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Thesis

Evaluation of Flight Test Methods for the Calibration of the Pressure Measured through a Static Port

in co-operation with:

DaimlerChrysler Aerospace Airbus GmbH, Hamburg

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Report handed in: 5th July 2000

Detailed arrangement for confidential information:

Duration of confidence: 12 months
Data of the A3XX may not be passed on

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Abstract

The measurement of the static pressure is required on board of aircrafts for the evaluation of altitude, vertical speed, speed, and Mach number. On the series aircraft, the static pressure is measured through a port in the aircraft fuselage. Several methods are available for the flight test calibration of the pressure measured through such a static port. These methods are described and evaluated for an application in civil flight test programs of transport category aircrafts. Different evaluation criteria are considered. The achievable accuracy of the calibration methods is one evaluation criterion of high importance. The applicable standards (FAR, JAR, ICAO) are discussed. Based on these standards, the acceptable error of the calibration methods are determined. For flight test calibration methods performed directly on the aircraft, the achievable accuracy depends on the position where measurements are taken. Possible measurement positions are e.g. in front of the aircraft nose, on the wing tip, or at the fin. The flow at each of these positions shows a different rate of disturbance by the aircraft itself. Flow disturbance rates are calculated in this thesis based on aerodynamic data predicted for the Airbus A3XX. The evaluation finally identifies a laser-based system offered by *Kayser Threde* as the most promising candidate for the calibration of the pressure measured through the static port.

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DEPARTMENT OF AUTOMOTIVE AND AEROSPACE ENGINEERING
Course in Aerospace Engineering

Evaluation of Flight Test Methods for the Calibration of the Pressure Measured through a Static Port

Diplomarbeit in compliance with § 21 of "Ordnung der staatlichen Zwischen- und Diplomprüfung in den Studiengängen Fahrzeugbau und Flugzeugbau an der Fachhochschule Hamburg"

Background

As part of the development and certification process performed jointly by the Airbus partners, it is necessary to calibrate the air data system. One task requires the measurement of the true static pressure not influenced by the aircraft itself. This task is performed today by means of a trailing cone system. The trailing cone with its pressure ports is connected to the fin of the aircraft with a tube, measuring approximately 150 m in length. The tube has to be extended and retracted in flight which requires the operation of an electrical winch. Future aircraft programs like the A3XX or the A400M might even require longer tubes to ensure measurements in the undisturbed atmosphere.

Task

- Compilation of requirements for static pressure measurements.
- Review and research in the area of static pressure measurement techniques.
- Evaluation and comparison of the static pressure measurement techniques (this may include small tests of selected techniques).
- Selection of a measurement technique.
- Integration of the selected technique into a selected aircraft considering:
  - aerodynamic and vibration parameters as well as component weight,
  - 3D integration tests checking for conflicting space requirements of aircraft components.
- Documentation of the selected flight test instrumentation and measurement technique consisting of a system specification, a wiring diagram, a functional description, assembly procedures, calibration procedures, recurring and non-recurring cost calculation.

The results have to be documented in a report. The report has to be written in a form up to internationally excepted scientific standards. The application of the German DIN standards is one excepted method to achieve the required scientific format.

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List of abbreviations

A/C	Aircraft
ADIRS	Air Data/Inertial Reference System
ADIRU	Air Data/Inertial Reference Unit
ADM	Air Data Module
AGL	Above ground level
AI	Airspeed indicator
ALTI	Altimeter
AMC	Aerodynamic mean chord
AOA	Angle Of Attack
APU	Auxiliary power unit
ARGARD	ADVISORY GROUP FOR AEROSPACE RESEARCH & DEVELOPMENT
ASI	Air Speed Indicator
CAPT	Captain
CAS	Calibrated airspeed
CL	Center line
DASA	DaimlerChrysler Aerospace Airbus GmbH
DDRMI	Digital Distance and Radio Magnetic Indicator
EAS	Equivalent airspeed
EFIS	Electronic Flight Instrument System
ESA	European Space Agency
F/O	First Officer
FAR	Federal Aviation Regulations
FL	Flight level
FRL	Fuselage Reference Line
GPS.	Global Position System
I.C.A.O.	International Civil Aviation Organization

IAS	Indicated airspeed
ISA	International Standard Atmosphere
JAR	Joint Aviations Requirements
MSL	Mean Sea Level
MSU	Mode Selector Unit
MTOW	Maximum Take-off Weight
SCG	System Configuration Guide
STBY	Stand by
SWP	Sweep
TAS	True airspeed
TAT	Total Air Temperature

List of symbols

a	Speed of sound
b	Starting point of a function
C	Origin of the coordinate system
Cp	Specific thermal capacity with constant pressure
c_p	Dimensionless pressure coefficient
Cv	specific thermal capacity with constant temperature
D	Diameter
E	Productivity
f	Focal length or function
g	Gravity
h	Height
l	Length
L	Lift
M	Molecular weight
m	Gradient
Ma	Mach number
n	Polytropic exponent
p	Pressure
P	Point
q	Dynamik pressure
R	Special gas constant
r	Radius or distance related to a point
R^*	Universal gas constant
t	Temperature in °C
T	Temperature in °K
v	velocity
x	Coordinate
y	Coordinate
z	Coordinate

List of Greek symbols

α	Angle or angle of attack
β	Angle or sideslip angle or backscatter ratio
Δ	Difference
ε_t	Wing twist angle
Φ	Potential of the velocity field
Γ	Vortex
η	
φ	Angle
κ	Isentropic exponent
λ	Wavelength
ν	Dihedral angle
ρ	Density
ξ	Distance ratio
Ψ	flow function

List of indices

∞	Undisturbed parameter
0	Standard value
c	Circulation
cal	Calibrated
comp	Compressible
e	Equivalent
h	Horizontal
i	Indicated
inc	Incompressible
m	Mean
Mo	Maximal operating
t	Total or true
tol	Permissible/ tolerance
v	Vertical
w	Wing

1 Introduction

For the certification of any aircraft, according to the relevant standards (FAR/JAR), the static-port must be calibrated in the test flight among other things. This working out concerns with the interpretation of these standards and the permissible faults resulting from it. The reasons for a calibration are because of a disturbed behavior of the incident flow. These are caused by the fuselage and the wing of an aircraft. Since the static pressure serves the basis determination of the height and for the speed measurement, it is to be determined to discover a very accurate value.

Furthermore the aerodynamic bases for a calculation of the environment parameters are presented and applied to the geometry of the Airbus A3XX.

The target of this working out is to find, by an assessment of different procedures for the calibration, a possible suitable method for the calibration. This method is to represent a simple and economical alternative, in relation to the systems so far used by Airbus. The method should be applicable flexibly also on different types of aircraft. From this connection, became this working out establishes for the department of ETF (flight test installation) at DASA Hamburg.

3 The theoretical foundations

Within the following subchapter, the theoretical bases for the different calibration procedures are regarded and described.

3.1 The atmosphere and the ISA

Although the atmosphere consists of different gases, each of these gases has different characteristics, this mixture can be regarded as an independent and ideal gas. However since the atmosphere is a subject of dynamic fluctuations a comparability is to be guaranteed. This guaranty was introduced by the I.C.A.O. (International Civil Aviation Organization) and they called it international standard atmosphere (ISA). If the print-out “standard atmosphere” or “norm atmosphere” is used in any standards for the airworthiness of aircrafts, at or after the 12. November 1966 their meaning is according to the **flugsport 1999** as described next:

a) air is a perfect, dry gas:

b) the physical constants are:

Central molecular weight at sea level:

$$M_o = 28{,}9644 \cdot 10^{-3} \frac{kg}{Mol} \tag{3.1}$$

Air pressure at sea level:

$$p_0 = 1013{,}25\, mbar = 1{,}013250 \cdot 10^5 \frac{N}{m^2} \tag{3.2}$$

Temperature at sea level:

$$\begin{aligned} t_0 &= 15°C\,(59°F) \\ T_0 &= 288{,}15°\,K \end{aligned} \tag{3.3}$$

Atmospheric density at sea level:

$$\rho_0 = 1{,}2250 \frac{kg}{m^3} \tag{3.4}$$

Temperature of the Ice point:

$$T_i = 273{,}15°\,K \tag{3.5}$$

Universal gas constant:

$$R^* = 8{,}31432 \frac{N \cdot m}{Mol \cdot K} \tag{3.6}$$

Height of the homogeneous atmosphere in according to [GERSTEN S.38]:

$$h_0 = \frac{p_0}{\rho_0 \cdot g} = 8434m \tag{3.7}$$

polytropic exponent in according to [GERSTEN S.38]:

$$n = 1{,}235 \tag{3.8}$$

Special gas constant:

$$R = \frac{R^*}{M_o} = \frac{8{,}31432}{28{,}9644 \cdot 10^{-3}} \left[\frac{\left(\frac{N \cdot m}{Mol \cdot K} \right)}{\left(\frac{kg}{Mol} \right)} \right] = 287{,}053 \frac{N \cdot m}{kg \cdot K} \tag{3.9}$$

c) the temperature

the temperature gradient of 5000 meters under sea level up to a height over sea, where the air temperature becomes -56,5 °C, amounts -0,0065 °C per meter; by this surface (11000 meter) up to a height over sea of 20000 meters the temperature gradient amounts to zero (0), and from 20000 to 32000 meters amounts the temperature gradient to +0,0010 °C per meter.

The further physical formulas can be inferred from the relevant literature as follows.

$$\frac{p}{\rho} = R \cdot T \tag{3.10}$$

(thermodynamic equation of state for ideal gases according to **Schlichting 1967** p. 4)

For the calculation of different changes in status of a gas first of all two changes in status are emphasized. On the one hand the isotherm change in status is to be mentioned. During this change in status it is assumed that the temperature is constant. For this case is the connection between pressure and density:

$$\frac{p}{\rho} = const. \tag{3.11}$$

(isotherm connection of pressure and density according to **Schlichting 1967** p. 5)

Hence the density is proportional to the pressure.

On the other hand the isentropic (adiabatic-reversible) change in status is to be emphasized. During this change in status it is assumed that no heat exchange with the environment effected and heat produced by friction remains unconsidered.
In this case is the connection between pressure and density given through:

$$\frac{p}{\rho^{\kappa}} = const. \tag{3.12}$$

(isentropic connection of pressure and density according to **Schlichting 1967** p. 5)

The isentropic exponent κ is calculated by

$$\kappa = \frac{c_p}{c_v} \tag{3.13}$$

(isentropic exponent according to **Schlichting 1967** p. 5)

whereby *Cp* and *Cv* mean the specific thermal capacity with constant pressure respectively constant volume. For air is the isentropic exponent as follows:

$$\kappa = 1{,}405 \tag{3.14}$$

(isentropic exponent of air according to **Schlichting 1967** p. 5)

$$c_p = \frac{\kappa \cdot R}{\kappa - 1} = \frac{1,4 \cdot 287,053}{1,4 - 1} = 1004,68 \left[\frac{N \cdot m}{kg \cdot K} \right] \tag{3.15}$$

$$c_v = c_p - R = 1004,68 - 287,053 = -717,627 \left[\frac{N \cdot m}{kg \cdot K} \right] \tag{3.16}$$

(specific thermal capacity with constant pressure respectively constant volume according to **Schlichting 1967** p. 150)

According to **Schlichting 1967** (p. 7) the LAPLACE formula for the speed of sound is

$$a^2 = \frac{dp}{d\rho} \tag{3.17}$$

If this formula with the isentropic equation of state and the thermodynamic equation of state for ideal gases is extended, the speed of sound can be described over a simple relationship as a function of the temperature.

$$a = \sqrt{\kappa \cdot R \cdot T} = \sqrt{\kappa \cdot \frac{p}{\rho}} \tag{3.18}$$

(isentropic formula for the speed of sound according to **Schlichting 1967** p. 7)

For the calculation of the atmospheric height we must consider the acceleration due to gravity *g*, since this size is dependent on the height. In according to **Dubs 1990** (p. 25)

$$g = g_0 \cdot \left(\frac{r_0}{r_0 + h} \right)^2 \tag{3.19}$$

with the middle radius of the earth

$$R = r_0 = 6{,}371210 \cdot 10^6 \, m \tag{3.20}$$

$$g_0 = 9{,}807 \frac{m}{s^2} \tag{3.21}$$

For the calculations in the flight technique, according to **Dubs 1990** (p. 25) it is generally calculated with g_0 within the range of the earth's surface to 20 km height.

$$\frac{p}{p_0} = \left(1 - \frac{n-1}{n} \cdot \frac{h}{h_0} \right)^{\frac{n}{n-1}} \tag{3.22}$$

(polytropic height formula following according to **Gersten 1991** p. 37)

$$h(p) = \frac{n}{n-1} \cdot h_0 \cdot \left(1 - \left(\frac{p}{p_0} \right)^{\frac{n-1}{n}} \right) \tag{3.23}$$

(polytropic height formula according to **Eck 1988** p. 8)

$$\frac{\rho}{\rho_0} = \left(1 - \frac{n-1}{n} \cdot \frac{h}{h_0} \right)^{\frac{1}{n-1}} \tag{3.24}$$

(polytropic density process following **Gersten 1991** p. 37)

$$\frac{T}{T_0} = 1 - \frac{n-1}{n} \cdot \frac{h}{h_0} \qquad (3.25)$$

(polytropic temperature gradient following **Gersten 1991** p. 37)

$$\frac{v^2}{2} + \frac{p}{\rho} + g \cdot h = const. \qquad (3.26)$$

(Bernoulli’s equation for compressible flows according to **Schlichting 1967** p.38)

The dimensionless ratio of flow velocity *v* to the speed of sound *a* is called Mach number (designated according to E. Mach, 1838 to 1916 and imported from Prof. J. Ackeret). It is the result of the so-called Mach' scaling law and represents thereby the substantial similarity characteristic of compressible fluid mechanics, i.e. different flow processes are comparable together in the gas dynamics only if their Mach numbers *Ma* are equal.

$$Ma = \frac{v}{a} = \frac{v}{\sqrt{\kappa \cdot R \cdot T}} \qquad (3.27)$$

(Mach number according to **Schlichting 1967** p. 13)

According to **Schlichting 1967** (p. 13) air can be treated as incompressible medium in the speed range under Mach = 0,3. For this case Bernoulli's equation (of 1738) can be used.

$$p_t = p + \frac{\rho}{2} \cdot v^2 = p + q \qquad (3.28)$$

(Total pressure= static pressure + kinetic pressure)

For speeds over Mach = 0,3 this formula must be expanded according to **Dubs 1990** (p. 43) with a correction considers the factor of the compressibility.

$$p_t = p + q + \Delta q = p + q + \left(\frac{q}{4} \cdot Ma^2\right) = p + q \cdot \left(1 + \frac{Ma^2}{4}\right) \tag{3.29}$$

The temperature rise of a gas by compression can be expressed according to **Schlichting 1967** (p. 9) as follows.

$$\Delta T = T_t - T_\infty = \frac{v^2}{2 \cdot c_p} \tag{3.30}$$

With the formulas above, the “ISA” can be calculated. Since two different exponents are available (κ= 1,4 and n = 1,235) there should be specified the difference of each. The isentropic exponent is for ideal air n = 1,4 according to general agreement. Since air represents a physical real gas, the value of the polytropic exponent n = 1,235 results from different measurements.

If the atmosphere is calculated, a low deviation results opposite the “ISA” if instead of n, κ is used.

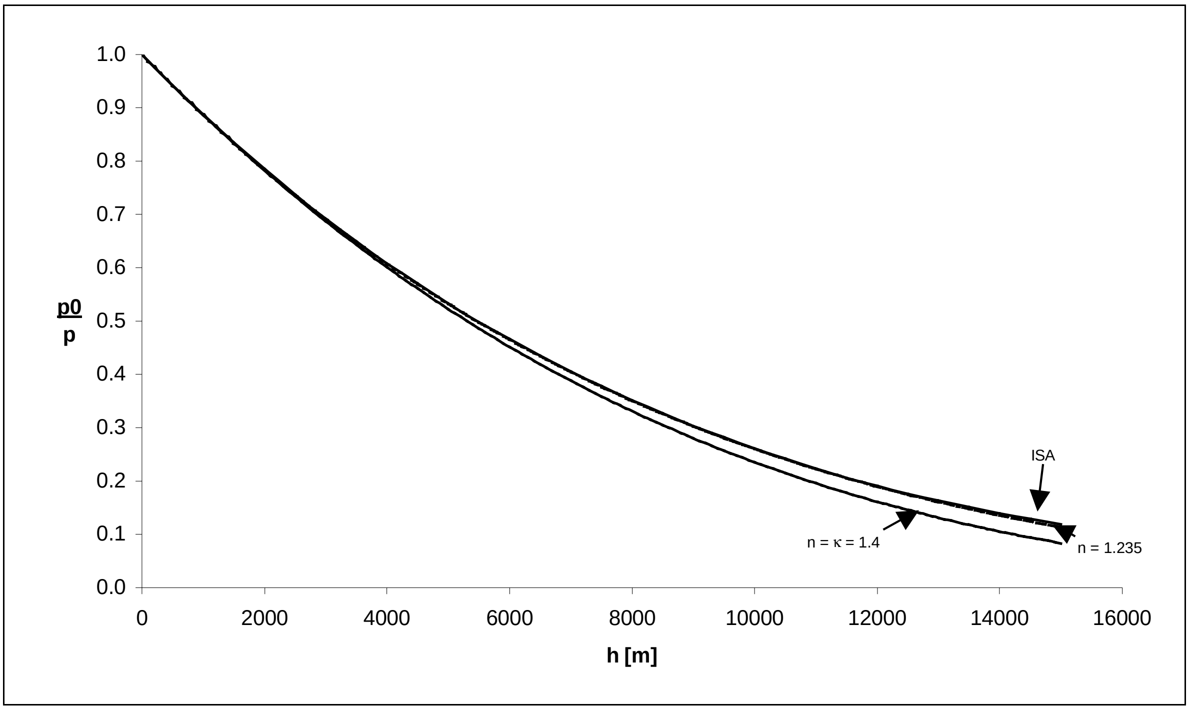

Fig.: 3-2 The different exponents of the atmosphere (p/p_0 over the height)

For this reason the static values of the atmosphere (pressure, density, height or temperature) are calculated in this working out with the polytropic exponent n = 1,235. The dynamic processes e.g. the Mach number will be calculated with κ= 1,4.

3.2 The aerodynamic foundations

For the further understanding the used basic aerodynamic principal equations are explicitly specified in detail as follows.

3.2.1 The displacement

A body which is moving in a medium or flowed around by the medium, it displaces this medium, depending on the speed at the dimensions as well. This displacement is accompanied by different pressure, temperature and speeds opposite the uninfluenced air. If the flow is made visible, the effect can be observed, seen as in the following picture.

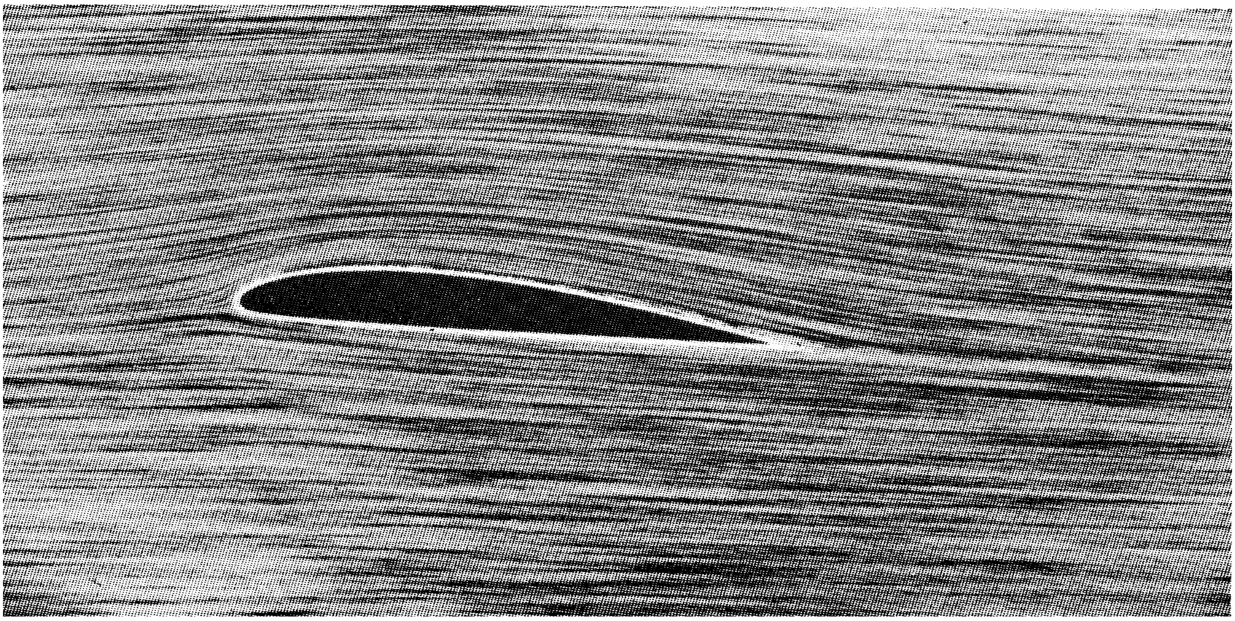

Fig.: 3-3 The displacement on a wing shape
(**Schlichting 1967** p. 257)

The calculation of such streamlines and first of all the speed outside of the outline, are based on the motion equations of “Navier Stokes”. However the friction neglected arises the “Euler motion equation”.

$$\rho \cdot \left(\frac{\partial v_x}{\partial t} + v_x \cdot \frac{\partial v_x}{\partial x} + v_y \cdot \frac{\partial v_x}{\partial y} + v_z \cdot \frac{\partial v_x}{\partial z} \right) = X - \frac{\partial p}{\partial x}$$
$$\rho \cdot \left(\frac{\partial v_y}{\partial t} + v_x \cdot \frac{\partial v_y}{\partial x} + v_y \cdot \frac{\partial v_y}{\partial y} + v_z \cdot \frac{\partial v_y}{\partial z} \right) = Y - \frac{\partial p}{\partial y}$$
$$\rho \cdot \left(\frac{\partial v_z}{\partial t} + v_x \cdot \frac{\partial v_z}{\partial x} + v_y \cdot \frac{\partial v_z}{\partial y} + v_z \cdot \frac{\partial v_z}{\partial z} \right) = Z - \frac{\partial p}{\partial x}$$
$$\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z} = 0 \qquad (3.31)$$

(Euler motion equation with continuity equation according to **Schlichting 1967** p. 44)

As a result of further simplification of these equations the equations of the “potentialtheorie” arise. These are based on the acceptance that the following conditions fulfill the flow.

The flow is:

- frictionless
- incompressible
- turn-free (turbulence less)

With the help of these conditions now two sizes can be introduced which for the further formal description are necessary. They fulfill the conditions described before as a function of *x*,*y*,*z*.

Ψ= flow function
Φ= potential of the velocity field

The flow function Ψ is to be not further described here. For the desired result it is only important to know that the flow function Ψ perpendicular stands on the potential function Φ and corresponds to the streamlines.
As well as we introduce this potential function Φ arises:

$$\frac{\partial^2 \Phi}{\partial x^2} + \frac{\partial^2 \Phi}{\partial y^2} + \frac{\partial^2 \Phi}{\partial z^2} = 0 \tag{3.32}$$

(potential equation or LAPLACE equation according to **Schlichting 1967** p. 50)

By this formula a flow can be simply described vectorially.
Therefore a translation flow corresponds to the function:

$$\Phi = a \cdot x + b \cdot y + c \cdot z = \frac{\partial \Phi}{\partial x} \cdot x + \frac{\partial \Phi}{\partial y} \cdot y + \frac{\partial \Phi}{\partial z} \cdot z = v_x \cdot x + v_y \cdot y + v_z \cdot z \tag{3.33}$$

(potential function of a translation flow according to **Schlichting 1967** p.54)

While the “Euler motion equation“ represents a function of v_x , v_y , v_z as well as the pressure *p*, results by the introduction of the simplification and the potential function *Φ* only a dependence on *Φ*. Since the potential function *Φ* is as linear defined, results besides the possibility of the superposition.

$$\Phi(x, y, z) = c_1 \cdot \Phi_1(x, y, z) + c_2 \cdot \Phi_2(x, y, z) \tag{3.34}$$

(superposition for potential equations according to **Schlichting 1967** p. 51)

For further simplification additionally two theoretical flow forms are introduced.
On the one hand, a punctiform “source”, from which a flow expands spatially with a productivity *E*.
On the other hand, a negative theoretically punctiform ”source“ is introduced, which exhibits same characteristics as those before. This means that a mass flow does not expand, but a mass flow is taken up by this that likewise a productivity *E* exhibits. For this reason this kind of “source” called “lower”. For a spatial source the following mathematical connections result. To it the formulas agree similar with those of the lowering flow only the sign of productivity *E* will be negative.

$$\Phi(x, y, z) = -\frac{E}{4 \cdot \pi} \cdot \frac{1}{r} \tag{3.35}$$

$$r = \sqrt{x^2 + y^2 + z^2} \tag{3.36}$$

(spatial potential equation **Schlichting 1967** p. 59)

For the case of compressible flow, the literature indicates the following correction factor for the distance vector *r*.

$$r_{inc.} = r_{comp.} \cdot \sqrt{1 - Ma_{\infty}^{2}} \tag{3.37}$$

(Prandtl Glauert law correction factor according to **Schlichting2 1967** p. 277)

$$\begin{aligned} v_x &= \frac{E}{4 \cdot \pi} \cdot \frac{x}{r^3} \\ v_y &= \frac{E}{4 \cdot \pi} \cdot \frac{y}{r^3} \\ v_z &= \frac{E}{4 \cdot \pi} \cdot \frac{z}{r^3} \end{aligned} \tag{3.38}$$

(spatial speed components according to **Schlichting 1967** p. 59)

According to **Schlichting 1967** resulting from the fact that the speed vector stands perpendicularly on a constant potential surface Φ= const. the resulting speed from the following connection.

$$v = \frac{E}{4 \cdot \pi} \cdot \frac{1}{r^2} \tag{3.39}$$

(resulting velocity of a source flow after according to **Schlichting 1967** p.59)

By overlay a source flow with a translation flow simple bodies of revolution, with defined body outline with also in x-direction in infinite ending, can be simulated. The zero point of the coordinate system is to lie here in the origin of the source. The x axis runs parallel to the translation flow.

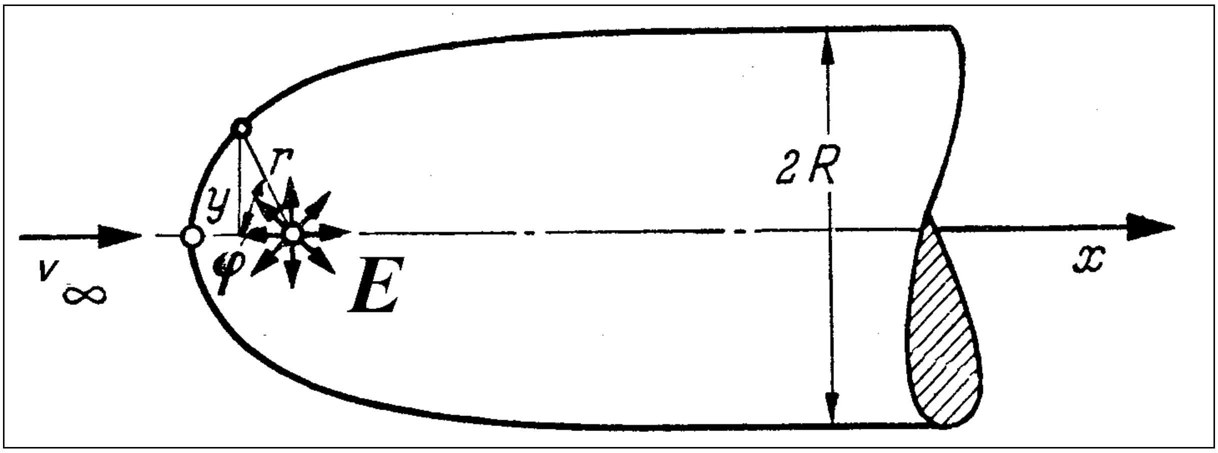

Fig.: 3-4 The simple bodies of revolution
(**Schlichting 1967** p.62)

The productivity *E* stands according to **Schlichting 1967** in dependence of the cross section of the body. The outline of the body can be represented in dependence of the origin of the body (the source) over a trigonometric function. The zero point x_0 results from the productivity *E* and the translation flow.

$$E = \pi \cdot R^2 \cdot v_\infty \tag{3.40}$$

(Formula of productivity according to **Schlichting 1967** p. 61)

For the case of compressible flow, the literature indicates *R* to the following correction factor for the fuselage radius:

$$R_{inc.} = R_{comp.} \cdot \sqrt{1 - Ma^2} \tag{3.41}$$

(Prandtl-Glauert law correction factor according to **Schlichting2 1969** p. 277)

From this follows for the productivity in the compressible case:

$$E_{comp.} = \pi \cdot \left(\frac{R_{inc.}}{\sqrt{1 - Ma^2}} \right)^2 \cdot v_\infty \tag{3.42}$$

The incompressible case can be described further according to **Schlichting 1967** (p. 63) as follows.

$$\frac{r}{R} = \frac{\sin\left(\frac{\varphi}{2}\right)}{\sin\varphi} \tag{3.41}$$

$$|x_0| = \sqrt{\frac{E}{4 \cdot \pi \cdot v_\infty}} \tag{3.42}$$

According to **Schlichting 1967** (p. 63) results for the speed components from the superposition:

$$\begin{aligned} v_x &= v_\infty + \frac{E}{4 \cdot \pi} \cdot \frac{x}{r^3} \\ v_y &= \frac{E}{4 \cdot \pi} \cdot \frac{y}{r^3} \\ v_z &= \frac{E}{4 \cdot \pi} \cdot \frac{z}{r^3} \end{aligned} \tag{3.43}$$

Over the variable *r* as a function of the origin the speed can be determined at any place on or outside the outline. Since a fuselage does not end in the infinite, one lower can be brought in additionally to in that retake the flow of the source. From it results a rotationally symmetric ellipsoids with defined dimensions. Since in the case of the A3XX no rotationally symmetric fuselage existed, the fuselage is simulated with three different beginnings.

1. Simulation of the front wave:

For this case a equivalent average fuselage from the elliptical real diameters is determined Since here the finite extents of the fuselage are not relevant this case can be computed with a simpler overlay by translation flow and source flow.

$$D_m = \frac{d_h + d_v}{2} = \frac{7136mm + 8693mm}{2} = 7914{,}5mm \tag{3.44}$$

This leads to:

$$E = \pi \cdot \left(\frac{D_m}{2}\right)^2 \cdot v_\infty = \pi \cdot \left(\frac{7{,}9145m}{2}\right)^2 \cdot v_\infty = 49{,}1968m \cdot v_\infty \tag{3.45}$$

$$v_x = v_\infty + \frac{E}{4 \cdot \pi} \cdot \frac{x}{\left(x^2 + y^2 + z^2\right)^{\frac{3}{2}}} \tag{3.46}$$

$$x_0 = \sqrt{\frac{E}{4 \cdot \pi \cdot v_\infty}} = \sqrt{\frac{49{,}1968 \cdot v_\infty}{4 \cdot \pi \cdot v_\infty}} = 1{,}9786m \tag{3.47}$$

2. Simulation of the displacement over and under the fuselage

For this case as decisive fuselage diameter the vertical real fuselage diameter is taken.

$$D_v = d_v = 8693mm \tag{3.48}$$

This leads to:

$$E = \pi \cdot \left(\frac{D_v}{2}\right)^2 \cdot v_\infty = \pi \cdot \left(\frac{8{,}693m}{2}\right)^2 \cdot v_\infty = 59{,}351m \cdot v_\infty \tag{3.49}$$

$$x_0 = \sqrt{\frac{E}{4 \cdot \pi \cdot v_\infty}} = \sqrt{\frac{59{,}351 \cdot v_\infty}{4 \cdot \pi \cdot v_\infty}} = 2{,}1732m \tag{3.50}$$

3. Simulation of the displacement on horizontal height of the centerline (CL)

For the third and last case the horizontal series diameter is consulted for computation.

$$D_h = d_h = 7136mm \tag{3.51}$$

This leads to:

$$E = \pi \cdot \left(\frac{D_h}{2}\right)^2 \cdot v_\infty = \pi \cdot \left(\frac{7{,}136m}{2}\right)^2 \cdot v_\infty = 39{,}994m \cdot v_\infty \tag{3.52}$$

$$x_0 = \sqrt{\frac{E}{4 \cdot \pi \cdot v_\infty}} = \sqrt{\frac{39{,}994 \cdot v_\infty}{4 \cdot \pi \cdot v_\infty}} = 1{,}784m \tag{3.53}$$

The length of the fuselage is in both simulations the same and corresponds to the expansion of the real fuselage up to the pressure bulkhead. For the simulation this length was selected, in order not to falsify the aerodynamic ending of the fuselage too much.

$$l = 56784mm \tag{3.54}$$

There the points of zero of a source lowering flow are known, from it results the positions of the source and lower with the given length *l*. Besides the coordinate origin put on the origin of the lower, results from it the following schematic even summary.

