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Static Source Error Calibration of a Nose Boom Mounted Air Data System on an Atmospheric Research Aircraft Using the Trailing Cone Method

Andreas Giez, Martin Zöger, Volker Dreiling, Christian Mallaun

Deutsches Zentrum für Luft- und Raumfahrt
Flugexperimente
Forschungsflugabteilung Oberpfaffenhofen

DLR Deutsches Zentrum für Luft- und Raumfahrt

Static pressure, static source error, inflight calibration, Trailing Cone Method, air flow sensor, nose boom, atmospheric research aircraft

Andreas Giez, Martin Zöger, Volker Dreiling, Christian Mallaun
Flugexperimente Forschungsflugabteilung, Oberpfaffenhofen

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The experiment covers the determination of the proper configuration (length) for the Trailing Cone assembly, the validation of the method itself and the subsequent calibration of the air data sensor. Several improvements were applied to the Trailing Cone method in order to reduce the flight test effort as well as to significantly enhance the accuracy of the method itself. As a consequence a total of only three test flights was necessary to validate the method and to calibrate the air data sensor.
The data analysis shows that the accuracy of the Trailing Cone reference measurement is very close to the pressure sensor calibration limit of 0.1hPa. The resulting accuracy of the corrected pressure measurement by the nose boom mounted pressure probe was demonstrated to be about 0.2 hPa, which represents the 3σ value. *(Published in English)*

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von

Dr. Andreas Giez

Dr. Martin Zöger

Dr. Volker Dreiling

Christian Mallaun, PhD

Deutsches Zentrum für Luft- und Raumfahrt

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Abstract

This work demonstrates the calibration of an experimental air data probe on an atmospheric research aircraft by means of the Trailing Cone method. The probe under investigation is located on a nose boom in order to minimize the aerodynamic influence of the fuselage on the pressure measurement ahead of the aircraft. However, the data from this experiment proves that this configuration is still subject to significant pressure deviations from the undisturbed atmospheric values. This work demonstrates the determination of this error and presents an appropriate parameterization of the data which is prerequisite to provide accurately corrected pressure readings from this sensor.

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Contents

Introduction

Some of the most essential information required by aircraft during flight relies on the precise determination of the static air pressure during flight. First of all aircraft altitude and speed are directly calculated from the atmospheric static and dynamic pressures, which are defined with respect to an undisturbed atmosphere. Since the associated pressure measurements are usually taken very close to the airframe the directly acquired data is always subject to an aerodynamic error caused by the airframe induced flow distortion.

The deviation of the static pressure measured at the aircraft from the undisturbed atmospheric value is called static source error and depends strongly on the location of the sensor itself on the aircraft as well as on the aircraft flight conditions like speed and altitude. It can reach a magnitude of several 10 hPa for jet aircraft which would cause unacceptable errors in the speed and altitude determination [17].

The increased air traffic over the years has led to very strict requirements for aircraft altitude data i.e. for aircraft pressure measurements in order to minimize the necessary safety distances between aircraft and to allow for more aircraft within a certain airspace. An example for this trend is the Reduced Vertical Separation Minimum (RVSM) Airspace, which accepts only very small residual errors in the static pressure (altitude) measurements of the participating aircraft [6].

Therefore, aircraft certification requires an accurate characterization and parameterization of this error and precise and effective static source calibration plays an important role in aircraft industry in order to characterize new aircraft models as well as one of a kind modified special mission platforms.

An accurate measurement of static pressure on an aircraft is also required in the field of airborne atmospheric research. In this case special sensors are used to determine the air flow vector and the pressure ahead of the aircraft which are used to precisely calculate the 3-dimensional wind speed vector in the free atmosphere. The requirements for these measurements which include static and dynamic pressure and the angle of attack and sideslip are very high. Therefore, the accuracy in the determination of the static source error is prerequisite for high accuracy atmospheric measurements.

The data and results shown in this work belong to a static source calibration of an experimental air data system of an atmospheric research aircraft which is mounted on a nose boom. Although the measurement configuration of this special mission aircraft is different from the sensors on a standard aircraft the calibration method and the data evaluation will apply identically to any other aircraft.

The Measurement of Static Pressure on an Aircraft

The Static Source Error

An instructive way to discuss the problem of measuring the static pressure on board an aircraft is to study the pressure distribution around an aircraft under typical flight conditions. This pressure field can be visualized by means of Computational Flow Analysis (CFD) tools. Figure 1 shows the result of such a calculation for an aircraft which is equipped with a nose boom at typical cruise speed.

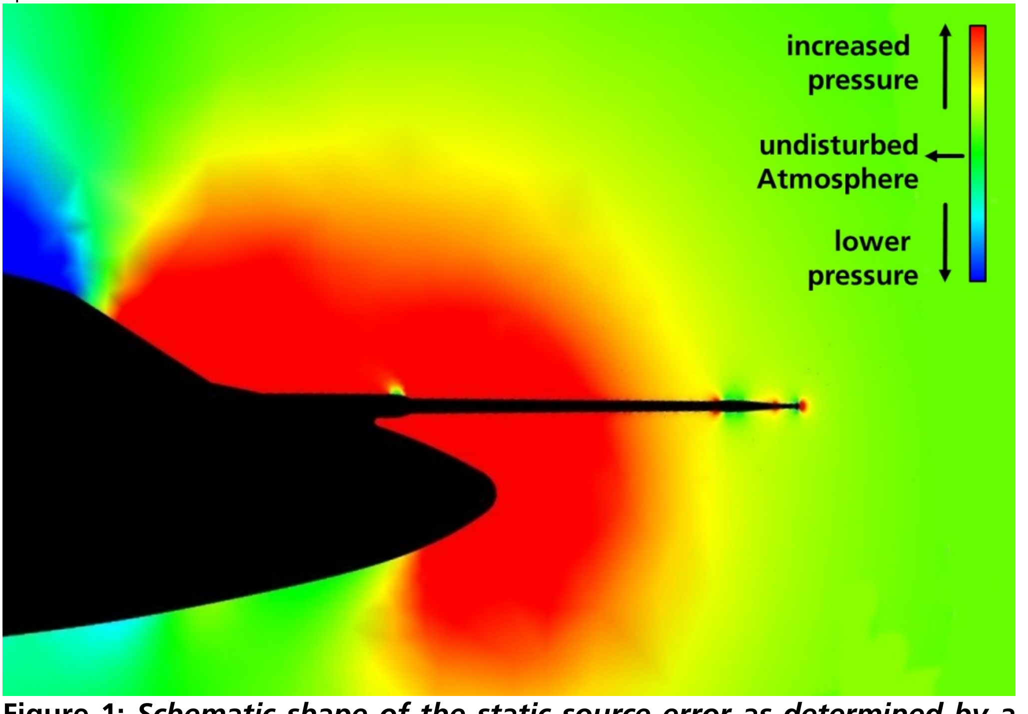

Figure 1: ***Schematic shape of the static source error as determined by a Computational Fluid Dynamics (CFD) analysis for a jet aircraft equipped with a nose boom. The air data probe is located at the tip of the boom. Areas with undisturbed atmospheric pressure are marked in green while higher and lower pressure values are represented by red and blue colour respectively.***

From the result it becomes obvious that the static pressure field is strongly deformed by the aircraft itself leading for example to a high pressure area ahead of the aircraft nose. One understands immediately that a measurement of static pressure in the vicinity of the airframe will almost always result in significant offsets from the desired value of the undisturbed pressure as found without the influence of the aircraft. Since CFD analysis also proves that the shape of this modified pressure field will change as a function of aircraft flight conditions there is no location on the aircraft which does not suffer any perturbation over the complete aircraft flight envelope.

Over the years extensive flight testing and many investigations have led to a good understanding of these effects. There are recommendations for the location of air data probes on the fuselage in order to minimize the pressure offsets (one of the best known is the schematic plot shown in Figure 2) and the parameterization and general behaviour of the effect is well understood [4]).

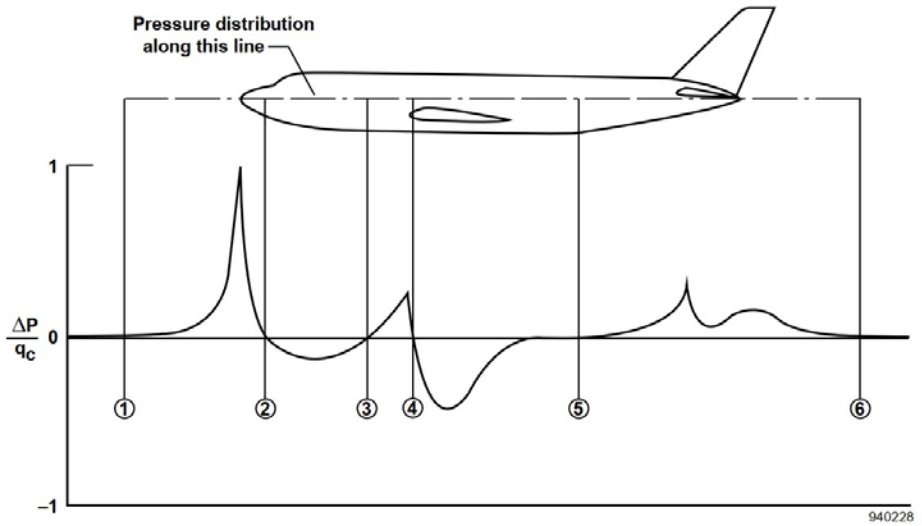

Figure 2: ***Typical static pressure distribution along an aircraft during flight. The numbers mark locations where static pressure can be measured with a minimum error (picture from [5]).***

The static source error Δp_s is defined as the difference between the so called indicated pressure p_{si} which is the biased static pressure value as measured directly by the air data probe and the undisturbed atmospheric (static) pressure p_s (i.e. the true pressure outside of the aircraft influence): $\Delta p_s = p_{si} - p_s$. The static source error is usually expressed in terms of $\Delta p_s / qc_i$ where qc_i is the indicated dynamic pressure with no corrections applied. $\Delta p_s / qc_i$ is supposed to be a function of Mach number only for a single aircraft configuration [4]. Additional correction terms account for significant changes in air flow direction relatively to the aircraft axes (e.g. angle of attack and angle of sideslip). Aircraft weight changes and modifications of the aircraft itself with impact on the aircraft shape or fuselage surface properties are possible factors which can cause additional corrections. Since the absolute value of the static source error for subsonic aircraft increases with Mach number the static source error is much more significant for "fast" aircraft. It is important to note that the independent parameter in the parameterization of these corrections is the indicated (i.e. uncorrected) value of the respective unit (i.e. $\Delta p_S = f(p_{si}, qc_i, M_i)$, where M_i is the indicated Mach Number, i.e. the Machnumber calculated directly from the indicated units).

The measurement of the pressure on an aircraft requires suitable pressure inlets or probes. A Pitot Tube is commonly used to measure the Total Pressure p_T which is the sum of static and dynamic pressure. Although the Pitot Tube is typically invariant to a certain range in the angle of attack it should be aligned with the mean local flow direction in order to minimize measurement errors. Furthermore, it should be placed far enough away from the aircraft fuselage to be well outside the boundary layer (i.e. the air layer containing an airspeed gradient caused by friction at the aircraft skin). In order to determine the dynamic and static pressure from the Pitot Tube data one needs to additionally measure the static pressure. This can be done by static pressure ports located directly on the aircraft skin or by using a Pitot-Static-Probe which combines a traditional pitot tube with a circular hole assembly on the tube which acts as a static port. The advantage of this assembly is the fact that both pressure ports

experience the same airflow conditions especially when the system is exposed to fast pressure changes as caused by aircraft maneuvers or wind gusts.
Of great importance is the fact that outside the aircraft boundary layer the total pressure is constant [5], [15]. Therefore, the total pressure can in principle be measured almost anywhere on the aircraft. However, this presumes that the associated time delay in the observation of a transient pressure modulation between static and total pressure sensor can be neglected. Another consequence of the above finding is the fact that the sum of static and dynamic pressure is the same for the undisturbed (corrected) pressure values as well as for the indicated values when measured at the same location:

$$p_t = p_s + qc = p_{si} + qc_i$$ **Equation 1**

It also means that the local static source error applies with different signs to both, the static and the dynamic pressure.
Among the recommended positions for the installation of an air data probe is the location ahead of the aircraft nose [5] and the parameterization and general behaviour of the effect is well understood [4]. The idea behind placing a sensor on the tip of a nose boom is to escape from the disturbed pressure field around the fuselage as indicated in Figure 1 and to become more independent of asymmetric flow conditions as generated during aircraft maneuvers.
Many investigations have been made to determine the optimum length L of a nose boom which is necessary to achieve an acceptable static source error [9], [10], [11], [4].
It turns out that this length depends on the shape of the aircraft nose itself and should be at least in the order of the aircraft body diameter D with respect to the aircraft nose. Even for the optimum nose shape the static source error for a boom with L/D=1 ist still 1% qc.
On the other hand the maximum length of a boom is always limited by structural and aeroelastic considerations in the certification process. A low vibrational Eigenfrequency causes not only a danger for the aircraft itself. In case

the probe is used for airflow vector measurements the vibration of the boom during flight will result in an artificial angle of attack signal which can lead to significant errors in the wind calculation. Therefore, the length of a nose boom always represents a compromise between stiffness of the installation and residual static source error. A desirable value of the Eigenfrequency for a composite nose boom which is already mounted to the aircraft is about 20Hz especially when accurate flow angle measurements have to be performed with this instrumentation.

One must assume that every air data probe on any aircraft experiences a static source error which can only be reduced but never eliminated by choice of an optimum installation location. Therefore, the initial certification of an aircraft and any modification with impact on the airframe shape requires an investigation on the static source error and its parameterization. The result from such an investigation is a correction scheme which allows for the calculation of the undisturbed static pressure from the indicated values.

This report presents the determination and parameterization of the static source error for an experimental air data probe on a special mission atmospheric research aircraft. The sensor itself is a so called 5-hole probe (Goodrich Aerospace, formerly Rosemount Aerospace 858 flow angle sensor) which is mounted on the tip of a nose boom. Compared to a standard pitot static sensor the probe is equipped with additional pressure ports which allow for the determination of the local angles of attack and sideslip. However, the presented methods and strategies are universal and apply to any air data installation.

William Gracey provides a plot of the expected static source error dependence for a nose boom mounted pressure probe over wide speed range[4]. As one can see from Figure 3 the error varies significantly with Mach number at low speeds and close to the sound barrier.

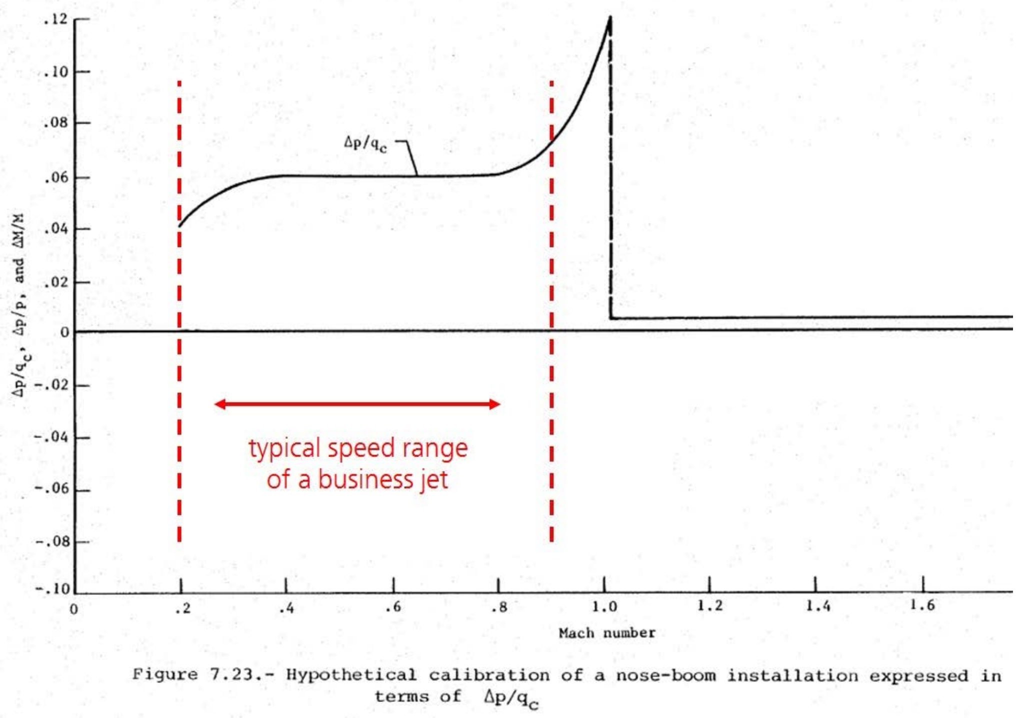

Figure 3: ***Typical dependence of the static source error on Mach number for a nose boom mounted pressure probe from [4] . The speed range of the aircraft under investigation in this report has been marked by dashed red lines***

Finding an Inflight Pressure Reference

As pointed out above the disturbed pressure field around an aircraft has an impact on two important pressure measurements: The static and the dynamic pressures. Both units play an important role for aircraft navigation since aircraft speed (i.e. Mach number, Calibrated Air Speed, True Air Speed, etc.) and (pressure) height are calculated directly from this data. The provision of accurate pressure values requires an exact quantification of the measurement error and the development of a correction algorithm for the measured raw data. The determination of these errors is achieved by means of flight tests. The major challenge of such an inflight calibration is to find a source for a reference pressure over the complete flight envelope of the aircraft under investigation in order to directly determine $\Delta p_s = p_{si} - p_s$. The following section briefly describes the available techniques which are used to provide a suitable reference pressure during flight.

Static Pressure

In case of the static pressure this can only be achieved by comparing the pressure measurement of the aircraft itself with a pressure which is determined outside the influence of the aircraft itself. This can be done in different ways:

- Trailing Cone (TC) or Trailing Bomb method: Measurement of the pressure in the undisturbed atmosphere which can be found behind the aircraft by means of a Trailing Cone or a trailing bomb. In this case a static pressure port is attached to a long tube which is towed behind the aircraft and connected to a pressure sensor inside the aircraft.
- Nose Boom: The measurement of undisturbed static pressure ahead of an aircraft by means of a boom mounted pressure probe. However, for most aircraft this is only a theoretical solution. As discussed before the length of a nose boom is limited by aeroelastic considerations and does usually not reach the required length where the static source error can be neglected. An exception are slow aircraft, where the absolute value of the static source error which is usually expressed as a fraction of qc becomes much smaller for a certain L/D.
- Pacer Aircraft Method: The aircraft pressure readings are compared to data from a calibrated reference aircraft flying in close formation. For this method it is necessary to additionally determine the height difference between the two aircraft with high accuracy.
- Tower Fly-Bys: Comparison to a pressure which is measured on the ground or on a tower and corrected for the height difference between reference sensor and aircraft. However, this method usually only covers a portion of the aircraft flight envelope (Mach Number range), especially in

case of jets. Furthermore, any height dependencies of the static source error cannot be estimated.

