicated over the dial. This is the direct visual input for pilot. Indicator deflects proportional to dynamic pressure.

Calibrated airspeed – When position errors and sensor errors are incorporated. Dependent on installation of probes.

Equivalent airspeed: When compressibility effects are incorporated in calibrated airspeed. Independent of aircraft.

True Airspeed: When density effect (altitude) is incorporated. Independent of aircraft.



Air data quantities and their importance for pilot

Calibrated air speed: This is the direct measure of impact pressure. Impact pressure and angle of incidence are indicator of aerodynamically generated life, drag and moments. Few of the aircraft parameters are given in terms of calibrated speed: rotation speed for takeoff, stalling speed and not to exceed speed in dive (structural limit).

Accurate measurement of aircraft's altitude is essential for the control of flight path in the vertical plane. Clearance from mountains, hill. During approach and landing, flying in clouds and night.

Pressure altitude: Air Traffic Control needs accurate measurement of pressure altitude for air traffic control. By this data safe vertical separation can be created. Pressure altitude will be same for all the aircraft at same altitude. ATC pressure altitude should be matched with pilot's altimeter.

True Airspeed: It is important for navigation purposes.

Air data quantities for pilot

<u>Mach number:</u> Aircraft behaves differently in subsonic and supersonic conditions. Performance and controllability is dependent on this. It is also used by many subsystems. Important for aircraft flying supersonic

<u>Vertical speed or rate of climb/descent:</u> It is important during the ground approach. It is also important during the turn to detect any tendency to lose height.

<u>Angle of incidence:</u> Same as angle of attack, it is important to monitor and avoid stall. At stall aircraft loses lift suddenly.

Air data for key subsystems

Air traffic control transponder: This reports automatically pressure altitude to ATC. Vertical separation of 1000 feet below 29000 feet and 2000 feet above 29000 feet. Pressure altitude may differ with true altitude or standard atmosphere due to variation in day to day conditions. Error is removed close to ground when ground pressure corrections is applied and it is large at higher altitude.

Flight control systems: Calibrated airspeed and pressure altitude is important for FCS. Automatic adjustment of gains for different airspeed and altitude. Also known as air data gain scheduling.

Autopilot system: Altitude hold/acquire, Mach number hold/acquire etc.

Navigation system: Pressure altitude for vertical navigation, mixed with inertial measurement. Velocity vector of aircraft is derived by mixing inertial velocity data and air data.

Flight management system: Required for most fuel efficient flight path.

Engine control system: Air density and airspeed are important for engine control.

Standard Atmosphere

Table 7.1 Pressure–altitude law constants.

Constant	Standard atmosphere value
Pressure at sea level, P_{S0}	101.325 kPa (1013.25 mb)
Temperature at sea level, T_0	288.15°K
Troposphere lapse rate, L	6.5×10^{-3} °C/m
Tropopause height, H_T	11,000 m (36,089.24 ft)
Tropopause temperature, T_{T*}	216.65°K (–56.5°C)
Stratopause height, H_S	20,000 m (65,617 ft)
Chemosphere rise rate, L	1.0×10^{-3}°C/m
Chemosphere height limit	32,004 m (105,000 ft)
g_0	9.80665 m/sec^2
R_a	287.0529 Joules/°K/kg
g_0/LR_a (Troposphere)	5.255879
g_0/R_aT	1.576885×10^{-4} m^{-1}
g_0/LR_a (Chemosphere)	34.163215

(a) *Troposphere region*: –914.4 to 11,000 m (–3,000 to 36,089 ft)

$$P_S = 1{,}013.25(1 - 2.25577 \times 10^{-5} H_P)^{5.255879} \text{ mb}$$

(b) *Stratosphere region*: 11,000 to 20,000 m (36,089 to 65,617 ft)

$$P_S = 226.32\, e^{-1.576885 \times 10^{-4}(H_P - 11{,}000)} \text{ mb}$$

(c) *Chemosphere region*: 20,000 to 32,004 m (65,617 to 105,000 ft)

$$P_S = 54.7482[1 + 4.61574 \times 10^{-6}(H_P - 20{,}000)]^{-34.163215} \text{ mb}$$

Static pressure and pressure altitude relationship

Table 7.3 Air data formulae.