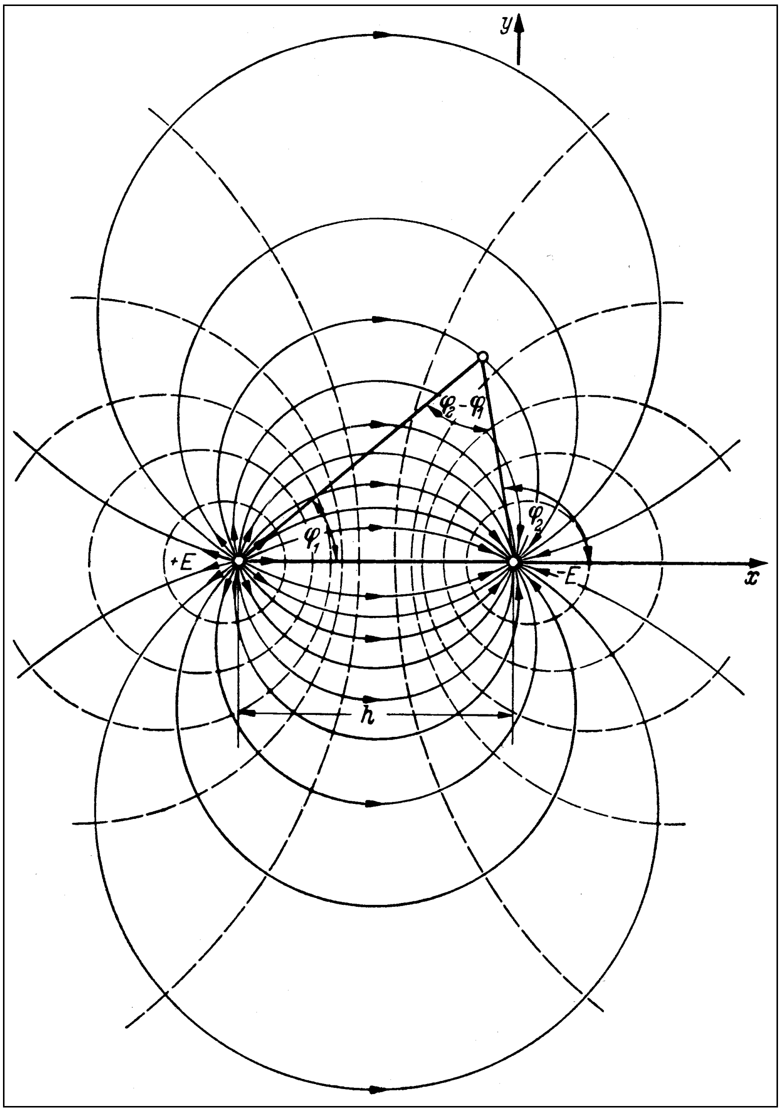

Fig.: 3-5 The source lowering flow
(**Schlichting 1967** p. 64)

$$v_x = v_\infty + \frac{E_1}{4 \cdot \pi} \cdot \frac{x_1}{\left(x_1^2 + y_1^2 + z_1^2\right)^{\frac{3}{2}}} - \frac{E_2}{4 \cdot \pi} \cdot \frac{x_2}{\left(x_2^2 + y_2^2 + z_2^2\right)^{\frac{3}{2}}}$$

(3.55)

with:

$$\begin{aligned} z_1 &= z_2 = z = 0 \\ E_1 &= -E_2 \\ y_1 &= y_2 = y \end{aligned}$$

(3.56)

$$\begin{aligned} v_x &= v_\infty + \frac{E}{4 \cdot \pi} \cdot \frac{x_1}{\left(x_1^2 + y^2\right)^{\frac{3}{2}}} - \frac{E}{4 \cdot \pi} \cdot \frac{x_2}{\left(x_2^2 + y^2\right)^{\frac{3}{2}}} \\ v_x &= v_\infty + \frac{E}{4 \cdot \pi} \cdot \left(\frac{x_1}{\left(x_1^2 + y^2\right)^{\frac{3}{2}}} - \frac{x_2}{\left(x_2^2 + y^2\right)^{\frac{3}{2}}} \right) \end{aligned} \quad (3.57)$$

For the definition of a calmed flow there is no reliable statement in the literature.
for this reason in this working out two set are pursued.

1.) The calmed flow is defined as transition in that 90 % of the disturbing effects are no longer present.
2.) Calmed flow is defined as transition in that 99,9% of the disturbing effects are no longer present.

From these two connections result the speeds for v_x:

$$v_{x1} = 1{,}1 \cdot v_\infty \quad (3.58)$$

$$v_{x2} = 1{,}01 \cdot v_\infty \quad (3.59)$$

For the determination of a suitable measurement distance, with consideration of the simulations defined before (in front of, beside, over/under), the suitable coordinates are applied graphically over the defined calming degrees.

1. Simulation of the front wave

With this calculation the formula (3.43) is changed over after x. The speeds v_y and v_z reach to zero.

$$x_1 = \sqrt{\frac{E}{4 \cdot \pi \cdot (v_x - v_\infty)}} \tag{3.60}$$

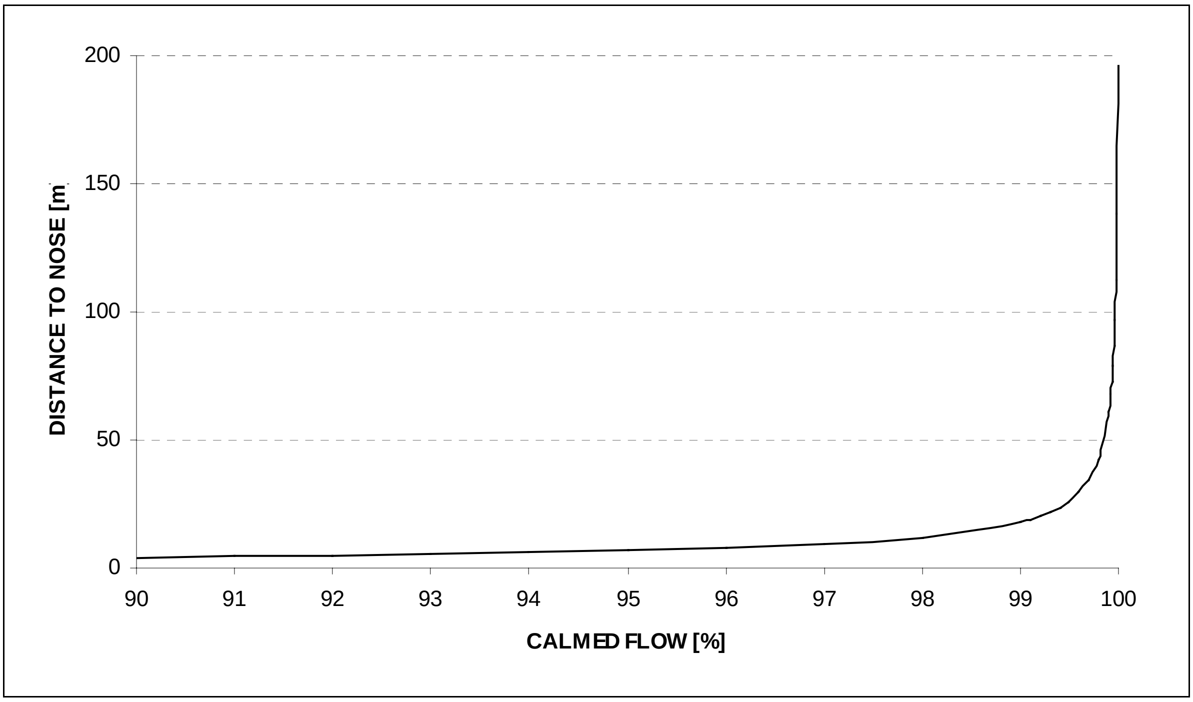

Fig.: 3-6 The calmed flow over distance to nose

2. Simulation of flow beside and over the fuselage

For the determination of the displacement around the fuselage the Y/Z - coordinate is intended over the formula (3.57) iterative and applied graphically over the proportional factor of the calming. The application happens on 5 different x-coordinates into 10 meters spacing measured from the fuselage front.

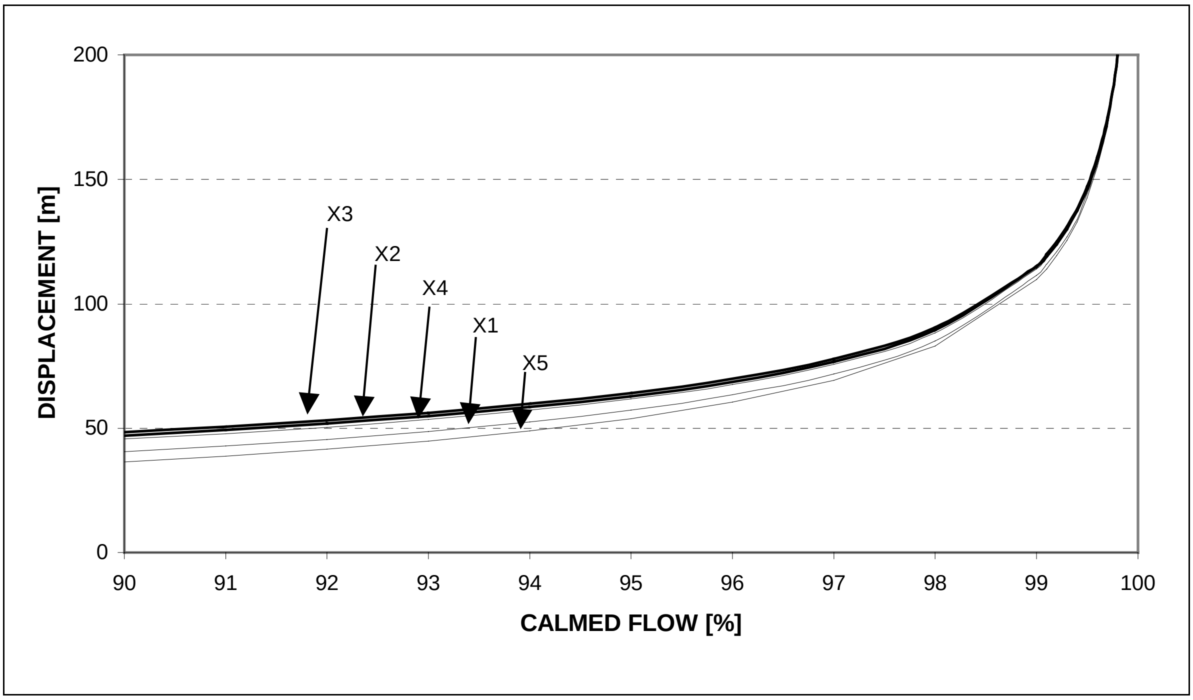

Fig.: 3-7 The calmed flow besides the fuselage over the displacement in x-steps

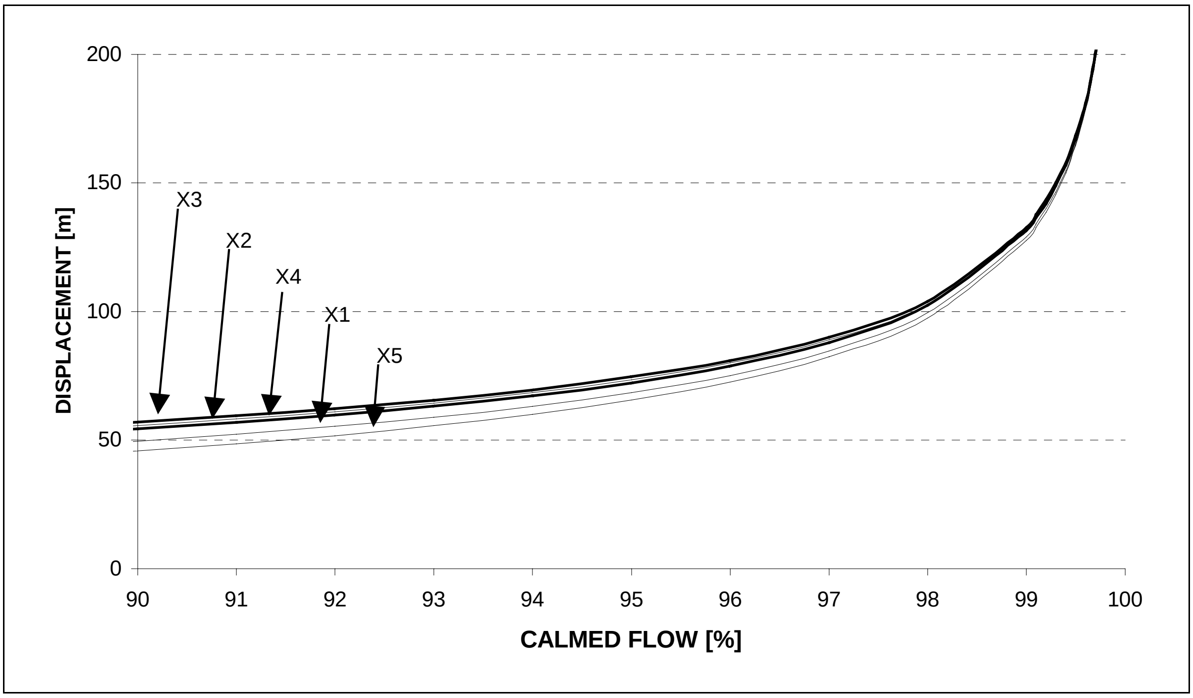

Fig.: 3-8 The calmed flow over the fuselage due to the displacement in x-steps

3.2.2 The circulation

The lift of a body, particularly a wing, is essentially created by the curvature of a profile and the vectorial incident flow. The over-pressure below the profile (flow slowed down) as well as the vacuum over the profile (flow accelerated) together result in the lift.

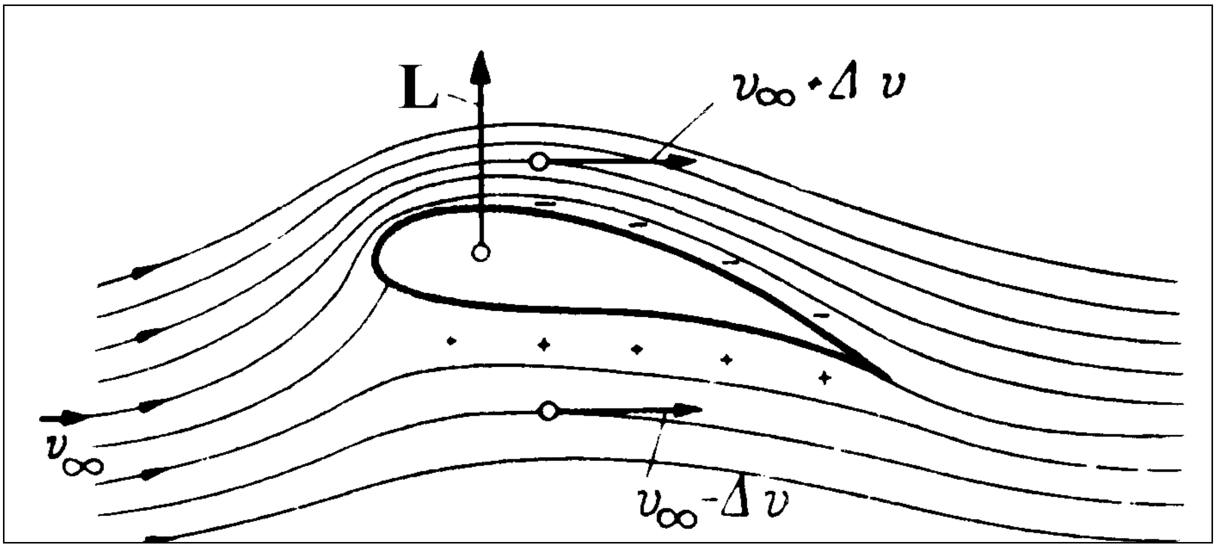

Fig.: 3-9 The lift of the wing shape
(**Schlichting 1967** p. 83)

In order to be able to evaluate the effects of this changed flow on the surrounding zone of flow, a vortex is introduced Γ as a substitute according to **Schlichting 1967** (p. 83). This is dependent on the speed and proportional to the lift. Exactly the same as the lift, attacks the vortex in the 25% line of a profile.

$$L = \rho \cdot l \cdot v_\infty \cdot \Gamma \tag{3.61}$$

(KUTTA JOUKOWSKY lift formula according to **Schlichting 1967** p. 85)

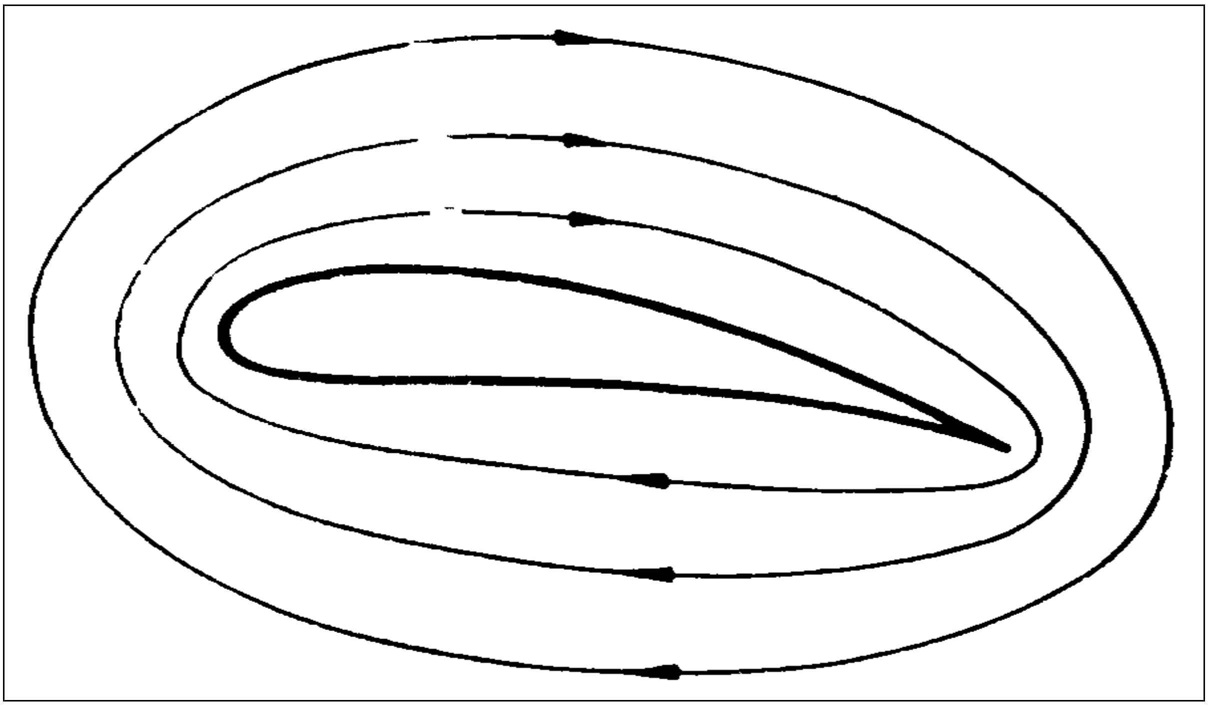

Fig.: 3-10 The circulation of the wing shape
(**Schlichting 1967** p. 83)

Thus a wing (finite span and elliptical lift distribution) can be replaced by different vortices. According to the third “HELMHOLT vortex theorem” according to **Schlichting 1967** (p. 92) are differentiated thereby three vortices.

1.) the bound vortex: simulate the lift at the profile.

2.) the free vortex: simulate the separation vortices at the ends of a finite profile.

3.) the starting vortex: simulate a vortex that with the first movement of the profile theoretically results and opposite to the bound vortex works.

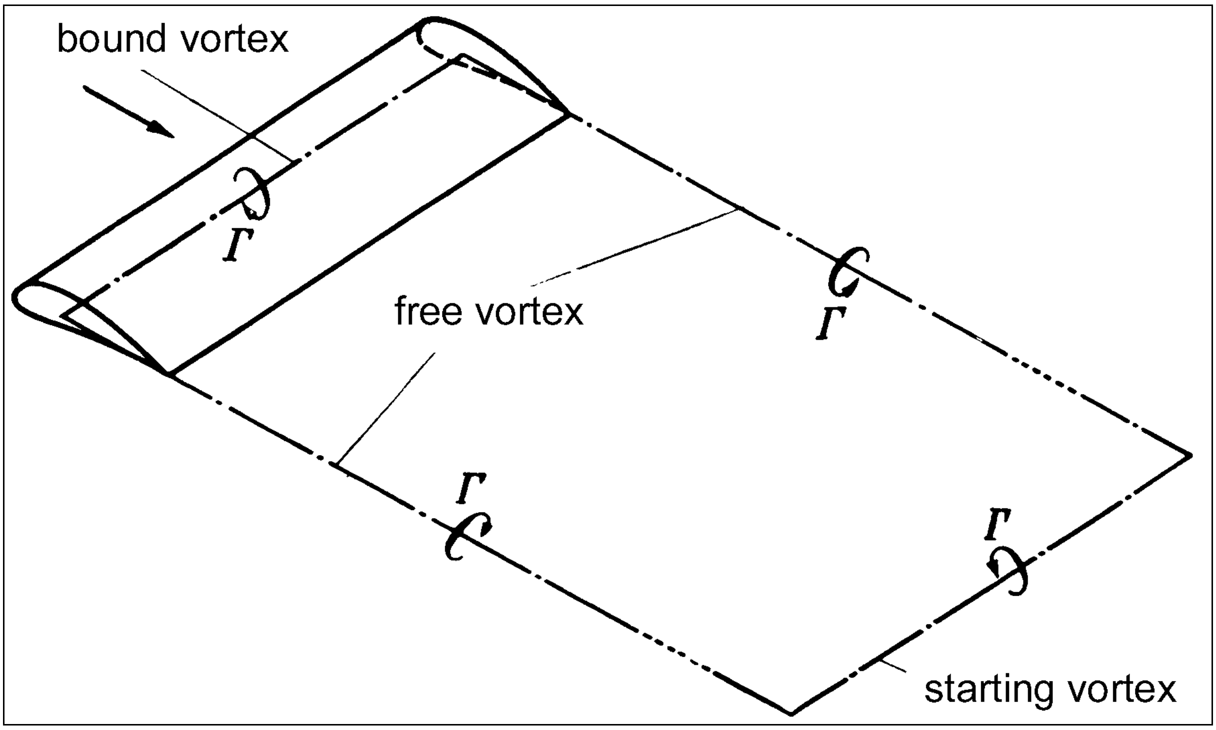

Fig.: 3-11 The circulation of the wing with finite span
(**Schlichting 1967** p. 92)

For the calculation of different speeds in the fuselage environment the "starting vortex" can be neglected according to **Schlichting 1967** (p. 93). From this connection the so-called "horse-shoe-vortex" result. The two free vortices are assumed thereby as infinitely long. With the help of the following connections, the effects of the circulation can be determined on the surrounding zone of flow.

$$v_c = \frac{\Gamma}{4 \cdot \pi \cdot r} \int_{\varphi_1}^{\varphi_2} \sin \varphi \cdot d\varphi = \frac{\Gamma}{4 \cdot \pi \cdot r} \cdot \left(\cos \varphi_1 - \cos \varphi_2\right) \tag{3.62}$$

(BIOT-SAVART law for vortices of finite expansion according to **Schlichting 1967** p.99)

$$v_c = \frac{\Gamma}{4 \cdot \pi \cdot r} \tag{3.63}$$

(BIOT-SAVART law for vortices of infinite expansion according to **Schlichting 1967** p.99)

Thereby is the speed vector always vertically to the source of vortex.

For the A3XX the wing is simplified represented and the length of the 25% line is consulted as length *l*.

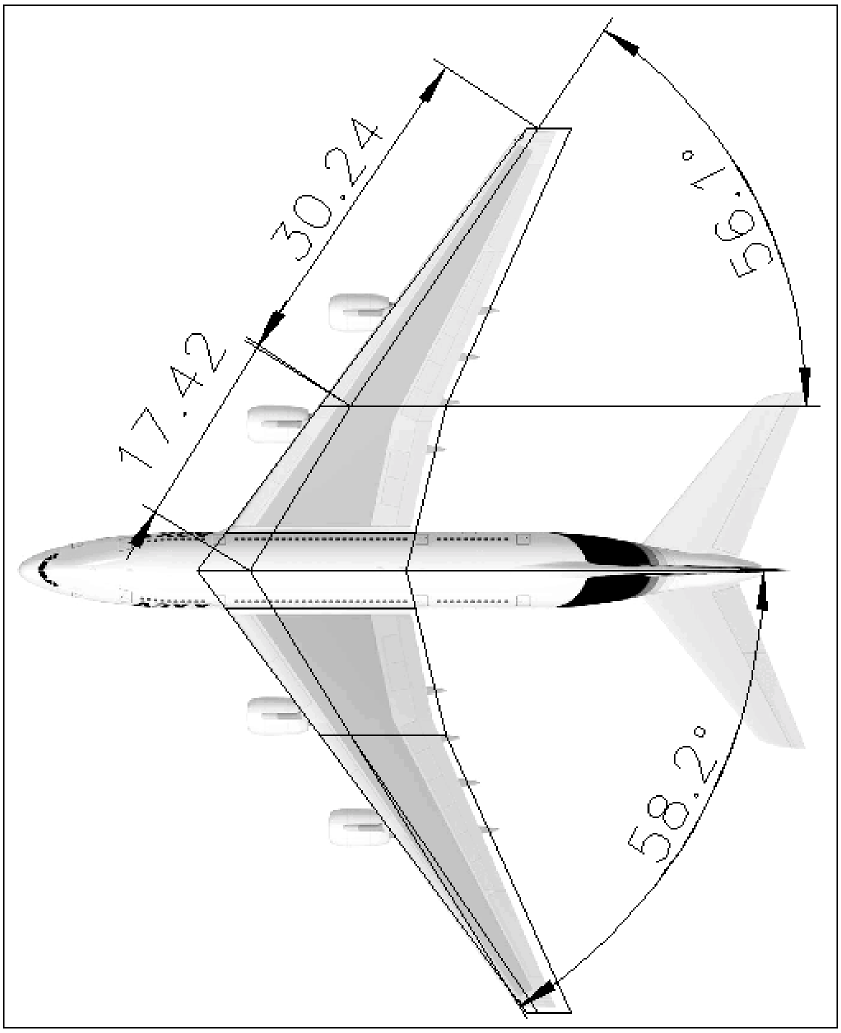

Fig.: 3-12 The simple geometry of the A3XX wing

As further simplification are defined:

- The wing is even (dihedral angle $\nu_w = 0$) and no twisting possesses (wing twist $\varepsilon_t = 0$)
- The wing is attached in the centers line (CL) (z = 0)
- The wing possesses an elliptical lift distribution
- The horizontal stabilizer does not find consideration

From this connection results a length *l* for the vortex line of:

$$l = 2 \cdot (17{,}42m + 30{,}24m) = 2 \cdot 47{,}66m = 95{,}32m \tag{3.64}$$

As the further simplification it is agreed upon that the vortex line is divided not in four lengths but only in two below an average angle to the x axis of:

$$\alpha = \frac{\alpha_1 + \alpha_2}{2} = \frac{56{,}1° + 58{,}2°}{2} = 57{,}15° \tag{3.65}$$

For the influence in front of the aircraft (y = 0, *z* = 0) the following geometrical dependence results.

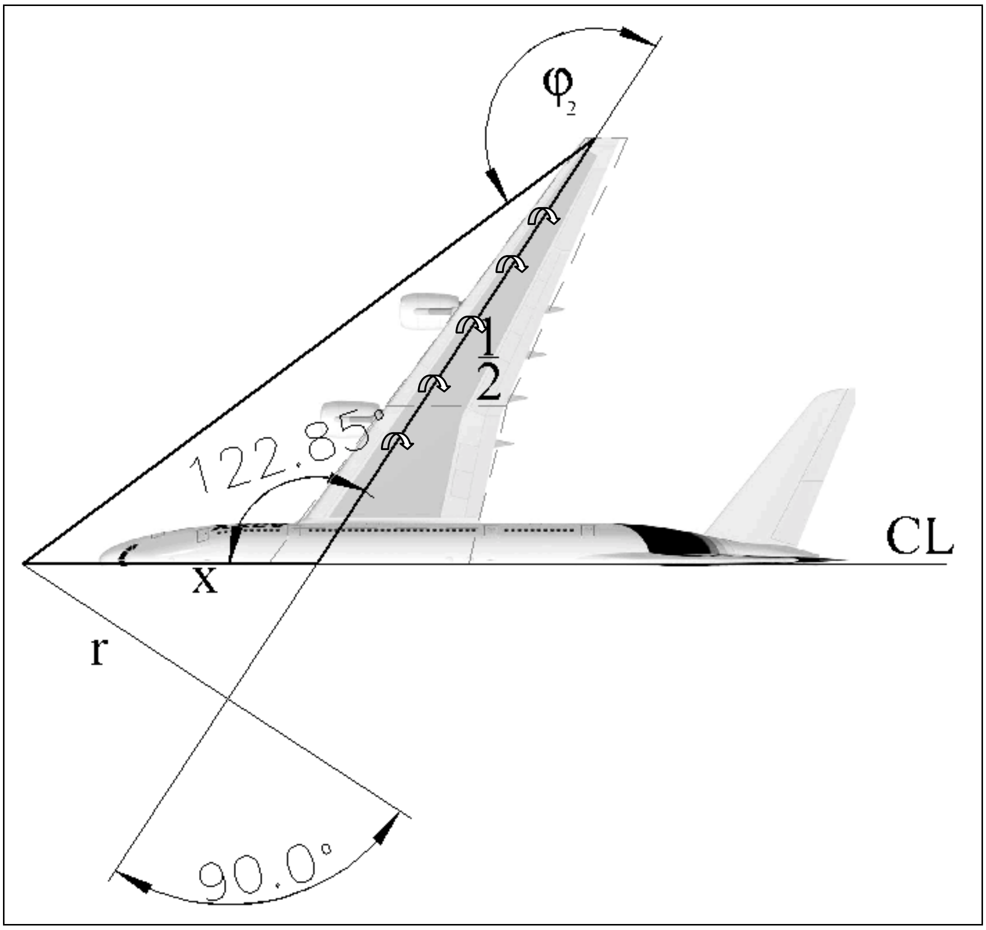

Fig.: 3-13 The circulation geometry for the nose calculation

For the angle φ_1 results from it a constant value of:

$$\varphi_1 = 180° - 57{,}15° = 122{,}85° = const. \tag{3.66}$$

$$\varphi_2 = 180° - \beta = 180° - \arcsin\left(\frac{x \cdot \sin\varphi_1}{\sqrt{x^2 + \left(\frac{l}{2}\right)^2 - 2 \cdot x \cdot \left(\frac{l}{2}\right) \cdot \cos\varphi_1}}\right)$$

$$\varphi_2 = 180° - \arcsin\left(\frac{x \cdot \sin 122{,}85°}{\sqrt{x^2 + (47{,}66m)^2 - 2 \cdot x \cdot 47{,}66m \cdot \cos 122{,}85°}}\right) \tag{3.67}$$

The perpendicular spacing r results out:

$$r = \sin\alpha \cdot x \tag{3.68}$$

For the case of the calculation above the aircraft the following geometry results:

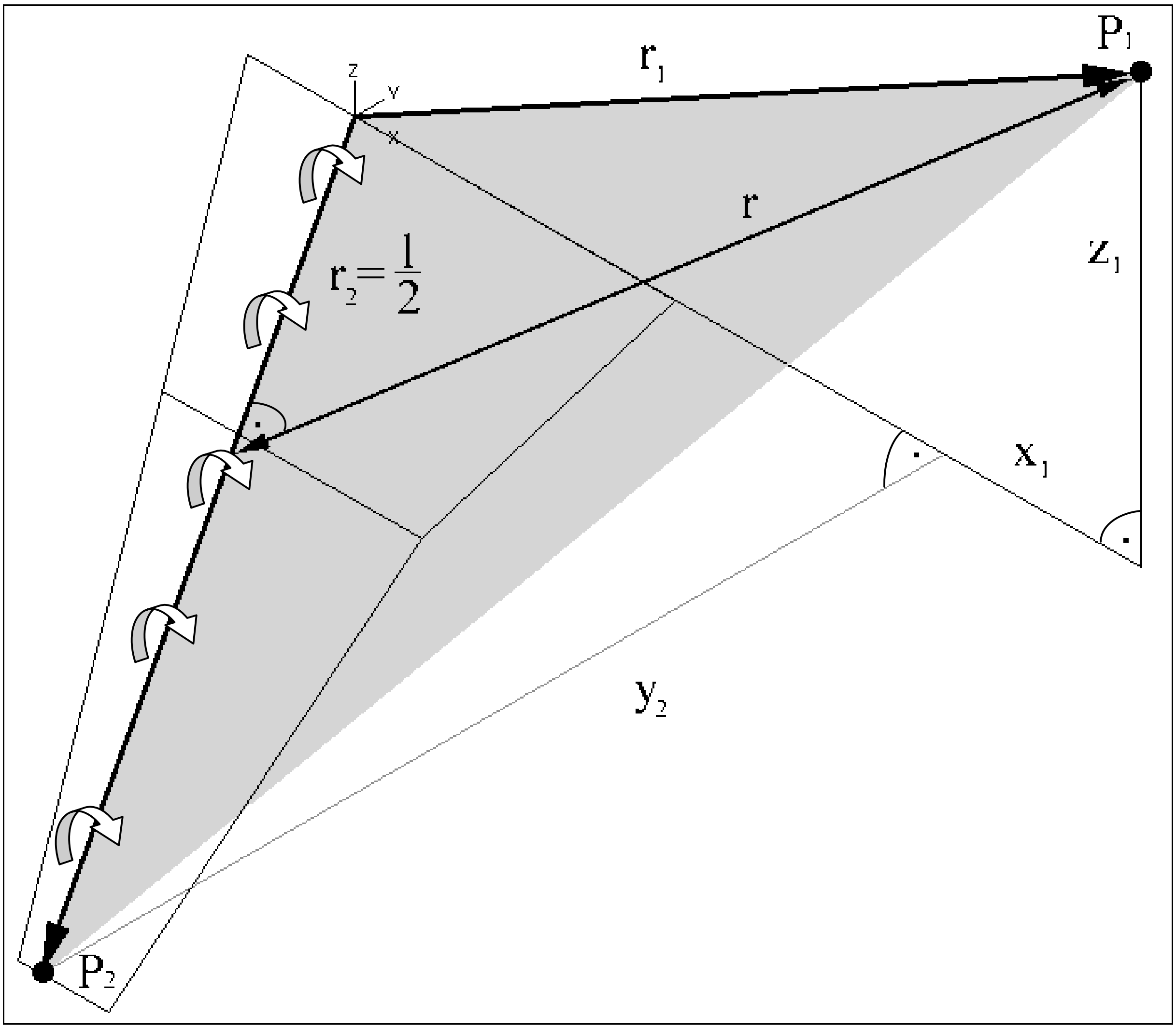

Fig.: 3-14 The circulation geometry of the calculation above the fuselage (CL)

The angle between the vector to the demand point of calculation r_1 in the x-z-plane and vortex line *r2* results from the coordinates of the end points P_1 and P_2 if the coordinate system in the origin of the two lines is set. The origin of the lines results from wing geometry and the connection that the wing lies in Z direction toward the CL (center line).