- Another method uses numerical weather prediction (NWP) data as a reference for the aircraft measurements. The idea is to compare the GNSS height above mean sea level which has to be measured with a precise reference system on the aircraft to geopotential height as determined by numerical weather prediction. First experiments proved that NWP analysis or predictions can in principle be used for testing the height keeping performance of an aircraft after or during operation [3], [14]. The cited study uses data from this trailing cone experiment.
- Height Monitoring Units (HMU) are used to regularly check the accuracy of a single aircraft which has to fly over the ground based facility. However, an HMU overflight is a spot check which is part of a quality management system and no calibration.

Dynamic Pressure

Dynamic pressure is crucial to measure the true air speed (TAS, i.e. the aircrafts speed relatively to the air) of an aircraft. Therefore, the calibration of qc is usually based on an independent determination of the TAS. The needed reference speed can be determined in different ways.

- GPS-Method: Comparison to ground speed data which is measured using the Global Positioning System. A GPS receiver located on the aircraft represents an accurate reference for the ground speed of the aircraft. GPS postprocessing can be used to further reduce the measurement error. The determination of ground speed by “traditional” methods like the measurement of flight time over a certain distance is no longer of interest, since GPS is more accurate, requires less experimental effort and is usually available or at least easy to implement on any aircraft. A problem arises from the fact that a GPS reference speed is a speed with respect to an earth fixed coordinate system (i.e. ground speed). Therefore, the intercomparison with aircraft data must take into account the influence of atmospheric wind speed which is part of the TAS. This can for example be achieved by choosing an appropriate flight pattern where the mean wind is compensated by flying at a certain direction relatively to the wind or by flying the same track in opposite directions to compensate the effect. However, all these methods are based on the assumption that wind speed is constant and does not vary over the time interval or the location of the measurement. This simplification can significantly reduce the calibration accuracy.

- Optical methods: True Air speed can be measured directly by optical sensors which use the Doppler effect to determine TAS [1].

However, it is important to note that the TAS does not yield directly a qc value since TAS is a function also of the static pressure and temperature [8]:

$$\mathrm{TAS} = \sqrt{C_2 \cdot T_S \cdot \left[\left(1 + \frac{qc}{p_S}\right)^{C_1} - 1\right]}$$ **Equation 2**

where

$$C_1 = \frac{\kappa - 1}{\kappa}, \quad C_2 = 2 \cdot \frac{R}{C_1}$$

κ is the adiabatic index
R the universal gas constant
T_S is the static air temperature

A precise calculation requires additional correction terms in the calculation of R and κ in order to account for the effects of humidity on air density. The calculation of the TAS requires the static pressure which at this point still suffers from the static source error which also biases the calculated dynamic pressure. However, an error analysis shows that due to the different pressure ranges of qc and p_S the impact of this effect on qc is rather small.

According to Equation 1 the static and dynamic pressure are not independent from each other. If the total pressure is known it is sufficient to determine only one of the two reference pressures since the second one can easily be calculated from these two values. This means that the availability of a total pressure measurement - which is usually easy to implement - greatly simplifies the calibration effort. In principle the p_T measurement can even be conducted at a different location away from the air probe under investigation [1].

The choice of the best and most efficient calibration method for a certain aircraft depends on the available instrumentation and infrastructure, the desired accuracy and the flight envelope which is covered by the respective aircraft. Since the static source error is a function of Mach number, many turboprop aircraft can be calibrated by means of tower Fly-Bys only. However, an aircraft with a large flight envelope (i.e. Mach number coverage) like a jet requires different flight altitudes in order to cover the complete speed range.

Atmosphere, Aircraft Motion, Sensors – the Limiting Factors

In order to get an idea about the achievable accuracy of an inflight calibration one has to discuss the different error sources of such an experiment. The respective analysis has to cover the data acquisition on the aircraft itself (i.e. the sensors and the data system being used) as well as external parameters which influence the data like fluctuations of atmospheric parameters or variations of aircraft state parameters. A proper analysis of error sources and the determination of error propagation in the data processing are mandatory in order to evaluate an inflight calibration and to quantify an overall error of the pressure measurement.

Sensor Calibration

Portable high accuracy transfer standards for pressure calibration provide accuracies slightly better than 0.01% of the full measurement scale. For an aircraft static pressure sensor this corresponds to about 0.1hPa in absolute pressure which is the equivalent of an altitude difference of 0.8m (2.7ft) at sea level. It is this accuracy which limits any kind of pressure measurements since every sensor being involved in the flight test has to be calibrated with this equipment. Therefore, the accuracy of the calibration source represents the lowermost error limit of any inflight calibration experiment. If there is no calibration equipment available in house, the sensors must be calibrated by external calibration laboratories.

Sensor Behaviour

In order to reach an optimum accuracy in the pressure measurement the sensors which are used for the flight test should not add significant errors to the calibration uncertainty. Therefore, only precision pressure sensors should be used throughout the experiment. The selected instrumentation should be insensitive to the environmental conditions at their location on the aircraft like temperature variations or acceleration effects. This requires active or passive temperature control of the sensor itself and the selection of an optimized sensor orientation to minimize the effect of acceleration forces acting on the pressure sensor membrane. Thus onboard an aircraft the pressure sensor membrane should be oriented perpendicular to the flight direction. Frequent calibrations of a sensor (for example directly before and after the experiment) will help to eliminate some sources of sensor errors like long term drift and nonlinearity.

Data Acquisition

It is important to note that “accuracy” always concerns the combination of sensor and data acquisition. This means that similar requirements as discussed above for the sensors apply to the data acquisition especially when analog sensors are being used. Important criteria for this error analysis are the data resolution (i.e. the "step size" in the recorded pressure data), temporal resolution (acquisition frequency) and the absolute accuracy of the analog to digital conversion of the data. In case of analog pressure sensors it is recommended to calibrate the sensors on the aircraft since such in order to cover the complete measurement chain including the data acquisition in one single step.

Atmosphere and Aircraft Motion

The flight tests should be realized with a stabilized aircraft in calm weather conditions. However, in reality neither the aircraft nor the atmosphere behaves ideally and the accuracy of an inflight pressure calibration is limited by several effects.

Figure 4 and Figure 5 show uncorrected dynamic and static pressure data as measured by an atmospheric research aircraft equipped with a nose boom mounted pitot static probe. The length of the time series is 1.5 minutes and the aircraft heading is opposite to the wind direction. Ground speed and pressure height variations are about 3m/s and 20m respectively, while wind speed varies by 1.5 m/s during this interval.

As one can see the observed pressure variations can be explained by aircraft behaviour and atmospheric effects as well. In case of the static pressure (Figure 4) the signal is strongly influenced by the variations of the geometric height. The superimposed impact of atmospheric effects is visible but significantly smaller and close to the calibration limit of the sensors.

In case of the dynamic pressure (Figure 5) the signal depends on speed variations of the aircraft itself but also on variations of the horizontal wind speed. In this example, a wind variation of 1m/s along the aircraft flight direction results in a 1hPa change of the static pressure signal.

The example is a worst case scenario, since the wind is aligned with the flight track and height and aircraft speed show variations which are above the level of a stable flight test point. However, it becomes clear that aircraft motion and the variability of atmospheric parameters influence the accuracy not only of the pressure calibration itself but also of any subsequent pressure measurement on any aircraft.

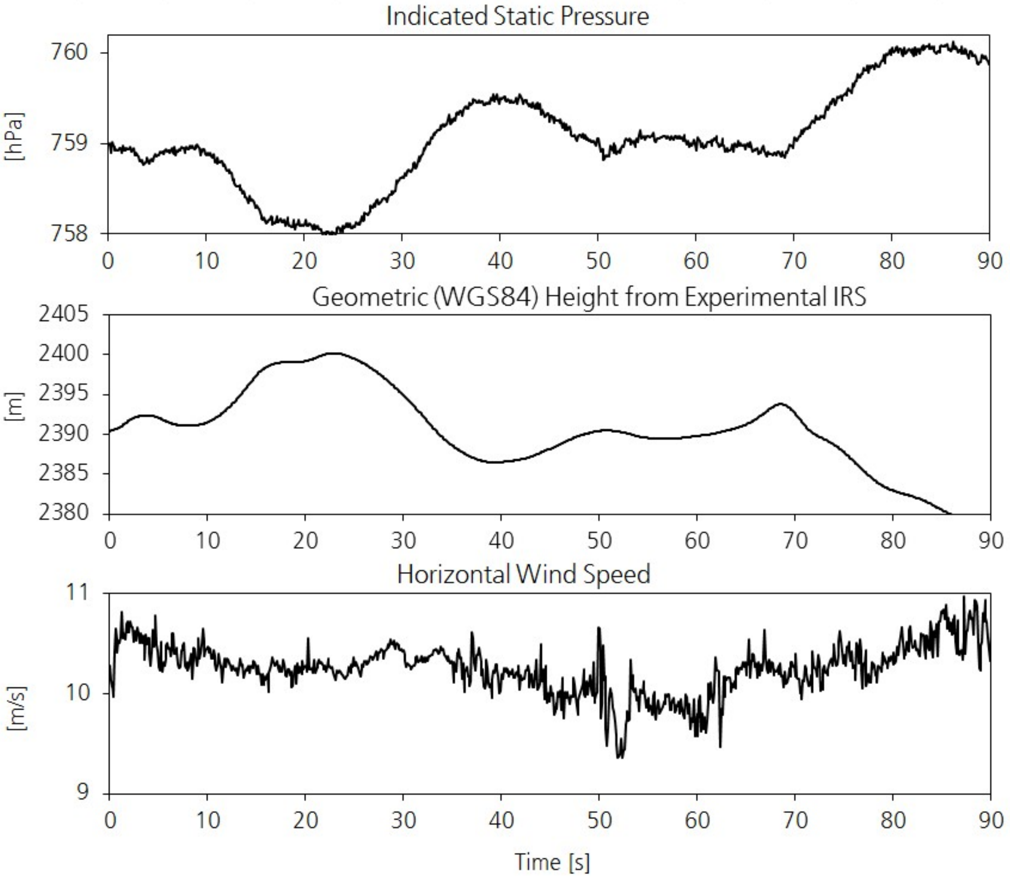

Figure 4: ***Variability of static pressure data. Typical atmospheric and aircraft data time series as measured by a calibrated atmospheric research aircraft flying at about 8000ft.***

Especially in case of the dynamic pressure wind speed and direction will always have a significant impact on the measurement. Besides an offset which is caused by a mean wind speed the qc calibration will always suffer from unpredictable wind variations which exist on all time scales.

For static pressure GPS information can be used to correct the pressure variations caused by aircraft vertical motion as described later in this report. However, this requires that all measurements used in a static source calibration must be performed with a sufficient temporal resolution to “see” the variations in the data and to allow for such corrections during post processing.

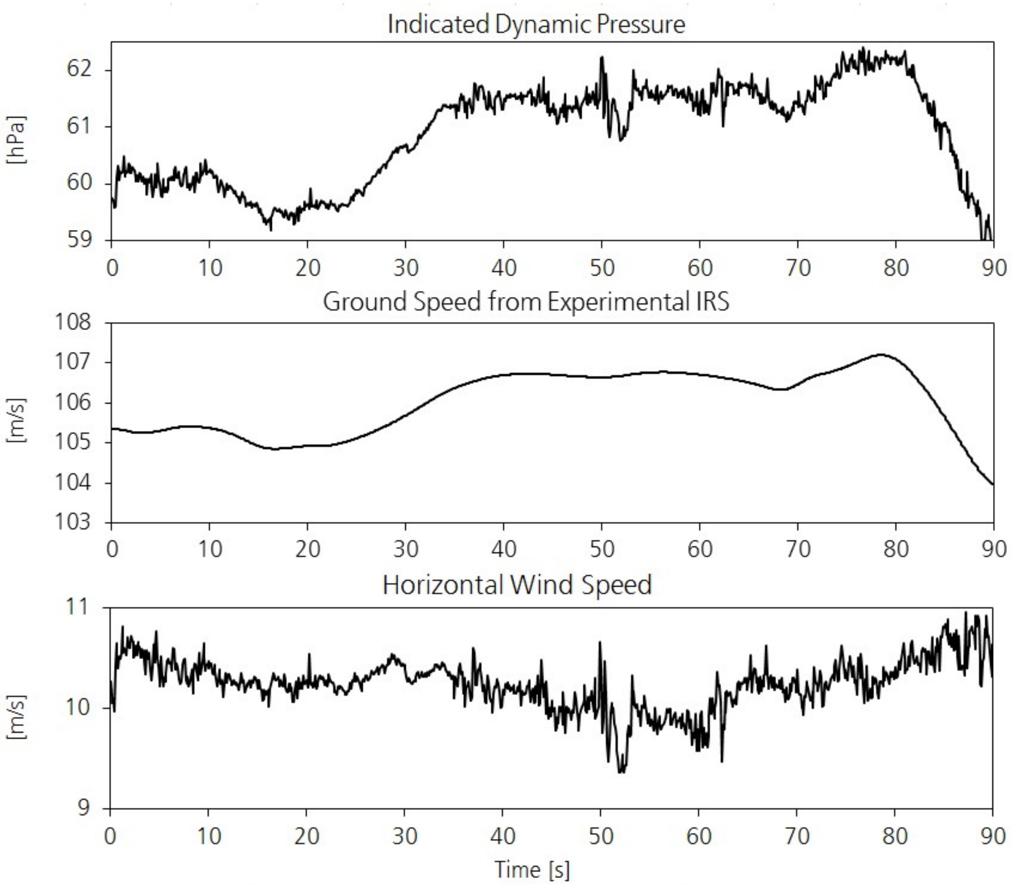

Figure 5: ***Variability of dynamic pressure data. Typical atmospheric and aircraft data time series as measured by a calibrated atmospheric research aircraft flying at about 8000ft.***

From this discussion it becomes clear, that a stable and uniform atmosphere greatly reduces these error sources. This means that accurate static source calibrations require certain weather conditions (weak high pressure systems, low winds and a stable boundary layer to avoid convection and turbulence). At mid latitude the morning of a calm winter day with clear conditions is an ideal candidate for this kind of flight test.

Another critical atmospheric effect for an inflight investigation on atmospheric pressure is a possible horizontal gradient of p_S which can become a problem especially when the static pressure (i.e. pressure height) is linked with GPS-height. Between a high and low pressure area the surface of constant pressure (isobar) is not horizontal any more.

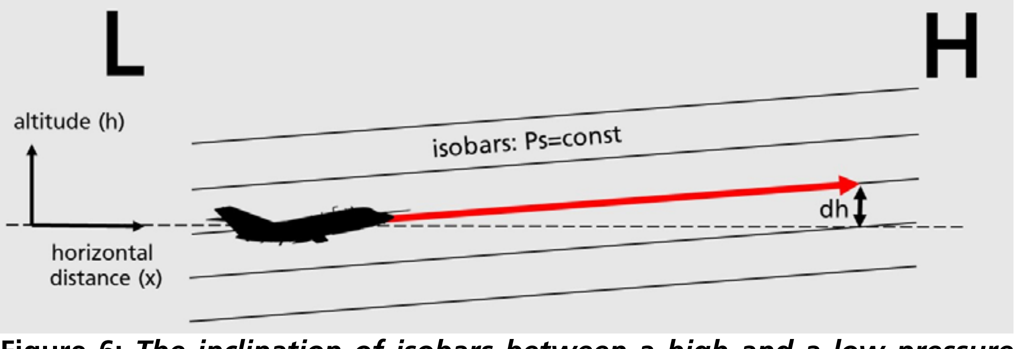

Figure 6: ***The inclination of isobars between a high and a low pressure fields leads to a change of aircraft geometric altitude above ground when it flies at constant pressure altitude.***

As shown in Figure 6 this leads to an offset dh between “real” aircraft height above ground and the pressure height as sensed by the aircraft. Since weather systems move this is not only a spatial but also a temporal effect. Figure 7 shows a real example for this phenomenon and proves that it can take place even over short time intervals.

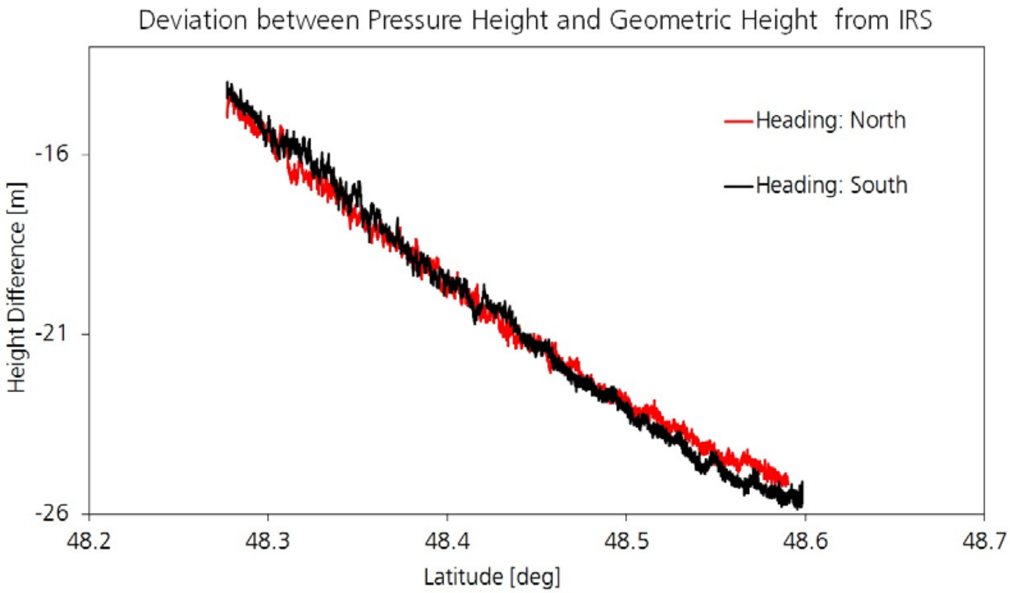

Figure 7: ***Difference of pressure height and geometric altitude from an experimental inertial reference system (IRS) as measured by an atmospheric research aircraft for a keyhole flight pattern plotted as a function of earth coordinate (latitude). Data taken during the turn is also plotted.***

Choosing the Right Calibration Method

The choice of the best method for a pitot static calibration depends on several factors. A commercial static source calibration usually has to satisfy only predefined accuracy limits. Therefore, the "best" calibration method doesn't necessarily have to be the most accurate one but an optimum compromise between accuracy and effort. It is important to check the available resources in terms of flight hours, engineering and data handling capabilities ahead of the planned experiment. For example the aircraft modifications necessary for a Trailing Cone installation require significant resources in the fields of engineering, certification and data work.

If the static source calibration aims at "best accuracy" the discussion will be a

different one. This is the case for the calibration of a reference (i.e. pacer) or a research aircraft where the higher effort is better accepted.
The choice of a method also depends on the aircraft itself. For some aircraft the complete flight envelope (Mach number range) can be covered at flight levels which allow for simple methods like Tower Fly-Bys . Others have to be calibrated at different height levels where some of the methods listed in "*Finding an Inflight Pressure Reference*" will not work.