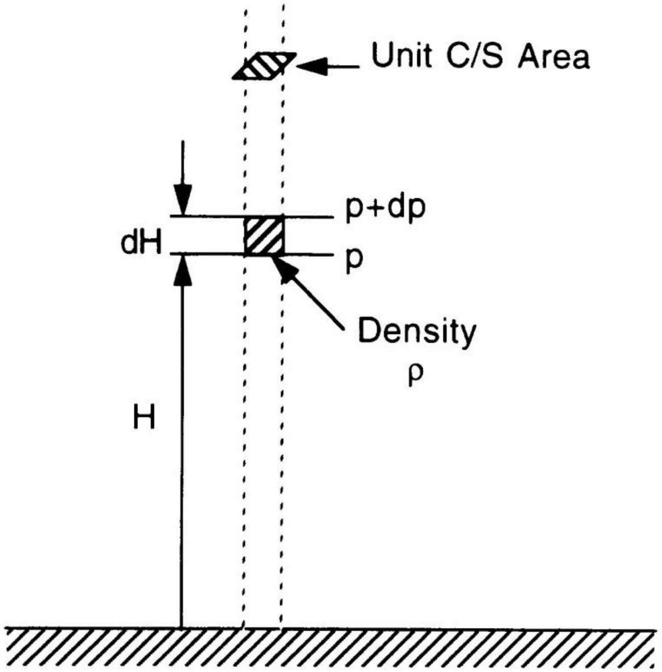
Quantity	Computational formulae
Geopotential pressure altitude H_P metres	(a) Troposphere 0–11,000 m (0–36,089 ft) $P_s = 101.325(1 - 2.25577 \times 10^{-5} H_P)^{5.225879}$ kPa (b) Stratosphere 11,000–20,000 m (36,089–65,617 ft) $P_S = 22.632\, e^{-1.576885 \times 10^{-4}(H_P - 11{,}000)}$ kPa
Air density ratio $\dfrac{\rho}{\rho_0}$	$\dfrac{\rho}{\rho_0} = \dfrac{P_S}{0.35164 T_S}$
Mach number M	(a) Subsonic speeds ($M \leq 1$) $\dfrac{P_T}{P_S} = (1 + 0.2M^2)^{3.5}$ (b) Supersonic speeds ($M > 1$) $\dfrac{P_T}{P_S} = \dfrac{166.92 M^7}{[7M^2 - 1]^{2.5}}$
Calibrated airspeed V_C m/s	(a) $V_C \leq A_0$ $Q_C = 101.325 \left[\left[1 + 0.2 \left(\dfrac{V_C}{340.294} \right)^2 \right]^{3.5} - 1 \right]$ kPa (b) $V_C > A_0$ $Q_C = 101.325 \left[\dfrac{166.92 \left(\frac{V_C}{340.294} \right)^7}{\left[7 \left(\frac{V_C}{340.204} \right)^2 - 1 \right]^{2.5}} - 1 \right]$ kPa
Static air temperature T_S °K	$T_S = \dfrac{T_m}{1 + r0.2M^2}$ °K
True airspeed V_T m/s	$V_T = 20.0468 M \sqrt{T_S}$ m/s

Altitude-static pressure relationship

Standard atmosphere defines the altitude above sea level as a single valued function. It is based on statistical data.

$$-\frac{dp}{P} = \frac{g}{R_a T} dH$$

R_a is gas constant of dry air



Temperature decreases linearly with altitude until troposphere.

$$T = T_0 - LH$$

T_0 temperature at sea level

L is temperature lapse rate 6.49 deg / km

$$P_s = P_{s0}\left(1 - \frac{L}{T_0} H\right)^{g_0/(LR_a)}$$

P_{S0} - Pressure at sea level

Air density vs Altitude relationship

Relationship between air density at any altitude and sea level air density

$$\frac{\rho}{\rho_0} = \left(1 - \frac{\mathbf{L}}{\mathbf{T}_0}\mathbf{H}\right)^{-1+\mathbf{g}_0/(\mathbf{L}\mathbf{R}_\mathbf{a})}$$

In practice air density is calculated from measured static pressure and static temperature.