From it results for the new coordinate system:

$$C = \begin{bmatrix} x = 22m \\ y = \ 0m \\ z = \ 0m \end{bmatrix} \tag{3.69}$$

For the points P_1 and P_2 results, related to the new coordinate system, in meters:

$$P_1 = \begin{bmatrix} x \\ 0 \\ z \end{bmatrix} \tag{3.70}$$

$$P_2 = \begin{bmatrix} 26{,}03 \\ 39{,}90 \\ 0 \end{bmatrix} \tag{3.71}$$

The angle geometry of the angle φ_1 for the vortex theorem results from the cosine law to:

$$\cos\varphi_1 = \cos\alpha_1 \cdot \cos\alpha_2 + \cos\beta_1 \cdot \cos\beta_2 + \cos\gamma_1 \cdot \cos\gamma_2$$

$$\cos\varphi_1 = \frac{x_1 \cdot x_2 + y_1 \cdot y_2 + z_1 \cdot z_2}{|r_1| \cdot |r_2|} \tag{3.72}$$

The length of the vector r_1 in the x-z-plane results from the position over the x and y coordinate, which can be given. With the help of the Pythagoras results:

$$r_1 = \sqrt{x_1^2 + z_1^2} \tag{3.73}$$

The vector r_2 corresponds to the vortex line of a side and is therefore in length and adjustment defined.

$$r_2 = \frac{l}{2} = 47{,}66m = const. \tag{3.74}$$

The perpendicular distance between the vortex line r_2 and the point which can be calculated results from the sine law.

$$r = \sin\varphi_1 \cdot r_1 \tag{3.75}$$

With the help of the cosine law the angle φ_2 results as the contained angle from 180 ° is subtracted.

$$\varphi_2 = 180° - \beta = 180° - \arcsin\left(\frac{r}{\sqrt{r_1^2 + r_2^2 - 2 \cdot r_1 \cdot r_2 \cdot \cos\varphi_1}}\right) \tag{3.76}$$

The lift of the aircraft is for simplification equated to the MTOW (maximum takeoff weight). For the A3XX-100 (conditions 14,08,98 status 10c) results thus:

$$L = g \cdot MTOW = 9{,}81\frac{m}{s^2} \cdot 540t = 5297{,}4kN \tag{3.77}$$

$$\Gamma = \frac{L}{\rho \cdot l \cdot v_\infty} = \frac{5297{,}4kN}{\rho \cdot 47{,}66m \cdot v_\infty} = \frac{55{,}575\frac{kN}{m}}{\rho \cdot v_\infty} \tag{3.78}$$

As a result of the compact form of the A3xx (slimness ratio) and by the relatively high weight and the high lift necessary thereby arises a large induced speed.

3.2.3 The velocity field

Past design fundamentals exclusively refer to the influence of surrounding air by individual speed changes. For a more accurate estimation of the total influence the single speeds v_x and v_c are vectorially added. Therefore results for the speed vector v:

$$v = \sqrt{v_x^{\ 2} + v_c^{\ 2}} \tag{3.79}$$

3.2.4 The pressure field

With the past formulas the flow influence can be determined by different speed changes.

For a determination of pressure changes opposite uninfluenced air a dimensionless pressure ratio c_p can be imported which exclusively dependents on the speeds.

$$c_p = \frac{p - p_\infty}{q_\infty} = 1 - \left(\frac{v}{v_\infty}\right)^2 \tag{3.80}$$

(dimensionless pressure ratio according to **Schlichting 1967** p. 154)

For compressible flow additionally the factor of the Prandtl-Glauert law is divided.

$$c_{p;comp.} = \frac{c_{p;inc.}}{1 - Ma_\infty^2} \tag{3.81}$$

(dimensionless pressure ratio for compressible flow according to **Schlichting2 1969** p. 277)

3.2.5 The wake

The distance of the aircraft tail from a calmed down uninfluenced flow behind the aircraft can be indicated according to **ARGARD 1995** (p. 11-7) in good approximation as the double span. For the A3XX results from it:

$$D = 2 \cdot b = 2 \cdot 79{,}8m = 159{,}6m \approx 160m \tag{3.82}$$

Generally the best position of the measurement can be determined by application of a variable measure behind the aircraft. By a distance change and the determined pressures thereby, the point can be determined with sufficient accuracy.

3.3 The laser

A laser (light amplification by stimulated emission of radiation) produces coherent light and consists generally of two mirrors, a source of suggestion and the active laser medium (gas, plasma, liquid or semiconductor). The mirrors ensure for the fact that photons cross the active laser medium several times, before they leave the laser as coherent part of the jet. Generally focusing concave mirrors are used, in order to adjust the beam effect by diffraction effects at the edge. As sources of suggestion are used discharges in gaseous laser media or external energy suppliers (e.g.. photo-flash lamps). In the active laser medium photons are strengthened by stimulated emission from put on conditions (a photon, which flies past at a lively atom, can cause the emission of a photon with almost identical frequency).

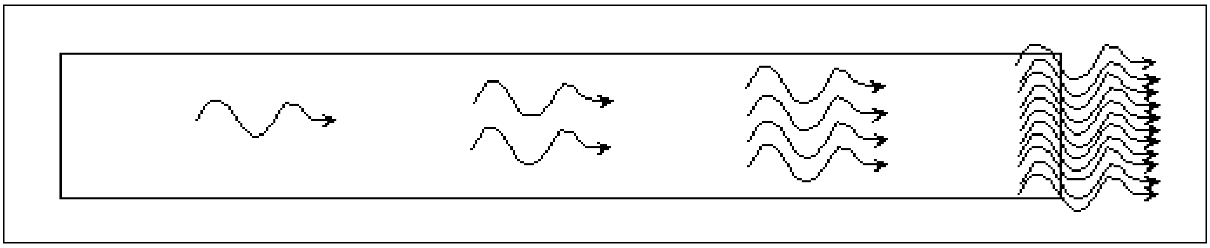

Fig.: 3-15 The laser beam

An almost parallel laser beam can be focused with a lens ideally. In relation to a normal light beam there is no focusing in a point. During the focusing of a laser this ties only on a minimum diameter *d* together and becomes thereafter against wide. According to **VDI 1992** (p. 483) this connection can be described for a laser with Gauss-shaped distribution of intensity over the following approximation formula.

$$d = \frac{4 \cdot \lambda \cdot f'}{\pi \cdot D} \tag{3.83}$$

with: f = focal length

λ = wavelength

d = waist diameter

D = jet diameter

Modern lasers do not focus any longer for a range finding or the determination of another parameter into this area. The determination of the distance takes place over a running time measurement of the laser beam.

3.4 The Doppler effect

When the distance between sound source and receiver decreases, the frequency of the received signal increases and vice-versa. This effect, named “Doppler Effect” and was discovered 1842 by Christian Doppler (1803-1853) is caused by superposition of the velocities of the sound and the source.

Similar to it this effect can be used with the help of a laser for speed measurement. In this case the measurement principle is based on the waves of the light frequency due to the scattering particle movement (of aerosols, molecules, of gases such as ozone and sulfur dioxide or dust particle). That means, a stationary observer detect not the send frequency, but the frequency changed by a moved object by the true airspeed of the particle. This procedure also called “Particle Image Velocimetry”, thus leads to the accurate analysis of the speed.

4 The pressure measurements

In principle the pressure in each airplane is measured according to the same pattern. The total pressure p_t together with the total temperature T_t over the pitot tube and the static pressure p over the static port.

4.1 The general pitot pressure measurement

The pitot tube is fastened at the front part of the fuselage and projects few centimeters into the flow. The sum of the static pressure p and the dynamic pressure q can be treated as constant value independent of the measuring position. The only condition for the positioning of the pitot tube is, that it must make its measurement outside of the boundary layer. A schematic representation by the example on wide body's is to be seen on the following page.

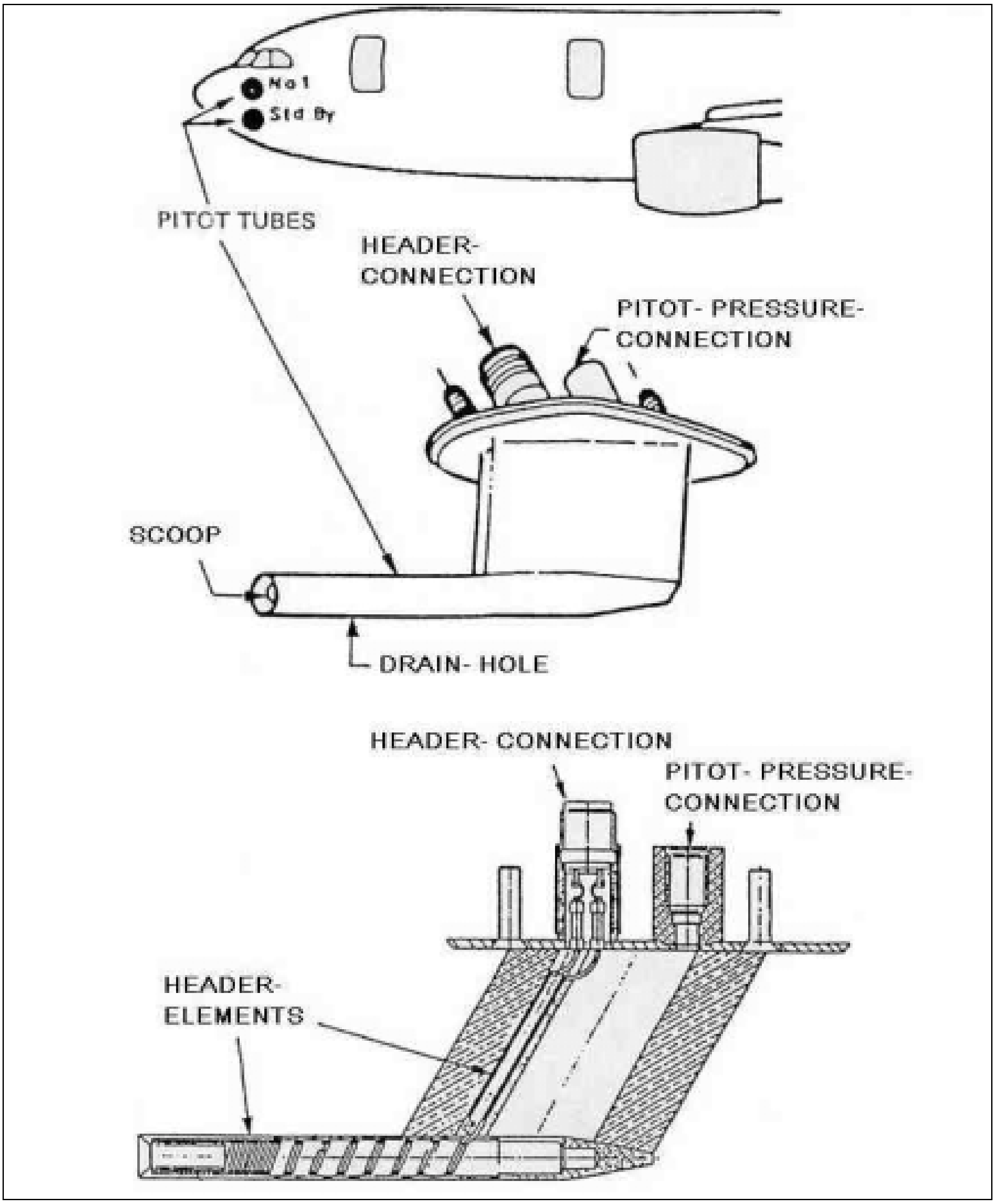

Fig.: 4-1 The pitot tube on aircraft
(**Bräunling**)

4.2 The general static pressure measurement

The static port consists of several simple holes in the outer skin in the front straight range of the fuselage. Since the static pressure works also perpendicularly to the direction of flow, it does not require measurement outside of the boundary layer. For the measurement it must be only ensured that no kinetic portions of the flow are seized. For this reason the primary detector is situates at a special place. At this place it must be ensured that the flow rests against the outline. In the following sketch, the position is outlined on the basis one wide body's.

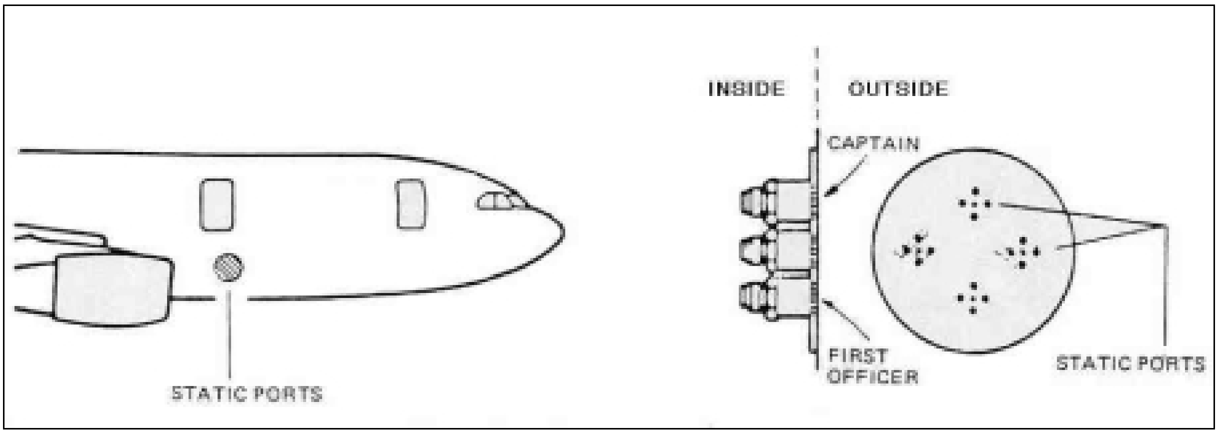

Fig.: 4-2 The static port
(**Bräunling**)

4.3 The pressure measurement on Airbus

Nowadays beside the prescribed analogue instruments the majority of the measurements is prepared digital. In the following we can see a pattern of the pressure and temperature measurement by the example of A330/A340.

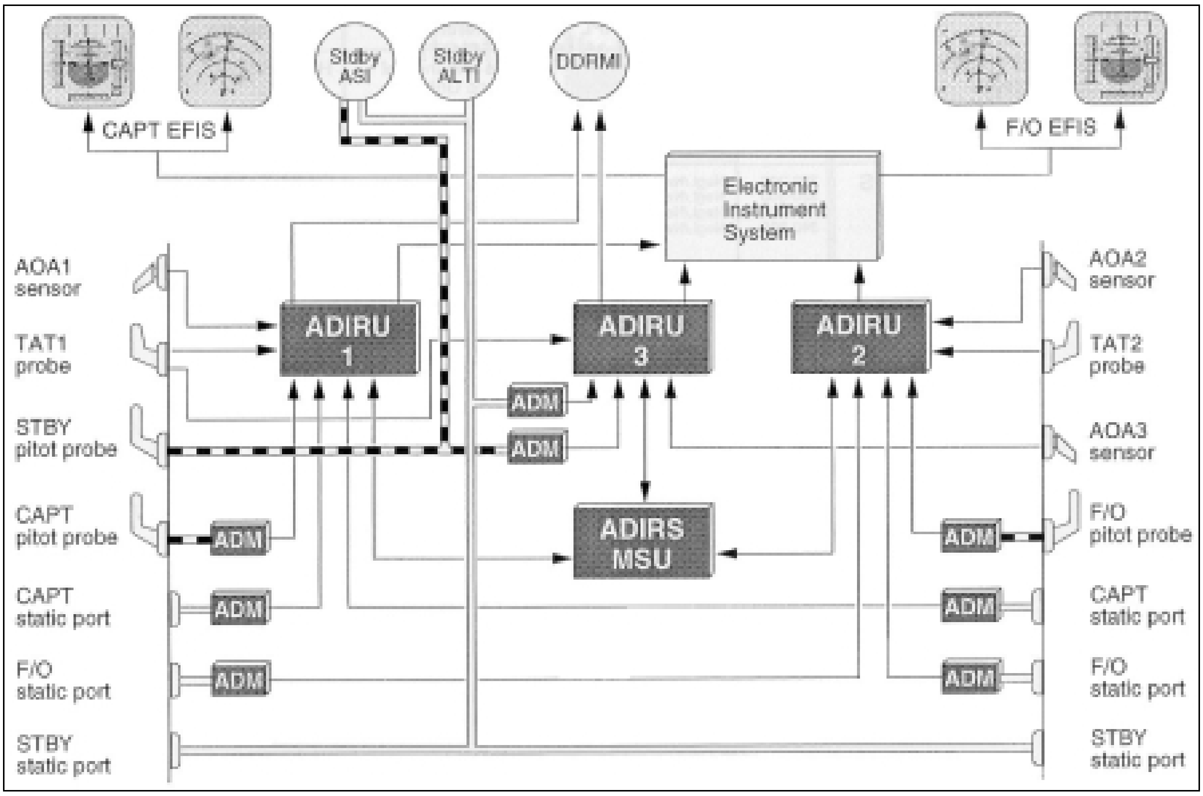

Fig.: 4-3 The pressure measurement system on Airbus A330/A340
(**SCG 1997**)

Tab.: 4-1 The pressure measurement system on Airbus A 330/ A340

Abbreviation	Definition
AOA	Angle Of Attack
TAT	Total Air Temperature
CAPT	Captain
F/O	First Officer
STBY	Stand by
ADM	Air Data Module
ADIRU	Air Data/Inertial Reference Unit
ADIRS	Air Data/Inertial Reference System
MSU	Mode Selector Unit
EFIS	Electronic Flight Instrument System
ASI	Air Speed Indicator
ALTI	Altimeter
DDRMI	Digital Distance and Radio Magnetic Indicator

5 The analog data instruments

For the determination of different pressure-dependent parameter analog equipment is prescribed according to the specifications of the FAR/JAR, for the emergency. These equipment must functioned independently of the electrical power supply. In the following chapters the most important are described briefly.

5.1 The analog altimeter

The barometric altimeter is responsible for the horizontal indication above ground. The height is determined by a static pressure measurement and the reference to the static pressure at sea level. The static pressure p is conducted on one or more diaphragm boxes (aneroids) in the isolated equipment. With pressure falling with increasing height the diaphragm box expands. This movement will transfer to one or more concentric pointers over lever linkages, toothed segments and wheels. The indication always refers to a certain department at the ground, to whose air pressure of the altimeters by means of a knurled knob after a special scale to adjusts. The effect of temperature differences by bimetal yokes are compensated.

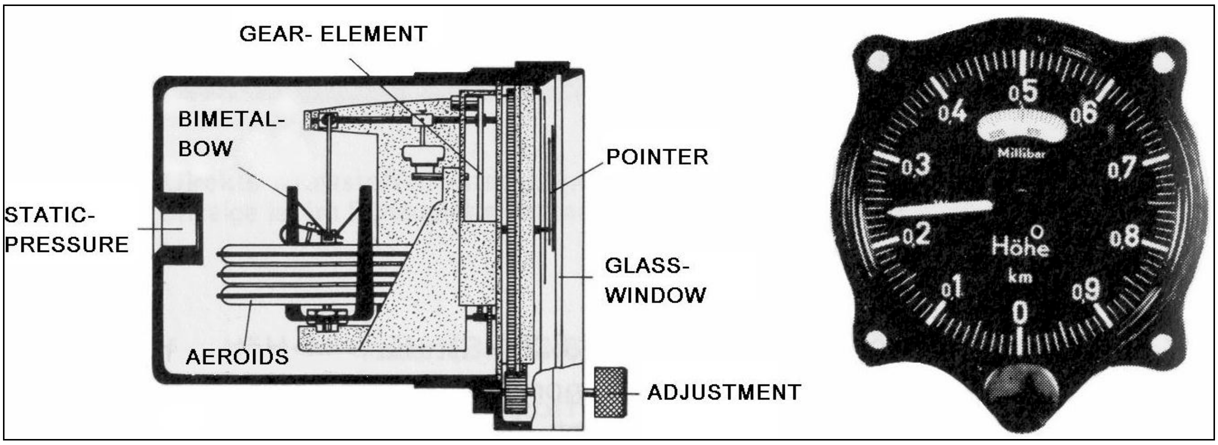

Fig.: 5-4 The analog altimeter
(**Götsch 1989**)

Tab.: 5-2 The different altitudes

Abbreviation	FAR definition
AGL	"Above ground level"
MSL	"Mean sea level"

According to the **AC 61-23C PILOT'S HANDBOOK OF AERONAUTICAL KNOWLEDGE\ CHAPTER 3** the following heights are differentiated.

Absolute Altitude-The vertical distance of an aircraft above the terrain
Indicated Altitude-That altitude read directly from the altimeter (uncorrected) after it is set to the current altimeter setting
Pressure Altitude- The altitude indicated when the altimeter setting window
(barometric scale) is adjust to 29,92. This is standard datum plane, a theoretical plane where air pressure (corrected to 15° C) is equal 29,92 in. Hg. Pressure altitude is used for computer solutions to determine density altitude, true altitude, true airspee, etc.

True Altitude- The true vertical distance of the aircraft above sea level-the actual altitude. (Often expressed in this manner; 10,900 feet MSL.) Airport, terrain, and obstacle elevations found on aeronautical charts are true altitudes.

Density Altitude- This altitude is pressure altitude corrected for nonstandard temperature variations. When conditions are standard, pressure altitude and density altitude are the same. Consequently, if the temperature is below standard, the density altitude will be higher than pressure altitude. If the temperature is below standard, the density altitude will be lower than pressure altitude. This is an important altitude because it is directly related to the aircraft's takeoff and climb performance.

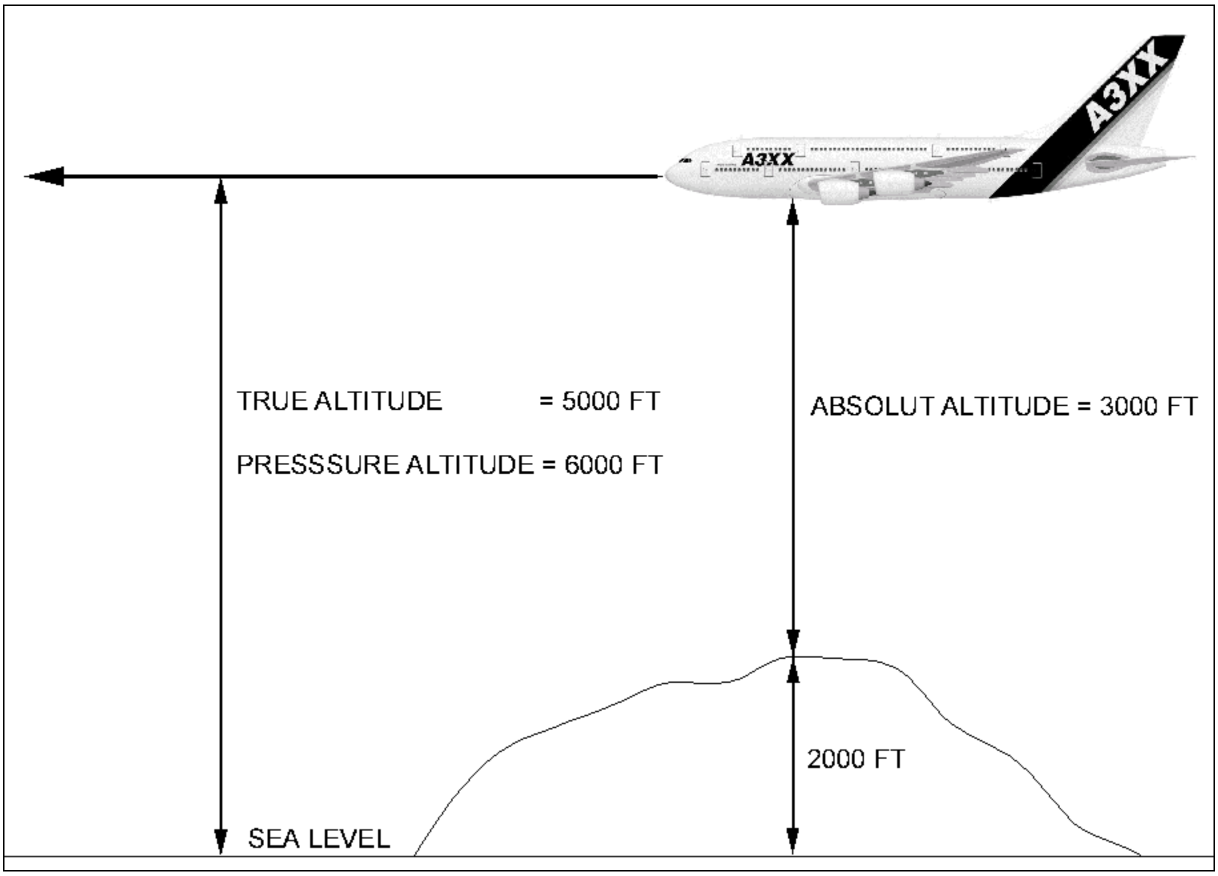

Fig.: 5-5 The sketch of the different altitudes

5.2 The analog airspeed indicator

The “AI” measures the pressure gradient between the total pressure p_t from the pitot tube and the static pressure p from the static port. This dynamic pressure q can be equated over a transmission inside the equipment the speed v.

$$p_t - p = q = \frac{\rho}{2} \cdot v^2 \tag{4.1}$$

Since the airspeed indicator is calibrated after the “ISA” shows it accordingly only the correct speed at sea level, if the conditions those the “ISA ” corresponds. The speed becomes corresponding with increasing height (change in density) and increasing speed (compressibility effect) differently strongly falsifies. For these cases there are tables or diagrams to correct these errors.

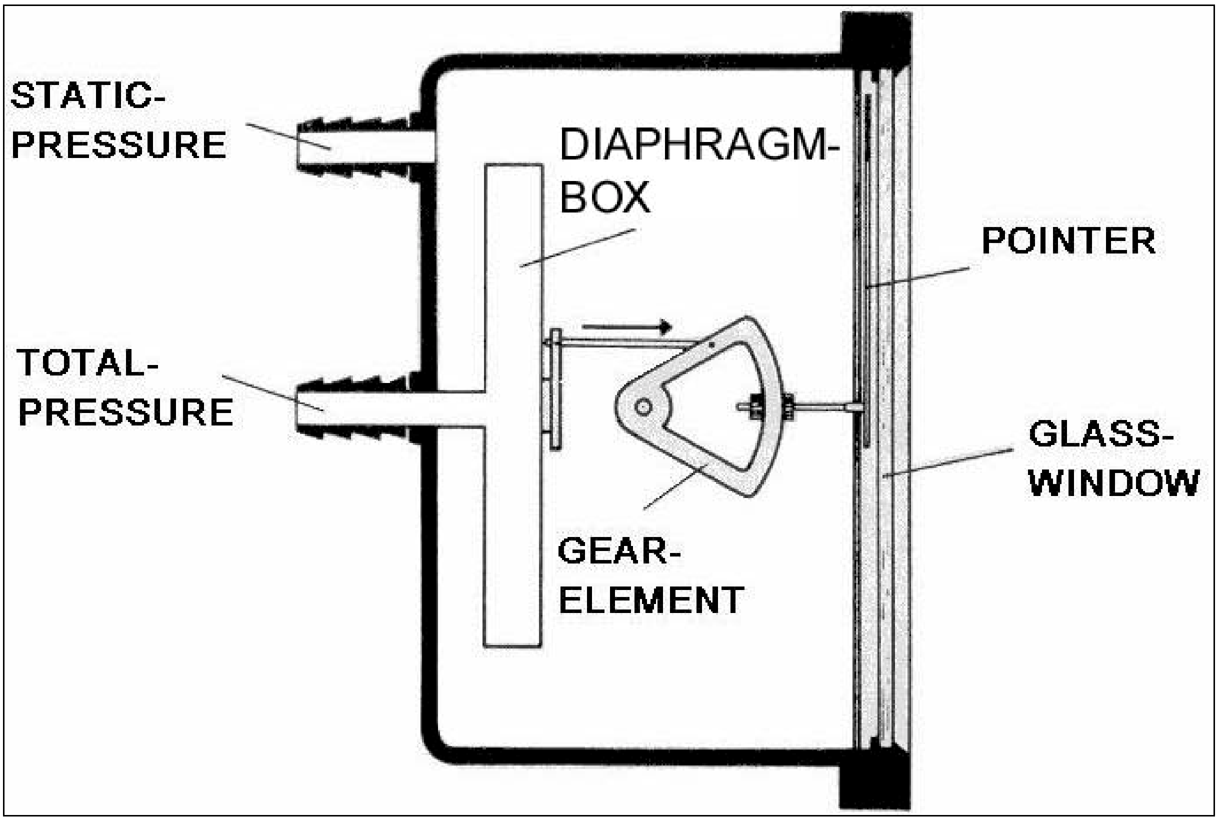

Fig.: 5-5 The analog airspeed indicator
(**Götsch 1989**)

Beside the simple “AI” there are also the so-called compensating airspeed indicators. These indicate the true speed, since they compensate height and temperature influences automatically. Three diaphragm boxes affect the indication. All three boxes affect simultaneous over a lever system the shaft of the pointer.

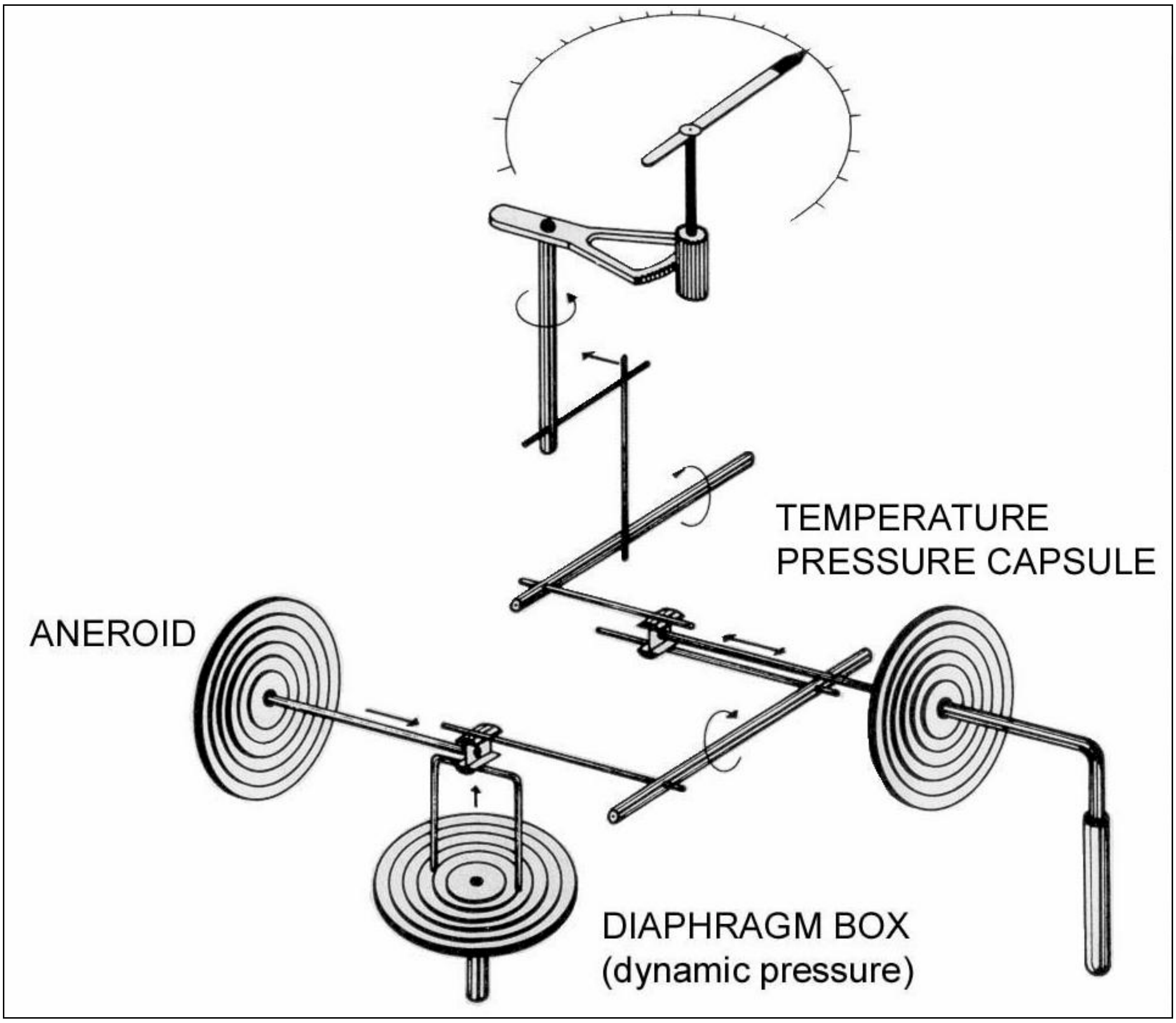

Fig.: 5-6 The analog compensating airspeed indicator
(**Götsch 1989**)

When discussing the airspeed indicator, it is helpful to understand the different types of airspeed as well as the various v-speeds associated with the instrument. The following is a brief review of these speeds.