The quality of any static source calibration depends on the availability and accuracy of an independent pressure reference value during flight. In any case the accuracy of this reference measurement has to be determined before the actual calibration starts. None of the methods is innately error free but requires a validation phase in order to quantify the error of the reference data.
The most important issues for this analysis are:

1. Does the reference represent a direct measurement of the calibrated unit? What is the overall error of this measurement?
2. If the reference is calculated from other units: What kind of additional measurements are needed? What is the uncertainty in the determination of these units and how do these errors propagate into the reference unit?
3. Does the calibration rely on assumptions or simplifications concerning the aircraft, the measurement itself or the atmosphere? Are these assumptions realistic? What is the resulting error of these simplifications?
4. How strong is the impact of "external" error sources on the reference signal? The most important ones are:
    a. Atmospheric effects with statistical character like wind or temperature variations.
    b. Systematic atmospheric effects with spatial or temporal character.
    c. Aircraft statistical behavior causing variations in flight parameters like speed or height.

> Can one reduce the influence of these effects during the experiment for example by choosing a special measurement strategy and what is a realistic estimation for the residual error in the reference unit which is caused by these effects?

It is for example obvious that a calibration of the qc using GPS-ground speed as a reference does not represent a direct reference measurement. As explained above the calculation of TAS from qc requires additional atmospheric data (temperature and static pressure) which – at this point - can still bear significant errors. Furthermore, there is a difference between ground speed and TAS due to the motion of the air (i.e. wind). This means that the calibration must make assumptions about the wind speed and wind direction concerning their temporal development and spatial distribution during the calibration. Therefore, as discussed above statistical wind variations on time scales which are comparable to the time interval between successive test points will create significant errors in the qc data which cannot be corrected.

The direct measurement of the TAS using optical methods will overcome the problem of wind variability but still suffers from the need for additional pressure and temperature data.

Tower Fly-Bys compare aircraft data to pressure data measured close to the ground which is extrapolated to the height of the aircraft above this reference point. This extrapolation needs a temperature measurement and an assumption about the vertical temperature gradient in this height interval as well as a precise determination of the height difference between the ground reference and the aircraft sensors.

There is only one method besides the Tower Fly-By which allows for the direct measurement of pressure close to the aircraft and which is able to cover the complete flight envelope of any aircraft: The Trailing Cone or trailing bomb method. Please note that a pacer aircraft is also typically calibrated with this technique. The method aims at the measurement of the undisturbed atmospheric pressure behind the aircraft with a static pressure probe which is attached to the end of a long tube which is towed behind the aircraft. The required pressure sensor is typically located at the other end of the tube inside the aircraft. The method is named after the device which is attached to the end of the tube in order to stretch and stabilize the whole assembly during flight [15].

It is clear that no pressure reference can be assumed to be error free per se. Therefore, it is mandatory for each method to investigate the accuracy of the reference measurement itself first before one can use it for the actual calibration. In case of the Trailing Cone method this investigation covers the determination of the appropriate tube length behind the aircraft as well as a check of the accuracy of the Trailing Cone reference data over the complete aircraft envelope. This validation is prerequisite in order to use the Trailing Cone for the actual air data calibration.

The following section describes the complete effort to calibrate an experimental pitot static system on an atmospheric research aircraft by means of a Trailing Cone. The experiment includes the validation phase for the Trailing Cone itself as well as the actual calibration. The general plot will be the same for any other method. However, the article will demonstrate that this method when properly applied is virtually error free and it describes procedures which help to reduce the influence of potential error sources which can be used for other calibration methods, too.

Calibration of the Nose Boom Air Data System

Experimental Setup

Aircraft Description

The described calibration experiment was performed by the German Aerospace Center (DLR) for the atmospheric research aircraft HALO (High Altitude and Long Range Research Aircraft) which can be seen in Figure 8. HALO is a modified Gulfstream G550 business jet which underwent significant modifications like fuselage apertures, instrument hardpoints on wings and fuselage and an experimental power system. A more detailed description can be found in [7].

Figure 8: ***Atmospheric research aircraft HALO. The picture shows the aircraft in the 'Belly Instrumentation Pod' configuration. Note the Trailing Cone in the park position at the end of the vertical stabilizer and the nose boom which carries the flow angle sensor to be calibrated .***

One of the major fuselage modifications concerns a large belly instrumentation pod which can be added to the aircraft for specific missions requiring payload to be mounted under the aircraft fuselage. It is obvious that the attachment of such a huge structure to the aircraft will have an impact on the flight performance and there is also a risk that the presence of this external modification changes the static source error of the nose boom or the aircraft pitot static system. Therefore, the certification of this pod required a check on the aircraft and the nose boom static source error. This report will focus on the nose boom calibration since only the experimental air data system allows to directly access the indicated pressure data with high accuracy and temporal resolution. This 'raw data' is required to perform a real calibration. In case of an aircraft air data system the original data is usually not available and the available pressure data is always processed data which subject to a correction which is usually treated as proprietary by the aircraft manufacturer.
However, this investigation will also present the impact of the belly pod installation on the aircraft systems by comparing the processed aircraft data with the reference pressure and by determining the residual static source error of the aircraft avionics (Air Data System) for the different configurations (with and without the belly instrumentation pod).
One of HALOs scientific installations concerns a data acquisition system with interfaces to the aircraft itself and to a sensor package for aircraft state and meteorological parameters. One component of the "Basic HALO Measurement and Sensor System" (BAHAMAS) is the nose boom mounted air data probe (Goodrich Aerospace, formerly Rosemount) 858AJ. The probe is a so called 5-hole probe with pressure ports for static pressure, dynamic pressure, angle of attack and angle of sideslip [12]. It is used to determine the airflow vector with respect to the aircraft in order to calculate a 3-dimensional wind speed with high temporal resolution.
The analog pressure sensors are placed on a "sensor tray" which is located just aft of the air data probe inside the tip of the nose boom. This keeps the pressure lines between the 5-hole probe and the sensors as short as possible as can be

seen in Figure 9. In order to be small enough to fit into the boom and to withstand the extreme environmental conditions during flight appropriate pressure sensors had to be developed by DLR. The sensors are based on a commercial sensor element (Memscap SP82). A three stage active temperature control of sensor housing, sensor element and electronics, custom designed signal conditioning and extensive testing in an environmental simulation chamber were necessary to achieve a 0.01% (of full scale) accuracy class which is equivalent to 0.15hPa over a temperature range from -70°C to 50°C.

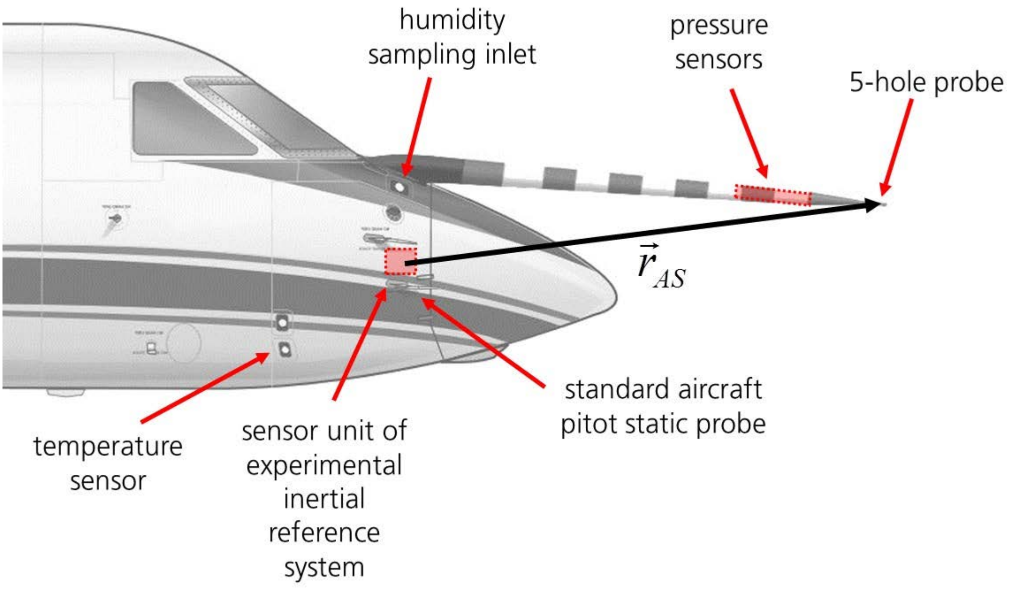

Figure 9: *HALO nose section showing the meteorological sensor instrumentation and the position of the experimental Inertial Reference System in the nose compartment.*

The whole sensor tray which also includes a 3 axis accelerometer to monitor possible boom vibrations has a weight of 1.5kg. The analog sensor signals are digitized by an 18bit data acquisition with an original sampling rate of 1kHz which is averaged down to 100Hz data rate for storage.

The sensors were calibrated using a Ruska 7750i Air Data Test Set (ADTS) [13]. The instrument accuracy can be seen from Figure 10 while the result of the calibration for the nose boom static pressure sensor is shown in Figure 11.

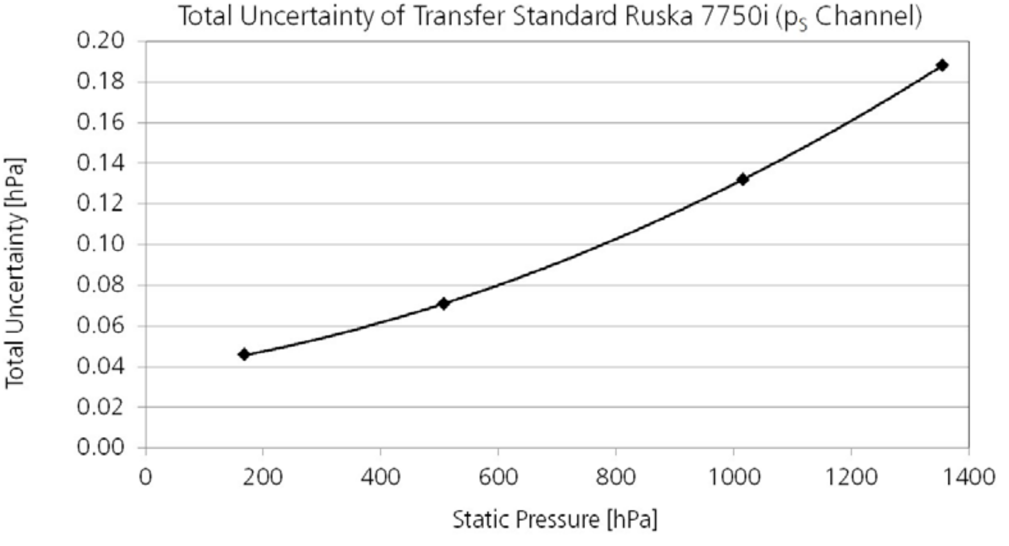

Figure 10: ***Total uncertainty of the pressure transfer standard Ruska 7750i used for the calibration of all pressure sensors from* [13]*. Total uncertainty is defined as the 3σ combined uncertainty of linearity, hysteresis, repeatability, thermal effects one year drift stability and the uncertainty in the primary standard, which includes the uncertainty from the national standard.***

The 3σ values of the transfer standard uncertainty correspond to a confidence level of 99.7%.

In order to perform a true end to end calibration including the data acquisition analog to digital conversion all sensors were calibrated while already installed on the aircraft. An adequate number of calibration reference points and frequent calibrations (before + after the experiment) help to eliminate some of the major sensor error sources like non-linearity and drift.

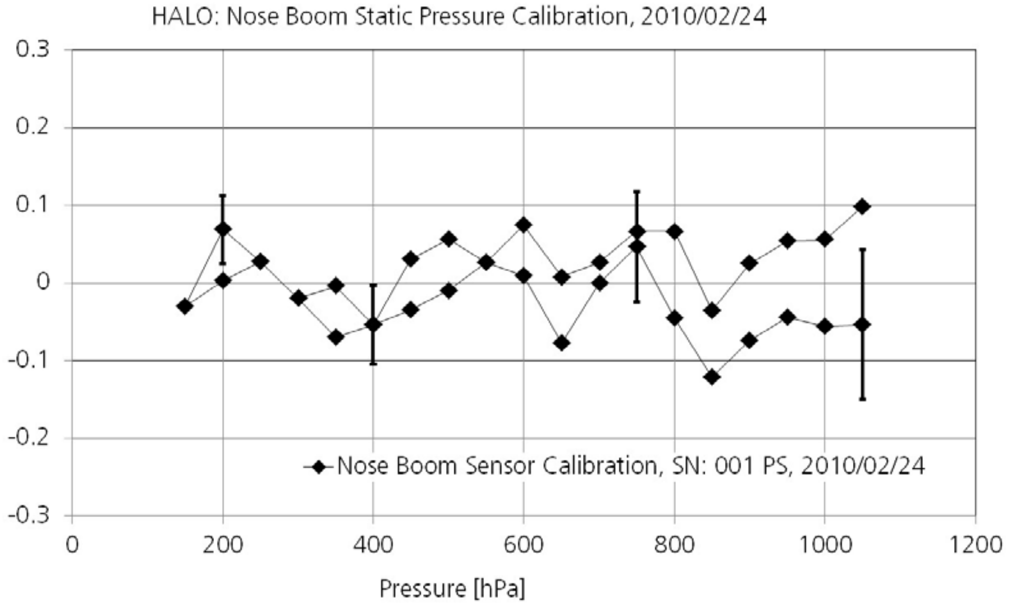

Figure 11: ***Calibration of the nose boom static pressure sensor. Deviation of the pressure sensor data from a fit between the recorded analog data and the reference pressure from the transfer standard.***

It is important to note that both sensors used for this experiment (i.e. Trailing Cone pressure sensor and nose boom static pressure sensor) were calibrated with the same transfer standard and almost at the same time. This eliminates some of the contributions to the overall uncertainty of the Ruska 7750i. An existing zero offset for example would cancel out during a comparison of both data sources. Figure 11 shows the result from the nose boom static pressure sensor. The error bars originate from the accuracy of the transfer standard and the variance (noise) in the sensor output during calibration. For simplicity we assume a constant calibration accuracy over the full static pressure range of the sensor which is 0.13hPa. This value was used for all data discussions throughout this paper and is equivalent to 0.01% of the pressure sensor full scale value (FSP).

Precise information on aircraft position, attitude and angular rate is important not only for the calculation of wind speed but also for the Trailing Cone data evaluation itself as can be seen later in this report. Therefore, HALO is equipped with an experimental Inertial Reference System (IRS) by Ingenieur-Gesellschaft für Interfaces (IGI) in Kreuztal/Germany. This IRS consists of a compact sensor unit (IMU-IIe) which is mounted as close as possible to the aircraft nose boom sensor, a GPS receiver and a main processor unit which is part of the data acquisition unit and therefore located inside the cabin. The IRS sensor unit which is certified for temperatures down to -55°C and altitudes of 55,000ft and is located in the aircraft nose just under the boom as one can see from Figure 9. The system uses real-time differential GPS (DGPS) information from a satellite link (OmniSTAR-HP) to correct the live data for maximum precision. This real time data stream is available via a UDP interface with a data rate of 100HZ and accuracies of:

position	0.1-0.3 m
pitch/roll angle	< 0.05°
heading angle	< 0.1°

Table 1: ***Accuracies of the experimental IRS in the real time DGPS mode as stated by IGI.***

For the data evaluation after a flight the IRS data were post-processed to achieve an even better accuracy (Software: GrafNav from Novatel). During this post processing the GPS raw data are corrected with precise satellite position and atmospheric correction data which are available 2-3 days after the measurements. Together with the linear and rotational acceleration measurements by IRS, and precise position and alignment data for the various sensors, it is possible to calculate the final position and attitude data in a second processing step (Software: AEROoffice by IGI) with extreme precision [2]:

position	0.05 m
pitch/roll angle	< 0.003°
heading angle	< 0.007°

Table 2: ***Accuracies of the experimental IRS after postprocessing [2].***

Trailing Cone Installation

On HALO the Trailing Cone was designed to be released from the vertical stabilizer aft section in order to keep it as far as possible away from the engine exhaust. A winch in the unpressurized tail compartment of the aircraft deploys the tube which is guided by means of aluminium conduits and a deflection wheel to the actual release point. A Polyamid (PA) tube of 50m length and a strength of 4000 N/cm^2 was selected for this experiment. A steel rod is attached to the end of the tube which holds the static pressure inlet which is an assembly of small holes drilled radially into the rod (compare to Figure 15). The Trailing Cone itself is attached to this rod by means of a steel wire. The winch was electrically operated from inside the cabin while a video camera was used to control and monitor the proper performance of the reel and to allow a shutdown of the whole installation in case of a failure. The tube extension behind the aircraft was determined by means of markers on the tube which were visible in the video image.

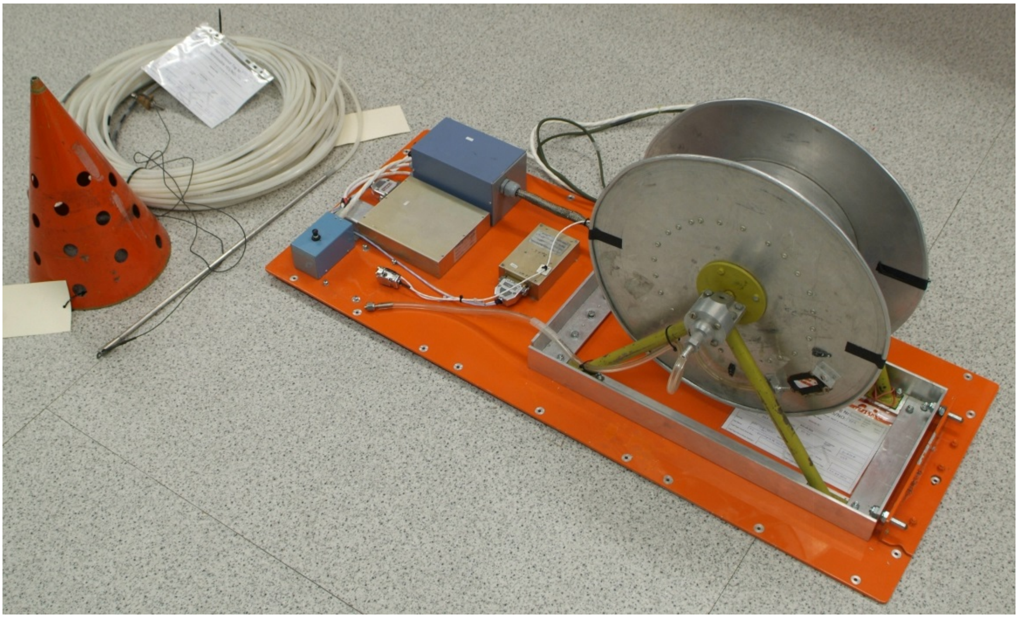

Figure 12: ***Trailing Cone assembly before installation in the aircraft rear compartment. Power supply, winch motor and electrical switch as well as the pressure reference sensor itself are located on the orange base plate next to the reel which deploys the PA tube. On left side one can see the Trailing Cone, the PA tube and the steel rod which contains the pressure ports. The Trailing Cone is attached with a steel wire to the end of this rod.***

A precision digital pressure sensor (Weston Aerospace DPM 78851B) was chosen as the pressure reference for the Trailing Cone. The sensor with a measurement range of 35-1300 hPa, has an accuracy of <0.01% FSP worst case and <0.005% FSP typical over an operating temperature from -40° to +70°. It is mounted on the winch base plate and connected to the end of the tube. Pressure information was transmitted by the serial data interface of the DPM 78851B to the aircraft data acquisition system inside the cabin. Figure 12 shows the reel unit before installation in the aircraft tail compartment while Figure 13 shows the TC in its park position at the end of the release conduit on the vertical stabilizer.