$$\frac{\rho}{\rho_0} = \frac{\mathbf{P}_\mathbf{S}}{\mathbf{P}_{\mathbf{S}0}} \frac{\mathbf{T}_0}{\mathbf{T}_\mathbf{S}}$$

$$\mathbf{T}_\mathbf{S} = \mathbf{T}_\mathbf{m} / (1 + \mathbf{r}0.2\mathbf{M}^2)$$

T_m – Measured temperature

Speed of sound

Speed of sound A is related to gas constant, temperature

$$\mathbf{A} = \sqrt{\gamma \mathbf{R_a T}}$$

Speed of sound at standard pressure and temperature

$$340.294\,\mathbf{m/s} = \sqrt{1.4\,\mathbf{x}\,287.0529\,\mathbf{x}\,288.15}$$

Speed of sound reduces with increase in altitude in troposphere and remains constant in stratosphere

Speed of sound at any altitude, A_0 is speed of sound at sea level.

$$\mathbf{A} = \mathbf{A}_0 \sqrt{1 - \frac{\mathbf{L}}{\mathbf{T}_0}\mathbf{H}}$$

Pressure-speed relationships

Relationship between total pressure, static pressure, true airspeed and local speed of sound

For Mach number < 1

$$Q_C = P_S\left[\left(1+0.2\frac{V_T^2}{A^2}\right)^{3.5}-1\right]$$

For Mach number > 1

$$Q_C = P_S\left[\frac{166.92(V_T/A)^7}{\left[7(V_T/A)^2-1\right]^{2.5}}-1\right]$$

For subsonic speed. Static pressure and total pressure relationship

$$\frac{\mathbf{P_T}}{\mathbf{P_S}} = (1+0.2\mathbf{M}^2)^{3.5}$$

For supersonic speed. Static pressure and total pressure relationship

$$\frac{\mathbf{P_T}}{\mathbf{P_S}} = \frac{166.92\mathbf{M}^7}{(7\mathbf{M}^2-1)^{2.5}}$$

Calibrated airspeed

It can be obtained by following relationship

For Mach number < 1

$$Q_C = P_S\left[\left(1+0.2\frac{V_C^2}{A^2}\right)^{3.5} - 1\right]$$

For Mach number > 1

$$Q_C = P_{S0}\left[\frac{166.92(V_C/A_0)^7}{\left[7(V_C/A_0)^2-1\right]^{2.5}} - 1\right]$$

Static air temperature

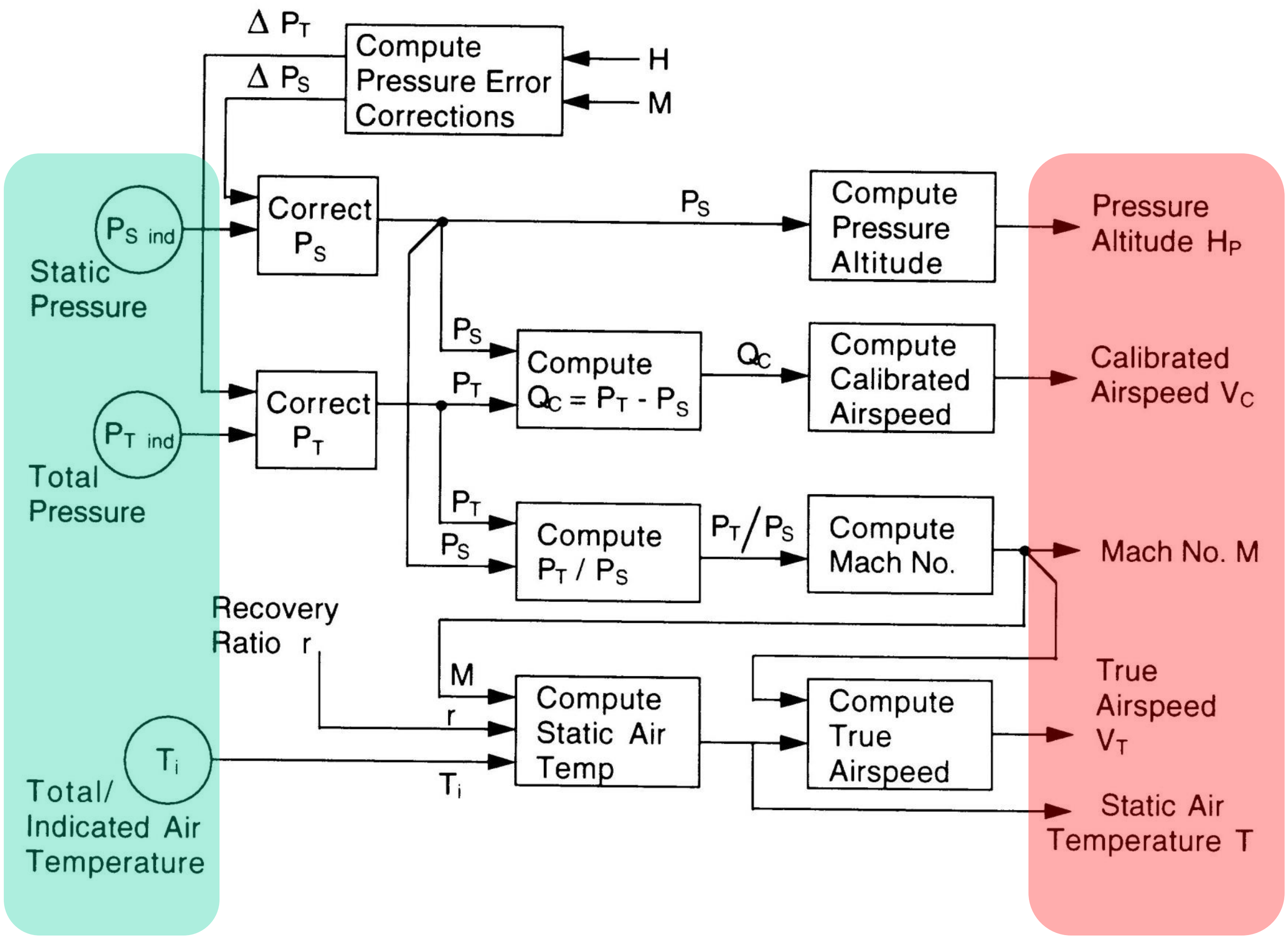
Any temperature measurement device will measure free air stream temperature plus the kinetic temperature due partial or full stagnation of air