Tab.: 5-3 The different airspeeds according to the FAR

Symbol	Abbreviation	FAR definition
v_i	IAS	"Indicated airspeed," means the speed of an aircraft as shown on its pitot static airspeed indicator calibrated to reflect standard atmosphere adiabatic compressible flow at sea level uncorrected for airspeed system errors.
v_{cal}	CAS	"Calibrated airspeed," means the indicated airspeed of an aircraft, corrected for position and instrument error. Calibrated airspeed is equal to true airspeed in standard atmosphere at sea level.
v_e	EAS	"Equivalent airspeed" means the calibrated airspeed of an aircraft corrected for adiabatic compressible flow for the particular altitude. Equivalent airspeed is equal to calibrated airspeed in standard atmosphere at sea level.
v_t	TAS	"True airspeed," means the airspeed of an aircraft relative to undisturbed air. True airspeed is equal to equivalent airspeed multiplied by (rho (0) / rho) 0,5.

5.3 The analog mach meter

With this instrumentation the Mach number can be shown

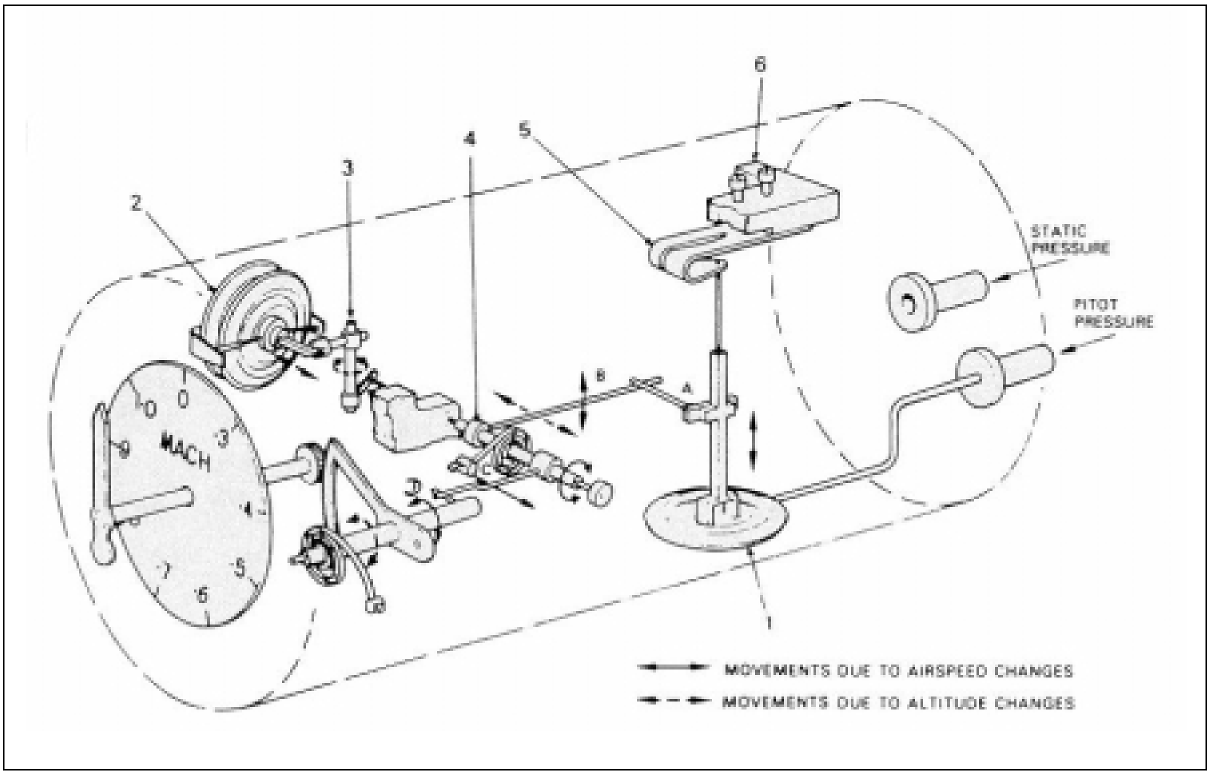

Fig.: 5-7 The analog mach meter
(**Bräunling**)

Tab.: 5-4 The definitions of the Mach meter elements shown in Fig. 6-7

Position	Definition
1	Pressure capsule (for speed)
2	Pressure capsule (for height)
3	Toggle lever (for height)
4	Adjustable shaft
5	Calibration spring
6	Calibration screw

6 The reasons to calibrate the pressure system

During the measurement of the different pressures, errors result depending upon flight attitude and speed. How declares in the previous, the pressure is measured with two different primary detectors. The total pressure p_t over the pitot-tube, the static pressure p over static port. While the total pressure p_t supplies an almost correct result independently of the flight attitude, results for the static pressure a so-called position an error.

The position error:

Since the fuselage of an aircraft represents a displacement body, results from it an interference factor within air. Therefore results separations, boundary layers as well as turbulences and thus different pressures at the fuselage. For the measurement of the static pressure a falsification results in relation to the real static pressure outside of the influence of a displacement body.

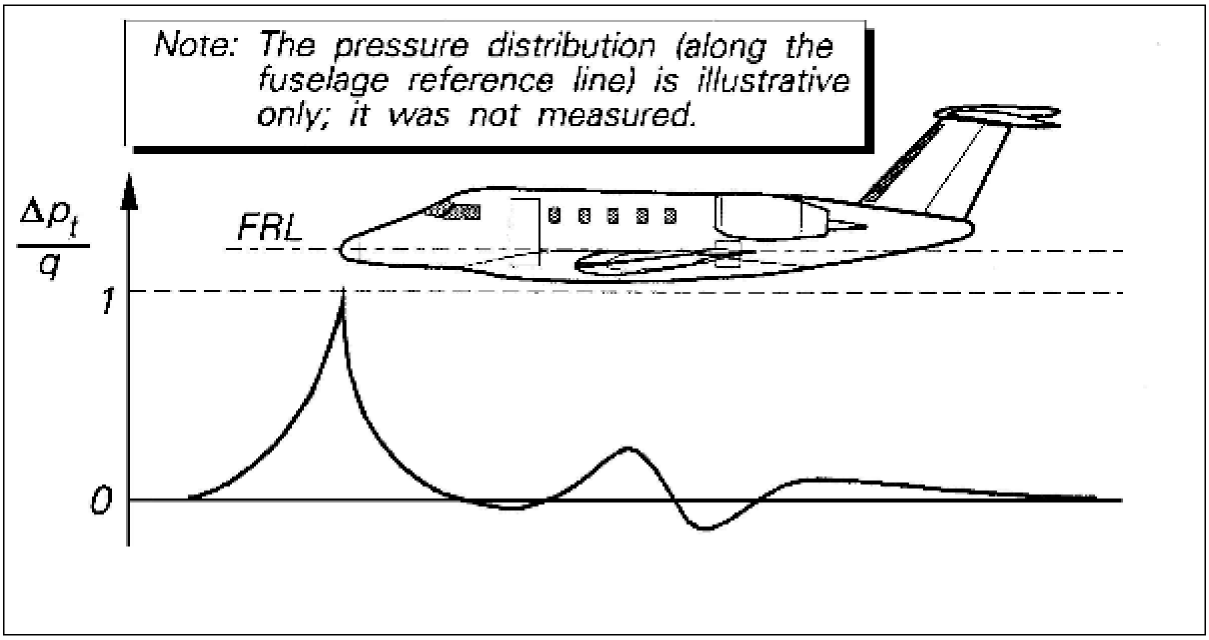

Fig.: 6-1 The position error
(**Ward 1993**)

7 The measurement demands

For the calibration of the pressure primary detectors there are special requirements on the part of the responsible authorization organizations such as **FAR** (Federal Aviation Regulations) or **JAR** (Joint Aviations Requirements). These prescribe types of conditions for the calibration and appoint themselves equally to the **I.C.A.O.**. The analyses of the two organizations are unfortunately not explicit and give a range of interpretation.

Thus both (FAR and JAR) contain the following regulation in the "Subpart F- Equipment":

> *"JAR 25.1325 Static pressure systems*
> *(d) Each pressure altimeter must be approved and must be calibrated to indicate pressure altitude in a standard atmosphere, with a minimum practicable calibration error when the corresponding static pressures are applied."*

The only meaningful regulation that I can find is in the same chapter.

> *"JAR 25.1325 Static pressure systems*
> *(e) Each system must be designed and installed so that the error in indicated pressure altitude, at sea-level, with a standard atmosphere, excluding instrument calibration error, does not result in an error of more than ±30 ft per 100 knots speed for the appropriate configuration in the speed range between 1·3 VS0 with wing-flaps extended and 1·8 VS1 with wing-flaps retracted. However, the error need not be less than ±30 ft."*

Since these instructions represent the only numerical values, they are valid to this working out as obligatory. In order to obtain for other speeds a realistic value, the data "+ / - 30 ft by 100 knots" is related to 1 m/s.

Therefore an error results converted into metric units from:

$$f\left(\Delta\right) = \frac{30ft}{100knots} = \frac{9{,}144m}{51{,}444\frac{m}{s}} = \frac{0{,}17775m}{1\frac{m}{s}} \tag{7.1}$$

The result is graphically applied over the Mach number and the height.

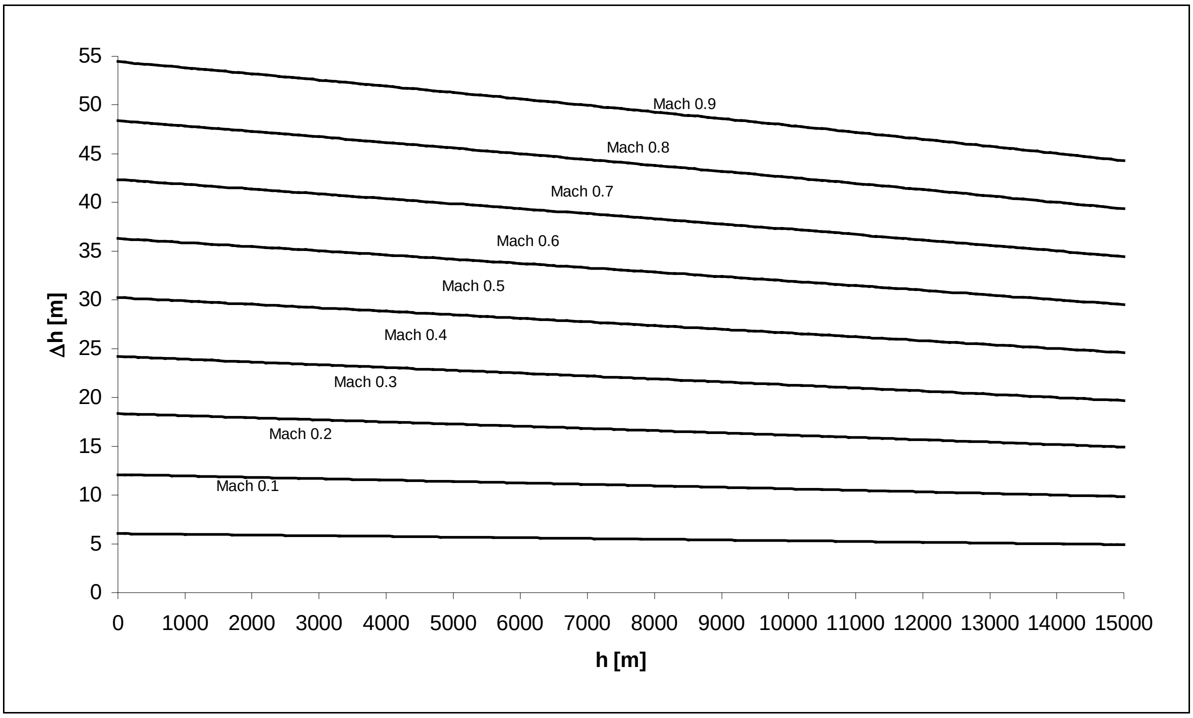

Fig.: 7-1 The altitude error of the FAR, over the height and Mach number

It is to be obvious that the condition of an practicable calibration error at larger speeds is no more given.

Further obligatory numerical values can be taken out of the **I.C.A.O. Circular 81-AN/68**.

> *"2. UNIFORM METHOD OF CALIBRATION OF POSITION ERROR*
> *2.1 Any method of calibration of the aeroplane static pressure system position error should have an accuracy within +/- 23 metres (+/- 75 feet) throughout the operating altitude and air-speed/Mach number limitations for which the aeroplane is certificated."*

Now as maximum value the accuracy published of the I.C.A.O. is set for 23 meters of + / -.
If this maximum value is related to Mach 1 and MSL, the following formula results from it.

$$f(\Delta) = \frac{23m}{340{,}29\frac{m}{s}} = \frac{0{,}06759m}{1\frac{m}{s}} \tag{7.2}$$

If this formula is likewise applied in dependence of the Mach number and the height, the following graphical result.

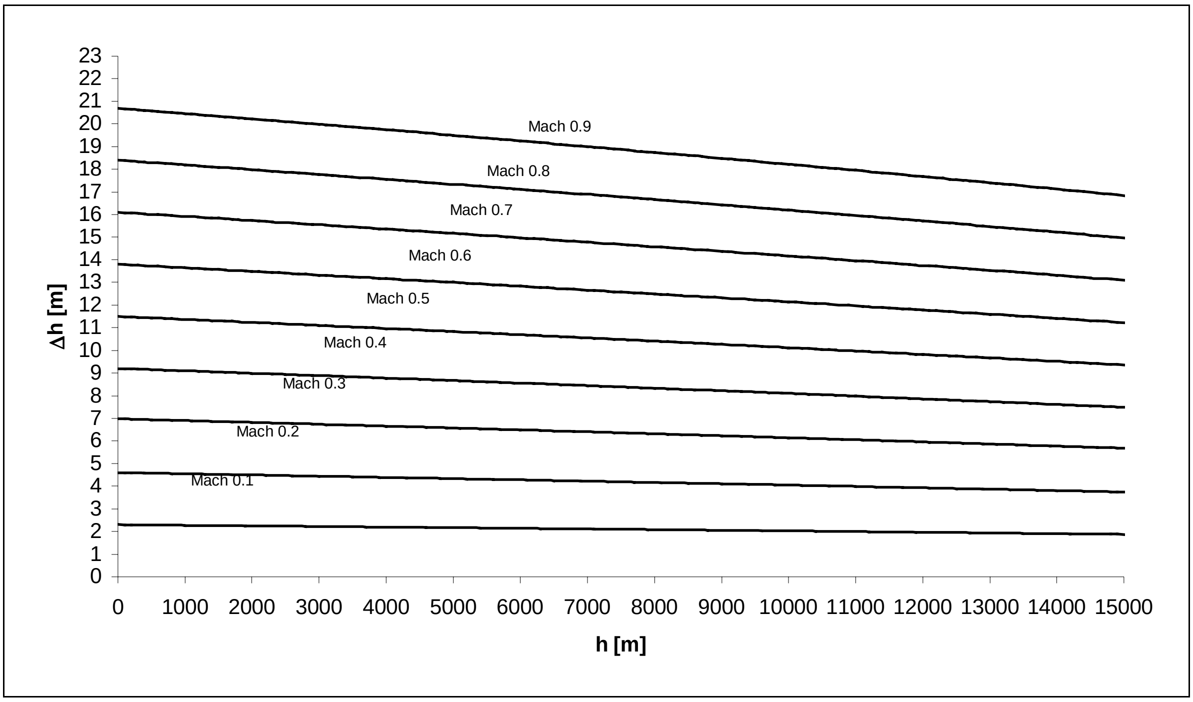

Fig.: 7-2 The altitude error of the I.C.A.O. over the height and Mach number

When both analyses are connected and inserted into a linear equation, the following conditional equation is received.

$$f(x) = m \cdot x + b \tag{7.3}$$

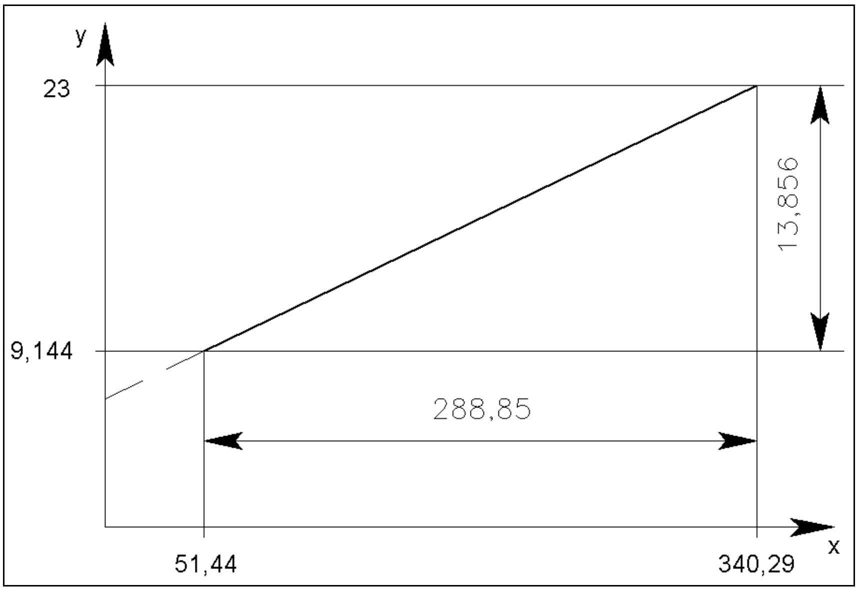

Fig.: 7-3 The graphical linear equation of the altitude error

$$f(v) = \left(\frac{23 - 9{,}144}{340{,}29 - 51{,}44} \right) \cdot v + b = 0{,}04797 \cdot v + b \tag{7.4}$$

$$b = f\left(51{,}44 \frac{m}{s} \right) - 0{,}04797 \cdot 51{,}44 = 9{,}144 - 2{,}4678 = 6{,}6762 \tag{7.5}$$

$$f(\Delta) = 0{,}04797 \cdot v + 6{,}6762 \tag{7.6}$$

If this function is likewise graphically applied over the Mach number and height, the following summary is receives.

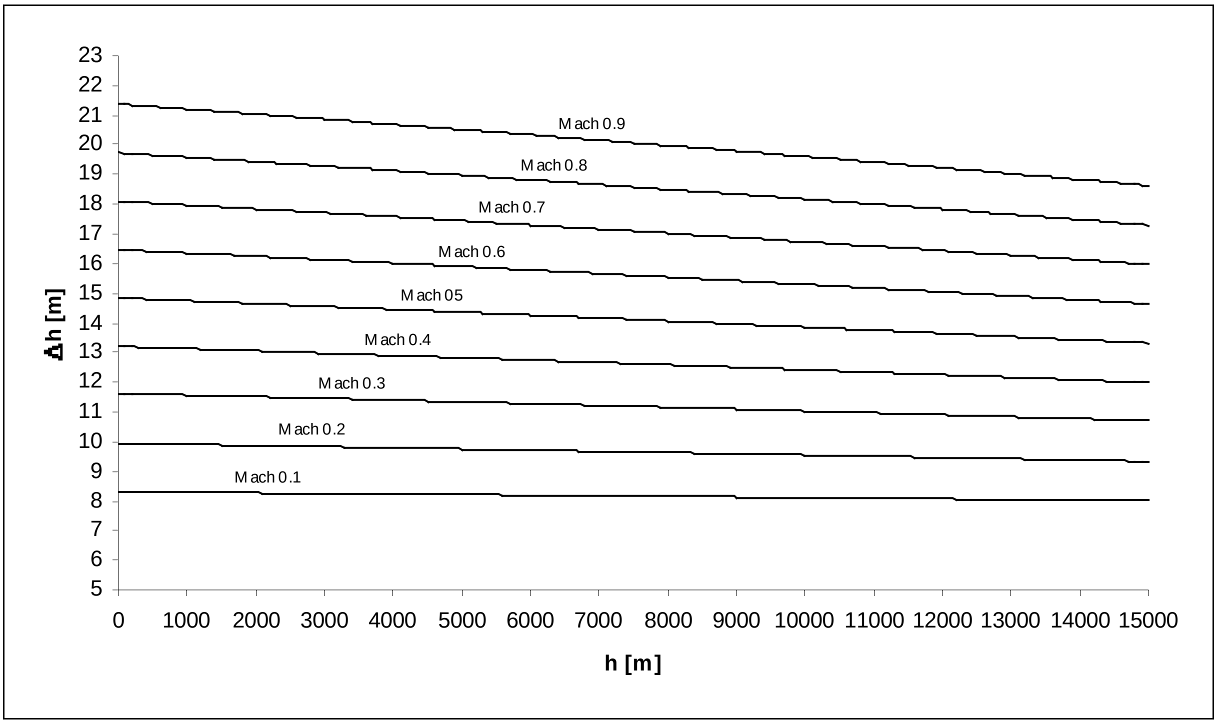

Fig.: 7-4 The altitude error of FAR and I.C.A.O. over the height end Mach number

Since the function is linear, the values for speeds under 100 knots (51,444 m/s) are smaller than the given 30 ft (9,1444m). For the further calculation the minimum of 30 ft (9,1444 m) will be defined.

In the **FAR/JAR** is additionally stated that a primary detector which calibrates the aircraft-own serial pressure primary detector, must have an accuracy of +/- 0,005 inch of Hg (+/- 0,00016931 bar) or better according to **AC 43-2B**.

> *"AC 43-2B 7. THE WORKING STANDARD BAROMETER*
> *a. Pressure measuring devices used in the rough calibration of pitot/static instruments may be either mercury or aneroid barometers with wider tolerances. However, the instrument used for final calibration of nonsensitive altimeters or sensitive altimeters certificated for use below 35,000 feet, should have a repeatable accuracy of at least .01 inch. Sensitive altimeters, altitude hold devices, altimeters used in Category II landing systems, or servoed equipment associated with air data computers, usually require test and calibration equipment with repeatable accuracies of .005 inch Hg or better."*

From this connection a measurement error results already from the beginning for the calibration. Over the formulas from chapter 5 this misprint can be converted into an altitude error.

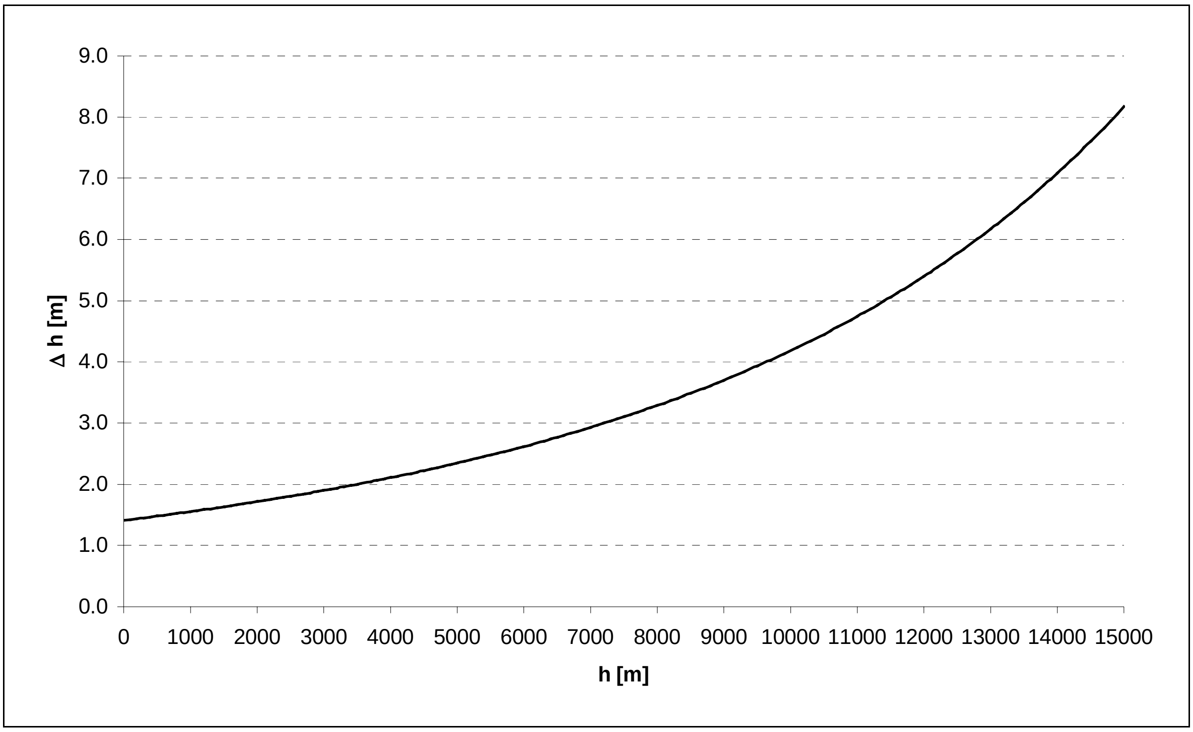

Fig.: 7-4 The altitude error of the calibration equipment

8 The calibration methods

In principle over the onboard measuring instruments are available both the total pressure p_t and the total temperature T_t with an almost error free accuracy according to **Wedrow 1959**. Over different physical connections, both the static pressure and other parameters can be determined. From the formulas specified in the chapters above the fundamental possibilities of the calibration can be concluded.

Primarily it is possible to measure the static pressure itself.

Over the formula (3.29)

$$p_t = p + q + \Delta q \tag{8.1}$$

with

$$\Delta q = \frac{q}{4} \cdot Ma^2 \tag{8.2}$$

and

$$Ma = \sqrt{\frac{2}{\kappa - 1} \cdot \left[\left(\frac{p}{p_t} \right)^{\frac{\kappa - 1}{\kappa}} - 1 \right]} \tag{8.3}$$

results from it

$$q = \frac{p_t - p}{1 + Ma^2} = \frac{p_t - p}{1 + \dfrac{\dfrac{2}{\kappa - 1} \cdot \left[\left(\dfrac{p}{p_t} \right)^{\frac{\kappa - 1}{\kappa}} - 1 \right]}{4}} \tag{8.4}$$

Thus also the airspeed indicator can be calibrated directly.

It is possible to determine the necessary static pressure with the relationship (3.29) by means of the airspeed.

$$p_t = \frac{\rho}{2} \cdot v^2 \cdot \left(1 + \frac{M^2}{4}\right) + p \tag{8.5}$$

extended with (3.18) and (3.27)

$$p_t = \frac{p}{2 \cdot R \cdot T} \cdot v^2 \cdot \left(1 + \frac{\frac{v^2}{\kappa \cdot R \cdot T}}{4}\right) + p \tag{8.6}$$

extended with (3.30)

$$p = \frac{p_t}{1 + \frac{v^2}{2 \cdot R \cdot \left(T_t - \frac{v^2}{2 \cdot C_p}\right)} \cdot \left(1 + \frac{\frac{v^2}{\kappa \cdot R \cdot \left(T_t - \frac{v^2}{2 \cdot C_p}\right)}}{4}\right)} \tag{8.7}$$

A further possibility is to determine the static pressure over the temperature.

$$p = p_t \cdot \left(\frac{T}{T_t}\right)^{\frac{\kappa}{\kappa - 1}} \tag{8.8}$$

Several techniques have been developed for the calibration of aircraft pitot-static systems. The primary objective of these test methods is to determine by flight-test the static system (position) error and airspeed error over performance envelope (speed, altitude, weight range and configuration) for which the aircraft is designed. The most important and widely used of these calibration techniques are described in subsequent chapters.

8.1 The computed static-port position

Generally it is possible to determine by complex computing procedures and wind tunnel tests a suitable position for the static-port. At this position the real static pressure can be measured. As is to be seen in the following figure, there are different divisions at the aircraft (here a DO 128 with nose boom for the meteorology measurement) that enable a measurement of the static pressure. In this example the labelled position 5 would be suitable for the measurement. While with the positions 1 and 6 the measurement lie outside of the aircraft, the positions 2 and 4 on offer the left and on the right apart from the actual measuring point a quick and steep rise or dropping of the pressure which can be measured. For this reason the measurement would indicate quickly a wrong value if the position is not exact computed. A soft transition as at the position number 5 is accordingly ideally to border errors.

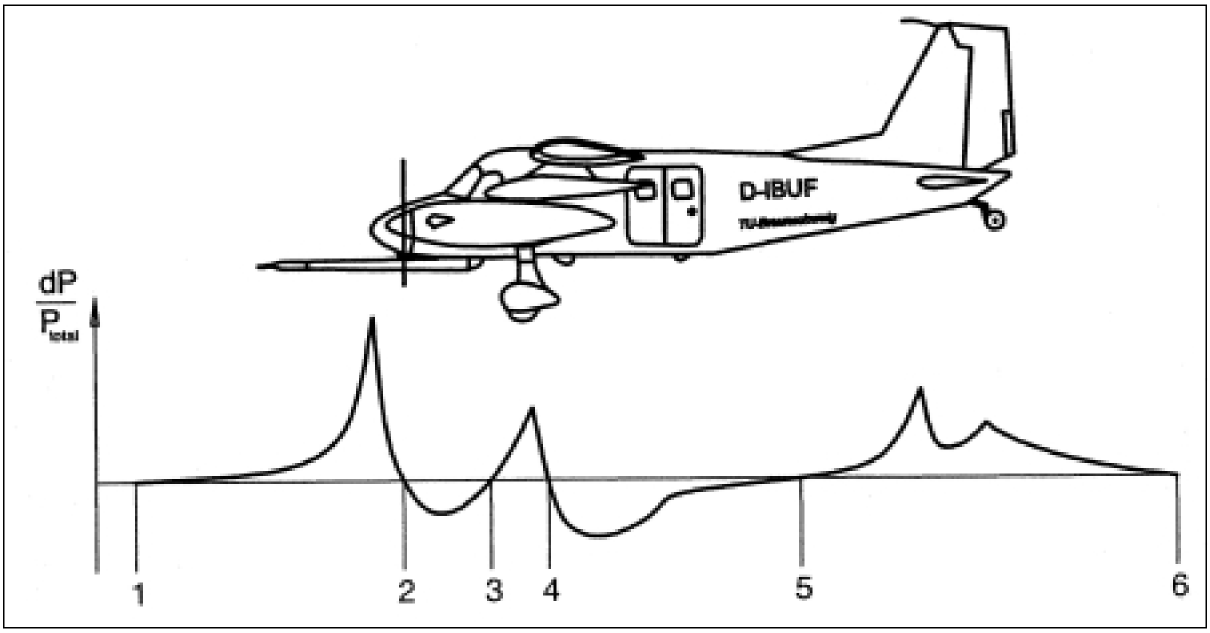

Fig.: 8-1 The computed position error on the DO 128 (**Delft 1999**)

8.2 The camera fly- over calibration method

In according to **ARP 1971** (chapter 5.1.1) flies in this calibration method the aircraft in flight test directly overhead above a camera. In an altitude range of 100 to 500 ft above the camera, the aircraft is measured by photographing. The height of the aircraft above the camera can be accurately determined by using the previously measured wingspan of the aircraft and calibrated focal length of the camera. The atmospheric pressure is measured both at the camera side and in the aircraft. At the camera site is also the temperature measured The true static pressure is computed for the fly-over elevation by using the measured height. The computed pressure is then compared with the actual pressure measured in the aircraft. The static pressure error of the aircraft at the particular Mach number, airspeed, weight, flap position and the angle of attack during the fly-over, resulting from the pressure difference.