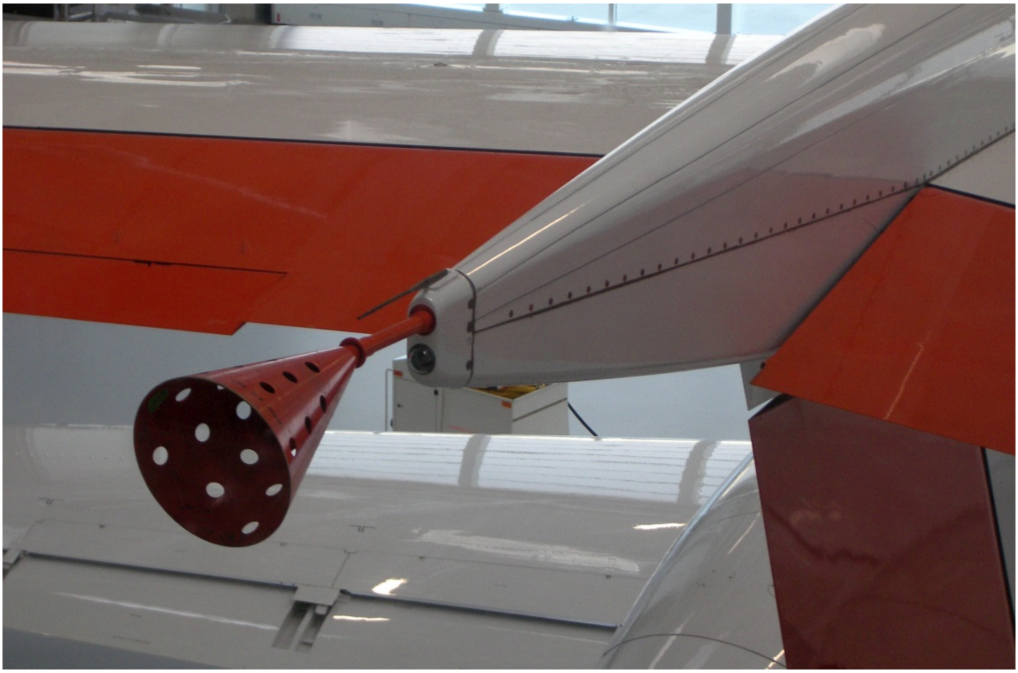

Figure 13: ***Retracted Trailing Cone and aluminium release conduit in takeoff position at the Aircraft vertical stabilizer.***

Figure 14: ***Trailing Cone during release procedure just behind the aircraft. The optimum release length was determined to be 35m.***

Figure 14 shows the TC in flight during the release procedure demonstrating the position well above the engines.

Handling of Pressure Data

Comparison of Measurements from Different Sensors

An atmospheric pressure measurement is always related to the location (height) of the pressure sensor since the weight of the air column inside the tube which connects the sensor with an inlet is part of this measurement. This becomes important when two independent pressure measurements have to be compared with each other. In this case one has to consider the pressure offset caused by a possible height difference between the two pressure sensors being used.
Keeping in mind that a height difference of 0.8m at sea level corresponds to a pressure change of ~0.1hPa it becomes clear that even small height differences between two sensors will cause significant errors in the comparison of measurements from different pressure sensors. However, if the height difference between the sensors is known one can calculate the respective pressure offset. The change of static air pressure dp_s over a small height step dh is given by

$$dp_s(dh) = p_s(h + dh) - p_s(h) = -\rho(h) \cdot g(h) \cdot dh \qquad \textbf{Equation 3}$$

where ρ(h) is the air density at the respective height h and g(h) the local gravity constant. 'Small height steps' means that the air density (i.e. the air temperature) can be seen as constant over dh.
During the planned nose boom static source calibration the measurements from the TC-reference sensor and the static pressure sensor on the nose boom instrument tray have to be compared with each other. Figure 15 shows the relative location of these two pressure sensors and the IRS on HALO. As one can see almost any change in aircraft attitude (e.g., pitch angle) and flight conditions (speed will influence the pitch angle) will have a direct impact on the relative height between the two pressure sensors. For a distance of 23m between nose boom and TC sensor a change of 1° in pitch corresponds to an additional 0.4m

height difference between both sensors.

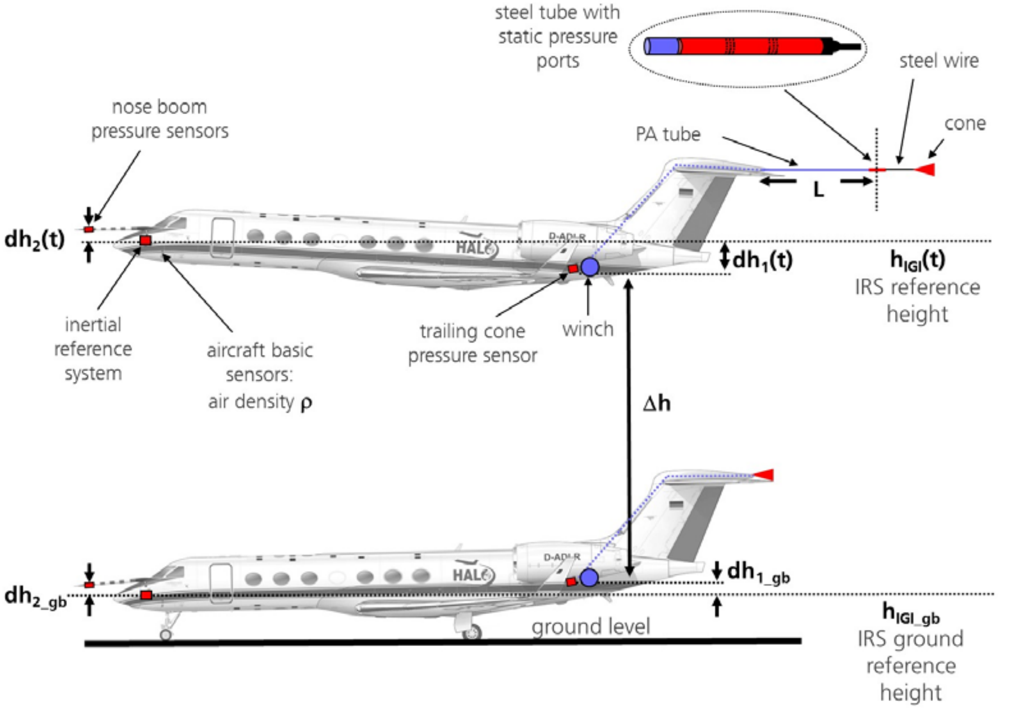

Figure 15: ***Determination of relative altitudes between TC reference sensor and the nose boom static sensor on the instrument tray during flight and on the ground. All measurements are referenced to the height of the experimental IRS sensor head.***

In case of HALO altitude data is referenced to the sensor head of the experimental IRS. dh_1 and dh_2 in Figure 15 represent the vertical offset from this location for the Trailing Cone sensor and the boom mounted pressure sensors, respectively. dh_1 and dh_2 are calculated from the relative distance of the sensors from the IRS and aircraft attitude by simple geometric considerations. According to Equation 3 the resulting time dependent pressure correction $dp_{s1,2}$ for the offset between both sensors is then given by

$$dp_{s1,2} = -\rho(h_{IGI}) \cdot g(h_{IGI}) \cdot [dh_1(t) + dh_2(t)] \qquad \textbf{Equation 4}$$

where $g(h_{IGI})$ is the gravitational constant at flight altitude and $\rho(h_{IGI})$ the air density which can be calculated from the air data (temperature, static pressure, humidity) measured by the aircraft itself.

Aircraft Motion Effects

Equation 3 also explains the dominant static pressure variations in Figure 4 which are caused by random changes of aircraft altitude. Therefore, the precise determination of sensor altitude helps to distinguish between aircraft induced and statistical (atmospheric or sensor noise) variance of the measured signal. By using Equation 3 the height measurement can even be used to correct the indicated pressure data for the effects which are caused by aircraft vertical motion.

Figure 16 demonstrates this for Trailing Cone data from a single calibration test point. As can be seen the dominant variations in the original Trailing Cone data almost completely vanish when the pressure variations calculated from the aircraft vertical motion are subtracted from the time series. It is obvious that the calculated pressure modulation from IRS data using Equation 3 almost perfectly explains the observed signal variation. The required value of the air density ρ was calculated from data of the scientific meteorological instrumentation.

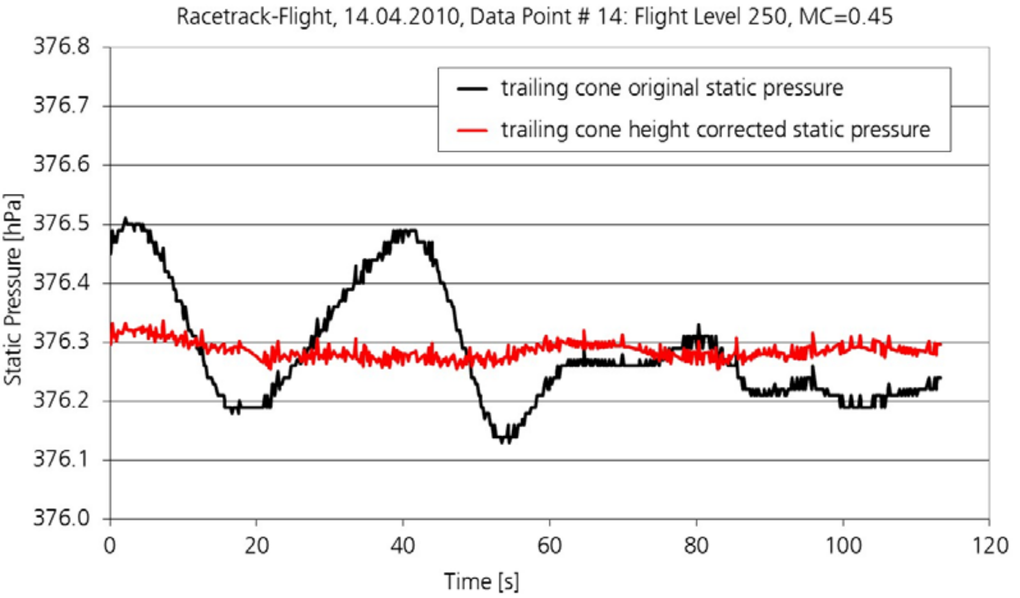

Figure 16: ***Typical time series of static pressure data from the Trailing Cone sensor for a single test point of the calibration. The data shows that most of the signal variance can be attributed to aircraft random vertical motion. Therefore, the determination of sensor vertical motion can be used to remove the associated pressure variance from the original data and to reference the measured pressure data to a single altitude.***

It is evident that this method can be used to eliminate aircraft motion effects from the Trailing Cone pressure data. This means that a time series can be attributed to one single aircraft altitude after correction and that it is possible to distinguish between random noise caused by atmosphere, data system or the sensor itself and the variance caused by aircraft motion. This correction of the aircraft induced pressure variation will play a major role in the Trailing Cone validation.

Trailing Cone Validation

Before the aircraft air data sensors can be calibrated it is necessary to prove and establish the accuracy of the reference pressure data, i.e. the Trailing Cone itself has to be tested and validated before the actual calibration can start. The determined accuracy of the Trailing Cone reference measurement limits the overall precision of the final air data system calibration.

At first one has to determine the optimum tube length for the Trailing Cone i.e. the right distance between the aircraft and the reference static pressure port which is towed behind the aircraft.

Once this length has been fixed the next step is the determination of the TC accuracy.

The procedure starts with Tower Fly-Bys. This method provides completely independent pressure reference measurement from the ground which are compared to the Trailing Cone data. However, since the validation must cover the complete flight envelope (i.e. Mach number range) many aircraft require additional test points at higher flight altitudes to access the complete speed range. This "envelope expansion procedure" is the third step in the TC validation. It builds up on reference test points taken with lower Mach numbers which have already been tested at lower flight altitudes.

Without this validation phase the TC cannot be used for calibration since there is no proof for the accuracy and reliability of the method. The following paragraphs demonstrate that in principle three flights are sufficient to not only validate the Trailing Cone but also calibrate the air data system over the whole flight envelope if the flights are properly planned.

Step 1: Trailing Cone Length

The determination of the right distance between the TC and the aircraft is essential for the whole calibration. A short tube will keep the TC in a pressure field which is still influenced by the aircraft. A too long tube will result in an unstable cone flying significantly below the release point entering the wake of the aircraft. The optimum length is specific for a certain aircraft and the chosen Trailing Cone installation. As a rule of thumb the right Trailing Cone length is in the order of two wingspans of the aircraft under investigation [5].

The right tube length has to be determined under stable flight conditions i.e. constant altitude, constant speed, wings levelled. Furthermore, a stable atmosphere (i.e. above the atmospheric boundary layer) is prerequisite to achieve good results. The Trailing Cone is released stepwise, each step representing a test point. For HALO the tube was released in steps of 5m and the aircraft speed was limited to 200kts in order to reduce the force on the winch motor. A single test point consists of a 10-20s measurement time interval for the respective tube length in order to provide sufficient data points for statistical reasons. For each step the mean TC pressure is determined and later plotted over the TC length. As already explained above the expected devolution of the pressure measurement as function of the distance behind the aircraft will first show a strong gradient leveling out in a plateau of constant pressure followed by a gradient again if the trailing becomes unstable and reaches the aircraft wake. Thus the ideal tube length will be in the middle of the plateau.

In principle this dependency can slightly change with aircraft speed therefore several runs at different speeds are required. Atmospheric turbulence and aircraft random motion will also degrade the measurement. This is the reason why the determination of TC-length usually requires multiple TC-releases.

Note that the error bars shown in the plots of this chapter are mainly due to the uncertainty in the aircraft altitude determination by the experimental IRS. The pressure sensor absolute accuracy can be neglected since theses results represent a relative measurement with respect to the first value on that leg. Furthermore, the Trailing Cone operation requires a relatively short time where sensor drift effects do not play a role.

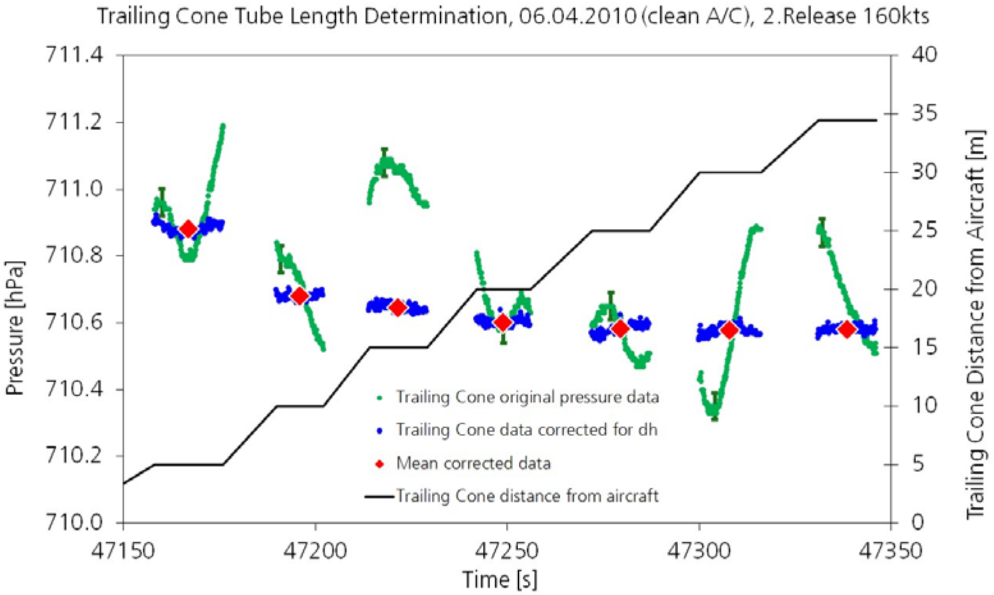

Figure 17: ***A single Trailing Cone release for the optimum tube length determination. The time series shows the distance of the Trailing Cone static pressure port from the aircraft (black line) and the original Trailing Cone static pressure measurement in green. The pressure time series plotted in blue represents the same data after being corrected for height changes of the aircraft (referenced to the mean value at 30m tube length). Mean data is plotted as red diamonds. The pressure data gaps refer to winch operation and an aircraft turn.***

Figure 17 shows the data from a Trailing Cone release from the park position to a distance of 35m. HALO was flying at an altitude of 2895m (FL95) at a speed of 160kts. As one can see the original Trailing Cone data (grey curve) show significant pressure variations which prevents the data interpretation since the expected plateau cannot be seen. The variations can be seen between different test points as well as during the time series from a single test point. In order to distinguish between the influence of the aerodynamic field behind the aircraft and the effect of aircraft vertical motion the data was height corrected as described above using data from the experimental IRS. The result is also plotted in Figure 17. It clearly shows that the altitude correction does explain most of the observed variance in the Trailing Cone data and that atmospheric effects or electronic noise from the sensor can be neglected.

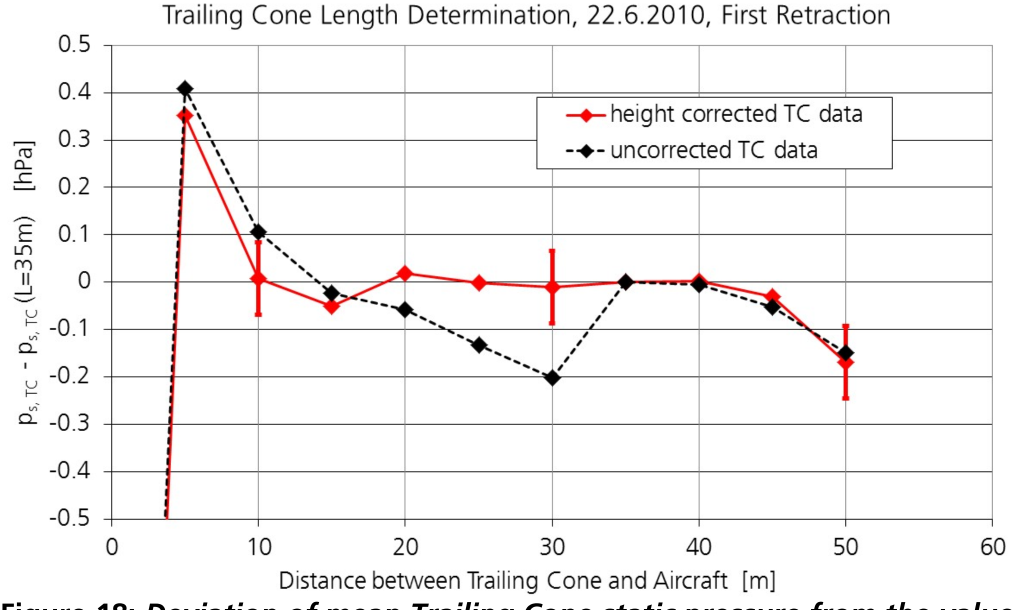

Figure 18: ***Deviation of mean Trailing Cone static pressure from the value at 35m as a function of distance behind the aircraft. Black line: original data, red line: pressure data corrected for changes in aircraft altitude.***

Another example from a different flight is shown in Figure 18. HALO was flying with 200kts at FL150 in a heavy aircraft (full fuel) configuration and the retraction started 50m behind the aircraft. From the plot of mean pressure over the released tube length one can see that the correction also strongly impacts the mean pressure values used for the TC length determination. The correction is obviously very helpful to clearly identify the plateau of constant pressure from the 'pressure over tube length' plot.