$$T_S = \frac{T_M}{(1+r0.2M^2)}$$

Recovery factor r is assumed constant, it can vary slightly due to change in heat transfer due to altitude. Large errors can occur when flying through clouds and rain.

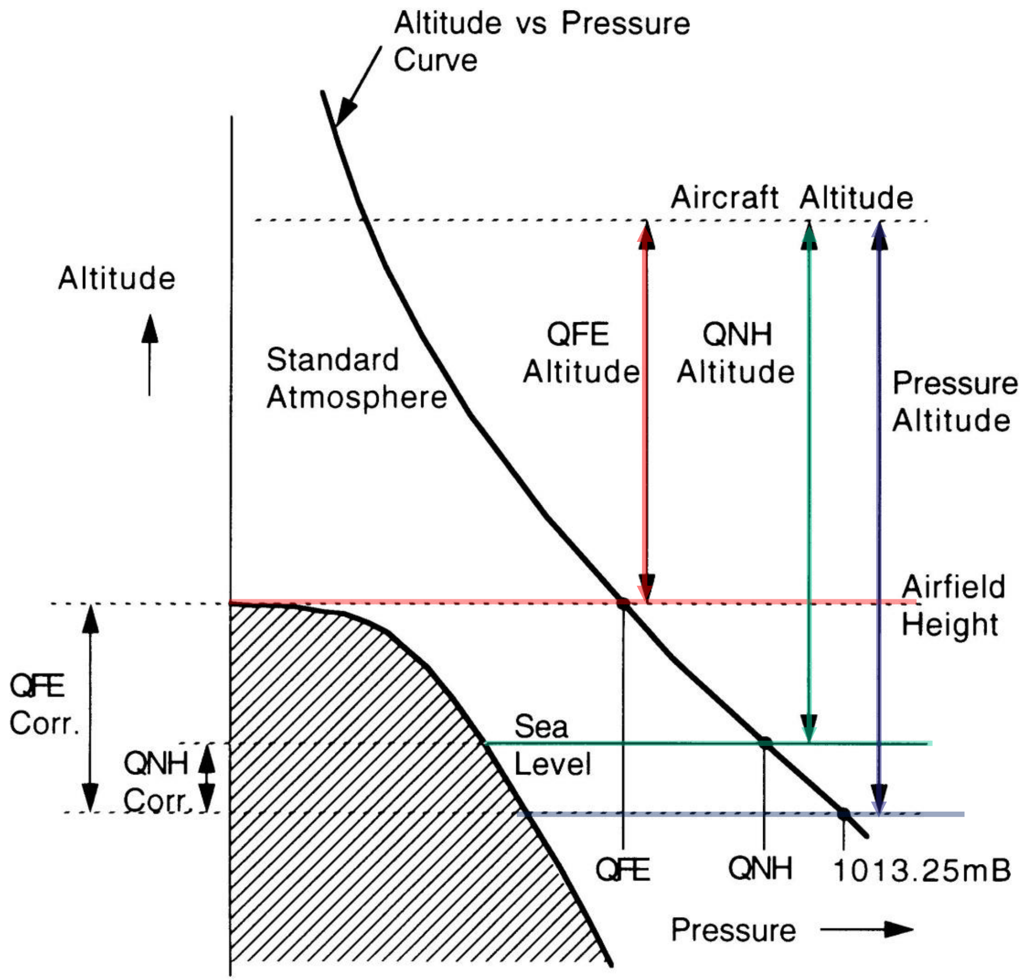
Air data computation flow diagram

Used in modern aircraft. Most of the data stored as lookup tables.



Altimeter ground pressure adjustment

QFE means above ground level (field elevation) and QNH means above sea level. Local pressure altitude(ground level) could be different compared to standard atmosphere. The information about QNH correction is given by ATC.



Altimeter ground pressure adjustment

QFE : means height above ground level (field elevation)

QNH means altitude above mean sea level.

QNE means altitude by standard atmosphere also known as flight level. Aircraft will fly at QNE altitude above transition altitude. Different airports may have different transition altitude (4000 ft for airports close to sea level altitude).

At transition level pilot gives correction for QNH to obtain QFE. This will give height above ground and it will be zero when aircraft is on runway..

Some incidents related to QNH setting reported here:

https://www.skybrary.aero/index.php/Altimeter_Setting_Procedures

Accuracy requirements

Static pressure sensor: 0 – 130 kPa, required to operate from –60C^o to +90C^o

$$dH = -\frac{RT}{g}\frac{1}{P_S}dP_S$$

Effect of 100 Pa (1 mb) error in static pressure measurement at sea level is equal to

$$8.32\mathbf{m} = \frac{287.0529\mathbf{x}288.15}{9.80665}\frac{1}{1013.25}1$$

Effect of 100 Pa (1 mb) error in static pressure measurement at an altitude of 13,000 m (42, 650 ft) when the static pressure is 16.5 kPa (165 mb)

$$38.43\mathbf{m} = \frac{287.0529\mathbf{x}216.65}{9.80665}\frac{1}{165}1$$

Inherent error due to installation could be of the order of 100 – 150 Pa, this put more stringent requirement on pressure sensor error < 30 Pa

Accuracy requirements

Total pressure sensor: Full scale pressure range 0 – 260 kPa (0-2600mb). 260 kPa corresponds to 426m/s at sea level.

Impact pressure, difference of total and static pressure

$$\mathbf{Q_C} = \frac{1}{2}\rho \mathbf{V_T^2}$$

$$\mathbf{dQ_C} = \rho \mathbf{V_T} \mathbf{dV_T}$$

Requirement for the measurement of airspeed to an accuracy of 0.5 m/sec at an approach speed of 50 m/sec

$$\mathbf{dQ_C} = 1.225\mathbf{x}50\mathbf{x}0.5 = 30.6\mathbf{Pa}$$

Maximum error in each sensor must be less than 15 Pa (0.15 mb) to get the required accuracy at 50 m/sec and it will be more demanding as the speed reduces.