8.3 The tower fly- by calibration method

According to **ARP 1971** (chapter 5.1.2) is the height of the test aircraft measured by triangulation in this method. At a height within a range between 100 and 500 ft above the ground flies the aircraft by a tower or tall building. The aircraft is in this method sighted through a reference grid arrangement at or near the tower by a camera or eyepiece located in the tower to determine elevation angle. By triangulation, the height of the aircraft above or below a fixed point in the tower can be determined. In this method must be accurately known the horizontal distance of the aircraft from the tower. By having the aircraft fly down the centerline of a runway is this usually accomplished.

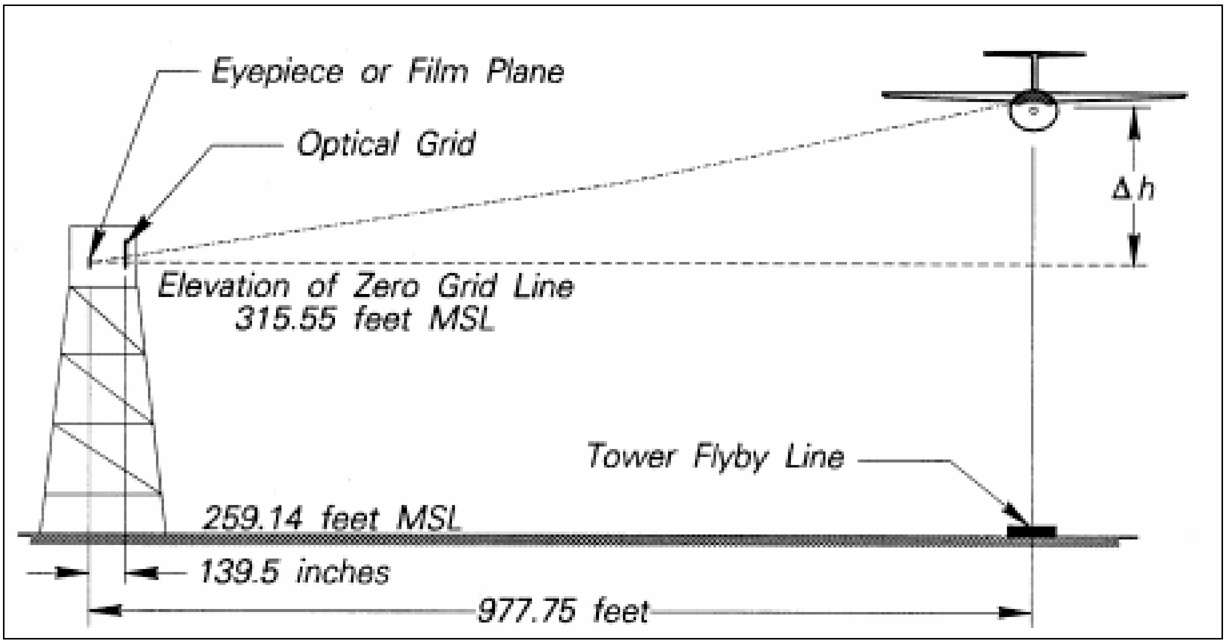

Fig.: 8-2 The tower fly-by calibration method
(**Ward 1993**)

8.4 The pacer aircraft calibration method

According to **ARP 1971** (chapter 5.1.3) the pressure altitude of the aircraft in test flight can be measured while a calibrated aircrafts or pacer flying in close formation. Both aircraft contain calibrated pressure instruments. The pressure data are simultaneously recorded in each aircraft, while flying in close formation at the same altitude and about one wing span apart (between wing tips). The pressure error of the test aircraft may be computed, by using this calibration and the difference in pressure recorded by the two aircrafts.

8.5 The radar tracking calibration method

In this method is, according to **ARP 1971** (chapter 5.1.4), the geometric altitude of the test aircraft determined by ground based radar-tracking equipment. This method is usually performed, flying at altitudes of 5000 ft or above, with the test aircraft. The aircraft in flight test must be previously calibrated in at least one condition (such as at a given indicated airspeed), and that this or other calibrated conditions be utilized in the calibration of pressure versus elevation above the radar. After calibration of the space is performed by the aircraft in test flight operating in the reference or previously calibrated mode or by weather balloons, the aircraft is then flown through the test zone at various Mach numbers. As the position error of the aircraft changes with Mach number and/ or angle of attack, in order to maintain indicated airspeed, the aircraft will increase or decrease altitude. Differences in altitude between the reference and test condition converted to pressure, plus the position error at the reference condition then equals the pressure error at the test condition.

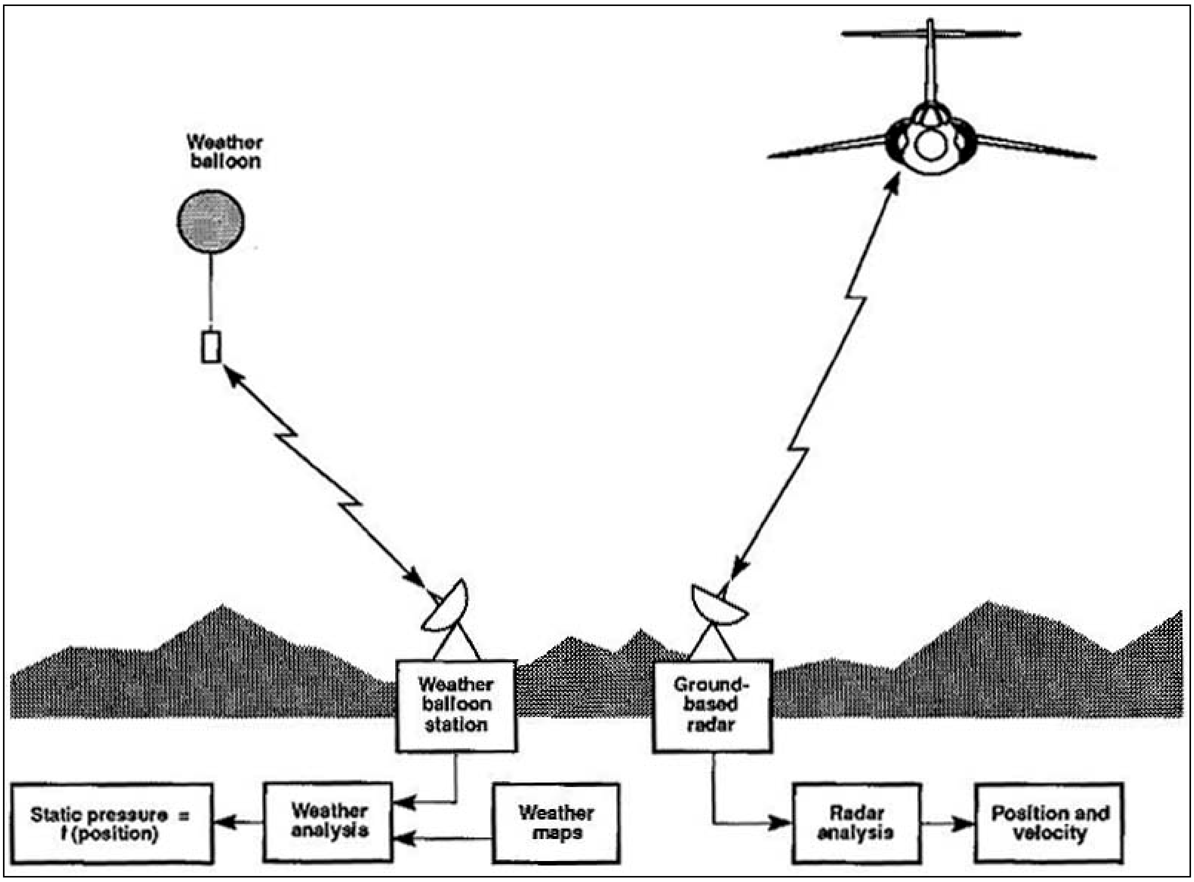

Fig.: 8-3 The radar tracking method
(**AGARD 1995**)

8.6 The trailing-cone calibration method

According to **ARP 1971** (chapter 5.1.5), the idea of this method is to suspend a static reference far enough behind an aircraft so that the ports are not affected by the aerodynamic disturbance of the airframe. Between the aircraft static ports and the trailing cone reference system is a differential pressure gage connected. The error in the static system may be determined by using measurements taken from these gages. The combination aircraft/trailing cone can be flown at all altitudes and in a speed range of nearly all Mach numbers.

Fig.: 8-4 The trailing cone calibration method on the A321
(**Airbus**)

8.7 The nose boom calibration method

The Nose Boom calibration method is equal the Trailing Cone calibration method with the difference that the measurement is not situated behind an aircraft its in front of the aircraft, realized with a long tube.

Fig.: 8-5 The nose boom calibration method on the F16
(**NASA**)

8.8 The laser anemometry calibration method

The Laser Anemometry Calibration Method gives the true airspeed to calibrate the static-port and the airspeed indicator. The principle is based on the Doppler effect, by this effect a Laser wave measured over the “reflection” of pollution in the air the variable distance (Particle Image Velocimetry). This variable distance is an indicator for the velocity.

8.9 The camera correlation calibration method

With this method over two high-resolution digitally cameras alternating pictures. within two laser-focused divisions are made on one side of the aircraft. By the time difference, that results if contaminations in the two different lasers light up, the airspeed can be determined by a correlation.

8.10 The speed-course calibration method

This method involves, according to **Smith** (chapter E), flying the aircraft over a course of known length and timing. A accurate way is to fly by GPS. A test range of known length must first be laid out.

Over an outward flight and a return flight on the same course, the wind component can be considered. By this connection can be determined the true airspeed (TAS). Over the TAS can be calculated on the contrary the static pressure.

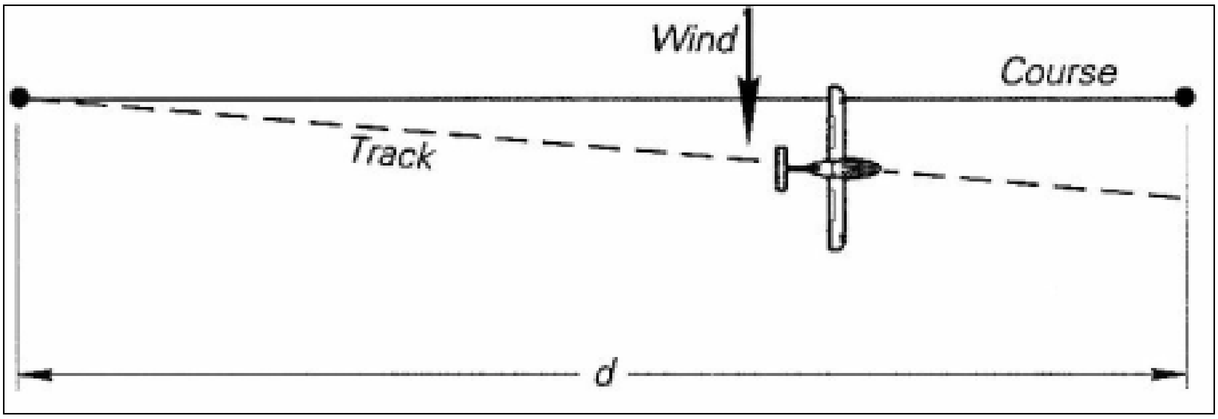

Fig.: 8-6 The speed-course calibration method
(**Ward 1993**)

9 The present calibration method at Airbus

With the consisting systems the calibration takes place either after the trailing cone principle or a laser system called ALEV.

The trailing cone system:

A winch with a coiled hose is situated in the passenger compartment. This hose can be unwound over the front spar of the vertical tail unit. Coming out at the fin tip, it can lead the pressure from behind the A/C to the pressure detector in the winch.

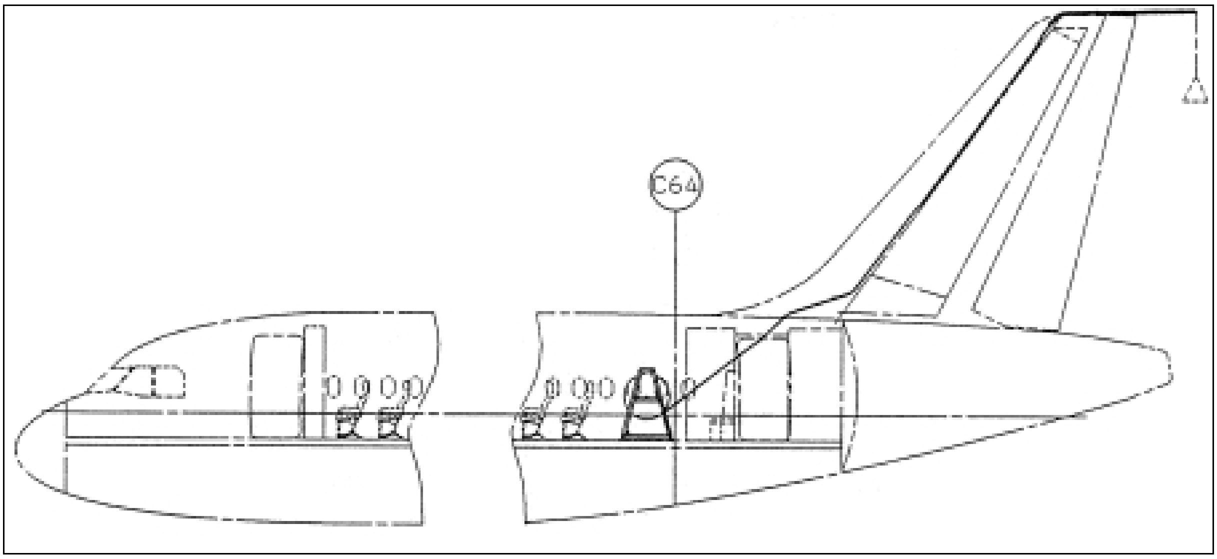

Fig.: 9-1 The trailing cone on Airbus (**ETF**)

The laser system:

It makes the conditions available of the laser technology of 1990 (Sextant Avionics). The laser is installed in the cabin at the window and is cooled with nitrogen. The optic consists of a special cabin window of Germanium. Additionally to the static-port calibration over the true airspeed (TAS) the angle of attack α and the sideslip angle β is measured with the laser. This takes place by means of the fact that three different laser beams are used.

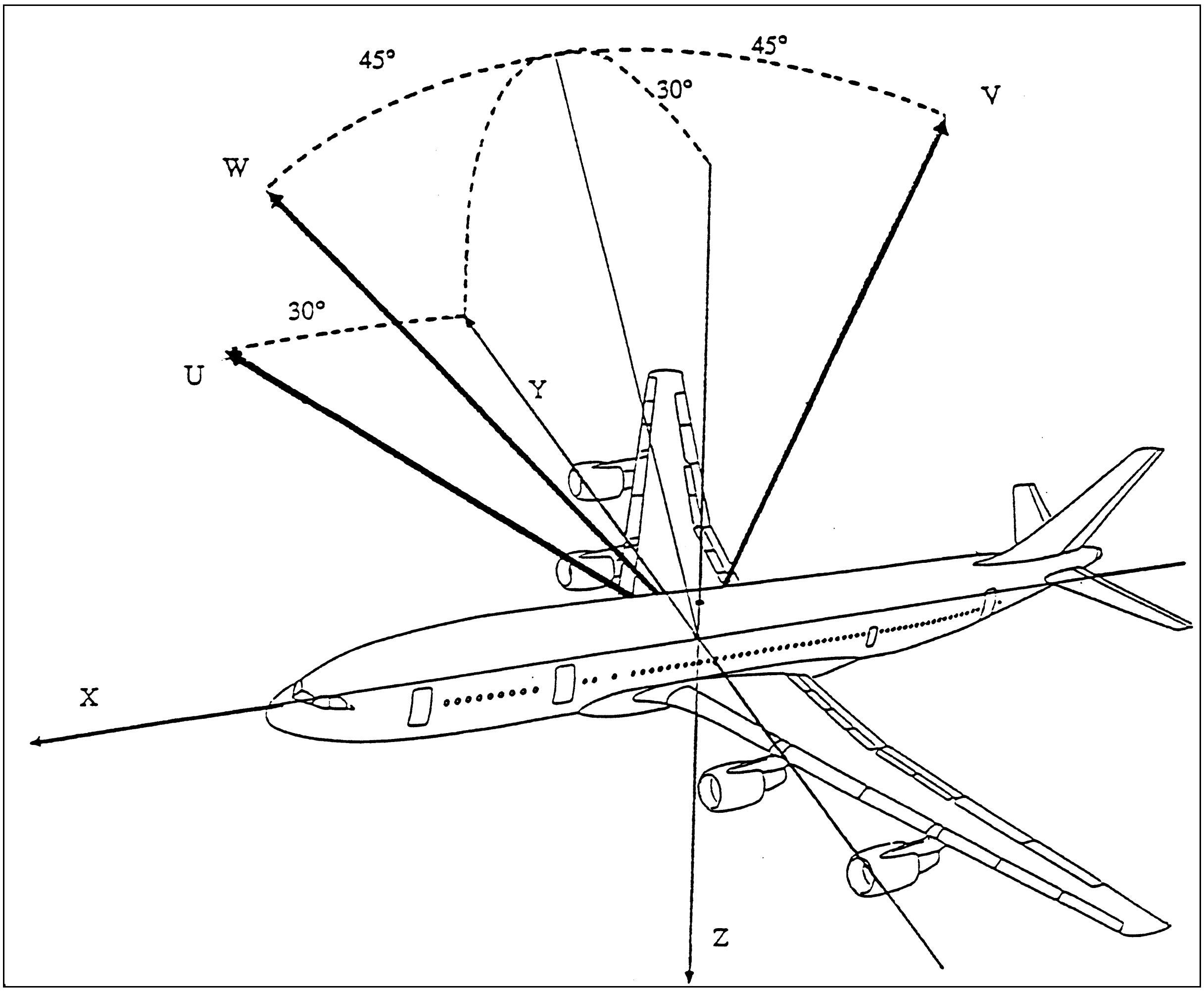

Fig.: 9-2 The 3D laserbeam overview of ALEV3
(**Hammer**)

- axis U : in the XY plane of the aircraft, closes with Y an angle of 30 °
- axis V : To the right above (60) ° and backwards (45 °of Y axis)
- axis W : To the right above (60) ° and forward (45 °of Y axis) symmetrically to V over the YZ plane

With both systems there are at present problems during the flight test. The laser offers a measurement possibility which can be installed easily for all flight maneuvers. This older technology, does not offer the necessary accuracy in higher altitudes, due to contaminations lacking.

In contrast to this the “trailing-cone” offers in all horizontal divisions sufficient accuracy. But with increasing size of the aircraft, problems result in the case of different flight maneuvers. Thus it occurs more frequently, that during a turning flight, the trailing-cone, most likely by a whip effect, tears off.

10 The calibration methods other A/C manufactures

The instructions for the certification of the different aircrafts must be naturally likewise observed by other aircraft manufacturers. Accordingly an airspeed and static-port calibration must be accomplished also on their aircrafts. After the evaluation of different flight test figures of other aircraft manufacturers it is to be recognized, that with larger machines the trailing cone principle is applied predominantly. In the following are shown different aircrafts of different manufacturers in flight test.

a) Boeing

As largest aircraft manufacturers of the world, with experience of many years, Boeing represents a direct competitor to the airbus consortium. After the fusion with Mc Donnell Douglas, the production line covers, according to Boeing data, 9 different aircrafts within the civilian division. The following data are part of the homepage (**Boeing**) introduction of the company.

> *“Boeing has been the world leader in commercial flight for more than 40 years. The main commercial products consist of the 717 (formerly the MD-95), 737, 747, 757, 767, and 777 families of jetliners as well as the MD-80, MD-90, MD-11 and Boeing Business Jet. The company has more than 11,000 commercial jetliners in service worldwide.”*

With the following aircrafts, recent date, flight test machines with trailing cone system are to be seen. Contrary to test flight of Airbus, Boeing uses partly two trailing cone systems. Unfortunately it was not possible to get further information from Boeing for this double system. Otherwise their system seems to be just like the Airbus system.

Fig.: 10-1 The Boeing 737-600 with trailing-cone (**FLUGREVUE**)

Fig.: 10-2 The Boeing 747-400 with trailing-cone (**DISCOVERY**)

Fig.: 10-3 The Boeing 767-400 with trailing-cone
(**FLUGREVUE**)

Fig.: 10-4 The Boeing 777 with two different trailing-cones
(**FLUGREVUE**)

Fig.: 10-5 The Boeing Osprey with nose boom
(**FLUGREVUE**)

b) Bombardier Aerospace

Mainly in the inferior market segment, up to 100 the seats comprehensive flier, transacts Canadian consortium of firms (Canadair, Learjet, de Havilland), uses the nose boom as calibration method.This can probably be declared on the lower extents of the fliers and the associated lower displacement before the aircraft.

Fig.: 10-6 The Bombardier CRJ700 with nose boom
(**FLUGREVUE**)

c) Cessna

The American manufacturer Cessna positions likewise, probably due to the lower displacement and the shorter measurement lance exerted by it, on the nose boom. The operation of the Textron group introduces itself on its homepage (**Cessna**) as the largest business jet manufacturer of the world and looks back to a 72 on year old firm history.

> *"Now in its 72nd year, the Cessna Aircraft Company has delivered over 180,000 aircraft, including 24,000 twin-engine airplanes, 2,000 military jets and over 2,900 Citations -- the largest fleet of business jet aircraft in the world. More than half the aircraft flying today are Cessnas. Worldwide, Cessna employs nearly 11,000 people in the design, manufacturing, sales, and service of general aviation aircraft and is registered as an ISO-9001 company in recognition of its quality systems and processes."*

Fig.: 10-7 The Cessna Citation CJ2 with nose boom
(FLUGREVUE)

d) Dornier

Today the Dornier company who belongs now to the American Fairchild group products business jets. Their future plans however aim to jets like the single aisle family of Airbus Industry.

Fig.: 10-8 The Dornier Fairchild 328 Jet with nose boom
(**FLUGREVUE**)

e) Embraer

The Brazilian Newcomer aims likewise into the division up to offering jets of 100 seats. Contrary to the others in this market segment Embraer operates with a trailing cone system which is underneath the fuselage.

Fig.: 10-9 The Embraer ERJ 135 with trailing-cone
(**FLUGREVUE**)

f) Mc Donnell Douglas

The aircraft manufacturer bought up in the meantime by Boeing, uses likewise like Boeing a double method for calibration. Contrary to Boeing are not used two trailing cone systems, but a boom at the vertical tail unit and a trailing cone system likewise attached to the vertical tail unit. In the following the MD11 is to be seen in flight test, which was established and tested as final aircraft in self-development of Mc Donnell Douglas.

Fig.: 10-10 The Mc Donnell Douglas MD 11 with trailing-cone and boom (**FLUGREVUE**)

g) Raytheon

The Raytheon company, with its subsidiary Raytheon aircraft, is an operation with a firm history of 75 in the USA. Predominantly in the business division and operating in the division of special aircraft, covers the product line, after firm data, 11 different types of aircraft. There product range also contains the “Premier I” which is shown in the flight test as follows.

Fig.: 10-11 The Raytheon Aircraft's Premier with nose boom (**FLUGREVUE**)

11 The preliminary evaluation criterion

For the first selection of the suitable measuring methods, different valuation criteria are required, which are described in the following.

Tab.: 11-1 The preliminary valuation criterion definition

Valuation criterion	**Definition**
Development cost	Under this point the accumulating costs of the design, production , become acquisition, installation, refurnishing will be regarded.
Maintenance possibility	Under this point the maintenance, accessibility and interference of other systems are evaluated.
Test procedure time	This subpoint evaluates the time, that must be spent, in order to accomplish the calibration. This means the preparation time needed f.e. for rising of measurement balloons as well as the time to evaluate afterwards or to disassemble the equipment.
Handling qualities	Within this criterion the feasibility of different flight maneuvers is evaluated under the different calibration methods.
Reliability	This subpoint evaluates the reliability of the system
Accuracy	Under this subpoint the accuracy is evaluated.

11.1 The priority for the evaluation criterion

For the priority of the valuation criteria these are compared individually and evaluated against each other.

- Development cost/ maintenance possibility:

  With a direct comparison of these valuation criteria against each other, those “development cost” represent a substantial additional expenditure, opposite to the “maintenance possibility”. Due to the system-specific characteristics those are “development cost” i.e. an unchangeable size. In contrast to this the “maintenance possibility” is a design changeable size.

- Development cost/ test procedure time:

  System-dependently results from the “test procedure time” the quantity of required flying hours. As one flying hour represents a substantial cost contains (approx. 40000 $) and this matter of expense compared with the “development costs” is a recurring size, outweighs the valuation criterion “test procedure time” in the direct comparison.

- Development cost/ handling qualities:

  For the calibration of the Anemometry it is necessary to accomplished different flight maneuvers. For this reason the valuation criterion “handling qualities” must in the comparison receive stronger attentions than the “development cost”.

- Development cost/ reliability:

  The “reliability” is one point, that indirectly represents a dependence for development and design. If this point is evaluated individually in the direct comparison those “development cost” must be subordinated automatically in this valuation criterion “reliability”.

- Development cost/ accuracy:

  There is the same dependence of the two criteria of evaluation as under subpoint “reliability”. Since the accuracy represents a prescribed size, this valuation criterion must be preferred before the “development cost.

- Maintenance possibility/ test procedure time:

The valuation criterion of the “maintenance possibility” represents a purely design criterion. A assessment in relation to the “test procedure time” must inevitably consider the high share of the cost. Accordingly results in the comparison a preference of the criterion specified at last.

- Maintenance possibility/ handling qualities:
  The “handling qualities” represent an indispensable demand for the calibration and must be preferred in the direct comparison to the “maintenance possibility”.

- Maintenance possibility/ reliability:
  Since the “reliability” can be classified as more desirable, this point in the direct comparison with the valuation criterion of the “maintenance possibility ” becomes priority.

- Maintenance possibility/ accuracy:
  In the comparison is the valuation criterion “accuracy” a given size, that only causes limited fluctuations and in relation to the “maintenance possibility” can be classified more highly.

- Test procedure time / handling qualities:
  The valuation criterion “test procedure time” is with approx. 40000 $/h a substantial cost factor. In contrast to this are “the handling qualities” in the connection with the “test procedure time”. A calibration method with that the valuation criterion “handlings qualities” is not evaluated to be very important, it can be calibrated over an increased expenditure of time likewise. For this reason becomes the valuation criterion “test procedure time” more highly evaluated.

- Test procedure time/ reliability:
  Even if the valuation criterion “reliability” describes an important point, it results in the direct comparison to the “test procedure time”, however due to the expense an imbalance in favor to the “test procedure time”.

- Test procedure time/ accuracy:

So far the valuation criterion “accuracy” was always preferred, but opposite to the subpoint “test procedure time” must a increased accuracy, within the specifications, be subordinated to the substantial costs of a flying hour.

- Handling qualities/ reliability:

  If these two criteria are compared, a preference to the “handlings qualities” results from the need of different flight maneuvers.

- Handling qualities/ accuracy:

  With a comparison of these valuation criteria, a favorite results over the need to cover different flight maneuvers also at expense of the accuracy.

- Reliability/ accuracy:

  The valuation criterion “reliability” becomes preference in relation to a increased accuracy, for reasons of the longevity of a system and with it the connected possible application/mission on different aircrafts.

Tab.: 11-2 The priority matrix of the preliminary valuation criterion

	Development cost	Maintenance possibility	Test procedure time	Handling qualities	Reliability	Accuracy
Development cost		0	1	1	1	1
Maintenance possibility	1		1	1	1	1
Test procedure time	0	0		0	0	0
Handling qualities	0	0	1		0	0
Reliability	0	0	1	1		0
Accuracy	0	0	1	1	1	
Points	1	0	5	4	3	2
Points +1	2	1	6	5	4	3
Priority %	9,52	4,76	28,57	23,81	19,05	14,29

11.2 The preliminary elevation

Now the different procedures become evaluated with the different evaluation criteria within a range from 1-3, among themselves. The assessment 1 places usable and the assessment 3 very well usable. Thereupon a summary without priority can be established.

a) Computed

Tab.: 11-3 The valuation of the computed calibration method

Valuation criterion	Allocation	Valuation
Development cost	For this system special conditions are valid, there development costs accompany with substantial cost of computation and wind tunnel tests. The installation covers besides several primary detectors, in different departments, in order to cover several flights. For these reasons this system is concerned with one point in this category.	1
Maintenance-possibility	As a calculated place for a pressure primary detector is always valid in each case for a certain flight, different primary detectors must be built in. Thus the possibility of the maintenance worsens substantially. Additionally no consideration to other systems can be given, with this procedure since the calculated positions are obligatory and can not be changed. Thus a bad assessment for this point results.	1
Test procedure time	Provided, that for all conditions of flight pressure primary detectors are installed, a very good "test procedure time" results.	3
Handling qualities	Since an installation of all primary detectors, for all conditions of flights, is very badly realizable, only a moderate assessment for this criterion results.	2
Reliability	With this procedure several primary detectors must be used. That leads to the fact that the reliability is weakened, since the probability of a failure with several primary detectors increases.	2
Accuracy	This criterion depends strongly on the theoretical design. A small miscalculation can have crucial Effects on the result.	2

b) Tower fly-by

Tab.: 11-4 The valuation of the tower fly-by calibration method

Valuation criterion	Allocation	Valuation
Development cost	The development costs for this system are insignificant, since only a data communication between the Tower and the test aircraft must consist. An installation and a refurnishing are easy to handle, so that in the final result this criterion with a bestnote is evaluated.	3
Maintenance possibility	This criterion is evaluated to be very good, since excluding a telemetry unit at a well accessible location must be placed.	3
Test procedure time	The "test procedure time" increases considerably, since an approach and a return flight are lost in each case as an unused flight time for the calibration. Thus a worse assessment results.	1
Handling qualities	Within this calibration method only flights near "ground level" are to be realized. Accompanying with it, for safety reasons, only a low airspeed.	1
Reliability	The "reliability" depends on the telemetry and the weather conditions near ground level. Since the weather is very dynamic near ground level, an average value results in the assessment.	2
Accuracy	Exactly the same as the valuation criterion "reliability" this criterion depends strongly on the weather conditions near ground level and the spacing to the reference measuring point. For this reason this criterion is in the center zone evaluated.	2

d) Pacer Aircraft

Tab.: 11-5 The valuation of the pacer aircraft calibration method

Valuation criterion	Allocation	Valuation
Development cost	The developing costs lie in the center zone, since two aircraft must be equipped with a suitable radio-based data communication.	2
Maintenance possibility	This criterion lies likewise in the center zone, since at two aircrafts maintenance work must take place.	2
Test procedure time	Since with this calibration method two aircraft are in the air, they double the “test procedure time”. Depending upon the “pacer aircraft” the costs vary for the flying hour however opposite the aircraft which can be tested.	1
Handling qualities	Theoretically two aircrafts can take accurately the same flight path next to each other. This would presuppose however a very intensive preparation as well as similar behaviors of the aircrafts. Since both is to be realized only at substantial expenditure, this criterion is in the center zone evaluated.	2
Reliability	This valuation criterion depends on two aircrafts and on their telemetry system. For this reason this point is settled in the center zone.	2
Accuracy	The accuracy depends on the possibility of the simultaneous flight path. With homogeneous horizontal flight and low maneuvers the accuracy can be evaluated to be very good.	3

e) Radar Tracking

Tab.: 11-6 The valuation of the radar tracking calibration method

Valuation criterion	Allocation	Valuation
Development cost	This criterion is arranged by the number of the individual components in the center zone.	2
Maintenance possibility	This point of assessment is likewise evaluated by the number of the different individual components in the center zone.	2
Test procedure time	Method-caused, an unused approach and return flight result also here. Thus results an increased expenditure of time, which can be settled only in the inferior assessment division.	1
Handling qualities	By the arrangement of the reference measuring points can be covered each speed range. By an easily increased additional expenditure several flight conditions can be likewise carried out. From this reason an assessment within the central division results.	2
Reliability	The reliability is dependent on many sensitive single parts and is thus arranged in the center zone.	2
Accuracy	This valuation criterion is determined by the spacing of the reference measurement to the test flyer. Additionally the effect of the weather is added, so that an assessment in the center zone appears appropriate.	2

f) Trailing-cone

Tab.: 11-7 The valuation of the trailing-cone calibration method

Valuation criterion	Allocation	Valuation
Development cost	This system already being in the application/mission and the relevant problems are known, results a very good assessment of this criterion, even if the installation and refurnishing are more complex.	3
Maintenance possibility	The maintenance of this system is trouble-free, because it is a very durable and simple procedure.	3
Test procedure time	This valuation criterion is evaluated at very good, since a measurement taking place in real time takes place in each flight condition.	3
Handling qualities	Each normal flight maneuver can be measured with this system. Exceptions consist in extreme maneuvers where the trailing cone, due to its inertia, can be maneuvered from the flight path. Since no extreme flights are however normally flown off , this criterion can be with very good evaluated.	3
Reliability	The reliability can be evaluated except for few exceptions as very good.	3
Accuracy	This valuation criterion results from the dependence to extreme flight maneuvers. Since these do not belong to the calibration flights, this criterion can be evaluated with very good.	3

g) Nose boom

Tab.: 11-8 The valuation of the nose boom calibration method

Valuation criterion	Allocation	Valuation
Development cost	Method-dependently results a very good assessment for this criterion, since no mobile parts exist and the outstanding parameters can be classified as familiar.	3
Maintenance possibility	Within a boom there are no mobile parts, so that this criterion can be evaluated with very good.	3
Test procedure time	This valuation criterion is evaluated with very good, since a measurement taking place in real time takes place in each flight condition.	3
Handling qualities	During a good arrangement of the boom there is no limitation for this criterion. For this reason it is very well evaluated.	3
Reliability	The reliability of a boom can be evaluated by its very simple construction with very good.	3
Accuracy	The only possibility of inaccuracy is if the boom dives into a wake of the aircraft. In the case of a good positioning this can be excluded, so that an assessment takes place in the upper division.	3

h) Laser

Tab.: 11-9 The valuation of the laser calibration method

Valuation criterion	Allocation	Valuation
Development cost	The development costs can be arranged so far badly. Since with this measuring method no system in self-development results, but a complete system can be bought to go with, the development costs range within limits. A later integration into the aircraft can be easily realized due to a compact complete system. For these reasons this point is evaluated with very good.	3
Maintenance possibility	This valuation criterion can be evaluated due to the compactness and flexibility of the system with very good.	3
Test procedure time	This valuation criterion is evaluated with very good, since a measurement taking place in real time and in each flight condition.	3
Handling qualities	Since a laser works independently of the incident flow and the boundary layer, each flying range can be covered. From this the bestnote for this procedure results.	3
Reliability	The reliability of the system depends exclusively on the quality of the components. The normal weather as well as the different flight conditions do not have effect on the system. For this reason the bestnote can be assigned.	3
Accuracy	System-dependently the accuracy depends on the frequency-displacement of the laser. This displacement can be compiled and evaluated with very large accuracy. For this reason this criterion can be evaluated with very good.	3

i) Camera correlation

Tab.: 11-10 The valuation of the camera correlation calibration method

Valuation criterion	Allocation	Valuation
Development cost	The measuring system of this method can be realized very favorably, since predominantly simple electronic components are applied, that can be installed easily.	3
Maintenance possibility	The construction of the measuring system can be arranged easily and with low-maintenance, so that the bestnote can be assigned .	3
Test procedure time	This valuation criterion is evaluated with very good, due to a measurement taking place in real time and in each flight condition.	3
Handling qualities	Since a visual system functions independently of the incident flow and the boundary layer, each flying range can be covered . From this the bestnote for this procedure results.	3
Reliability	Depending upon used components, can be specified as only variable the disturbance climatic conditions, whereby this system appears during the assessment in the center zone.	2
Accuracy	System-dependently the accuracy depends on the dispersion of the laser beams at the aerosols. If a sufficient dispersion is present the speed can be determined with very large accuracy. For this reason this criterion can be evaluated with very good.	3

j) Speed- course

Tab.: 11-11 The valuation of the speed- course calibration method

Valuation criterion	**Allocation**	**Valuation**
Development cost	For the calibration of the Anemometry system no installation or considerable development is necessary on application of this method. For this reason the bestnote will assign.	3
Maintenance possibility	Maintenance is not required due to missing test equipment.	3
Test procedure time	There an unused approach and return flight method-cause are required, can only the worst assessment be assigned.	1
Handling qualities	Method-caused each speed range can be covered. With the different maneuver flights there are however limitations. From this an assessment within the central division results.	2
Reliability	The reliability can be evaluated due to missing auxiliary components with very good.	3
Accuracy	Since this method of the calibration is in dependence to the weather, an assessment takes place in the central division.	2

Tab.: 11-12 The Summary of preliminary valuation

	Development cost	Maintenance possibility	Test procedure time	Handling qualities	Reliability	Accuracy
Computed	1	1	3	2	2	2
Tower Fly-By	3	3	1	1	2	2
Pacer Aircraft	2	2	2	3	2	2
Radar Tracking	2	2	1	3	2	2
Trailing Cone	3	3	3	3	3	3
Nose Boom	3	3	3	3	3	3
Laser	3	3	3	3	3	3
Camera correlation	3	3	3	3	2	3
Speed- course	3	3	1	2	3	2

If the priority is consulted now, a solution results, which supplies an objective overview, whereby the method with the highest numerical value is to be regarded as favorite.