Due to the length of the tube the Trailing Cone pressure shows a time delay when compared to IRS height data. This has to be taken into account before calculating the correction term. For HALO this delay was determined by a cross-covariance analysis (aircraft altitude, Trailing Cone pressure, nose boom pressure). The time shift was found to be between 0.5s at Tower Fly-By level and 1.5s at FL350.

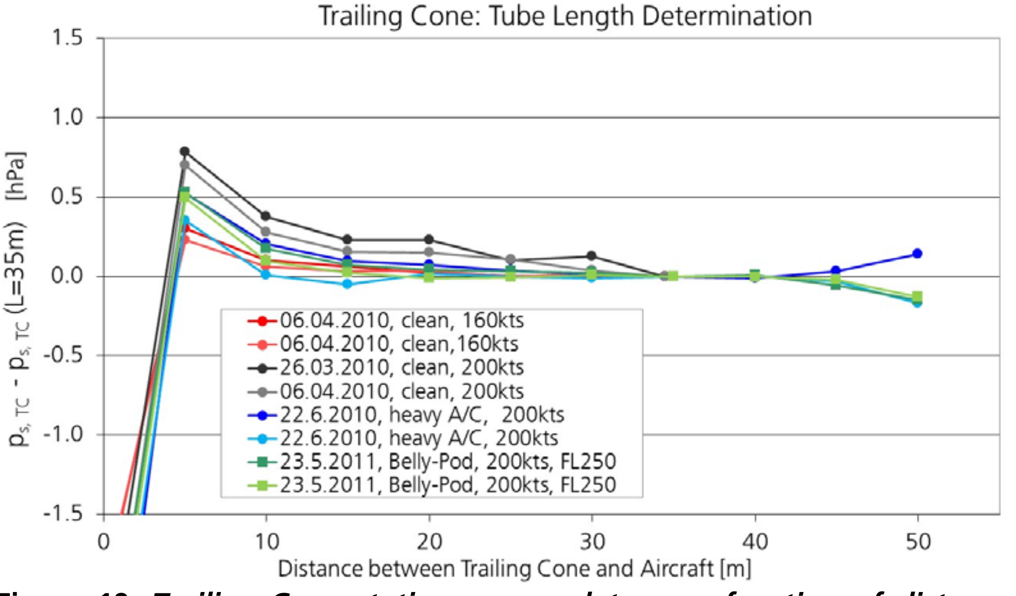

Figure 19: ***Trailing Cone static pressure data as a function of distance behind the aircraft. All data is referenced to the value at 35m and corrected for aircraft vertical motion. The different curves represent different flight conditions (speed) as well as aircraft configurations (aircraft weight, external installation 'Belly Pod').***

Figure 19 summarizes the results obtained from different flight tests covering different aircraft speeds, configurations and flight levels. The data indicates that the optimum tube length is independent of these parameters. The results show a stable pressure measurement between 20-45m behind the aircraft. Therefore, the optimum tube length was chosen to be 35m.

Step 2: Low Mach Number Validation (Tower Fly-By Calibration)

The choice of an optimum tube length guarantees stable pressure measurements which are independent of speed and aircraft configuration changes. However, this does not mean yet that the indicated Trailing Cone pressure is identical to the atmospheric pressure outside the aircraft aerodynamic perturbation.

In order to prove this the Trailing Cone data has to be compared with the ‘real’ atmospheric pressure. This is done by means of Tower Fly-By at different aircraft speeds.

The standard Tower Fly-By method as described by e.g. [5] compares the aircraft measurement during a low pass above the runway with a pressure measurement which is taken on the ground and extrapolated to the flight altitude using the hydrostatic equation. To get rid of ground effects, that mainly disturb the temperature measurement, the reference measurement of pressure and temperature are placed on a tower. The height difference between tower and aircraft are generally determined by optical methods.

In absence of a tower or to avoid the usage of an additional reference pressure sensor a modified version also is practicable. This so called ground block method uses the aircraft sensor as reference when the aircraft is at rest on ground below the overflight point. The ground block measurement is taken at the beginning and the end of the test run. Ground pressure and temperature measurement are then linearly interpolated to each test point. Improved accuracy can be achieved by continuous monitoring of ground pressure in between both ground blocks [16].

The requirements for a single Tower Fly-By test point are a properly stabilized aircraft which flies as low as possible above the runway without getting into ground effects and an absolutely stable (‘quiet’) atmosphere with low winds. These conditions can be found for example during winter time and in the early morning before any significant turbulence starts above the runway. The aircraft

usually flies a racetrack pattern with sufficient length to allow for a proper speed setting and stabilization ahead of the runway. A single test point should always represent a mean over at least some seconds of data which is important for statistical reasons and a proper error analysis.
We developed a method based on the ground block method that minimizes effort to achieve best possible accuracy.

Determination of Ground Reference Data

The reference pressure $P_{s,groundref}(t)$ on the ground is usually determined from the two measurements taken during the ground blocks (gb) before and after the flight by placing the aircraft in the middle of the runway (i.e. the reference point) at rest. The reference ground pressure for each test point is then calculated by linear temporal interpolation between these two points.
We propose to determine the reference pressure by measuring a ground pressure start value $P_{s,gb}$ using the Trailing Cone sensor on the aircraft during the ground block. This value is determined as a mean value over 30s. The temporal development of ground pressure is then determined as a relative change of a pressure $P_{s,ground}(t)$ which is measured by an independent sensor located as close as possible to the runway on the ground, i.e.

$$dP_{s,ground}(t) = P_{s,ground}(t) - P_{s,ground}(t = t_{gb})$$ **Equation 5**

The change in ground pressure is then added to the mean ground block value:

$$P_{s,groundref}(t) = P_{s,gb} + dP_{s,ground}(t)$$ **Equation 6**

The start pressure $P_{s,gb}$ is measured at a sensor height h_{gb} which becomes the ground reference altitude throughout the whole TC-calibration. From Figure 15 one can see that

$$h_{gb} = h_{IGI\_gb} + dh_{1\_gb}$$ **Equation 7**

There is an obvious advantage in this concept: In using the same sensor for the absolute measurement of the ground block reference pressure and the Trailing Cone pressure during flight the Trailing Cone data becomes a differential measurement taken by the same sensor. This means that certain error sources of the sensor like offset or long term drift will be eliminated completely which would not be the case if two independent sensors were used. Furthermore, this ground reference measurement is made exactly on the reference location above which the TC data is determined during the Tower Fly-Bys.
Another advantage of this method is given by the fact, that no exact calibration is required for the second sensor on the ground, since it measures only relative pressure changes in a very small pressure range over a short time interval of 1-2h, which also cancels some of the sensor measurement errors. Furthermore, no exact height determination is needed for this sensor.
Figure 20 demonstrates the difference between the classical interpolation of two ground block values and the proposed new method which was used for the Tower Fly-Bys of this experiment. It is evident that the actual change of the ground pressure leads to deviations of more than 0.1hPa compared to the interpolated ground block values over a 1.4h time interval. These deviations would otherwise directly degrade the accuracy of the calibration.

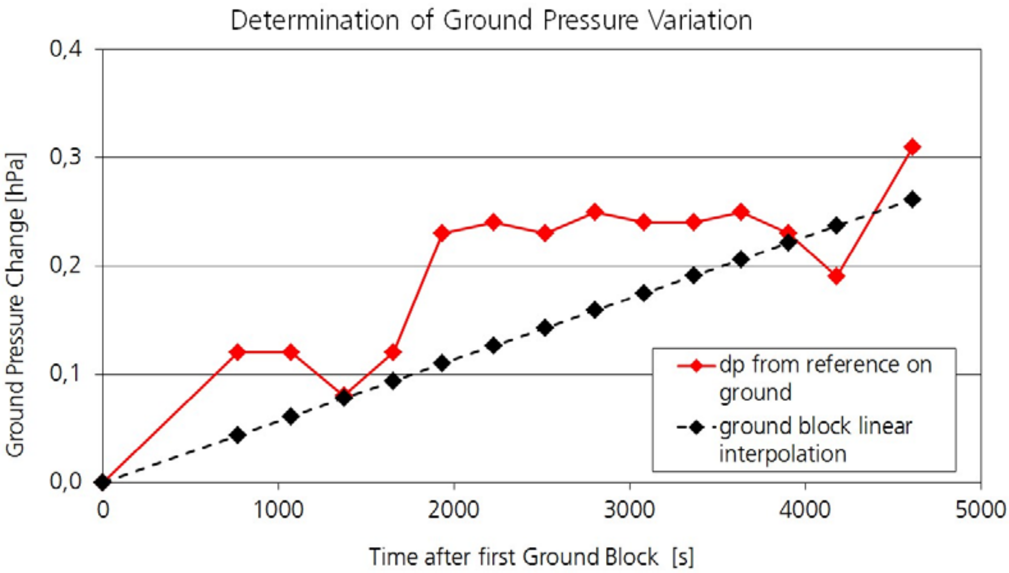

Figure 20: ***Development of ground pressure as measured by a separate instrument on the ground compared to the traditional linear interpolation of aircraft ground block data. The last point corresponds to the second ground block***

Aircraft Altitude Measurement

In the traditional Tower Fly-By method best accuracy in the determination of the aircraft height is derived by expensive optical tracking systems that are not available for the majority of aircraft operators and facilities. Alternatives like photo analysis and geometric reconstruction or the use of a radio altimeter are easier to handle but do not reach the same level of accuracy.

As pointed out above the accuracy of the post processed height data from the experimental IRS on HALO is sufficient for this task which greatly simplifies the "height above runway" determination. The only important information required for this method is the exact time when the aircraft crosses the reference point.

For each test point the Trailing Cone and nose boom pressure measurements must be related to the altitude of the respective sensor. Figure 15 shows how

this altitude is derived from the position of the inertial reference system h_{IGI} and the relative height of the pressure sensors of the nose boom (dh_2) and the Trailing Cone (dh_1). Both values can be calculated by simple geometric considerations based on the sensor distance from the IRS and aircraft attitude data.
The height difference between TC sensor and the ground block reference height for a single test point is then given by

$$\Delta h(t) = h_{IGI}(t) + dh_2(t) - h_{gb} \qquad \textbf{Equation 8}$$

Use of Air Data

To calculate the reference pressure at flight altitude during the Tower Fly-By using the hydrostatic equation (Equation 3) its necessary to know the air density ρ which is a function of pressure (p), temperature (T) and humidity (H). Unfortunately temperature measurement directly on the ground are not very representative for a mean air density between aircraft and ground due to the large variation in surface properties and the fact that strong temperature gradients are typical close to the ground. Therefore, the density calculation uses temperature and humidity data measured by the scientific instrumentation of HALO.
To calculate the mean density we assume a linear pressure dependence of the air density over the small height interval from ground to aircraft. The mean air density which was used for the height correction thus is calculated with an extrapolated pressure p_{sh} halfway between aircraft and ground as $\rho(p_{sh},T,H)$ with:

$$p_{sh}(t) = p_{s,groundref}(t) - \rho(p,T,H) \cdot g(H) \cdot \frac{dh_{DPM}(t)}{2} \qquad \textbf{Equation 9}$$

p, T and H represent temperature and humidity as measured at the aircraft.

Test Points

The aircraft was flying a racetrack pattern. A single test point was followed by a 180° turn and the new speed was already adjusted on the opposite flight leg. After another 180° turn the aircraft was stabilized (i.e. wings levelled, constant speed and altitude) before it reached the airport runway again. Since the stabilisation required some time the length of the racetrack increased with increasing speed. The test point itself was marked with an electronic event marker in the data.

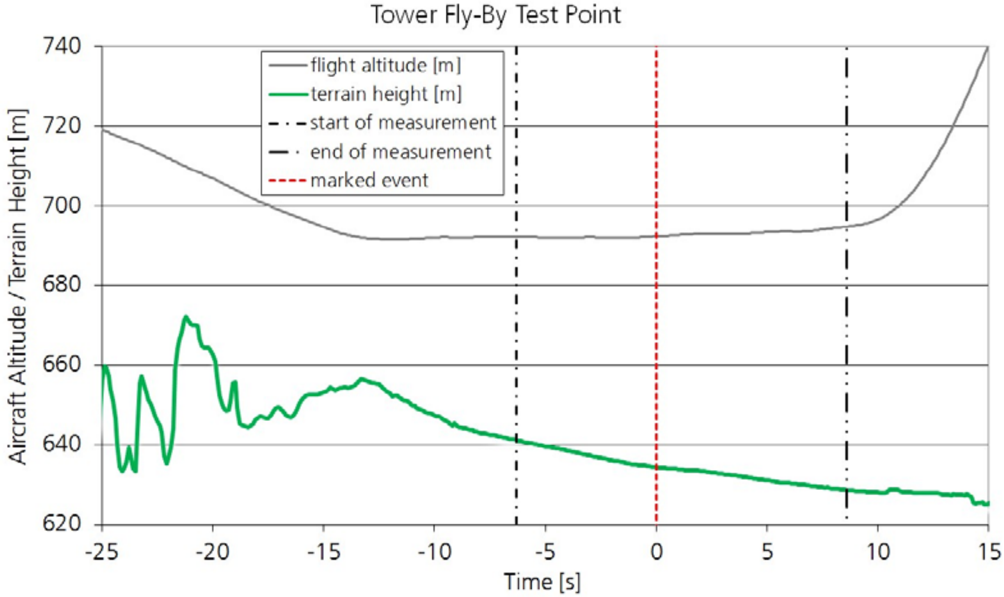

Figure 21: ***Tower Fly-By test point. The plot shows the terrain height and the flight path during the approach. Vertical lines identify the runway reference point (time=0) as well as the start and end of the time window which was used to calculate average data.***

During the data processing we determined a time window around this marker in order to improve data quality by averaging. This can be seen in Figure 21. The determination of this window is based on a detailed investigation of different

flight parameters. The criteria are: stable values of aircraft attitude, height and speed. A correlation analysis between height and static pressure was used to check for gust and sudden changes in wind speed. A typical time period for a successful test point was 10-15s.
Before any pressure data could be averaged to reduce statistical noise we had to correct the Trailing Cone data for the aircraft random height changes. The correction which is shown in Figure 22 is necessary in order to calculate a mean pressure for the single height which is marked by the electronic topper during the actual event.

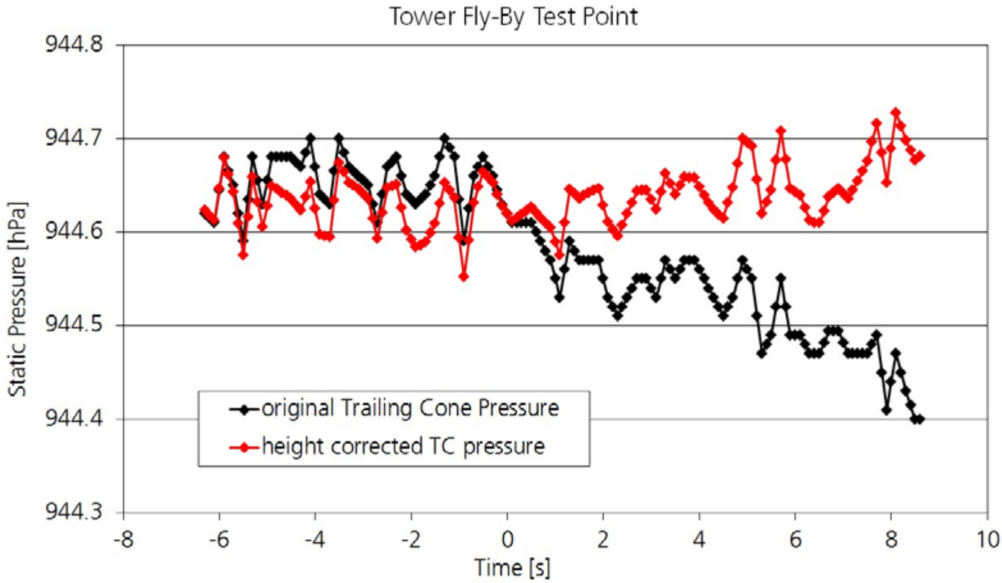

Figure 22: ***Effect of the height correction when applied to tower Fly-By data. The plot shows the time series which was used to calculate average data before and after the correction.***

Result

Figure 23 shows the result of the Tower Fly-By validation of the Trailing Cone. As one can see, the static pressure reading from the Trailing Cone agrees very well

with the extrapolated ground pressure. Note the error bar which represents the accuracies of the ADTS which was used for the sensor calibration and the uncertainty in aircraft altitude measurement by the experimental IRS.
The result proves that the Trailing Cone measurement accurately represents the true atmospheric pressure for low Mach Numbers of up to 0.4.
Now the validity of this statement must be extended to the complete flight envelope of the aircraft. In order to do this the full Mach number range of HALO has to be covered. This requires a different strategy.

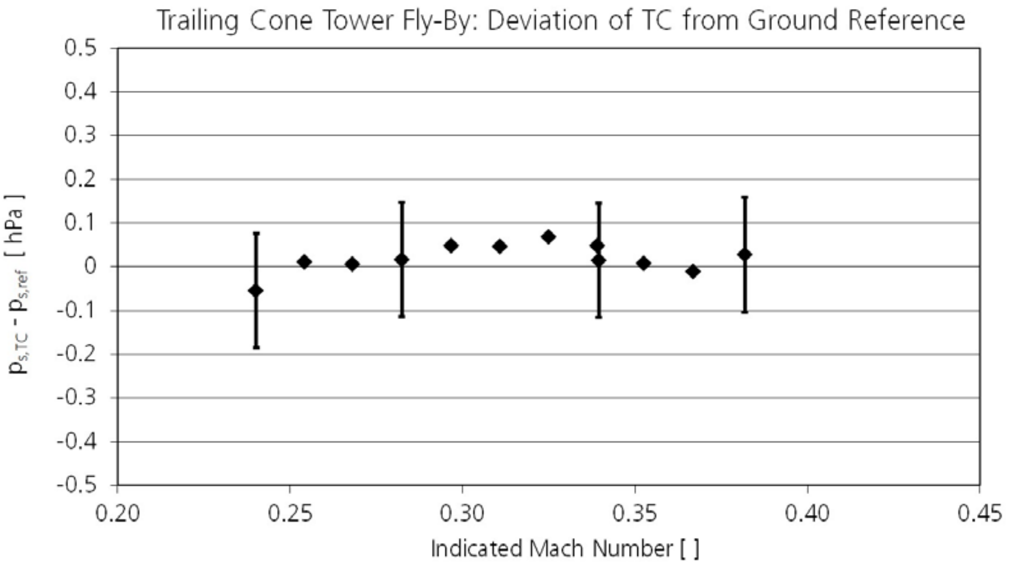

Figure 23: ***Result from the Trailing Cone validation using tower Fly-Bys. The plot shows the deviation between Trailing Cone pressure sensor reading and the extrapolation of ground pressure to the aircraft altitude as a function of aircraft speed. The 3σ error of the data is 9.3Pa.***

Step 3: Flight Envelope Expansion to Higher Mach Numbers

The Tower Fly-Bys have proven that the TC works for the Mach numbers which are accessible at low flight altitudes. Higher Mach numbers can only be flown on higher flight levels where independent measurements of atmospheric pressure are difficult to realize.