Five hole probe

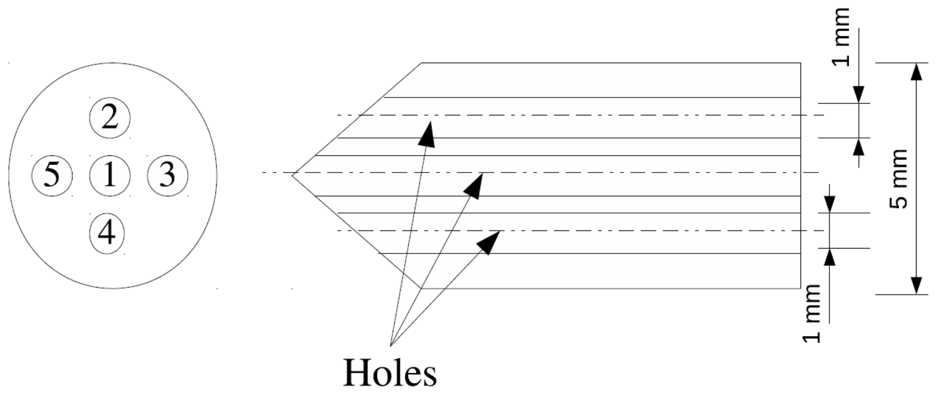


Figure 2.5: Schematic of five-hole probe

Figure 2.6: Five-hole probe

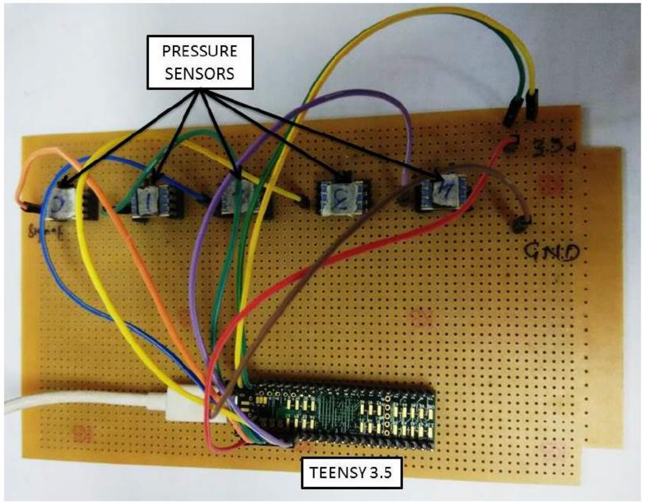


Figure 2.8: Pressure sensors and Teensy 3.5 board

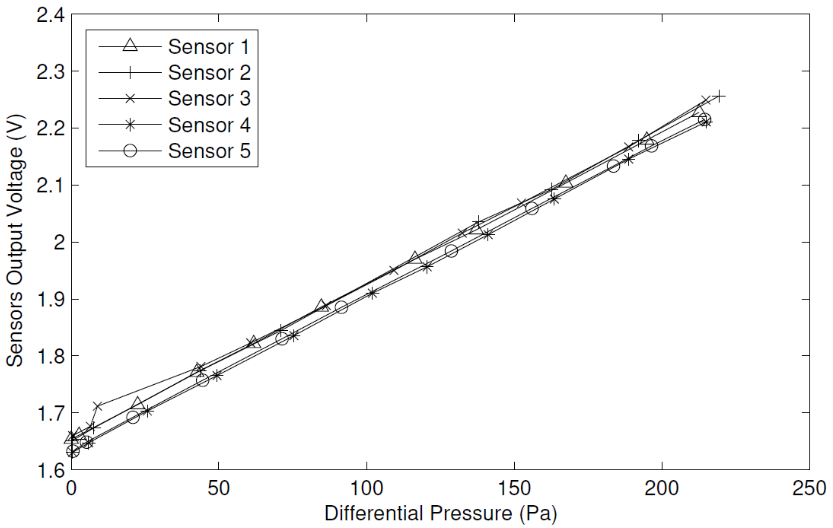
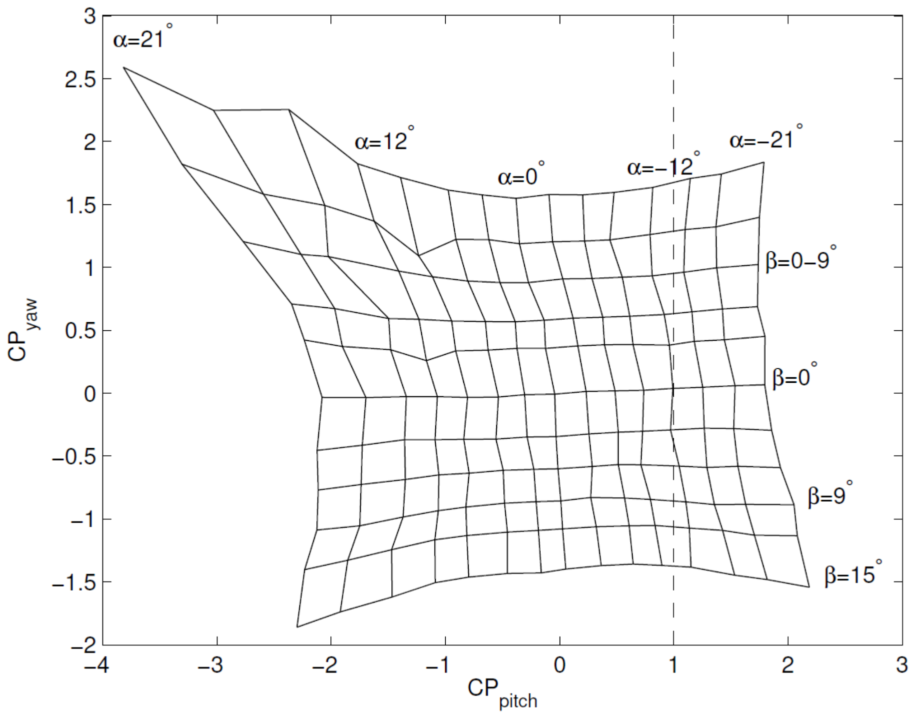