Tab.: 11-13 The valuation of the calibration methods inclusive the priority factor

	Development cost	Maintenance possibility	Test procedure time	Handling qualities	Reliability	Accuracy	Σ
Computed	9,52	4,76	85,71	47,62	38,10	28,57	214,29
Tower Fly-By	19,05	9,52	28,57	23,81	38,10	28,57	147,62
Pacer Aircraft	19,05	9,52	57,14	47,62	38,10	28,57	200,00
Radar Tracking	19,05	9,52	57,14	23,81	38,10	28,57	176,19
Trailing Cone	28,57	14,29	85,71	71,43	57,14	42,86	300,00
Nose Boom	28,57	14,29	85,71	71,43	57,14	42,86	300,00
Laser	28,57	14,29	85,71	71,43	57,14	42,86	300,00
Camera correlation	28,57	14,29	85,71	71,43	38,10	42,86	280,95
Speed- course	28,57	14,29	28,57	47,62	57,14	28,57	204,76

The solution resulting from it documents that several procedures would be suitable. It in additional a certain factor of uncertainty in the assessment is considerate, four systems can be taken into the closer selection.

- Trailing Cone
- Nose Boom
- Laser
- Camera correlation

In order to guarantee a renewed comparison of these methods objectively, these methods in the following are regarded more accurately.

12 The trailing-cone measurements

For the calibration measurement after the trailing cone principle result different possibilities of the realization. Dependent on the position and the type of the measurement, different variations in the following are presented.

12.1 The trailing-cone position

The position of the trailing cone system results from the affected zone of flow of the aircraft and the characteristics of the measuring method as described in the following.

- As a trailing cone is pulled results only a technically convertible position behind or under the aircraft.
- An outlet at a closed edge is well suitable for design reasons.
- Additionally to the closed edge, it is still added that behind the vertical tail unit are the lowest turbulences.
- An accommodation of the system in the wing is not convertible due to the strong final vortices.

For the reasons specified above, the variation trailing cone in the vertical tail unit is to be preferred here. It is to be marked that for other aircraft samples with t tail unit, e.g. the A400M, this possibility, due to the trim ability of the horizontal stabilizer, is only conditionally realizable.

12.2 The trailing cone direct measurement

With this type of the measurement the pressure primary detector is situated in the trailing-cone coming out from the vertical tail unit. Thus this measures the direct calmed down static pressure, in the height where the primary detector is situated. In order to make a calibration of the onboard systems, the position of the primary detector must be known, in this case in relation to the aircraft-own primary detector which must be calibrated.

From this condition two possibilities result:

- A possibility consists, bringing the measuring probe (trailing cone) with own lift into the correct position. Whereby an inspection of additional camera observation or a laser range finding must take place.

- A further possibility is given by determining directly over a camera observation the difference in height to the aircraft-own primary detector.

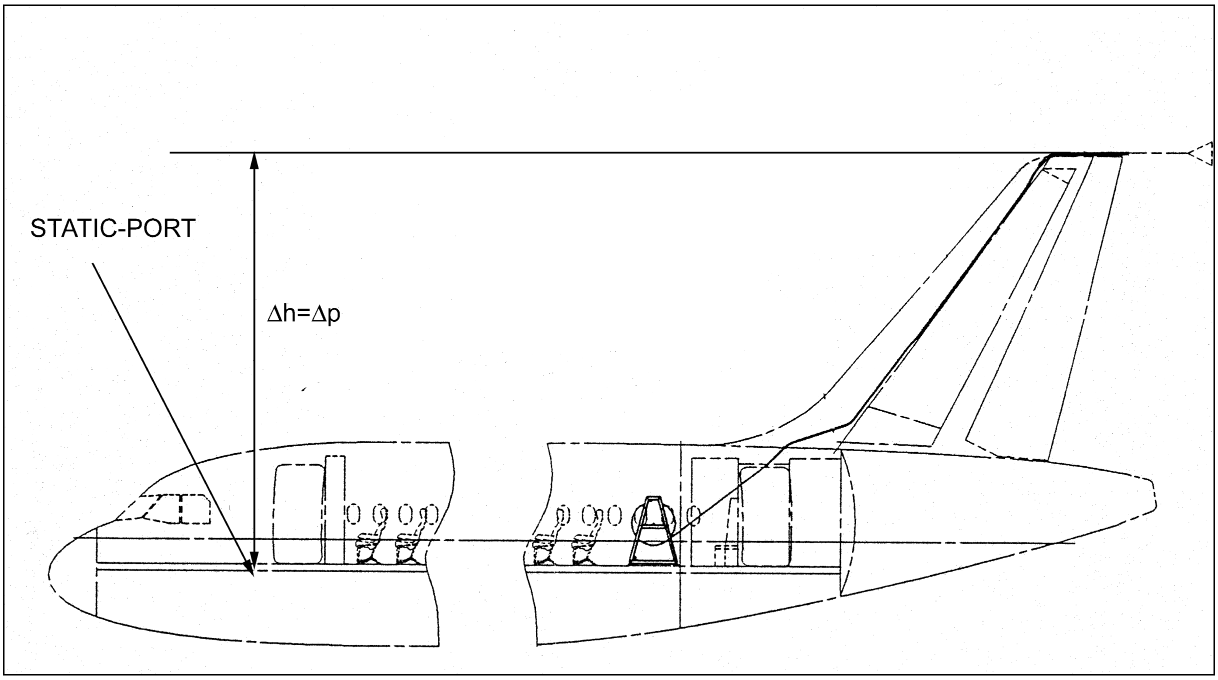

Fig.: 12-1 The trailing cone direct measurement (**ETF**)

Additionally it must be considered that the primary detector is exposed to the climatic conditions of the atmosphere. Thus, in order to guarantee the accuracy of the primary detector, it must be possibly particularly protected or heated.

As benefit a space-saving integration of the winch component can be presupposed here, since a lighter tension element can be used (glass fiber, wire). It must be considered that such a tension element must possibly convey additionally the data and a power supply must be guaranted.

12.3 The trailing cone indirect measurement

The indirect measurement of the calmed down static pressure, as applied in the consisting system, permits the accommodation of the primary detector within the airplane structure. Thus the height of the probe, in relation to the aircraft, is not relevant and does not have to be specially determined. By the forwarding of the pressure with a tube, increases the winch diameter and thus the accommodation worsens.

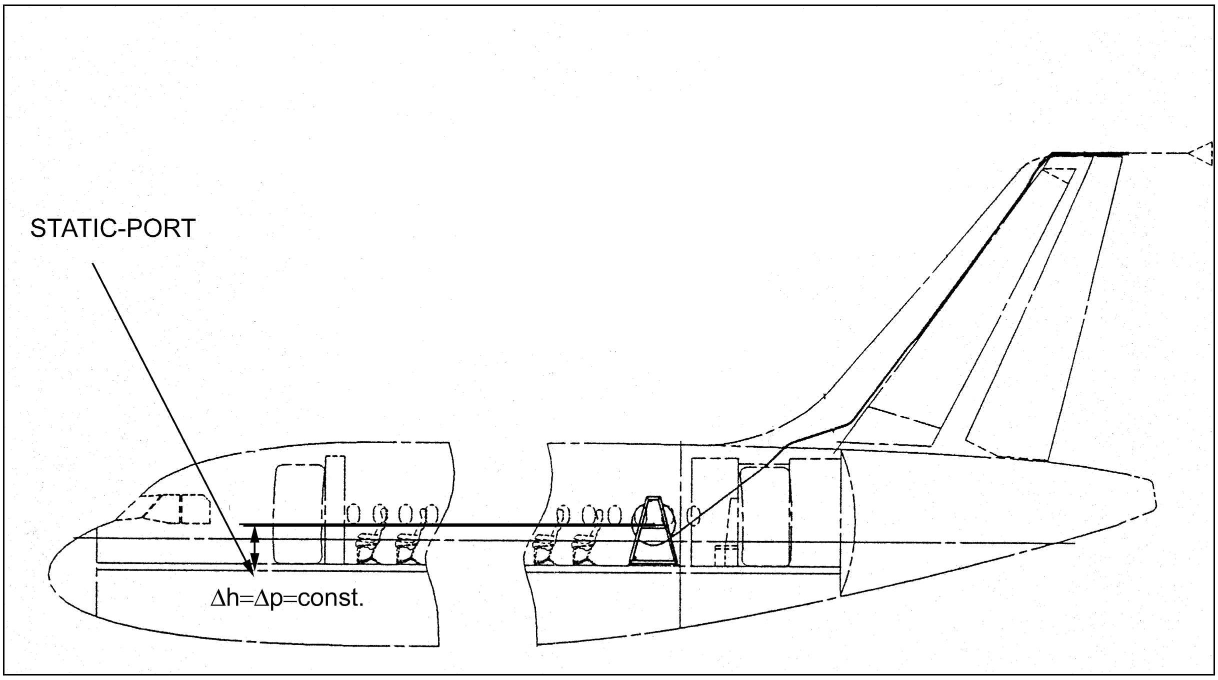

Fig.: 12-2 The trailing cone indirect measurement (**ETF**)

13 The boom measurements

With the help of a boom, just as numerous variations of the positioning can be taken up. The method of the calibration with the help of a boom, offers additionally the possibility for attaching other primary detectors. As example for this an angle primary detector for the incident flow can be integrated.

13.1 The boom at fin position

This constellation does not permit, after evaluation of the bases from chapter 5, a possibility for a suitable measurement in according to the precision demands. For the flow computation, if the upper edge of the vertical tail unit is set, results it the following constellation after a graphic evaluation. The calming degree, with Mach 0,3, in different heights, shows, that the flow contains strong disturbance.

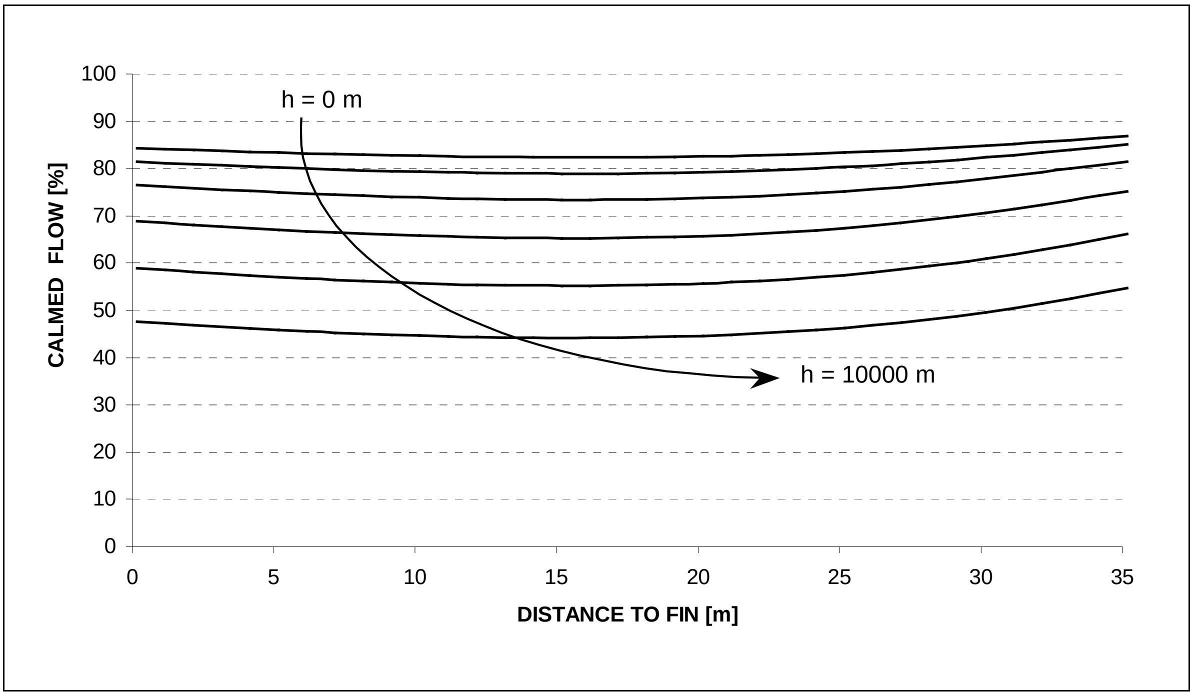

Fig.: 13-1 The calmed flow over distance to fin in variable height (Mach 0,3)

Over the dimensionless factor c_p applied, results from it:

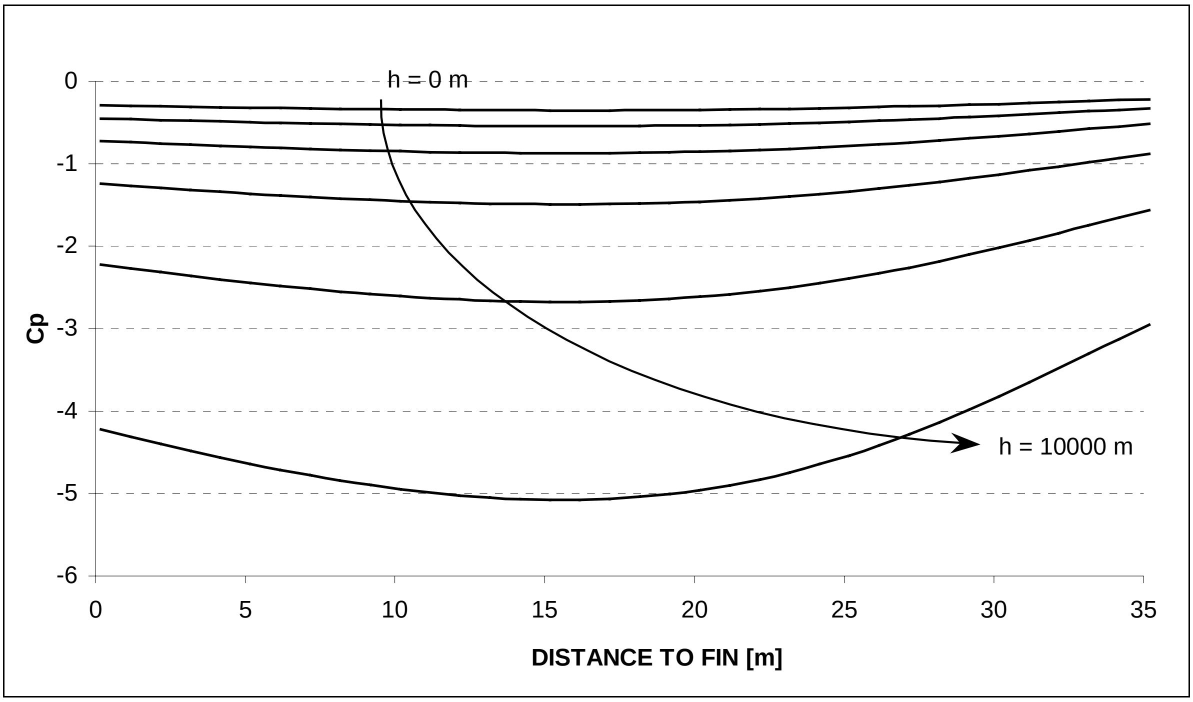

Fig.: 13-2 The pressure coefficient c_p over distance to fin in variable height (Mach 0,3)

From the measurement requirements, from chapter 7., a fault size results, for different speeds and different heights. The installation of a boom is regarded under the strictest conditions. From it the following conditions result.

- The formulas for the calculations of the disturbance within air, is only valid within the incompressible frictionless area. From it a view results in a speed range of Mach 0,1 to Mach 0,3.

- The strictest tolerance are on height of MSL, so that this division is of special interest.

For these installed conditions result the following fault sizes.
At a speed between Mach 0,1 and 100 knots results a maximum fault in the height of Δh_{max}= 30 feet (9,144 m). To the pressure primary detector of the calibration system, is valid a maximum fault at a defined value (MSL) of Δh_{cal} = 1,409 m.

From it a still permissible fault in the height Δh_{tol} results of:

$$\Delta h_{tol} = \Delta h_{\max} - \Delta h_{cal} = 9{,}144m - 1{,}409m = 7{,}735m \tag{13.1}$$

In the case of a speed of Mach 0,2 results a maximum fault in the height of Δh_{max}= 9,941 m. To the pressure primary detector of the calibration system further a maximum fault at a defined value (MSL) of Δh_{cal} = 1,409 m is valid.
From it a still permissible fault in the height Δh_{tol} results of:

$$\Delta h_{tol} = \Delta h_{\max} - \Delta h_{cal} = 9{,}941m - 1{,}409m = 8{,}532m \tag{13.2}$$

In the case of a speed of Mach 0,3 results a maximum fault in the height of Δh_{max}= 11,627 m. To the pressure primary detector of the calibration system further a maximum fault at a defined value (MSL) of Δh_{cal} = 1,409 m is valid.
From it a still permissible fault in the height Δh_{tol} results of:

$$\Delta h_{tol} = \Delta h_{\max} - \Delta h_{cal} = 11{,}627m - 1{,}409m = 10{,}218m \tag{13.3}$$

From the dimensionless parameter c_p calculated before, the working static pressure can be determined, at the position in question. Over the height formula (3.23) can be calculated the height resulting from it less the real height (MSL) as Δh . This height is positioned into relation to the still permissible fault in the height Δh_{tol},. From it a dimensionless factor results which clearly indicates whether the measurement is suitable.

If the factor is larger or equal one, the position is considered as suitable point for calibration.
If the factor is smaller one, the position is considered as unsuitable point for calibration.

Graphically applied results from it:

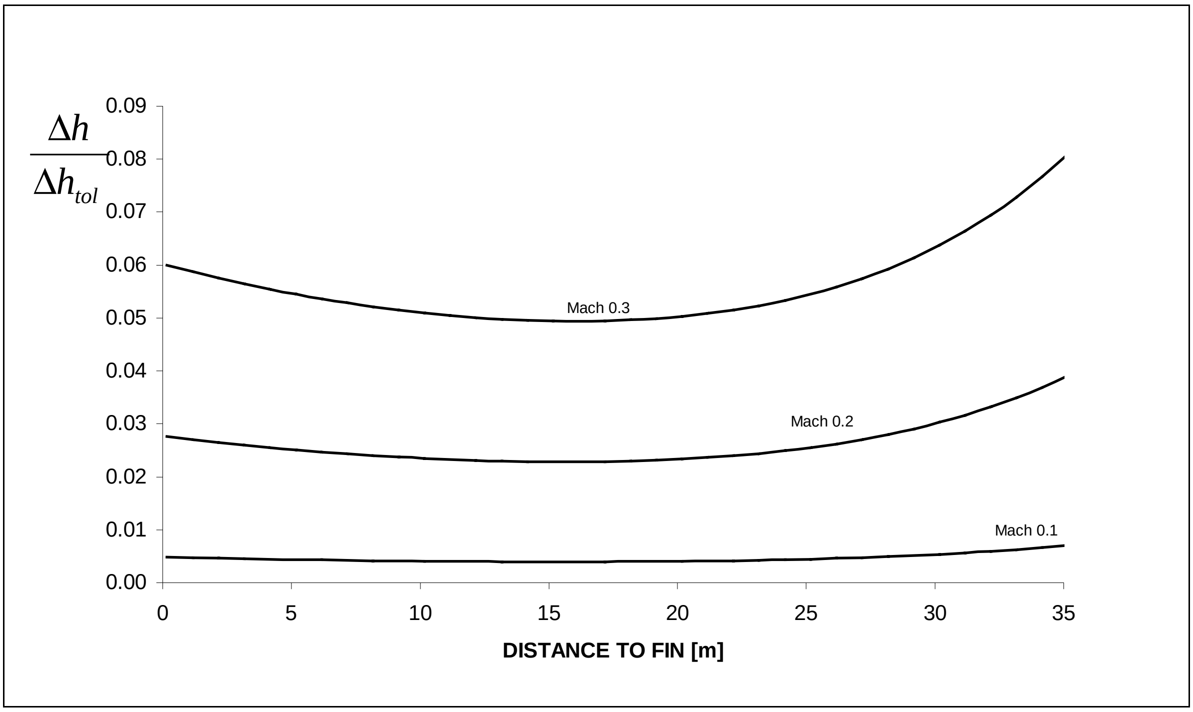

Fig.: 13-3 The height error relation over distance to fin (Mach 0,1–0,3)

As alternative to it, the possibility results of letting the boom end over the vertical tail unit. This is realizable over an additional rack which can be built up. The aerodynamic disturbance and weight effects occurring thereby, are here however not to be specified. The following assessment, refers in general form to the method! From the calculation installed before it is however already well-known that this method for the A3XX cannot supply usable measured values. Since this working out is occupied generally not only with the A3XX, the assessment of the method can represent a decision aid and for this reason it is specified for other types of aircraft.

13.2 The boom at wing position

Also with the boom an integration is possible in the wing. Here is however conceivable, that this position can lead to vibrations and accordingly to flutter.

13.3 The boom at nose position

The integration of the boom as nose boom is generally possible, require however a large expansion in order to arrive into the calmed flow division (3.2 aerodynamic foundations). Furthermore it is to be noted here that no radar can be used during the test flight. The calming degree of flow already defined is applied over the distance from the nose, is to be recognized, that the flow starting from a distance of approx. 10 m begins to calm down oneself constantly. In contrast to the fin position, results only a negligible dependence on the speed. This is because of the fact that the induced circulation of the wing is overlaid by translation flow and the spacing is relatively large. Therefore the largest interference depends on the displacement of the fuselage. Since this is relatively constant over the height, only one graph is particularly emphasized (MSL, Mach 0,3). All other graphs are not considered, since they lie one above the other or only insignificantly beside.

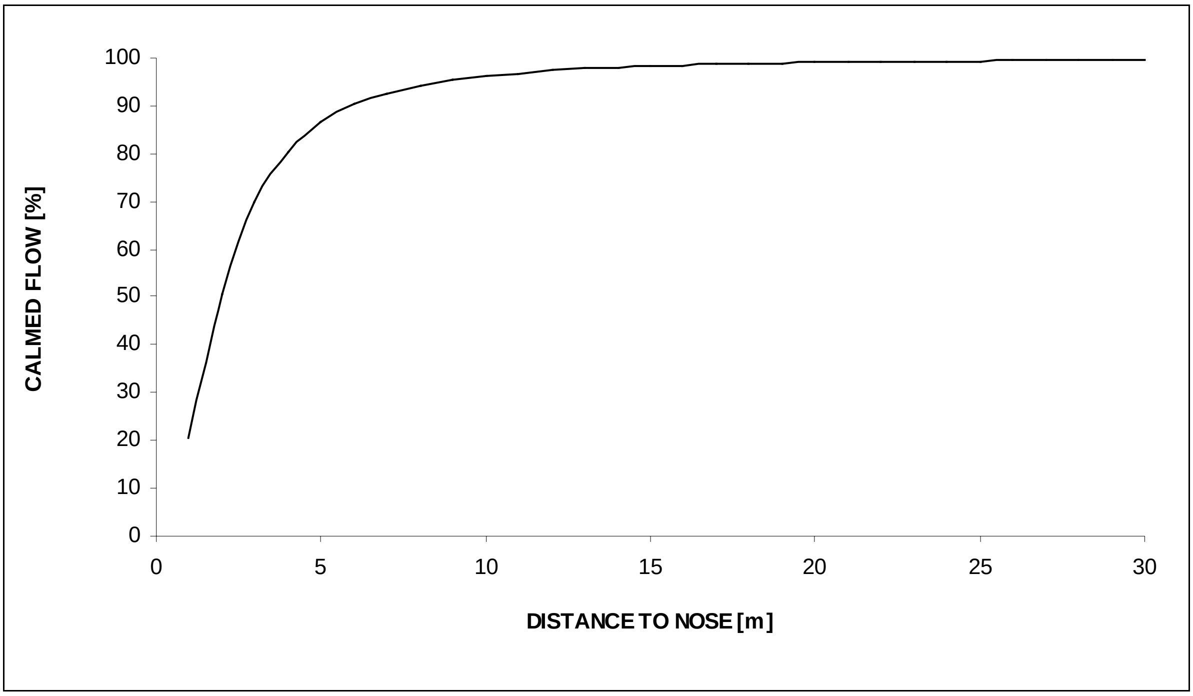

Fig.: 13-4 The calmed flow over distance to nose

Over the dimensionless factor c_p applied results from it:

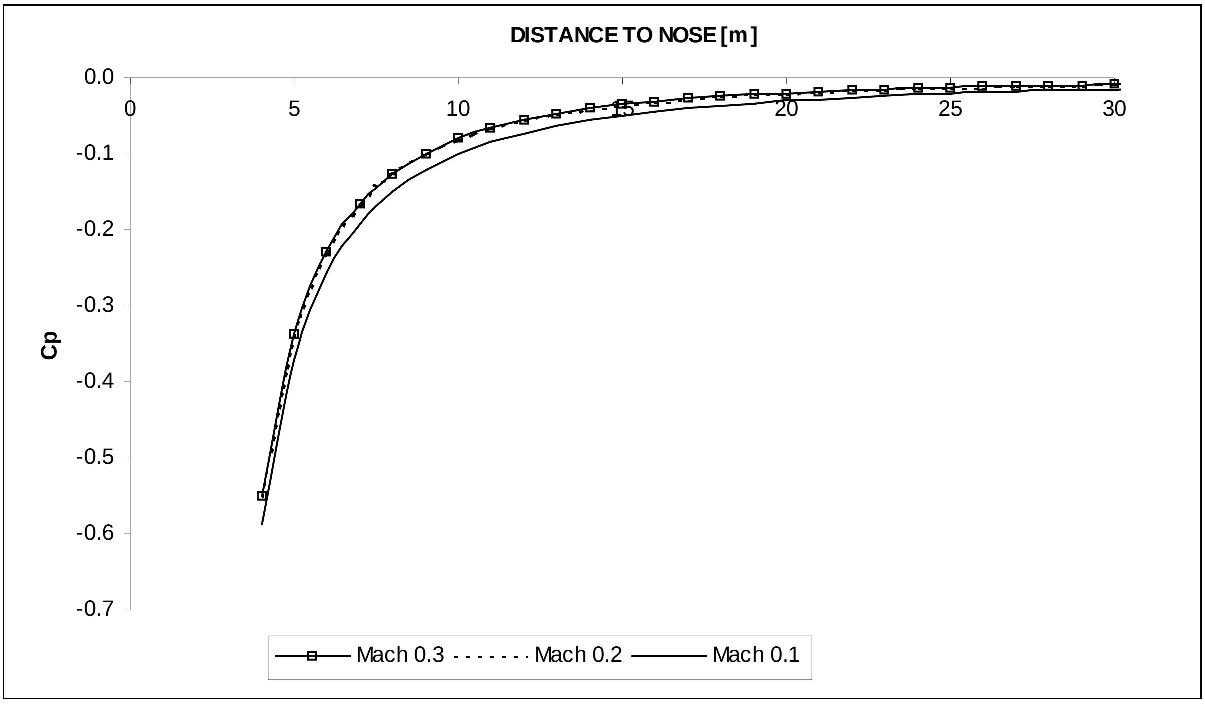

Fig.: 13-5 The pressure coefficient c_p over distance to nose (Mach 0,1-0,3)

From the measurement requirements, from chapter 7., a fault size for different speeds and different heights results. The installation of a boom is regarded under the strictest conditions. From it the following conditions result.

- The formulas for the calculations of the disturbance within air, is only valid within the incompressible frictionless area. From it a view results in a speed range of Mach 0,1 to Mach 0,3.

- The strictest tolerance are on height of MSL, so that this division is of special interest.

For these installed conditions result the following fault sizes.

At a speed between Mach 0,1 and 100 knots results a maximum fault in the height of Δh_{max}= 30 feet (9,144 m). To the pressure primary detector of the calibration system, is valid a maximum fault at a defined value (MSL) of Δh_{cal} = 1,409 m.

From it a still permissible fault in the height Δh_{tol} results of:

$$\Delta h_{tol} = \Delta h_{\max} - \Delta h_{cal} = 9{,}144m - 1{,}409m = 7{,}735m \tag{13.4}$$

In the case of a speed of Mach 0,2 results a maximum fault in the height of Δh_{max}= 9,941 m. To the pressure primary detector of the calibration system further a maximum fault at a defined value (MSL) of Δh_{cal} = 1,409 m is valid.
From it a still permissible fault in the height Δh_{tol} results of:

$$\Delta h_{tol} = \Delta h_{\max} - \Delta h_{cal} = 9{,}941m - 1{,}409m = 8{,}532m \tag{13.5}$$

In the case of a speed of Mach 0,3 results a maximum fault in the height of Δh_{max}= 11,627 m. To the pressure primary detector of the calibration system further a maximum fault at a defined value (MSL) of Δh_{cal} = 1,409 m is valid.
From it a still permissible fault in the height Δh_{tol} results of:

$$\Delta h_{tol} = \Delta h_{\max} - \Delta h_{cal} = 11{,}627m - 1{,}409m = 10{,}218m \tag{13.5}$$

From the dimensionless parameter c_p calculated before, the working static pressure can be determined, at the position in question. Over the height formula (3.23) can be calculated the height resulting from it less the real height (MSL) as Δh . This height is positioned into relation to the still permissible fault in the height Δh_{tol},. From it a dimensionless factor results which clearly indicates whether the measurement is suitable.