The flight envelope extension is based on the assumption that a possible error in the Trailing Cone measurement is a function of Mach number only. In this case the validation on a higher flight level can use a reference pressure which was determined by the Trailing Cone itself at an aircraft speed (Mach number) where the proper performance of the method has already been demonstrated before at lower levels. Starting with this value the Trailing Cone performance can then be tested over the full Mach number range on the respective flight level.

Three flight levels were chosen to cover the whole flight envelope (Mach number range) of HALO and to give enough overlap in aircraft speed between them:

Flight Level	Mach number range
FL150	0.30 - 0.65
FL250	0.45 - 0.80
FL350	0.60 - 0.88

Table 3: *Flight envelope expansion of Trailing Cone validation: flight levels and speed range.*

Starting with the low altitudes the validation procedure is as follows: On each flight level the reference pressure is measured by the Trailing Cone at an already established Mach number for this method. The speed is then increased step by step up to the maximum speed on this level. The procedure is repeated for the other flight levels until the whole Mach number range is covered.

However, in order to reduce possible error sources we introduced several improvements to the traditional procedure during the HALO flight trials:

Height Correction

The intercomparison of pressure data which is measured at different speeds requires that all data is referenced to one common altitude. From this reason it becomes clear that the height correction described by Equation 3 becomes mandatory for the flight envelope expansion. The correction uses air data from the aircraft scientific instrumentation and height information from the experimental IRS. It was performed for each flight level separately.

Flight Pattern

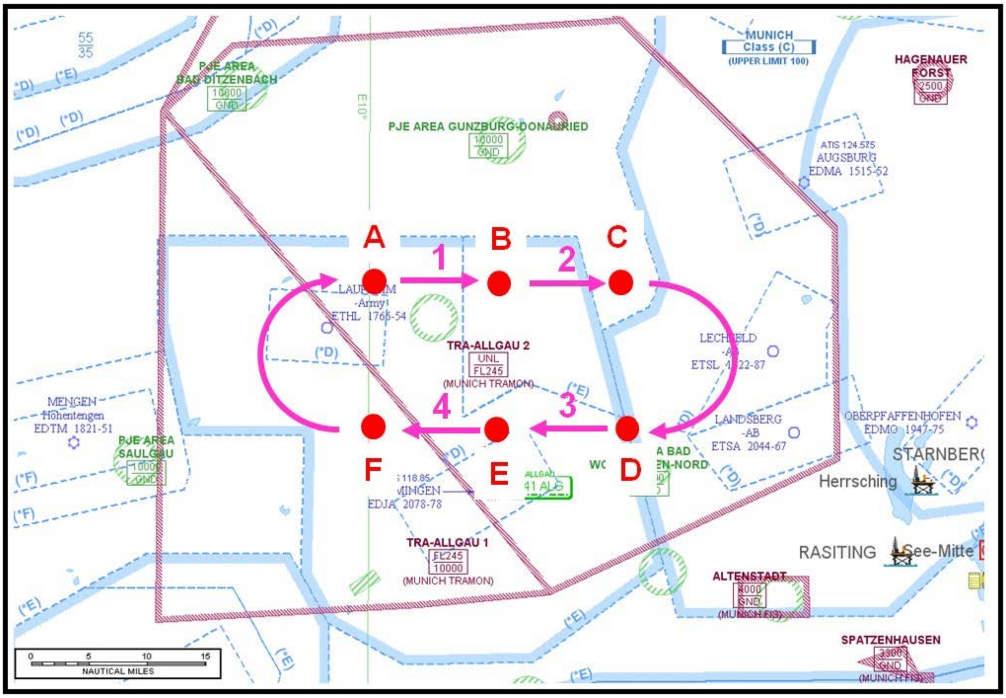

Figure 24: ***Flight test pattern for the Trailing Cone validation at higher Mach numbers. The racetrack pattern contains 6 waypoints (A-F) and 4 straight flight legs (1-4) in order to discriminate spatial effects in the pressure measurement. Each flight leg makes up one test point.***

A racetrack pattern was chosen according to Figure 24 with 4 straight flight legs (1-4). Each leg corresponds to one single test point which is calculated as a mean value from the height corrected data similar to the procedure described for the Tower Fly-Bys.

The legs of the race tracks must be long enough to change speed and to stabilize the aircraft between the required test points. The time interval which was used for averaging was determined using the same criteria as for the Tower Fly-Bys. The flight pattern ensures that a single test point can be related to one of four fixed locations in the test area.

Flight Strategy: Determination of Atmospheric Influence on the Data

For a perfectly working Trailing Cone one would expect to observe no trends or changes of the height corrected pressure signal during the different test points on a single flight level.

However, if the Trailing Cone pressure is not constant during such a speed run there are still two possible explanations for this observation:

- The Trailing Cone itself does show Mach number effects i.e. the method does create a (systematic) error
- The atmosphere itself is responsible for this effect. As shown in Figure 6 inclined isobars will lead to a systematic (spatial) pressure offset in the data. A similar problem arises, when a frontal system moves into the test area, which would result in an additional temporal drift in the corrected pressure data.

The proposed racetrack pattern and a proper choice of the test point parameters can help to distinguish between Mach number effects and the atmosphere and thus simplifies the data interpretation. We chose the following strategy for a single height level:

1. In a first step the complete racetrack is flown using an already established Mach number from a lower flight level. For the first flight leg at 15,000ft this would be for example MC=0.4 which was successfully tested during the Tower Fly-Bys. The four test points obtained from this

run are used to check for a possible spatial atmospheric effect. Since these test points are flown with the same configuration and under identical flight conditions any observable data trend must be attributed to atmospheric effects.

2. After this reference measurement the Trailing Cone pressure is measured over the complete accessible Mach number range at this altitude (0.3-0.65 in steps of 0.5 at FL150) using the pre-defined test point locations which have already been covered in step 1.
3. Finally a second reference measurement is performed above all four test points using the same speed (MC=0.4 at FL150) as for the first reference run described in step 1. This data data is used to check for a possible time drift during step 2 and to confirm any spatial effect observed during the measurement.

This measurement strategy was applied to each flight level. The experiment started on FL350 and ended with FL150.

The error bars in the following plots represent the uncertainty in the aircraft altitude neasurement (by the experimental IRS) which is used to correct the pressure data as well as the estimated short term stability of the Trailing Cone pressure sensor since the results represent a relative pressure change measurement with respect to the first value on that flight leg.

Results and Discussion

Figure 25 shows the result of the validation for a single flight level (FL250). The data set consists of 16 test points and represents a 65 minute time interval during the test flight. According to Table 3 the accessible Mach number range at this altitude is 0.45-0.80.

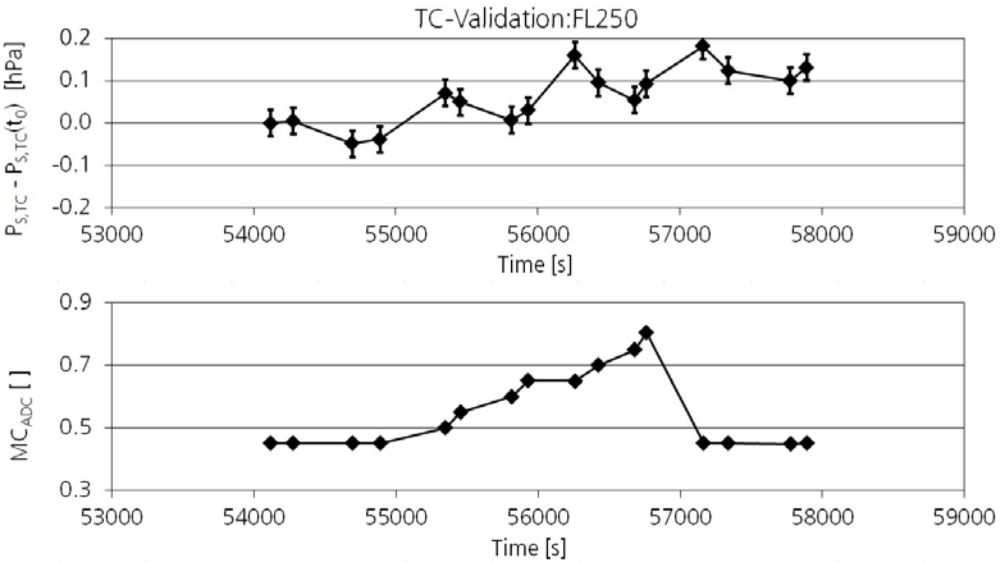

Figure 25: ***Result of the envelope expansion at FL250: Time series of aircraft Mach number from aircraft avionics (lower plot) and of the difference of height corrected Trailing Cone pressure from the first value which was determined on this flight leg (upper plot).***

As can be seen in Figure 25Figure 27 the observed variations of the Trailing Cone pressure are larger than the sensor calibration accuracy and it seems that there is a correlation between reference pressure and aircraft speed.

However, from the same plot it becomes immediately clear, that this cannot be explained by a Mach number effect of the Trailing Cone method: The obvious discrepancy between the data from the two "reference racetracks" which were flown under identical flight conditions (speed, height and location) at the start and end of the measurement clearly proves that a change in the atmospheric structure must have taken place during the 60 minutes of this run.

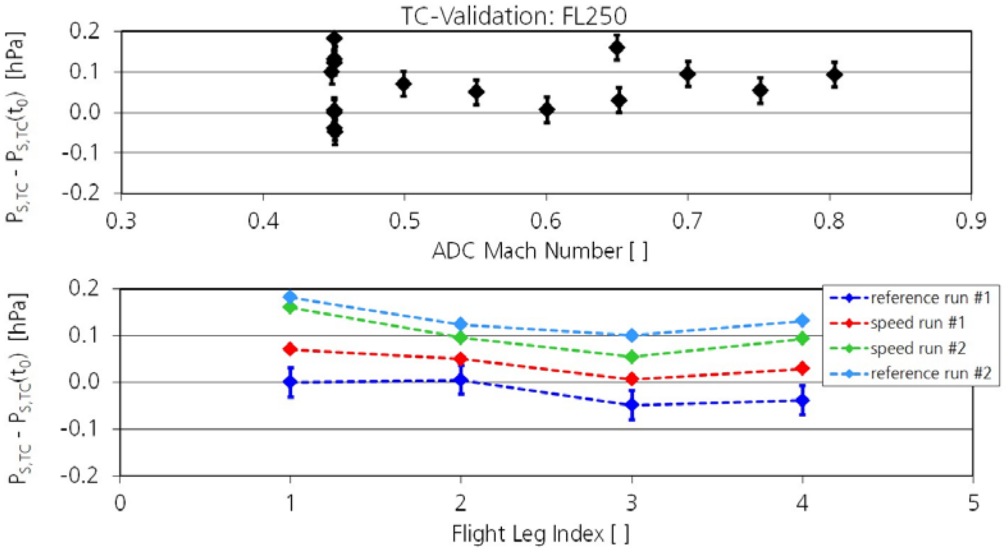

Figure 26: ***Result of the envelope expansion at FL250. Deviation of height corrected Trailing Cone static pressure data from the first value on this level as a function of Mach number (from aircraft avionics, upper plot) and location in the flight track pattern (lower plot).***

This observation becomes even more obvious from Figure 26 where the data are plotted as a function of Mach number and flight leg index (as defined in Figure 24). The offset between the 2 reference measurement becomes clearly visible in the upper plot. Moreover, the lower plot indicates that this offset seems to be associated with an almost constant drift since the results from the single racetracks are separated by an almost constant offset.

Besides this temporal effect the periodic signature in the lower plot of Figure 26 indicates that an additional spacial modulation of the pressure signal is also present.

If we assume for simplicity that the change of the atmosphere vertical structure is a linear function of time one can fit a linear trend into the pressure data as indicated in Figure 27. The fit uses only data from the two reference runs to avoid that other effects are mixed into this parameterization. By subtracting the trend from the original pressure data one can correct the original envelope expansion data for the observed atmospheric trend. The result is also shown in Figure 27 and the pressure data now lies within the calibration accuracy of the sensor.

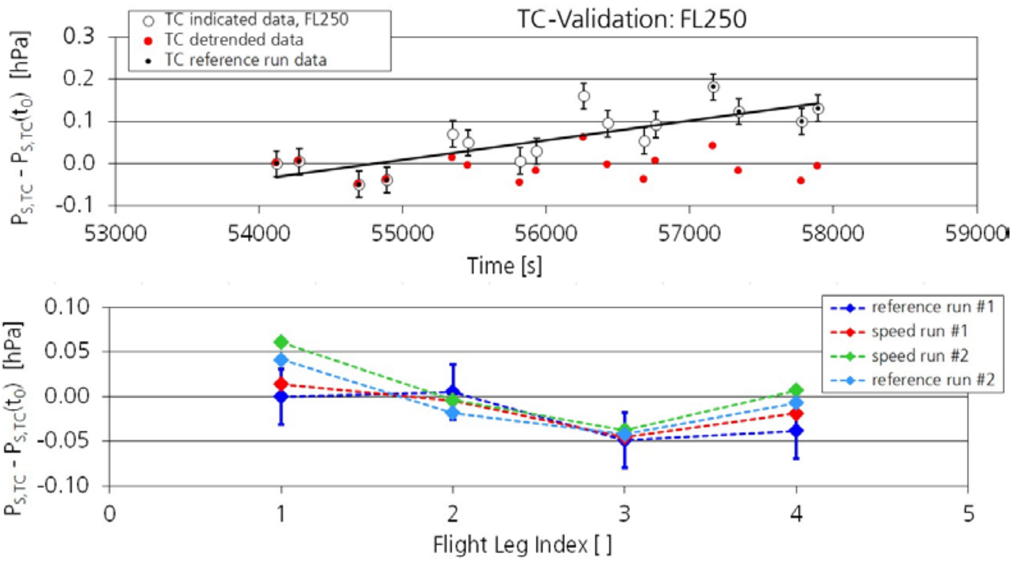

Figure 27: ***Detection of a temporal drift and a spatial variation in the Trailing Cone data at FL250 which is caused by a changing atmosphere. The two reference measurements with identical speed at the start and end of the Mach number series allow for identification of temporal (upper plot) and local (lower plot) variations in the atmospheric pressure field. The lower plot shows the detrended data.***

The obvious spatial inhomogeneity of the atmosphere in the test area which is still visible in the flight leg plot of Figure 27 can also be investigated and corrected for. We do this by also using the data from the reference measurements which directly yields the spatial dependence independent of any

Trailing Cone effect. From the two reference runs we calculate a mean pressure offset value for each flight leg and substract it from every test point taken on the respective flight leg. This correction only works if the spatial pressure modulation doesn't change too much during the measurement on this flight leg. We will later see that this is not allways the case but by applying the mean we get a fairly representative data set for the flight level.
The result of this procedure can be seen in Figure 28.

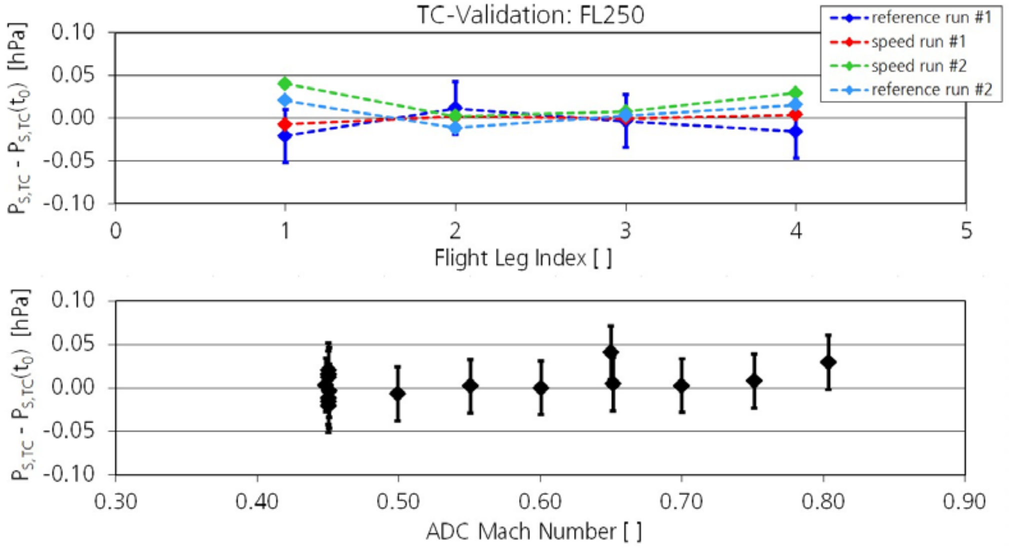

Figure 28: ***Trailing Cone envelope expansion data (height corrected according to*** **Equation 3*****) on FL250 after correction of the temporal drift and the spatial variation caused by a changing atmosphere. Dependence of the trailing cone pressure deviation from first value on this level on flight leg (upper plot) and Mach number (lower plot). The residual error (3σ) of the pressure data on this flight level is 4.7Pa.***

Since the remaining variation of the Trailing Cone pressure data in Figure 28 is significantly smaller than the pressure sensor accuracy we conclude that the envelope expansion on FL250 yields no measurable dependence of the Trailing cone method on the aircraft Mach number for the speed range flown at this altitude. By using the proposed flight strategy with reference test points at the beginning and end of the measurement we were able to show that the complete observed variation of the original Trailing Cone data can be attributed to spatial and temporal inhomgenities of the atmospheric structure.