Figure 2.9: Calibration curves of different pressure sensors

Five hole probe



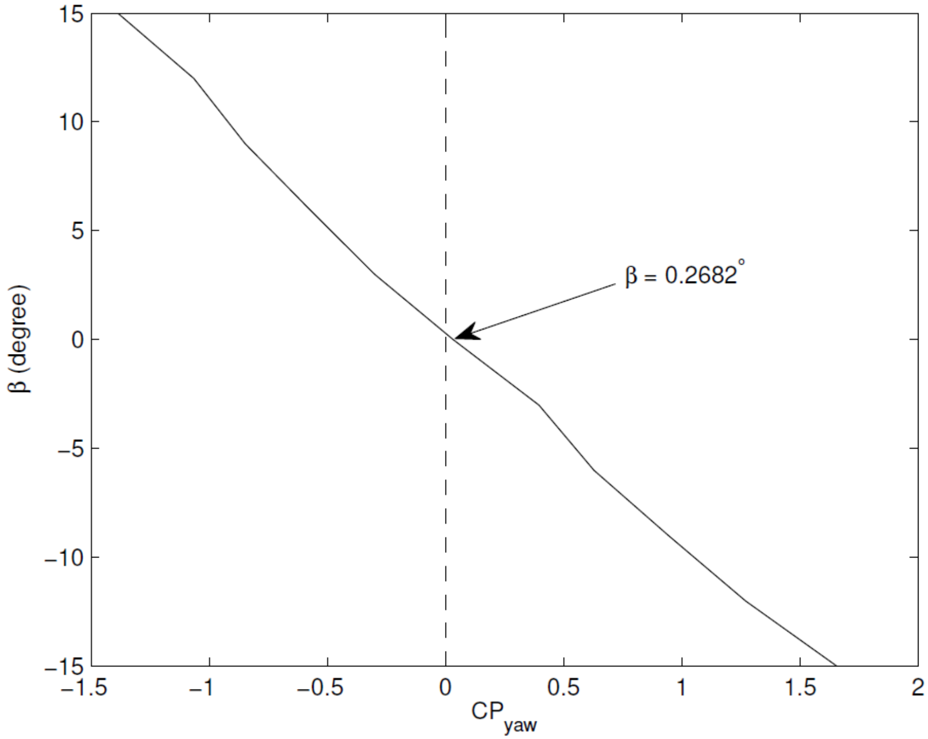


Figure 2.11: $C_{P_{beta}}$ vs β

$$C_{P_{pitch}} = \frac{P_2 - P_3}{P_1 - \bar{P}}$$

$$\bar{P} = \frac{P_2 + P_3 + P_4 + P_5}{4}$$

$$V = \frac{\sqrt{\frac{2P_1}{\rho}}}{\cos\alpha\cos\beta}$$

$$C_{P_{yaw}} = \frac{P_4 - P_5}{P_1 - \bar{P}}$$

Five hole probe

Figure 2.4: Wings level test of Bixler