If the factor is larger or equal one, the position is considered as suitable point for calibration.
If the factor is smaller one, the position is considered as unsuitable point for calibration.

Graphically applied results from it:

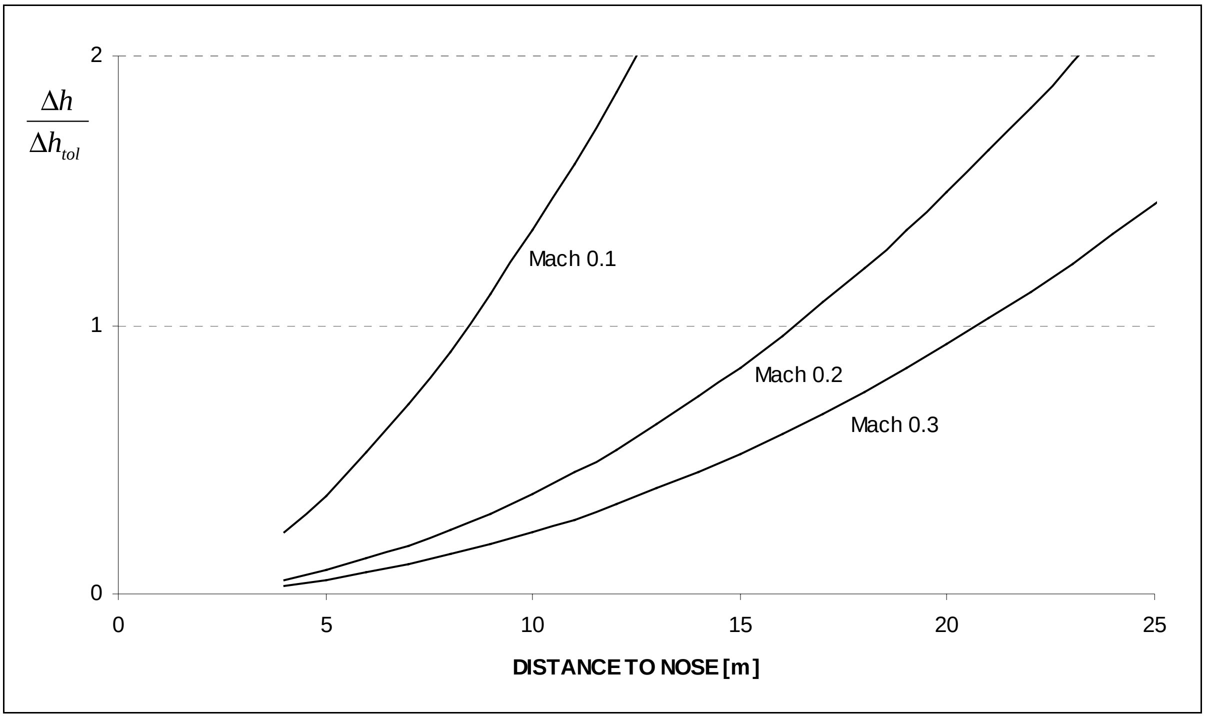

Fig.: 13-6 The height error relation over distance to fin (Mach 0,1–0,3)

From the diagram it is to be recognized that for a correct calibration measurement the length of the boom must be approx. 21 m. From the aerodynamic values provided by AIRBUS likewise a similar result can be estimated. After the undocumented pressure coefficient diagrams of the fuselage, the following summary for the fuselage of the A3XX results in the low speed division.

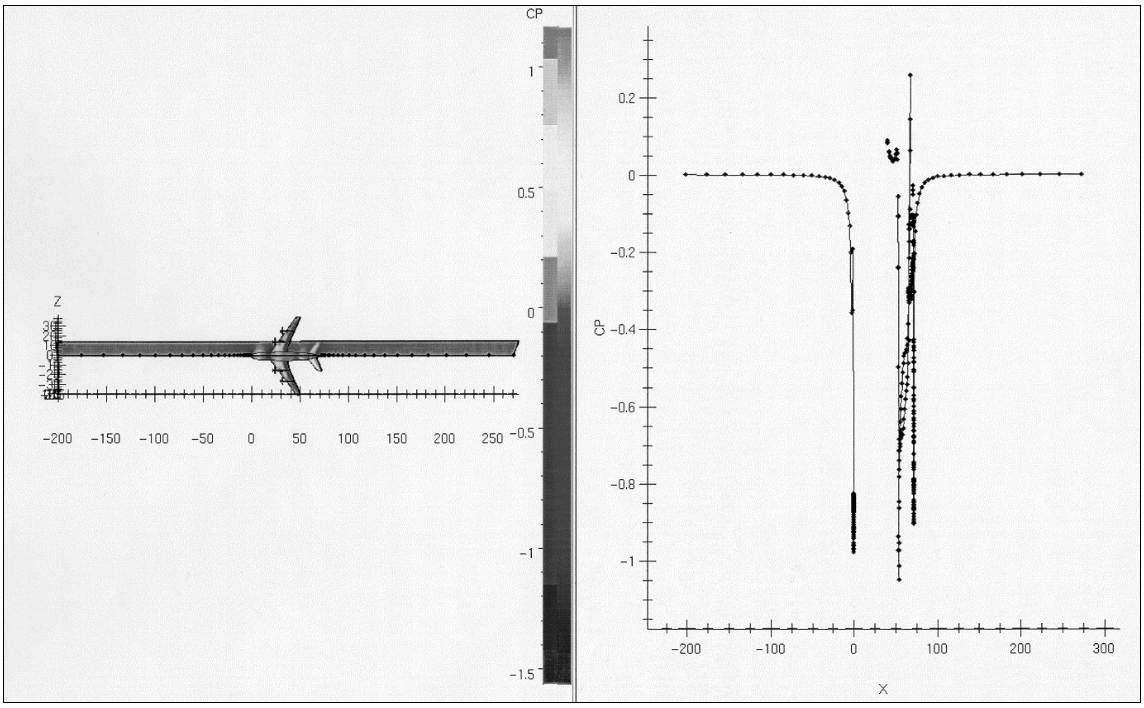

Fig.: 13-7	The pressure coefficient c_p for the A3XX
(**EFD**)

By a separate view and enlargement of the relevant division, can be determined a length of approx. 19 m.

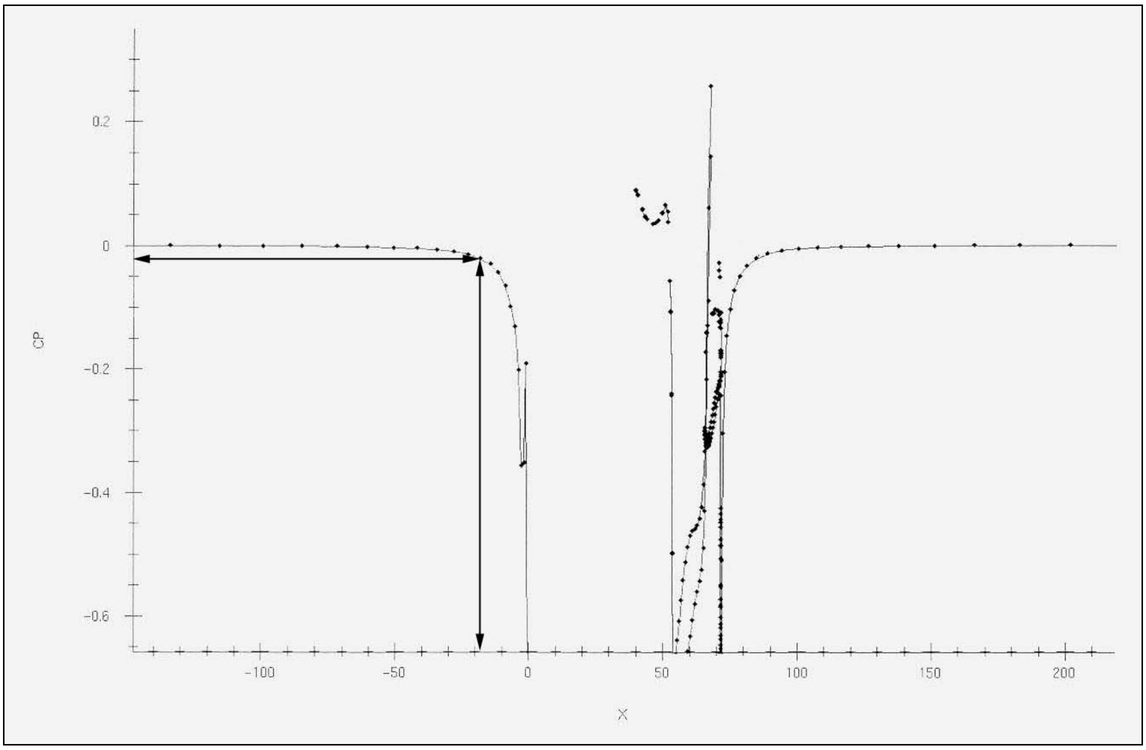

Fig.: 13-8	The detail overview of pressure coefficient c_p
(**EFD**)

14 The laser measurements

The measurement over the particle image velocimetry with the help of a laser permits many variations at different positions. Four different variations are to be regarded in the following. The laser offers the possibility, beside the airspeed- and static-port calibration, to take over also the functions of the laser in application, ALEF3.

The accuracy of a laser system is not certain by the installation position. In this working out is assumed that the measurement in flight direction takes place. The position of the measuring point is indicated in a spacing to the nose. For an estimation of a fault size, the same fault in the height is taken into consideration, that is set also for the calibration of the pressure sensor.

The defined calming degree of flow is applied over the distance from the radome, thereby is to be recognized, that the flow starting from a distance of approx. 10 m begins to calm down itself constantly. A negligible dependence on the speed results. This is because of the fact that the induced circulation of the wing is overlaid by translation flow and the spacing is relatively large. Therefore is the largest interference dependent on the displacement of the fuselage. Since this is relatively constant over the height, only one graph is particularly emphasized (MSL, Mach 0,3). All other graphs are not considered, since they lie one above the other or only insignificantly beside.

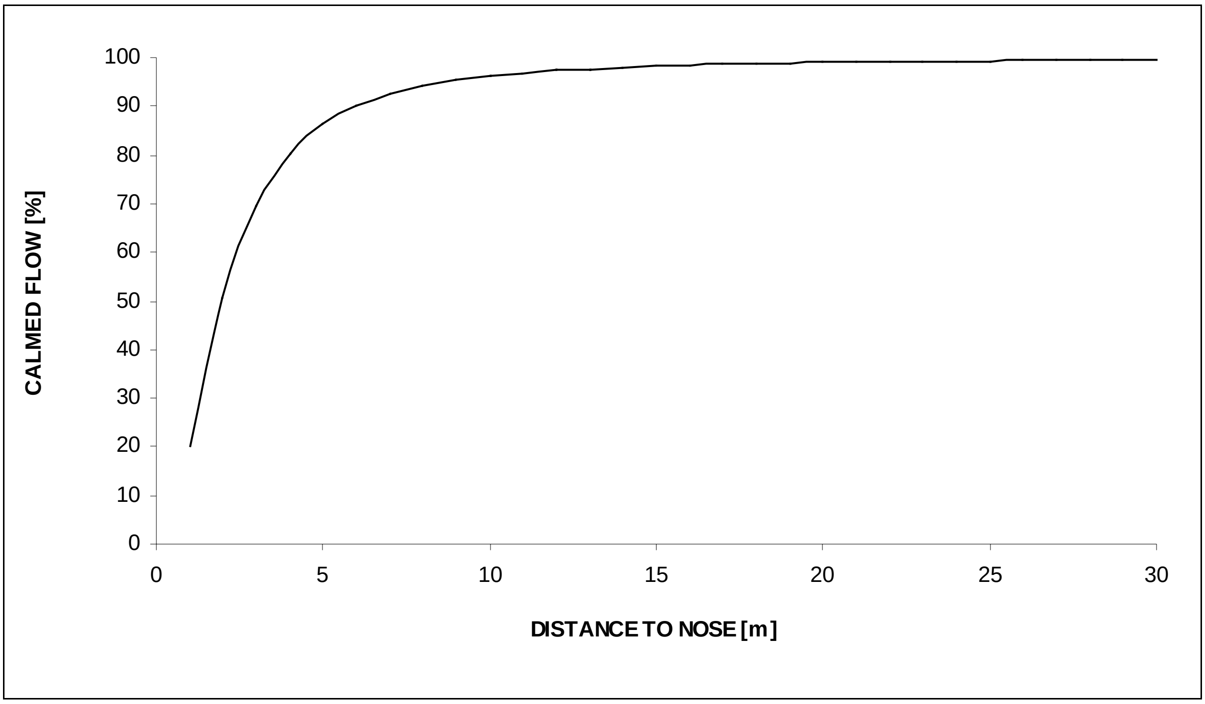

Fig.: 14-1 The calmed flow over distance to nose

From the measurement requirements, from chapter 7., a fault size for different speeds and different heights results. The installation of a laser is regarded under the strictest conditions. From it the following conditions result.

- The formulas for the calculations of the disturbance within air, is only valid within the incompressible frictionless area. From it a view results in a speed range of Mach 0,1 to Mach 0,3.
- The strictest tolerance are on height of MSL, so that this division is of special interest.
- The measurement distance for a laser system can be indicated in a range from 50 m to 2000 m.

For these installed conditions result the following fault sizes.
At a speed between Mach 0,1 and 100 knots results a maximum fault in the height of Δh_{max} = 30 feet (9,144 m). To the laser system is valid a maximum fault at a defined value (MSL) of Δh_{cal} = 1,409 m. From it a still permissible height error Δh_{tol} results of:

$$\Delta h_{tol} = \Delta h_{\max} - \Delta h_{cal} = 9{,}144m - 1{,}409m = 7{,}735m \tag{14.1}$$

In the case of a speed of Mach 0,2 results a maximum height error of Δh_{max}= 9,941 m.
To the laser system further a maximum fault at a defined value (MSL) of h_{cal} Δ= 1,409 m is valid. From it results a still permissible height error Δh_{tol} of:

$$\Delta h_{tol} = \Delta h_{\max} - \Delta h_{cal} = 9{,}941m - 1{,}409m = 8{,}532m \tag{14.2}$$

In the case of a speed of Mach 0,3 results a maximum height error of Δh_{max}= 11,627 m. To the laser system is valid further a maximum fault at a defined value (MSL) of Δh_{cal} = 1,409 m. From it results a still permissible height error Δh_{tol} of:

$$\Delta h_{tol} = \Delta h_{\max} - \Delta h_{cal} = 11{,}627m - 1{,}409m = 10{,}218m \tag{14.3}$$

From speeds calculated before and the formula (8.7) for the calibration, the working static pressure in the considered position can be determined. It is assumed that the total pressure is measured error free and just like the temperature as ISA value is registered. Over the horizontal formula (3.23), now the height resulting from it can be calculated less the real height (MSL) as Δh. This height is positioned in relation to the permissible height fault Δh_{tol},. From it a dimensionless factor results over that it is quickly recognizable whether the measurement is suitable.

If the factor is larger or equal one, the position is considered as suitable point for calibration. If the factor is smaller one, the position is considered as unsuitable point for calibration.

Graphically applied results from it:

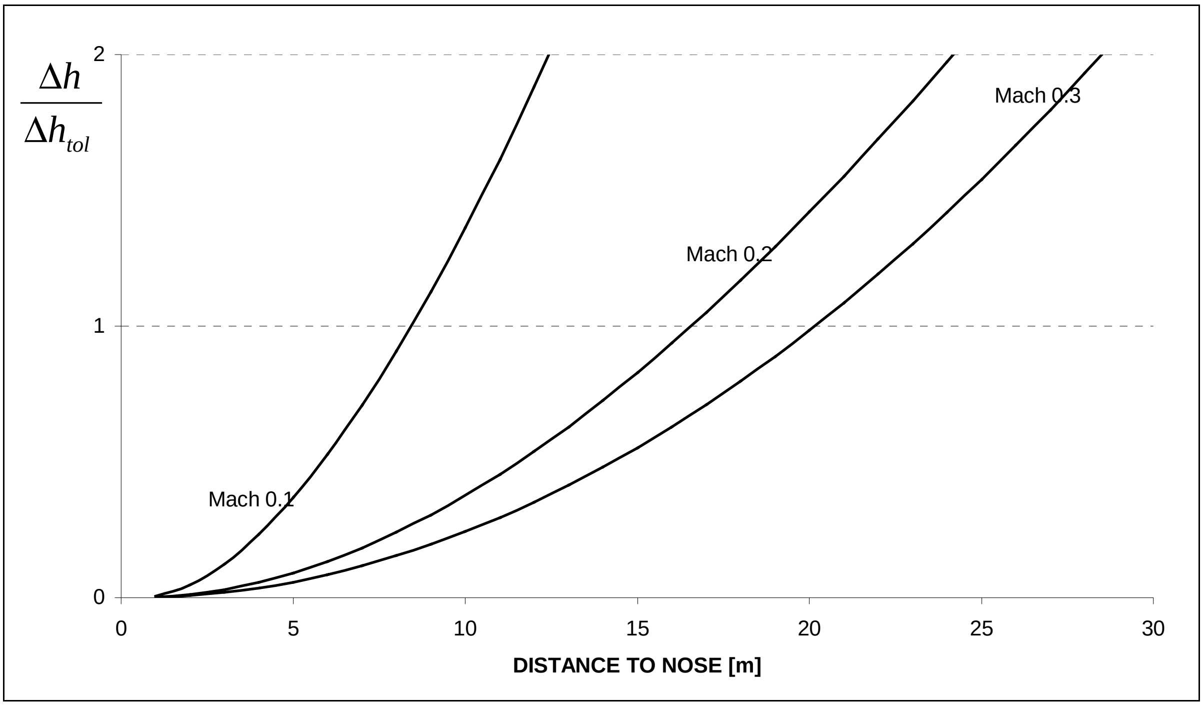

Fig.: 14-2 The height error relation over distance to nose (Mach 0,1-0,3)

14.1 The laser at cabin position

A simple possibility of the positioning of a laser system is to place it in the cabin at a window. A possible transfer of the data cables is unnecessary by different badly accessible sections e.g. the vertical tail unit. In addition the laser is freely accessible and without larger expenditure adjustable. Additionally to the laser an optics must be installed, because the laser on the desired measuring range focuses.

14.2 The laser at fin position

The positioning in the vertical tail unit represents a simple possibility of the primary detectors arrangement. The laser can be assembled either in a department in the leading edge or in the fin tip of the vertical tail unit. A measurement to the rear as well as forward is conceivable and convertible.

14.3 The laser at wing position

Generally a positioning of the laser is possible also in the wing, if it authorizes the place. Since the laser can make measurements far enough forward or rear, even the strong turbulences in the wing wake would not be a decisive factor. For the positioning the fact is problematic that as soon as the laser is positioned into the outer wing, it could create in the worst case vibrations, or occurring vibrations could disturb the measurement.

14.4 The laser at nose position

Since a calibration flight is a test flight under special conditions, the laser can be positioned also in the radome in place of the radar. This methodic would have crucial benefits, since a fixture is already present and possibly the data lines of the radar can be used. The crucial disadvantage is, that with the calibration flights the radar must be removed and thus it is not available.

15 The camera correlation

For the time of the creation of this documents it can be only said to this measuring method that this is still in the early development stage and thus it is considered not in the closer selection.

16 The evaluation criteria

In the previous assessment it resulted that the three variations are considered as favorites. In the case of the closer view it results that these methods can be divided further, dependent on the positioning and the type of the measurement. As valuation criteria are now introduced:

Tab.: 16-1 The evaluation criteria definition

Evaluation criterion	Definition
Flexibility	Under this point is evaluated, whether the type of the calibration method, also for other aircraft types without larger modifications is suitable and possibly masters different functions additionally.
Practicability	Contains the expenditure for the integration of the system into the flight test machine as well as the feasibility of the method.
Safety/ Disturbing	This point of assessment evaluates the safety, which possibly is no longer completely guaranteed by this system and possible disturbing of other equipment services.
Failure	Evaluates the linking of possible fault sizes.

16.1 The priority for the evaluation

The processing and determination of a favorite happen according to the same pattern as in chapter 11, First a priority for the individual evaluation criteria in form of a matrix is installed.

- Flexibility/ Practicability

  If these two evaluation criteria are compared, it is preferable to develop a system, which is not limited to a certain testbed. With increasing flexibility and the application/mission on other aircraft types, resulting from it, can the accumulating fixed costs of the system more quickly be amortized. Possible taking over of additional measurement functions is to be emphasized accordingly likewise positively. Out of this reason the evaluation goes in favor of the criterion “flexibility”.

- Flexibility/ Safety

The safety is always highest in each case to evaluating. For this reason it is preferred also in this case to the criterion of the “flexibility”.

- Flexibility/ Failure

  The compensation of possible faults is a complex process. This expenditure can exceed and destroy each flexibility of a measuring method. For this reason the evaluation criterion “failure” in the direct comparison is more highly evaluated.

- Practicability/ Safety

  The safety is always highest in each case to evaluating. For this reason it is preferred also in this case to the criterion of the “practicability”.

- Practicability/ Failure

  A calibration method can fulfill very well the criterion “practicability”. It can cause a worse final result which by complex measures must be corrected by the linking of possible fault sizes. For this reason the criterion “failure” is more highly settled in the comparison.

- Safety/ Failure

  The safety is always highest in each case to evaluating. For this reason it is preferred also in this case to the criterion of the “failures”.

Tab.: 16-2 The priority matrix of the evaluation criterion

	Flexibility	Practicability	Safety	Failure
Flexibility		0	1	1
Practicability	1		1	1
Safety	0	0		0
Failure	0	0	1	
Points	1	0	3	2
Points +1	2	1	4	3
Priority %	20,0	10,0	40,0	30,0

Afterwards the individual calibration procedures are confronted to the individual evaluation criteria in a matrix and evaluated with numerical values of 1-3.

16.2 The elevation

1) Cone direct measurement

Tab.: 16-3 The evaluation of the cone direct measurement calibration method

Evaluation criterion	Allocation	Evaluation
Flexibility	The “measuring probe” can fulfill this criterion in each case. However in relation to another aircraft type the winch and accordingly the tension element must be change, due to the modified distance of the calmed down static pressure. Due to is dependence the assessment can be applied in the center zone.	2
Practicability	This evaluation criterion is to be fulfilled only at substantial expenditure, since an intensive fault rectification makes the design more difficult.	1
Safety	By the measuring methods conditioned arrangement no handicap of the safety is to expected.	3
Failure	Depending on the measuring method an increased expenditure is necessary for the fault clearing. For this reason this criterion is arranged in the inferior division.	1

2) Cone indirect measurement

Tab.: 16-4 The evaluation of the cone indirect measurement calibration method

Evaluation criterion	Allocation	Evaluation
Flexibility	The “measuring probe” can fulfill this criterion in each case. However in relation to another aircraft type the winch and accordingly the tension element must be change, due to the modified distance of the calmed down static pressure. Due to is dependence the assessment can be applied in the center zone.	2
Practicability	This criterion is arranged by accumulating complex mechanical command in the center zone.	2
Safety	By the measuring methods conditioned arrangement no handicap of the safety is to expected.	3
Failure	The simple interpretation of this measuring method compensates automatically different faults. In relation to the direct measurement a horizontal compensation is not required. For this reason this criterion can be evaluated with very good.	3

3) Laser cabin position

Tab.: 16-5 The evaluation of the laser cabin position measurement calibration method

Evaluation criterion	Allocation	Evaluation
Flexibility	Since the laser system represents a compact equipment, which is besides in no dependence to the experimental aircraft, it fulfills highest requirements of this evaluation criterion.	3
Practicability	This evaluation criterion is fulfilled in particular within this arrangement on the simplest.	3
Safety	By the measuring methods conditioned arrangement no handicap of the safety is to expected.	3
Failure	Since the today's procedures for the determination of the frequency are very accurate and this represents the only fault size, the system can be evaluated with the bestnote.	3

4) Laser fin position

Tab.: 16-6 The evaluation of the laser fin position measurement calibration method

Evaluation criterion	Allocation	Evaluation
Flexibility	Since the laser system represents a compact equipment, which is besides in no dependence of the experimental aircraft, it fulfills highest requirements of this evaluation criterion.	3
Practicabil-ity	This evaluation criterion is fulfilled within this arrangement. The only larger expenditure consists making of it a data link to the com-puter equipment.	3
Safety	By the measuring methods conditioned arrangement no handicap of the safety is to expected.	3
Failure	Since the today's procedures for the determination of the frequency are very accurate and represent this the only fault size, can be evalu-ated the system with the bestnote.	3

5) Laser nose position

Tab.: 16-7 The evaluation of the laser nose position measurement calibration method

Evaluation criterion	Allocation	Evaluation
Flexibility	Since the laser system represents a compact equipment, which is besides in no dependence of the experimental aircraft, it fulfills highest requirements	3
Practicabil-ity	This evaluation criterion is fulfilled within this arrangement. The only larger expenditure consists is making a data link to the com-puter equipment. Within this configuration the data line of the radar can be possibly used.	3
Safety	Due to the removal of the standard radar facility the safety is not necessarily endangered, an impairment of the systems however took place. Thus the assessment is applied in the center zone.	2
Failure	Since the today's procedures for the determination of the frequency are very accurate and represent this the only fault size, can be evalu-ated the system with the bestnote.	3

6) Laser wing position

Tab.: 16-8 The evaluation of the laser wing position measurement calibration method

Evaluation criterion	Allocation	Evaluation
Flexibility	Since the laser system represents a compact equipment, which is besides in no dependence of the experimental aircraft, it fulfills highest requirements	3
Practicability	This evaluation criterion is only partially fulfilled within this arrangement. The problem consists in the integration of the voluminous laser unit in relation to the wing tip.	2
Safety	Due to possible influence of the laser optics on aerodynamics of the wing, it can possibly come to vibrations or flutter. Since the effect can be judged only experimentally and the disturbances by the system are of only minimum value, the evaluation within the central division is defined.	2
Failure	By the oscillations, straight within the outer division of the wing, occurring during the flight, a misinterpretation of the airstream can not be excluded. For this reason a central evaluation is defined.	2

7) Boom fin position

Tab.: 16-9 The evaluation of the boom fin position measurement calibration method

Evaluation criterion	Allocation	Evaluation
Flexibility	Since the length of the boom is essentially dependent on the dis-placement by the aircraft body, a boom can be used only particularly for a type of aircraft or a similar aircraft. During a transformation, e.g. on a smaller aircraft type, the boom can be used only with an oversized length. From this reason a central assessment dimension for this criterion results.	2
Practicabil-ity	The simple construction of a boom and the relatively low extents, result in the best evaluation of the criterion.	3
Safety	By the measuring methods conditioned arrangement, is not to be expected any endangerment of the safety.	3
Failure	The simple interpretation of this measuring method compensates automatically different faults. For this reason this criterion can be evaluated with very good.	3

8) Boom wing position

Tab.: 16-10 The evaluation of the boom wing position measurement calibration method

Evaluation criterion	Allocation	Evaluation
Flexibility	Since the extents of the boom are essentially determined by the displacement by the aircraft body, a boom can be used only particularly for a type of aircraft or a similar aircraft. During a transformation, e.g. on a smaller aircraft type, this can be used only with an oversized length. From this reason results a central assessment dimension for this criterion.	2
Practicability	The integration of the boom into the wing, can lead complications due to the size. From this a central assessment of the criterion follows.	2
Safety	By the attachment of a boom at the wing, a moment will initiate into the wing. For this reason a system influence exists. Thus the wing can become lively oscillating. A very critical state, which entails the worst evaluation of the criterion.	1
Failure	By the oscillations occurring in the flight straight within the outer division of the wing, can not be excluded a misinterpretation of the airstream. For this reason is defined a central evaluation.	2

9) Boom nose position

Tab.: 16-11 The evaluation of the boom nose position measurement calibration method

Evaluation criterion	Allocation	Evaluation
Flexibility	Since the extents of the boom are essentially determined by the displacement by the aircraft body, a boom can be used only particularly for a type of aircraft or a similar aircraft. During a transformation, e.g. on a smaller aircraft type, this can be used only with an oversized length. From this reason results a central assessment dimension for this criterion.	2
Practicability	The extents of a boom within the front division, are only difficult to realize by the displacement with increasing size of the A/C.	1
Safety	Due to the removal of the standard radar facility the safety is not necessarily endangered. Nevertheless an impairment of the systems consists. Thus the assessment is applied in the center zone.	2
Failure	Since the extents of a boom are considerable in the front division, this can be shifted by flow in oscillation. This can cause a fault, which cannot or difficulty be compensated. From this reason an average results in the assessment.	2

The individual criteria are confronted in the following in a matrix.

Tab.: 16-12 The Summary of evaluation

	Flexibility	Practicability	Safety	Failure	Σ
Cone Direct Measurement	2	1	3	1	7
Cone Indirect Measure-ment	2	2	3	3	10
Laser Cabin Position	3	3	3	3	12
Laser Fin Position	3	3	3	3	12
Laser Nose position	3	3	2	3	11
Laser Wing position	3	2	2	2	9
Boom Fin Position	2	3	3	3	11
Boom Wing Position	2	2	1	2	7
Boom Nose Position	2	3	2	3	10

To this matrix now, the individual priorities installed before are added

Tab.: 16-13 The evaluation of the calibration methods inclusive the priority factor

	Flexibility	Practicability	Safety	Failure	Σ	Evaluation
Cone Direct Measurement	40,0	10,0	120,0	30,0	200,0	7
Cone Indirect Measurement	40,0	20,0	120,0	90,0	270,0	3
Laser Cabin Position	60,0	30,0	120,0	90,0	300,0	1
Laser Fin Position	60,0	30,0	120,0	90,0	300,0	1
Laser Nose position	60,0	30,0	80,0	90,0	260,0	4
Laser Wing position	60,0	20,0	80,0	60,0	220,0	6
Boom Fin Position	40,0	30,0	120,0	90,0	280,0	2
Boom Wing Position	40,0	20,0	40,0	60,0	160,0	8
Boom Nose Position	40,0	30,0	80,0	90,0	240,0	5

The method with the highest score can be rated as favorite. For the evaluated matrix results as favorite, the lasers methodology integrates in the cabin or the vertical tail unit. A special explanation of favored methodology, using example system, is described in the following.

17 The example laser system of "Kayser Threde"

The prestigious company "Kayser Threde", offers a complete laser system for the calibration of the static port. After longer experience with a ground-based laser system (ODIN-1) for wind monitoring, this experience is to be used to prepare an onboard system (ODIN-3).

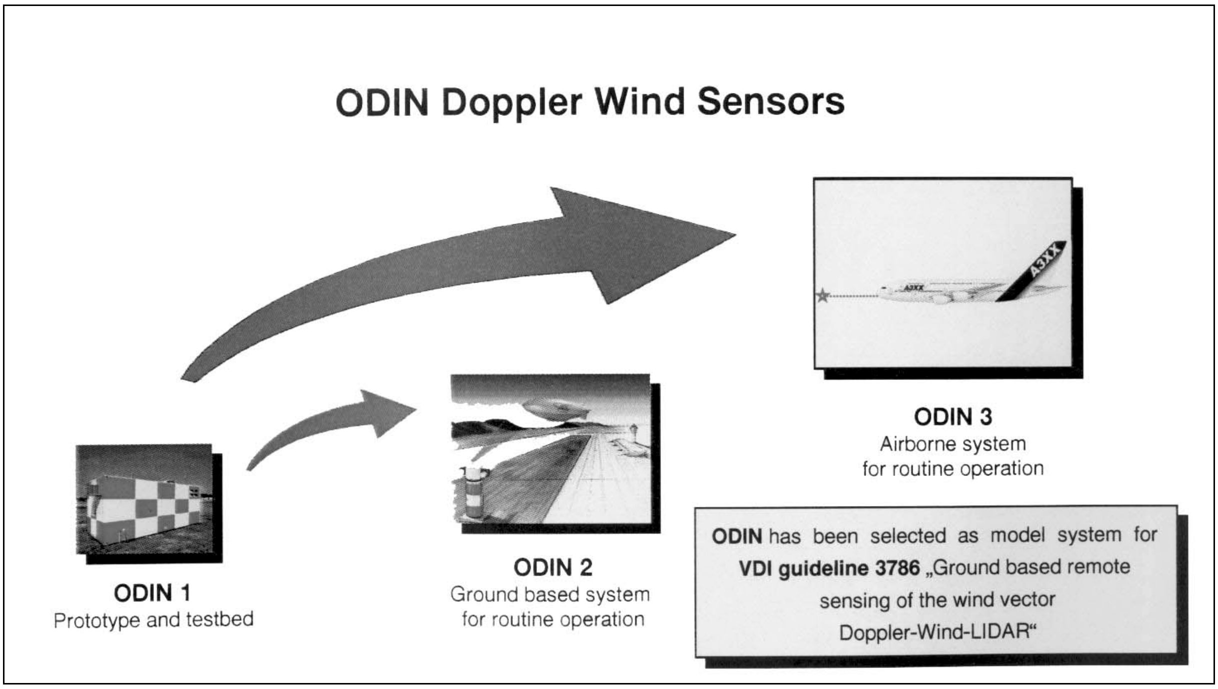

Fig.: 17-1 The development of ODIN-1 to ODIN-3 (**Kayser**)

Beside the laser unit (optical transceiver) offers ODIN-3 a complete unit for the evaluation of the data (inclusive software) as well as a control member in form of a display.