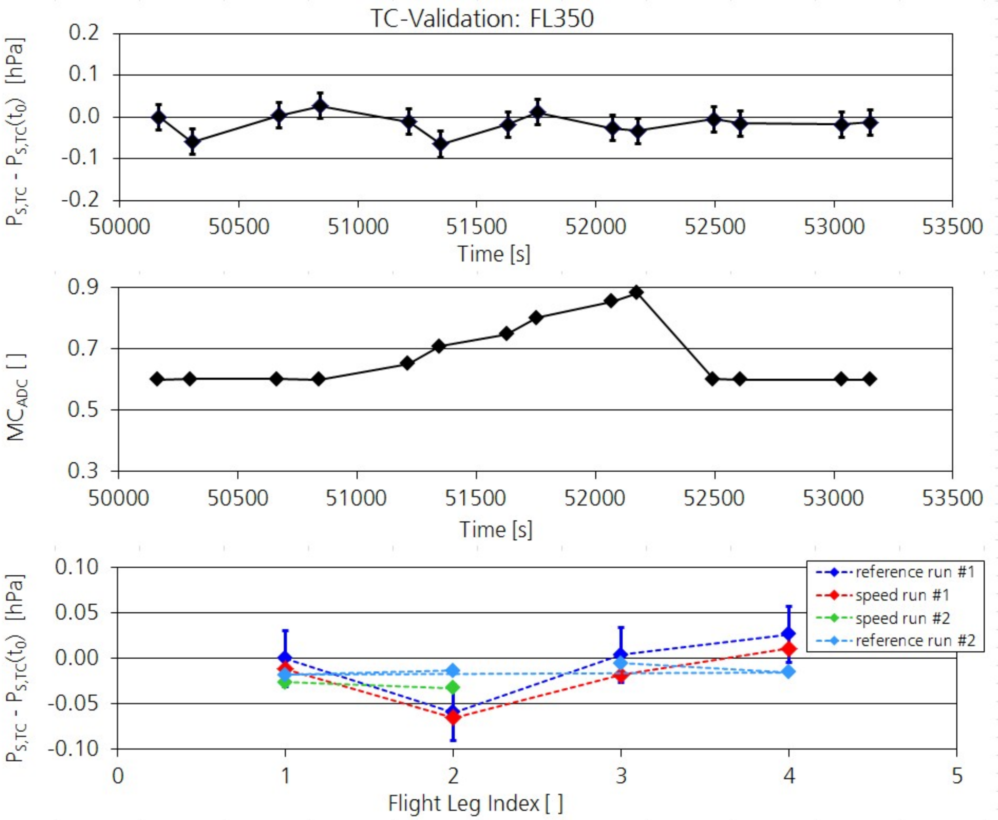

Figure 29: ***Result of the envelope expansion at FL350. Difference of Trailing Cone pressure data (height corrected according to* Equation 3*) from first value on this level. Visualisation of a possible temporal drift and spatial effects in the Trailing Cone data caused by variations in the atmospheric structure. The two reference measurements with identical speed at the start and end of the Mach number series allow for identification of temporal (top plot) and spatial (lowest plot) variations in the atmospheric pressure field.***

The same procedure was applied for flight level FL350 and the results can be seen in Figure 29 and Figure 30.

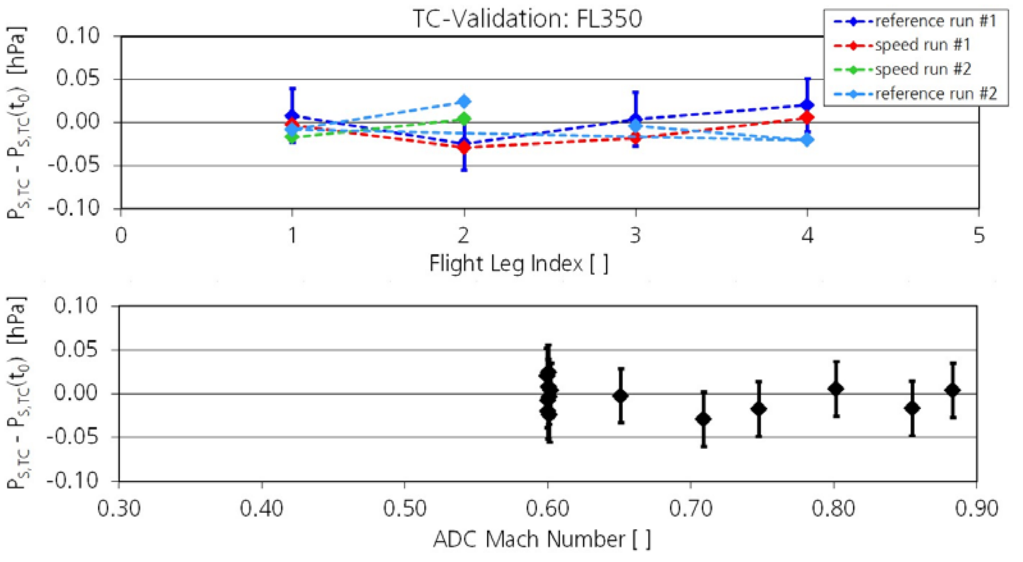

Figure 30: ***Trailing Cone envelope expansion data (height corrected according to*** **Equation 3*****) on FL350 after correction of the temporal drift and the spatial variation caused by a changing atmosphere. Dependence of the trailing cone pressure deviation from first value on this level on flight leg (upper plot) and Mach number (lower plot). The residual error (3σ) of the pressure data on this flight level is 4.7Pa.***

The data on this level which was flown first shows practically no temporal drift. Therefore, the atmospheric correction of the Trailing Cone reference data on this level is significantly smaller and consists of a small spatial contribution only. It is interesting to note that the spatial effect is not constant and shows a different structure with the Minimum at the flight leg 2 (instead of 3 on FL250).
However, the result for this flight level is same as for FL250: no Mach number dependent error can be detected in the Trailing Cone data for this flight level.

The last level flown in the validation was FL150 and the results can be seen in Figure 31 and Figure 32.

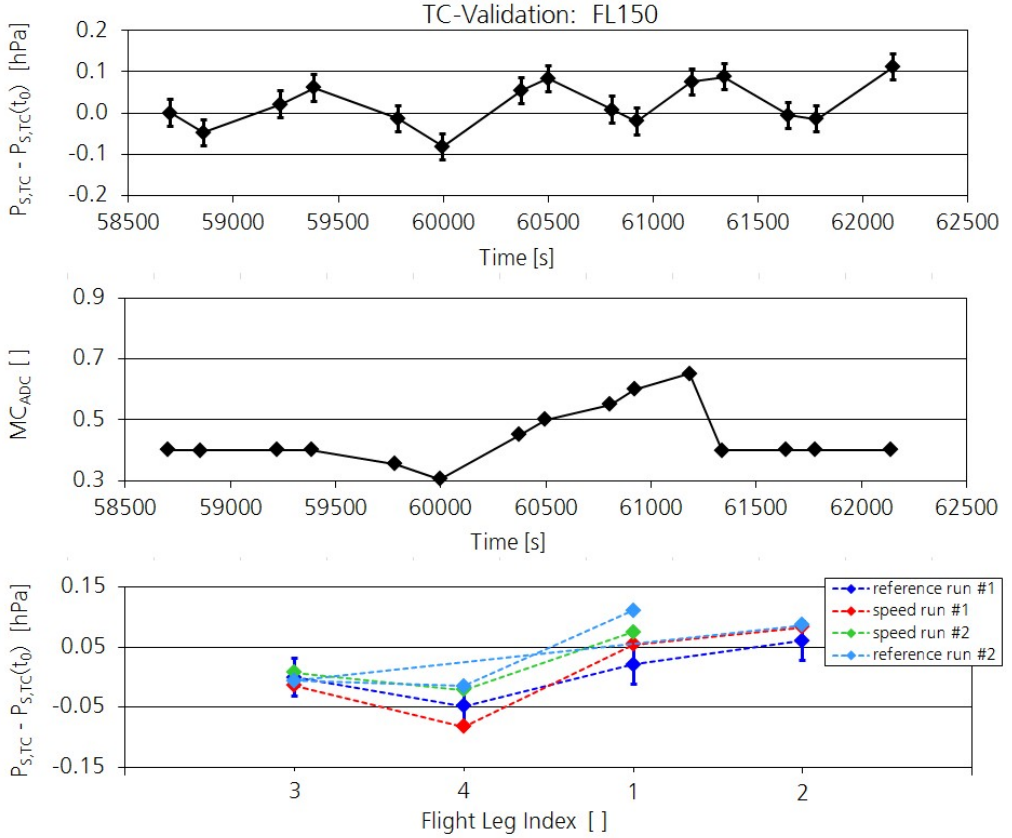

Figure 31: ***Result of the envelope expansion at FL150. Difference of Trailing Cone pressure data (height corrected according to*** **Equation 3*****) from first value on this level. Visualisation of a possible temporal drift and spatial effects in the Trailing Cone data caused by variations in the atmospheric structure. The two reference measurements with identical speed at the start and end of the Mach number series allow for identification of temporal (top plot) and spatial (lowest plot) variations in the atmospheric pressure field.***

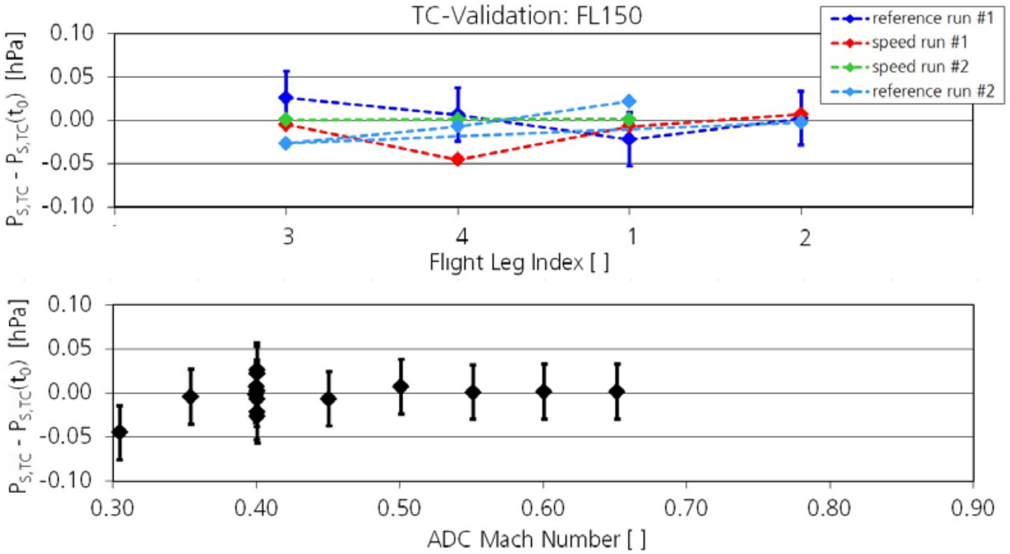

Figure 32: ***Trailing Cone envelope expansion data (height corrected according to* Equation 3*) on FL150 after correction of the temporal drift and the spatial variation caused by a changing atmosphere. Dependence of the trailing cone pressure deviation from first value on this level on flight leg (upper plot) and Mach number (lower plot). The residual error (3σ) of the pressure data on this flight level is 5.2Pa.***

Note that the racetrack measurement on this level started on flight leg 3. Therefore, the x-axis of the flight leg plots was changed to simplify plotting.
Figure 31 indicates that a small temporal drift is present in the data which shows the same sign as for the preceeding flight level FL250. A spatial structure can also be seen in the data. However, compared to the preceeding level it changed again now having the minimum at flight leg 4 which proves that the atmospheric structure is moving. This is in accordance with the time drift observation.
Concerning the envelope expansion on this level the corrected data shows the same small variability as for the preceeding flight levels and the conclusion that the Trailing Cone measurement is independent of the Mach number is the same.

Therefore, we can conclude that

1. The Trailing Cone measures the undisturbed static pressure in the vicinity of the aircraft with no detectable systematic error caused by aerodynamic effects.
2. This statement is valid for the complete flight envelope of HALO
3. The observed variations in the static pressure data of the Trailing Cone on a single flight level are caused by the spatial and temporal variability of the real atmosphere. An appropriate flight strategy allows for the detection and correction of this effect.
4. Therefore, the Trailing Cone can be used as an accurate pressure reference for the calibration of air data systems of the aircraft.
5. The statement is true for this specific Trailing Cone design (pressure port and location, cone design) and configuration (release point and length) on this aircraft only.
6. The uncertainty of the statement “no error” for the Trailing Cone reference pressure data is better than 0.1hPa (as determined during the tower Fly-Bys and visualized in Figure 23)
7. The statement “no systematic errors caused by arodynamic effects” was proved with an accuracy of 5Pa.

We also conclude that the proposed flight strategy for the Trailing Cone validation is mandatory in order to distinguish between atmospheric effects and an actual aerodynamic (Mach number) influence on the Trailing Cone method. Without the information from the two reference racetracks it would have been impossible to identify and separate these two effects.
We have to point out the difference between the absolute and the relative accuracy of a pressure sensor. Some of the observed modulations in the pressure data are smaller than the calibration error bar. However, if the sensor itself is stable over the time interval of the measurement one will still be able to detect relative changes much smaller than the calibration limit.

Calibration of the Air Data System

Once the Trailing Cone has been validated as an accurate pressure reference the method can be used to calibrate the aircraft air data system which is in our case the scientific instrumentation of the nose boom.

The calibration requires a comparison of the nose boom pressure data with the Trailing Cone reference pressure over the whole flight envelope of the aircraft. In principle this requires another test flight which has to cover the complete aircraft flight envelope. However, all these test points have been measured already during the Trailing Cone validation flights. This means that the required data set already exists if the boom instrumentation was operated during these flights. In this case no additional test flights are necessary to obtain a suitable calibration data set.

In order to investigate the result of the nose boom calibration the pressure data from the boom must be referenced to the height of the Trailing Cone sensor by using Equation 4. The required height differences dh_1 and dh_2 are calculated from the respective lever arms between the instruments and attitude data from the IRS.

The result of the nose boom calibration is then calculated as

$$\frac{\Delta p_s}{qc_i} = \frac{(p_{si,nb} + dp) - p_{si,tc}}{qc_{i,nb}}$$ **Equation 10**

where $p_{si,nb}$ is the indicated static pressure of the nose boom, dp the height correction for this sensor with respect to the TC-pressure sensor, $p_{si,tc}$ the indicated reference pressure from the Trailing Cone sensor and $qc_{i,nb}$ the indicated dynamic pressure as measured by the nose boom.

Result of Air Data System Calibration

Figure 33 shows the plot of this data as a function of a Mach number which was calculated from the indicated pressure values from the boom which were not subject to any kind of correction. As one can see this result is in good agreement

with theory (Figure 3) showing the expected general shape for a nose boom mounted air data probe. However, the absolute values differ significantly from “typical values” which is due to the relatively short boom of HALO which was designed as a best compromise between vibrational behavior (stiffness) and static source error. Figure 33 also includes data from an additional calibration flight for a heavy aircraft configuration which will be discussed later.
The error bars in the following results reflect the accuracy of the Trailing Cone and nose boom pressure sensors as well as the uncertainty of the height measurement used for data correction.

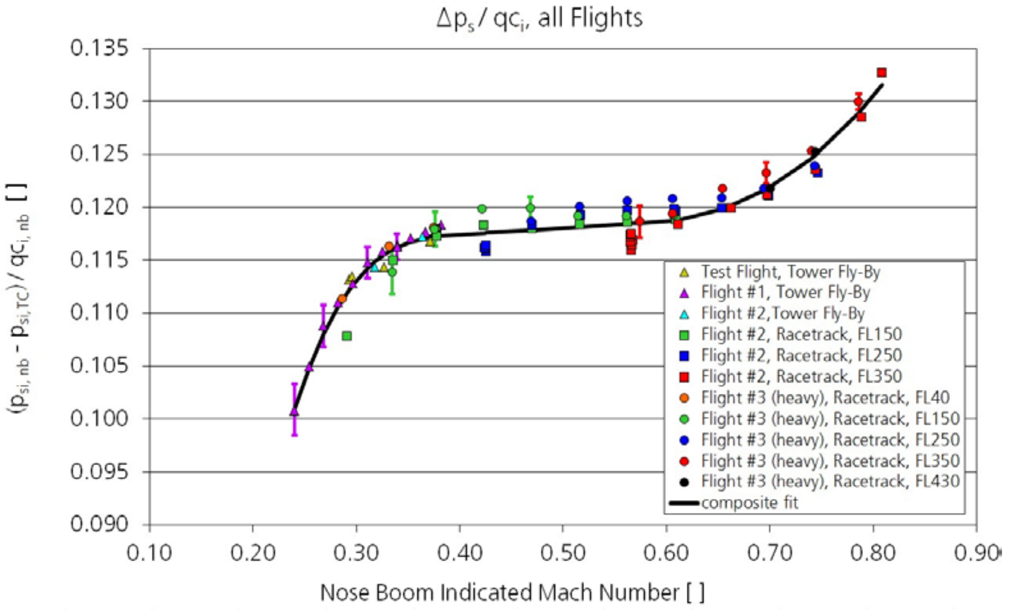

Figure 33: ***Result of the nose boom static source error calibration for HALO in the clean aircraft configuration. The plot shows basically data from 3 flights: Tower Fly-By (#1), envelope expansion which was performed for a light aircraft (#2) and data taken over the complete aircraft envelope for a heavy aircraft (#3). Tower Fly-By data from an earlier test flight were added to demonstrate the repeatability of the measurement.***

Discussion

In order to discuss this result in detail we plot the data from a single flight only which can be seen in Figure 34. The data indicates that there must be a weak dependence of the static source error on static pressure (i.e., aircraft altitude), since the $\Delta p_i/qc_i$ data from the three flight levels shows a bend towards smaller values at different (indicated) Mach number values. The small scatter of the eight data points belonging to the Mach number which was chosen for the reference run on each level proves the accuracy of the TC method as well as the quality of the pressure instrumentation on the boom.

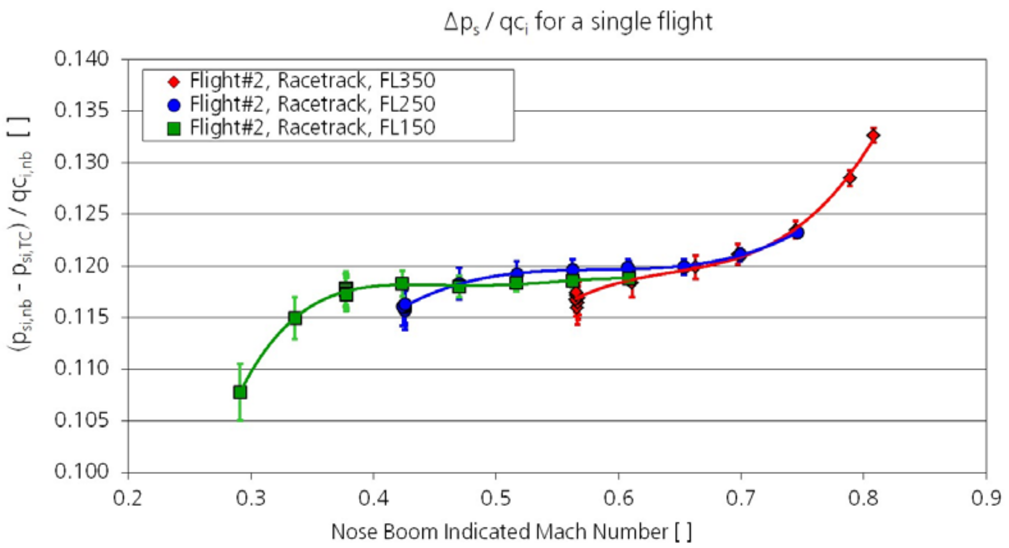

Figure 34: ***Result of the nose boom static source error calibration for HALO in the clean aircraft configuration for a single flight. The height levels are plotted in different colors.***

In order to further investigate this observation a fit was applied to the $\Delta p_i/qc_i$ data in Figure 33. By plotting the deviation from this fit over Mach number for a single flight the system behind these deviations becomes more obvious as one can see from Figure 35. The measured static source error is smaller than the fitted values when approaching the maximum and minimum speed on a certain flight level. Furthermore, the center of this parabola shaped curve is shifted towards higher Mach numbers with increasing flight altitude. Note that Figure 35 shows absolute pressure values and that the absolute value of this residual error is relatively small with maximum values of about 0.2 hPa.

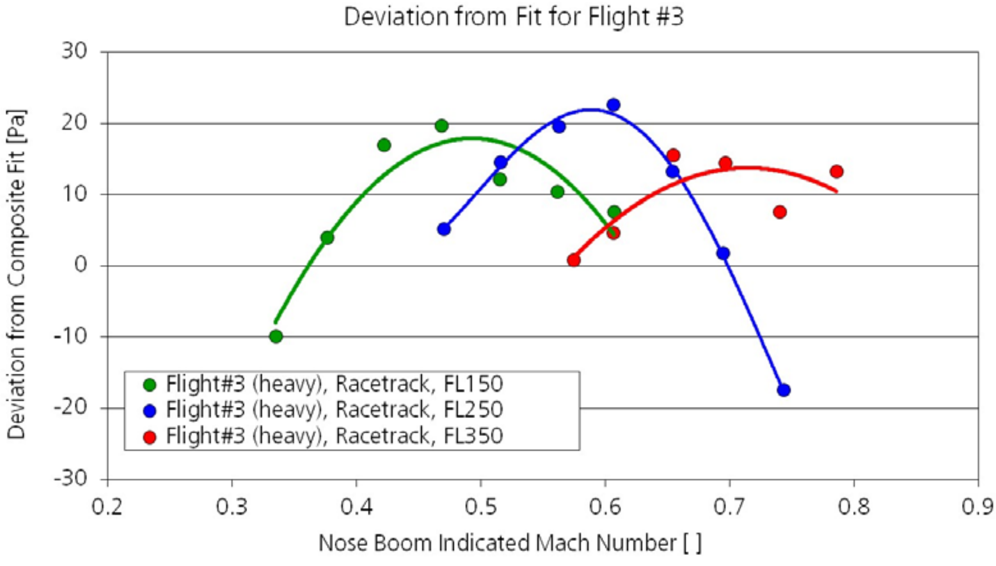

Figure 35: ***Deviation of Trailing Cone pressure from a mean fit into the complete static source error data from Figure 34. The data is from a single flight and was converted into absolute pressure units.***

Based on this observation we added a second correction term to the parameterization of the static source error. This was achieved by shifting the error curves of Figure 35 onto each other and applying a fit to the resulting error distribution. Figure 36 shows that the necessary shift in MC_i can be parameterized as a function of static pressure.

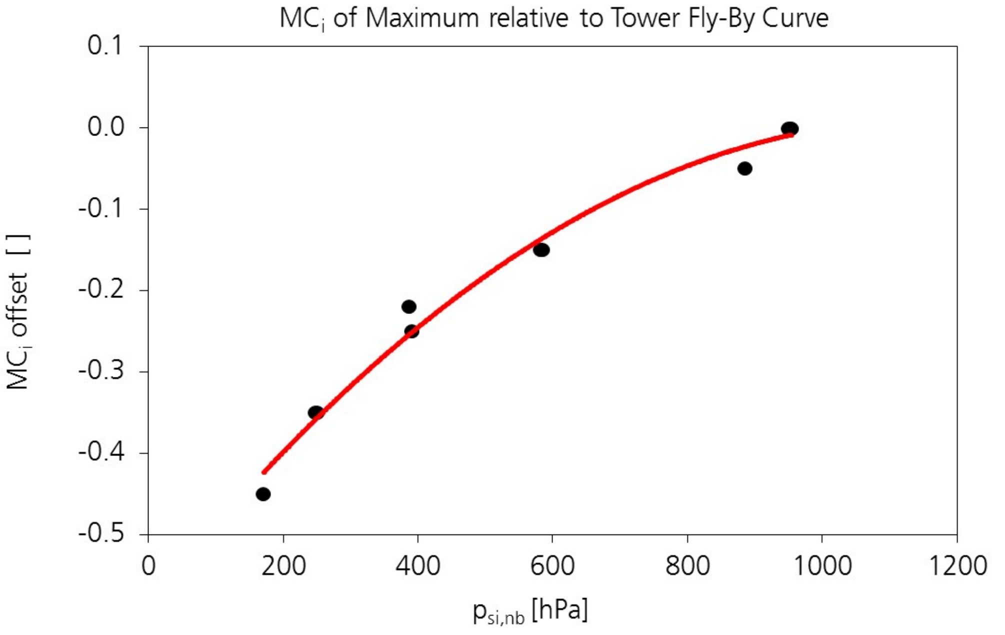

Figure 36: P*arameterization of the shift in MC$_i$ which is necessary to align the error curves in* Figure 35 *with respect to their maximum. The plot contains data from all flights including the heavy aircraft configuration and the flights with the belly pod.*

The difference between the complete parameterization of $\Delta p_i/qc_i$ and the actual data gives an idea how well the measured static source error can be parameterized and how much statistical uncertainty is caused by the method itself or the test conditions.

This result is shown in Figure 37. As one can see the parameterization works very well: the static source error can directly be calculated from the non-corrected boom data with a maximum deviation of about 0.2 hPa (3σ) which is close to the instrument error of the sensors being used. This is remarkable especially since the included data was acquired from different flights which took place over a time period of more than two months. The error bar for a single test point is about 0.1 hPa and is mainly due to the calibration of the sensor itself. We therefore conclude that the total uncertainty in the prediction of the static source error as a combination of these two values is about 0.2 hPa.

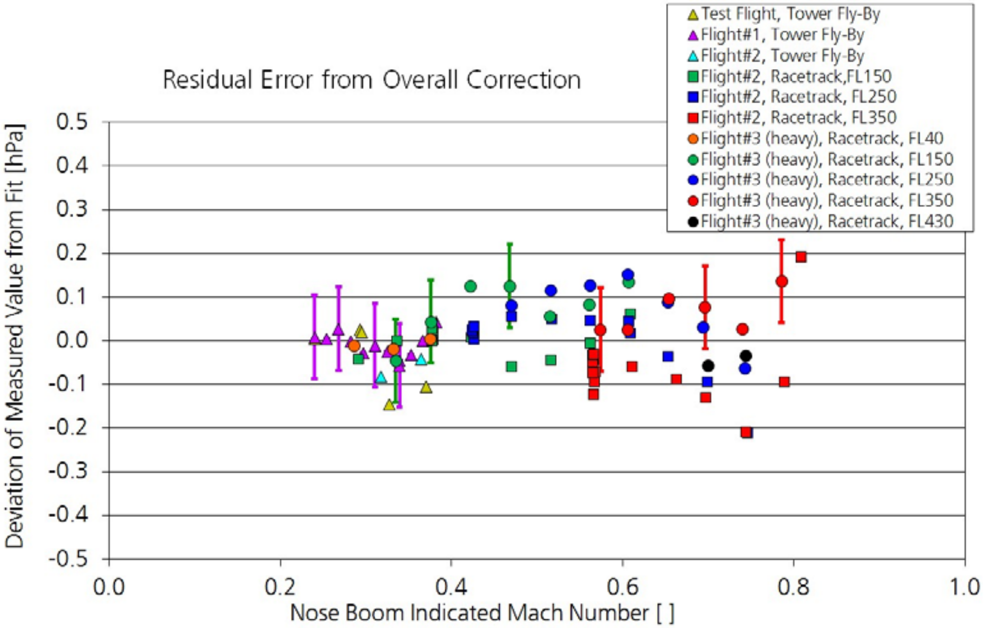

Figure 37: ***Deviation between the static source error as measured directly using a Trailing Cone and the value which was calculated from Mach number and static pressure using the parameterization which was derived from the data. The plot shows data from test flights performed with a "light" and "heavy" aircraft configuration over the full aircraft envelope.***

The data analysis shows that the flight test data allows for an accurate parameterization of the observed data. The comparison of the calculated static source error to real data from the TC measurement proves that the static source error parameterization is robust and that no significant additional dependencies on other flight parameters exist. The best result was achieved by a parameterization of $\Delta p_i/qc_i$ as a function of indicated Mach number (i.e. a Mach number calculated from the non-corrected pressure measurements) with an additional small correction term which also uses the indicated static pressure.

Influence of Aircraft Weight and Configuration

As mentioned above the calibration of an air data system is valid for the respective aircraft configuration only. Any change to the aircraft with impact on the aircraft shape, aerodynamics or flight behavior can potentially influence the static source error.

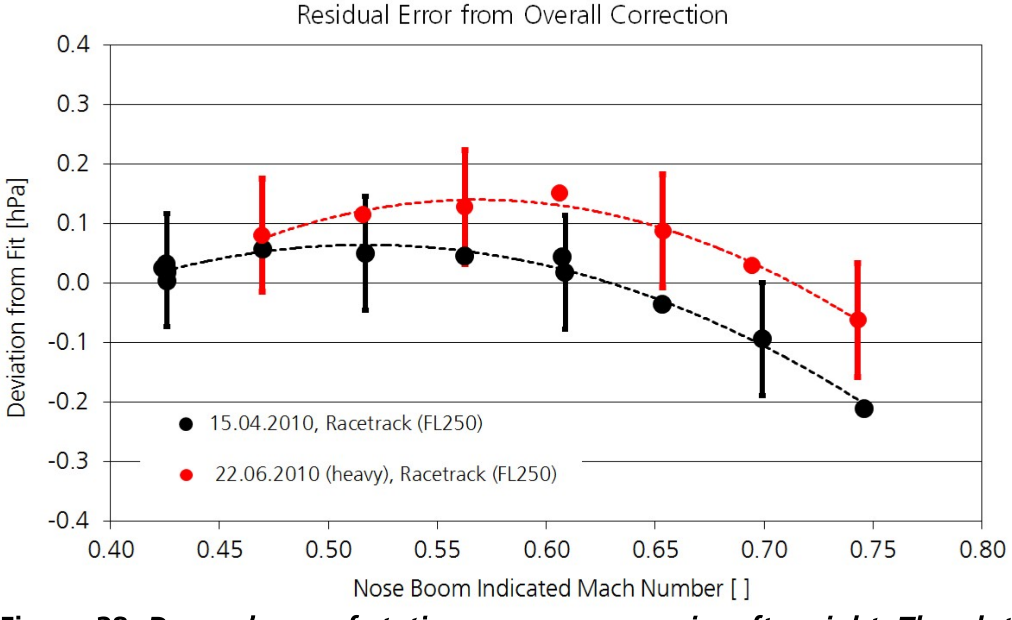

Figure 38: ***Dependence of static source error on aircraft weight. The plot shows the deviation between the actual static source error as measured directly by the Trailing Cone and the value calculated from the (mean) parameterization which was found from the data of all test flights for these two aircraft configurations. Note the small scatter among the 8 data points at the left side which represent the two reference runs at start and end of the measurement on this level.***

The first investigation on this issue concerned the aircraft weight. The initial test flights for the Trailing Cone validation in April 2010 were performed with a light aircraft. A second test flight in June 2010 was performed with the same aircraft operated close to the maximum takeoff weight (max fuel). On this flight we also checked the correct TC length using the same procedure as for the light aircraft. The measurements can be seen in Figure 19 and the result was identical to the value which was found for the light aircraft.

As one can see from Figure 38 the aircraft weight does influence the static source error of the pressure measurement taken by the instrumented boom. The effect seems to increase with higher Mach numbers. The results on the other two flight levels are almost identical. However, this effect is small and close to the calibration accuracy of the pressure sensors.

One year after the TC calibration of the nose boom for the clean aircraft configuration HALO underwent flight tests with the new belly instrumentation pod which is shown in Figure 8. Due to the size of this structure one would expect a significant impact on the aircraft air data system. In order to investigate this effect HALO was equipped again with the TC during these flights. Again, the TC length was checked. Figure 19 clearly shows that the result was the same as for the other aircraft configurations.

The experimental nose boom instrumentation was reconfigured for these flights and due to an error in the sensor temperature control the nose boom data accuracy turned out to be insufficient to perform a proper calibration. Therefore, we cannot present static source error data from the nose boom for the belly pod experiment.

However, we are able to show the influence of aircraft configuration on one of the three standard air data systems (ADS-2) of the aircraft, which is regularly recorded by BAHAMAS via an ARINC429 interface. The aircraft air data systems use two pitot static probes which are symmetrically installed at the right and left part of the aircraft nose as one can see in Figure 9. The ADS-2 internally applies a static source error correction to the measured pressure data and provides the corrected value as “static pressure” on its digital interface. Figure 39 shows the difference of this static pressure from the Trailing Cone values.

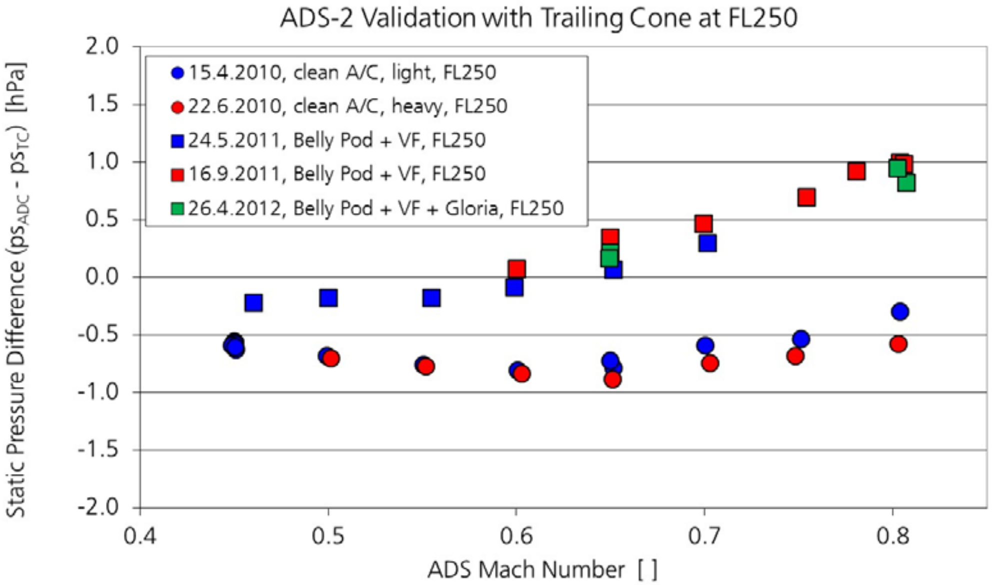

Figure 39: ***Check of the HALO air data system for different aircraft configurations on flight level FL250. The plot shows the impact of aircraft weight and outer shape caused by the attachment of the belly instrumentation pod.***

One immediately sees the impact of this huge external installation on the ADS pressure measurement. While the aircraft weight effect is small and comparable to the impact on the nose boom data the belly instrumentation pod shifts the static source error by almost 1.5 hPa. It is interesting to see that this shift goes into the “right direction” i.e. the error in the static pressure data from the ADS is reduced for lower Mach numbers. This data can directly be used to check the RVSM requirements for ADS-2. In order to do this, the above results have to be converted into (pressure) height units according to the international standard atmosphere. The result is shown in Figure 40 for a single flight leg along with the applicable limits in Mach number and altitude error.

By certification the HALO is treated as a non-group aircraft. Therefore, the aircraft has to meet the non-group requirements for RVSM operation throughout an aircraft specific RVSM Envelope of MC = 0.86 between 29,000feet and 41,000feet.

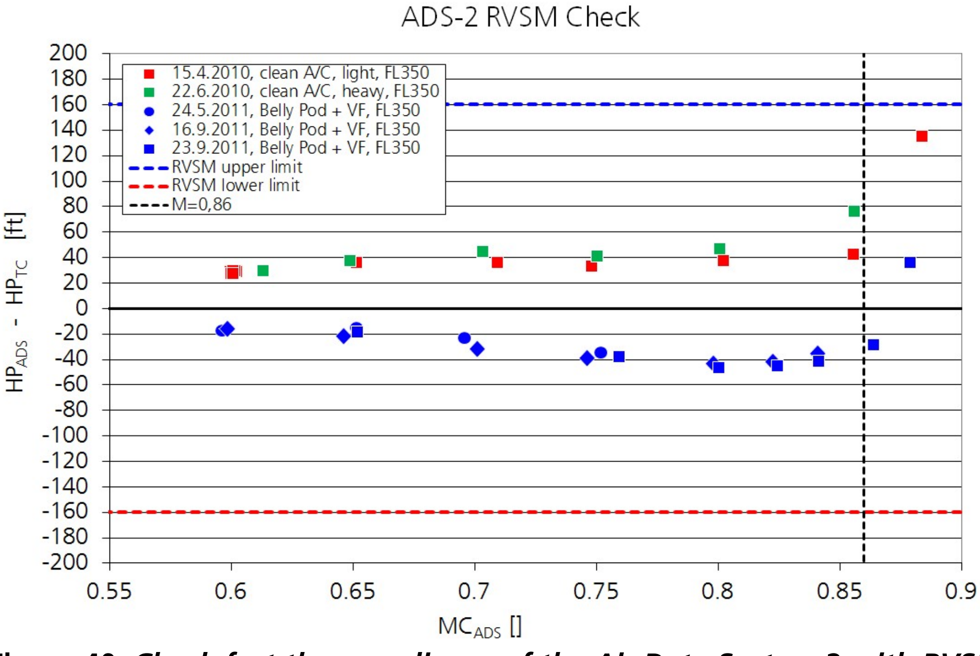

Figure 40: ***Check fort the compliance of the Air Data System 2 with RVSM requirements on FL350. The applicable height and Mach number limits are plotted along with the data for different aircraft configurations on Flight Level FL350.***

As can be seen from Figure 40 the air data system ADS-2 which has been recorded throughout the nose boom calibration flight trials fulfills the RVSM requirements as stated in the aircraft certification. The data also shows that this statement is valid for the different possible aircraft configurations (light aircraft, heavy aircraft and the external installation "Belly Pod").

Summary/Conclusion

We have demonstrated the successful implementation of a Trailing Cone (TC) system on the German atmospheric research aircraft HALO. The validation of the TC system proved that the Trailing Cone shows no detectable systematic error within the calibration limit of the pressure transfer standard being used. This could be demonstrated over the complete flight envelope of the aircraft.

The successive calibration of an experimental nose boom mounted air data system with the Trailing Cone method resulted in a parameterization of the static source error which can reproduce the experimental results with an accuracy of about 0.2hPa over the full flight envelope of the aircraft. This calculation almost completely depends on Mach number and contains only a small additional pressure dependent term. We also investigated the influence of the aircraft configuration concerning the aircraft weight or the installation of an external structure on the static source error.

We were able to show that it takes only three test flights to implement the TC on an aircraft and to perform the complete calibration of an air data system. These flights concern the Trailing Cone length determination (#1), the Tower Fly-By validation (#2) and the envelope expansion (#3). Flights #2 + #3 are also used to calibrate the air data system.

For an efficient flight test and in order to achieve the maximum accuracy we propose three important improvements to the classical TC experiment:

1. Use of a high precision inertial reference system with post processing capabilities to accurately determine the height above runway during tower Fly-By.
2. The application of a height correction to the TC raw data for the validation test points in order to eliminate variations caused by aircraft vertical motion and to reference the pressure data to a single height.
3. Choice of a racetrack pattern for the TC envelope expansion. Measurement of a reference pressure at the beginning and the end of a

speed run on each flight level and for every test point location in order to discriminate spatial and temporal atmospheric effects in the data.

Among the existing methods which can be used to provide a ground reference pressure during tower Fly-Bys we strongly recommend to determine this pressure as a differential measurement by using the aircraft Trailing Cone sensor data from the ground block. The time dependent relative variation of ground pressure during the flight can then be added from an independent sensor.

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