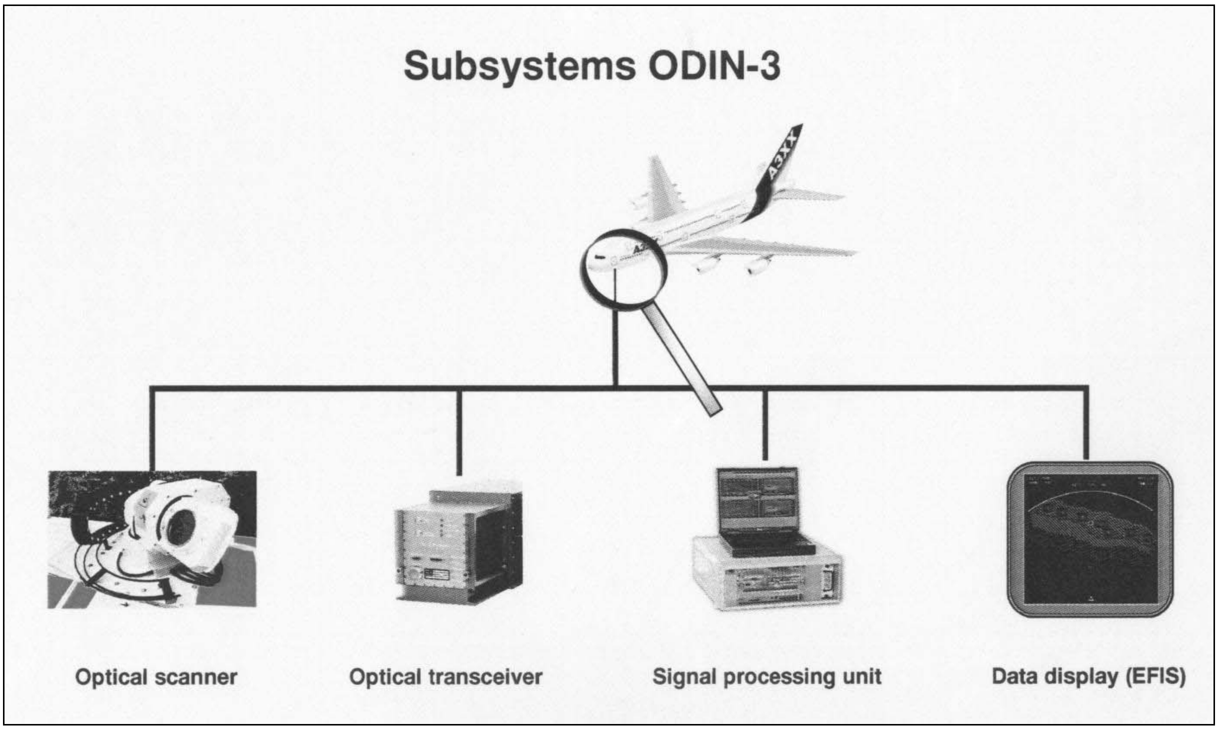

Fig.: 17-2 The subsystems of ODIN-3
(**Kayser**)

The system offers, after firm data, the following benefits and features:

- Flexible adaptation to actual flight situation.
- Data interface to standard avionics bus (e.g. via ARINC) with real time data output and storage.
- Several optional data display modes for routine operation and precise data analysis.
- Operation of sensor is independent of any airframe configuration.
- Optimized compact steering optics (scanner) for onboard operation.
- Real time data output.

Based on the older system ODIN-1 the following technical and operating Data result accordingly to the firm data.

Tab.: 17-1 The technical and operating data based on ODIN-1

Property	**Value**
System concept	IR Pulse Doppler System
Measurement range (clear air) (Rain: 3 mm/h) (Rain: 12 mm/h)	 8000 m 4000 m 2000 m
Range resolution	50 m
Speed range	25 m/s – 340 m/s
Speed resolution	0,5 m/s
Measurement speed	500 sec^{-1}
Electrical supply	115 V/ 400 Hz or 28 V DC
Power consumption	< 1000 W
System control	automatic/ manual

In place of the height error from chapter 7., the speed resolution is inserted into the formula (8.7) for calculating the pressure over the speed. For the incompressible range up to Mach 0,3 receives the following graphical summary.

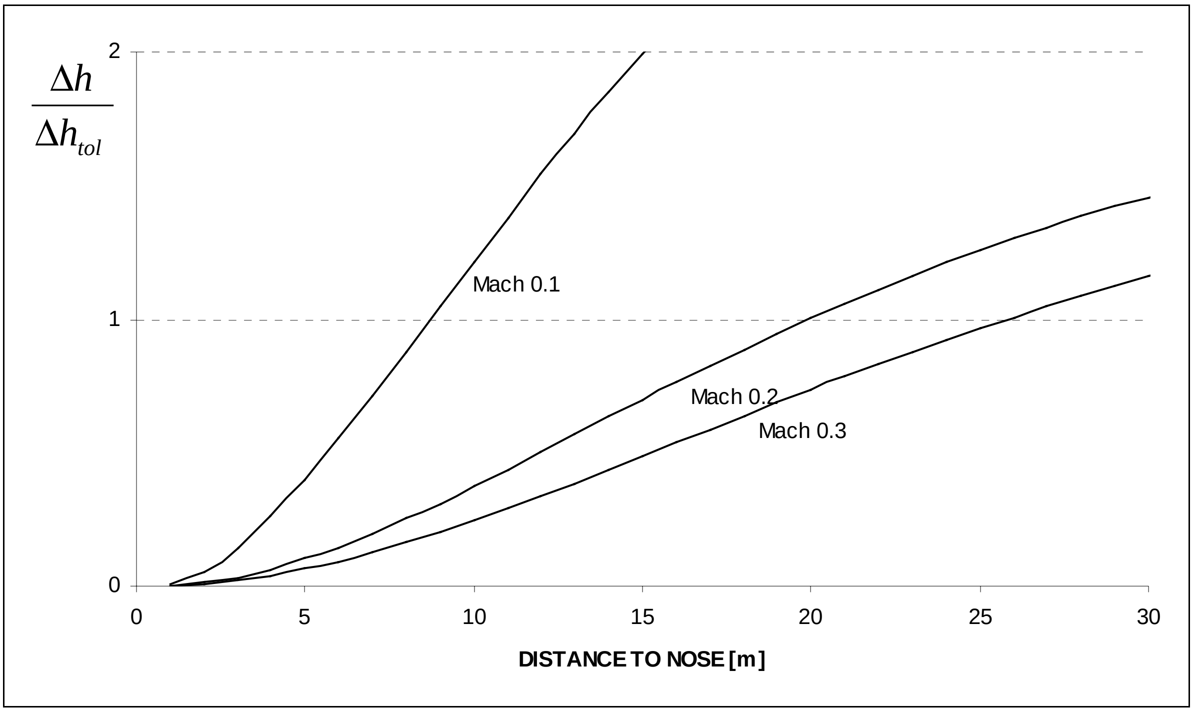

Fig.: 17-3 The height error relation over distance to nose (Mach 0,1-0,3) at MSL

For the case of compressible flow, the factors of the Prandtl-Glauert law from chapter 3.2 are used the formulas of the displacement from the same chapter. For the simulation of the front wave result the following parameters.

Tab.: 17-2 The properties of compressible flow

Mach	$\frac{E}{v_\infty}$	x_0	**Mach**	$\frac{E}{v_\infty}$	x_0
0,0	49,20	1,98	**0,5**	65,60	2,28
0,1	49,69	1,99	**0,6**	76,87	2,47
0,2	51,25	2,02	**0,7**	96,46	2,77
0,3	54,06	2,07	**0,8**	136,66	3,30
0,4	58,57	2,16	**0,9**	258,93	4,54

For the calculation of influenced flow, only the induced speed is considered due to the displacement. The disturbance of compressible flow due to the circulation does not find consideration in this working out. Because of the complexity and the relatively low effects, it can be neglected. From it a decrease of the distance to nose resulted, due to the missing circulation component, in relation to the incompressible flow. In the tendency it is to be recognized that up to higher speeds, an only insignificant distance change takes place in relation to the measuring range of the laser. Graphically evaluated, the following summary resulted for the height error relation, applied over the distance to nose, under different Mach numbers and the height of MSL.

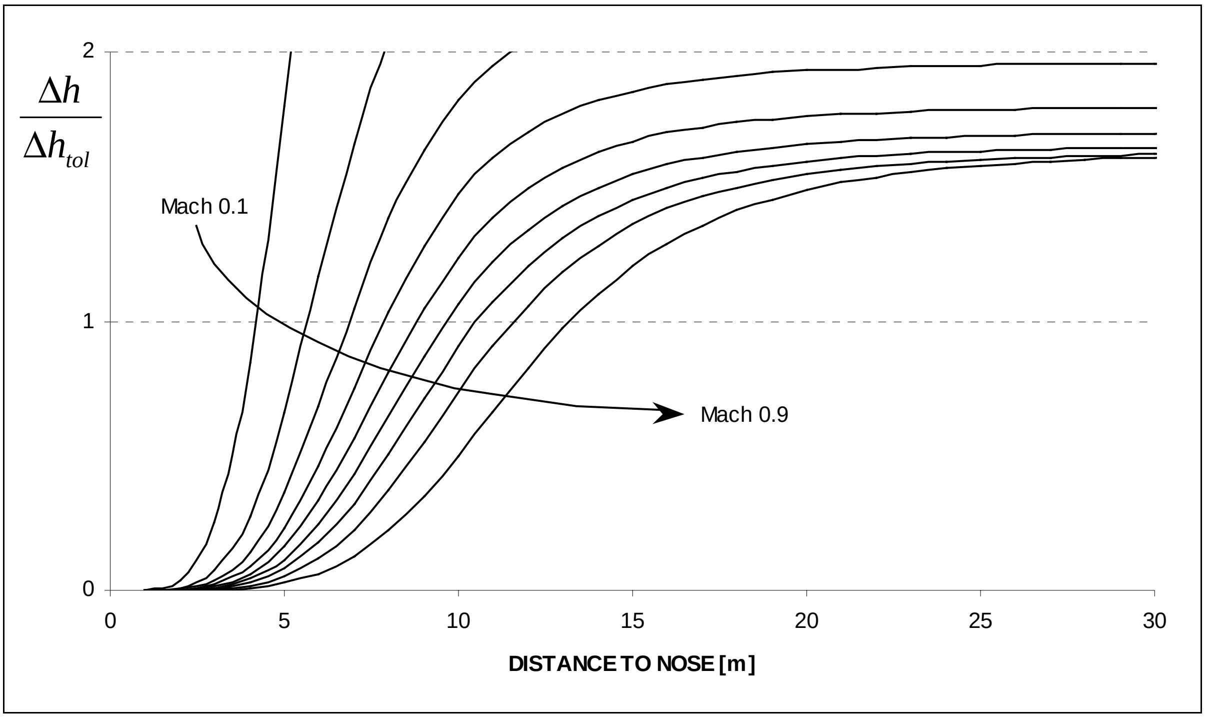

Fig.: 17-4 The height error relation over distance to nose (Mach 0,1-0,9) at MSL

In order to guarantee a precision demand suitable measurement in different heights, the height error relation is graphically evaluated with Mach 0,9 over the distance to nose under different heights.

From this follows:

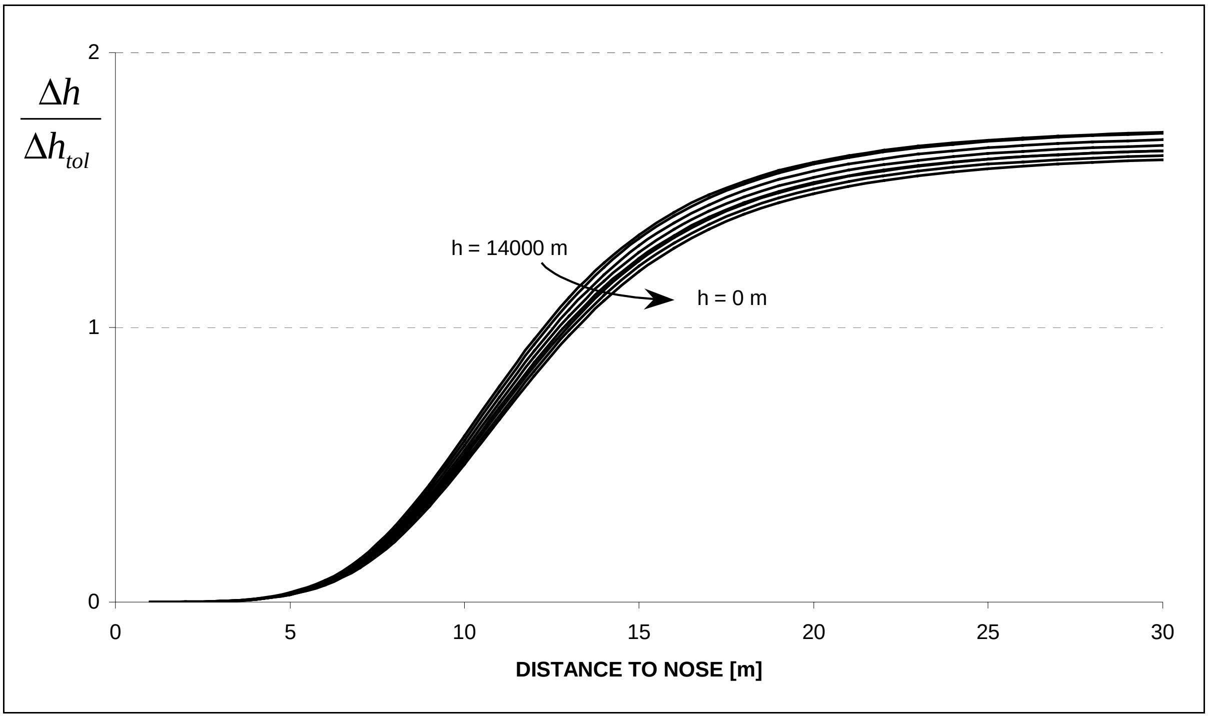

Fig.: 17-5 The height error relation over distance to nose in steps of 2000 m (Ma 0,9)

Based on the calculations, with consideration of a safety factor, results a safe measurement distance of at least 25 m for the laser. In the case of the given range for a laser measurement, this distance does not result in a problem. For a precise measurement the measurement distance is substantially increased.

As a condition of a successful measurement in higher altitudes, a sufficient backscattering coefficient is valid to the laser. This is given by the aerosols in air. For the atmosphere the ESA (European Space Agency) accomplished measurements of this backscattering coefficient and published it. From it result, related to the value at height of MSL, over the height applied the following graphically quotient course.

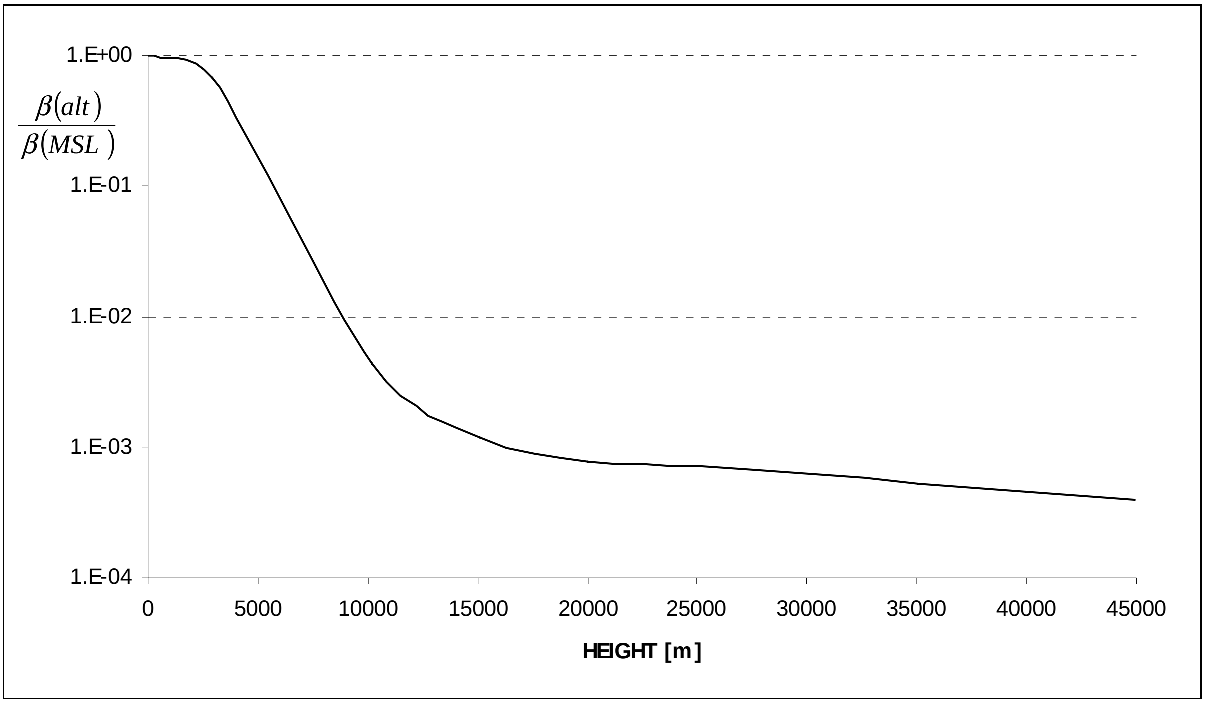

Fig.: 17-6 The aerosol backscatter ratio over the height

Besides the measurement depends on the signal reinforcement due to the measurement distance. The firm "Kayser Threde" indicates 10000 m as practical maximum measurement distance (MSL). Over a square ratio formation this value can be converted to a distance factor for other distances. For a measurement distance of 100 m, in place of the 10000 m, therefore results around the calculated factor a stronger or weaker backscatter signal. As symbol for this calculation the small Greek letter ξ (xi) is introduced.

$$\xi = \frac{10000^2}{100^2} = 10000 \qquad (17.1)$$

Over the distance applied, the following graphic resulted.

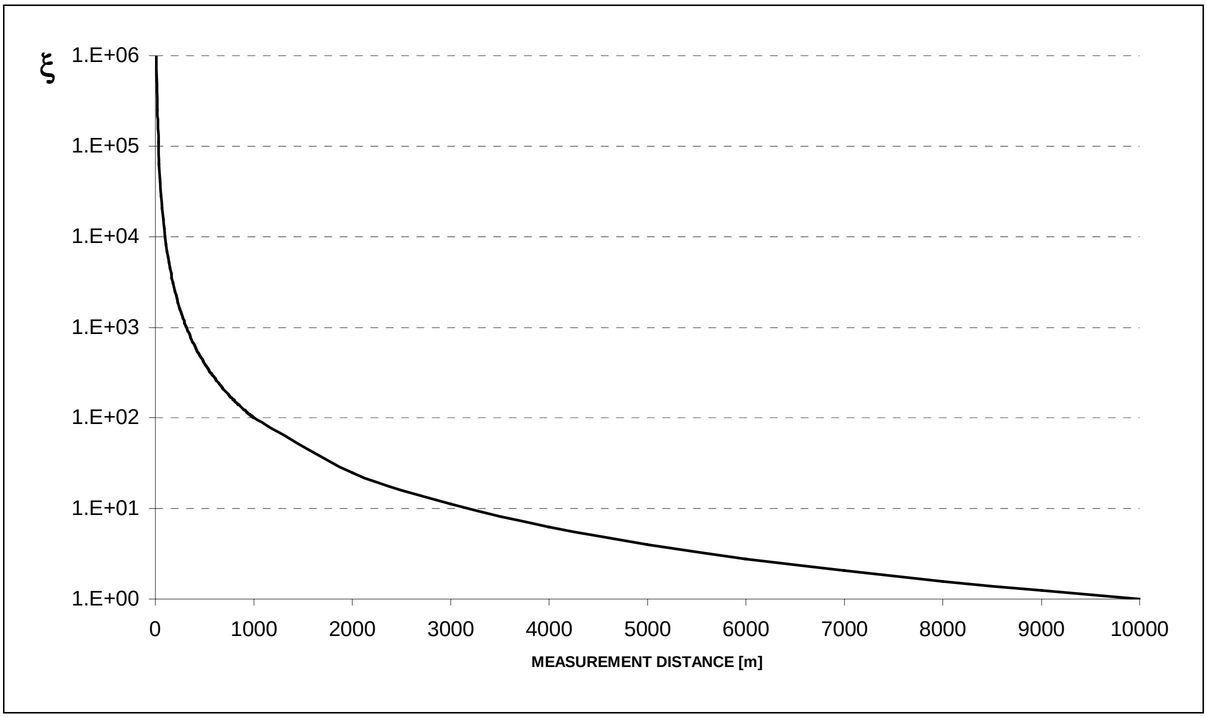

Fig.: 17-7 The distance-ratio over the measurement distance for ODIN-3

For an estimation of a suitable measurement in higher altitudes, the distance ratio ξ can be multiplied by the backscatter ratio. For this result, is introduced as symbol the small Greek letter η (eta). If a result over one is obtained, the measurement is sufficient.

$$\eta = \xi \cdot \frac{\beta(alt)}{\beta(MSL)} \geq 1 \tag{17.2}$$

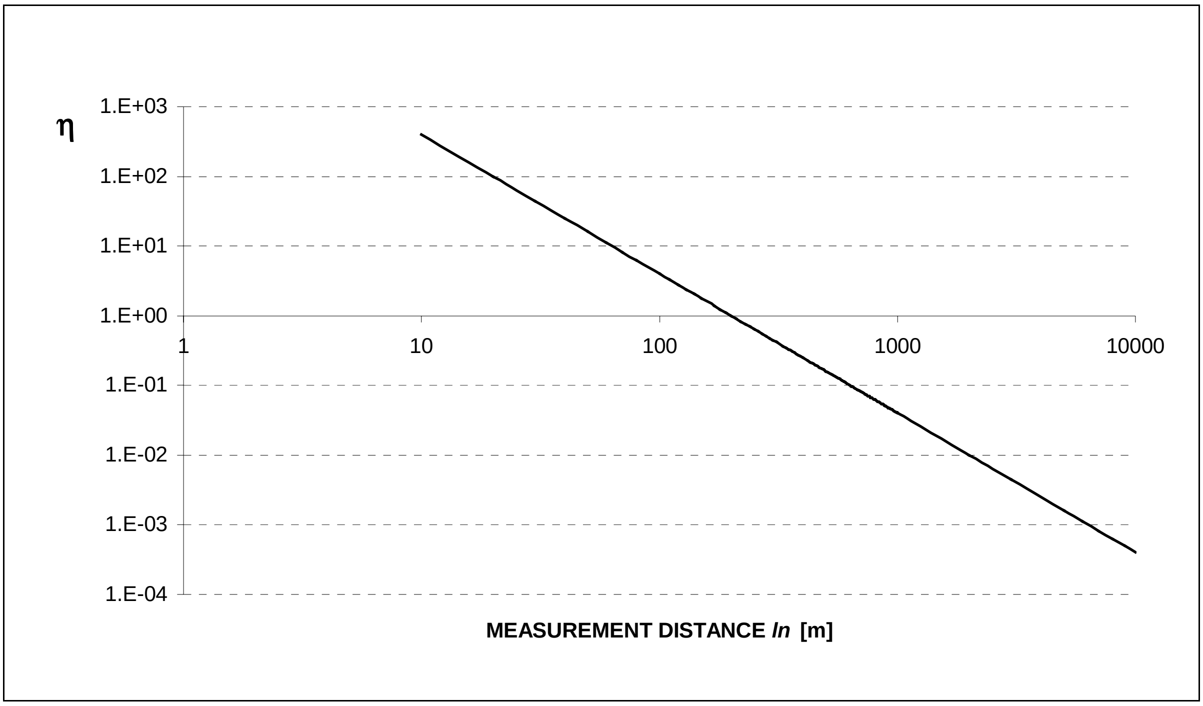

Fig.: 17-8 The measurement distance due to η in the height of 45000 ft

From this diagram it follows that a distance of 200 m is sufficient in the indicated height for a measurement.

17.1 The example assembly of the laser system

Since the database is not available for the A3XX yet to the full extent, an integration can be accomplished only by using a simplified example. For the laser can be introduced a black box as a substitute, those corresponds with the future basic dimensions of the transceivers.

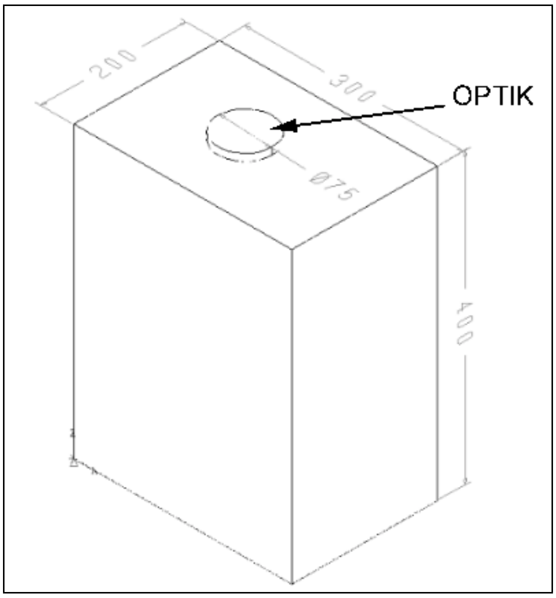

Fig.: 17-9 The laser ODIN-3

Additionally a rack can be established over this basic dimensions, which consists for example of two bent plates and a Honeycomb plate.

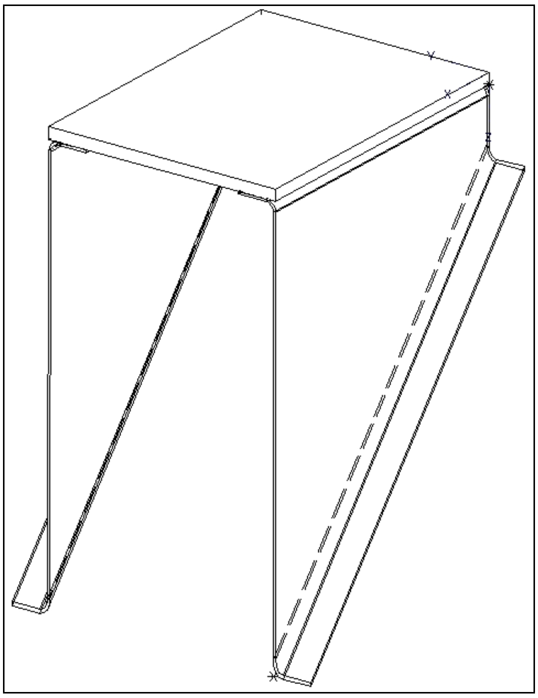

Fig.: 17-10 The rack

On this rack the laser can be attached.

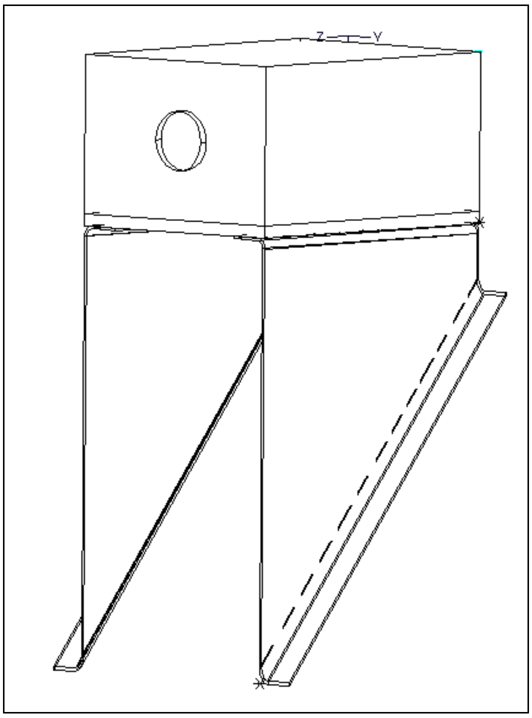

Fig.: 17-11 The laser rack assembly

With the help of these simple components, the laser system can be attached for example to the front spar of the vertical tail unit.

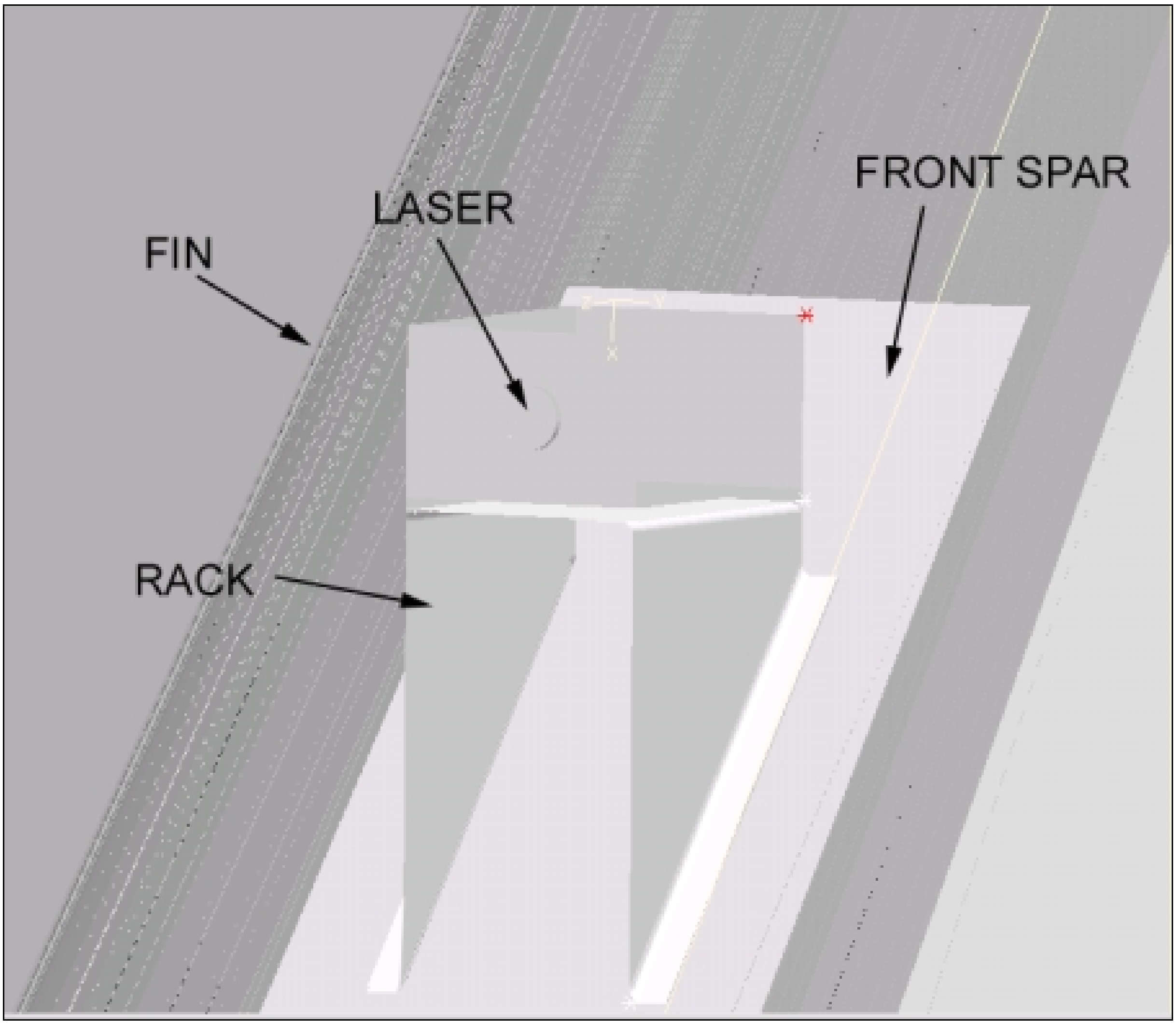

Fig.: 17-12 The laser attached on the front spar of the fin

With this integration variation it must be noted that the equipment must be protected additionally against the temperature influences of the upper atmosphere. This can be achieved with the help of “climatic box”. Furthermore must be checked whether a disturbance of the surrounding equipment (e.g. HF antenna) via the laser taken place.

18 Summary

It is to be again pointed out here that the assessment matrix refers only to the method. The results due to the calculations are not brought in, in this assessment. This procedure serves for it to give an objective estimate also for other aircraft than the A3XX.

Even if design fundamentals in this working out represent only an estimation related to the real condition, a clear trend can be determined with it. As showed, the fault lies only insignificantly apart from the values determined by airbus. For this reason, even if the calculations do not again-reflect the accurate value, can result a clear assessment. The assessment results in a clear result, which justifies an estimation in particular for the A3XX.

A problem consists in the not clear specifications of the FAR/JAR. The determined tolerance are an interpretation that make possible an estimation.

Finally it can be said that the conventional calibration methods for smaller aircraft have quite their authorization. But by the development of the A3XX is to be recognized that these conventional methods possess crucial disadvantages. In order to calibrate both, large aircraft and smaller aircraft also with the same method, it requires a very flexible calibration system. The calibration, by means of a newer compact laser system, results than logical consequence. It is a considerable degree flexibly and good to placed. Regarding the interpretation of the specifications (FAR/JAR), more accurate values than with all other tested systems result with this system.

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